ASSESSMENT OF A VIRTUAL POWER AND STORAGE PLANT FOR PROVISION OF MARKET-DRIVEN AND REGULATED ACTIVITIES

Ismael MIRANDA
Efacec & UP/FE – Portugal
dee12002@fe.up.pt

Nuno SILVA
Efacec – Portugal
nuno.silva@efacec.com

Helder LEITE
INESC TEC / UP/FE - Portugal
hleite@fe.up.pt

ABSTRACT

Distributed renewable generation challenge the traditional planning and operation paradigm of distribution networks, demanding strategies of active network management and operational flexibility. Distributed Energy Storage Systems (DESS) will play an important role under current and future renewables integration levels, providing multiple services within the electric sector structure, both regulated and market-driven. In fact, performing a single service is often recognized as insufficient for DESS to surpass its costs. This work introduces the concept of Virtual Power and Storage Plant (VPSP) which represents an aggregator of renewables and DESS connected in the same medium voltage distribution network. The objective is to optimally coordinate the distributed storage systems to increase their operational and economic value.

INTRODUCTION

There are several technical, economic and environmental drivers for the growth of attention towards energy storage. These are related with the massive challenges that the electric sector is facing such as the deregulation of the sector, the increase in peak demand in some parts of the world, and the high penetration of RES along with changes in energy storage technologies economics. Benefits of DESS are potentially both systemic and of local nature. On one hand, DESS can contribute to the decarbonization of the electric sector by enabling higher shares of variable renewables; on the other hand, DESS can tackle local operational challenges such as voltage control increasing the flexibility of distribution networks.

However, there are still technical, economic and regulatory hurdles to the integration of DESS. Questions such as who owns and controls DESS, what combination of services shall DESS provide to surpass its costs, how to measure the “split benefits” that DESS can be responsible for, are among the questions yet to be answered. This presents difficulties to the comparison of DESS against alternative means of flexibility such as flexible generation and demand response. Moreover, the distributed character of DESS as well as the typical fit-an-forget approach to the planning and operation of distribution networks are barriers to the potential welfare of storage in present and future distribution networks [1].

This work develops a Virtual Power and Storage Plant (VPSP) i.e. an aggregator of stand-alone DESS and RES coupled with DESS within a common medium voltage (MV) distribution network. The VPSP is responsible for optimizing the functioning of the aggregated systems according to a certain portfolio of value streams. The goal of the VPSP is to optimally manage its resources in a combined way to perform both market-driven and regulated activities in order to maximize the integration of renewables with the most operational and economic efficiency of the network. The market activities focused on this methodology include participation in the spot market and regulation markets. Regulated activities provided to the distribution system operator (DSO) or the transmission system operator (TSO) include reactive compensation, capacity support and voltage control.

DISTRIBUTED STORAGE SYSTEMS

Storage technologies have their characteristics and potential defined by the limited range of physical or chemical processes that make them capable of storing electricity [2]. Storage systems that do not possess a special site requirement, being available to be deployed along distribution networks frame the definition of distributed energy storage systems (DESS). Storage technologies range from flywheel and supercapacitors to battery based systems (e.g. Lead-acid or Li-ion batteries), each presenting different applicability. For instance, supercapacitors can be deployed to ameliorate power quality while lead-acid based batteries are more suitable for energy management. Nonetheless, independently of the storage technology, the general constitution of a DESS is presented in Figure 1.

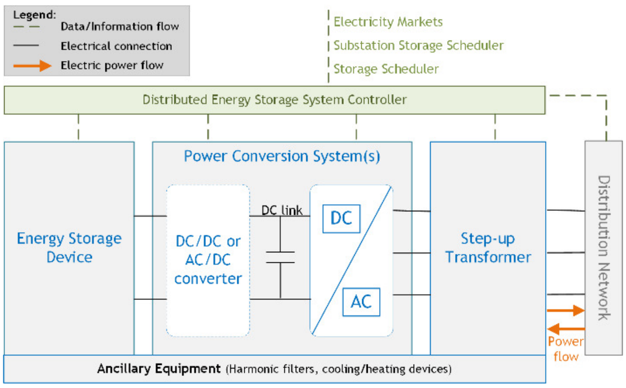

Figure 1 – Distributed Energy Storage System constituents

A DESS includes the energy storage device itself and an interface (including system monitoring and control) with the distribution network to which the system is connected. Coupling the energy storage device with an electrical network requires a Power Conversion System (PCS) as all DESS have DC power output or variable-frequency AC output. The limits of DESS to inject or absorb power from the grid are defined by the charge or discharge capability of the storage device itself or by the PCS. The active power exchange is often limited by the storage device while the PCS limits the apparent power exchange, making possible the management of reactive power. The grid interface usually includes monitoring/control systems, protective devices, a step-up transformer and harmonic filters. In addition, ancillary equipment is required to perform the cooling/heating of the energy storage device and the PCS, and also to control the environment (e.g. ventilation).

THE VIRTUAL POWER AND STORAGE PLANT

Technical and economical challenges of integrating distributed storage systems and renewable sources in distribution networks can be tackled by the introduction of the Virtual Power and Storage Plant concept. The VPSP represents an aggregator of the DESS and renewable sources coupled with DESS existent downstream of a high-voltage medium-voltage (HV/MV) primary substation. The VPSP takes into consideration the intrinsic services of each of its storage resources but manages them with the broader awareness of the distribution grid to which they are connected. The architecture of the Virtual Power and Storage Plant is presented in Figure 2. The aggregator architecture is constituted by a functional component i.e. the Substation Storage Scheduler (SSS). It is not only responsible for the day-ahead planning of the operation of the distribution network but also requests adjustments of active and reactive power from the aggregated resources in order to handle grid voltage and current constraints or even requests from upper control layers (central systems, control centre, etc.) or the TSO.

The day-ahead planning of operation integrates the objective functions (e.g. maximization of electricity market revenues) and technical constraints of each aggregated resource (e.g. their SoC and power capacity) and considers forecasts of the MV distribution network demand and renewables production, the network model, location of the renewables and DESS resources as well as typical power factors at the MV/LV secondary substations (depending on percentages of capacity of commercial, industrial and domestic consumers). A mixed integer linear programming (MILP) method is implemented to optimize the day-ahead scheduling.

During operation, due to forecasting errors, the DSO may require schedule adjustments of the VPSP in order to cope with operational constraints such as substation capacity insufficiency and reactive compensation. The SSS distributes the DSO requests to the stand-alone DESS and renewable connected DESS (hybrid system) regarding their capacity availability, their location and the minimization of market-driven services penalties due to the non-fulfilment of electricity markets commitments. For example, adjustments of active power of DESS to cope with network constraints lead to penalties not only in the period of adjustment but moreover can potentially jeopardize the fulfilment of DESS planned power output in the following periods due to unavailability of energy capacity.

The business model

The economic assessment of the VPSP is framed under a business model that follows the approach proposed by the authors in [3]. The concept of DESS as a shared resource is the core characteristic of the proposed business model. In the presence of the VPSP, the idea is that the aggregator operates different storage systems not only to perform intrinsic activities to each constituent but also to share the storage resource with third parties through service provision and thus maximize the utilization of the power and storage resources.

The value streams of the VPSP, therefore, result from the provision of intrinsic objectives of each DESS and from contractually guaranteeing the commercial control of storage resources to a third party i.e. assure the availability of a certain power and energy capacity in certain periods. For example, the VPSP can provide capacity during peak periods to the DSO and thus deferring or even avoiding primary substation' capacity upgrades (e.g. investing in a power transformer). Consequently, this framework enables the provision of both market-driven and regulated services. The translation into economic benefits of provision of regulated services is performed in terms of opportunity cost. The opportunity cost in the perspective of the VPSP results from the difference between the expected revenues if no regulated services are performed and the revenues if regulated services are performed. In the perspective of the DSO, the value of the VPSP services result from the reduction on the Capital Expenditure (CAPEX) and the Operation Expenditure (OPEX) that the renewables and storage aggregator is capable of providing.

Distribution System Operator services

In this work, the services that the VPSP provides to the DSO include capacity support, reactive compensation and voltage regulation. In the business model, these services are third party services and, thus, stand as a constraint in the mathematical model included in the SSS.

Capacity support

In the capacity support service, the VPSP at request of the DSO uses its power and storage capacities to locally inject active and reactive power in order reduce maximum currents on grid assets.

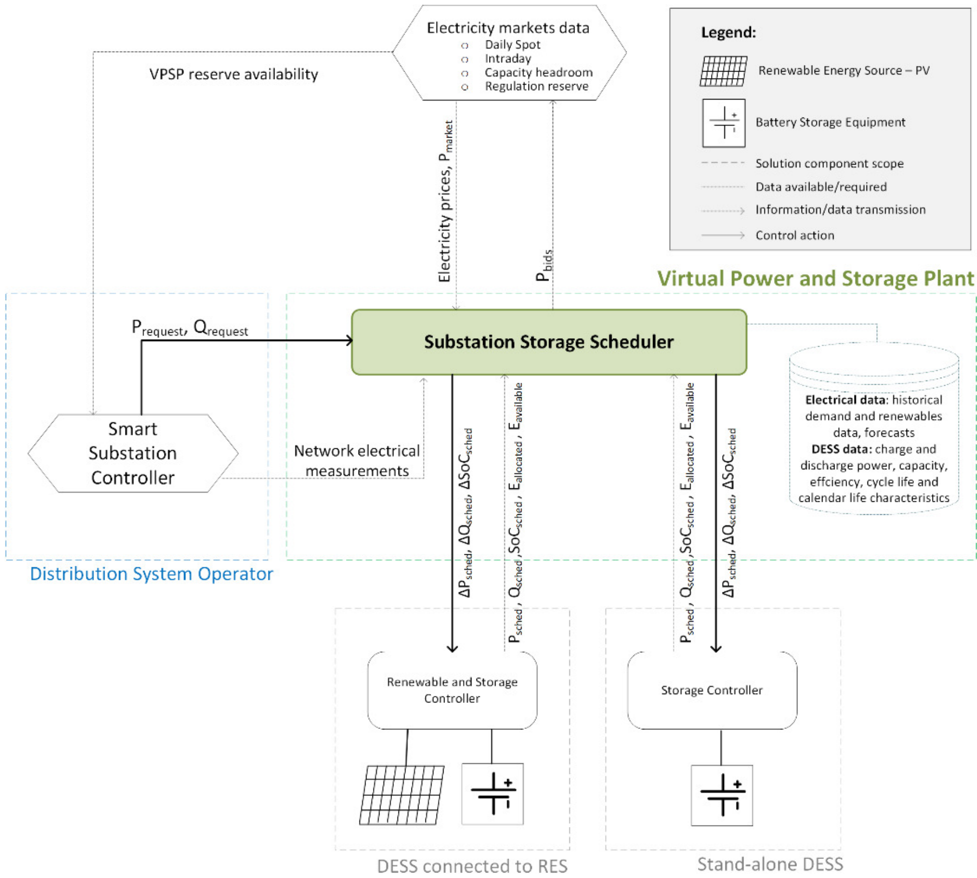

Figure 2 – Virtual Power and Storage Plant architecture

In addition to reduction in network losses, this can avoid bottlenecks and thus reduce or even defer network upgrade investments. In the day-ahead planning, this service is represented by the following constraint.

$$\left(P_{load}^{fc}(t) - \sum_{m=1}^{M} P_m(t).\pi_m^P(t) - \sum_{h=1}^{H} P_h^{fc}(t).\pi_l^P(t).\alpha_h(t)\right)^2 + \left(Q_{load}^{fc}(t) - \sum_{m=1}^{M} Q_m(t).\pi_m^Q(t) - \sum_{h=1}^{H} Q_h(t).\pi_l^Q(t)\right)^2 \leq S_{sub}^2 \quad (1)$$

where $P_{load}^{fc}(t)$ and $Q_{load}^{fc}(t)$ are the forecasted total active and reactive power demand for hour t; $P_m(t)$ and $Q_m(t)$ are the scheduled active and reactive power injection (if >0) or absorption (if <0) by the stand-alone DESS; $P_h^{fc}(t)$ and $Q_h(t)$ are the forecasted active output (based on the renewable forecast and adjusted by parameter $\alpha_h(t)$) and scheduled reactive power injection or absorption by the hybrid system (renewable coupled with DESS); and S_{sub}^2 is the HV/MV primary substation capacity (in MVA).

Coefficients $\pi_m^P, \pi_l^P, \pi_m^Q$ and π_l^Q reflect the location of the VPSP participants within the distribution network and account their estimated effect on losses. For example, during peak demand periods, the injection by a DESS of 1 MW at the end of a feeder results in a reduction of active power of more than 1 MW in the substation as it reduces the feeder power flow and, hence, also its losses. Nonetheless, these coefficients correspond to a linearization of the actual non-linear effects. Through power flows algorithms, these coefficients are defined à priori in a look-up table according to different levels of load and independently for active and reactive power. Eq. (1) defines a non-linear constraint that is approximated by the method presented in [4].

Reactive Compensation

The interaction between the DSO and the TSO requires an effective local management of the reactive power by the DSO. For example, in Portugal the DSO cannot inject reactive power in the upstream transmission network during valley hours. During peak hours, the DSO is obliged to cope with a $\tan\varphi \leq 0.3$ in order to avoid congestions in the transmission system. The DSO incurs in economic penalties in the case of non-fulfilment of these criteria. Furthermore, regulation dictates that renewables connected to the MV level with an installed capacity lower than 6 MW have to ensure a $\tan\varphi = 0.3$ during peak consumption periods. The reactive compensation service provides the DSO enhancements in voltage control and thus a higher flexibility in the operation of the distribution network.

Voltage Control

DSO's are regulatory obliged to deliver power within adequate voltage levels according to the EN50160 (e.g. ±10% of nominal voltage). Moreover, under or overvoltage situations may cause the tripping of protections at the expense of reliability and continuity of service.

This work implements a technique developed in [5] where an optimal power flow method based on the total hourly forecasted demand and its expected distribution among the secondary substations is used to estimate the hourly limits to the power outputs of the various storage resources aggregated at the VPSP to avoid creating voltage problems. Although typical MV distribution grids present physical characteristics that allow effective voltage control through both active and reactive power, this work considers that voltage control is performed by controlling only reactive power as it does not influence storage systems' SoC. Due to the presence of multiple DESS, the limits to reactive power injection or absorption are first calculated for the DESS closest to the voltage problem location. In the case this DESS is insufficient to solve the voltage problem or the required reactive power unable the provision of this DESS' intrinsic services, the limits are calculated for following closest DESS.

Market-driven services

The VPSP presents the objective of potentiating the participation of DESS and renewables coupled with DESS in electricity markets including ancillary services markets. This works considers the participation in spot markets (following the market design in place in the Iberian Peninsula) and secondary reserve markets (following the market design in place in Portugal). Nonetheless, these types of markets are common in Europe [6].

Spot Market Participation

The objective function (see Eq.(2)) of the participation of the VPSP in spot markets is given as follows.

$$\max \sum_t^T \left(\sum_m^M P_m(t).\lambda^{SM}(t) + \sum_h^H P_h^{fc}(t).\alpha_h(t).\lambda^{SM}(t) \right) \quad (2)$$

where $\lambda^{SM}(t)$ is the spot market clearing price in hour t. It is assumed that the VPSP acts as the price-taker of the market and the uncertainty of electricity market prices is disregarded. Each forecasted renewable production is adjusted by parameter $\alpha_h(t)$ that takes into consideration the initial SoC of the DESS of the hybrid system and the spot market prices. The objective is to adjust the SoC of the DESS in order to enable the system to follow the committed market bids during the larger possible portion of time. The adjustment in each hour in weighted by the forecasted power volume and the market price in order to perform the most economic adjustment with the minimum storage effort.

Secondary Reserve Market Participation

The proposed integration methodology is capable of not only contributing to an efficient local operation, but it can allow DESS and renewables coupled with DESS to perform systemic services i.e. perform system' ancillary services. The secondary reserve is managed by the TSO that requests to the market participants power output adjustments during operation to bring frequency to its nominal value and/or interconnection power flows to the planned values. A probabilistic approach (see Eq.(3)) is followed in the definition of the objective function as there is no foresight of the TSO requests.

$$\begin{aligned} \max z = & \sum_{t=1}^T \lambda^{SR}(t).\left(P_{up}^{SR}(t) + P_{down}^{SR}(t)\right) + \\ & \sum_{t=1}^T \lambda_{up}^{SR}(t).P_{up}^{SR}(t).\sigma_{up} - \\ & \sum_{t=1}^T \lambda_{down}^{SR}(t).P_{down}^{SR}(t).\sigma_{down} \end{aligned} \quad (3)$$

The first term $\lambda^{SR}(t).\left(P_{up}^{SR}(t) - P_{down}^{SR}(t)\right)$ represents the revenue (in €/MW) for the capacity headroom provided by the aggregator. The second term $\lambda_{up}^{SR}(t).P_{up}^{SR}(t).\sigma_{up}$ represents the expected revenue in the case the TSO requests an upward power variation. σ_{up} combines the probability of a upward request and the expected amount of energy relative to the contracted capacity headroom required (based on historical market behaviour).

CASE STUDY: SYNOPSIS OF THE RESULTS

The concept of the Virtual Power and Storage Plant is assessed in a case study of a real distribution network fed through a 20-MVA HV/MV primary substation. The 2013 Portuguese power system load profile is used to model the demand at the substation level with an adjusted peak demand of 18 MW and $\cos\varphi = 0.9$. A 5-MW PV source is deployed in the middle of a feeder having coupled a 4-MW/5-MVA/6.5MWh DESS. The criteria for sizing the storage system are the minimum power and energy requirements that allow firming PV output during 95% of solar hours. A 1-year real PV production sample is used in which the source presents a capacity factor of 18.3%. The objective of coupling DESS is the firming of the PV output therefore enabling the participation of the hybrid system in electricity markets. Moreover, a stand-alone DESS of 2-MW/3-MVA/4MWh is connected to the primary substation MV busbar. The sizing of the system corresponds to the minimum power and energy requirements to ensure a 15% installed capacity security margin at the primary substation level. Both DESS are li-ion batteries based presenting a roundtrip efficiency of 90% and a minimum SoC of 10%.

Table I presents the synopsis of the economic results. Results demonstrate that the VPSP, by potentiating the participation in electricity markets, particularly ancillary services markets, enhances the value of DESS when used in a coordinated fashion. Nonetheless, it is perceptible that the kind of VPSP participants (Stand-alone DESS and PV coupled with DESS) strongly influence the scheduling strategies defined by the Substation Storage Scheduler of the VPSP. In the case of the stand-alone DESS the focus is on the participation on the secondary reserve market and the day-ahead spot market is used to adjust the DESS SoC to ensure that the system is capable of providing reserve in the case of a TSO's request (this results in a negative income on the spot market auctions). However, the hybrid system primarily sells its energy in the spot market and, in addition, aims at maximizing the utilisation of its storage capacity by providing reserve.

Table 1 – Synopsis of the results

Participant	Market Revenue	VPSP w/o DSO requests	VPSP w/ DSO requests
Stand-alone DESS	Spot (k€)	-100	-54
	Reserve (k€)	980	860
Hybrid system	Spot (k€)	305	311
	Reserve (k€)	348	229
VPSP total	Spot (k€)	205	257
	Reserve (k€)	1 328	1 117
	Total (k€)	1 533	1 374
	Opportunity cost (k€)		159

The provision of services to the DSO results in a reduction on the potential revenues of the VPSP's participants. This occurs particularly due to the required allocation of active and/or reactive power necessary to perform capacity support or reactive compensation. In the case there is no capacity in the substation to support network demand, the stand-alone DESS needs to participate in the spot market to bid for energy selling during the expected peak periods. As shown in Table I, this results in a higher revenue of the participation in the spot market. However, this comes at the expense of a higher reduction of the secondary reserve market' revenue. In this case, a 46 k€/year higher spot market revenue leads to a reduction of 120 k€/year of the revenue of ancillary services market.

The opportunity cost presented in Table I reveals the minimum revenue that the VPSP should attain due to the provision of regulated services. Nonetheless, this analysis is performed for a single year, therefore it does not take into account the distribution network demand growth. In fact, the value of the opportunity cost of 159 k€/year tends to increase as demand in the grid increases. The more the grid is congested, the more VPSP aggregated resources will have to be requested which would further reduce VPSP net revenues i.e. increase the opportunity costs of regulated services provision.

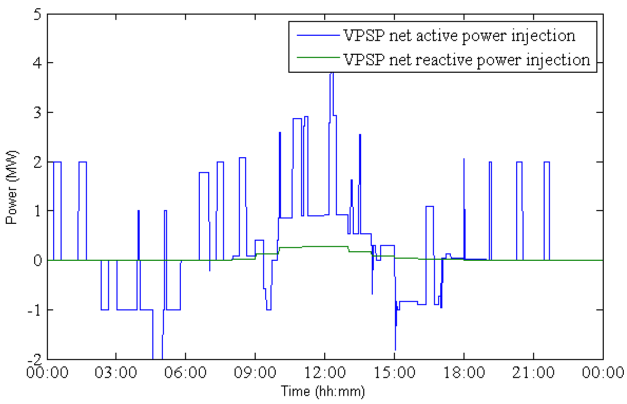

Figure 3 – Aggregated power exchange of the VPSP

Figure 3 the aggregated power exchange between VPSP participants and the distribution network during a day (minute by minute resolution). It is perceptible that the storage resources are capable of suppressing the fast fluctuations of the PV source. Nonetheless, it presents several short-duration power peaks during the day that correspond to requests from the TSO for secondary reserve provision. The storage systems also inject reactive power during PV production periods in order to maintain the ratio of reactive power and active power seen at the primary substation within the limits i.e. $\tan \varphi \leq 0.3$.

REMARKS

This work develops the concept of the Virtual Power and Storage Plant and its underlying functional components (e.g. Substation Storage Scheduler) to tackle current technical and economic challenges that are posed to the integration of distributed energy storage systems in distribution networks. The VPSP represents an aggregator of stand-alone and renewable generating units coupled with DESS (hybrid systems) that contemplates the provision of market-driven and regulated services. Therefore, the objective is to maximize VPSP' participants revenues while taking into account their electrical environment in order to ensure a flexible and efficient grid operation. Results demonstrate the adequacy of the methodology as a mean of DESS integration in MV distribution networks as it is capable of not only potentiating the value of DESS but further increase the value of renewable energy as it increases its controllability. In addition, an analysis and discussion on the sensibility of the opportunity costs of the VPSP for providing services to the DSO is performed. Nonetheless, the VPSP increases the complexity of the distribution network operation as it demands a greater observability of the grid, higher knowledge exchange and manage variables with inherent uncertainty.

REFERENCES

[1] E. E. R. A. E. European Association for Storage of Energy (EASE), "European Energy Storage Technology Development Roadmap Towards 2030," 2013.

[2] A. M. Gopstein, "Energy Storage & the Grid - From Characteristics to Impact," *Proceedings of the IEEE,* vol. 100, pp. 311-316, 2012.

[3] I. Miranda, N. Silva, and H. Leite, "Integration of Distributed Energy Storage Systems as shared resources in distribution networks," CIRED Workshop 2014, 2014.

[4] R. Moreno, R. Moreira, and G. Strbac, "A MILP model for optimising multi-service portfolios of distributed energy storage," *Applied Energy,* 2014.

[5] I. Miranda, N. Silva, and H. Leite, "Technical and economic assessment for optimal sizing of distributed storage," in *Innovative Smart Grid Technologies (ISGT Europe),* 2012.

[6] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A Survey of Frequency and Voltage Control Ancillary Services Part I: Technical Features," *Power Systems, IEEE Transactions on,* vol. 22, pp. 350-357, 2007.