Applied Energy 162 (2016) 40–48

Contents lists available at ScienceDirect

Applied Energy

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

Coordinated dispatch in multiple cooperative autonomous islanded microgrids

Xinli Fang [a,c,d], Qiang Yang [a,*], Jianhui Wang [b], Wenjun Yan [a]

[a] College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China
[b] Decision and Information Sciences Division, Argonne National Laboratory, USA
[c] Hangzhou Huachen Electric Power Control Co. Ltd., Hangzhou 310014, China
[d] Huadong Engineering Co. Ltd., Hangzhou 310014, China

HIGHLIGHTS

- We exploit the coordinated energy dispatch across multiple autonomous microgrids and present an algorithmic solution.
- Key metrics are included into consideration in optimizing MG operation and DG utilization.
- The solution keeps supply–demand balance through adaptively identifying appropriate mappings between DGs and loads.

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 8 October 2015
Accepted 9 October 2015
Available online 11 November 2015

Keywords:
Cooperative control
Autonomous microgrids
Network topology matrix
MST
LMI

ABSTRACT

As various forms of renewable distributed generators (DGs) embedded in microgrids (MGs) often exhibit unstable characteristics, matching the generation to the demand whilst optimally utilizing the DGs is a non-trivial task. This paper investigates the optimal coordinated operation of multiple autonomous MGs and reveals the potential technical benefit. The proposed solution identifies the optimal network topologies and allocates the critical loads (CLs) to appropriate DGs based on the minimum spanning tree (MST) algorithm with power loss and reliability considerations. The non-critical loads (NLs) are determined to be supplied by the MGs based on the Linear Matrix Inequality (LMI) approach, which effectively improves the global utilization efficiency of DGs. Through the event-driven resource reallocation across multiple cooperative MGs, the dynamic balance between the power generation and demand can be attempted. The proposed approach is verified by using the IEEE 33-bus network model and its performance and scalability are further assessed through a large-scale IEEE 300-bus network scenario. The numerical results confirm that the suggested cooperative control of multiple MGs can effectively promote the capability of secure power supply to CLs, and simultaneously improves the global utilization efficiency of DGs significantly, even without any energy storage in the network.

1. Introduction

With the penetration of a massive number of small-scale distributed generators (DGs) (e.g., wind turbines and photovoltaic equipments) into the current medium/low voltage power distribution networks, a new form of power supply paradigm, i.e. microgrid (MG), emerges. MGs can be flexibly operated in conjunction with the power utility or in an autonomous mode where the power demand is expected to be met by the DGs [1]. MGs have been adopted with renewable DGs to promote the power supply reliability with reduced cost. However, the power output of wind and solar based generators exhibits non-deterministic and intermittent characteristics due to the local meteorological factors [2]. It also has been recognized that the current operated MGs may not have adequate energy storage system (ESSs) with appropriate location and capacity [3]. In addition, MGs need to operate in an autonomous mode under certain circumstances, e.g. no power supply from the power utilities upon network outage due to cascading failures or nature disasters, and the places without power utility infrastructures (e.g. offshore islands). Not surprisingly, this may directly undermine the performance of power supply in autonomous MGs in many aspects: the CLs which need to operate at their power ratings may have to be curtailed without stable power supply; it may also happen that within the individual MGs, the DGs generate more power than their own demands and the excess energy cannot be utilized by neighboring MGs. This imposes an urgent technical challenge that the cooperative operation across

* Corresponding author. Tel.: +86 151 6713 8974; fax: +86 571 8795 1625.
E-mail address: qyang@zju.edu.cn (Q. Yang).

http://dx.doi.org/10.1016/j.apenergy.2015.10.076
0306-2619/

Nomenclature

P_{CLs}	the supplied CLs
P_{NLs}	the NLs, which can be supplied or shed flexibly at any time during MG operations
$P_{DG\_\min}, P_{DG\_\max}$	the upper and lower bounds of DG capacity
$U_{\min}, U_{\max}$	the upper and lower voltage limits of node i and U_i is node voltage
p_i, q_i	the injected active and reactive power of node i
$p_{DG\to i}, q_{DG\to i}$	the injected active and reactive power from DG to node i
P_j, Q_j	the active and reactive loads of node i
Y	the admittance matrix
$\sum \omega_{\forall(DG\to CL)}(t)$	the weight sums from any DG to any CL at time t

multiple autonomous MGs needs to be studied such that the global resource utilization efficiency and energy security of the power distribution network encompassing multiple MGs can be optimized at the network level.

In autonomous MGs, it is important to keep generation-demand balance whilst guarantee the power supply security to CLs with economical benefits maximization (e.g. [4]). In the literature, much research effort has been made to address this technical challenge (e.g. [5–17]. The authors in [5] presented a multi-agent system (MAS) based solution to coordinate the operation of islanded MGs in the power market context. However, the operational complexity as well as the network reinforcement cost imposed by this control structure can be prohibitive for large-scale networks as a large number of control devices need to be embedded to fulfill the management functionalities. In [6], the authors investigated the economical and environmental benefits and presented a cost minimization based optimization approach to appropriately coordinate a large number of MG components, but without including the crucial network operational metrics, e.g., system reliability, power loss, into the optimization process. In [7], the "token ring" algorithm was proposed to acquire the DG operational details so as to carry out the optimization tasks for MG operations. In fact, the operational information can be inaccurate or even unavailable due to the lack of a sufficient number of high performance electronic power processors (EPPs), which can significantly deteriorate the effectiveness of this solution. Inspired by the Tree Knapsack Problem (TKP), the authors in [8] followed the similar line of research and proposed a strategy based on the islanded division model to optimize the design of MG control structure. These attempts have been carried out merely based on the knowledge of physical network topologies without considering the operational characteristics of the power network. In parallel, an autonomous division strategy of power distribution network with DGs was proposed for enhancing system operation and self-healing capability [9], but again the operational aspects have not been assessed. In addition, the authors in [10] proposed an optimal cooperative design solution for MGs with distributed wind and PV generators. The studied network scenario considers the fuel based energy storage devices, and thus the potential benefits of cooperative operation cannot be clearly identified. Most recently, the authors in [11,12] presented the smart grid design solutions with the focus on improving the self-healing capability and power security in network planning based on the heuristic Tabu Search (TS) algorithm. Such design solutions are carried out offline due to the computational complexity and searching uncertainties, and hence they are suitable for network planning tasks, rather than optimizing the network performance during operation. These previous results have confirmed our intuition that the power supply reliability and DG energy utilization in multiple autonomous MGs can be significantly promoted by appropriately coordinating their operations in a cooperative fashion, even without sufficient energy storage facilities and hardware devices running complex control applications. In [13], an energy management approach for a residential grid-tied microgrid was proposed to control energy exchange through a battery system, but its performance firmly relied on the storage capacity and prediction of state-of-charge (SOC). In [14], the issue of simultaneous energy supply and demand planning in microgrids was addressed through a rolling horizon optimization based approach. In addition, [15] carried out the study in realistic residential microgrids considering both electrical and thermal storage devices, and [16] reviewed the optimization techniques and considerations in microgrids with hybrid energy systems. In [17], the authors developed a modified simulated annealing triple-optimizer for energy management considering the electricity prices, which provided an optimal or sub-optimal solution with limited computation efforts. However, the aforementioned studies of energy dispatch and operational optimization have restricted the view to either individual or small-scale microgrids, which have not explored the potential benefits of coordination across multiple operational MGs.

This paper attempts to address this technical challenge in the context of interconnected autonomous MGs and exploit the potential benefits of leveraging the dynamics of renewable DGs and demands by coordinating multiple MGs through a cooperative energy dispatch solution. The key technical contributions made in this paper can be summarized as follows: (1) we exploit the coordinated energy dispatch across multiple autonomous MGs embedded with different forms of intermittent renewable DGs, and present a cost-effective algorithmic solution which can be adopted in practice with minimal deployment hurdles; and (2) a set of key operational metrics, e.g. power loss and system reliability statistics, are explicitly incorporated into the MG operation optimization to promote the level of DG utilization efficiency and demand supply security. In this work, aiming to directly quantify the potential benefits of cooperative dispatch across multiple MGs, distributed energy storage units, e.g. ESS, are not explicitly included into consideration. The basic idea behind this proposed approach is to optimally match the DG generation to the demands through adaptive mapping between DGs and critical demands with optimized power loss and supply reliability. In this paper, we consider that a number of small-scale winds and photovoltaic based DGs are embedded in the MGs and evaluate the presented control approach for a range of network operational scenarios by using two standard models (IEEE 33-bus and 300-bus networks) through a set of numerical simulation experiments.

The remainder of the paper is organized as follows: Section 2 formulates the optimization problem of multiple cooperative autonomous MGs; Section 3 explains the details of the proposed algorithmic solution and considerations; the numerical simulation results are presented and analyzed in Section 4; followed by Section 5 giving a set of additional remarks inspired by our observations; finally, the conclusions and future research directions are presented in Section 6.

2. Problem formulation and optimization model

This section presents the problem formulation and preliminaries before presenting the proposed control solution. When a MG is operated in the autonomous mode, the demand can only be