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Energy Storage Sizing and Location in Distribution Networks Considering Overall Grid Performance

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***Abstract*—Energy Storage Systems (ESSs) are promising solutions for mitigating the technical problems created by high penetration of Distributed Generation (DG) in distribution grids. This paper presents a methodology for the ESS sizing and placement within the distribution networks. Those are found through an optimization routine that considers the impact of the use of storage on voltage regulation and system losses. Several scenarios, varying the load and PV panels power, are investigated. In addition, the impact on the energy storage requirements of a basic residential self-consumption scheme is evaluated. The proposed method has demonstrated to be effective in determining the ESS size in the studied scenarios. Furthermore, the results show that the location that requires the lowest ESS rating does not necessarily offer satisfactory performances in terms of losses reduction and voltage control. Also, the paper shows that by encouraging residential users to self-consume the energy produced by the PV panels installed in their house, the grids ESS requirements can be significantly reduced.**

I. Introduction

Recent developments in the electricity sector have encouraged the proliferation of Renewable Energy Source (RES) based generation. The integration of non-controllable generators into the current grids lead to new challenges in distribution networks, resulting in increased difficulty for Distribution System Operators to guarantee a safe and reliable operation. Reverse power flow, feeders congestion, and over-voltage are some of the problems that modern grids are more likely to be subjected to [1]. More importantly, the temporal mismatch, due to different daily profiles between generation and demand, requires a flexible solution for managing the network.

Energy storage systems (ESSs) can be used to absorb the energy of the peak of the PV production and inject it back in the moments of light loading. Through the time decoupling of production and consumption, ESSs are promising solutions for mitigating the impact of the new generators. Battery Energy Storage Systems (BESSs) have been proved technically effective for congestion management, voltage control, and energy flow reduction [2]. Storage can also be adopted as an alternative to network reinforcements, such as upgrades of distribution transformers or the installation of additional cables [3]. In this perspective, BESSs can decrease the peak power seen by the network and thus, increase the temporal match between demand and production. As a positive consequence, network power losses can be reduced [4].

The optimal location of energy storage units in distribution grids has been tackled using several techniques, as convex optimization, analytical methods, and artificial intelligence based algorithms [5]. In [6] the optimal placement is found through a mixed-integer second-order cone program that targets the minimization of the costs of both the power purchase and of the energy storage. The optimal size and location of energy storage units for controlling the voltage in distribution grids are found through voltage sensitivities and a semidefinite program in [7]. In this paper, the energy storage size is found through an optimization routine where the objective function is the reduction of both the network branch overloading and the bus over-voltages that can be caused by the increased penetration of Photovoltaic (PV) systems. The ESS location, instead, is evaluated not only in terms of the ESS size required to solve the network congestion but also by estimating the impact of the use of storage on the network operation. As discussed in [8], designing the optimal ESS location problem only through the minimization of the energy storage capacity can lead to blind decisions in terms of the other grid parameters. The results of this study indicate how, for the scenario considered, multiple locations are suitable for the placing of energy storage and with small changes in terms of ESS size. However, network losses and nodes' voltages have significant variations between the different locations. Several scenarios are considered varying the rated power of the loads and PV generators. In this way, the possible future evolution of the distribution grids are explored, where rooftop PV further decreases in capital costs, and residential electrification grows, due to the switching from gas to electricity for cooking and heating. A residential self-consumption scheme is also modelled, to evaluate its influence in the energy storage requirements. The self-consumed energy can be increased, both shifting the energy consumption when the energy production peaks or by installing energy storage inside the buildings [9]. In this study, the last option is considered.

The main contributions of this paper are the methodology for the energy storage sizing in different scenarios and the insights given in relation to the influence of its location on network losses and on nodes' voltages. It is shown that the optimal site is not necessarily the one that requires the lowest energy storage capacity. Instead, the choice of the optimum can be driven as well by the effectiveness of the ESS to control the voltage or to reduce the losses. Moreover, a future scenario when residential users install appropriate storage devices inside their houses for increasing the self-consumed energy is considered. The differences in terms of energy storage requirements between the last scenario and the case without residential storage are compared.

II. Problem Formulation

The proposed method aims at evaluating the flexibility requirements of a LV distribution grid. In the scenarios considered in this paper, the network is overloaded by the peak PV production. The approach adopted provides insights on the sizing and the location of the energy storage, plus it highlights the impact that the operation of the energy storage unit has on voltage and system losses.

A. System description

A modified version of the IEEE European LV Test Feeder, depicted in Fig. 1, is adopted for the simulations [10]. The network represents a residential scenario composed of 55 loads, each one coupled with a PV generator. Loads are modelled as symmetric three-phase loads to represent the aggregation of few houses. Loads are characterized by different daily profiles, which are given in [10], and they are indicated in Fig. 1 with a black square, while the MV/LV substation feeder by a red square. The PV penetration is considered uniform along the network; the same generation profile is applied to all the houses. The profile adopted represents a day with full irradiation, without shadowing. In this way, it is possible to obtain the worst over generation case scenario when all the PV generators produce at their peak, and the network is likely to suffer congestion and over-voltage.

To increase the computational performances, only the nodes in the grid's backbone, marked with black and cyan colours and identified with a node number in Fig. 1, are considered for ESS placing. These nodes will be referred to as candidate nodes in the remainder of the paper. The remaining nodes, named derivation nodes in the rest of the paper, are not considered. This choice is driven by the fact that derivation nodes are connected through a low capacity cable, and this can limit the effectiveness of the ESS when deployed as a network-wide solution. According to this assumption, the number of candidate nodes for locating the ESS is reduced from 110 to 30, which produces a significant computational advantage.

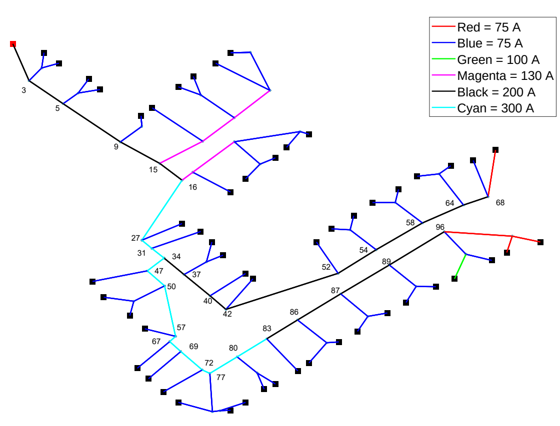


Fig. 1: The IEEE European LV Test Feeder [10].

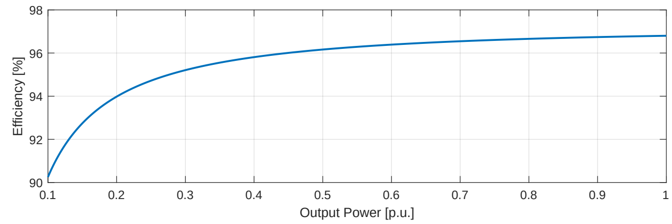


Fig. 2: DC-AC converter and auxiliary system efficiency curve used for the modelling of the battery energy storage system modelling.

The adoption of multiple units is not considered; only one battery storage unit is used for the provision of flexibility. The battery storage system efficiency depends on the DC-AC converter and on the electrochemical storage. The converter efficiency η_c is modelled as shown in Fig. 2, where the curve is obtained through analytically modelling the power losses in a two-level converter and considering a power absorption of 750W/100kW for the auxiliary systems. The battery cells efficiency, instead, is modelled as Equation (1),

$$\eta_b = \left(1 - 0.03\frac{P}{P_{nom}}\right) \tag{1}$$

where P is the output power and P_{nom} is the nominal power of the battery. The full system efficiency is then $\eta_{BS} = \eta_c \cdot \eta_b$ and at nominal power it is equal to 94%.

B. Residential self-consumption

In most European countries, PV panels installation is subsidized, and incentives have pushed for the deployment of RES based generators [11]. However, the residential user is not encouraged to match his domestic consumption profile with the one of the PV production. In the absence of incentive schemes on PV energy, such as Net Metering, users will be pushed to consume the energy produced by the panels installed in their premises, rather than feeding it back into the grid. For this purpose, each load and PV couple is equipped with a storage unit rated to 5kW/7kWh. The residential storage unit is charged when the PV production is higher than the load and discharged otherwise. The target of the system is to increase the total daily self-consumed energy, i.e., the reduction of the maximum power is not considered. Additionally, behavioural change in the load profile due to the installation of energy storage systems are not considered. The absence of net metering scheme could, in fact, favour the shifting of the load during the peak of the PV production. The load and residential storage aggregated profile is found for all the loads and applied for the flexibility requirement evaluation algorithm. The average self-consumed energy among all 55 loads, as a percentage of the total daily load energy, is shown in Fig. 3 for the cases where the load nominal value is set to 3 kW and 7 kW. Fig. 3 shows how increasing the rated power of the rooftop PV, the percentage of self-consumed energy grows. It is possible to notice also that by implementing this scheme, there is a robust initial gain that gets attenuated after the PV power exceeds 3 kW. The addition of the home battery provides a significant increase in the percentage of self-consumed energy, reaching almost 90% with the load rated 3 kW.

III. Energy Storage Requirements Evaluation

The flowchart in Fig. 4 shows the algorithm adopted for evaluating the grid's flexibility requirements. The simulations are run for one day, with a time step of 15 minutes. The algorithm starts selecting the first candidate bus. Then, for each time step, it runs the power flow and checks the node voltage and branch loading. The maximum voltage variation allowed is set to +/- 10 % the nominal value, according to the European Standard EN 50160 [12], while the conductors' ampacity limits are shown in Fig. 1. When current or voltage exceed the limits, the algorithm finds the minimum power injection/absorption at the selected node (2) that brings the network parameters, node voltage (3)-(4) and branch loading (5) inside the boundaries. The node voltage V_j and the branch current $I_{m,n}$ are calculated through solving power flow equations (6) and (7) with the MATPOWER package of MATLAB [13] and they are respectively the voltage at node j and the current flowing in the branch that connects bus m to bus n.

$$\min_{P_{st,i}} \quad P_{st,i} \tag{2}$$

$$\text{s.t.} \quad V_j \leq V_{max} \tag{3}$$

$$-V_j \leq -V_{min} \tag{4}$$

$$I_{m,n} \leq I_{m,n-max} \tag{5}$$

$$P_i = \sum_{k=1}^{N} |V_i|\,|V_k|\,(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \tag{6}$$

$$Q_i = \sum_{k=1}^{N} |V_i|\,|V_k|\,(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \tag{7}$$

If the optimization is solved successfully, the algorithm goes to the next time step and repeats the procedure. In case that it is not possible to eliminate the network violation at a specific node, that node is marked as unfeasible, and the algorithm proceeds to the next node starting from the first time instant. When the last time step is reached, the daily ESS power profile at the selected node has been found. Afterwards, for that node, the algorithm calculates the energy storage rated capacity and power, and the system parameters, total losses, and variation of the maximum voltage due to the ESS operation. The algorithm then passes to the next candidate node.

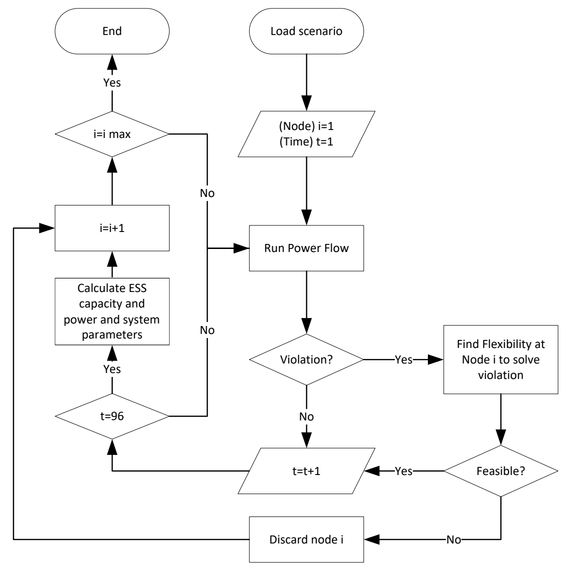


Fig. 4: Methodology for evaluating the required BESS size.

The daily ESS power profile reflects its injection and absorption of power from the grid point of view. The daily State of Charge (SoC) profile is then evaluated through Equation (8)

$$SoC_i(t) = \sum_{j=0}^{t} \left(\frac{|P_i(j)| - P_i(j)}{2}\eta_{BS} - \frac{|P_i(j)| + P_i(j)}{2\eta_{BS}} \right) \Delta t \tag{8}$$

where $SoC_i(t)$ is the State of Charge of a battery located at bus i at the time instant t, $P_i(j)$ is the ESS power injection or absorption at the bus i at the time instant j, η_{BS} is the battery storage system efficiency. The power is divided by the efficiency when positive, the battery is discharging, while the efficiency is multiplied to the power when negative, the battery is charging. The battery capacity is then given by the absolute value of the highest daily SoC variation, while the rated power is the highest between the positive and negative values of the daily power profile previously found. In this way, the energy storage rated capacity and power for solving the network violations are found. Furthermore, the daily network losses are calculated, also considering the losses related to the energy storage operation, and the impact on the voltage. Regarding the last point, the voltage variation is computed as follows. The maximum daily voltage values of the two main feeders, the ones ending with nodes 68 and 96 in Fig. 1, are found. These values are compared to the maximum daily voltage of the two feeders without energy storage. The difference between the two is the voltage variation due to the use of storage. The variations for the two main feeders are

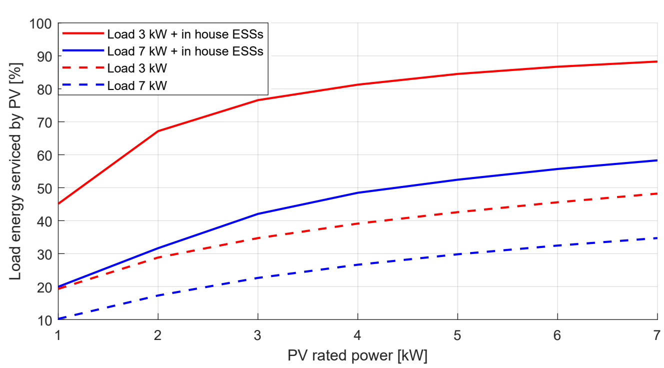


Fig. 3: Percentage of load energy covered by the in home PV varying PV rated power.

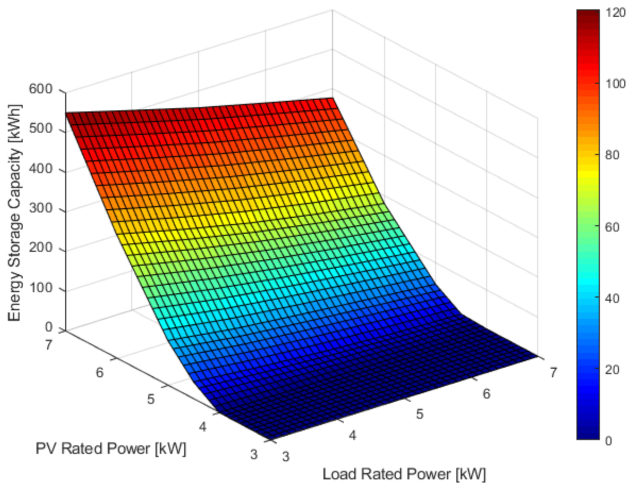


Fig. 5: Energy storage capacity and power required to keep network parameters inside boundaries when the storage unit is installed in node 16.

summed in order to have a single index, and this value is used for further analysis. The highest is the decrease in the maximum voltage, the better the ESS impacts on the network voltage. Considering both the two main feeders and not only the highest network voltage, but it also allows determining at which node the battery operation has the highest influence on the overall network, not only locally.

The algorithm first runs with the load profiles given in [10]. Secondly, the load profiles are substituted with the aggregated load and residential storage profiles, obtained as described in Section II, and the algorithm is re-run.The rated load and PV power is varied between 3 and 7 kW, and for each combination of these the process is repeated. For each scenario, the outputs of the algorithm are the battery rated capacity and power, total system losses, the impact on the voltage, and the number of buses where it is feasible to solve the network violations.

IV. Results and Discussion

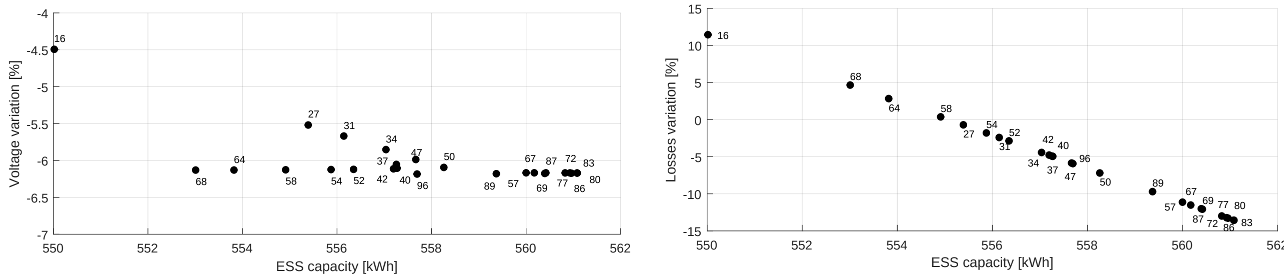
The evaluation of the energy storage size is performed for several nodes and different values of PV and load power. In the scenarios considered, the main limiting factor for the grid hosting capacity is the loading of the conductors, since the voltage limits are never reached. For each PV and load power combination, the required energy storage capacity and power are shown in Fig. 5, where the minimum values between all the considered nodes are displayed. From the graph, it is possible to see that the current grid has a PV hosting capacity of around 4 kWp for each load bus. By increasing the PV rated power, the conductors will be overloaded, and so the deployment of ESS is one of the possible solutions to bring the grid parameters back into the limits. For example, to increase the PV power to up to 7 kW it is necessary to install one battery rated at least 550 kWh, nonetheless, with an increase of the load power, the required capacity of the ESS reduces, i.e., up to 400 kWh for loads rated 7 kW. A higher load then mitigates the impact of the PV panels. The power and the capacity of the energy storage show roughly a 1 to 5 relation, meaning that the ESS installed is required to sustain the operation at rated power for 5 hours. This indicates that mitigating congestion is an energy intensive service, and this should be carefully considered when choosing the energy storage technology.

The contribution of this paper consists of the investigation of the energy storage placement impact on conductor losses and voltage regulation. Concerning this point, only the results for the worst-case scenario, maximum PV penetration (7kW), and low load (3 kW), are reported. Nevertheless, the analysis of the other cases shows similar trends. For each of the candidate nodes, the losses and voltage variations are plotted in Fig. 6, where the BESS size at each location, indicated with the number according to Fig. 1, is in the x-axis. Analyzing the data reported in Fig. 6 it is possible to highlight the following points:

- When the ESS is located closer to the substation it does not show good capabilities on regulating the voltage. In Fig. 6(a) it can be seen that, in the examined scenario, an ESS positioned in bus 16 can reduce the overvoltage of 4.5%, while in the other nodes the reduction is higher, around 6%.
- ESS deployment can bring significant reductions in network losses, in this scenario, up to 15%, as shown in Fig. 6(b).
- The impact on losses is strongly dependent on the ESS location, Fig. 6(b) shows how the nodes closer to the bulk PV production offer better performances.
- The nodes closer to the substation have the worse overall performances, meaning that the overvoltage reduction and the losses reduction is lower, nonetheless at these locations, the lowest ESS capacity is required.

It has been shown that, whereas the differences between the nodes in terms of losses and voltage regulation capabilities are significant, the ESS size marginally varies. The lowest and the highest values, for the selected case scenario, differ roughly 11 kWh, which represents around 2% of the total capacity. In this respect, it is shown how evaluating the optimal ESS placing only in terms of ESS capacity does not necessarily give the best overall performances.

As specified in Section III, the energy storage size at different locations is evaluated, also considering different load profiles that reflect in-house batteries installed by residential users to increase their self-consumed energy. The results obtained in these scenarios are here compared to the cases when there are no incentives on increasing the residential self-consumed energy. For a fixed load power of 3 kW and 7 kW and variable PV power, the ESS capacity required to keep the network parameters inside the boundaries is calculated. The results are plotted in Fig. 7, where the dashed lines represent the cases without residential storage, while the solid lines represent the ones when the self-consumed energy increases. It is possible to see that encouraging residential users on self-consuming the energy they produce has a positive impact on the grid hosting capacity, that increase of 5% and 17% with the load power of 3 and 7 kW, respectively. Furthermore, for



(a) (b)

Fig. 6: ESS size and impact on nodes voltage (a) and on network power losses (b) when placed at different locations, indicated with the numbers following the description in Fig. 1.

the same PV power, the ESS capacity required is significantly lower, meaning that grid operators or ESS investors would incur a lower investment.

V. Conclusions and Future Work

This paper presented an approach for the ESS location and size determination in distribution grids. The methodology proposed aims not only at choosing the ESS location based on the capacity of the energy storage, but also considering the impact of its use on system losses and its capability on regulating the voltage. In the scenarios considered, it has been shown how the nodes that require the smallest ESS battery do not necessarily offer good performances in terms of losses reduction and capability on regulating the voltage. Besides, significantly better performances in this respect are reached at the expense of slightly higher battery capacity. In this respect, the approach here exposed shows how formulating the ESS sizing and location problem only as minimization of the ESS installed capacity can lead to blind solutions in terms of other grid parameters. Several simulation scenarios have been considered, varying the load, the PV rated power, and introducing a residential self-consumption scheme. In these scenarios, it is found that the conductors overloading due to the peak PV production is the hosting capacity limiting factor. Also, the self-consumption scheme considered leads to a significant reduction of the ESS size for the same installed load and PV generators power.

Future work will focus on implementing a more comprehensive scenario of future distribution networks, including electric vehicles and the possibility of installing multiple ESS storage units, and on the economic analysis of the results. In this way, the optimal ESS location can be defined as the node that leads to the lowest system costs.

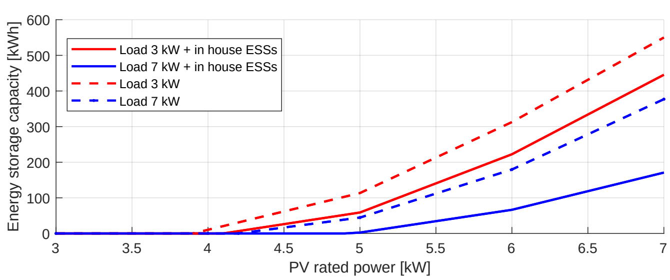


Fig. 7: Residential self-consumption influence on ESS capacity required for maintaining network parameters in the boundaries.

VI. Acknowledgment

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