Energy management of cooperative microgrids: A distributed optimization approach

Tian Liu¹, Xiaoqi Tan¹, Bo Sun¹, Yuan Wu², Danny H.K. Tsang³

¹ Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong
² College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, China

ARTICLE INFO

Keywords:
Cooperative microgrids
Distributed energy resources
Direct energy exchange network
Distribution networks
Distributed algorithms

ABSTRACT

The cooperation of multiple networked microgrids (MGs) can alleviate the mismatch problem between distributed generation and demand and reduce the overall cost of the power system. Energy management with direct energy exchange among MGs is a promising approach for improving energy efficiency. However, existing methods on microgrid cooperation usually overlook the underlying distribution network with operating constraints (e.g., voltage tolerance and power flow constraints). Hence the results may not be applicable to actual systems. This paper studies the energy management problem of multiple MGs that are interconnected by both the direct current (DC) energy exchange network and the alternating current (AC) traditional distribution networks. In our problem, each MG is equipped with renewable energy generators as well as distributed storage devices. In order to handle the non-convex power flow constraints, we exploit the recent results of the exact optimal power flow (OPF) relaxation method which can equivalently transform the original non-convex problem into a second-order cone programming problem and efficiently determine the optimal solution successfully. The objective of our problem is to minimize the overall energy cost in a distribution network consisting of multiple MGs, with the practical operating constraints (e.g., power balance and the battery’s operational constraints) explicitly incorporated. Considering the privacy and scalability, we propose a distributed algorithm with convergence assurance based on the alternating direction method of multipliers (ADMM). We also implement our method based on the model predictive control (MPC) approach in order to handle the forecasting errors of the renewable energy generation. Simulations are made for different MG exchange topologies on three radial distribution network testbeds. Numerical results demonstrate that certain topologies are more favorable than others, and the cooperation strategy for the energy exchange is significantly affected by the MGs’ locations in the distribution network.

1. Introduction

1.1. Motivation and Methodology

Microgrids (MGs) are localized grids which accommodate a variety of distributed energy resources (DERs) and different types of energy users. They are believed to be a promising paradigm that can improve the utilization of DERs and also users’ benefits [1]. However, in order to ensure the stability and reliability of MGs, many tough problems need to be resolved, among which, the mismatch between the distributed generations and loads due to the intermittent nature of DERs (e.g., photovoltaic (PV) generators and wind turbines (WT)) is a key issue and draws lots of attention. In order to handle this, several approaches can be employed.

One solution is to take advantage of distributed storage (DS) devices (e.g., batteries), which however suffer from two drawbacks: a huge capital investment increases dramatically with DS capacities, and significant energy transfer loss occurs due to the inefficiency of charging and discharging processes. Therefore, relying solely on DS units is not enough. Another promising solution is the direct energy exchange among neighboring and cooperative MGs by dedicated energy exchange network (denoted as EEN hereinafter). An EEN is composed of direct power lines connecting a cluster of geographically correlated MGs, enabling energy sharing and trading among them [2]. By exploiting the diversified distributed generation and consumption profiles, EENs have the following advantages: first, reduced power transmission loss thanks to the short distance between MGs, and second, lower energy bills for the MGs because the internal energy trading price is higher than the buyback price, while lower than the selling price of the utility company [3,4]. Thanks to these advantages, MGs will have enough incentives to...
Nomenclature

Abbreviations

\( (\cdot)^i, (\cdot)^f \) local, consensus variables
\( cp, np \) coupling, non-coupling variables
AC alternative current
ADMM alternating direction method of multipliers
DC direct current
DER distributed energy resource
DS distributed storage
EEN energy exchange network
LAO local area operator
MG microgrid
MPC model predictive control
OPF optimal power flow
PCC point of common coupling
PV photovoltaic
TOU time-of-use
WT wind turbines

Functions

\( C^{ES}_i (\cdot) \) battery’s operational cost
\( C_i (\cdot) \) battery’s operational cost
\( C^t_i (\cdot) \) total energy purchase cost

Index

\( i \) index of bus (node)
\( i_0 \) index of parent bus of \( i \)
\( i_n \) bus index of MGs in distribution networks
\( k \) index of iteration
\( m, n \) index of MGs
\( t \) index of time

Parameters

\( \Omega^i, \Omega^t_n \) constraint sets for consensus and local variables for MGs
\( \Omega_{\text{LAO}}, \Omega_{\text{LAO}}^t \) constraint sets for consensus and local variables for LAO
\( \Delta \) duration of a time slot

\( \eta \), \( h \) charging and discharging efficiencies
\( \delta \) branch set
\( \mathcal{N} \) node set
\( \mathcal{M} \) set of MGs
\( \mathcal{N}^i \) index set of MGs
\( \mathcal{T} \) tree representation of distribution networks
\( \mathcal{N}^i \) index set of MGs in distribution networks
\( \omega \) weighting factors
\( \mathcal{T}_L, \mathcal{T}_U \) upper and lower bounds for storage level at the end of the time horizon

\( E^{ES}_{inj}, E^{ES}_{rp} \) upper and lower bounds of energy storage
\( P^{inj}, P^{rp}_{\text{upper}}, P^{rp}_{\text{lower}} \) charging and discharging power limits
\( \mathcal{T}_L, \mathcal{T}_U \) upper and lower bounds of squared magnitude of bus voltage
\( H \) total number of time slots
\( N \) number of microgrids
\( N_t \) set of the children buses
\( P_{\text{nE}} \) renewable energy generation
\( P_{\text{TOU}} \) TOU price
\( r_{\text{og}, \text{nE}} \) line resistance between \( M_{\text{og}} \) and \( M_n \)
\( S^{A}_{\text{inj}}, P^{A}_{\text{inj}}, Q^{A}_{\text{inj}} \) apparent, active and reactive loads
\( U_{\text{inj}, \text{r}}, U_{\text{inj}, \text{g}} \) sending end transmission voltage between \( M_{\text{og}} \) and \( M_n \)
\( z_{\text{r}, \text{r}}, z_{\text{r}, \text{g}}, z_{0} \) impedance, resistance and reactance of branch
\( K \) number of branches

Variables

\( X^{(1)} \) vector of decision variables
\( X^{(1)}_{\text{cp}}, X^{(1)}_{\text{np}} \) vector of coupling, non-coupling variables for LAO/MG
\( E_{\text{nE}} \) remaining energy in the battery
\( I_{\text{inj}}, I_{\text{rp}} \) branch current
\( l_{\text{inj}}, l_{\text{rp}} \) squared magnitude of branch current
\( P^{E_{\text{inj}}, E_{\text{rp}}}^{\text{upper}}, P^{E_{\text{inj}}, E_{\text{rp}}}^{\text{lower}} \) charging and discharging power
\( S^{A}_{\text{inj}}, P^{A}_{\text{inj}}, Q^{A}_{\text{inj}} \) apparent, active and reactive power drawn from the distribution network
\( S_{\text{inj}}, P_{\text{inj}}, Q_{\text{inj}} \) apparent, active and reactive power flows
\( T_{\text{inj}, \text{nE}} \) power transfer from \( M_{\text{og}} \) to \( M_n \)
\( V_{\text{inj}}, V_{\text{rp}} \) complex bus voltage
\( v_{\text{inj}}, v_{\text{rp}} \) squared magnitude of bus voltage

cooperate with each other in order to minimize the overall cost of the system [5] and benefit from the energy sharing via the EEN. In fact, the similar concept of the peer-to-peer direct current (DC) EEN among MGs has been proposed in [6,7], and this DC EEN is in parallel to the underlying AC distribution network. Accordingly, we add the structured relationship between these two networks in Fig. 1. From the figure, we can see that each MG is connected to the traditional AC distribution network and at the same time, they are interconnected by a dedicated DC EEN. The EEN enables the direct energy exchange among MGs and the connection to the distribution network can ensure the balance between supply and demand for each MG.

The coordinated energy management of networked MGs with energy sharing has been warmly discussed in the literature [8,5,9–15]. Gregoratti et al. [5] developed a distributed convex optimization framework for energy trading between islanded MGs, where all MGs cooperate with one another to minimize the total cost of the system. Lakshminarayana et al. [8] analyzed the tradeoff between the use of storage and the cooperation by energy sharing among DG resources with the objective of minimizing the time average cost of the energy exchange within the grid. A problem in these prior works is that the transmission loss incurred by the energy sharing is either ignored [8,5,9–11] or oversimplified by a linear model [12,13], both of which are not realistic in practice. In contrast to these, some recent works considered the energy sharing problem of MGs with a more accurate loss model [14,15], by using a quadratic function of the energy transferred. Another issue in [8,5,9–15] is that their models were proposed in an abstract way with the underlying distribution networks neglected. In fact, the MGs, if not operated in an islanded mode such as those in remote areas, are connected with the main grid via the points of
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