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Optimal siting and sizing of distributed energy storage systems via alternating direction method of multipliers ☆

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ABSTRACT

Energy Storage Systems (ESSs) will have an important role in the optimal operation of Active Distribution Networks (ADNs). Within this context, this paper focuses on the problem of ESSs optimal siting and sizing. Following similar approaches already proposed by the Authors, this paper proposes a multi-objective procedure that accounts for various ancillary services that can be provided by ESSs to ADNs. The proposed procedure takes into account the voltage support and network losses minimization along with minimization of the cost of energy from external grid and congestion management. For the case of large-scale problems, accounting for networks with large number of nodes and scenarios, the selection of the solution methodology is a non-trivial problem. In this respect, the paper proposes and discusses the use of the Alternative Direction Method of Multipliers in order to define an efficient algorithm capable to treat large-scale networks and, also, address the issue of the optimality of the solution. A real large-scale network with real profiles of load and distributed photovoltaic generation is used as the case study to analyze the effectiveness of the proposed methodology.

Introduction

Active Distribution Networks (ADNs) are changing significantly by integrating new technologies aiming at improving their level of control. Energy Storage Systems (ESSs) have an important role in this context [1]. Indeed, they have the ability to be indirectly used to control the network providing several services like load shaving, supplementing renewable resources, and, as a consequence, postpone investments needed for network reinforcements (e.g., [2,3]). They are also capable of providing network ancillary services like support to voltage and frequency controls and indirect control line congestions. Additionally, they can be also used for network losses reduction [4–6]. In this respect, one of the main problems associated to the use of ESSs in ADNs is to find their best location and size (i.e., power and energy ratings) in order to maximize their impact on the grid.

In this context, several works have been done related to optimal planning of ESSs in ADNs. This issue has been addressed in both microgrids and ADNs. The Authors of [7] have proposed the use of a Genetic Algorithm (GA) to find the optimal capacities of ESSs with the objective to minimize the operation costs of the targeted microgrid. A methodology to site and size different types of ESSs within the microgrid context has been proposed in [8]. A GA is used to find the best solution to maximize the total net present value. A methodology for optimal siting and sizing of ESSs in a medium voltage distribution network, with the goal of decreasing wind energy curtailment and minimizing annual cost of the electricity, is presented in [9]. A hybrid GA, sequential quadratic programming algorithm is proposed in [10] to size and site DGs, energy storage and reactive power compensation systems. The goals of the planning problem are the minimization of the total network losses and the operation costs. The Authors of [6] have presented a hybrid method integrating dynamic programming with GA to find the best siting, rating and control strategy of ESSs, in order to minimize the overall investments and network costs (energy cost and losses). A cost-benefit analysis methodology is presented in [11] to find the best sizing and siting of ESSs in distribution networks. The goal of the optimization is to maximize the Distribution Network Operator (DNO) profits from energy transactions, investment and operation cost savings. The planning of ESSs connected to transmission networks is also investigated in the literature (e.g., [12,13]). In [12] the optimal planning of ESSs in a network with renewable, and consequent uncertain energy production, is presented. The objective of the optimization is to minimize the

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Nomenclature

ESS	Energy Storage System
DG	Distributed Generation
SoC	State of Charge

Parameters

$\pi_{Sc}(t)$	energy price at time t for the scenario *Sc*
I_P, I_E	investment costs of ESS with respect to power rating and energy reservoir respectively
$E_{s,max}E_{s,min}$	maximum/minimum allowed *SoC* of ESS s
$s_{i,Sc}(t)$	complex power load at node i, time t, and scenario *Sc*
$S^{ger}_{i,Sc}(t)$	DG complex power production at node i, time t, and scenario *Sc*
z_{ij}	longitudinal impedance of the line between nodes i and j (line l)
W_{EP},W_{vol},W_{loss}	weighting coefficients of different terms in objective function
r_s	resistive loss factor of ESS s
$f_{ij,max}$	squared values of the rated current of the line between buses i and j
v_{min}, v_{max}	squared values of maximum/minimum limits of the network nodal voltages
β_{Sc}	probability of each scenario
α	interest rate
y	number of years after ESS installation corresponding to each scenario

Variables

$C_{i,Sc}(t)$	load curtailment at node i, time t, and scenario *Sc*
P^{cap}_s,E^{cap}_s	power rating and energy reservoir capacity of ESS s
$v_{i,Sc}(t)$	square of voltage at node i, time t, and scenario *Sc*
$f_{ij,Sc}(t)$	square of current flow on line ij at time t, and scenario *Sc*
$E^{Ex}_{Sc}(t)$	energy flow from substation transformer at time t and scenario *Sc*
$E_{s,Sc}(t)$	energy stored in ESS s at time t, and scenario *Sc*
$P_{s,Sc}(t)Q_{s,Sc}(t)$	active/reactive power consumed/produced by ESS s at time t, and scenario *Sc*
$L_{s,Sc}(t)$	resistive losses of ESS s at time t, and scenario *Sc*
$S_{ij,Sc}(t)$	complex line power flow between nodes i and j at time t, and scenario *Sc*
m^k, n^k	primal and dual residuals

Sets

t	index of time
s	index of energy storage systems
Sc	index of scenarios
ij, l	index of lines
i	index of busses
k	ADMM iteration

operation and investment costs of energy storage devices. The application of ESSs in optimal allocation of wind capacity related to distant wind farms is investigated in [13]. The methodology simultaneously optimizes the wind power capacity of each site, its ESS and the required transmission connection capacity.

A limitation of the above-listed papers is represented by the fact that they have not accounted in the problem formulation the ancillary services (e.g., voltage control) that ESSs can provide to ADNs. In this respect, the Authors of this paper have proposed in [4] a specific algorithm for assessing the optimal siting of ESSs to maximize their contribution to voltage control. Voltage sensitivity coefficients, as a function of the nodal power injections, were used to linearize the objective function of the problem and some of the constraints. The augmented problem of optimal allocation of ESSs in ADNs with a multi-objective (i.e., loss, energy cost, and voltage deviation minimizations) has been investigated in [14] by using a hybrid approach of GA and non-linear programming. Although the approach proposed in [14] provides satisfactory results, it is computationally expensive and the global optimal solution is not guaranteed due to the non-convexity of the problem. As a matter of fact, the computational inefficiency of this approach resulted into limiting the possibility of solving large-scale problems associated to: (i) networks with large number of nodes and (ii) multiple scenarios related to load and renewable resources volatilities (i.e., seasonal variability and yearly evolutions). In [15] a Second Order Cone Programming (SOCP) formulation of the optimal power flow (OPF) is used to define the problem of the optimal siting and sizing of ESSs in ADNs. It considers both technical and economical goals. However, as expected, the size of the problem increases drastically with the increase of both network size and number of scenarios. As a consequence, a dedicated decomposition method might be required. These drawbacks have motivated this contribution. Indeed, long-term optimal planning problems are normally large-scale ones since they should include a reasonable number of scenarios to address the variations and uncertainties of various parameters. Decomposition methods can be used to breakdown large-scale problems into smaller ones. They have been used for several power system problems and typical application examples can be found in these references [16,17].

The purpose of the methodology presented in this paper is to provide a tool to the ADN operator's capable to define the optimal planning of their own energy storage systems to support the network operation in presence of massive stochastic distributed generation. In this respect, it is important to underline that the paper does not focus on the comparative assessment of different technical solutions to support to the ADN operation. In this work we propose to use the Alternating Direction Method of Multipliers (ADMM) [18,19] to break down the original problem and have a distributed parallel convex optimization. The Second Order Cone programming (SOCP) OPF approach of [20] is adapted to formulate the problem of the optimal siting and sizing of ESSs in ADNs in order to obtain a convex problem. In this respect, it is worth mentioning that the convex formulation of ESSs planning is a peculiar aspect of the problem that has not been sufficiently addressed in the literature. The proposed approach also accounts for a non-simplified power flow in which the reactive power associated to shunt admittances of lines/cables is represented. Additionally, the ESSs are accurately modeled in terms of efficiency and *SoC*. Also their interfaces to the AC grid are represented by means of active and reactive power capability limits. The targeted problem is formulated as a multi-objective one including voltage deviations, network losses, in addition to investment and operation cost minimizations. It should be finally noted that this paper is an extended version of [21] which has been presented at the 18th Power System Computation Conference and was invited to be published in this journal.

The rest of the paper is organized as follows: the section 'Problem description' illustrates the problem and provides its formulation. The section 'Solution methodology' explains the proposed methodology to breakdown and solve the problem. The

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