Two-stage Coordinated and Dynamic Economic Dispatch of Multi-microgrid System Considering Hierarchical Structure

A L Kong¹, X Zhu²*, H X Liu¹, C Zhou¹ and L J Chen²

¹ China Electric Power Research Institute (Nanjing), Nanjing 210003, China
² School of Electrical Engineering, Southeast University, Nanjing 210096, China

* E-mail address: tinro_chu@qq.com; Telephone number: (086)18795888303

Abstract. Multi-microgrid (MMG) system consists of several microgrids (MGs) close to each other in space, and is more resilient to uncertainties and economical in operation than single MG. To coordinate the different goals of MMG system and individual MGs, a hierarchical dispatch structure is firstly established in this paper. Based on this, a two-stage dynamic economic dispatch (DED) scheme is then proposed to achieve the compromise between global and local scope. In Stage I, MMG system’s operation cost is minimized to determine the power exchange among MGs, while in Stage II, each MG’s purchased power from main grid is optimized to realize local economy. Finally, numerical tests are performed on a triple-MG system and different cases are studied to demonstrate the effectiveness and feasibility of the proposed dispatch strategy.

1. Introduction

With the increase of distributed generation’s penetration rate, microgrid (MG) has undergone an unprecedented development by virtue of its reliability and efficiency in power supply [1-2]. MG is a small-scale power generation and distribution system, which consists of various distributed generations (DGs), power electronic converters, loads, energy storage systems (ESSs) and monitoring and protection devices [3]. By freely switching between grid-connected and grid-off mode, MG can realize self-management and flexible control.

As more and more MGs are appearing in the network, the concept of multi-microgrid (MMG) comes up on the stage. MMG system is constituted by interconnection of a certain amount of MGs, which are in close spatial distance to each other [4]. MMG can not only enhance the stability of individual MGs, but also reduce their costs through cooperative operation. Therefore, MMG system is more resilient to uncertainties and economical in operation, and has great prospect in reality.

The economic dispatch problem of MGs can be classified into static and dynamic ones. Dynamic economic dispatch (DED) considers the interaction between time intervals and better reflects system’s operating requirements. Hence, it’s of great significance to investigate MGs’ DED problem.

Many scholars have carried out relevant researches on this problem. Reference [5] considered the MG including combined heat and power, electricity and heat storage system and DGs, and established the DED model to minimize MG’s cost and emission. Reference [6] proposed an optimal operation strategy for MG, and embedded operation maintenance cost and emission cost into objective function. In [7], a multi-time scale (day-ahead and day-in) MG energy management model was built to coordinate the control of DGs and load. All the above studies put focus on single MG’s dispatch while neglecting the tendency of MGs’ evolving into groups, and thus have certain limitations.
As to MG’s dynamic dispatch, the MG groups were divided into three layers in [8-9], i.e. component layer, MG layer and MMG layer, which improved the efficiency of system’s coordinated optimization. In [10], non-cooperative and cooperative schemes of MMG system were studied in its energy management considering the optimization of battery energy storage system’s capacity, and distributed algorithms were presented for these two formulations. For the DED problem of stand-alone MMG, reference [11-12] put forward a distributed optimal scheduling strategy based on alternating direction method of multipliers. Although these studies establish MMG optimization models and utilize distributed algorithms to ease the computational burden, the MMG systems considered tend to be simple and coordination among MGs is not well reflected.

In this paper, a hierarchical dispatch framework for MMG is built. Based on this, a two-stage dynamic optimization scheme is proposed to coordinate the operation of MMG system and each MG, achieving the compromise between global and local scope. The main contributions of this paper include: (i) establish a hierarchical MMG dispatch architecture to improve the entire efficiency; (ii) present a two-stage optimization model integrated with the operation goals of both MMG system and individual MGs.

The rest of this paper is organized as follows. In Section 2, a hierarchical MMG architecture is introduced. Then in Section 3, a two-stage dynamic optimization model with different objective functions is set up. Furthermore, simulation analysis is implemented on a triple-MG system in Section 4, and conclusions are drawn at last in Section 5.

2. Hierarchical Dispatch Architecture of MMG

Figure 1 gives the diagram of hierarchical MMG dispatch architecture, where n MGs can be connected to the same bus at the point of common coupling (PCC). In each MG, there are different devices, including generation equipment like photovoltaic (PV), wind turbine (WT) and other controllable units (CUs), ESS and load.

Hierarchical dispatch process has two procedures: information uploaded from bottom to top and instructions distributed from top to bottom. For each MG, its dispatch center collects device information such as forecasted power of renewable energy sources, parameters and status of CUs, and submits these to system dispatch center. Then MMG system dispatch center optimizes all the resources on the system level according to certain objective, and distributes dispatch commands downwards, which will be executed by all MGs. It’s necessary to mention that MG dispatch center also possesses autonomy and can choose whether to participate into MMG dispatch process or not, based on self-interest.

Figure 1. Diagram of hierarchical dispatch architecture.
3. Two-stage Dynamic Optimization Model

In this paper, it’s supposed that all MGs are in grid-connected mode and respond to instructions issued by system dispatch center. Concretely, MMG system dispatch center is responsible for the minimization of system’s operation cost and determines the exchanged power among MGs (Stage I). Then each MG dispatch center minimizes MG’s power purchase cost from main grid by optimizing the generation power of controllable units, the charging and discharging power of ESS (Stage II).

3.1. Objective Functions

For system dispatch center, the objective is to realize optimal global operation, that is

\[
\min F = \sum_{t=1}^{N} \left( C^{CU}(P^{CU}_t) + C^{ESS}(P^{ESS}_t) + \pi_t (P^{grid}_t) \right) I
\]

(1)

where \( F \) is system’s operation cost and \( N \) is total time periods. \( P^{CU}_t \) and \( P^{ESS}_t \) are vectors composed of the generation power of controllable units and ESSs in MMG, respectively. \( P^{grid}_t \) is \( n \) by 1 vector whose elements denote the purchased power from main grid at time \( t \) (\( n \) is the number of MGs), and \( \pi_t \) represents the purchase price. \( I \) is the vector with all elements equaling to 1. \( C^{CU} \) represents the generation cost of controllable unit, which can be approximated as a quadratic function [13]. \( C^{ESS} \) is the operation maintenance cost of ESS.

For MG dispatch center, the objective is to minimize the power purchase cost, which is given by

\[
\min f_i = \sum_{t=1}^{N} \pi_t (P^{grid}_t) e
\]

(2)

where \( e \) is unit vector with the \( i \)-th component equaling to 1.

3.2. Constraints

Electric power balance:

\[
\left( P^{RES}_t \right)^T I + \left( P^{CU}_t \right)^T I + \left( P^{ESS}_t \right)^T I = \left( P^I_t - P^{grid}_t \right)^T I
\]

(3)

where \( P^{RES}_t \) is vector consisting of the generation power of renewable energy sources (RESs) in MMG, and \( P^I_t \) is load vector. It’s necessary to point out that \( P^{RES}_t \), \( P^{CU}_t \) and \( P^{grid}_t \) may have different sizes and this all depends on the number of RES, CU and ESS.

(3) is power balance constraint of MMG, which cannot indicate power exchange. Here, we rewrite the above formula in terms of each MG, as follows.

\[
\sum_j P^{RES}_{j,t} + \sum_k P^{CU}_{k,t} + \sum_m P^{ESS}_{m,t} + (I - e)^T P^{ex}_t e = (P^I_t - P^{grid}_t)^T e \quad j,k,m \in \text{MG} \#i
\]

(4)

where \( P^{RES}_{j,t} \) is the \( j \)-th component of \( P^{RES}_t \), so are \( P^{CU}_{k,t} \) and \( P^{ESS}_{m,t} \). \( P^{ex}_t \) is \( n \) by \( n \) matrix, as given by (5). For any element \( P^{ex}_{ji,t} \), it represents the exchanged power between MG \#i and \#j at \( t \), and is positive if flowing to MG \#j. It’s specified that all \( P^{ex}_{ji,t} \) equal to 0. \( j,k,m \in \text{MG} \#i \) denotes that these devices are in MG \#i.

\[
P^{ex}_t = \begin{bmatrix}
P^{ex}_{11,t} & \cdots & P^{ex}_{1n,t} \\
\vdots & \ddots & \vdots \\
P^{ex}_{n1,t} & \cdots & P^{ex}_{nn,t}
\end{bmatrix}
\]

(5)

MMG system operation constraints:

\[
0 \leq P^{RES}_{t} \leq P^{forecast}_t
\]

(6)

\[
P^{CU}_t \leq P^{CU}_t \leq \bar{P}^{CU}
\]

(7)

\[
\left| P^{CU}_t - P^{CU}_{t-1} \right| \leq R^u
\]

(8)

\[
\left| P^{CU}_t - P^{CU}_t \right| \leq R^d
\]
where $P_{\text{forecast}}^t$ is the forecasted power of RESs. (7) and (8) are constraints of controllable units. In (7), $P_{\text{CU}}^t$ and $P_{\text{CU}}^\text{max}$ are minimum and maximum output of CU, respectively. (8) represents CU’s ramping rate limits, and $R^u/R^d$ denotes ramping up/down limit.

For ESS, there have been extensive work about its operation model, thus it won’t be covered here. Specific process can be referred to [14].

\[
\left(P^\text{TL}\right)^T e \leq \left(I - e\right)^T P_{\text{ex}}^t e + \left(P_{\text{ex}}^\text{out}\right)^T e \leq \left(F^\text{TL}\right)^T e
\]

(9) is MG’s tie line (TL) capacity constraint, where $P^\text{TL}_T$ and $P^\text{TL}_T$ are minimum and maximum capacity vectors ($n$ by 1). (10) describes the relationship of exchanged power between interconnected MGs and is intelligible.

4. Simulation Analysis

4.1. Development Environment

Based on Yalmip in Matlab, the MMG system’s two-stage optimization problem is modelled, and IBM CPLEX optimizer is used to solve the model.

4.2. Case Description

For the MMG system shown in figure 1, this paper considers three MGs ($n = 3$), where MG #1 is industrial, MG #2 is commercial and MG #3 is residential. CUs include diesel engine (DE), fuel cell (FC) and micro-turbine (MT), and specific configurations are listed in table 1.

| Table 1. Configuration of each MG. |
|-----------------------------------|
| Category | Number | Capacity/kW | Ramping limit/kW·(15 min)$^{-1}$ |
|----------|--------|-------------|----------------------------------|
| MG #1    |        |             |                                  |
| WT       | 1      | 100         | -                                |
| DE       | 1      | 200         | 100                              |
| MG #2    |        |             |                                  |
| PV       | 1      | 60          | -                                |
| FC       | 1      | 100         | 50                               |
| MT       | 1      | 80          | 45                               |
| MG #3    |        |             |                                  |
| WT       | 1      | 50          | -                                |
| PV       | 1      | 30          | -                                |
| MT       | 1      | 110         | 60                               |

Both MG #1 and #2 have an ESS, 250 and 200 kWh respectively. To highlight the coordination, ESS takes the form of electric vehicle (EV) battery in MG #3, and there are ten EVs (all 30 kWh). The charging and discharging efficiency are both 0.9, and for ESSs in MG #1 and #2, the initial energy levels are 40% and 50% of their capacity, while this value is random for EVs in MG #3. The maximum and minimum energy levels are 95% and 15%. For CU, it has minimum technical output, and this value is set to be 30% of its capacity [15].
Load profiles of all MGs in a day are depicted in figure 2. The forecasted power of RES is sampled and generated according to its probability distribution function. In this paper, purchase price $\pi_t$ adopts the time-of-use (TOU) electricity price in [16], given by table 2.

| Period                | Price (¥/kWh) |
|-----------------------|---------------|
| 23:00-07:00           | 0.3818        |
| 10:00-15:00, 18:00-21:00 | 1.3222        |
| Other                 | 0.8395        |

### 4.3. Simulation Results

To demonstrate the effectiveness of proposed model, two cases are conducted and the results are then compared.

**Case 1:** All MGs participate into the two-stage coordinated and dynamic optimization process.

**Case 2:** Each MG only interacts with main grid and there is no power exchange among MGs.

Table 3 presents the comparison of optimization results in Case 1 and 2. As is seen, both MMG operation cost and MGs’ power purchase costs in Case 1 are lower than those in Case 2. This is because MGs coordinate with each other, reducing the purchased power from main grid. The purchase cost of MG #2 in Case 2 is 0, which is owing to its light load.

| Case | MMG total operation cost/¥ | MG #1/#2/#3 power purchase cost/¥ |
|------|---------------------------|-----------------------------------|
| 1    | 24187.9727                | 53.6230/162.4348/347.6195         |
| 2    | 27283.6763                | 316.0243/0/1400.2921              |

Figure 3 shows the power exchange in Case 1. As we can see, MG #2 provides power for MG #1 all the time ($P_{ex12}$ is negative). The reason for this is that load power in MG #2 is lower, which means it has larger generation margin. MG #3 also offers power support to MG #1 during valley time, but this is inverse when its load becomes heavy.
It’s necessary to mention that the exchanged power determined in Stage I may be sufficient and thus cannot be completely consumed in Stage II. Take $P_{ex}^{13}$ as an example, and the power surplus is depicted in figure 4. This also exists between MG #1 and #2 ($P_{ex}^{12}$). The reason is that Stage I and II are global and local optimization, respectively, and MMG system has different operation goal with individual MGs. Thus, system dispatch center should provide certain compensation for supply-type MGs when power abandonment happens, so that they’re motivated in coordinated dispatch.

Output power of controllable units are shown in figure 5, and FC and MT keep in full operation state throughout the day due to their more economy than DE.

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**Figure 3.** Exchanged power among MGs.

**Figure 4.** Surplus of exchanged power $P_{ex}^{13}$.

**Figure 5.** Output of controllable units.
Figure 6 illustrates ESS’s generation schedule (positive/negative if discharging/charging). As is shown, ESS mostly charges during valley period and discharges when load is heavy. In MG #3, EV #5 and #7 are chosen for demonstration due to their minimum and maximum initial energy levels (15% and 95%). Although single EV’s power is low (7 kW in this paper), it plays a significant role in peak shaving and valley filling, considering its scale effects.

![Figure 6. Generation power of ESSs.](image)

Figure 7 presents the state of charge (SOC) curve of EVs. As we can see, all EVs’ SOCs increase to 0.8 at 24:00, meeting EV owners’ travel demand, while this cannot be guaranteed in static optimization. Consequently, dynamic dispatch is more realistic than static one.

![Figure 7. SOC of EVs.](image)

5. Conclusion

To coordinate the operation of MMG system and individual MGs, a two-stage DED strategy is proposed in this paper. In Stage I, MMG system’s operation cost is minimized to determine the exchanged power among MGs. Based on this, each MG’s power purchase cost is optimized in Stage II, realizing local economy. Simulation analysis shows that:

1) The two-stage optimization scheme can reduce the cost of both MMG system and MGs, and promote the interaction among them, which enhances the flexibility of power supply.
2) Compared with static optimization, dynamic optimal dispatch can better reflect MMG’s operating requirements and thus is more adaptive.

3) Hierarchical control can improve the efficiency of complex systems such as MMG. Besides, more EVs are connected to grid (forming EV cluster), while hierarchical structure is beneficial for their coordination. Therefore, it’s prospective in practical application.

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