Optimal Integration of Distributed Energy Storage Devices in Smart Grids

Guido Carpinelli, *Member, IEEE*, Gianni Celli, *Member, IEEE*, Susanna Mocci, *Member, IEEE*, Fabio Mottola, *Member, IEEE*, Fabrizio Pilo, *Member, IEEE*, and Daniela Proto, *Member, IEEE*

***Abstract*—Energy storage is traditionally well established in the form of large scale pumped-hydro systems, but nowadays is finding increased attraction in medium and smaller scale systems. Such expansion is entirely complementary to the forecasted wider integration of intermittent renewable resources in future electrical distribution systems (Smart Grids). This paper is intended to offer a useful tool for analyzing potential advantages of distributed energy storages in Smart Grids with reference to both different possible conceivable regulatory schemes and services to be provided. The Smart Grid Operator is assumed to have the ownership and operation of the energy storage systems, and a new cost-based optimization strategy for their optimal placement, sizing and control is proposed. The need to quantify benefits of both the Smart Grid where the energy storage devices are included and the external interconnected grid is explored. Numerical applications to a Medium Voltage test Smart Grid show the advantages of using storage systems related to different options in terms of incentives and services to be provided.**

***Index Terms*—Smart grids, distributed energy storage, network planning, genetic algorithms.**

I. Nomenclature

B_{0b}	Cost for building branch b.
C_{CAP}	Cost of installation of capacitors.
C_{DESS}	Cost of installation of DESSs.
C_{LOSS}	Cost of losses.
C_{PA}	Cost of energy for price arbitrage.
$C_{Q,\mathrm{HV}}$	Cost of reactive power imported from HV grid.
$C_{Q,\mathrm{DG}}$	Cost of reactive power provided by DG units.
C_{UP}	Cost of network upgrading.
C_{0b}	Cost for upgrading branch b.
$E_{\mathrm{DESS}i,j,k}$	Energy stored in the DESS located at node j and at the end of the kth time interval of the ith year.
M_{0b}	Cost of branch j maintenance.
$N_{\mathrm{days},i,k}$	Number of days of the ith year characterized by a specified load and generation level at the kth interval.
$N_{L,i}$	Number of time intervals at the ith year.
N_Y	Number of years of the planning period.
$P_{\mathrm{DESS\_base}}$	Size of DESS base unit.
$P_{\mathrm{DESS},i,j,k}$	Active power of DESS at jth node and kth time interval of the ith year.
$P_{\mathrm{DESS},i,k}$	Total DESSs active power at kth time interval of the ith year (sum of $P_{\mathrm{DESS}i,j,k}$ on all grid nodes).
$P_{L,i,k}$	Distribution system active power losses at kth interval of the ith year.
$\mathrm{Pr}_{\mathrm{CAP}}$	Installation price of capacitor base unit.
$\mathrm{Pr}_{\mathrm{DESS}}$	Installation price of DESS base unit.
$\mathrm{Pr}_{\mathrm{DG},i,k}$	DG reactive power price at kth time interval of the ith year.
$\mathrm{Pr}_{L,i,k}$	Losses price at kth time interval of the ith year.
$\mathrm{Pr}_{\mathrm{HV},i,k}$	HV reactive power price at kth time interval of the ith year.
$\mathrm{Pr}_{\mathrm{En},i,k}$	Active energy price at the kth time interval of the ith year.
$Q_{\mathrm{CAP\_base}}$	Size of capacitor base unit.
$Q_{\mathrm{DG},i,k}$	DG total reactive power at kth time interval of the ith year.
$Q_{\mathrm{HV},i,k}$	Reactive power imported from HV grid at kth time interval of the ith year.
$Q^{sp}_{\mathrm{HV},i,k}$	Specified value of $Q_{\mathrm{HV},i,k}$.
R_{0b}	Residual value of branch b.
$m_{\mathrm{DESS},j}$	Number of DESS base units at node j.
$m_{\mathrm{CAP},j}$	Number of capacitor base units at node j.
n	Total number of nodes.
n_{CAP}	Total number of nodes where capacitors are installed.
n_{DESS}	Total number of nodes where DESSs are installed.
n_{branches}	Total number of branches in the network.
a	Discount rate.

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G. Carpinelli, F. Mottola, and D. Proto are with the Department of Electrical Engineering, Università Federico II of Napoli, Naples, Italy, (e-mail: guido.carpinelli@unina.it, fmottola@unina.it, danproto@unina.it).

G. Celli, S. Mocci, and F. Pilo are with the Department of Electrical and Electronic Engineering, University of Cagliari—Italy (e-mail: celli@diee.unica.it, susanna.mocci@diee.unica.it, pilo@diee.unica.it).

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α_{DESS}	Rate of change of $\mathrm{Pr}_{En,i,k}$.
α_{DG}	Rate of change of $\mathrm{Pr}_{\mathrm{DG},i,k}$.
α_{HV}	Rate of change of $\mathrm{Pr}_{\mathrm{HV},i,k}$.
α_L	Rate of change of $\mathrm{Pr}_{L,i,k}$.
η_c	DESSs charging efficiency.
η_d	DESSs discharging efficiency.
$\Delta T_{i,k}$	Duration of the kth time interval of the ith year.

II. Introduction

THE POWER sector has been undergoing several changes in the last decade. However, the steps taken are just the presage for a challenging development that will occur in several aspects. For instance, between 2005 and 2030, the share of renewable energy sources (RES) in the 27 European Union member states gross power generation will be more than double from 14.3% to 36.1%. In fact, the share of intermittent RESs will reach 20.7% of the total power generation in 2030. In this framework, electrical energy storage systems may play a crucial role, not by replacing existing components of the electricity value chain, but rather allowing the existing ones to do their job better and cheaper [1].

Several benefits of energy storage systems can be identified along the entire value chain of the electrical system, each related to a particular stakeholder [2], [3].

For the distribution system operator (DSO), storage system benefits are mainly related to voltage support, distribution losses reduction, capacity support and deferral of distribution investment.

For the transmission system operator (TSO), the main benefits are related to the reduction of transmission congestion and deferral of transmission investment.

For independent system operators (ISO), the benefits are related to regulation, fast regulation, spinning reserve, non-spinning reserve, black start and price arbitrage.

The benefits for end-users are related to power quality and reliability improvement, reduction of time of use and demand charges.

Finally, further benefits can be related to the provision of local capacity in not easily served areas of the grid and to the integration with RESs. In fact, the intermittency of wind and solar generation is a serious challenge that, at distribution level, requires new protection and control strategies, enhanced automation, voltage and VAR management, and, in some cases, enforcement of distribution grid infrastructure [4], [5]. The intermittent nature of the wind and solar generation poses planning and operational challenges not only at distribution, but also at transmission level, including additional ramping and regulation requirements and impacts on system stability.

The regulatory framework under which storage systems operate will have a significant impact on the aforementioned benefits and, then, efforts are in place to identify a clear regulatory environment that defines which incentive scheme should be adopted [6].

In this context, it is widely recognized that storage systems will be of the greatest importance in the development of future smart grids (SGs) where their benefits can be maximized. In fact, SGs will be characterized by the coexistence and interaction of different stakeholders of the electricity market and, then, SG storage systems can take advantages from several benefits across multiple categories.

This paper focuses on a medium voltage SG including distributed generation (DG) units owned by a third party. The smart grid operator (SGO) is assumed to have the ownership of distributed energy storage systems (DESS) which are under its full control. This makes DESSs particularly useful for avoiding DG dispatching or curtailment as well as reducing the need of VAR generation from both RESs and HV grid.

Of course, taking into account the high installation cost of storage devices, it would be difficult to evidence the convenience of installing DESSs if only the typical benefits of DSO are assumed to be achieved (i.e., voltage support, distribution losses reduction, capacity support and deferral of distribution investment) [2]. Then, some critical aspects that foster the use of DESSs must be considered.

For this reason, nevertheless the lack of an already established regulatory framework, in this paper, the SGO is given the opportunity to achieve a further revenue by performing price arbitrage in view of the electricity cost premium derived by storing energy when the price is low and supplying energy during peak load periods [7], [8]. Moreover, the use of DESSs is supposed to be supported also by further incentive mechanisms [6]. In more detail, two possible DESSs incentive mechanisms were considered in this paper: 1) specific tariffs for balancing services, and 2) capital grant to support the initial installation of new electricity storage facilities.

In particular, this paper deals with the problem of DESSs optimal sizing and location, with reference to battery energy storage systems. This is a crucial problem since, as is well known, DESS benefits are strictly related to their location and sizing as well as storage technology [9]–[15].

In the relevant literature, DESSs optimal sizing and location were addressed in [10]–[13].

In [10] a method is proposed to find the optimal placing for DESSs and small generators in a microgrid with the aim of losses minimization.

In [11] an analytical method for the optimization of location and sizing of DESSs at the peak load level is proposed in order to gain energy loss reduction while serving the primary goal of energy injection in the form of energy arbitrage. Moreover, the combination of storage devices and capacitor placement to achieve a higher loss reduction is also considered. DESS installation costs are not considered so disregarding one of the most critical aspects of DESSs.

In [12] and [13], optimal DESS allocation methods were proposed with the aim of reducing losses and deferring network upgrading. In both papers genetic algorithms (GAs) were used as solution procedures and the optimal charge/discharge pattern of DESSs for the intraday optimization was considered and solved by developing inner algorithms based on dynamic programming (DP) [12] and sequential quadratic programming (SQP) [13], respectively. Regarding the inner algorithms adopted in [12], [13], it should be noted that for obtaining accurate results a thin discretization of the DESS charge level in the DP-based approach is required so expanding the required computational burden, whereas in the SQP-based approach DESS charge level

is a continuous variable. On the other hand, the DP-based approach is characterized by a more simple and intuitive implementation that facilitates the adoption of probabilistic load flow calculations, essential to deal with all the uncertainties introduced by the renewable generation and the risk to overcome technical constraints (like nodal voltages).

Since the planning application proposed in this paper does not use a probabilistic approach, the authors use the method proposed in [13] for the optimal allocation of DESSs and improve it by including new significant and substantial contributions.

First of all, the optimization model was modified so that the DESSs are fully exploited to provide advanced services to the SGO (that is considered a distributed energy resource aggregator) as well as a further service to the TSO. The additional service considered in this paper is the provision of suitable reactive power to the TSO, thus participating to the VAR/voltage regulation; also other active power-based services for the TSO can be easily included in the model.

Further innovations are related to the possibility of taking into account the price arbitrage and the adoption of one of the aforementioned regulatory schemes (tariffs for balancing services and capital grants). Moreover, DESS modelling was improved by including charge/discharge efficiency to better evaluate its negative effect on cost analysis, and by taking into consideration the impact of charge/discharge cycles and discharge depth on the DESS expected life time.

Finally, the new optimization model includes the linearization of the power flow equations (equality constraints) aimed at reducing the computational burden.

The new model formulation and the numerical results deriving from its application to actual cases can be a useful tool not only for SGOs but also for who is interested in analyzing the possible means to apply incentives on DESSs (i.e., an independent Authority).

The structure of the paper is the following. Section III describes the proposed model and algorithm. Section IV discusses the results of the numerical applications performed on a small test SG. Conclusions and future works are drawn in Section V.

III. The Proposed Location and Sizing Method

A medium voltage (MV) SG connected to a high voltage (HV) grid through a HV/MV transformer is considered. The SG includes DG units owned by a third party and DESSs owned by the SGO. DESSs are assumed to be battery energy storage systems connected to the grid through dc/ac, and PWM-controlled static converters. The power converter enables a fast control of active and reactive power [16]. Moreover, among all devices that can be involved in VAR/voltage regulation (D-VAR, OLTC, capacitors), for the sake of simplicity and without loss of generality, only capacitors are considered.

The load demand and DG power productions are assumed to be known, characterized by assigned typical daily variations and growing rates in the planning time horizon.

The considered planning problem aims at optimally siting and sizing DESSs and capacitors in order to provide services internal (i.e., loss minimization) and/or external to the SG (i.e., the provision of suitable reactive power to the TSO). The optimal solution is obtained minimizing the whole costs, taking into account also the price arbitrage and the possibility of adoption of different regulatory schemes (tariffs for balancing services and capital grants to support the initial installation of new electricity storage facilities).[1] Among the costs, also the network upgrading cost is included. In fact, the connection of distributed energy sources and natural growth of load demand can determine currents greater than the line thermal limits and intolerable voltage variations. According to the passive paradigm of distribution systems, those operational problems are to be solved at the planning stage with the expansion or the upgrade of the network (*connect & forget* approach). Modern vision of distribution business, based on active control of the systems, aims at truly operating the distribution system by exploiting distributed energy resources (DERs) and DESSs as well as active demand to defer investments without jeopardize reliability or impeding the integration of RESs.[2]

The aforementioned planning problem can be formulated in terms of minimization of an objective function, while proper equality and inequality constraints are met, i.e.:

$$\min f_{\mathrm{obj}}(\boldsymbol{X}, \boldsymbol{C}) \tag{1}$$

subject to:

$$\psi(\boldsymbol{X}, \boldsymbol{C}) = 0 \tag{2}$$

$$\eta(\boldsymbol{X}, \boldsymbol{C}) \leq 0, \tag{3}$$

where $\boldsymbol{X}$ is the system state vector (e.g.: voltage at all system busbars) and $\boldsymbol{C}$ is the control vector (output of the optimization procedure). The information stored in $\boldsymbol{C}$ is the position of DESSs and capacitors in the network, capacitors' size, DESSs' optimal rated capacity, DESSs' charge/discharge pattern, reactive powers of DESSs, DG, and HV grid.

The optimization problem (1)–(3) is a mixed integer, nonlinear, constrained optimization problem that can be solved by using GAs [15]. However, GAs can require high computational effort due to the extension of the planning period and the daily variations to be taken into account. Then, a hybrid approach is used in this paper, including the GA and an inner algorithm based on SQP optimization (Fig. 1).

The GA creates an initial population whose individuals are characterized by proper codified variables referring to the allocation nodes of DESSs and capacitors and their size. Once generated the initial population, the inner algorithm performs an optimization aimed at finding the optimal daily charge/discharge cycles of DESSs (including initial and final state of charge) and the reactive power that DG and DESSs have to provide for each individual in the population.

The fitness function of each individual in the population is calculated by using the inner optimization output. If GA does not converge, a next population generation is provided.

Input variables of the optimization problem (1)–(3) are the DG locations and active powers, and the load demand over the planning period. Other inputs are the installation costs of DESSs and capacitor base units and the costs of 1) network upgrading,

[1]In many countries, the distribution companies are regulated bodies that are committed to operate the distribution systems. The investments return depends on the weighted average cost of capital (WACC). Therefore, with the aim to promote innovation, smart grid and storage development has been supported by means of subsides extended by regulatory agencies thus reducing the total cost of funding.

[2]It should be noted that, without the DESSs and/or upgrading, control actions should be taken to reduce power injections or to make the demand more flexible. All those operation actions have costs. For instance, the power producers may have the production curtailed and the society may fail in reducing greenhouse emissions.

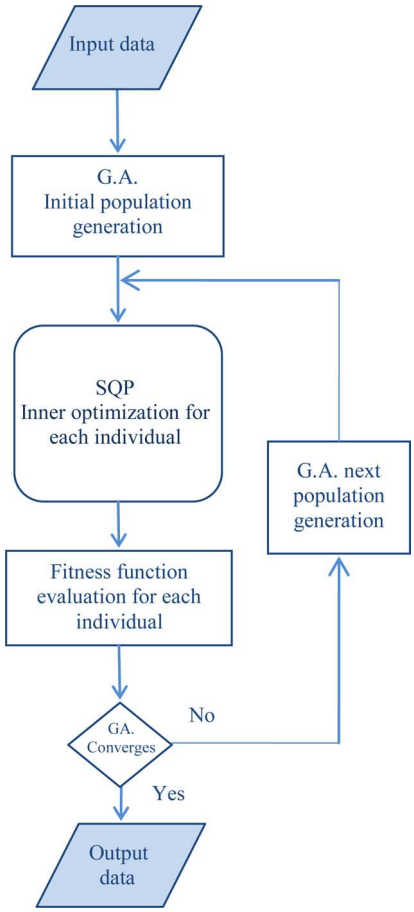

Fig. 1. Flowchart of the proposed procedure.

2) energy for price arbitrage, 3) losses, 4) reactive power imported by the HV grid, and 5) those provided by DG units. The load demand and power productions are assumed to grow in the planning time horizon according to specified step functions.

Output of the problem is the optimal size and location of capacitors and DESSs. Other outputs are DESSs optimal charge/discharge patterns, and the daily DG, DESS and HV grid reactive power schedule.

In the following subsections more details on the GA and SQP based algorithm implementations are given.

A. Genetic Algorithm Implementation

The GA individuals are characterized by the allocation nodes and number of elements of a pre-assigned size of DESSs and capacitors. DESSs and capacitors are assumed to be integer multiples of a unit base; for example, by assuming the DESS base unit equal to BU, the size at each bus can assume the values $[0, BU, 2BU, 3BU, \ldots, N_{\max}BU]$. The same applies to the capacitors. The value of the pre-assigned size of DESSs and capacitors are imposed on the basis of economic considerations.

The GA fitness function includes all the costs sustained by the SG owner over the whole planning period. More in detail the fitness function is:

$$F_{\mathrm{GA}} = C_{\mathrm{LOSS}} + C_{Q,\mathrm{HV}} + C_{Q,\mathrm{DG}} + C_{\mathrm{PA}} + C_{\mathrm{DESS}} + C_{\mathrm{CAP}} + C_{\mathrm{UP}} \quad (4)$$

where:

$$C_{\mathrm{LOSS}} = \sum_{i=1}^{N_Y}\left[\left(\frac{1+\alpha_L}{1+a}\right)^{i-1} \times \sum_{k=1}^{N_{L,i}}\left(N_{\mathrm{days},i,k}P_{L,i,k}\mathrm{Pr}_{L,i,k}\Delta T_{i,k}\right)\right]$$

$$C_{Q,\mathrm{HV}} = \sum_{i=1}^{N_Y}\left[\left(\frac{1+\alpha_{\mathrm{HV}}}{1+a}\right)^{i-1} \times \sum_{k=1}^{N_{L,i}}\left(N_{\mathrm{days},i,k}Q_{\mathrm{HV},i,k}\mathrm{Pr}_{\mathrm{HV},i,k}\Delta T_{i,k}\right)\right]$$

$$C_{Q,DG} = \sum_{i=1}^{N_Y}\left[\left(\frac{1+\alpha_{\mathrm{DG}}}{1+a}\right)^{i-1} \times \sum_{k=1}^{N_{L,i}}\left(N_{\mathrm{days},i,k}Q_{\mathrm{DG},i,k}\mathrm{Pr}_{\mathrm{DG},i,k}\Delta T_{i,k}\right)\right]$$

$$C_{\mathrm{PA}} = \sum_{i=1}^{N_Y}\left[\left(\frac{1+\alpha_{\mathrm{DESS}}}{1+a}\right)^{i-1} \times \sum_{k=1}^{N_{L,i}}\left(N_{\mathrm{days},i,k}P_{\mathrm{DESS},i,k}\mathrm{Pr}_{En,i,k}\Delta T_{i,k}\right)\right]$$

$$C_{\mathrm{DESS}} = \mathrm{Pr}_{\mathrm{DESS}}\sum_{j=1}^{n_{\mathrm{DESS}}}\left(m_{\mathrm{DESS},j}\cdot P_{\mathrm{DESS\_base}}\right)$$

$$C_{\mathrm{CAP}} = \mathrm{Pr}_{\mathrm{CAP}}\sum_{j=1}^{n_{\mathrm{CAP}}}\left(m_{\mathrm{CAP},j}\cdot Q_{\mathrm{CAP\_base}}\right)$$

$$C_{\mathrm{UP}} = \sum_{b=1}^{n_{\mathrm{branches}}} C_{0b} = \sum_{b=1}^{n_{\mathrm{branches}}} B_{0b} + M_{0b} - R_{0b}$$

The upgrading cost, C_{UP}, is the sum of the capital expenditures related to every branch, C_{0b}, annualized to the starting year of the planning period with the net present value. The cost of the bth branch is the sum of building, management and residual costs. Further details on the upgrading cost evaluation can be found in [12].

It should be noted that by assigning proper values to the cost of installation of DESSs (capital grant) or to the active energy unitary cost for price arbitrage (specific tariffs for balancing services) different regulatory environments can be simulated. By minimizing (4), the term C_{PA} would assume negative values so that it would be a revenue rather than a cost. Of course, some terms of (4) may be omitted or some others may be added coherently with established objectives.

Inequality constraints can be imposed in the GA optimization that are the maximum and minimum number of allocable DESSs and capacitors of pre-assigned size (e.g., $N_{\max}$) whose value is depending on economical and technical aspects related to the specific application. No equality constraints are considered in the GA.

The results of the SQP-based optimization are used to evaluate the fitness function of each individual.

Regarding the stopping criterion, the algorithm ends when the best fitness function value remains constant over an assigned

number of generations or the maximum number of iterations is reached.

B. SQP-Based Inner Algorithm Implementation

An optimal power flow (OPF) is formulated considering the DESS charge pattern during the day as a continuous variable. For each time interval, the variables considered are the active and reactive powers provided by DGs and DESSs together with the initial DESS state of charge (that has to be equal to the initial value of the next day).

The OPF, solved with an SQP-based inner algorithm, is simultaneously performed for all the time intervals of the day. This approach is required because the DESS charge level at each interval is depending on the value assumed in the preceding interval. The OPF minimizes a function obtained by the sum, on the whole day, of several terms, each referring to a single interval of the day. The equality and inequality constraints are also formulated and simultaneously satisfied for all the intervals of the day.

Referring to the planning period of N_Y years the objective function to be minimized is given by:

$$F_{\mathrm{OPF}} = C_{\mathrm{LOSS}} + C_{Q,\mathrm{DG}} + C_{Q,\mathrm{HV}} + C_{\mathrm{PA}}, \tag{5}$$

where the costs are evaluated as in (4).

The *equality constraints* to be satisfied are:

— power flow equations,
— DESS energy balance equations, and
— reactive power balance equation at the interconnection bus, if suitable reactive power to the TSO has to be provided.

Regarding the power flow equations, a linearized form of the classical equations is properly formulated to reduce computational efforts. The active and reactive powers produced by DG and DESSs are control variables, so they are included in the power flow balance equations.

The DESS energy balance equations impose that the energy stored in the DESS must be the same at the beginning and at the end of each day. Then, the DESS energy variation in each time interval is evaluated as reported in (6) and (7) [9]. Thanks to the balance (6) and (7), DESS modelling includes efficiency for a more precise assessment of the impact on costs.

Regarding the specified reactive power value at the interconnection bus, the equality constraint in the kth time interval can be formulated as:

$$Q_{\mathrm{HV},i,k} = Q^{sp}_{\mathrm{HV},i,k} \tag{8}$$

By imposing $Q^{sp}_{\mathrm{HV},i,k} = 0$ in (8), the SG becomes autonomous from the reactive power point of view. Of course, other external services can be offered to the TSO by simply imposing a similar constraint at the interconnection bus to other variables, for example the active power.

The *inequality constraints* to be satisfied involve the maximum allowable energy stored in the DESSs, that depends on DESS capacity and charging time [9], [17]. Other constraints related to the voltage and power limits are [13]:

— voltages at all busbars have to fall into the range $[V_{\min} - V_{\max}]$ p.u.;
— DESS and DG active powers are limited by their rated power capacities;
— DESS and DG active and reactive powers are also limited by the rated capacity of the power converter;[3]
— energy stored in the DESS has to fall into an admissible range, defined by a prefixed maximum depth of discharge.

The analytical formulation of the constraints is easy to derive so, for the sake of conciseness, it is omitted.

It should be noted that also the number of DESS charge/discharge cycles is controlled during the procedure; it cannot exceed a maximum value according to the life cycle of DESSs which is related to the depth of discharge. This last constraint is included in order to make DESS life span feasible with reference to the planning time horizon.

When voltage and current constraints are not complied with and consequently the SQP algorithm does not converge, upgrade of the network is performed.[4]

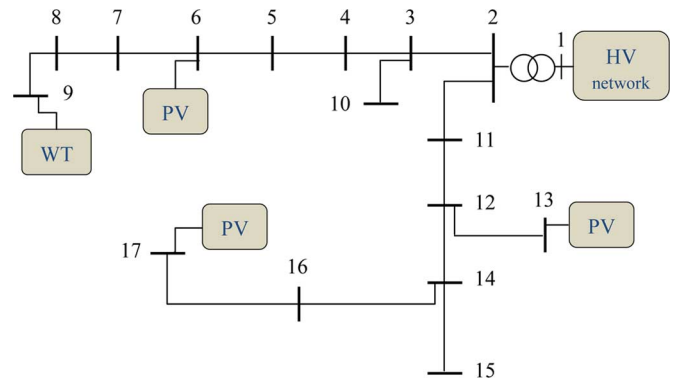

Fig. 2. Test smart grid.

IV. Numerical Applications

The planning problem formulated in the previous section was solved with reference to the 17-busbar MV balanced 3-phase network shown in Fig. 2 [18] that is widely used in the technical literature for planning studies [19]–[21].

The test system data including the load base values are reported in the Appendix. The SG is connected to the HV network through a 138/12.5 kV, 18 MVA transformer.

[3]The size of the static converter is usually based on the size of the energy source (DESS or DG), so reactive power can be provided only when the active power is lower than the rated capacity of the power converter. The static converter might be also oversized in order to provide a reactive power service that is not completely constrained by the active power generated, this choice depending on the particular application and on the economic objectives of the energy source owner.

[4]The algorithm reinforces those branches characterized by a power flow greater than the rated thermal capacity. If the nodal voltage is out of the tolerable range, network reinforcements are adopted to put the voltage within its boundaries. In this application no changes are allowed to network topology.

$$E_{\mathrm{DESS}i,j,k} = E_{\mathrm{DESS}i,j,k-1} - \frac{P_{\mathrm{DESS}i,j,k}}{\eta_d}\Delta T_{i,k}, \quad \text{for } P_{\mathrm{DESS}i,j,k} > 0 \tag{6}$$

$$E_{\mathrm{DESS}i,j,k} = E_{\mathrm{DESS}i,j,k-1} - \eta_c P_{\mathrm{DESS}i,j,k}\Delta T_{i,k} \quad \text{for } P_{\mathrm{DESS}i,j,k} \le 0 \tag{7}$$

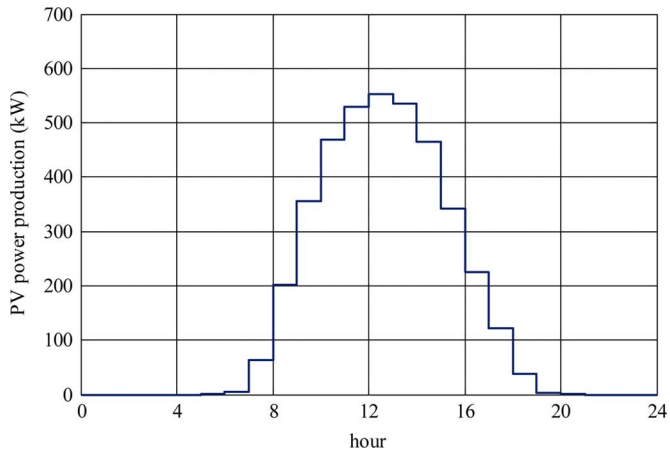

Fig. 3. PV power production at bus #6.

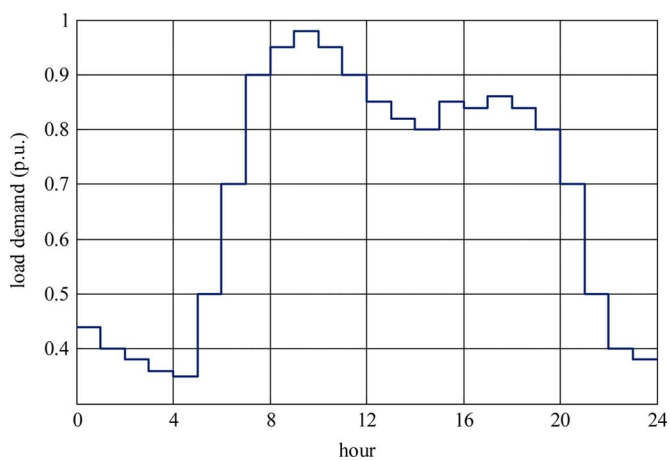

Fig. 4. Daily load demand of a generic SG bus.

Three 1 MW peak power PV generators are located at buses #6, #13 and #17 and characterized by a specified forecast of the daily production. As an example, Fig. 3 reports the daily power production of the PV unit at bus #6. Each PV unit is connected to the SG with 1 MVA dc/ac static converter.

A 1 MW wind turbine (WT) is connected at bus #9 through 1 MVA static converter.

Regarding the DESS typologies, 1 × 250 kW-5h or 1 × 500 kW-5h REDOX batteries have been considered. The rated power of converters depends on the number of batteries installed at the same bus, as it will be explained in the next subsections.

A step function was used to approximate the daily load curve for all network nodes. As an example, Fig. 4 shows the load demand curve with reference to a generic SG bus. The pattern reported in Fig. 4 refers to both active and reactive power demands. Increments of the load powers were considered starting from 85% of the values reported in Appendix up to a value of 100% in the last year. The period considered for the planning study is 15 years. In order to guarantee DESSs' life span coherent with this planning horizon a maximum depth of discharge of 75% has been accepted [14]. Regarding DESS efficiency, the value of 0.85 was considered in both charging and discharging stages [14].

The daily energy tariffs are assumed to be 152 €/MWh from 8:00 to 19:00 (peak hours), 126 €/MWh from 7:00 to 8:00 and from 19:00 to 23:00, and 90 €/MWh in the rest of the day (off-peak hours) [22]. As far as the other costs are concerned,

TABLE I
ALLOCATION BUS AND SIZE OF DESSS AND CAPACITORS (CASE 1)

DESSs		*Capacitors*	
Allocation node	*Rating*	*Allocation node*	*Rating*
-	-	5	7 × 450 kVAr
-	-	14	3 × 450 kVAr

typical values were assumed for the cost of DG and HV reactive powers [23], DESSs installation and network upgrading [12], [13]. In particular, the DG reactive power cost is 0.01 times the cost of energy, the HV imported reactive power cost is equal to 0.003 times the cost of energy and the DESSs installation cost is 300 €/kWh. This last value includes also O&M costs that were assumed equal to 1% of the capital cost [2]. Capacitor installation costs are 18 €/kVAr. All unitary costs have been assumed to increase by 2% per year, and the discount rate has been assumed equal to 5% for the present value calculation.

A maximum allowable number of nodes for DESSs location was assumed; in fact, in MV systems the trend is to concentrate such facilities in a reduced number of nodes. An equivalent constraint has been assumed also for capacitors.

In order to highlight the potentialities of DESSs in the SG framework, the following four cases are shown in detail:

— *Case 1*: only price arbitrage is considered;
— *Case 2:* as Case 1 with additional specific tariffs for balancing services;
— *Case 3:* as Case 1 with additional capital grant for new energy storage facilities;
— *Case 4:* as Case 3 with the provision of an additional external service related to reactive power.

In the following, the results of the proposed procedure applied to the SG of Fig. 2 are shown. In all case studies the maximum number of allocation nodes is two for both DESSs and capacitors. Moreover, network upgrading was not needed in none of the analyzed case studies. This allowed evidencing the influence of price arbitrage and other incentive mechanisms on DESS penetration.

All the figures reported in the next subsections refer to a day of the last year of the planning period.

Case 1: The results of the proposed procedure, in terms of siting and sizing of DESSs and capacitors, are reported in Table I. When incentives are not considered, the high installation costs penalize the use of DESSs, and only capacitors are installed.

Figs. 5 and 6 show the reactive power of the DG unit located at bus #9 and that exchanged with the high voltage grid.

Fig. 5 shows how the reactive power injection of the DG unit is concentrated during the peak load period. Similar patterns characterize also the other DG units. This behavior is justified by the goal of reducing power losses.

In Fig. 6, the reactive power exchanges with the HV grid are depicted. The negative values during the off peak hours (i.e., the reactive power is exported to the HV grid) are caused by the relevant number of allocated capacitors which are supposed to be always connected. It is worth noting that the capacitors' reactive power is much less variable versus time than DESS or DG reactive power, and not far from its rated value (reported in Table I). This is due to the fact that, in the paper, fixed capacitors were considered, always connected at the same bus whatever the

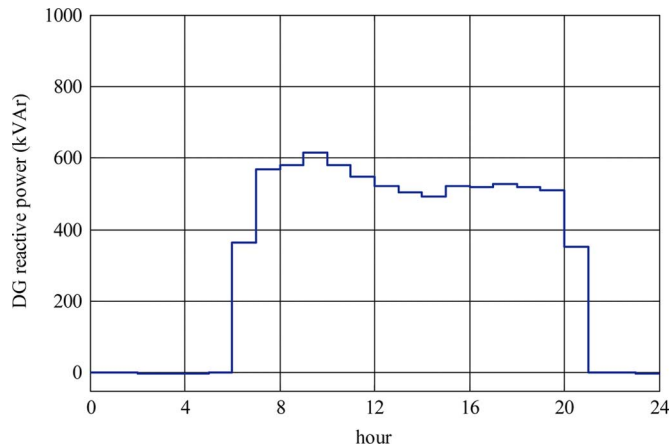

Fig. 5. Daily reactive power of DG at bus #9 in case 1.

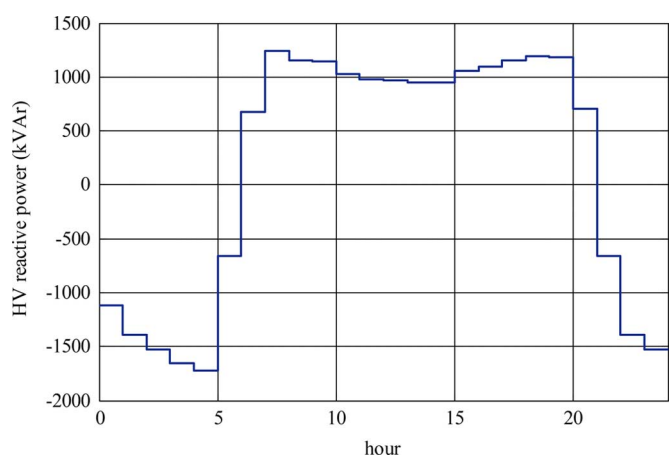

Fig. 6. Daily reactive power at the interconnection bus in case 1.

load level might be; thus, their reactive power depends only on the applied voltage.

Case 2: In this case, tariffs for balancing services are applied to compensate the energy exchanged between grid and DESSs. To simulate such incentive mechanism, the energy price in the peak hours was increased and it was decreased in the off peak hours. In both cases the price arbitrage variation was assumed to be equal to 27%.

The results of the optimization procedure are reported in Table II where it clearly emerges the role of incentives to promote the installation of 250 kW DESS at node #16. It should be noted that the amount of incentive considered in this application (27%) does not allow an extensive use of DESSs since this is a boundary value for incentive effects; in fact, other simulations were performed that demonstrated how a slightly greater incentive results in a considerable increase of allocated DESSs. In more detail, with an incentive of 30%, more than 10 DESSs were allocated. On the other hand, a further simulation with an incentive of 25% resulted in no allocated DESSs. This confirms a strong nonlinear relationship between incentives and DESS penetration.

With reference to this case study (incentive value 27%), Fig. 7 shows the daily DESS active power. Fig. 8 reports the corresponding stored energy daily profile. Figs. 9 and 10 depict the daily reactive power of the DESS and DG located at bus #9, respectively. Fig. 11 shows the daily reactive power imported from the HV grid.

TABLE II
ALLOCATION BUS AND SIZE OF DESSS AND CAPACITORS (CASE 2)

DESSs		*Capacitors*	
Allocation node	***Rating***	***Allocation node***	***Rating***
16	1x250kW	6	7 × 450 kVAr
-	-	12	3 × 450 kVAr

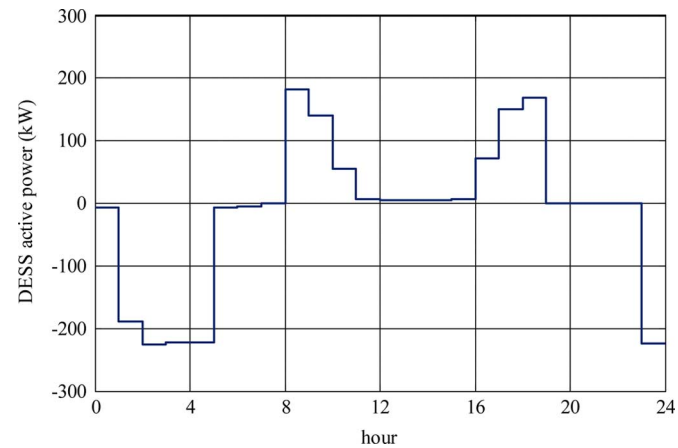

Fig. 7. Daily DESS active power in case 2.

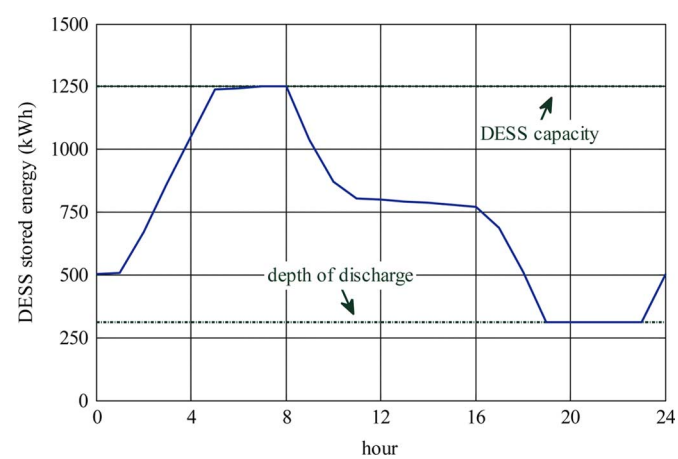

Fig. 8. Daily DESS stored energy in case 2.

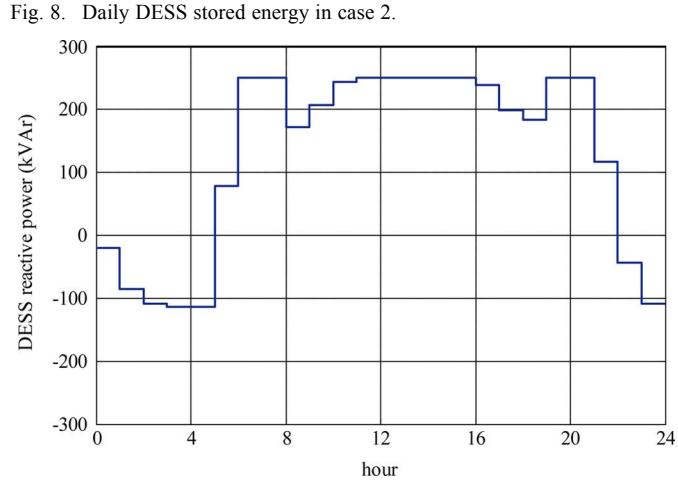

Fig. 9. Daily DESS reactive power in case 2.

As foreseeable, DESS charges during off peak hours and discharges during peak hours (Fig. 7). Correspondingly, DESS energy varies within the admissible limits in terms of capacity and

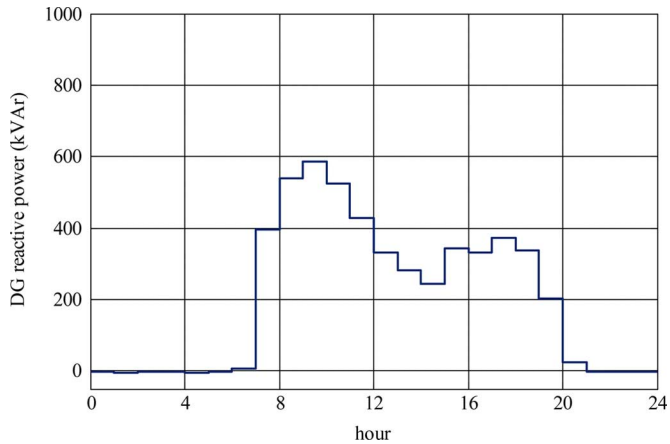

Fig. 10. Daily reactive power of DG at bus # 9 in case 2.

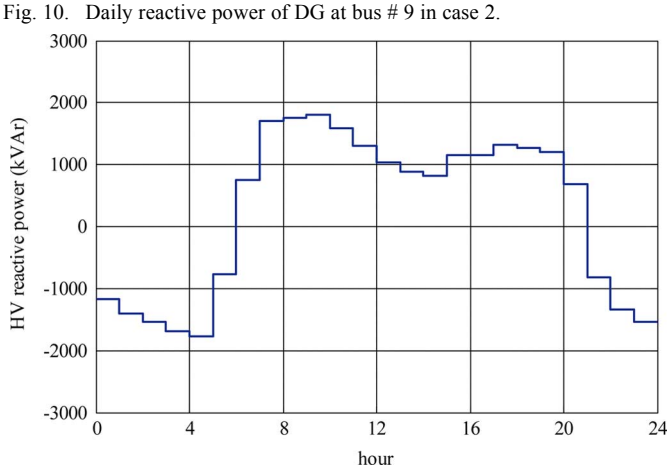

Fig. 11. Daily reactive power at the interconnection bus in case 2.

TABLE III
ALLOCATION BUS AND SIZE OF DESSS AND CAPACITORS (CASE 3)

DESSs		*Capacitors*	
Allocation node	***Rating***	***Allocation node***	***Rating***
7	3x500kW	6	5 × 450 kVAr
16	1x500kW	14	2 × 450 kVAr

depth of discharge (Fig. 8). Fig. 9 shows the noticeable contribution of the DESS in terms of reactive power. By comparing Figs. 7 and 9 it can be seen that the maximum DESS converter rating (250 kVA) is almost always reached. In fact, there is not any additional cost for reactive power since the SGO is the owner of the DESSs and hence, when active power is not involved (e.g., at the 20th hour), the corresponding reactive power is 250 kVAr.

With reference to Fig. 11, also in this case a negative value of reactive power imported from the HV grid can be noted during the off peak hours.

Case 3: The incentives considered in this case are assumed in the form of DESSs capital cost reduction. The capital cost of each DESS is reduced by 70%.

From the analysis of the results of Table III, it appears that such incentives encourage the use of DESSs though, also in this case, a considerable number of capacitors is used for voltage regulation and losses reduction. Other simulations were performed for analyzing the sensitivity of DESS allocation to the incentive which demonstrated that with lower values of the incentive (e.g., 60%) no DESS were allocated.

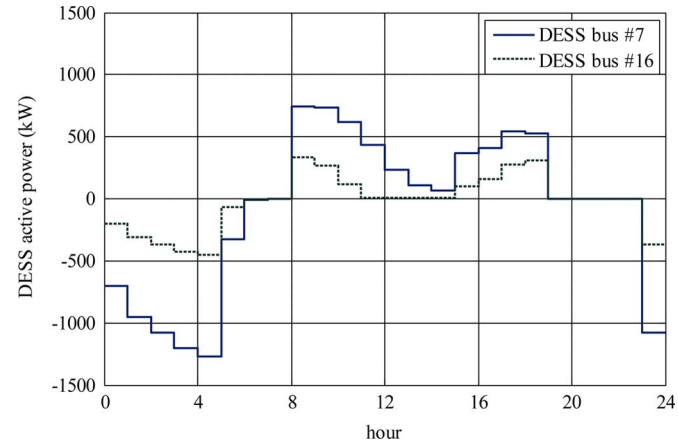

Fig. 12. Daily active power of DESSs at buses #7 and #16 in case 3.

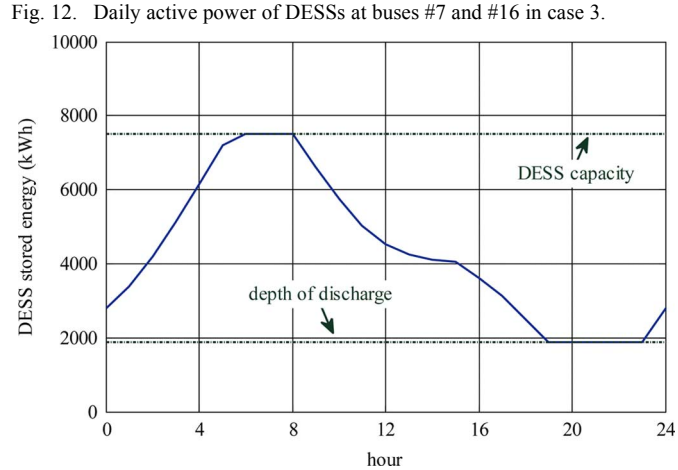

Fig. 13. Daily energy stored in the DESS at bus #7 in case 3.

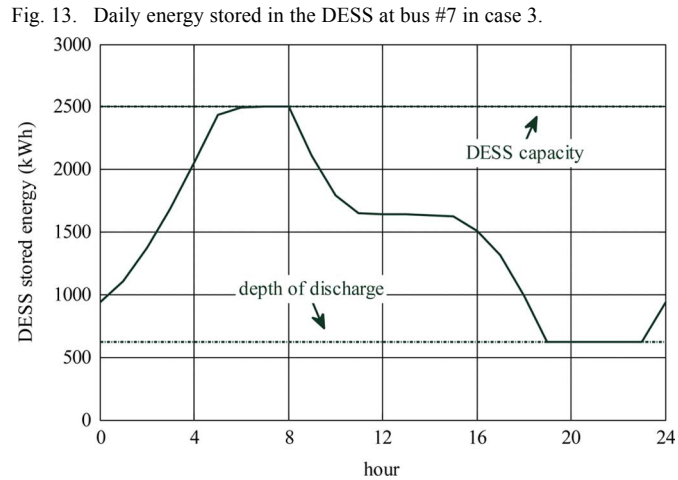

Fig. 14. Daily energy stored in the DESS at bus #16 in case 3.

As further results of the proposed approach, active and reactive power profiles of the energy sources (DG, DESS and HV grid) are depicted in Figs. 12–17.

Once again DESSs charge during off peak hours and discharge during peak hours (Fig. 12); DESSs' energy varies within the admissible limits in terms of capacity and depth of discharge (Figs. 13 and 14). Moreover, as foreseeable, the DESSs located at different busbars always charge/discharge at the same time.

Fig. 15 shows the noticeable contribution of DESSs in terms of reactive power. Moreover, it can be seen that the maximum DESS converters' rating (1500 and 500 kVA, respectively) is often reached.

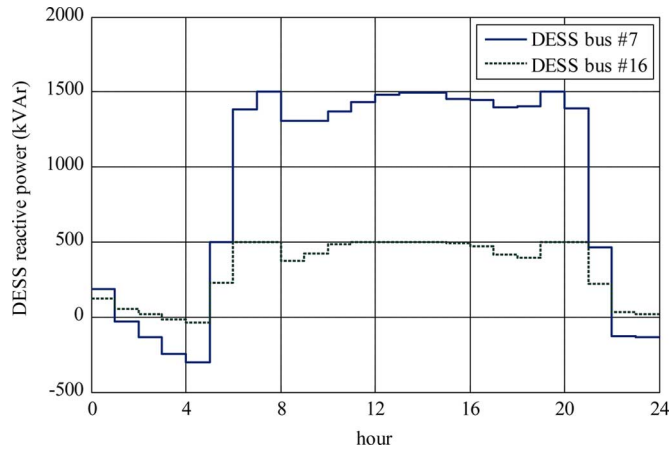

Fig. 15. Daily reactive power of DESSs at buses #7 and #16 in case 3.

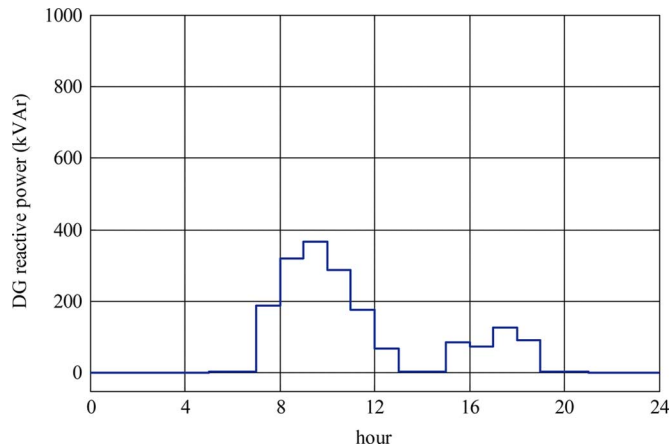

Fig. 16. Daily reactive power of DG at bus # 9 in case 3.

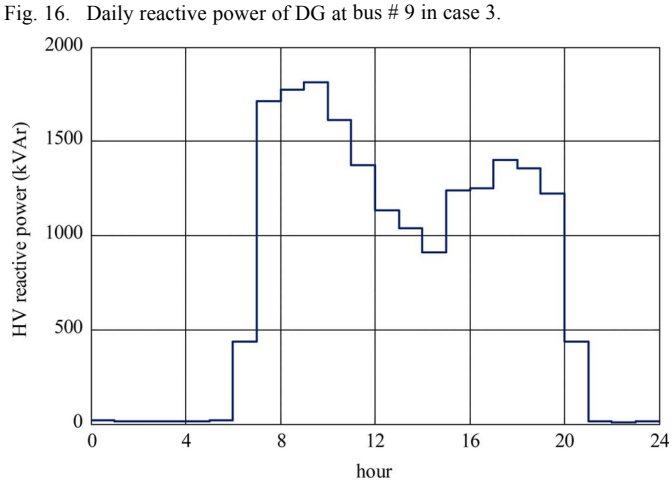

Fig. 17. Daily reactive power at the interconnection bus in case 3.

Finally, by comparing Figs. 16 and 5 a reduction of DG reactive power contribution can be noted due to the increased contribution of DESSs.

It is worth noting that in this case the reactive power, imported from the HV grid (Fig. 17) during the off peak hours, does not assume negative values. Once again, this is due to the massive presence of DESSs.

Case 4: A zero value is imposed on the reactive power exchanged at the interconnection HV bus (independence of the SG in terms of reactive power). In this case, the external service consists in relieving the HV network from the reactive power provision.

TABLE IV
ALLOCATION BUS AND SIZE OF DESSS AND CAPACITORS (CASE 4)

DESSs		*Capacitors*	
Allocation node	***Rating***	***Allocation node***	***Rating***
5	3x500kW	6	5 × 450 kVAr
16	1x500kW 1x250kW	11	3 × 450 kVAr

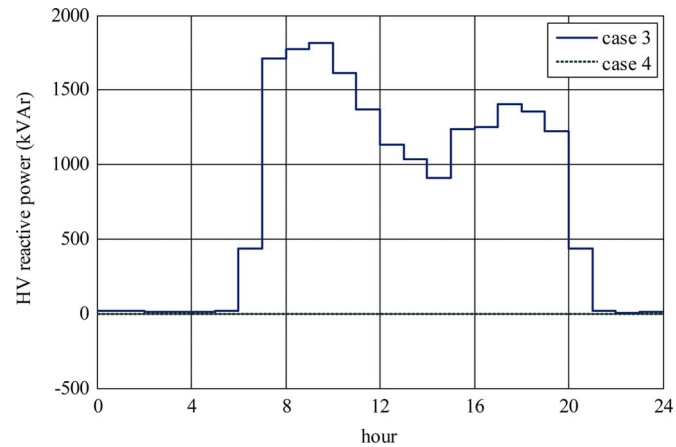

Fig. 18. Daily reactive power at the interconnection bus in cases 3 and 4.

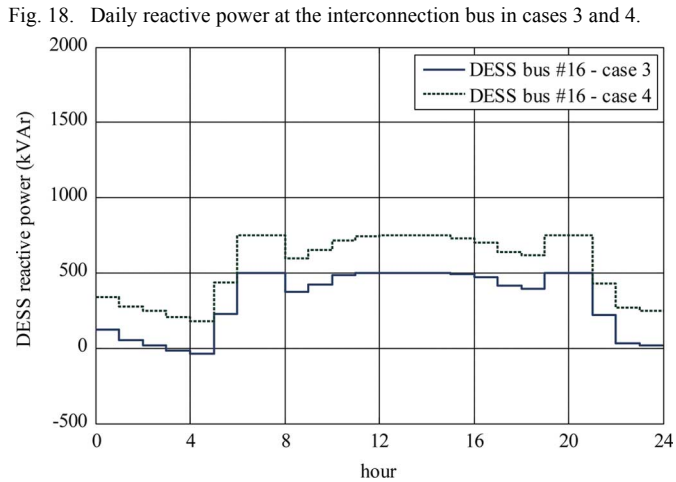

Fig. 19. Daily reactive power of DESS at bus #16 in cases 3 and 4.

The results summarized in Table IV show few differences with case 3, in terms of both allocation nodes and sizes. In particular, with reference to the size, one additional 250 kW DESS and one additional 450 kVAr capacitor are necessary.

Fig. 18 shows the daily reactive power imported from the interconnection bus in Cases 3 and 4.

As shown in Fig. 18, slight variations in siting and sizing of the distributed resources allow satisfying the external constraint on the reactive power.

From the analysis of Figs. 19 and 20, it appears that DGs and DESSs have to increment their reactive power production. This is due to the constraint on the reactive power imported from the HV bus that in this case is equal to zero. Obviously, this results in a slight increase of the objective function value (roughly 1%).

Eventually, in Table V the daily losses for each case in a generic day of the first and last year of the planning horizon are reported.

From the analysis of Table V it follows that in both the first and last years, the decrease of losses is related to the increase of DESS rating. An exception can be noted in case 4 of the first year

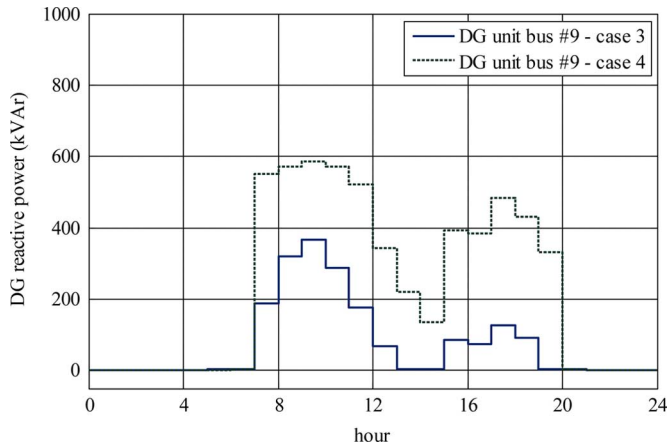

Fig. 20. Daily reactive power of DG at bus #9 in cases 3 and 4.

TABLE V
DAILY ENERGY LOSSES

case	Daily losses (MWh)	
	First planning year	Last planning year
case 1	1.417	1.978
case 2	1.394	1.954
case 3	1.287	1.849
case 4	1.297	1.821

which depends on the further constraint imposed to the value of the reactive power at the interconnection bus. Moreover, the increased value of losses in last year compared to those observed in the first year can also be noted which essentially depends on the increment of the power load demand along the planning period.

V. CONCLUSION

The wide deployment of intermittent solar and wind generation is challenging transmission and distribution systems. DER management, energy storage, dispatch of wind and solar resources as well as demand response strategies could alleviate some of these challenges. Among those remedies, the integration of DESSs may exalt the potentialities of SGs to make the SGO an aggregator capable to offer also ancillary services to TSO, without asking to RES excessive participation to voltage/VAR regulation.

In this paper, starting from previous preliminary experiences, a new method for the optimal DESSs and capacitors integration at minimum cost is proposed. The optimal solution allows SGO to achieve voltage improvements, defer network upgrades and offer VAR regulation to the TSO.

The proposed approach is a useful tool for analyzing potential advantages of distributed energy storages in SGs with reference to different possible conceivable regulatory schemes and services to be provided. Numerical applications explored different means to provide incentives to the use of DESSs showing some of the benefits obtainable by their use.

The main outcomes of the paper are that, in the examined cases:

— DESSs were not installed when only price arbitrage was considered and then incentive mechanisms are needed to justify the use of DESSs.

— Specific tariffs for balancing services and capital grant for new energy storage facilities can be easy and useful mechanisms to incentive the DESSs penetration in SGs.

— The provision of further services to the TSO could represent an interesting way to enhance the DESS penetration process.

Moreover, it is worth noting that in the analyses presented in this paper network upgrading was never needed. Consequently, a further increment in the penetration of DESSs is expected in those cases for which network upgrading is required and DESSs are capable to defer it.

Future works will deal with the application of multiobjective programming to better consider different technical and economical objectives that can be pursued with DESSs in the SG framework. Moreover, the increasing values of distributed generation penetration and the possible consequent gradual deployment of DESS and capacitor devices will be also dealt with in future improvements. Besides DESSs and capacitors, other voltage regulation devices will be also object of future analyses. To reduce the computational effort of the GA, techniques for the reduction of the search space will be also investigated.

APPENDIX

TABLE VI
TEST SYSTEM DATA [18]

Line		R (p.u.)	X_L (p.u.)	X_C (p.u.)
1	2	0.00312	0.06753	0
2	3	0.00431	0.01204	0.000035
3	4	0.00601	0.01677	0.000049
4	5	0.00316	0.00882	0.000026
5	6	0.00896	0.02502	0.000073
6	7	0.00295	0.00824	0.000024
7	8	0.01720	0.02120	0.000046
8	9	0.04070	0.03053	0.000051
3	10	0.01706	0.02209	0.000043
2	11	0.02910	0.03768	0.000074
11	12	0.02222	0.02877	0.000056
12	13	0.04803	0.06218	0.000122
12	14	0.03985	0.05160	0.000101
14	15	0.02910	0.03768	0.000074
14	16	0.03727	0.04593	0.000100
16	17	0.02208	0.02720	0.000059

TABLE VII
LOAD BASE VALUES (P_{BASE} = 10 MVA) [18]

Node	P_c (p.u.)	Q_c (p.u.)	cosφ
1	0	0	-
2	0	0	-
3	0.02	0.012	0.86
4	0.04	0.025	0.85
5	0.15	0.093	0.85
6	0.30	0.226	0.80
7	0.08	0.05	0.85
8	0.02	0.012	0.86
9	0.10	0.062	0.85
10	0.05	0.031	0.85
11	0.10	0.062	0.85
12	0.03	0.019	0.84
13	0.02	0.012	0.86
14	0.08	0.05	0.85
15	0.05	0.031	0.85
16	0.10	0.062	0.85
17	0.02	0.012	0.86

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Guido Carpinelli (M'92) was born in Naples, Italy, in 1953. He received his degree in electrical engineering from the University of Naples, Italy, in 1978.

He is currently a Professor in Energy Electrical Systems at University of Naples "Federico II," Naples, Italy. His research interests are power quality and electrical power system analysis.

Gianni Celli (M'99) was born in Cagliari, Italy, in 1969. He graduated in electrical engineering at the University of Cagliari in 1994.

He became Assistant Professor of Power System in 1997 in the Department of Electrical and Electronic Engineering of the University of Cagliari. Current research interests include distribution network planning and operation with distributed generation, optimization techniques, and power quality.

Susanna Mocci (M'04) was born in Cagliari, Italy, 1973. She graduated in electrical engineering from the University of Cagliari in 2001, and she received the Ph.D. degree in industrial engineering from the same university in February 2005.

Her current research activity is focused on distributed generation, renewable energy sources and distribution system planning and operation.

Dr. Mocci is a Member of AEIT.

Fabio Mottola (M'07) was born in Benevento, Italy, in 1977. He received the Laurea and Ph.D. degrees in electrical engineering from the University of Naples, "Federico II," Napoli, Italy, in 2004 and 2008, respectively.

His main interests are lightning effects on power lines and problems of power system optimization.

Fabrizio Pilo (M'98) was born in Sassari, Italy, in 1966. He received the Laurea degree (*magna cum laude*) in electrical engineering from the University of Cagliari, Cagliari, Italy, in 1992 and the Ph.D. degree from the University of Pisa, Pisa, Italy, in 1998.

He is currently Associate Professor of electrical power systems at the University of Cagliari. His research interests include power systems, electric power distribution, distribution planning, and distributed generation.

Daniela Proto (M'09) was born in Napoli, Italy, in 1972. She received the M.Sc. and Ph.D. degrees both in electrical engineering from the University of Naples, "Federico II," Napoli, Italy, in 2000 and 2004, respectively and a Postgraduate Master's degree in software technologies from the University of Sannio, Benevento, Italy, in 2001.

She is currently a Research Associate at the University of Naples, "Federico II." Her research interests include Electrical Power Systems and Electrical Transport Systems.