MULTI-OBJECTIVE OPTIMIZATION OF ENERGY STORAGE SYSTEM SCHEDULING IN AN ITALIAN LOCAL ENERGY COMMUNITY

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ABSTRACT

Energy Storage Systems are becoming necessary for the upcoming Smart Distribution Systems thanks to the flexibility they introduce in the network operation. Since their costs are still high, optimal planning and management of these devices are crucial to identify specific configurations that can support storage installation. This consideration has motivated a strong interest of the researchers in this field that, however, have separately solved the optimal storage systems location and their optimal schedule. In the paper, a novel Multi-Objective approach is presented, based on the Non-dominated Sorted Genetic Algorithm – II integrated with a real codification that allows joining in a single optimization all the main features of an optimal storage implementation project. The paper is focused on the potential of a Local Energy Community of residential prosumers (with photovoltaic and storage systems) that can support the operation of the distribution system. In particular, pilots selected in the EU project StoRES (Promotion of higher penetration of distributed PV through storage for all) constitutes the Local Energy Community. Application examples are presented to illustrate the algorithm effectiveness.

INTRODUCTION

Energy storage is finding increased attraction in medium and smaller scale systems. Such expansion is complementary to the wider uptake of intermittent renewable resources, which are likely to present a whole range of new business opportunities for storage systems and their suppliers. Energy Storage System (ESS) can introduce important benefits to the whole electric system: it should be seen as provider of peak-load shaving or load-shifting functionalities or as an operational tool to facilitate efficient usage of electricity. ESS can incentivise end users to engage in demand response by optimising their power consumption as a response to market-reflective end-user prices. It includes all modifications to customers' electricity consumption patterns that are intended to alter the timing and level of instantaneous demand or total electricity consumption. Placing energy storage devices at the local distribution grid could empower customers to become more active in steering their electricity consumption.
The connection and coordination of an increasing number of ESS lead to new challenges for the maximum exploitation of their technical and economic potentials. The paper is focused on the potential of a Local Energy Community (LEC) of residential prosumers (owners of photovoltaic system - PV - and ESS) to support the operation of the distribution system and get the opportunity to manage electricity costs by time-shifting low-priced electricity and by using storage devices to arbitrage in the wholesale market and possibly provide cheaper electricity as a "service" when needed, and to enhance power quality by avoiding supply interruption for customers in case of service outage.
In the paper, a Multi Objective optimization procedure is proposed to identify the Pareto set of solutions for a given LEC (fixed in its topology, and including existing PV-ESS with fixed rating, number and locations). The methodology is based on the Non-dominated Sorting Genetic Algorithm – II (NSGA-II), with different objective functions (e.g. voltage profile, power quality, and minimisation of the energy cost or maximization of the self-consumption) [1],[2]. The decision variable is the daily schedule of the energy stored in each device.
The optimal scheduling is found by considering the current Regulation, which only allows using energy storage for increasing the self-consumption, and new schemes with storage and generation freely used to offer services to the network with a Micro Grid (MG).

ENERGY STORAGE SYSTEMS BENEFITS

Whereas the long-term benefits of decentralised storage are the motivation behind the development of the future smart grid, it is actually the short-term benefits that help devise a starting strategy for achieving that goal. In integrating the concept of supply of services from decentralised storage into their investment decisions, DSOs will be encouraged to assess alternative grid asset and system investments more fully. At a time when investment in smarter grids is urgently needed to achieve agreed political targets, this will create an incentive to consider new ways of doing electricity distribution business and the inclusion of emerging technologies. Compared with long-term future services of the smart grid, most important short-term benefits of decentralised electricity storage for distribution system operators involve the following:

- Deferring system upgrade costs and replacements by reducing load peaks;
- Improving service reliability and stability support where conventional solutions (new power lines or substations) might not be readily available;
- Allowing more recovery time for the power system during scheduled or accidental power interruptions;

- Providing short-term flexibility to strategically develop and implement less costly, more efficient responses to changing business conditions and system operations.

On the load (consumption) side, storage facilities may help to shift demand for electricity from peak times to off-peak times, levelling the asset load, improving the utilisation and serving the consumer.

MULTI-OBJECTIVE OPTIMIZATION

New planning tools for distribution networks able to define the optimal placement, rating and control strategies of distributed storage systems that minimize the overall network cost are very useful.
The nature of most real-world problems is intrinsically multi-objective. Thus, MO optimization (also called multi-criteria or vector optimization) is become very popular and important for scientists and engineers. Differently from single-objective optimization problems that may have a unique optimal solution, MO problems present a possibly uncountable set of solutions. This set is found by applying the Pareto's Optimality Theory. A solution belongs to the Pareto set, or it is said Pareto optimal, if no improvement is possible in one objective without worsening in any other. Thus, identifying the Pareto set is the key point for decision maker's selection of a compromise solution that satisfies all goals as better as possible [3].
Due to its recognized efficiency and robustness, the NSGA-II technique has been adopted in this paper as optimization's engine. It assigns the fitness with a *Domination-based* approach, through the definition of two attributes, the *non-domination rank* and the *crowding distance*. The first attribute groups the solutions into different fronts of non-dominance, whereas the second is used to preserve diversity in each Pareto front, by rewarding those solutions located in the less crowded regions of the front.
The solution coding adopted permits the ESS optimization. The integration of distributed battery storage units with the existing PV installations allows even higher shares of PV generated electricity. At the same time, issues related to grid stability and battery storage utilization are addressed aiming to enhance the resilience of the energy system.

THE PROPOSED ALGORITHM

The authors have developed in the past decades a planning tool for the optimal integration of Distributed Energy Resources (DER) in the distribution networks [3],[4]. This software is based on a Probabilistic Load Flow (PLF) solved for the 24 hours of one or more typical days both in steady state and emergency network configurations (the latter obtained removing one network element at a time in an N–1 analysis). The daily load/generation profiles are characterised in each hour with a mean value and a standard deviation (assumption of Gaussian distribution). The result of the calculation is the probability distribution of the nodal voltages and the branch currents, allowing the technical constraints check based on the concept of risk. In other words, network upgrade investments are not decided by finding a priori the worst operating conditions (maximum generation – minimum load, maximum load – no generation), but by considering the occurrence probability of each operating condition and comparing the risk of the technical constraints violation with the maximum level of acceptable risk.
For each hour, the PLF is executed and the risk of technical constraints violation is calculated. Whether the risk is acceptable the procedure advances to the next hour otherwise the network must be revamped. When the technical constraints are satisfied for all hours of a typical day in all the possible network configurations the value of Objective Functions (OFs) are calculated. If not all technical constraints are complied after the network upgrade, the design alternative is penalised with the lowest rank in the fitness assignment within the NSGA-II algorithm.
Regarding the ESS probabilistic representation, the mean value of the active power is directly derived from scheduling. Instead, the standard deviation is estimated in each hour on the basis of the difference between the nominal power of the storage device and the actual power exchanged with the network in that hour.

OBJECTIVE FUNCTIONS

Several benefits can be associated to the installation of ESSs in the electric distribution networks: those that affect the final prosumers and those that directly interest the distribution system operator (DSO).
In the paper, the following OFs have been considered.

OF1: Reduction of Joule energy losses

The Joule energy losses (E_L) in the network are calculated with (1).

$$E_{Lj} = \sum_{h=1}^{24} \sum_{j=1}^{N_{branches}} \left(3 \cdot r_j \cdot L_j\right) \cdot I_{jh}^2 \qquad (1)$$

I_j is the current in the hour h of the day, $N_{branches}$ is the number of the branches in the network, r_j and L_j are respectively the conductor's resistance per kilometre and the length (km) of the j^{th} branch.

OF2: Improvement of voltage regulation

The goal is not the reduction of the voltage constraint violations but the measurement of the voltage profile goodness achievable with the ESS. The proposed metric is a measure of the maximum variability of the nodal voltage in the whole network in the last year of the planning period, estimated with the probability distribution of the nodal voltages obtained with the PLF. This index has been defined with (2).

$$V_{reg} = \sum_{i=1}^{N_{nodes}} \sum_{h=1}^{24} \left(V_{i,h}^{\max} - V_{i,h}^{\min} \right) \quad (2)$$

In (2) the maximum and minimum voltages in each node in every hour are obtained by adding or subtracting to the mean three times the standard deviation, respectively.

OF3: Maximization of Self-consumption

The goal is to boost self-consumption with the optimal operation of the storage systems.
The self-consumption rate is defined by the ratio between the PV energy which is used directly E_{DU} or used for charging the battery E_{BC} and the overall produced PV energy E_{PV}:

$$s = \frac{E_{DU} + E_{BC}}{E_{PV}} \quad (3)$$

The degree of self-sufficiency describes the share of the load consumption that is supplied by the PV battery system. The degree of self-sufficiency d is calculated with the directly used PV energy E_{DU}, the energy discharged from the battery E_{BD} and the load demand E_L:

$$d = \frac{E_{DU} + E_{BD}}{E_L} \quad (4)$$

In the proposed algorithm the maximization of the self-consumption rate is performed by (5), where n_{ESS} is the number of ESS:

$$\max(s_{AVG}) = \max\left(\sum_{i=1}^{n_{ESS}} \frac{s_i}{n_{ESS}}\right) \quad (5)$$

CASE STUDY

The network

The case study network has been derived from the Italian suburban distribution network, identified by the EU project StoRES (*Promotion of higher penetration of distributed PV through storage for all*). In fact, the prosumers selected as pilot sites in the project StoRES (Fig. 1) are included in the application, forming a LEC.

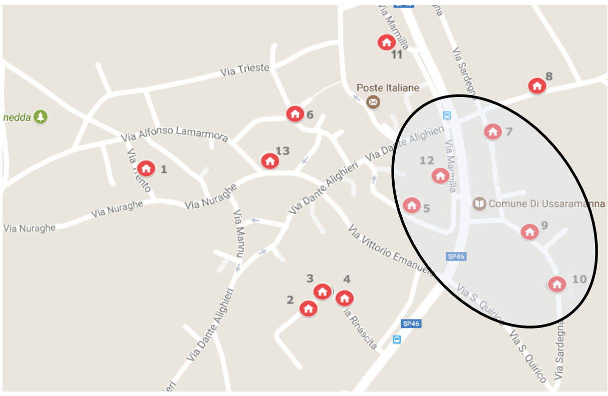

Fig. 1 Selected Pilot sites in Municipality of Ussaramanna – Italy.

The LV network (Fig. 2) includes a subset of the pilot sites (nr. 5-7-9-10-12 in Fig. 1). It consists of 37 nodes (residential loads for a total amount of about 112 kW) supplied by one 160 kVA 20/0.4 kV transformer and disposed on 3 feeders of different lengths (mostly small cross section ABC cable for a total extension of about 1.3 km).

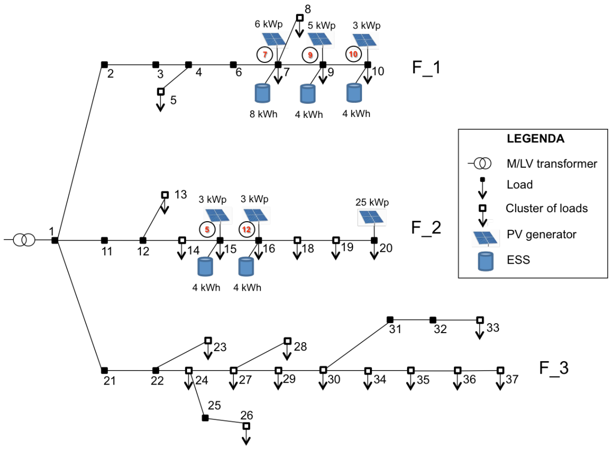

Fig. 2 LV Case study.

Local generation is connected to the network as it is shown in Fig. 2. The total rated capacity of PV generation is 45 kWp; the municipality owns the biggest generator, 25 kWp, the remaining ones are owned by citizens (Fig. 2). Each PV has been equipped with a suitable Lithium iron phosphate battery. The prosumers' daily load curves depicted in Fig. 3 have been used to find the size of the ESS that maximises the local consumption of the energy produced by the PV plants. Besides the prosumers' consumption and generation patterns, the optimal size of ESS is also determined by a constraint on the minimum and maximum allowable State of Charge (SoC) of the battery. SoC is constrained in a range between 20% and 80% of the nominal battery capacity in order not reduce the expected life of the battery.

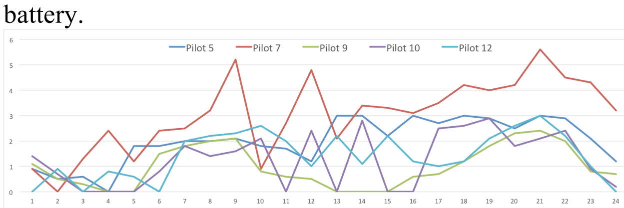

Fig. 3 Daily load profiles of consumers in the selected pilots [kW].

RESULTS AND DISCUSSION

The optimization algorithm has been applied assuming a population size of 250 individuals and a maximum number of 10 generations have been chosen. The result of the optimization is the optimal scheduling of storage usage. Each schedule differs from any other because minor adjustments in the exchanged power lead to slight variations in continuous OFs (like the Joule losses reduction).
First of all, it has been assumed that ESSs charge from the PV energy, and discharge to supply load demand as it is allowed by current Regulation. Then, LEC prosumers benefit from ESS by increasing their self-

consumption reducing the cost for purchasing energy from the network. The optimal scheduling obtained with the proposed optimization algorithms gives higher self-consumption (on average +120% referring to the case without ESS), but obviously lower increasing in the other OFs (i.e., no improvement in OF1 and -0.02% in OF2). The ESS charging/discharging profiles for the case that maximizes OF3 are shown in Fig. 4A.
Then, in order to take into account the LEC potential in providing services to the LV grid, the assumption that the prosumers can operate a MG has been introduced. In this case, ESS can modify their profiles by charging/discharging from/to the grid to avoid some contingencies. By applying the proposed MO methodology the Pareto solutions can result in a lower increase in the average self-consumption of the prosumers (OF3), but with increased system benefits (OF1 and OF2). In particular, in the Pareto front the compromise solution is characterized by lower increase in the self-consumption (+97% referring to the case without ESS), a relative improvement in OF2 (-0.02%) and a Joule losses reduction of 9%. The ESS charging/discharging profiles for this compromise solution are shown in Fig. 4B.
The MG with an MGCC (MG Central Controller) could then use the set-points obtained by the optimization algorithm to reduce energy losses and improve the quality of voltage. It clearly emerges that maximising the self-consumption of locally produced energy does not necessarily represent the optimal condition for the network. Leaving the ESS owners the freedom to use the devices could have positive impacts on the system.

CONCLUSIONS

Energy storage has an important role to play in the proposed energy transition offering suitable services for several applications both at utility and behind the meter. The ESS technology is still lightly used and solutions are at an early stage of development, requiring extensive work and trials to meet the needs of the interconnected grid. The optimization of ESS allows the further deployment of RES, predominantly small residential PV systems, in the energy mix of LEC. The coupled PV-ESS solutions have been tested in the pilot sites and by taking into consideration the different local specificities. Following this, different scenarios for optimizing self-consumption have been studied with the most advantageous and beneficial to be developed in order to offer a potentially cost-effective and sustainable option. The actual regulation scenario does not permit the full exploitation of ESS, as in an MG operation, and barriers related to storage should be removed to fully consider ESS as useful resources to solve grid contingencies.

Fig. 4 ESS Charging profile: A- LEC; B- MG.

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