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Siting and Sizing of Energy Storage Systems to Maximize DG Integration in MV Distribution Networks

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SUMMARY

The expected growth of Distributed Generation (DG) penetration in distribution systems will fundamentally alter both planning and operating procedures of Distribution Network Operators (DNO). This means that distribution networks can no longer be considered as a passive appendage to the transmission network and should be explored actively to take full advantage of the capabilities of DG units available and avoid technical problems (such as line overloading or poor voltage profiles) resulting from massive integration of this type of sources.

Presently, when the capacity of the generation, transmission and distribution systems is exceeded, the traditional utility response is expanding or reinforcing existing circuits through large investments in power transformers, substations or distribution feeders. However, in some situations such as in congested metropolitan areas these actions can have prohibitive costs or simply be impossible due to space restrictions, for instance.

Although current investment costs of many solutions for energy storage remain extremely high, recent developments and advances in both energy storage technologies and power electronic interfaces are opening new doors to the inclusion of Energy Storage Systems (ESS) as a potentially viable solution for modern power applications, including their use in distribution network planning and operation.

This paper presents a heuristic approach for siting and sizing of ESS in distribution networks in order to maximize the capacity of DG that can be integrated in the grid without bringing technical problems to network operation. The proposed methodology enables a technical and economical comparison between a strategy based on ESS deployment and exploitation and typical traditional DNO grid reinforcement strategies. Several technologies for ESS were considered, each one with different costs and technical characteristics. The proposed methodology was validated using a real Portuguese Medium Voltage (MV) distribution network.

KEYWORDS

Network Planning, Energy Storage Systems, Distributed Generation, Siting and Sizing

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INTRODUCTION

The large increase in Distributed Generation (DG) integration in distribution networks is inducing several changes to power system operation. Traditional vertically integrated systems, dominated by centralized generation, are evolving to a new paradigm, where numerous small generation units are dispersed throughout the networks. This means that distribution networks can no longer be considered as a passive appendage to the transmission network and should be explored actively in order to take full advantage of the capabilities of the DG units available.

However, large-scale integration of DG units may lead to poor voltage profiles or line overloads in parts of the network with high concentration of these technologies [1]. This may occur especially during periods when DG units are generating large amounts of energy and overall consumption is low.

Presently, when the capacity of distribution systems is exceeded, traditional Distribution Network Operator (DNO) response consists on expanding or reinforcing existing equipment and infrastructures. This option may require large investments in power transformers or line reinforcements. In addition, the expansion or reinforcement actions needed may be extremely difficult or even impossible to perform due to land-use limitations (in highly dense metropolitan areas or cultural/historical sites), environmental restrictions (in natural parks and other protected areas) or health issues (electric and magnetic fields exposure) [2]. Therefore, a different approach is required in order to solve problems related with network components overloading. One possible way of achieving this is resorting to Energy Storage Systems (ESS). Besides enabling large scale exploitation of DG technologies, these devices offer an alternative planning approach to utilities regarding demand growth satisfaction and maintenance of the quality of service [3]. In addition, the inclusion of ESS may also bring other benefits for grid operation, since they are capable of performing load following, contributing to improve voltage profiles, providing primary frequency control and contributing to reduce the peak load [4]. There are several ESS technologies currently available in the market that can be used for grid operation enhancement purposes. A thorough characterization of the most common ESS, including their main advantages and drawbacks for power system applications, can be found in [5]. Nevertheless, it is very important to define accurately the size and location of the ESS in the grid in order to take full advantage of their presence. Many papers have already studied only the sizing problem using a large range of optimization techniques. In [6] and [7], for instance, dynamic programming and tabu search algorithms, respectively, were used to quantify the benefits due to energy price differences between valley and peak periods and to determine the optimal ESS size. Other works, like the one presented in [8], besides the sizing, also addresses the siting problematic. Nevertheless, this study defines the optimal location of ESS focusing only in the economic benefits that can be obtained from the operation of these devices.

This paper presents a novel approach for ESS siting and sizing in Medium Voltage (MV) networks, whose main goal is to maximize the capacity of DG that can be integrated into the distribution grids, quantifying at the same time the investments deferral achieved with these technologies. The work developed enables making a technical and economic comparison between the ESS-based methodology and the traditional grid reinforcement strategies. In order to perform this, a typical Portuguese MV grid with large DG integration was used as test case and the simulations were carried out considering a time horizon between 2010 and 2030.

METHODOLOGY

The methodology proposed here was developed with the objective of providing an efficient procedure for ESS siting and sizing in MV grids, in order to maximize the capacity of DG that can be integrated in the distribution system without requiring traditional grid reinforcements. The main steps of this methodology are described next:

1. Define the evolution of the load demand and amount of DG present in the grid during the time horizon analysed. In order to avoid mixing the effects of load and DG growth on network performance, it was assumed that the demand was constant along the years. This assumption allowed focusing exclusively on DG impacts. The evolution in the DG installed capacity considered by technology type is presented in Fig. 1.
2. Run power flows in order to identify the branches that get overloaded in the period 2010-2030 due to the increase of DG integration in the grid (without the presence of any ESS). This procedure also allows quantifying the investments needed to keep the grid operating within its

technical limits, when a traditional reinforcement strategy is followed. The reinforcement strategy followed in this work consists on replacing a given line by a new one, with a higher capacity, as soon as it gets overloaded.

3. Define the number and precise location for installing the ESS required. This process is accomplished by installing one ESS in each feeder that exhibits congested branches (identified in Step 2). The ESS should be located in one of the buses downstream from the last congested branch of each feeder in order to maximize the benefits for grid operation.
4. Evaluate the type of ESS that can be purchased and the corresponding capacity based on the investment cost calculated in Step 2, considering different technologies and different costs.
5. Define the capacity of each ESS to be installed in the network, taking into account the number of devices required (as defined in Step 3) and total capacity purchased (as defined in Step 4). The total capacity purchased is divided by all the ESS installed in the network proportionally to the congestion level of the overloaded branches identified in Step 2.
6. Run power flows for the new network conditions (including ESS) in order to identify the number of years that the DG growth can be handled by exploiting the ESS installed. During these simulations it was assumed that the ESS technologies have the capability of providing an amount of power equivalent to their capacity, during the period of one hour (see Table 1).
7. Evaluate the performance of the method proposed by making a technical and economic comparison between the ESS-based methodology and traditional grid reinforcement strategies.

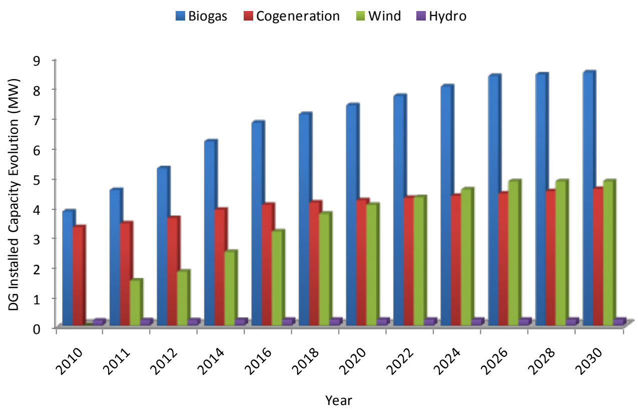

Fig. 1 – Evolution in DG Installed Capacity

It must be stressed that since in MV networks line reactance is dominant over resistance, the methodology proposed was specifically developed to analyse technical violations related with branch overloading problems rather than dealing with voltage violations.
The flowchart of the overall approach proposed here is shown in Fig. 2.

RESULTS OBTAINED

Traditional Reinforcement Strategy

Using a typical Portuguese MV network, it was possible to identify the branches that exhibited overloads in the period 2010-2030 following the increase in DG integration shown in Fig. 1. This was done by running several consecutive power flows for the 20-year period considered with increasing DG capacity integration. This allowed quantifying the investments required for grid reinforcement in order to maintain safe operation of the MV-distribution system within technical limits. In this case, for the period considered, three lines presented overloads, requiring two line reinforcements each, that correspond to a total investment of 278'918 € (including total line cost as well as installation costs). As stated in the previous section, these reinforcements were done by replacing the overloaded line by another one with a higher rated power, which corresponds to the traditional strategy employed by the Portuguese DNO. Regarding lines costs, typical values were obtained from Portuguese cable manufacturers and used here [9].

ESS Siting

As mentioned in the previous section, several line overloads have been identified in the considered time-horizon. Fig. 3 shows the congestion levels for the worst hour of the day (corresponding to a scenario with the highest power injection by the DG and low consumption) identified in 2030 (grading

between blue and red stands for increasing values of congestion, from 0% to 100%). In this case, reverse power flows occur that causes overloading in several lines.
Therefore, a heuristic approach was used in order to select the location for the ESS required. It was decided to include 2 ESS in the two problematic feeders in order to relieve the power flow for the lines in these areas. The location of the ESS installed is also shown in Fig. 3. It was seen that the proximity of the ESS to the DG sources, while consuming power, allows relieving the overload in the most problematic lines.

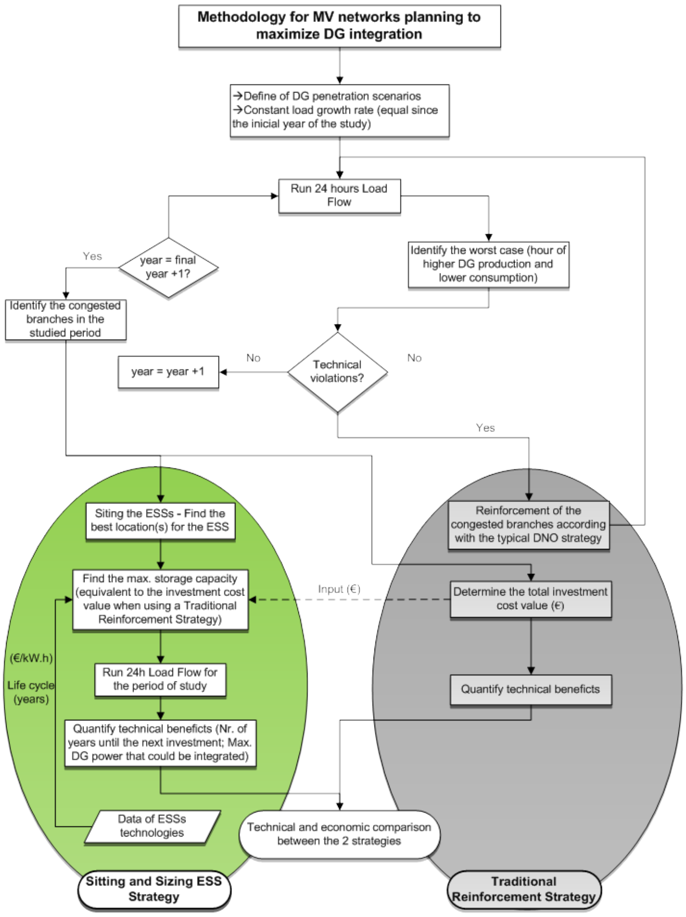

Fig. 2 – Flowchart of the Proposed Methodology

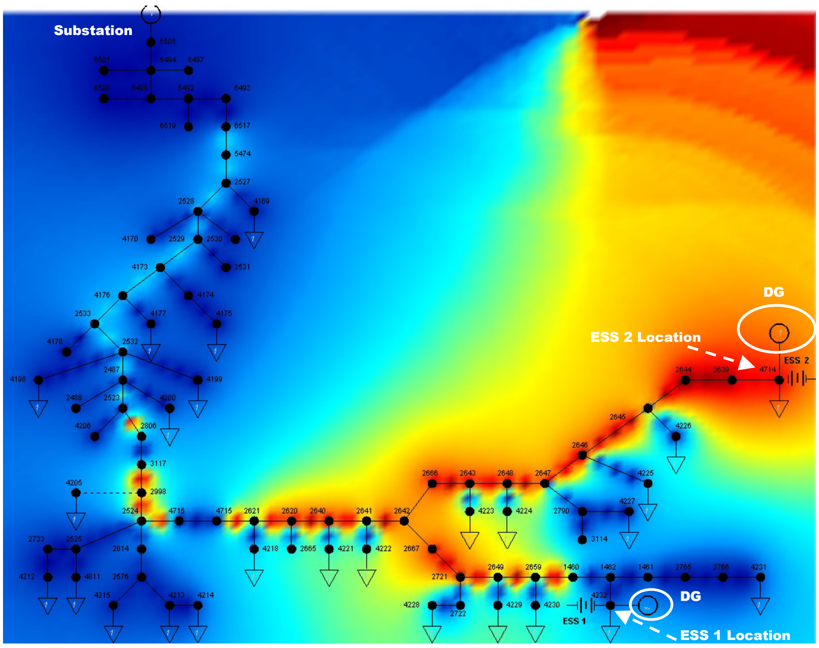

Fig. 3 – Branches Congestion Levels and ESS Location

ESS Selected Technologies

The main characteristics (life cycle and price) of the most common ESS solutions currently available in the market, oriented to grid congestion management, are presented in Table 1 (columns 3 and 4), considering two different scenarios. In this table, Scenario 1 and Scenario 2 correspond to a realistic and an optimistic prospect for future ESS prices, respectively. Naturally, in order to decide on the ESS technology to be employed, the technical characteristics of each solution was analysed and compared.

The capacity of each ESS tested was defined by assuming that its cost should be equal to the investment required in the traditional grid reinforcement strategy presented previously. As an example, considering Scenario 2 for the lead-acid technology, with the investment cost of the traditional reinforcement strategy (~278'900 €) it is possible to purchase an ESS with 5'578 kWh capacity (50 €/kWh * 5'578 kWh = 278'900 €). All the results obtained are presented in column 5 of Table 1.

Table 1 – ESS Capacities According to Technology and Scenario [5, 10]

Technology	Scenario	Life Time (years)	Price (€/kWh)	Capacity Purchased (kWh)	Cap. ESS1 (kWh)	Cap. ESS2 (kWh)
Lead-Acid	Scenario 1	15	100	2'789	1'310	1'480
	Scenario 2	15	50	5'578	2'700	2'880
Li-Ion	Scenario 1	15	1'000	279	120	160
	Scenario 2	15	250	1'116	490	630
Na-S	Scenario 1	15	1'500	186	80	110
	Scenario 2	15	500	558	250	310
Flow	Scenario 1	15	150	1'859	840	1'020
	Scenario 2	15	100	2'789	1'310	1'480

ESS Sizing

After determining the number and total storage capacity of the ESS to be installed in the previous sections, the next step is to define the size of each individual ESS. In order to do this, the total capacity for the ESS was divided proportionally to the overload level identified in the branches for the corresponding part of the network where each ESS is located. Consequently, the values presented in the last two columns of Table 1 have been obtained.

RESULTS ANALYSIS

Considering the size and location of the ESS, new power flows were computed in order to determine the number of years that DG growth can be sustained without causing technical problems (line overloading) by exploiting the ESS installed. Then, the proposed method was compared to the DNO traditional reinforcement strategy. Table 2 presents the results obtained regarding investments deferral and the total DG capacity that can be integrated in the network with all the solutions tested.

Table 2 – Investments Deferral and Total DG Capacity Integrated

Technology	Scenario	Nr. of year gained until the next investment	Total DG capacity integrated (MW)	Total Investment Cost (€)
Lead-Acid	Scenario 1	9	16.43	278'900
	Scenario 2	15	17.92	278'900
Li-Ion	Scenario 1	1	12.69	279'000
	Scenario 2	2	13.59	279'000
Na-S	Scenario 1	0	10.83	279'000
	Scenario 2	1	12.69	279'000
Flow	Scenario 1	5	15.12	278'850
	Scenario 2	9	16.43	278'900
With traditional grid reinforcement (if reinforcements are feasible)		*	18.05	278'918
Without ESS nor grid reinforcement			10.83	0

* Not possible to calculate due to the limited time horizon of the simulations.

As the results presented in Table 2 show, without grid reinforcements, it is only possible to integrate 10.83 MW of DG. If a traditional reinforcement strategy is followed, it is possible to integrate up to 18.05 MW of DG. It is important to stress that this strategy is preferable to the ESS-based solutions only if no restrictions exist in what regards equipment reinforcement, given that the ESS would have to be replaced in the end of their 15 years life cycle, while the network equipment upgraded, usually, can be kept operating in normal conditions for a larger number of years.

If equipment reinforcements are impossible to perform, then the ESS solutions would have major advantages. As it can be observed in Table 2, with the lead-acid batteries it is possible to integrate 16.43 and 17.92 MW of DG in scenarios 1 and 2, respectively, while the need for investments are postponed 9 and 15 years (see Fig. 4 a) and b), respectively). The flow batteries, in scenario 2, also

proved to be a solution to be taken into consideration, as with this technology it is possible to integrate 16.43 MW of DG and attain a 9 years period of investment deferral (see Fig. 4 b)).
Fig. 4 compares the traditional strategy considering grid reinforcement with the solution using ESS, considering several different storage technologies, in what regards the congestion level of the most loaded line in the grid (line between buses 2998 and 3117).

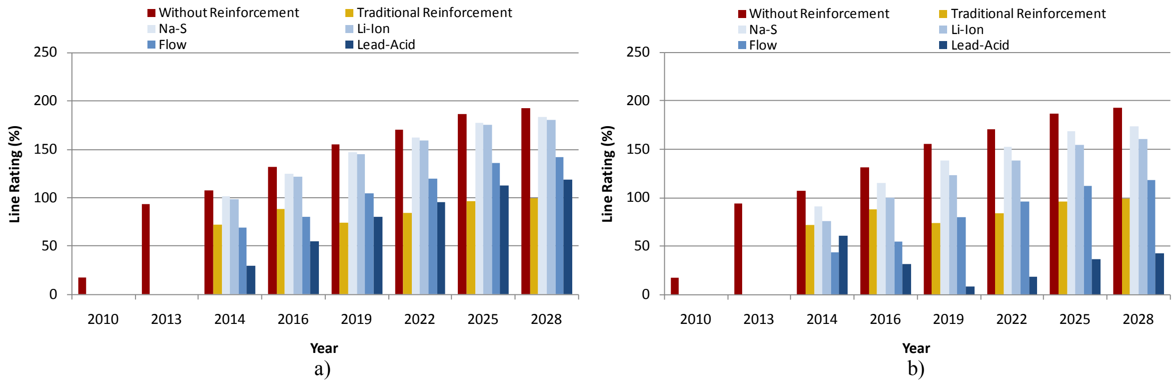

Fig. 4 – Loading Percentage of the Most Loaded Line for a) Scenario 1 and b) Scenario 2

CONCLUSION

This paper proposed the inclusion of ESS in MV distribution systems as a valid approach for distribution network planning in order to allow maximizing the integration of DG.
From the analysis performed it was seen that adequate location and sizing of ESS in distribution networks, depending on the technology costs, may be an interesting alternative to grid reinforcement strategies, which are traditionally used by the DNO, in particular for the situations where expansion or reinforcement actions are difficult to perform due to land-use limitations, environmental restrictions or health issues. Moreover, it should be stressed that the ESS usage might bring additional benefits for grid operation. They can be used to absorb energy in valley hours and inject it later during the peak periods. This procedure, besides reducing substation transformers and adjacent lines overloading, during the peak hours, may also contribute to reduce network losses and improve voltage profiles.
Nevertheless, the general methodology presented here, although replicable for other networks, may lead to significantly different conclusions in face of the type of network, DG technology employed and the ESS technologies price.

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