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On bilevel planning of advanced microgrids☆

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ABSTRACT

This paper proposes a hierarchical decision making model for a coupled planning and operation problem of an advanced microgrid. The proposed model, is formulated as a bilevel optimization problem and recast as a mathematical program with equilibrium constraints (MPEC) where the decision variables of the two problems are independently controlled. The upper problem determines the strategic investment decision and optimal configuration of the microgrid, the needs for carbon emission permits and peak charges from using neighbouring network capacity, while the lower problem optimizes the output of the distributed energy resources (DER) through the implementation of an energy management system (EMS). The proposed approach was applied to the energy infrastructure of a remote mine. Results obtained through its application show significant savings in the cost of energy and improved benefits to stakeholders. They also show the advantages of a bilevel approach over other state-of-the-art microgrid planning methodologies.

1. Introduction

With an increased focus on reliability and a desire to reduce its environmental impacts, power system planners are exploring the advantages of distributed energy resources (DERs) to compliment central grid infrastructures. Government policies, technological advancement, economic and environmental incentives are changing the features of power systems, while DERs gradually increase their presence. Many key industrial players have developed energy saving strategies and are investing in renewable energy.

In the same vein, microgrids can be seen as vehicles for a greater integration of renewable energy resources (RES), the reduction in emissions of greenhouse gases, improving local system reliability and efficiency, as well as to manage and control power generation. It is defined as a group of interconnected loads and DERs within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid [1]. It can operate connected to the grid or in isolation. Nevertheless, the microgrid concept and functionalities have evolved over the years from providing emergency energy supply for reliability to include an energy management system (EMS) that should optimally allocate energy resources to minimize cost. The concept and its changing functionalities characterizing advanced microgrids are described in detail in [2]. It is clear that the successful implementation of advanced microgrids will require advance planning strategies to best capture operational and financial benefits.

1.1. Literature review

Most research work reported in literature on microgrid planning and operation tends to decouple the investment planning problem from the microgrid operational problem. The literature here can be categorized into three groups.

The first category pertains to microgrid operational planning challenges. Papers within this group assume a known microgrid design capacity/configuration, and they propose different optimization algorithms to minimize the systems' operational cost considering environmental and reliability implications [3–13]. Their applications span remote networks all the way to industrial applications. Recent publications within this group have focused on energy management strategies that deal with supply/demand uncertainties and highlight the value of flexible resources within the network [6–8].

From the planning perspective, the second category of contributions proposed planning problem formulations seeking to configure and size the assets of microgrids. The design problem formulations here are

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Nomenclature

Indices

i	index for all energy resources
t	index for hour
h	superscript for heat/thermal resources
e	superscript for electrical resources
y	index for years of project lifetime
r	index of demand response (DR)

Sets

B	set of indices for new DERs
$\overline{B}$	set of indices of new DERs except storage
A	set of existing resources i in the network
D	set of indices of diesel generating units
N	set of combined heat and power (CHP) units
G	set of dispatchable generating units ($G = D \cup N$)
Q	set of non-CHP gas fired thermal units
S	set of electrical energy storage (ESS) devices
U	set of remote community power resources
W	set of indices of wind power generating units
Y	set of indices of years in the project lifetime J
T	set of indices of time t within a year

Parameters

ν_i	energy to capacity ratio of storage resource i
k_r^e	electrical DR energy to power ratio
k_r^h	thermal DR energy to power ratio
w_r^e	percentage of electrical load available for DR
w_r^h	percentage of thermal load available for DR
C_i^b	budget constraint for resource i
C_i^c	capital expenditure of resource i
C_i^f	fuel cost of resource i
C_i^u	cost of purchased energy from remote community power resource i
C_y^z	cost of carbon permit per kg CO_2 in year y
C_i^m	maintenance cost for resource i
$\mathscr{D}_{u^y}$	demand charge per kW peak power from the remote community energy provider
$X_i^{\max}$	maximum power capacity for a new resource i
$P_i^{\max}$	maximum power output of existing resource i
$P_i^{\min}$	minimum power output of existing resource i
$L^e(y,t)$	electrical load at time t in year y
$L^h(y,t)$	thermal load at time t in year y
$L^{e,\max}$	peak electrical load
$L^{h,\max}$	peak thermal load
a_i	power capacity of existing asset i
η	storage charging and discharging efficiency
ς	electric to heat ratio of CHP unit

Operation level variables

$P_i^e(y,t)$	electrical output of resource i at time t in year y
$P_i^h(y,t)$	thermal output of resource i at time t in year y
$P_r^e(y,t)$	electrical output from DR at time t in year y
$P_r^h(y,t)$	thermal output from DR at time t in year y
$E_r^e(t)$	records of electrical DR energy already interrupted
$E_r^h(t)$	records of thermal DR energy already interrupted
$E_i^e(y,t)$	electrical energy level of ESS i at time t in year y

Design level variables

$\mathscr{R}_y^p$	peak power drawn from neighbouring community resources in year y
x_i	capacity of DER assets to be installed
Υ_y	carbon permits bought in year y

generally presented either as single or as multiobjective optimization problems [14–18]. Each of them has a generic cost minimization objective with some variations around constraints, objective functions and available technologies. Specifically, the proposed approach in [14] utilizes a mixed-integer linear programming (MILP) formulation and solution algorithm to determine the configuration of a potential microgrid that minimizes its energy procurement cost and CO_2 emissions, while a benefit to cost ratio is also considered in [16] for determining the best planning option. Complex, cumbersome and costly fuel logistics unique to several remote networks are also highlighted in [18] where heuristics are used to establish the microgrid design.

The third category of contributions, within which this paper belongs, investigates joint microgrid design and operations [19–21]. Particularly, in [19], authors have developed a two-step mixed-integer linear programming (MILP) model that optimizes the configuration of a hybrid microgrid and seeks to determine an operating policy based on the design. The first step solves an MILP to select and size the microgrid assets, while this solution is then passed to a second step where a data mining analysis is used to establish the logic of a microgrid controller. Also, a bilevel optimization design approach for ESS sizing in microgrids is proposed in [20] where the upper level's objective of minimizing cost and the lower level's variable operation cost are aligned [20]. The authors of [21] also attempt to nest the microgrid planning and operational problem in the form of a generalized double shell framework based on an evolutionary algorithm; however, the economic analysis of the design options in [21] are not established systematically. Also, the objectives of the upper level and the lower level problem are aligned. The aligned objectives may defeat the necessity of a bilevel optimization approach since other mathematical programming models such as multistage or multiobjective planning models are capable to solve similar problems with aligned sub-objectives with lower modeling complexity and lower computational cost.

1.2. Gaps in the state-of-the-art and contributions

From the above survey, it can be concluded several challenges must be addressed when considering joint microgrid asset and operations planning, as this paper does. Specific gaps include (1) the need to include the widest range of asset classes for system designers, (2) the need to design multi-energy microgrids systematically, and (3) to formulate joint optimal design-operation problems that represent with better fidelity the actual flow of decision making and that can exploit the capabilities of available high-performance optimization solvers.

More specifically, what motivates our approach here is that in practice the objective of a system planner may not be entirely aligned with that of the operator of that system. As seen above with [21], most coupled microgrid planning/operations problems have both the operational and planning objectives aligned, generally to global annualized cost minimization or net present value maximization. The challenge we present in this paper is for the case where the objective of a microgrid planner and that of its operator are not fully aligned, *i.e.*, are non-co-linear.

This paper addresses these challenges by proposing a systematic design approach for microgrids acknowledging the wide array of technologies available to microgrid designers: generation (to installed in the microgrid and/or to be obtained from a neighbouring community