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Role of storage systems and market based ancillary services in active distribution networks management

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SUMMARY

The diffusion of Distributed Generation (DG) in MV distribution networks is continuously growing, being supported by the improving performances of small generation units, by the renewable incentives introduced to meet the environmental targets and by the current electrical system liberalisation process. A high DG penetration, however, can be limited by technical factors, especially if consumers and generators are not optimally located and their consumption and generation diagrams are of random and intermittent nature. The network operator will thus have to face some new constraints (e.g. redeployment of power flow along feeders, possible feeder ampacity violations, impact on voltage) which may severely limit the maximum number and size of connectable DG plants, in order to avoid irregular system operations. For the purpose of coping with the electrical grid constraints arising from extensive DG penetration, the adoption of appropriate energy storage systems, together with the introduction of suitable ancillary service markets for promoting user participation to the network regulation, is envisaged to be of crucial importance. Distributors are called to adopt in the next future innovative network controllers to coordinate the operation and the management of their electrical systems and energy storage systems may thus provide interesting features.

In this work the feasibility of exploiting storage systems for strategically differing distributed generator and load curves is evaluated, aiming to improve the overall network performance while increasing the level of DG penetration. Issues deriving from the adoption of energy storage systems have been extensively investigated for islanded systems, whereas this work deals with their use in distribution networks, and aims to provide a tool enabling Distributors to easily assess the optimal sizing, siting and managing strategy for grid connected storage systems.

The method presented in this paper determines, on the basis of suited preliminary analysis, a reference profile for an ideal storage system and, subsequently, the operation profile for the energy storage system, accounting for its size, capacity and integral operational constraints. Results on a realistic MV system case study are presented and discussed.

KEYWORDS

Distributed Generation (DG), Distributed Energy Storage (DES), MV distribution networks, Energy Storage System (ESS), Storage Management and Planning

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1. Introduction

Interest in distributed Energy Storage Systems (ESS) is increasing due to their ability to supply the stored energy when and where it is critically needed. Energy devices can add flexibility to the electrical grid providing ancillary services, improving the stability of the system and the management of a high penetration of distributed generators, reliability of supply, power quality and offering a variety of services for the grid support [1].

Thanks to their ability to shift the absorption/generation of energy in time and space, energy storages can provide load levelling and increase the generation capacity, participating in spinning reserve too, and the renewable generators availability, adversely influenced by stochastic behaviour, as well as the transmission capacity, by reducing loading of lines when it is necessary [2][3]. Recent development in both storage and electronic interface technologies make storage devices able to rapidly supply big amount of power, both active and reactive. In this way, it is possible to provide fast response in emergency conditions and power, voltage and frequency regulation [4][5]. The overall effect is the increase of the efficiency of generators and systems, from a technical point of view (generators can work at high efficiency conditions), but also from an economical and environmental perspective (for example reduction of fuel consumption and emissions using more efficient generators at more efficient conditions).

Many technologies are available to provide these services. For example, pumped hydroelectric systems and Compressed Air Energy Storage (CAES) are used in particular to produce electricity during peak periods at lower costs; flywheels to provide high power for a short time period; capacitors, modular and with high power density, Superconducting Magnetic Energy Storage (SMES), characterized by high efficiency and large scale applications, batteries, modular and with high energy density, are used for fast response and capacity reserve. However, these technologies are penalized by high investment costs, siting and technical characteristics limitations, which are described with more details in literature, for example in [5].

There appears to be a high interest by batteries manufactures in power applications and battery technologies are rapidly improving, the most promising being *NAS (Sodium Sulphur Batteries), ZEBRA (Sodium Metal Chloride)* and *VRB (Vanadium Redox Battery)* [6]. A synthetic comparison of the main indicative cost/performance characteristics of these types of batteries actually available on the market is shown in Table I.

Table I – Main features of NaS (Sodium Sulphur), Zebra (Sodium Metal Chloride) and VRB (Vanadium Redox) batteries currently available for MV network installations.

	Investment cost, w/o DC/AC converter [€/kWh]	Cycle life [cycles]	Charge/ Discharge Efficiency	Additional costs	Regeneration
NaS	400 – 500 (capacity 6 MWh)	2000 ÷ 4000 (declared)	90%	– Energy cost, to compensate thermal losses; – Back-up generator operating cost, to prevent lethal warming and cooling cycles.	– Container, thermal insulation and power electronics could be regenerated; – Exhausted cells may not be regenerable.
Zebra	400 – 600 (capacity 1 MWh)	2000 (proved) 3000 (estimated)	88%	– Energy cost, to compensate thermal losses (losses are very low, in cyclical service they vary between 1 and 6 kW per MWh of capacity)	– Container, thermal insulation and power electronic could be regenerated; – Exhausted cells may not be regenerable.
VRB	800 (capacity 120 kWh)	10.000 (declared)	80%	– Auxiliary services costs (pumps and valves)	

The belief that adoption of ESSs could bring many advantages for DSOs appears to be realistic; it thus becomes of importance to verify the existence of these hypothetical advantages and quantify their technical and economic attractiveness and feasibility. Usually the optimal ESS installation is limited to the correct choice of storage technology and size, high energy rather than high power devices, based on the network specific requirements. However, a similar approach cannot be exhaustive for the optimal use of ESSs, in fact there are also other key factors to be taken into account in order to exploit to the best the storage capabilities; for example identify the most suited grid connection point, adopt an adequate storage operation management and enhance the network operation by the introduction of customised services market.

The present work, in particular, focuses on the conception and development of a procedure which could be adopted by DSOs for carrying out a preliminary analysis, before installing ESSs, but also for an appropriate management of such resources connected to the grid. This tool could also be effectively employed for assessing the goodness of the chosen connection point and the adequacy of selected storage technical characteristics (size in terms of power, capacity in terms of energy and depth of discharge, charge and discharge efficiencies).

During normal network operation, the correct management of this new resource available for the distribution system would lead to losses reduction. In case of critical situations in the network regulation and operation (violation of maximum or minimum bus voltages or lines overloadings), ESSs would operate primarily in order to settle these violations and subsequently would try to improve distribution network efficiency, if possible. The ESSs operation, especially with regard to voltage regulation, should be coordinated with the tap-changer of HV/MV transformer located in the primary substation.

2. ESS management problem formulation

The problem to be solved is a constrained optimization of ESSs operation during a chosen time interval, typically 24 hours, which brings as results the daily diagrams of active, and potentially also reactive, power demanded and offered by ESSs. This optimization is subject to constraints arising from both the electrical grid and the storage system features; network constraints must be fulfilled in order to assure the correct operation of the distribution system, whereas ESSs constraints must be satisfied for the daily power diagrams to be consistent with the ESSs technical characteristics.

For the sake of clarity and without loss of generality, the problem concerning the optimal management of ESSs will be treated in the following disregarding the choice of the connection point, storage size and technical features, all these data being supposed as known.

As can be seen in (1) below, the problem variables are magnitude and phase angle of bus voltages, active and reactive power at slack bus, active and reactive power injected at the ESSs' grid connection nodes, HV/MV transformer ratio; each of these variables is a 24 values vector, one for each hour considering a 24-hours analysis period. In addition, the initial State Of Charge (*SOC_0*) for each ESS connected to the grid has been introduced in the variables vector, in order to obtain also useful indications about the best suitable initial SOC of ESSs and how much it could affect the whole distribution system management.

$$\underline{x} = \begin{bmatrix} \vartheta_{i,h} \\ V_{i,h} \\ P_{SL,h} \\ Q_{SL,h} \\ P_{sto,j,h} \\ Q_{sto,j,h} \\ m_{tr,h} \\ SOC_{0,j} \end{bmatrix} \quad with \quad \begin{array}{l} h = 1,\ldots,24 \\ \\ i = 1,\ldots,n_{bus} \\ j = 1,\ldots,n_{sto} \\ tr = 1,\ldots,n_{transf} \end{array} \tag{1}$$

The optimization is subject to different kinds of constraints: punctual (or instantaneous) constraints, as listed in (2), and integral constraints, formulated as in (3), (4) and (5) below.

$$\left\{\begin{array}{lll} \vartheta_{\min,i} & \leq \vartheta_{i,h} & \leq \vartheta_{MAX,i} \\ V_{\min,i} & \leq V_{i,h} & \leq V_{MAX,i} \\ P_{\mathrm{SLmin}} & \leq P_{SL,h} & \leq P_{\mathrm{SLMAX}} \\ Q_{\mathrm{SLmin}} & \leq Q_{SL,h} & \leq Q_{\mathrm{SLMAX}} \\ P_{\mathrm{sto,min,j}} & \leq P_{sto,j,h} & \leq P_{\mathrm{sto,MAX,j}} \\ Q_{\mathrm{sto,min,j}} & \leq Q_{sto,j,h} & \leq Q_{\mathrm{sto,MAX,j}} \\ m_{\min,t} & \leq m_{t,h} & \leq m_{MAX,t} \\ SOC_{0,\min,j} & \leq SOC_{0,j} & \leq SOC_{0,\max,j} \\ P_i(\vartheta,V) & = g_{P,i} - d_{P,i} & \\ Q_i(\vartheta,V) & = g_{Q,i} - d_{Q,i} & \\ I_l(\vartheta,V) & \leq I_{MAX,l,h} & \end{array}\right. \tag{2}$$

Punctual constraints have to be satisfied at any specific temporal instant and their compliance will not affect the problem solution during other time intervals. They are, respectively, all network variables bounds (bus voltages phase angle and magnitude, active and reactive power at slack bus, active and reactive ESSs rated power, transformer ratio), initial SOC constraints of each ESS, active and reactive power balance at each bus and maximum lines loading. Integral constraints, instead, must be verified during the whole time period of analysis, so they will influence the problem solution in its entirety. They are attributable only to the optimal ESSs management and they can be expressed as follows:

- Energy balance along the 24 hours, required in order to ensure identical starting and final SOC of each ESS:

$$\int_0^{24} \eta(t) \cdot P_{sto,j}(t)\, dt = \sum_{h=1}^{24} \eta_h \cdot P_{sto,j,h} = 0 \tag{3}$$

- Maximum charging power, evaluated for each hour, taking into account the SOC at the end of previous hour and charging efficiency. This constraint is necessary to prevent the storage system from charging more than its maximum capacity.

$$P_{sto,j,h} \leq \left(E_{MAX} - E_{h-1}\right) / \eta_{charge} \tag{4}$$

- Maximum discharging power. Similarly to the above, this constraint prevents the storage system from discharging more than its maximum depth of discharge.

$$P_{sto,j,h} \geq \left(E_{MIN} - E_{h-1}\right) \cdot \eta_{discharge} \tag{5}$$

3. Decoupled solution method

The optimization problem formulated as above, although formally correct, can easily lead to a hardly bearable number of variables and constraints and long computing times when applied to real distribution networks, even with a limited number of bus-bars.

A suitable way to cope with the ESS management challenge is here presented and consists of a three-step solution method, which deals with punctual and integral constraints separately. This method can be easily applied also to a network with a considerable number of buses and allows containing the problem size, and consequently the solving time.

Step 1: Network sensitivity analysis

Assuming as given the grid topology, hourly load and generation diagram at each network bus (provided by a suitable forecasting procedure) and the ESS grid connection point, this first step carries out a sensitivity analysis of the network as a function of the active/reactive power exchanges with an ideal unlimited ESS.

For each temporal interval the maximum value of active/reactive power which can be injected or absorbed by the ESS without causing any network limits violation, is identified. This preliminary analysis is aimed at identifying the maximum allowable values of active and reactive power injected at the storage system grid connection node P_{sto} and Q_{sto}, for each hour ($P_{b1,h}$ and $P_{b2,h}$, $Q_{b1,h}$ and $Q_{b2,h}$), able to avoid intolerable network operations, in terms of maximum ΔV (it represents the voltage difference between the bus with higher voltage and the one with lower) or maximum lines loading violations.

This first step would thus provide a band within which the daily diagram of ESS active power can move. Furthermore, this algorithm section can be effectively used as a tool to identify the possible ESS size and capacity, in terms of both power and energy, together with the most suited grid location.

Step 2 – ESS Reference operation profile

Applying the same hypothesis as in Step 1 above, Step 2 aims at determining the optimal hourly operation diagram, corresponding to the active power demanded/offered by the ESS at each time interval which minimizes the distribution system active losses.

The diagram calculated in this way will be taken, in the next step, as a reference curve for the operation of the installed ESS.

As shown in (6), in this step the variables are a subset of those composing the general problem described in (1) above; more specifically, for each hour h^*, they are only those concerning the electrical network status, without integral variables and constraints (which are treated in Step 3).

$$\underline{x}_{2,h*} = \begin{bmatrix} \vartheta_{i,h*} \\ V_{i,h*} \\ P_{SL,h*} \\ Q_{SL,h*} \\ P_{sto,h*} \\ Q_{sto,h*} \\ m_{tr,h*} \end{bmatrix} \qquad with \qquad i = 1,\ldots,n_{bus} \tag{6}$$

Also the Step 2 constraints, listed in (7), are just a part of those previously shown in (2). It should be noted that in this step there are no constraints on the active and reactive power at the ESS grid connection node. In this way it is possible to obtain useful information about the distribution system requirements and a reference profile whose validity is independent of the ESS.

$$\begin{cases} \vartheta_{\min,i} & \leq \vartheta_{i,h*} & \leq \vartheta_{MAX,i} \\ V_{\min,i} & \leq V_{i,h*} & \leq V_{MAX,i} \\ P_{\mathrm{SLmin}} & \leq P_{SL,h*} & \leq P_{\mathrm{SLMAX}} \\ Q_{\mathrm{SLmin}} & \leq Q_{SL,h*} & \leq Q_{\mathrm{SLMAX}} \\ m_{\min,tr} & \leq m_{tr,h*} & \leq m_{MAX,tr} \\ P_i(\vartheta,V) & = g_{P,i} - d_{P,i} & \\ Q_i(\vartheta,V) & = g_{Q,i} - d_{Q,i} & \\ I_l(\vartheta,V) & \leq I_{MAX,l,h*} & \end{cases} \tag{7}$$

The resulting reference profile should lay within the allowed band formerly evaluated in Step 1, in order to ensure compliance with the network punctual constraints.

Step 3 – ESS operation planning

This last step identifies the optimal ESS operation plan, during the whole day, aiming to achieve a suitably chosen objective. First of all it is required that ESS demanded/offered power daily diagram lies within the allowed band, preventing the ESS causing network limits violations while contributing to solve existing network criticalities. The third step solution takes into account the ESS power and energy constraints, too.

The problem variables, shown in (8), relates now only to the ESS: its hourly input/output and its initial SOC. The punctual constraints (9), that have to be satisfied, bind the daily working ESS diagram to stay within the allowed band $[P_{b1,h} \div P_{b2,h}, Q_{b1,h} \div Q_{b2,h}]$ during each hour. The solution has to comply also with maximum active and reactive power exchanged between grid and ESS, and SOC_0 bounds. The resulting profile will be computed in order to obey also to the integral constraints listed in (3), (4) and (5) above.

$$\underline{x}_3 = \begin{bmatrix} P_{sto,h} \\ Q_{sto,h} \\ SOC_0 \end{bmatrix} \quad with \quad h = 1, \dots, 24 \tag{8}$$

$$\begin{cases} P_{\mathrm{b1,h}} & \leq P_{sto,h} & \leq P_{\mathrm{b2,h}} \\ Q_{\mathrm{b1,h}} & \leq Q_{sto,h} & \leq Q_{\mathrm{b2,h}} \\ P_{\mathrm{sto,min}} & \leq P_{sto,h} & \leq P_{\mathrm{sto,MAX}} \\ Q_{\mathrm{sto,min}} & \leq Q_{sto,h} & \leq Q_{\mathrm{sto,MAX}} \\ SOC_{0,\mathrm{min}} & \leq SOC_0 & \leq SOC_{0,MAX} \end{cases} \tag{9}$$

The objective function to be minimized (10) is a convenient linear combination of two terms: the first one represents the difference between the ESS power profile and the reference one evaluated in Step 2, while the second one quantifies the charge/discharge losses attributable to the ESS, both of them opportunely weighted.

$$\min \sum_{h=1}^{24} \left[\alpha \cdot \left(P_{sto} - P_{sto,ref} \right)^2 + \beta \cdot P_{loss,sto} \right] \tag{10}$$

This third step can be useful to check the chosen ESS size and capacity propriety, considering how much its operation profile can approximate the reference one, but also to compare different ESS technologies, comparing how their charge and discharge efficiencies affect the result.

4. Case study

A reference distribution system has been investigated with the proposed decoupled solution method; the network, as shown in Figure 1, consists of a primary HV/MV substation, with OLTC transformer, and three MV distribution feeders.

One of the three feeders, feeder A, is characterised by heavy DG penetration, in particular wind, photovoltaic and biogas generators, with an overall rated power of about 21,4 MVA, whereas only loads are connected to feeders B and C. The whole rated power of loads connected to the grid is 16,82 MW/9,04 Mvar differently allocated among feeders (feeder A 7,58 MW/3,86 Mvar, feeder B 5,38 MW/3,06 Mvar, feeder C 3,85 MW/2,11 Mvar). Five kinds of loads are considered: residential, agricultural/farm, industrial, tertiary and public lighting.

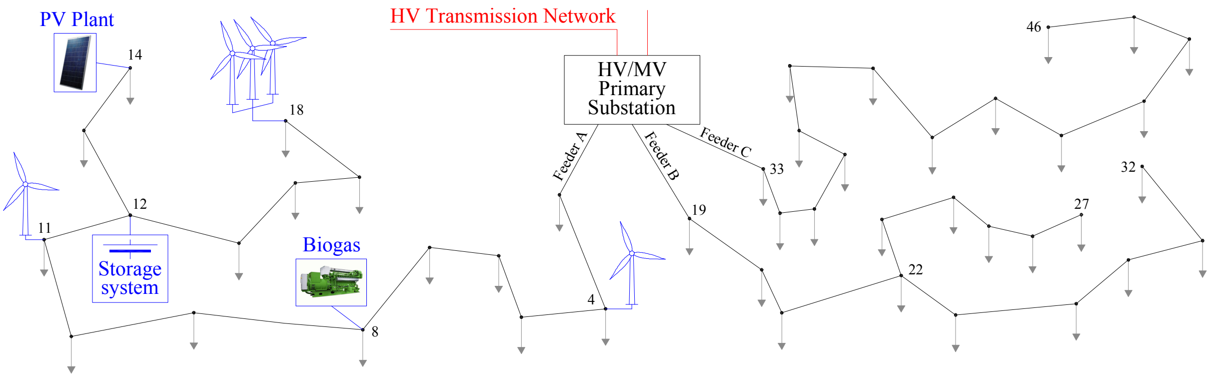

Figure 1 – Case study: MV distribution network with three feeders (total length about 90 km)

Any DG unit or load has been modelled with a daily profile describing the generated/demanded power during the 24 hours, on which basis the DG units/loads working points for each hourly interval have been determined.

The ESS grid connection bus has been strategically chosen, looking for a relevant bus where power supply/withdrawal have the overall highest impact on the network voltages and considering that lines overloading can be generally compensated by an ESS only if the overloading occurs on lines upstream the storage connection bus, but pertaining to the same feeder. On the basis of the preliminary Step 1 analysis, the ESS sizing was chosen in terms of power and capacity, respectively equal to 7 MW and 30 MWh. A 92,97% charge efficiency and 91,07% discharge efficiency are considered.

4.1 Grid optimization with the ESS

A proper ESS management requires a detailed grid operation knowledge in order to evaluate the band of allowed working points for the ESS and the reference operation profile. In this case study, for the sake of clarity, the ESS is assumed to work at unity power factor (Q_{sto} = 0) and to try to best fit the reference operation profile ($\alpha = 1, \beta = 0$).

In Figure 2, results obtained in Step 1 and Step 2 are presented. It is noticeable that, as a result of the optimization, the ESS can discharge stored energy only in some hours of the day, from 6 to 21.

In the same figure the optimal ESS operation profile is reported: it clearly appears that the ESS is forced to charge (positive power values) during the night hours, when there is a lot of power available from wind farms. Trying to satisfy the grid requirements during the following hours, the ESS will thus discharge the full amount of energy previously stored. It should be emphasized that this operation performance is possible only if the ESS is set to a suitable initial SOC_0 (for this case study the optimized value of SOC_0 results about 8,96 MWh).

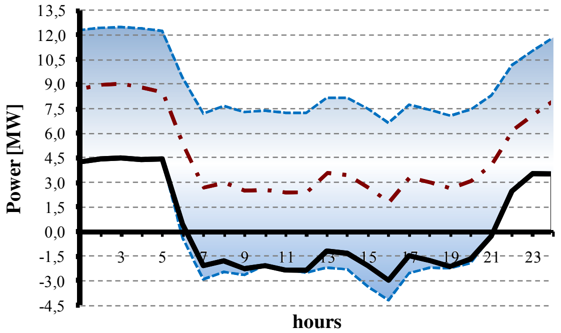

Figure 2 – Allowed band limits (dashed light blue lines), reference operation profile (dash-dot line) and optimal ESS operation profile (black solid line).

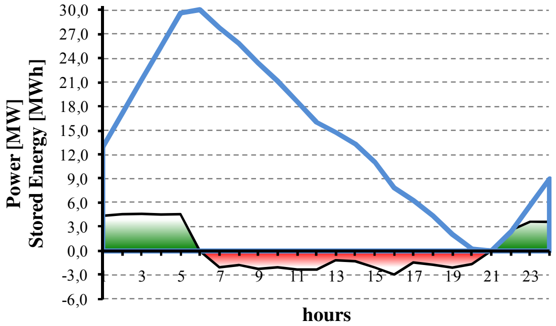

Figure 3 – Optimal daily power (green areas charging, red area discharging) and energy ESS profile (light blue solid line).

Operation ESS profiles in terms of power and energy can be seen in Figure 3; in particular, with the optimized value of SOC_0, at the end of the 6th hour the storage system reaches its maximum capacity, whereas at the end of the 21st hour it is fully discharged. This totally discharged status is possible because in this case study the storage system depth of discharge has been assumed equal to 100% of the ESS capacity; however this particular choice can be modified in order to match a specific battery technology constraint.

The results obtained demonstrate that during the 24 hours operation of this case-study, the ESS optimised operation can solve several constrained violations (in terms of max/min bus voltage and max lines loading) which the network would experience without ESS. As an example, a snapshot relating to the 4th hour of the day is shown in Figure 4 and Figure 5.

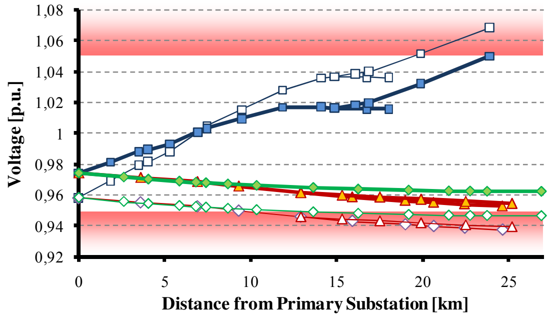

Figure 4 – Voltage profiles with (coloured markers) and without (white markers) the ESS, at 4 am. Blue, green and red colours distinguish feeder A, B and C. Red shaded-off bands indicate not allowed voltage values.

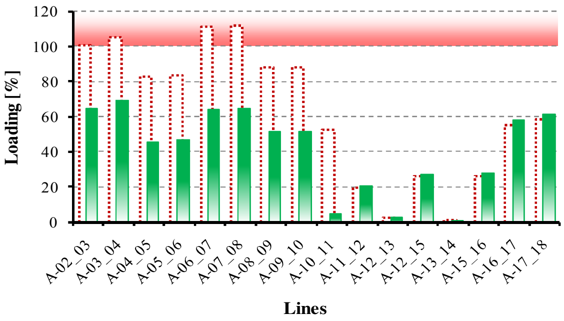

Figure 5 – Lines loading with (green bars) and without (white with dotted contour bars) the ESS, at 4 am. Red shaded-off band indicates not allowed loading values.

The optimal storage management allows avoiding constraints violation and, moreover, would potentially permit a greater DG penetration, since lines appear to be far enough from their maximum capabilities. Daily Joule losses in the initial network configuration, with no ESS and many constraints violations, were about 9,87 MWh/day. These losses decrease to about 8,25 MWh/day when the ESS is working as planned, while total losses affecting the ESS during his daily operation amount to 4,71 MWh/day. The 24-hours loss profiles are shown in Figure 6.

4.2 Comparison with an alternative solution

The grid control obtained with an adequate ESS management has been compared with an alternative grid regulation approach based on a spot-pricing energy market. The theoretical explanation of such an innovative kind of market can be found in [7][8]. In this alternative case study, it has been supposed that biogas generator connected to bus number 8 will be price sensitive and able to conveniently react to market signals. In this scenario, when network criticality increases, this generation becomes less convenient and, sometimes, leads the owner to shut down the biogas plant.

This, of course, will appear as an additional cost for the network. The social cost, that is the difference between total operational costs for energy generation and total benefit achieved by consumer using the electrical energy demanded, will rise up to 3873,17 €/day, whereas it will be 3283,67 €/day with the ESS installed and operated as shown above. In Figure 7 the hourly social cost is represented for both the proposed solutions.

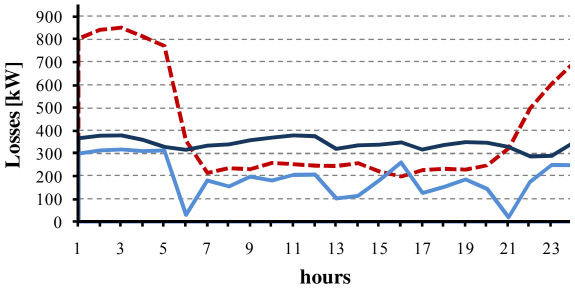

Figure 6 – Network losses without (dashed line) and with (dark blue continuous line) the ESS; losses due to ESS charge and discharge efficiencies (light blue continuous line).

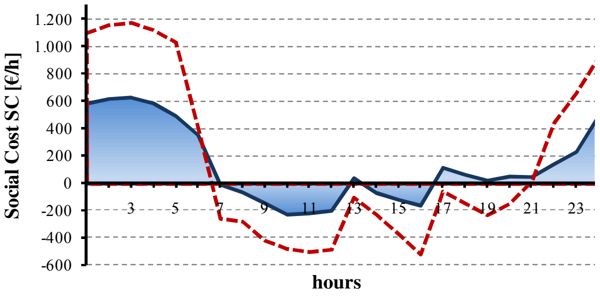

Figure 7 – Hourly social cost for network management with ESS (continuous line) and with price responsive biogas generator (dashed line).

5. Conclusions

In this work, a procedure is proposed for defining the optimum charge and discharge profile of an ESS installed in active distribution networks, which is capable to provide support services to the electrical network for solving operational constraints.

The complexity of the ESS optimization problem is due to the need of simultaneously considering both punctual constraints for all electrical network variables (ampacity and voltage for all busses) and integral constraints for the stored energy of the ESS.

The proposed solution, easily applicable even to large size networks, is based on a decoupled solution algorithm, which is characterised by the following three steps: (i) a network sensitivity analysis that provides a band within which the daily diagram of ESS active power can move, (ii) determination of the ESS reference operation profile that minimizes the distribution system active losses, and (iii) identification of the ESS operation planning, able to achieve chosen objective.

Application of the procedure on a realistic MV network demonstrates the feasibility of the approach in selecting the appropriate size and capacity of the ESS and in determining its optimal management while complying with network limitations. Moreover it can also represent a useful tool for the Distributor for comparing the ESS adoption with other possible solutions in order to better exploit the network and increase DG penetration level.

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