Electric Power Systems Research 163 (2018) 154–163

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Distribution energy storage investment prioritization with a real coded multi-objective Genetic Algorithm

Gianni Celli*, Fabrizio Pilo, Giuditta Pisano, Gian Giuseppe Soma

University of Cagliari, via Marengo 2, 09123, Cagliari, Italy

ARTICLE INFO

Keywords:
Multi-objective optimization
Energy Storage System
Distribution Network Planning
Real Coding Genetic Algorithms

ABSTRACT

Energy Storage Systems (ESSs) are progressively becoming an essential requisite for the upcoming Smart Distribution Systems thanks to the flexibility they introduce in the network operation. A rapid improvement in ESS technology efficiency has been seen, but not yet sufficient to drastically reduce the high investments associated. Thus, optimal planning and management of these devices are crucial to identify specific configurations that can justify ESSs installation. This consideration has motivated a strong interest of the researchers in this field that, however, have separately solved the optimal ESS location and the optimal ESS 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 ESS implementation project: siting, sizing and scheduling. The methodology has been tested on a real-size rural distribution network.

1. Introduction

In the last decade, the electric distribution system has started a revolutionary transition towards a “smarter” operation that should reduce costs, enable new services and business opportunities and increase the hosting capacity for renewable energy production and electric vehicles. Flexibility is the key for the success of this transition and it can be provided by several actions, among which the installation of Energy Storage Systems (ESSs) plays a crucial role [1]. Indeed, the capability of changing behaviour from generator to load depending on variable needs makes the ESS suitable to be employed for a large range of potential applications in the distribution networks, like (but not only) load levelling, renewable energy integration, network congestion relief, voltage control and loss reduction. However, the connection and coordination of an increasing number of ESS also lead to new challenges for the maximum exploitation of their technical and economic potentials, due to the still high costs of installation. Moreover, the solutions to these issues are strictly dependent on the development scenario assumed for the distribution system, e.g. which actors (grid companies, end users, third parties) own and operate ESSs; which business model is supposed; and which services the ESS is enabled to offer. Consequently, several design options can be created and have to be examined, whose number inevitably becomes overwhelming making the decision process hard to be solved. The first step of this decision process is the identification of the optimal ESSs configuration (i.e. location, size and optimal scheduling) with benefits greater than capital and operational expenses.

The energy storage planning in electric distribution network is an optimization problem that has been increasingly attracting the attention of researchers as demonstrated by the high number of papers published, dealing with different combination of multiple synergic applications of the ESS and proposing a variety of models and methodologies [2,3]. Due to the “non-deterministic polynomial-time hard” nature of the problem (NP-hard) and the non-linear behaviour of the electric system, the majority of the researchers adopts a meta-heuristic solution method, which does not guarantee finding a global optimal solution, but has proven to be robust (provided solutions are acceptable in practice). Various meta-heuristic methods are used including Genetic Algorithms (GA) [4,5], Particle Swarm Optimization [6], Artificial Bee Colony [7] and Differential Evolution [8]. Researchers have also proposed some mathematical programming techniques to find the optimal solution of an approximated model. Particularly, in Ref. [9] a mixed integer linear programming (MILP) approach is used to solve an optimal power flow (OPF) that minimizes electricity cost and network losses and determines the optimal ESS size and location. In Ref. [10] the AC OPF model for radial distribution network is converted to a second order cone programming model (SOCP) and used to optimally locate and dispatch a fixed number of ESS for minimizing investment, maintenance and operational costs. In the vast majority of contributions, benefits and costs of ESS are converted in monetary terms and summed

* Corresponding author.
E-mail addresses: celli@diee.unica.it (G. Celli), pilo@diee.unica.it (F. Pilo), giuditta.pisano@diee.unica.it (G. Pisano), ggsoma@diee.unica.it (G.G. Soma).

https://doi.org/10.1016/j.epsr.2018.06.008
Received 10 November 2017; Received in revised form 8 June 2018; Accepted 10 June 2018

together into a single objective formulation of the problem [4–9]. Anyway, monetizing all benefits, even those that are hard to be monetised, for building a weighted combination of economic terms, often implies subjective assumptions and simplifications that can reduce the quality of final results. In this context multi-objective (MO) programming is very effective to make the decision process more transparent and impartial, and it can be used for both financial (i.e. company decision making) and socio-economic analysis (e.g., definition of regulation). Currently, few papers present a true MO approach [11], since most of them still uses a weighted sum method [10,12]. Sometimes, the optimization is focussed on the siting and sizing goals only, because it does not consider objective functions (OFs) dependent on the ESS scheduling [7,9,11]. When also this aspect is included, the overall problem is solved by splitting the ESS operation and the ESS planning [6] or by arranging the optimization procedure with nested sub-problems [4,5,8], but always considering a single OF for the optimal ESS scheduling.

In the paper, a full MO optimization procedure has been developed to identify the Pareto set of design options with fixed network topology for a given MV network. The optimization methodology is based on the Non-dominated Sorting Genetic Algorithm – II (NSGA-II) with a real codification of the simultaneously optimized decision variables: the ESS number, the ESS locations (nodes of the MV network), the ESS rating (nominal power and duration), and the daily schedule of the energy stored in each device as well as the cross-section of conductors, and the rated capacity HV/MV and MV/LV transformers.

It should be noted that daily schedule of ESS operation is fundamental since the convenience of an ESS can be obtained by only considering the benefits of multiple services at the same time, and not with an exclusive operation for a single goal. Thus, it should not be preferential the identification of the daily schedules optimal tailored for specific targets, but the ones of compromise among different targets and overall optimal. The simultaneous optimization of all the ESS features relevant to the set of offered services and the use of multi-objective approach that avoids monetizing all benefits (e.g., externalities and environmental benefits) are advancements with respect to the state of the art. The original codification of the NSGA-II with real quantities, which allows finding the ESS optimal daily scheduling, is another element of novelty compared to existing Literature.

2. Multi-objective optimization

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 (as a rule) present a possibly uncountable set of solutions. This set is found by applying the Pareto 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, the identification of the Pareto is crucial in decision making that looks for fair compromises amongst contrasting needs and stakeholders.

Among the multitude of approaches proposed in Literature, evolutionary algorithms are particularly suitable to solve multi-objective optimization problems. Indeed, they simultaneously deal with a multitude of possible alternatives, (the so-called population) which allows to find an entire set of Pareto optimal solutions in a single run of the algorithm, instead of having to perform a series of separate runs as in the case of the traditional mathematical programming techniques (as the linear combination of weights or the ε-constraint method). Additionally, evolutionary algorithms are less susceptible to the shape or continuity of the Pareto front [13].

Generally speaking, when an evolutionary algorithm is used, two important implementation issues have to be tackle: (i) how to assess the quality of each individual (Fitness Function), and (ii) how to code the solution of the problem for an effective application of the optimization process.

Due to its recognized efficiency and robustness, the NSGA-II technique has been adopted in this paper as optimization engine. It assigns the fitness with a *Domination-based* approach [14], 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 developed for the ESS allocation problem represents one of the main novelties of the paper.

3. Multi-objective optimal allocation of Energy Storage Systems

The traditional binary coding of the Genetic Algorithms (GAs) makes them particularly suitable for solving facility allocation problems. Indeed, in the research field of power distribution system, they have been used extensively for siting and sizing many types of equipment like generators, capacitor banks, measurement and control devices, and in the last decade also ESSs.

For ESSs the optimal allocation problem is even more complex, since the diverse benefits they can provide depend not only on the ESS size and location but also on the daily mode of operation and the share among different functionalities (e.g. energy losses reduction, voltage regulation, peak shaving). Usually, the ESS usage is optimized separately from the main MO optimization for the ESSs siting and sizing. Thus, the scheduling of the energy stored in the ESS is defined as a single-objective problem, limiting the multi-objective vision of the ESS allocation problem. In order to fill this gap in the Literature, in the paper the ESS daily scheduling has been included in the chromosome used to code the individual.

3.1. Solution representation

The chromosome of the generic solution has been organized for including four pieces of information:

1. the position (MV node) of the ESS in the distribution network;
2. the rated power (expressed in kW);
3. the nominal energy (number of hours at the rated power);
4. the State of Charge (SoC) at the beginning of each hour in the typical day of the year, expressed as percentage of its nominal energy.

Consequently, the chromosome section of a single ESS assumes the representation of Fig. 1. The whole solution vector is obtained by repeating this schema for all the possibly installed devices.

It can be observed that the solution space of the multi-objective optimization problem is essentially formed by continuous variables (e.g., SoC of the ESS, nominal power, and duration). Thus, instead of the traditional binary coding, a real-number codification has been adopted, more effective for continuous domains [15]. Indeed, it avoids the concern of an adequate precision of the optimal solutions when the search space is discretized for applying the binary coding. Moreover, Real Coded Genetic Algorithms (RCGAs) have the ability to exploit the gradualness of functions of continuous variables (i.e. small changes in the variables cause small changes in the function).

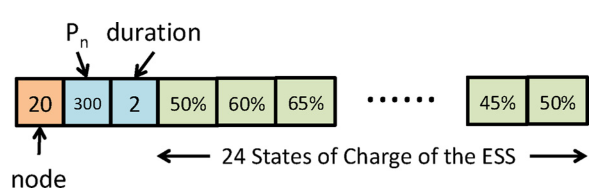

Fig. 1. Chromosome section for a storage device.