DISTRIBUTED ENERGY STORAGE POTENTIATING THE PARTICIPATION OF PV SOURCES IN ELECTRICITY MARKETS

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ABSTRACT

Distributed Energy Storage is gaining attention from different electric stakeholders as a mean of mitigating the variability and intermittency of photovoltaics. Moreover, distributed energy storage enables the participation of renewable generation in electricity markets and enhances their value by providing ancillary services. This paper proposes a functional architecture and an underlying optimisation method that aims at potentiating the participation of photovoltaic sources in spot and secondary reserve markets through an optimal utilisation of distributed storage capacity. The developed method is validated on a 3-MW medium voltage distribution network connected hybrid system case study. Results demonstrate that the proposed methodology enhances the technical and economic value of the photovoltaic coupled with distributed storage.

INTRODUCTION

Renewable Energy Sources (RES) are expected to represent 50% of power generation by 2050 [1]. Particularly, generation from photovoltaics (PV) will reach 9% of net generation in the current European Union energy reference scenario which corresponds to more than doubling current PV capacities. A significant portion of PV sources will be connected at the distribution system level challenging the adequate accommodation of this technology. The growth in PV and other intermittent energy sources needs to be facilitated by distribution network upgrade or new equipment for actively managing grid operation (e.g. smart grid components) and controlling flexible resources, such as energy storage, in order to tackle the operational and flexibility challenges posed by these sources [1].

Distributed energy storage systems (DESS) are deemed as fundamental both by distribution system operators (DSO) and by the solar industry if increasing shares of variable renewable sources are to be achieved with the highest operational efficiency. DESS can tackle the local operational challenges such as voltage support posed by PV sources while enhancing distribution grid flexibility and reliability [2]. Moreover, hybrid systems where DESS is coupled with PV (PV+DESS system) allow firming PV power output thus enabling an effective electricity market participation as well as the provision of ancillary services. This paper details a methodology developed to maximize the value of a PV+DESS system participating in electricity markets. The provision of multiple services that present distinct technical and market characteristics, economic value and time frames (from the planning to the actual operation) is the core of the developed method. Firming PV output, participation on spot and secondary reserve markets are the functionalities focused in this work. Therefore, a functional architecture that takes into consideration the positioning of DESS within the electric infrastructure is established in order to cope with the aforementioned integration challenges of the hybrid system.

PV CONNECTED DISTRIBUTED ENERGY STORAGE

The present and expected future integration levels of variable renewable energy sources and particularly PV in the distribution infrastructure will not only demand a more constant, predictable and reliable generation but also require these sources to support grid operation by providing ancillary services. Therefore, coupling a PV system or combination of systems with DESS stands as a technological solution that can contribute to the accommodation of renewable power. In recent years, the connection of DESS and PV with the objective of tackling the aforementioned operational and market challenges has been the focus of several studies.

Works on PV+DESS systems present usually an operational algorithm along with a DESS sizing methodology. The typically high investment cost of DESS leads studies to pursue the minimum DESS' power and energy requirements to perform a single [3-5] or a combination of services [6] such as PV fluctuations suppression [7], voltage regulation [6], firming PV output [4, 5], or peak shaving [8]. In addition, distributed storage technologies such as lead-acid [5] or li-ion [8] battery systems or ultracapacitors [3] have been identified as suitable for the PV+DESS design. In spite of the potential performance of a hybrid system in an electrical market environment, studies on its provision of ancillary services are often reduced to non-competition and local services such as local voltage control [6].

Functional architecture

In order to address integration challenges and widen the potential technical and economic benefits of a PV+DESS system connected to a medium-voltage distribution network, a functional architecture is proposed in this work (see Figure 1). The idea is, on one hand, to enable the hybrid system to cope with local and intrinsic operational constraints (e.g. PV output fluctuations);

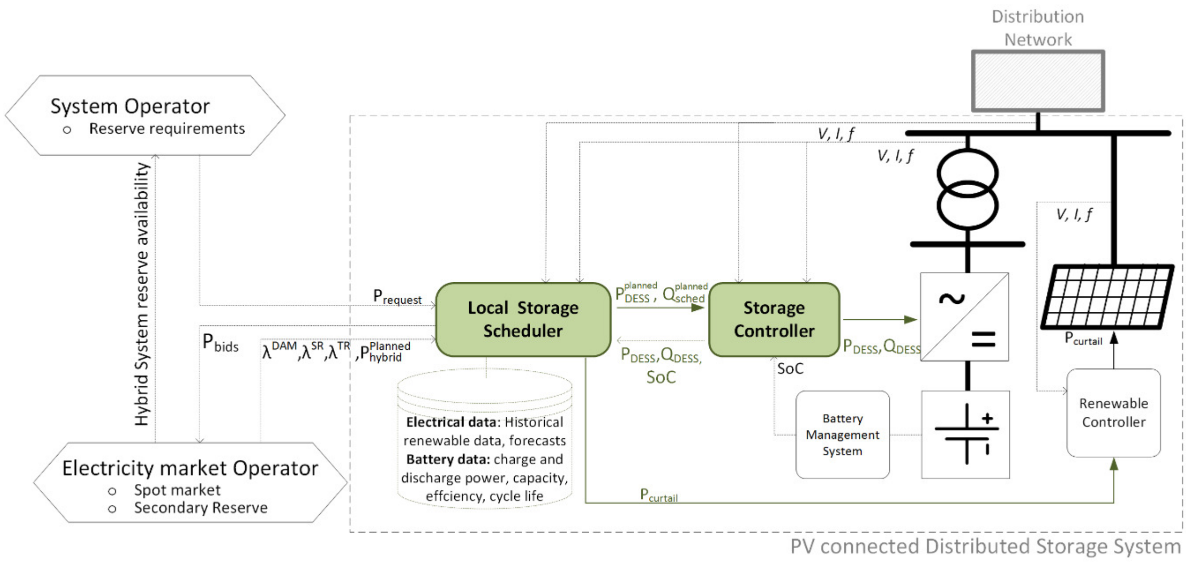

Figure 1 - Proposed architecture for a PV connected distributed energy storage system

on the other hand, the architecture promotes the capability of participating in multiple markets such as the day-ahead spot market and the secondary reserve market. However, reserve management is responsibility of the grid operator and, thus, the architecture takes into account its requests of active power adjustments.

This functional architecture is constituted by two main operational and control components of local nature: the Storage Controller (SC) and the Local Storage Scheduler (LSS). The presence of both components is justified by the different characteristics of the functionalities that the hybrid system can perform in terms of time requirements (e.g. time scales, time horizons and response time) and complexity of optimisation processes (e.g. proportional-integral response, linear programming). The LSS, due to its broader knowledge of the positioning and electric environment of the PV+DESS system, handles less time-constrained but more complex optimisation developments. The SC responds to fast variations in local electric measures and references of active and reactive power previously calculated by the LSS, representing the upstream hierarchic controller of the DESS' power conversion system (PCS) and storage device.

The Storage Controller

The following equation dictates the combined output of the PV+DESS system:

$$P_{hybrid}(t) = P_{PV}(t) + P_{DESS}(t) \quad (1)$$

with P_{hybrid} corresponding to the power effectively injected into the distribution grid, P_{PV} being the present PV production and P_{DESS} representing the charge (if $P_{DESS} < 0$) or discharge (if $P_{DESS} > 0$) of the storage system. The Storage Controller integrates the PV firming functionality that aims at producing a constant combined power output following periodic active power references calculated by the Local Storage Scheduler. This application allows the mitigation of PV intermittency and, in addition, the participation on the hybrid system in electricity markets as it increases the controllability of PV generation. The basic equation that manages the firming functionality is as follows:

$$P_{DESS}(t) = P_{hybrid}^{planned}(t) - P_{PV}(t) \quad (2)$$

with $P_{hybrid}^{planned}$ representing the combined power day-ahead planned in the LSS and hourly sent as a reference to the SC. Furthermore, due to the limited power and energy ratings of DESS, the SC includes limitations for the P_{DESS} and for DESS' State of Charge (SoC). The charging and discharging powers of DESS are limited by the storage device itself and/or its PCS, while the SoC is limited by the storage technology and the energy capacity of the storage device. For instance, battery technologies such as lead-acid are susceptible to higher energy capacity degradation if subjected to extreme SoC conditions, which imposes limits to the utilization of the stored energy. In the case the upper (e.g. SoC=100%) or lower (e.g. SoC=10%) limits of the SoC are reached, the intermittency of the PV source would no longer be addressed. Consequently, it is implemented a second operating mode that is activated in near-limit SoC events with the objective of ensuring continuity in the suppression of severe PV's power fluctuations while leading the SoC to appropriate PV firming operating conditions.

METHOD OF PV MARKET PARTICIPATION

The Local Storage Scheduler, along with handling technical constraints, is committed to the maximization of the economic revenue of the PV+DESS system. Therefore, the LSS day-ahead plans the operation of the hybrid system according to the forecasted PV generation, the available storage resource and spot and secondary reserve markets information. In addition, requests of upward and downward secondary reserve from the system operator are addressed during the actual performance of the planned operation. The Iberian electricity market and the Portuguese ancillary services market are the market designs underlying the developed PV market participation method. These markets, due to their technical and economic features are fairly representative of European markets [9].

Spot electricity market participation

The participation of PV in spot electricity markets requires forecasting the PV production for the next day. As developing forecast techniques is not the objective of this work, a forecast error is imposed to the available time-series of PV output as it may be regarded as the perfect PV forecast. An exponentially weighted moving average (EWMA) method of seventh order is applied in order to emulate typical forecasting errors and dependencies between successive periods.

$$P_{PV,i}^{fc} = \delta P_{PV.i} + \delta(1-\delta)P_{PV,i-1} + \cdots + \delta(1-\delta)^7 P_{PV,i-7} \quad (3)$$

Equation (3) means that the forecasted PV generation in hour i is the weighted sum of actual PV realizations, with δ being the weight factor. This factor is defined by the imposed forecast error magnitude and the forecast horizon. The auction of the spot market occurs at the twelfth hour of the previous day meaning a forecast horizon between 13 and 36 hours. The forecast error is assumed to proportionally increase between 20% and 50% between these periods [4]. The PV generation profile auctioned in the spot market is defined as follows:

$$\sum_{i=1}^{N} P_{hybrid,i}^{planned} = \sum_{i=1}^{N} \gamma_i . P_{PV,i}^{fc} \quad (4)$$

where γ_i is a time-dependent adjusting parameter. This parameter reflects the expected storage losses due to the charging and discharging cycles to maintain the PV+DESS system output as planned (see Eq.(2)). Moreover, it serves the purpose of adjusting storage SoC in the most economical way i.e. according to spot market prices. A $\gamma_i > 0$ means that the bids presented in the market are higher than the forecasted PV power which implies compensation by the DESS, thus reducing storage' SoC. However, the magnitude of γ_i is biased by spot market prices in order to maximize the hybrid system revenues. Nevertheless, Eq. (4) ensures that the hybrid system does not inject nor absorb power in non-solar periods. It is assumed that spot market clearing prices are known a priori and are not influenced by the hybrid system which acts as a price taker.

Upward and downward deviations from of the planned PV+DESS system output (with a 5% allowed threshold [9]) are economically penalized according to the market price of the regulation energy that needs to be shifted to compensate the surplus or lack of PV+DESS production. In the case the hybrid system's power deviation occurs in the direction required by the system operator, the hybrid system does not incur in an economic penalty.

Secondary Reserve market participation

The potential of DESS to allow the participation in secondary reserve markets implies a significant increase in the flexibility and controllability of PV-based systems. Secondary reserve is managed by the system operator as it is used to bring frequency to its nominal value and/or maintain interconnection power flows at the planned levels. On the contrary of frequency control that is often a regulated and mandatory service (e.g. Portugal), making available secondary reserve is a market-driven service. The auction occurs after the spot market auction on the twentieth hour of the day before power delivery. Although European markets typically present minimum power capacity requirements, this work assumes that the conditions of eligibility to participate in this market are fulfilled [9].

The objective function (see Eq. (5)) aims the maximization of the expected revenue value of performing the secondary reserve service. The probabilistic approach is justified by the fact that there is no foresight to the periods where upward or downward secondary reserve will be requested. Nevertheless, the hybrid system is considered as a price-taker participant with a priori knowledge of secondary reserve prices.

$$\max z = \sum_{i=1}^{N} \lambda_i^{SR} . \left(P_{up,i}^{SR} - P_{down,i}^{SR}\right) + \sum_{i=1}^{N} \lambda_{up,i}^{SR} . P_{up,i}^{SR} . \sigma_{up} + \sum_{i=1}^{N} \lambda_{down,i}^{SR} . P_{down,i}^{SR} . \sigma_{down} \quad (5)$$

s.t. $(\forall i \in N)$

$$P_{up,i}^{SR} + 2 . P_{down,i}^{SR} = 0 \quad (6)$$

$$P_{up,i}^{SR} \leq P_{hybrid}^{max} - P_{hybrid,i}^{planned} \quad (7)$$

$$P_{up,i}^{SR} \leq \overline{P_{DESS}} \quad (8)$$

$$-P_{down,i}^{SR} \leq P_{hybrid,i}^{planned} \quad (9)$$

$$-P_{down,i}^{SR} \leq \underline{P_{DESS}} \quad (10)$$

$$-\sum_{k=1}^{i} \frac{P_{up,k}^{SR} \cdot \sigma_{up}}{\eta_d \cdot E_{DESS}} - \sum_{k=1}^{i} \frac{P_{down,k}^{SR} \cdot \sigma_{down} \cdot \eta_c}{E_{DESS}} \leq \overline{SoC} - SoC_0 \quad (11)$$

$$\sum_{k=1}^{i} \frac{P_{up,k}^{SR} \cdot \sigma_{up}}{\eta_d \cdot E_{DESS}} + \sum_{k=1}^{t} \frac{P_{down,k}^{SR} \cdot \sigma_{down} \cdot \eta_c}{E_{DESS}} \leq -\underline{SoC} + SoC_0 \quad (12)$$

$$-P_{down,i}^{SR}, P_{up,i}^{SR} \geq 0 \quad (13)$$

The proposed mathematical model for the participation of the hybrid system in the secondary reserve market is presented in Eq. (5-13). The economic valuation of this service is constituted by two terms. The first term is the capacity headroom, given by $P_{up,i}^{SR} - P_{down,i}^{SR}$, that the hybrid system is capable of providing and that is independent of whether the hybrid system is called by the system operator to provide reserve. This term is valorized according to the secondary reserve market price λ_i^{SR} in €/MW representing a deterministic revenue. The second term represents the expected effective energy provided due to the provision of the capacity headroom. $P_{up,i}^{SR} . \sigma_{up}$ and $P_{down,i}^{SR} . \sigma_{down}$ correspond to the expected energy provided in a upward or downward secondary reserve request by the system operator, respectively.

The concepts of energy-to-contracted-upward-capacity and energy-to-contracted-downward-capacity ratios i.e.

σ_{up} and σ_{down} are introduced. These probabilistic parameters model the relationship between the capacity headroom auctioned and the amount of energy that the hybrid system is expected to provide by the system operator. In order to calculate these values, an analysis of the historical secondary reserve market behaviour is performed. In the Portuguese ancillary services market, between 2009 and 2012, these values are estimated to be $\sigma_{up} = 0.163$ and $\sigma_{down} = 0.075$. Eq.(6) models a constraint of the secondary reserve market in which bids of upward and downward capacity headroom are required to be proportional. For example, to bid 2 MW of upward adjustment a 1 MW bid in the downward direction in the same hour needs to be in place. Eqs. (7-13) manage the overall behaviour of the hybrid system as well as the power and energy limits of the DESS. During operation, in the case the hybrid system not being capable to accomplish a reserve request by the system operator, it is economically penalized as follows:

$$\beta_i = K.\left(\left(P_{up,i}^{SR} - P_{up,i}^{actual}\right) + \left(P_{down,i}^{actual} - P_{down,i}^{SR}\right)\right).\Delta t_i^{fl}.\lambda_i^{SR} \qquad (14)$$

where K is the failure coefficient that is 1.5, $\left(P_{up,i}^{SR} - P_{up,i}^{actual}\right) + \left(P_{down,i}^{actual} - P_{down,i}^{SR}\right)$ correspond to the difference between the bided capacity headroom and the actual capacity headroom that the hybrid system is able to provide, and $\Delta t_i^{fl}$is the proportional of time in which the hybrid system is not able to adequately respond to the system operator requests in hour i.

SYNOPSIS OF THE CASE STUDY

The developed method is validated on a case study of a 3-MW PV system connected to a medium voltage distribution network. A real time-series of a Portuguese PV park on a minute sampling rate of instantaneous production data during a 1-year period is used. The studied PV source presents a capacity factor of 18.2%.

In addition, this study includes the year 2013 markets data of the Iberian spot market and the Portuguese ancillary services market. As the available data from the Portuguese system operator only contemplates the volume, the direction and the hour of secondary reserve requests, it is assumed that requests to the hybrid system are always in accordance with the capacity headroom bided and the energy required is proportional to the total secondary reserve energy used in the whole system.

A 3MW-4.5MWh li-ion based DESS is deployed to potentiate the participation of the PV source in electricity markets. The sizing of the system corresponds to the minimum DESS' power and energy requirements that can ensure a 95% reliability of the planned hybrid system profile when only participation in the spot market. This means that the hybrid system is capable of following the planned production during 95% of solar hours. The performance of the hybrid system when participating in the spot market and the secondary reserve market is compared with its performance when participating only in the spot market. Moreover, in spite of not performing the firming functionality, the participation of the PV source without DESS in the spot market is analysed to establish reference results. The synopsis of the results is presented in Table I.

Table 1 – Synopsis of the assessment of the hybrid system performance

Yearly Revenue	PV source w/o DESS	Hybrid system only in spot market	Hybrid system in spot and reserve market
Spot market	213.5 k€	219.2 k€	182.7 k€
Spot market penalties	52.8 k€	2.1 k€	4.1 k€
Reserve market	-	-	253.7 k€
Reserve market penalties	-	-	15.8 k€
Net revenue	**160.7 k€**	**217.1 k€**	**438.5 k€**

Table I reveals that non-firmed PV output results on spot market penalties of about 25% of potential. This value is strongly dependent on the PV forecast accuracy as reduced forecast errors would lead to spot market penalties reduction. In spite of the forecast dependency, the intermittency of the PV source would still not be addressed. The hybrid system participating only in the spot market can increase the potential revenues while mitigating penalties for production deviations. Albeit energy losses of the charging and discharging cycles could reduce the potential revenues of spot market participation (yearly losses are 85 MWh), the method is capable of achieving an increase in potential revenues. This is due to adjusting factor γ_i which selects the most profitable periods to adjust the DESS SoC. The spot market penalties are reduced although the storage system being only capable of ensuring the hybrid system output firming during 95% of the solar periods. This is explained by the fact that in the periods that DESS cannot firm the PV output, it is capable of maintaining it closer to the planned. The hybrid system achieves a substantial increase in yearly revenues when participating in both spot and secondary reserve markets. Revenues increase by 202% when compared with the scenario of participating only in the spot market and by 273% compared to the case without the deployment of DESS. In fact, the secondary reserve market is the main component of total revenues at the expense of a reduction in potential revenues from the spot market. This reduction is due to the need of targeting a higher DESS SoC as the expected energy required when the hybrid system is called in the upward direction in the reserve market is higher than the expected energy required in the downward direction.

Nevertheless, participating in both markets adds the uncertainty of PV output to the uncertainty of reserve provision which leads to higher penalties to the hybrid system.

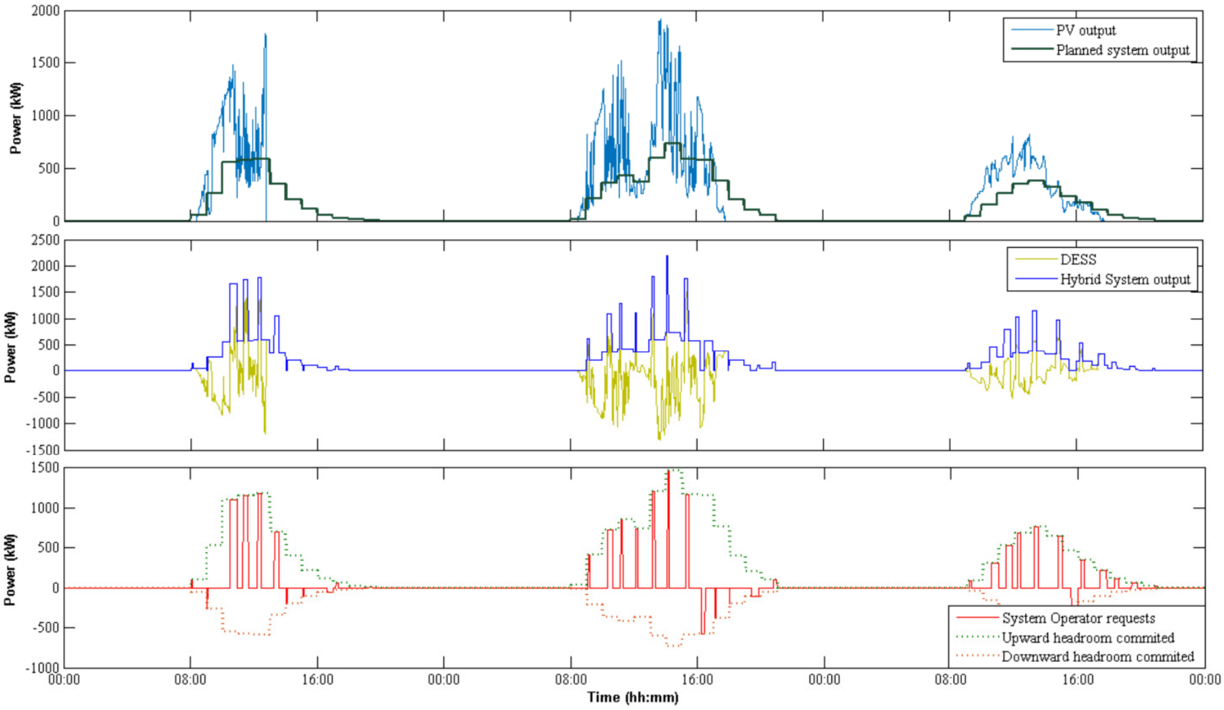

Figure 2 – 3-day simulation of the operation of the hybrid system, including the participation in the secondary reserve market

These penalties are due to its limited energy capacity but can be mitigated in the case of the hybrid system is also participating in intra-day markets. Figure 2 illustrates a 3-day minute by minute operation of the hybrid system. The hybrid system is capable of following the output planned at the LSS level during operation while adequately responding to the power changes requests of the system operator. Moreover, fast fluctuations of PV output are suppressed by the presence of the DESS.

REMARKS

Distributed energy storage systems are capable of playing a crucial role to mitigate the variability and intermittency of renewable sources. Particularly, DESS will be fundamental in the European energy reference scenario if PV technology that is based on a distributed resource meets the expected net generation.

This work presents a functional architecture and a mathematical formulation with the objective of enabling the participation of hybrid systems in spot and secondary reserve markets. The developed method not only enhances the technical value of PV power but also increases the economic perspectives of PV participation in electricity markets. Results demonstrate that the proposed integration architecture and underlying mathematical model can significantly increase the value of PV sources coupled with DESS. Moreover, the integration of PV technology in electricity markets in a fair and non-discriminatory way i.e. taking into account its technical, economic and environmental benefits is fundamental to measure its impact against alternative generation solutions.

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