COMPARISON OF PLANNING ALTERNATIVES FOR ACTIVE DISTRIBUTION NETWORKS

Gianni CELLI Gian Giuseppe SOMA Fabrizio PILO Emilio GHIANI Rocco CICORIA Sergio CORTI
University of Cagliari, Italy RSE S.p.A., Italy
{celli, ggsoma, pilo, emilio.ghiani}@diee.unica.it {rocco.cicoria, sergio.corti}@rse-web.it

ABSTRACT

A key element on the development of the future active distribution networks is to provide the network with storage devices, in order to compensate possible negative effects brought by a large integration of unpredictable generation. Software tools to aid Distributors to correctly assess the effectiveness of the use of storage as an alternative to traditional planning solutions (e.g. upgrading of the distribution lines) can be useful to planner engineers. The tool developed by the authors assists the DSO in defining the best integration strategies of distributed storage systems in distribution networks and in assessing their potential as an option for a more efficient operation and expansion of future electricity distribution networks. Examples derived by a representative distribution network are presented.

INTRODUCTION

In the last decade, numerous factors forced the restructuring of the electricity supply market, along with the increasing penetration of distributed energy resources. For these reasons, the Smart Grid is fundamental for a sustainable energy future in order to achieve the necessary operation flexibility (power flows management, congestion answer, better reconfiguration capability in case of outages) and, at the same time, to compensate possible negative effects brought by a large integration of unpredictable generation (e.g., wind and solar generation) [1]. The active management is an essential part of the SG paradigm that allows exploiting the dispatching of Distributed Generation (DG) (i.e., Generation Curtailment), the provision of Ancillary Services from DG, the storage devices and Demand Side Integration [1]. The active management can give higher profits to the producers and it also allows Distribution System Operator (DSO) postponing CAPEX caused by the load growth or by the DG and Renewable Energy Sources (RES) connection without posing intolerable economic barriers. In the paper, an optimization algorithm, able to consider on-line network reconfiguration, Demand Side Response (DSR) and the optimal Active and Reactive Power Control is used for the active management of the system with Distributed Energy Storage (DES) installed [2]. By assuming that the DSO has the ownership and operation of storage, a procedure is proposed able to define the control strategies (optimal charge/discharge pattern) of DES devices in a given distribution network [3]. The use of DES is limited by constraints on energy reserve, charge and discharge times and efficiency, effect on losses, and hourly energy prices. The Dynamic Programming (DP) is adopted to solve the DES optimal scheduling problem [6]. In order to perform analytical comparisons of different planning solutions, this new procedure has been integrated in a software planning tool for the optimal MV distribution network expansion, developed in the previous year [6]. The planning procedure will assist the DSOs in defining the best strategies for DES integration and in assessing the potential of DES as an option for a more efficient operation and development of future electricity distribution networks. Finally, the results of the optimization of a real MV distribution network expansion in a prefixed planning period are presented and discussed, comparing traditional and new planning alternatives.

DISTRIBUTION ENERGY STORAGE

The interest of the industrial world (manufacturers and electric utilities) and of the scientific community for DES is high and ever-increasing, but it clashes with the lack of a clear regulatory environment that defines who can possess these devices, which operation constraints can be imposed, which mechanisms of grants (like the feed-in tariff for renewable energy) can be exploited by the investors. All these issues are very important because the costs of the technologies used for the storage devices in the distribution networks are still high and can weight on the investment's profitability. Anyway, the expansion of energy storage is entirely complementary to the wider uptake of intermittent renewable resources and to DG in general, which are likely to present a whole range of new business opportunities for storage systems and their suppliers [4-5]. However, the optimal integration of DES requires to take into consideration their optimal control strategies (charge/discharge patterns), which depend on DESs technology, location and capacity, and on the load and generation patterns. DES might be viewed both as a consumer and producer of power, thereby participating to the market as both a load and generator. Alternatively, storage might be treated as an integral part of the distribution network, thereby removing it from the normal energy market. This might be linked to the question of who will be allowed owing the storage: load customers, generators, independent storage operators, or the network operator. The regulation concerning the separation of roles in the electricity system varies from country to country and the ownership and operation of storage will vary as a consequence. If the DSO is allowed to own storage devices, it can profit from DES by compensating possible negative effects caused by the connection of the DG. In fact, in Italy, the distribution grid code established by the Authority imposes to the DSO to accept any request of DG connection and DES might be useful with renewable generation to reduce connection costs and relieve operation issues (e..g., Volt/VAR regulation issues). In fact, DES located where utility distribution systems are approaching the capacity limit can provide significant economic benefits. These benefits are the deferment of distribution equipment upgrades that may involve a large increment in capacity such as the addition of a second transformer in a substation. In this contest, DES may be used for load leveling, voltage regulation, and peak shaving, that can differently affect the cost of the distribution system. In particular, the load leveling and the voltage regulation influence mainly the operation of the distribution networks, whereas the peak shaving is effective essentially in emergency configurations (after a faulted network component has been disconnected).

DYNAMIC PROGRAMMING

Dynamic Programming (DP) is a commonly used method for optimally solving complex problems by breaking them down into simpler sub-problems [7]. Typically, DP needs to divide the problem into *stages* with a *decision* (policy) required at each stage. A finite number of *states* is associated with each stage and the decision at one stage transforms one state into a state in the next stage (Fig. 1).

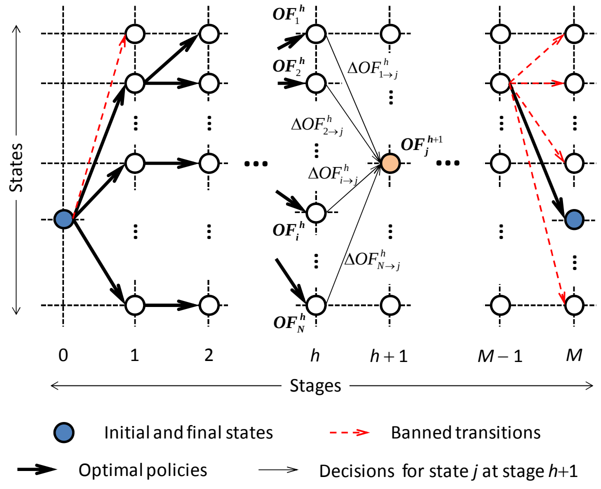

Fig. 1 – Optimal DES operation with Dynamic Programming.

Moreover, a recursive relationship must exist that identifies the optimal decision for each state in the next stage (*h*+1), and this relationship depends only on the states at the current stage (*h*) and not on the way these states have been reached (forward approach). For instance, if the optimization problem requires a minimization, the optimal policy to reach a state *j* in a generic stage starting from any state of the previous stage can be obtained as:

$$OF_j^{h+1} = \min_{i\in S_h}\left(OF_i^h + \Delta OF_{i\to j}^h\right) \qquad (1)$$

where OF_i^h is the Objective Function associated to the i^{th} state at stage *h*, $\Delta OF_{i\to j}^h$ is the value of the decision to transit from the i^{th} state at stage *h* to the j^{th} state at stage *h*+1, and S_h is the set of possible states at stage *h*. In other words, each state will be reached at minimum cost, passing through a state that was also reached optimally. This means that each policy to reach a state will include optimal sub-policies and, according to the Bellman's Principle of Optimality, it will be optimal itself.

In planning studies, the optimal scheduling problem of the energy storage in distribution system can be solved with the DP. The DES scheduling period (typically, a day) is divided in hours (*stages*). Given rates and durations of the DES devices, their storage capacities are discretized in *states* that identify their State Of Charge (SOC) at the beginning of each hour. Consequently, the *decision* of changing the state between two successive stages represents the power exchanged (absorbed or generated) with the distribution network during each hour. In the paper, DES has been used for load leveling and the objective function assumed has been the minimization of Joule losses. It should be notice that not all the decisions are always allowed due to internal and external constraints. Specifically, any decision cannot imply the violation of the maximum charge and discharge rates and the final state at the end of the DES scheduling period must be equal to the initial state.

DISTRIBUTION NETWORK PLANNING WITH DISTRIBUTED ENERGY STORAGE

The distribution network planning aims at defining the expansion and the reinforcements that are necessary to face the natural rise of energy demand, the connection of new customers and DG. The goal of planning is to minimise the sum of CAPEX and OPEX during a given time period. In last years, the authors have developed a software for optimal network planning [6], based on probabilistic techniques, that allows the optimal planning of MV distribution networks with DG, taking into account expansion over time and usual technical constraints. The optimization procedure minimizes the generalized cost of the network constituted by the CAPEX (e.g., investments for new lines, for upgrading existing lines and primary substations, and for network automation) and the OPEX (e. g., losses and maintenance). The optimal solution has to comply with constraints on the voltage profile, the maximum exploitation of assets, etc. The random behaviour of both distributed generation and loads is fully considered with the adoption of a probabilistic load flow.

In this paper, the authors have developed a new planning optimization algorithm that considers the usage of DES in electric distribution as a valid option for optimal expansion planning. In the paper, a generalised network cost - the sum of CAPEX and OPEX – is the objective function of the planning problem. The finding of the optimal planning procedure is the brownfield expansion plan that complies with the constraints and minimises the global costs. Each alternative examined by the optimization algorithm takes into consideration the optimal exploitation of the installed DES with an inner

optimization loop that aims at finding the optimal charge/discharge pattern by resorting to the DP.
The output of the whole optimal planning methodology will be not only the design of the network in the given planning horizon with an indication of CAPEX and OPEX, but also the daily scheduling of the storage planned (charge and discharge time intervals). In this sense, the DES may be regarded as a technology that allows the integration of DG overcoming the existing technical and economical barriers.

RESULTS AND DISCUSSION

In order to show the role of DES in distribution planning, a test network has been created by merging portions of real Italian distribution networks (Fig. 2).

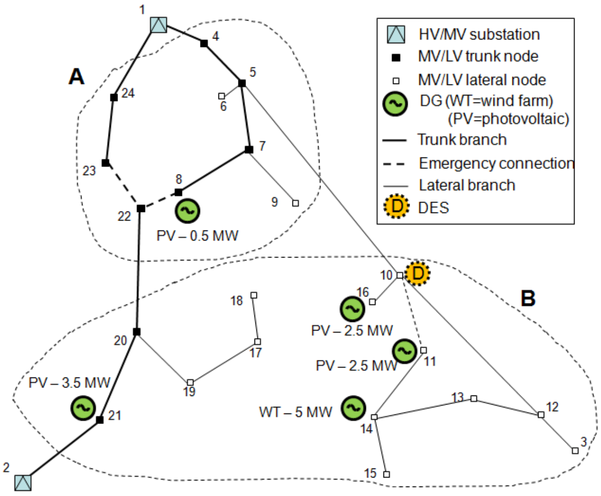

Fig. 2 - Case Study

Two primary substations feed 22 MV nodes (9 trunk nodes and 13 lateral nodes) that deliver power to MV and LV customers. The network is radial with emergency tie connections. The period taken into account for the planning study is 5 years long. For each MV/LV node a constant power demand growth rate of 3% per year has been assumed. Two typologies of loads have been considered: residential and agricultural. Also 5 renewable generators have been included in the network: a 5 MW wind turbine (WT, in node 14) and 4 photovoltaic generators (PV, 0.5÷3.5 MW, in nodes 8-11-16-21), modelled with typical production curves that take into consideration the unpredictability and availability of the primary source, by means of normal probabilistic distribution function (*pdf*).
In particular, the wind generation is modelled with a constant value of the mean output power with high standard deviation, equal in each hour. The photovoltaic generator has a high production during the day and no production during the night, with a standard deviation variable hourly (low in the sunrise and sunset, and high in the midday hours). Two areas (A and B in Fig. 2) can be identified in the network. In the area A (urban zone) urban/industrial loads have to be supplied. Here underground cables with bigger cross sections are used due to the high load density. The increasing of the energy demand in this area may easily lead to overloads and major investments may be necessary. The network in this area is constituted by a 95 mm^2 underground cable. In the B area (rural zone), the network is constituted by an existing overhead trunk feeder with 35 mm^2 conductors, and lateral branches with 16 mm^{2}conductors. The long overhead lines and the extended laterals with radial structure makes these networks electrically weak and, consequently, problems of voltage regulation and overloads may arise when renewable intermittent generators (wind and photovoltaic) are connected. Such a scenario is currently common in many countries because RES based generation plants are frequently installed in remote areas, far from urban or industrial districts where the demand is typically concentrated. With the current passive management of the distribution system, the growth of RES connection may cause massive investment on the rural distribution network. This is one of the reasons that urge on the adoption of a smarter distribution system, of which the active management represents the first step of implementation.
In the paper, four different planning alternatives have been considered in the simulations (obtained by using the tool presented by the authors in previous works [6]):

- *Case 1*. Current passive management, with reinforcement of the existing network;
- *Case 2*. Active management of distribution network to preserving the existing assets. Two different options have been examined: PQ control of DG (*Case 2a*) and DSR (*Case 2b*). With reference to DSR, 5 customers in the zone A participate to the DSR by offering a total or partial load shedding service that can be used by the DSO to solve critical network conditions (only during emergencies);
- *Case 3*. Distribution planning with DES. In this alternative, the DES may be controlled in order to reduce losses and/or defer the network investments;
- *Case 4*. Distribution planning with DES and active management. In this scenario, the DES and the active management (DSR) are simultaneously adopted.

In the next sections the different planning alternatives are analyzed. Table I reports the network costs during the planning period for all planning alternatives; in the same table, C_{INV} represents CAPEX during the study period, whereas C_{LOSS} is the cost of Joule energy losses (the term of the global OPEX to be minimised).
In case 1, according to the passive management, as expected, in the A area the trunk feeder has been reinforced with the 240 mm^2 cross section conductors. Similarly, in B area, the voltage regulation requires the reinforcement of the lines with the replacement of the 35 mm^2 cross section conductors with 150 mm^2 ones (trunk feeder) and 16 mm^2 with 25 mm^2 (lateral branches). In this condition, the total cost of the network is roughly 1400 k€

(Tab. I).

Table I. Network cost for planning alternatives

	C_{INV} [k€]	C_{LOSS} [k€]	C_{TOT} [k€]
Case 1 (Passive)	466	372	1438
Case 2a (PQ)	440	865	1305
Case 2b (DSR)	280	1040	1320
Case 3 (DES)	282	925	1207
Case 4 (DES&DSR)	34	1084	1118

In case 2a, the expansion of the network is studied considering the benefit of controlling the active and reactive power injected by the DGs in some critical hours of the day. The global cost of the network is smaller (Tab. I), because the PQ control solves almost all the overvoltage contingencies that reduces the conditions that require the refurbishment of overhead lines (laterals with DGs). In case 2b, responsive loads can give a significant contribution to network operation by participating to load control policies. With DSR, the underground cables in the urban areas have to be refurbished with 150 mm^2 instead of 240 mm^2. The final result is a CAPEX reduction equal to 186 k€ (Tab. I).

In case 3, only one DES has been used for the simulations (REDOX battery in node 10, 3000 kW - 8h). The results show that the total cost of the network is reduced by DES units in comparison to passive management and active network (Tab. I). The presence of DES can reduce the negative impact of the DG, limiting the need to upgrade the network. The charge/discharge pattern depicted in Fig. 3 shows that by charging DES in the midday hours of the day (in this period the PV production is fundamental to charge the DES), the network may be operated with smaller operation costs (i.e., less energy losses) and with less capital expenditures (i.e., smaller upgrading costs). The general remark is that DES reduces losses by avoiding that excessive power generation may cause reverse power flows in the network. By artificially increasing with DES the load close to intermittent power generation, the power exceeding the demand is used close to DG and not reversed to the HV system with a significant improvement of the efficiency. Furthermore, network upgrading is reduced because DES increases the homotheticity between the power generated and the load making the refurbishment less necessary (the charge pattern follow the PV production). Indeed, in the off-peak hours line overload is due to excessive power generation and reverse power flow, in the peak hours overload is caused by high load demand that exploits lines beyond the allowable rated ampacity. In conclusion, the use of DES is useful to increase the DG hosting capacity in distribution systems even without active distribution controls in place. The DSO has only to control the DES to operate the network without any sharing of responsibilities with producers.

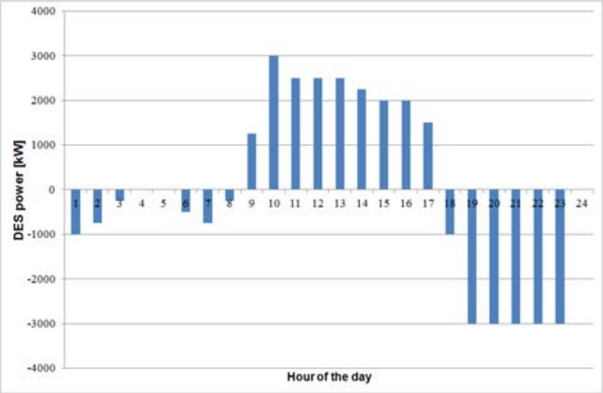

Fig. 3. Optimal daily DES charge/discharge profile.

The planning alternative in case 4 is the best solution (only few branches have been refurbished). In fact, in this condition the DES reduces the contingencies in the rural zone (the DES is allocated in node 10, B area) whereas the DSR, in emergency condition, relieve the overload conditions in the A area. Similar results as in case 4 can be obtained with an additional DES able to work in emergency condition allocated in the urban zone.

ACKNOWLEDGEMENTS

This work has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between ERSE and the Ministry of Economic Development - General Directorate for Energy and Mining Resources stipulated on July 29, 2009 in compliance with the Decree of March 19, 2009.

REFERENCES

[1] P. Djapic, C. Ramsay, et al., “Taking an active approach”, IEEE power & energy magazine, 2007.
[2] F. Pilo, G. Pisano, G. G. Soma, “Optimal Coordination of Energy Resources with a Two-stage on-line Active Management”, IEEE Trans. on Industrial Electronics, Issue 99, 2011.
[3] G. Celli, S. Mocci, F. Pilo, M. Loddo, “Optimal Integration of Energy Storage in Distribution Networks,” in Proc. PowerTech, 2009.
[4] J.A. McDowall, Opportunities for electricity storage in distributed generation and renewables, Transmission and Distribution Conference and Exposition, 2001 IEEE/PES.
[5] J. Baker, Electrical energy storage: challenges and new market opportunities, Energy world, 2004.
[6] G. Celli, F. Pilo, G. Pisano, G.G. Soma, “Optimal Planning of Active Networks”, Proc. of PSCC 2008.
[7] Larson R. E., Costi J. L.: “Principles of Dynamic Programming”, M. Decker, New York, 1978-1982.