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Hierarchical framework for optimal operation of multiple microgrids considering demand response programs

Mohammad Saeed Misaghian[a], Mohammadali Saffari[a], Mohsen Kia[b], Mehrdad Setayesh Nazar[a], Alireza Heidari[c], Miadreza Shafie-khah[d], João P.S. Catalão[d,e,f,*]

[a] Faculty of Electrical Engineering, Shahid Beheshti University, A.C, Tehran, Iran
[b] Department of Electrical Engineering, Faculty of Engineering, Pardis Branch, Islamic Azad University, Pardis, Tehran, Iran
[c] University of New South Wales (UNSW), Sydney, Australia
[d] C-MAST, University of Beira Interior, Covilha 6201-001, Portugal
[e] INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal
[f] INESC-ID, Instituto Superior Tecnico, University of Lisbon, Lisbon 1049-001, Portugal

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ABSTRACT

This paper proposes a framework for the optimal operation of multi Micro Grids (multiMGs) based on Hybrid Stochastic/Robust optimization. MultiMGs with various characteristics are considered in this study. They are connected to different buses of their Up-Stream-Network (USN). Day-Ahead (DA) and Real-Time (RT) markets are contemplated. The proposed optimization structure in this paper is a bi-level one since both MGs operators' and USN operator's decisions are considered in the proposed model. The advantages of using time-of-use demand response programs on the optimal operation of USN in the presence of multiMGs are investigated. The uncertainty of different components, including wind units, photovoltaic units, plug-in electric vehicles, and DA market price is captured by using stochastic programming. In addition, robust programming is utilized for contemplating the uncertainty of the RT market price. Furthermore, the grid-connected and island modes of MGs' operation are investigated in this paper, discussing also the virtues of utilizing multiMGs over single MG. Finally, IEEE 18-bus and 30-bus test systems are considered for MGs and USN networks respectively to scrutinize the simulation results.

1. Introduction

MicroGrids (MGs) are one of the noticeable solutions for providing reliable electricity in a power system and they comprise loads, Distributed Energy Resources (DERs), including Distributed Generations (DGs), and Energy Storage Systems (ESSs). Moreover, MGs can operate in grid-connected or island modes and a bi-directional power flow with their up-stream network (USN) is practicable [1,2].

MG is an inseparable part of power system research and gains many attentions recently and one of which is its participation in the power markets through bidding. As Renewable Energy Sources (RESs) account for the high percentage of the MGs generation units, intermittent nature associated with them leads to significant uncertainty in the secure operation of MGs [3]. However, Dispatchable DGs (DDGs) are a key solution for tackling this issue in the renewable-based MGs [4]. In this context, Refs. [5–10] scrutinize bidding strategy in the presence of uncertain resources. In Ref. [5], a two-stage stochastic programming for MG bidding is presented, while building thermal dynamics constraints are taken into account. In Ref. [6], a joint active and reactive power market structure is presented, where DERs can offer active and reactive power and uncertainties of wind units and forecasted loads are addressed via stochastic programming. The uncertainty of pool market price is handled by robust optimization in Ref. [7], where optimal bidding strategy for maximizing the profit of a price-taker retailer in the pool market is its main scope. A comparison between stochastic and robust optimization for incorporation of a price-taker producer in the market is performed in Ref. [8]. One of the efficacious approaches for capturing uncertainties in the optimization problems can be a combination of stochastic and robust optimizations methods, which is deployed in Refs. [9,10] and it is called as Hybrid Stochastic/Robust (HSR) optimization approach. A bidding strategy for an electric vehicle aggregator for participating in the Day-Ahead (DA) market is presented in Ref. [9], where the market prices along with their uncertainties are considered by stochastic programming and robust programming is used

* Corresponding author at: INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal.
E-mail address: catalao@ubi.pt (J.P.S. Catalão).

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Nomenclature[1]

Indices

ess	Index of electrical storage systems
i/i_{cu}	Index of dispatchable/conventional generators
i_b	Index of boilers
j	Index of price-elastic loads
k	Index of markets scenarios
n, m	Indexes of buses
mg	Index of MGs
pev	Index of electric vehicles
pv	Index of photovoltaic units
s	Index of scenarios for the uncertainty of RESs and PEVs
t	Index of time periods
t′	Index of TOU time periods, including LTP, OTP, and PTP
th	Index of thermal groups
tss	Index of thermal storage systems
w	Index of wind units

Continuous variables

$D_{jkst}^{P_{PEL}}$	Price elastic load *j* in scenario *ks* at time *t*
$Flow_{nm,kst}$	Active power flow of line connecting bus *n* to bus *m* in scenario *ks* at time *t*
$HD_{tss,kst}/HC_{tss,kst}$	Generated/absorbed power by *tss* in scenario *ks* at time *t*
$H_{i_b,kst}$	Generated heat by boiler i_b in scenario *ks* at time *t*
$P_{(i-pev-ess-w-pv-i_{cu})kst}$	Unit $(i - pev - ess - w - pv - i_{cu})$ active power in scenario *ks* at time *t*
$P\_buy_{kt}^{MG}/P\_sell_{kt}^{MG}$	Buying/selling active power in scenario *k* at time *t* regarding MG
$P_{mg,kst}^{MG}$	Bided power of MG *mg* in scenario *ks* at time *t* from USN point of view
$\delta_{n,kst}$	Voltage angles of bus n in scenario *ks* at time *t*
$\rho_{kt'}^{LTP-DA}$, $\rho_{kt'}^{OTP-DA}$, $\rho_{kt'}^{PTP-DA}$	TOU rates of LTP, OTP, and PTP periods in scenario *k* at time *t′*
$\Delta D_{n,kt}^{DR}$	Demand change of bus *n* in scenario *k* at time *t* after implementing of TOU program
$\Delta\rho_{kt}^{LTP}$, $\Delta\rho_{kt}^{OTP}$, $\Delta\rho_{kt}^{PTP}$	Price change in LTP, OTP, and PTP periods in scenario *k* at time *t*

Constants

D_t^{elec}	Total electric load at time *t*
$D_t^{0-elec-USN}$	Initial demand of USN at time *t* before implementation of TOU program
$D_t^{P_{fix}}$	Fixed load at time *t*
$D_{jt}^{P_{PEL}^{\min}}$	Minimum consumption of PEL *j* at time *t*
$D_{(th),t}^{thermal}$	Thermal demand of group thermal *th* at time *t*
DRP^{up}/DRP^{down}	Parameters in range of [0,1]
$e_{tt'}$	Cross elasticity coefficient, showing elasticity for load alteration at time *t* due to price change at time *t′* in TOU program
$P\_buy_{kt}^{MG-ACC}/P\_sell_{kt}^{MG-ACC}$	Accepted values of buying/selling active power bids in scenario *k* at time *t* regarding MG
$x_{n,m}$	Reactance of line connecting buses *n* to bus *m*
$\alpha_{mg,t}$, $\beta_{mg,t}$, $\lambda_{mg,t}$	Bidding quadric function cost coefficients of MG *mg* function at time *t* in USN
ρ_{kt}	Price of active power market in scenario *k* at time t
$\mu_{jt}^{\max}$	Maximum bidding price of PEL *j* at time *t*
ϑ_{jt}	Price elasticity of PEL *j*
ψ_{kt}	RT market price deviation fromρ_{kt}^{RT} in scenario *k* at time *t*
Γ_k	Robust control parameter in scenario *k*
$\pi_{k/s}$	The probability of scenarios *k*/*s*
λ^{PEL}	Contribution coefficient of PELs
λ^{fix}	Contribution coefficient of fix loads
ξ_i	Waste heat factor of CHP unit *i*

for capturing the uncertainty of driving requirements. In Ref. [10], an HSR optimization is exploited for MG bidding strategy, where the uncertain behavior of Real-Time (RT) market price is coped by robust optimization and the uncertainty associated with other parameters are captured via stochastic optimization.

By increasing the number of MGs in the power system, multiple MGs may connect to a distribution system, which causes new challenges for the Independent System Operator (ISO). According to Ref. [11], separating the distributed system into several MGs results in improvement of the reliability and the operation of the distribution system. The optimization of multiMGs has been investigated in recent articles [12–16]. In Ref. [12], a bi-level framework is proposed for optimal operation of an active distribution system, where multiMGs exist and the cooperation between distribution company and multiMGs is considered. An innovative control strategy is presented in Ref. [13], where its optimization framework consists of two levels and the distribution network optimization is considered in the upper level and the MGs optimization is done in the lower level. In Ref. [14], an innovative structure is proposed for multiple independent MGs that are connected to a common point to operate optimally in both normal and fault-occurred conditions. A dynamic Energy Management (EM) strategy is presented in Ref. [15], where multiMGs and an active distribution system are considered and its novelty centers at EM, while large-scale RESs in active distribution systems exist. An optimal DA EM problem for multiMGs with assorted DERs and participation of electric vehicles is presented in Ref. [16], where a new probabilistic index is introduced for evaluating the result of EM in the presence of uncertainty. In Ref. [17], a scheduling problem for multiMGs on a daily basis along with a new EM system is introduced and the effect of Demand Response (DR) on them is investigated. Overall, the aforementioned papers mainly have addressed the EM problem and the interaction between MGs and active distribution system in order to minimize the total costs, however, they lack analyzing the bidding procedure of multiMGs, while the MG Operators' (MGOs) decisions about biddings and the USN Operator's (USNO's) decisions about accepting or rejecting the received bids are considered.

Another point to be mentioned is the pivotal role of DR programs in the optimal operation of the power system [17–22]. A short-term n-1 contingency Security Constrained Unit Commitment (SCUC) problem is presented in Ref. [18], where the incorporation of DR providers in the wholesale electricity market for supplying reserve is considered. The application of time-of-use (TOU) programs in the n-1 contingency SCUC problem is investigated in Ref. [19]. A flexible n-1 contingency SCUC is proposed in Ref. [20], where the uncertainty of wind turbines is taken into account and TOU scheme is considered. A maximization of social welfare by considering a full model of price elastic loads (PELs) is presented in Ref. [21], where the energy and spinning reserve markets are considered and demands have the capability to bid in them. In Ref. [22], a model for the optimal operation of MG is presented, where new

[1] Superscript max/min and C/D with any of the above notions stand for the maximum/minimum value and charge/discharge status of the corresponded symbol, respectively. In addition, superscript DA/RT with any of the above symbols presents the value of them in the Day-Ahead and Real-Time periods. Also, the superscript USN with any of the above symbols demonstrates that it is used in up-stream network. Set• runs from 1 to *N*.