Electric Power Systems Research 163 (2018) 164–173

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Privacy-preserving optimal scheduling of integrated microgrids

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ARTICLE INFO

Keywords:
Distributed energy resources
Grid-connected operation
Integrated microgrids
Islanded operation
Privacy-preserving optimal scheduling

ABSTRACT

The increasing penetration of microgrids in distribution networks, as a viable option for end-use customers to increase load-point reliability and power quality, will result in formation of many interconnected microgrids in a not so far future. This paper considers a case in which multiple microgrids are geographically close and electrically connected, and studies anticipated interactions among these microgrids and also between the microgrids and the utility grid, during grid-connected and islanded operation modes. A model for the optimal scheduling of integrated microgrids is further proposed. The model is first developed with the objective of minimizing the aggregated operation cost and is accordingly decomposed into individual optimal scheduling problems using the Lagrangian relaxation method to take prevailing privacy issues into account. The microgrids capability in operating in the islanded mode for multiple hours is scrutinized by a T–τ islanding criterion. Numerical simulations exhibit the merits and the effectiveness of the proposed model via simulations on a system of integrated microgrids.

1. Introduction

Microgrids, as small-scale power systems integrating various types of distributed generators (DGs), controllable loads, and distributed energy storage (DES), are significantly deployed over the past few years and are anticipated to grow more in the near future. Microgrids improve the overall system security, resiliency, and load-point reliability and further address challenges related to economics and environmental concerns by enabling the utilization of emission free renewable DGs, such as solar photovoltaic (PV) and small wind turbines [1–4]. Microgrids are capable to be fully islanded from the utility grid during upstream disturbances, which is recognized as the microgrids' most significant feature. This feature enhances the load-point reliability for the local customers and provides considerable societal cost savings [5–8]. This growing penetration will result in emergence of networks of microgrids, which not only exchange power during the grid-connected mode, but could also provide support for other microgrids during the islanded mode. This integration can potentially provide considerable benefits for the system and also for individual customers, including (1) reducing the system aggregated operation cost and customer electricity payments, (2) reducing power losses at the distribution level and increasing energy efficiency, (3) reducing potential load curtailments during islanded operation, and (4) supporting renewable generation integration.

Several studies on integrated microgrids, which are also commonly called interconnected microgrids, networked microgrids, or microgrid clusters, can be found in the literature. The application of the game theory in managing the operation of integrated microgrids was discussed in Refs. [9,10]. In Ref. [11] two microgrids were integrated and tested using the HOMER software. In Ref. [12], an optimization problem was studied based on model predictive control for a network of microgrids. The study in Ref. [13] solved an off-line optimization problem and proposed a distributed algorithm for the optimal off-line energy management solution of integrated microgrids. The study in Ref. [14] proposed a method of joint optimization and distributed control of integrated microgrids. In Ref. [15] a distributed optimization method for generation scheduling of integrated microgrids using the alternating direction method of multipliers was proposed. A modeling framework for estimating the power exchange capability between the integrated microgrids and a distribution network was developed in Ref. [16]. The study in Ref. [17] proposed a technique based on recurrent neural network to achieve optimal operation of a microgrid connected to the utility grid. From the perspective of cybersecurity and resilience studies in integrated microgrids, a cyber-network communication system was proposed for multiple microgrids in Ref. [18]. In Ref. [19], the interactions between distribution network operation and integrated microgrids were characterized. In addition to cybersecurity and resilience, state estimation was implemented in integrated microgrids in Ref. [20]. A multi-microgrid state estimation and fuzzy state estimation were presented in Ref. [21], aiming to study the increase of microgeneration

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https://doi.org/10.1016/j.epsr.2018.06.007
Received 14 November 2017; Received in revised form 13 May 2018; Accepted 8 June 2018

Nomenclature

Indices

ch	Superscript for energy storage charging mode
d	Index for loads
dch	Superscript for energy storage discharging mode
i	Index for DERs
s	Index for scenarios
t	Index for time
m,n	Index for microgrids

Sets

A	Set of all DERs
D_A	Set of adjustable loads
G	Set of dispatchable units
T_K	Set of intra-hour time periods
M	Set of microgrids
N	Set of scenarios
S	Set of energy storage systems
T_T	Set of inter-hour time periods

Parameters

c	Generation marginal cost
DR	Ramp down rate
DT	Minimum down time
E	Load total required energy
MC	Minimum charging time
MD	Minimum discharging time
MU	Minimum operating time
U	Islanding state (0 when islanded, 1 otherwise)
UR	Ramp up rate
UT	Minimum up time
γ	Step size for Lagrangian multiplier update
ρ	Market price
λ	Connected microgrid power exchange price
α, β	Specified start and end times of adjustable loads
η	Energy storage efficiency
μ	Penalty coefficient
υ	Value of lost load
Ψ	Probability of islanding scenarios

Variables

C	Energy storage available (stored) energy
D	Load demand
I	Commitment state of dispatchable units (1 when committed, 0 otherwise)
LS	Load curtailment in islanded operation
P	DER output power
P^M	Utility grid power exchange
P^G	Power exchange with the connected microgrid
SD	Shut down cost
SU	Startup cost
T^{ch}	Number of successive charging hours
T^{dch}	Number of successive discharging hours
T^{on}	Number of successive ON hours
T^{off}	Number of successive OFF hours
τ	Time period
u	Energy storage discharging state (1 when discharging, 0 otherwise)
v	Energy storage charging state (1 when charging, 0 otherwise)
z	Adjustable load state (1 when operating, 0 otherwise)

penetration in distribution network through the exploitation and extension of the microgrid technology. Control problems of integrated microgrids were studied in Refs. [22–28]. A study to assess the merits and drawbacks of the integrated microgrids using multi-criterion decision aids was presented in Ref. [22]. Advanced control functionality to manage the increased penetration of DGs, DES, and active loads under microgrid and integrated microgrids concepts were presented in Ref. [23]. The study in Ref. [24] described a method for tertiary control level for load sharing. A real-time tertiary control algorithm for DC microgrid clusters with high penetration of renewable DGs is implemented and developed in Ref. [25]. In Ref. [26], a strategy for designing a communication and control infrastructure in a distribution system based on the virtual microgrid concept was presented. In Ref. [27], a new decentralized control scheme for managing integrated microgrids through self-organization, and decentralized scheduling and dispatch was proposed. Distributed control schemes were presented and tested in [28] for integrated low-voltage DC microgrids. Research focusing on the compromise between reliability and cost in integrated microgrids was discussed in Refs. [29–32]. In Ref. [29], the concept of integrated microgrids was discussed and the question of how to dispatch the integrated microgrids in a distribution system was raised. The small signal modeling and stability issues in DC microgrids and integrated DC microgrids was addressed in Ref. [30]. Modular-architecture microgrids were discussed in Ref. [31] to assure reliability, expansibility, and controlled cost in integrated microgrids. In Ref. [32], a probabilistic Monte Carlo based iterative methodology for the optimal planning of integrated microgrids was applied to a six-microgrid system operating in the islanded mode. A promising type of integrated microgrids, called provisional microgrids, was put forward and discussed in detail in Refs. [33–35]. As provisional microgrids do not have the ability to be islanded on their own, they will transfer power from coupled microgrids in the islanded mode. Many studies were made in the literature on the optimization of integrated microgrids. In Ref. [36], an algorithm for multi-objective optimal power flow was used, and decentralized power dispatch model was described in Ref. [37]. The study in Ref. [38] dealt with potential benefits from individual and integrated microgrids in terms of economy, loss avoidance, and emissions reduction, using electricity market prices, with different renewable generation penetration levels. The study in Ref. [39] presented an integrated energy exchange scheduling for a multi-microgrid system under a pricing strategy using adjusted prices, and further proposed a decentralized optimal scheduling strategy for the microgrid central controller to minimize the microgrids operation cost and satisfy the consumers' needs. The study in Ref. [40] developed a joint energy trading and scheduling strategy for integrated autonomous microgrids. In addition, it designed an incentive mechanism using Nash bargaining theory and investigated the possible interaction among the integrated microgrids. An optimal economic dispatch strategy utilizing a genetic algorithm was proposed in Ref. [41] for two integrated microgrids that are connected with a single energy storage system. The objective is to minimize the operation cost and find the optimal production of the distributed generators. In Ref. [42] a distributed mechanism for energy trading between the integrated microgrids was proposed in a competitive market based on a game-theoretic analysis, where the proposed game-theoretic strategy provides incentives for energy trading between the integrated microgrids. The study in Ref. [43] proposed a stochastic and probabilistic modeling framework to minimize the operation cost of each microgrid in a multi-microgrid system, and utilized the particle