Electrical Engineering (2018) 100:1939–1948
https://doi.org/10.1007/s00202-017-0672-6

ORIGINAL PAPER

Integration of storage systems in distribution networks through multiobjective optimization

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Received: 6 March 2017 / Accepted: 6 December 2017 / Published online: 19 December 2017

Abstract

The use of storage systems in distribution networks allows smoothing the load diagram. In fact, the cost of energy is different along the day and companies can be encouraged to use these systems, since the extra energy required to charge the storage system can be obtained in periods where the cost of the energy is lower and used in periods when the energy cost is higher. Storage systems also allow reducing losses of the lines and improving voltage profile. However, in distribution networks there are benefits in using distributed storage instead of centralized storage. Under this context, this paper proposes a multiobjective optimization approach for the location and sizing of storage systems. In this problem, the objective functions are in conflict. Increasing the number of storage systems leads to a reduction in the peak power and losses, but also will increase the investment cost. This approach allows obtaining solutions of different trade-offs with respect to the two objectives. An IEEE 69 buses and a real 94 buses test feeders are used to demonstrate the effectiveness of the proposed approach.

Keywords Distribution networks planning · Storage systems · Multiobjective optimization · NSGA-II

List of symbols

m	Indicates the first (or preceding) bus of the radial branch
B_m	Bus m
$t, t+1, t+2, \ldots, t+n$	Indicates the following buses, considering n buses connected to the first bus of the radial branch
$\overline{I}_{(t+i)}$	Current flowing from the bus t+I, t+i, with i=1,..., n, and n the number of branches fed from bus m
$\overline{V}_{(t+i)}$	Voltage at bus $t+I, t+i$, with $i = 1, \ldots, n$, and n the number of branches fed from bus m
$\overline{I}_m$	Current flowing from the bus m (A)
$\overline{S}_{(t+i)}$	Apparent power delivered from bus $t + I$ (VA), with $i = 1, \ldots, n$, and n the number of branches fed from bus m
$\overline{S}_m$	Apparent power delivered from bus m (VA)
$\overline{V}_m$	Voltage at bus m (V)
$\overline{Z}_m$	Falta
$\overline{V}_{m(t+i)}$	Difference between voltages at buses m and $t + i$, with $i = 1, \ldots, n$, and n the number of branches fed from bus m
$\overline{S}_{\mathrm{Load}}$	Apparent power of the load directly connected to the bus m
$\overline{S}_{\mathrm{Storage}}$	Apparent power of the storage system connected to bus m
P_{S_m}	The active power that the storage system will inject to the grid or in charge condition
$V^i_{\mathrm{bus}k}$	Voltage at bus k for interaction i of the power flow algorithm
$V^{\max}_i$	Voltage upper limit at interaction i
$V^{\min}_i$	Voltage lower limit at interaction i
a^k_m	Binary decision variable denoting whether or not a storage system of type j is installed in bus m
c_j	Storage (P_{Sj}) cost where $j = 1, \ldots, Y$ represents the storage type
b_m	Variable related to the technical feasibility of installing storage systems at bus m
d	The mode of operation of the storage system (charge or discharge)

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1 Introduction

Planning electrical distribution networks have been extensively studied in the last decades. These studies are on several areas such as optimal power flow, distribution generation allocation, reducing system losses, improving voltage profile, network reliability, among other themes [1–5]. In these studies is usual to consider mesh and/or radial network structures, since electrical distribution systems can be found in these two types of topologies. One of the areas that have been extensively studied is the allocation of compensating devices such as shunt capacitors with objective of reducing losses in the system.

The use of compensating devices such as shunt capacitors in radial distribution networks improves voltage profile and reduces losses. In fact, due to the important role that these systems play in this distribution networks an extensively number of works have been published [6,7]. Another device that can be used in radial distribution networks is the energy storage systems. However, although it has been developed an extensive work with reactive devices in radial distribution networks, studies about the use of storage devices in these networks are still reduced.

The storage devices can be an alternative solution for the regulation of the network voltage profile since they can limit the active power that flows in the lines. In fact, it has been verified that this approach is much more effective than to compensate the reactive power to regulate the voltage in the distribution lines [8]. Under this context, several works have been published. Most of these works are focused on networks with high penetration of renewable energies. In fact, networks in these conditions present problems related to the voltage rise. To overcome this problem, several research works proposed the use of these kinds of storage systems since they can help to prevent overvoltages originated by high penetration of renewables in distribution networks [9–12]. According to this, in [13] was presented a work for the determination of the energy storage systems size under the context of variable energy resources. The contributions of battery energy storage systems in regulating the system frequency, improving the power quality and peak shaving applications taking into consideration the wind diesel power system high penetration were analyzed in [14]. This type of systems was also proposed to support renewable energies but in the context of microgrids [15]. An optimization of photovoltaic systems (PV) with energy storage systems for islanded grid was presented in [16]. Likewise, other works have been focused on the use of the storage systems to provide peak load shaving [17]. A study about the optimal power flow taking into consideration the renewable energy resources and storage was also presented in [18]. In [19] were investigated the customer-side energy storage system operations to minimize the electricity bill under a peak load limitation constraint and uncertain environments. The use of storage systems also allows reducing the peak demand and presents several advantages such as increasing the capacity of the transmission and distribution system, reducing the losses and reducing the cost of the energy. Under this context, the optimal sizing of batteries has been addressed in [20–23], but mainly limited to the load leveling application. A methodology to calculate the peak demand for a given battery under monotonic controllers and electrical load quantification using arrival curves was proposed in [24]. In [25], it was presented a sizing methodology and optimal operating strategy for a battery energy storage system, but for a large industrial customer. The planning of distribution networks taking into consideration the energy storage systems was also addressed in [26]. However, this work focused on the problem of the reliability improvement in radial electrical distribution networks.

This work proposes a multiobjective approach for the planning of distribution networks incorporating storage devices. The main objectives are reducing power losses and costs associated with the installation of storage devices. Since there is more than one objective, it is not possible to find one unique optimal solution, but a set of good solutions called non-dominated (Pareto optimal) solutions. They are feasible solutions for which no improvement in all objective functions is possible simultaneously—in order to improve an objective function, it is necessary to accept worsening at least the value of one other objective function. In real-world problems, a high number of diversified non-dominated solutions generally exist. Therefore, it is important to characterize as extensively as possible the Pareto optimal front, namely in order to grasp the trade-offs between the objective functions that are at stake in different regions, which are relevant for decision support purposes [13]. Each solution found proposes both locations and the sizes of storage devices, associated with the corresponding cost and the energy losses.

Although this approach can be used in the context of the integration of renewable dispersed generation, the main idea is to apply it to classical distribution networks in order to provide peak load shaving. In fact, storage systems will allow supplying energy at peak hours and receiving at off-peak hours allowing in this way to smooth the load diagram. It also allows improving the voltage profile. Although the companies must invest in storage equipment, they also have financial benefits since the cost of the energy at peak hours is more expensive than the cost of the energy at off-peak hours. Under this context, there is a conflict in the objective function that is considered (i) integrating storage systems in the distribution network and (ii) minimization of the investment cost. Thus, two different objective functions are considered, but simultaneously optimized to obtain a set of non-dominated solutions. A multiobjective evolutionary algorithm is applied in order to obtain a Pareto front that is characterized by the optimal compromises between conflicting design objectives.

The proposed planning approach is validated on standard IEEE 69 bus.

2 Integration of storage systems in radial distribution networks

Several benefits can be listed from using storage systems in distribution networks. One of the advantages is to avoid large reverse power. This helps to eliminate voltage violation in distribution networks with high penetration of renewable generation. However, even in classical distribution networks (without dispersed generation), these systems allow to smooth the load diagram. Due to this, companies can be encouraged to use these systems since the cost of energy is different along the day. The cost of the energy usually is related to the load diagram. Thus, the energy required to charge the storage system can be obtained in periods where the cost of the energy is lower, and used in periods when the energy cost is higher. However, instead of using centralized storage there are benefits in using decentralized storage since it allows to obtain a better voltage profile, minimal losses and even higher reliability of the storage systems.

The works that have been focused on the optimization of the use of storage systems in distribution networks [12] addressed the problem of the location and size of these systems tacking in consideration the voltage deviations, losses and energy cost. These variables and the investment costs are integrated in a unique fitness function. From the results is possible to verify that normally there are allocated only a reduced number of storage systems and with dispersed sizes. Since the objective functions are all merged in one objective function, only one final solution is presented. This work adopted a different strategy to allocate the storage systems in radial distribution networks. Since storage systems are expensive, it is proposed a standard group of storage systems in order to obtain a large number of systems with the same characteristics. Other characteristic of this solution is that also allows for a more simple maintenance with reduced costs. On other hand, it was adopted the use of storage systems with reduced sizes in order to spread them into the network. This also allows a higher reliability of the system, since a fault in one storage device will not have a large impact. Since it is used a multiobjective approach for the problem, a set of Pareto solutions will be obtained. Thus, the decision maker will have the possibility to verify compromises between the several non-dominated solutions.

The advantages of using distributed storage systems in distribution networks for peak load shaving can then be summarized as:

- Reduction in the losses in the distribution network since they are dependent of the current square (the reduction in the power losses during the peak hours will be higher than the increase in the power losses during the off-peak hours).
- Reduction in the energy cost since that cost is different along the day, being more expensive during the peak hours.
- Increase in the infrastructure capacity since there is a reduction in the power that flow in the distribution lines during the peak hours.

As described in the previous section, this work uses storage systems with batteries. However, to ensure the connection of these storage devices with the AC grid, it is required the use of power electronic converters. These converters allow to control the power that will be injected or received from the grid [17,27]. Thus, taking into consideration this interface and from the point of view of the grid these storage systems can be considered as a device with a bidirectional capability of power [28]. This work considers that the storage systems are controlled in order to charge or discharge at a specific power.

According to the exposed before, this work considers the optimization of the size and the location of storage systems. Taking into account the cost and size of the storage systems, batteries were chosen to realize this study. As described, it will be considered several standard fixed types of batteries, according to their capacity. In order to obtain the maximum benefit, for the first objective function it will be considered the minimization of the losses in the distribution network at peak hours when the batteries are supplying energy. More batteries will allow reducing the power consumption from the transmission system during the discharge period of the storage systems and reducing the losses of the network. For the second objective function, it will be considered the investment cost. Since the two objective functions are in conflict, a carefully analysis between the benefits of using more storage systems and the investment costs must be made.

3 Problem formulation

The problem is formulated as a true multiobjective problem by considering the minimization of two objective functions that are in conflict. In this work, the objective functions are related to losses in the distribution network and cost of the storage systems.

3.1 Objective functions

The objective functions are defined according to the considered problem. In this work, the first objective function is the minimization of distribution losses. According to this, the real-valued decision variables are the active power flowing

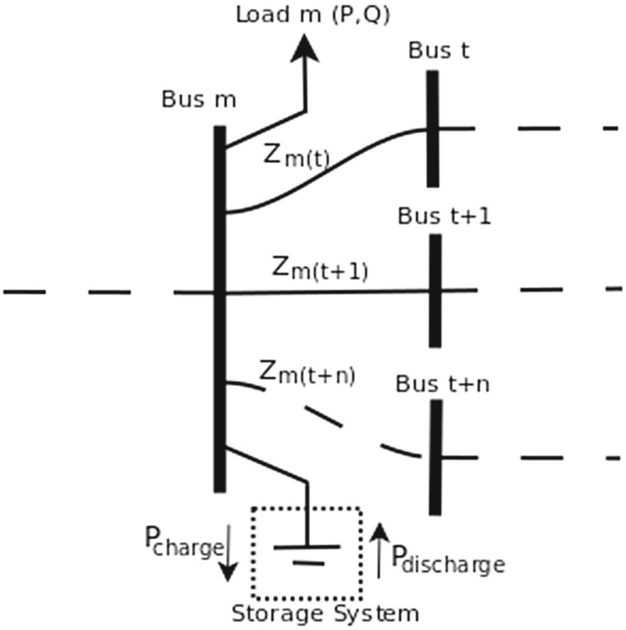

Fig. 1 Single-line diagram of a generic branch

in the network and the voltage magnitudes. In order to define this objective function, a distribution system load flow solution is used to find the power loss and also the voltage at each branch. Thus, taking this into consideration and a radial distribution system, an iterative power flow method dependent of the current branch is used [29,30]. This method can be used in any kind of radial distribution networks. The equations used in this method can be obtained from the single-line diagram shown in Fig. 1. In this diagram, a generic bus m with storage and load directly connected to the bus is considered. The storage system is considered a load (with a specific power consumption) when in charging mode or a generator that deliveries a fixed power in discharging mode. Bus m is fed by a preceding bus and supplies several buses following it $(t, t+1, \ldots, t+n)$. Connecting branches are characterized by their impedance (resistance and reactance). According to this, the main process is the following:

1. Define voltage at buses assuming initially that all voltage buses are equal to 1 pu with zero angle.
2. Consider in this step the next interaction (i), determination of the current in each node by the following equation (considering only bus t):

$$\overline{I}_t = \left(\frac{\overline{S}_t}{\overline{V}_t}\right)^* \tag{1}$$

3. Compute the voltage and apparent power in each of the buses through the following expressions (considering only buses m and t):

$$\overline{V}_t = \overline{V}_m - \overline{Z}_m \times \left(\frac{\overline{S}_t}{\overline{V}_t}\right)^* \tag{2}$$

$$\begin{aligned}\overline{S}_m = {} & \sum_{i=0}^{n} \overline{S}_{t+i} + \sum_{i=0}^{n}\left(\overline{V}_{m(t+i)} \times \left(\frac{\overline{S}_{t+i}}{\overline{V}_{t+i}}\right)^*\right) \\ & + \overline{S}_{\text{Load}} + \overline{S}_{\text{Storage}}\end{aligned} \tag{3}$$

4. Verify the voltage convergence condition of all buses (where k represents a generic bus) according (4). If all conditions are not verified (the difference of voltage buses between interactions is higher than the defined precision ε), then go to step 2.

$$\left|V^{i}_{\text{bus}k} - V^{i-1}_{\text{bus}k}\right| \langle \ \varepsilon \tag{4}$$

The decision variables are represented by the variables a^k_m formulated in (5), whether or not a new storage equipment of a type k is installed in a given bus B_m. For each storage type and location defined by those variables, the electrical real-valued variables are computed using the power flow algorithm. At each type, corresponds a storage system that is able to charge or discharge a maximum specific power for a given time. That power will be included in expression (3).

$$a^k_m = \begin{cases} k & \text{if the new storage } P_{F_j} \text{ is installed in } B_m \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

As described, this approach is formulated as a true multiobjective problem since uses two different objective functions. The first objective is to minimize the total power loss of the feeders considering constraints under a specified load pattern. Thus, the mathematical model of the problem can be given by (where $\overline{V}_{m(t+i)}$ represents the voltage in each of the network branches):

$$\text{Min } F_1 = \text{Min} \sum_{m=1}^{M} \left\{ \text{Re}\left[\sum_{i=0}^{n} \left(\overline{V}_{m(t+i)} \times \left(\frac{\overline{S}_{t+i}}{\overline{V}_{t+i}} \right)^* \right) \right] \right\} \tag{6}$$

The second objective function is the cost associated with the introduction of the storage systems (where no batteries means no cost) and can be formulated by the following condition:

$$\text{Min } F_2 = \text{Min} \sum_{M=0}^{M} \sum_{j=1}^{Y} a^j_m c_j \tag{7}$$

where c_j is the storage (P_{Sj}) cost ($j = 1, \ldots, Y$), a^j_m the binary decision variable denoting whether or not a storage system of type j is installed in bus m (5), b_m the technical feasibility of installing storage systems at bus m (10), d the mode of operation of the storage system given by (9) and P_{S_m} the active power that the storage system will inject to the grid or in charge condition and formulated by ($\overline{S}_{\text{Storage}} = P_{S_m}$):

$$P_{S_m} = b_m a_m^j d\ P_{Sj} \tag{8}$$

$$d = \begin{cases} +1 & \text{Storage system in charging mode} \\ -1 & \text{Storage system in discharging mode} \end{cases} \tag{9}$$

3.2 Constraints

The constraints considered were the power balance equations which guarantee that the load demand is meet by considering the distribution losses of the distribution network.

Another constraint that is considered is associated with quality of service related to the upper and lower bounds of voltage magnitude at each bus (i), as formulated by:

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{10}$$

A final constraint is related to the possibility to install a storage system in a specific bus B_m. Thus, this constraint is formulated according to:

$$b_m = \begin{cases} 1 & \text{if it is possible to locate a storage at } B_m \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

4 Multiobjective genetic algorithm NSGA-II

The elitist non-dominated sorting genetic algorithm (NSGA-II) is presented in [31]. Unlike the majority of elitist multiobjective EAs, NSGA-II uses not just an elite-preserving strategy but also an explicit diversity-preserving mechanism.

NSGA-II provides an efficient procedure for introducing elitism into a multiobjective evolutive algorithm (MOEA) while guaranteeing a diversity-preserving mechanism, assuring in this way a good convergence toward the Pareto optimal front without losing solution diversity. In this algorithm, in generation (iteration) t, the offspring population E_t is created by using the parent population D_t both of size N. However, instead of finding the non-dominated front of E_t only, the two populations are first combined together to form a population R_t of size $2N$. This population is classified with a non-dominated sorting algorithm. Although this requires more effort compared with performing a non-dominated sorting on E_t alone, it allows a non-dominance check among offspring and parent solutions. After this procedure, the new population is filled by solutions of different non-dominated fronts, one at a time. The process starts with the best non-dominated front and continues with solutions of the second non-dominated front (that is, the non-dominated front after the solutions of the first front have been removed) and so on. Since the size of R_t is $2N$, not all fronts may be accommodated in the N slots available in the new population, and they are simply deleted. When the last front is being considered, there may be more solutions in the last front than the remaining slots in the new population. Instead of arbitrarily discarding some members from the last front, a niche strategy is used to choose the members of the last front that reside in the least crowded region in that front.

The standard NSGA-II algorithm is outlined below (see also [31,32]). Initially, a random population D_0 is created. The population is sorted into different non-dominance levels. Each solution is assigned a fitness equal to its non-dominance level (1 will be assigned to the first non-dominated front). Accordingly, the minimization of the fitness will be assumed. Binary tournament selection, recombination and mutation operators are used to create an offspring population E_0, of size N. The stopping criterion is the limit number of generations (iterations).

Step 1 Combine parent and offspring populations to create $R_t = D_t \cup E_t$. Perform a non-dominated sorting in R_t and identify different fronts F_i, $i = 1, 2, \ldots$.
Step 2 Set a new population $D_{t+1} := \varnothing$. Set counter $i = 1$. While $|D_{t+1}| + |F_i| < N$, do $D_{t+1} := D_{t+1} \cup F_i$ and $i := i + 1$.
Step 3 Perform the crowding-sort ($F_i < c$) procedure (mentioned below) and include the most widely spread ($N - |D_{t+1}|$) solutions into D_{t+1}, by using the crowded distance values in the sorted F_i.
Step 4 Create an offspring population E_{t+1} from D_{t+1} by using the binary crowding tournament selection, crossover and mutation operators.

The process of non-dominated sorting and filling the population D_{t+1} steps can be performed together, so that every time a non-dominated front is found its size can be used to check if it can be included in D_{t+1}. If it is not possible, no more sorting is needed.

In Step 3, the crowding–sorting of the solutions in front F_i, which is the last front that could not be completely accommodated, is performed by using a crowded distance metric. The crowding comparison operator compares two solutions and returns the winner of the tournament. The winner is selected based on two attributes: the non-dominance ranking r_i and the local crowding distance d_i, in the population. This crowding distance attribute of a solution i is a measure of the search space around i, which is not occupied by any other solution in the population. d_i is an estimate of the perimeter of the cuboid formed by using the nearest neighbors as the vertices (which is called the crowding distance). Based on r_i and d_i, the binary crowding tournament selection operator works as

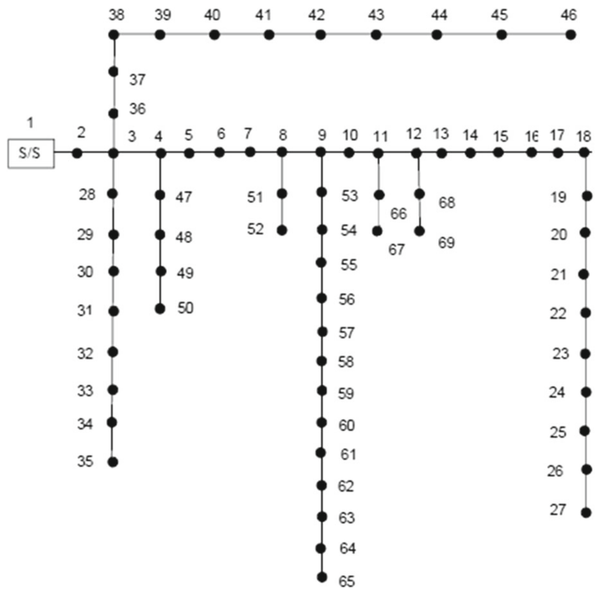

Fig. 2 IEEE 69-bus radial distribution system

follows—a solution i wins a tournament over another solution j if any of the following conditions is true:

1. If $r_i < r_j$ (this assures that the solution chosen lies on a better non-dominated front).
2. If $r_i = r_j$ and $d_i > d_j$ (this is applied when both solutions lie on the same front and the condition above cannot be applied; in this case, the solution residing in a less crowded area, with a larger d_i, wins).

5 Numerical results and analysis

To verify the effectiveness of the proposed planning of the distribution networks with the integration of storage systems using a multiobjective optimization, an IEEE 69-bus radial distribution system is considered for case study. Figure 2 presents the single-line diagram of this system.

For the storage system, it was adopted gel lead–acid batteries. These are characterized by their capacity and cost. For this study, it was considered a load diagram composed by three fixed powers along the day, as shown in Fig. 3. The peak hours correspond to the power defined by the data of the IEEE 69 bus [30]. For the shoulder hours, it was considered 80% of the total power, and for the off-peak hours, it was considered 50%. The number of hours related to the off peak, shoulder and peak periods are 8, 12 and 4, respectively. Thus, the batteries will charge over the 8 h of the off-peak period and will discharge over the 4 h related to the peak period. This will correspond to an average power related to the batteries of 5, 10 and 15 kW, respectively. Table 1 presents the relationship between the three types of storage systems (according to the nominal power and correspondent storage capacity) used in this work and the cost. The capacity of the batteries was sized to supply per day a constant instantaneous power during 4 h (with the power described in Table 1). Batteries sizing was made bearing in mind the depth of discharge (DOD) and the efficiency of the energy-conversion process. In this case was considered a DOD of 50% which takes into considered the aging process. Thus, according to these considerations it was considered a set of 17 (for type 1), 34 (for type 2) and 51 (for type 3), 12 V-200 Ah batteries. The energy storage was controlled in order to inject into the grid at the peak hours the nominal power associated with each type, as described in Table 1, for the all period (4 h). However, the period related to the off-peak hours is higher than the period of peak hours. Due to this, the charge of the storage system is controlled at reduced power. Since the number of hours related to the off peak is the double of the peak, the storage system will be charged at half of the power considered in the discharged mode.

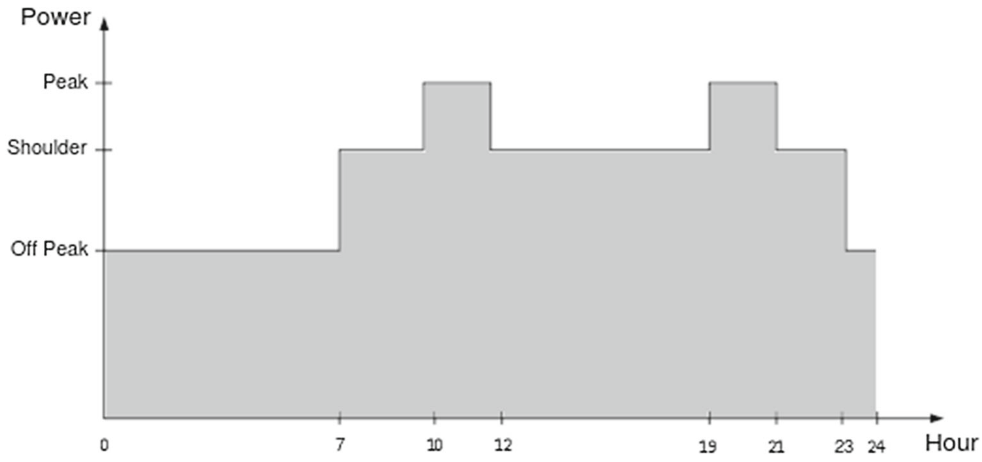

Fig. 3 Daily load diagram

Table 1 Types of storage systems used in this case study

Type of storage system	Storage system (kW)		Cost (Euros)
	Nominal power (kW)	Capacity (kWh)	
1	5	20	20,500
2	10	40	45,000
3	15	60	67,000

As described before, the optimization of the size and location of the batteries (according to Table 1) was implemented using the multiobjective genetic algorithm, NSGA-II. The number of buses that was considered to be compensated was limited to 25. It should be noted that there are not any technical constraint about that this limitation. At the limit, the number of buses to be compensated can be all of them. However, it was considered this limitation in order to limit the costs to values that normally the utility decision maker will accept. So, this was introduced as a parameter of the program and defined by the decision maker. On other hand, with this limitation the algorithm normally will be more effective.

The implementation of the NSGA-II algorithm was made tacking into consideration the minimization of the costs of the storage systems (7) and the instantaneous power losses of the distribution system in the peak hours (6). Since it was considered a fixed instantaneous power during the peak hours, the energy during that period is proportional to the instantaneous power losses of the distribution system. However, if the power profile is not constant, then it should be considered the energy losses of the distribution system during that period, since the power losses are dependent of the current square. Figure 4 shows the non-dominated solutions obtained using this algorithm, where the cost is in euros and the instantaneous power losses of the distribution system in the peak hours is in kW. From this figure, it is also possible to observe that the Pareto front is well defined and with a good distribution.

The location and type of the storage systems for each of the best non-dominated solutions are presented in Table 2. As expected, for the less costly solution storage systems with less number of batteries (less capacity) are required, while for the solution with the best reduced distribution losses is the opposite, more number of batteries (higher capacity) are needed.

With the introduction of the storage systems, the losses in the distribution system reduce at peak hours but increases at off-peak hours. Figure 5 shows the losses for the distribution systems without storage systems and for the extreme points of the Pareto front (best solution for losses and best solution for costs) for each of the periods. As expected, the losses in the off-peak hours increase (since the storage systems are in charging mode), and at shoulder hours, the losses are the same (the storage systems are off). From these results, it is possible to verify that the reduction in losses during the peak hours is higher than the increase in the losses during the off-peak hours. Comparing with the distribution system without the storage systems, the reduction in the losses during the peak hours is 12 and 4.9% and the increase in the losses during the off-peak hours is 9.6 and 3.8%.

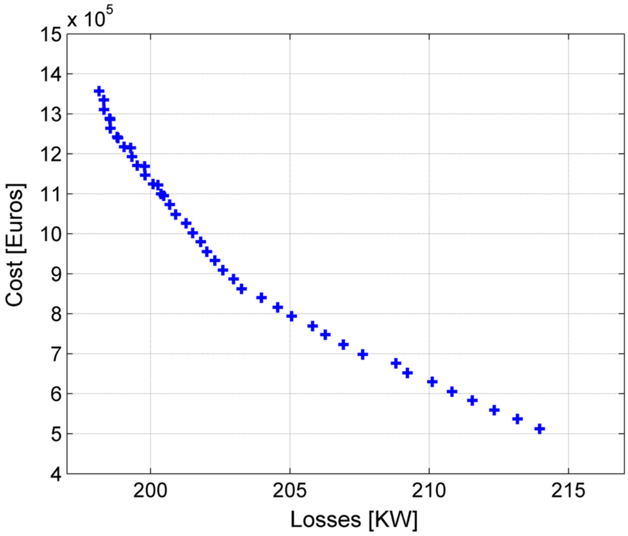

Fig. 4 Best obtained Pareto front for the IEEE 69 bus

Figure 6 shows the power consumption with and without storage systems for the solutions of the extreme points of the Pareto front. In these results, power consumption represents the sum of the instantaneous power of the loads and the instantaneous power losses of the distribution lines. These solutions were obtained for the peak hours period. As in the previous results, it was adopted the power since it was considered a constant load for each of the periods. From this figure, it is possible to confirm the positive effect of the storage systems during the peak hours. The solution with higher-cost results in higher decreased peak demand from the grid (with a reduction of 8%). This solution also has the greatest increase in the power consumption during the off-peak hours (increase of 6.5%).

The voltage profile of the distribution network before and after the placement of the batteries is shown in Fig. 7. The voltage profile associated with the existence of batteries is related to the best solution for losses. This is the solution that presents the best voltage profile. From this figure, it is possi-

Table 2 Location and type of storage systems for the best non-dominated solutions for each objective function

Cost[k€]	Losses [kW]	Location and type of storage systems in the distribution network
512,5	213,9	Buses with storage systems: 7 14 17 20 21 23 26 27 46 51 53 55 56 57 58 59 60 61 62 63 64 65 66 67 68 Type of storage system: 2 3 2 2 2 1 3 3 3 1 2 3 1 3 3 3 2 3 1 3 3 3 3 3 3
1357	198,1	Buses with storage systems: 4 7 14 17 20 21 23 26 27 43 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 Type of storage system: 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

"0" section with no equipment, "1" section with a switch and "2" section with a battery bank

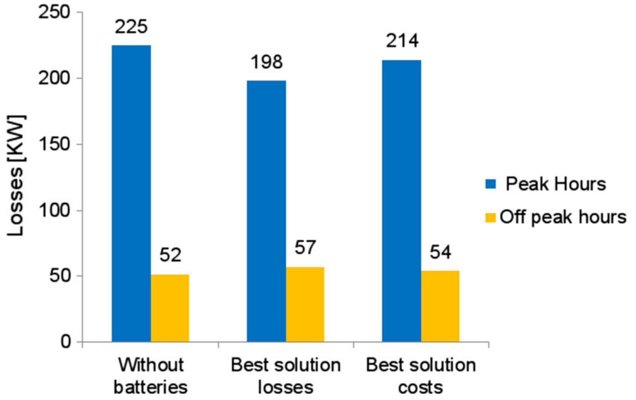

Fig. 5 Losses for each of the three periods for the system with and without storage systems

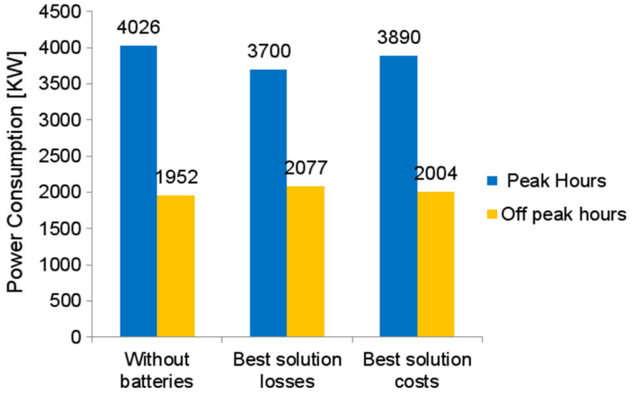

Fig. 6 Power consumption before and after the placement of the batteries

ble to verify that especially in the buses with lower voltage there is a clear improvement of that voltage. In fact, the minimum voltage that was obtained for this solution is 0.915 pu

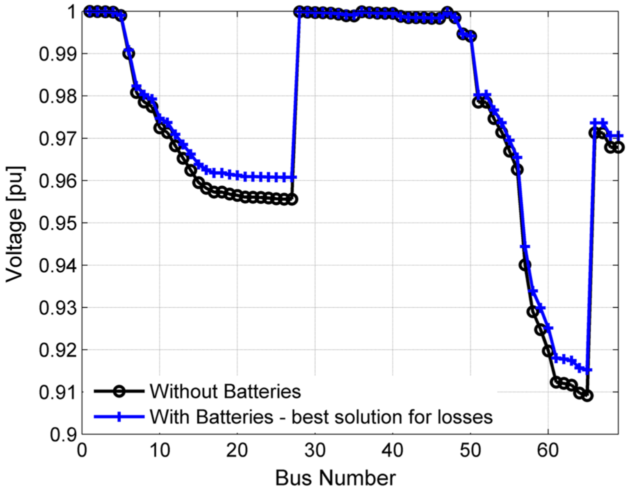

Fig. 7 Voltage profile before and after the placement of the batteries

at bus 65. Comparing with the base case (0.909 pu), it is possible to confirm the improvement of the minimum voltage.

Figure 8 illustrates the energy consumption for the peak and off-peak hours without storage systems and for the solutions of the extreme points of the Pareto front. These results have been obtained considering a 30-day period. From this figure, it is possible to confirm the effective reduction in the energy consumption during the peak hours when it is used the storage systems.

6 Conclusions and future research

In this paper, a multiobjective model and a NSGA-II-based approach to provide decision support in the size and location of storage system in distribution networks problem have

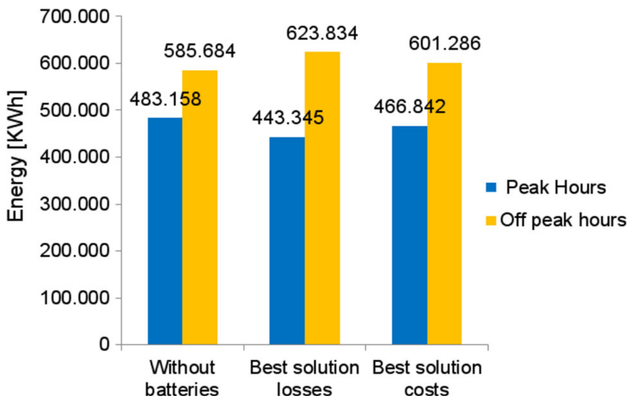

Fig. 8 Energy consumption for each of the two periods (peak and off-peak hours) for the system with and without storage systems

been presented. The proposed approach uses storage systems to provide peak load shaving in this kind of networks. One of the characteristics of this approach is the use of a standard group of storage systems in order to obtain a large number of these systems with the same specifications. Due to this, it can be obtained a more simple maintenance with reduced costs. On other hand, it was adopted the use of storage systems with reduced sizes in order to spread them into the network. This also allows a higher reliability taking into consideration all system, since a fault in one of the storage systems will not have a large impact. The proposed approach also formulates the problem tacking into consideration that the objective functions that are in conflict are not merged. These objective functions are: minimizing line losses and minimizing storage system costs. The mathematical model explicitly incorporates the conflicting nature of the objectives, and the discrete nature of the decision variables. Non-dominated solutions were computed by using a methodology based on the NSGA-II. This methodology leads the search toward a region of potentially non-dominated solutions with good characteristics, allowing the decision maker to choose the solution which best achieves a compromise between the objective functions, taking account his/her preferences. The proposed methodology has been applied to the IEEE 69 buses test feeder. The results showed the effectiveness of the proposed approach in the reduction in the losses, improvement of the voltage profile and costs of the energy. It was also compared the gains that can be obtained through the extreme solutions of the Pareto front. In fact, through the comparison between the best solutions (losses vs costs) and the distribution system without the storage systems, the reduction in the losses during the peak hours is 12 and 4.9% and the increase in the losses during the off-peak hours is 9.6 and 3.8%. Since the cost of the energy at the peak hours is higher than at the off-peak hours, there was also a reduction in the energy cost. The implementation of the distributed storage systems also allowed to improve the voltage profile. The minimum voltage that was obtained for the best solution of the losses is 0.915 pu at bus 65. Through the comparison with the base case (0.909 pu), it was possible to confirm the improvement of the minimum voltage.

Distributed energy storage systems are the answer to the challenges that power systems already have and will increasingly face in the future. With the emerging of distributed electrical renewable energy production centers, distributed storage systems maybe the answer not only to smooth the load diagram and to reduce system losses, as demonstrated in this work, but also to face other type of problems. Thus, a more profound research regarding the need to alleviate the variability of non-dispatchable wind power and other forms of renewable energy sources directly connected to the distribution networks, under the context of the distributed energy storage systems, is one of the key points. Finally, another important issue is to take into consideration the demand side management.

Acknowledgements This work was supported by national funds through FCT— Fundação para a Ciência e a Tecnologia, under Project UID/CEC/50021/2013.

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