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A cooperative game approach for coordinating multi-microgrid operation within distribution systems

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HIGHLIGHTS

- A coalitional operation model for multiple microgrids to achieve global optimum.
- A cost allocation method from cooperative game theory to achieve local optimum.
- A linearized optimal power flow with voltage constraints to realize cooperation.
- The economy benefits of multi-microgrid cooperation are simulated and analyzed.

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ABSTRACT

This paper focuses on simulating the potential cooperative behaviors of multiple grid-connected microgrids to achieve higher energy efficiency and operation economy. Motivated by the cooperative game theory, a group of individual microgrids is treated as one grand coalition with the aim of minimizing the total operation cost. Next, given that each microgrid operator is an independent and autonomous entity with the aim of maximum self-interest, a cost allocation method based on the concept of core in the cooperative game is implemented to ensure a fair cost share among microgrid coalition members, which guarantees the economic stability of the coalition. Considering the combinatorial explosive characteristic of the cost allocation problem, Benders Decomposition (BD) algorithm is applied to locate the core solution with computational efficiency. In addition, since microgrid coalition is formed at the distribution system level, network losses is not negligible. After considering network losses, the coalition operation model of multi-microgrid becomes an optimal power flow problem. A linearized optimal power flow for distribution (LOPF-D) model is applied instead of the conventional ACOPF model to reduce computation burden, meanwhile maintaining adequate accuracy. Case studies on standard IEEE systems demonstrate the advantages of multi-microgrid cooperation and the robustness of the formulated grand coalition. In addition, comparisons with the conventional ACOPF model verifies the high performance of the proposed LOPF-D model.

1. Introduction

The worldwide energy and environmental crisis has led to the large-scale development of renewable energy sources (RES) and distributed energy resources (DER), which in return has brought microgrid technology under spotlight in the power industry. A microgrid is a small-scale electric power system which contains distributed resources and load, and can operate in either grid-connected mode or islanded mode [1]. Currently, emerging new types of demand-side resources have been spotted in microgrids, including electrical vehicles, air conditioning loads, and refrigerators, which add considerable flexibility to microgrid operation. The advantages of integrating microgrids into distribution systems are multifold: first, the DER units that reside in a microgrid can support the local energy demand, hence reduces its reliance on the upper-level utility grid and enhances the reliability of power supply; second, it follows that microgrid facilitates environmentally-friendly energy consumption by utilizing renewable energy-fueled generators, i.e., wind turbines, photovoltaic panels, and fuel cells; last but not least, by supplying the energy demand via local distributed generators (DGs), microgrid can reduce long-distance transmission loss, as well as the

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Nomenclature

$\pi_P(t)$, $\pi_Q(t)$	active/reactive power exchange price between distribution system and transmission system at interval t, in \$/MWh
$P_{grid}(t)$	active power exchange (power flow at PCC) at time interval t, in MW
$Q_{grid}(t)$	reactive power exchange (power flow at PCC) at time interval t, in MW
$P_{MT,m}(t)$	micro turbine generation of the m^{th} microgrid at time interval t, in kW
C_{gas}	fuel cost of micro turbine, in \$/kWh
η_{MT}	efficiency of micro turbine
P_{MT}^{min},P_{MT}^{max}	lower and upper bound of micro turbine, in kW
P_b^{min},P_b^{max}	lower and upper bound of boiler, in kW
ν_h	heat to electricity ratio of micro turbine
$S_{th,m}(t)$	energy level of thermal energy storage in m^{th} microgrid at time interval t, in kWh
$S_{th,m}^{cap}(t)$	capacity of thermal energy storage in m^{th} microgrid at time interval t, in kWh
$S_{th,m}^{min}(t)$	minimum energy level of thermal energy storage in m^{th} microgrid at time interval t, in kWh
$P_{th,m}(t)$	charge/discharge rate of thermal energy storage in m^{th} microgrid at time interval t, in kW
η_h	charge/discharge efficiency of thermal energy storage
$P_{b,m}(t)$	boiler generation of the m^{th} microgrid at time interval t, in kW
$P_m^D(t)$	electrical load of the m^{th} microgrid at time interval t, in kW
$p_{Load,m}^h(t)$	thermal load of the m^{th} microgrid at time interval t, in kW
$P_{PV,m}(t)$	PV generation of the m^{th} microgrid at time interval t, in kW
$P_{WT,m}(t)$	wind turbine generation of the m^{th} microgrid at time interval t, in kW
$P_{solar,m}(t)$	thermal solar energy of the m^{th} microgrid at time interval t, in kW
$P_i^D(t)$,$Q_i^D(t)$	active/reactive load at bus i in distribution system at time interval t
$P_i^G(t)$,$Q_i^G(t)$	active/reactive generation at bus i in distribution system at time interval t
$r_k(r_{ij})$, $x_k(x_{ij})$	the resistance and reactance of the k^{th} line in the distribution system
$P_{L_k}(t)$,$Q_{L_k}(t)$	active and reactive power flow on the k^{th} line in the distribution system at time interval t
$P_{Loss}^{L_k}(t)$,$Q_{Loss}^{L_k}(t)$	active and reactive line loss on the k^{th} line in the distribution system at time interval t
$\partial P_{Loss}^{L_k}/\partial P_i^G$,$\partial P_{Loss}^{L_k}/\partial Q_i^G$	active loss factor of the k^{th} line to the i^{th} bus generation
$\partial Q_{Loss}^{L_k}/\partial P_i^G$,$\partial Q_{Loss}^{L_k}/\partial Q_i^G$	rective loss factor of the k^{th} line to the i^{th} bus load
$V_i(t)$	voltage magnitude of bus i at time interval t, in p.u.
V_i^{min},V_i^{max}	lower and upper voltage level of bus i, in p.u.

investment on large-scale transformers and transmission lines.

Most recently, with the increasing penetration of renewable energy into power systems, the concept of multi-microgrid (MMG) comes up on the stage, which refers to a cluster of microgrids connected with each other in close electrical or spatial distance [2,3]. The aim of MMG is to achieve resilience and stability via fast power exchange and to further obtain a high and smooth penetration of DERs into the bulk system. Possible architectures for multi-microgrid regarding layout and interfaces accompanied by cost and reliability analysis are discussed in [4]. To achieve a coordinated penetration of multi-microgrid into the bulk power system, a hierarchical control strategy is proposed in [5,6], which includes the primary droop-control of power electronic devices, the secondary control for voltage/frequency restoration and synchronization, and the tertiary control of real and reactive power. The last one is in association with microgrid energy management system, and can be formulated as an economic dispatch problem with the aim of maximizing economic profit.

The focus of this paper lies in the tertiary control level of a multi-microgrid system. In retrospect, existing works mainly cover two topics related to this field: planning and operation. In terms of the former, Ref. [7] applies the Decision-Tree (DT) method to plan the capacities of energy storage devices within microgrids to realize local power balance; Ref. [8] includes the coupling physical and operational constraints of electrical and heating/cooling networks for multi-energy microgrids in the design of the capacities of DER units; Ref. [9] combines both DER sizing and placement problems into one mixed integer linear programming, where microgrid is modeled as a multi-node system instead of an aggregated single-node model to better consider power flow and heat flow balances.

With regard to operation, existing research works mainly adopt two approaches to coordinate MMG economic dispatch: the centralized approach and the decentralized approach. The main idea behind the centralized optimization method is to aggregate all the entities into the system as one unity with a collective objective. In the case of multi-microgrid coordination, a central controller is selected (i.e. distribution system operator, DSO) to organize the operation of all the DGs and loads regardless of their individual interests. In this aspect, Ref. [10] establishes a centralized control model of a group of microgrids that can exchange power with their neighbors, where the objective is to maximize the total profit of all microgrid operators. Simulation results indicate that local energy exchange improves individual operation economy by making full use of the zero-cost renewable energy. In [11], the interactions between the upper-level distribution system and the multi-microgrid system are further considered, and the DSO is included as an additional independent entity in MMG coordination. To decrease model complexity and improve computational efficiency, decentralized dispatch methods have been applied in [12,13], where the global optimization model is decomposed into several independent sub-problems using Lagrange relaxation method and solved by local entities. Model predictive control (MPC) scheme is implemented in [14,15] in a distributed manner to address the uncertainties of load and renewable energy within the microgrids and to maintain a steady power exchange with the rest of the distribution system. The authors in [16,17] explore the optimal risk-constrained bidding strategies of microgrids for providing ancillary service to the utility grids using decentralized and centralized approaches, respectively.

There exist some challenges with the above conventional models [18]: in the centralized method, since it requires full communication among all entities within the entire network, it is not scalable, especially not suitable for plug-and-play DERs like electrical vehicles; in the decentralized method, since local entities independently work on their own optimal dispatch schedule without the information from other entities, this complete isolation from the rest of the system usually cannot reach global optimum. In summary, the centralized method has a simple implementation to realize global optimum, while the decentralized method focuses on local optimum. Nevertheless, there remains some gap between the two goals, which may sabotage the coordinated operation of the multi-microgrid. The reason is that each microgrid is a highly independent and profit-driven entity with the goal of maximizing its self-interest. Thus conflicts of interests between the local microgrid (local optimum) and the system operator (global optimum) may drive microgrid away from coordination.

The motivation of this work is to address the above mentioned concerns between global optimum and local optimum. In this paper, we