ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Optimal planning of microgrid power and operating reserve capacity☆

Mike Quashie[a], Chris Marnay[c], François Bouffard[a,b,c,*], Géza Joós[a,c]

[a] Department of Electrical and Computer Engineering, McGill University, Montreal, QC H3A 0E9, Canada
[b] Groupe d'études et de recherche en analyse des décisions (GERAD), Montreal, QC H3T 1J4, Canada
[c] Trottier Institute for Sustainability in Engineering and Design, McGill University, Montreal, QC H3A 0E9, Canada

HIGHLIGHTS

- A bi-level model for a microgrid power and reserve capacity planning is developed.
- The model is cast within the context of a distribution system operator (DSO).
- The DSO and microgrid relationship is established in a structural/economical manner.
- Results obtained show bi-level optimization decreases overall operating cost.

ARTICLE INFO

Keywords:
Bilevel optimization
Distributed energy resources
Economic analysis
Energy management
Microgrid planning

ABSTRACT

This paper proposes a bi–level formulation for a coupled microgrid power and reserve capacity planning problem, cast within the jurisdiction of a distribution system operator(DSO). The upper level problem of the proposed bi–level model represents a microgrid planner whose goal is to minimize its planning and operational cost, while the lower level problem represents a DSO whose primary duty is to ensure reliable power supply. The microgrid planner, pursues its interest by co–optimizing the design configuration and power output of individual distributed energy resources (DERs), while the DSO maximizes the capacity of flexible reserve resources. The proposed model is recast as a mathematical program with equilibrium constraints (MPEC) wherein the decision variables of the two problems are independently controlled. Application of the proposed approach to the energy infrastructure of a Canadian utility network is discussed. Results obtained through its application are compared to an alternative multi–objective planning model and the improved benefits are assigned to the corresponding stakeholders.

1. Introduction

The electric power industry has undergone notable changes in recent years. The traditional central grid is experiencing a shift toward distributed generation, increased penetration of renewable energy and utilization of demand response (DR) resources [1]. The gradual transformation of the grid and penetration of intermittent energy resources challenge utilities' ability to maintain reliable and economical system operations. Many solutions have been suggested, and among them is microgrid technology, which comes with the promise of integrating renewable resources and improving local system reliability and efficiency [2,3]. Microgrids can also provide valuable grid services, e.g. ancillary services and demand-side management [4]; however, these resources can only contribute significantly to displacing capacity and flexibility of the main grid through aggregation and effective power system management and control. Another important issue is that, the transmission system operator (TSO) has no visibility and control of microgrid resources, and traditionally, the distribution system operator (DSO) also has very limited control over these assets. Further, the small scale and large numbers of diverse assets would push the limits of current control technology. Taking full advantage of services and benefits provided by microgrids will challenge the megagrid; consequently, the operational and planning arrangements within power systems must be revised to support a new distribution system operation paradigm that enables the provision of grid services by microgrids.

To this end, new roles have been proposed for a future DSO within a new DSO construct/paradigm [1,5–7] structured to accommodate microgrids and other prosumers. The DSO is responsible for local ancillary

☆ This work was supported in part by Natural Sciences and Engineering Research Council of Canada (NSERC), Ottawa, ON, through a grant to the NSERC Smart Microgrid Network (NSMG-NET).
* Corresponding author at: Department of Electrical and Computer Engineering, McGill University, Montreal, QC H3A 0E9, Canada.
E-mail addresses: mike.quashie@mail.mcgill.ca (M. Quashie), chris.marnay@mcgill.ca (C. Marnay), francois.bouffard@mcgill.ca (F. Bouffard), geza.joos@mcgill.ca (G. Joós).

http://dx.doi.org/10.1016/j.apenergy.2017.08.015
Received 15 April 2017; Received in revised form 4 August 2017; Accepted 6 August 2017

Please cite this article as: Quashie, M., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.08.015

Nomenclature

Indices and sets

i	index for all energy resources
r	index for reserve
t	index for hour
y	index for years of project lifetime
z	index for demand response (DR)
A	set of existing resources i in the network
B	set of indices for new distributed energy resources (DERs)
$\overline{B}$	set of indices of new DERs except storage
D	set of indices of diesel generating units
G	set of dispatchable generating units
S	set of electrical energy storage (ESS) devices
T	set of indices of time t within a year
W	set of indices of wind power generating units
Y	set of indices of years in the project lifetime J

Parameters

k_z^e	electrical DR energy to power ratio
k_z^h	thermal DR energy to power ratio
v_i	energy to power ratio of storage resource i
w_z^e	percentage of electrical load available for DR
w_z^h	percentage of thermal load available for DR
C^b	budget constraint for resource i
C_i^c	cost per unit capacity of resource i
C_i^f	fuel cost of resource i
C_u	unit cost of purchased energy from utility i
C_i^r	cost of reserved capacity of resource i
$C_y^{\wp}$	cost of carbon allowance per $kgCO_2$ in year y
C_i^m	maintenance cost for resource i
$X_i^{\max}$	maximum power capacity of a new resource i
$P_i^{\max}$	maximum power output of an existing resource i
$P_i^{\min}$	minimum power output of an existing resource i
$L^e(y,t)$	electrical load at time t in year y
$L_y^h(y,t)$	thermal load at time t in year y
$L_y^{e,\max}$	peak electrical load
$L_y^{h,\max}$	peak thermal load
η_i	storage charging and discharging efficiency
ς_i	electric to heat ratio of CHP unit

Microgrid planner level variables

$E_i^e(y,t)$	electrical energy level of ESS i at time t in year y
$P_i^e(y,t)$	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
$P_z^e(y,t)$	electrical output from DR resource z at time t in year y
$P_z^h(y,t)$	thermal output from DR resource z at time t in year y
x_i	capacity of DER assets i

DSO Level variables

R_i	reserve capacity provided by resource i
$P_i^r(y,k,t)$	post-contingency power output of resource i following contingency event k at time t in year y.

service (AS) markets, acting as an interface between the TSO and demand-side or distribution-level market players. Also, operational and planning information or orders are exchanged and coordinated between the DSO and the TSO to ensure the successful operation of local AS markets, while, the DSO may request reserve provision from local retail market agents, including microgrids. A microgrid planner working within this new DSO paradigm faces a dilemma between satisfying the DSO reserve capacity requirement, and pursuing its own interest of minimizing the design and operational cost of its microgrid. To assist microgrid plannners make such difficult choices, researchers have proposed various operational strategies and models. Among these is the market-based mechanism developed by the authors in [8], which enables a *smart microgrid operator* to offer regulation service while meeting the associated obligation of fast response to commands issued by a wholesale market independent system operator (ISO). Furthermore, an energy management tool for next-generation photovoltaic (PV) installations, including storage units, is proposed in [9] to provide flexibility to DSOs. Several microgrid planning models have been proposed in [10–18] to minimize costs and improve reliability, as well as deliver other microgrid benefits. Particularly, a particle swarm optimization approach is proposed in [13] to co-optimize DERs for community microgrids while meeting U.S. Department of Energy (DOE) requirements and state renewable energy mandates.

A reflection of the relationship between the DSO and microgrids at their planning/design stage is needed for an effective operation of microgrids within the new DSO paradigm. Bi–level programming models are well suited to characterize such complex relationships. These models are characterized by two decision makers at different hierarchical levels, each independently controlling only a limited set of decision variables, and each may have single or multiple objectives. The lower level executes its policies after the upper one, considering its decisions; while the higher level optimizes its objective in anticipation of the reactions of the lower level. Further reading on bi-level programming can be found in [19–23]. Within the context of microgrid applications, bi-level models have been proposed by authors in [24–26] to minimize coupled design and operational costs. In [26], the authors propose a microgrid planning and operational problem, nested in the form of a generalized double-shell framework. The outer shell minimizes the microgrid's capital cost, which is aligned with the inner shell's objective of minimizing the operational cost. The aligned objectives of these formulations may not merit a bi-level approach since other mathematical programming models such as multistage or multi-objective planning models are adequate.

This paper proposes a non co–linear bi-level power and reserve planning formulation for the DSO and microgrid planning problems, wherein, a DSO whose duty is to ensure reliable power supply may request reserve capacity from a microgrid planner whose interest is to minimize its planning and operational cost. The proposed formulation can be seen as a classical example of a Stakelberg game where the upper level or leader's problem characterizes the actions of the microgrid planner, and the lower level or follower's problem represents that of the DSO. The proposed model also seeks to establish a better representation of the potentially conflicting relationship between the microgrid planner and a DSO within the new DSO construct.

The rest of the paper is structured as follows: Section 2 provides an overview of the new DSO construct while Section 3 outlines the proposed bi–level formulation and its transformation into a mixed integer linear programming problem (MILP). Section 4 discusses a case study implementation for a Canadian utility network. Section 5 discusses the results obtained and Section 6 provides brief concluding remarks.

2. Overview of the new DSO construct

Given that the likely future power grid will have numerous distribution-level market agents and a matrix of interconnected microgrids, a new DSO construct is required to define new roles for a future DSO as well as clarify the extent to which a DSO can actively contribute to macro system operation. The new construct has the DSO accept