Plug-in and plug-out dispatch optimization in microgrid clusters based on flexible communication

Jie YU¹, Ming NI², Yiping JIAO³, Xiaolong WANG³

Abstract With large-scale development of distributed generation (DG) and its potential role in microgrids, the microgrid cluster (MGC) becomes a useful control model to assist the integration of DG. Considering that microgrids in a MGC, power dispatch optimization in a MGC is difficult to achieve. In this paper, a hybrid interactive communication optimization solution (HICOS) is suggested based on flexible communication, which could be used to solve plug-in or plug-out operation states of microgrids in MGC power dispatch optimization. HICOS consists of a hierarchical architecture: the upper layer uses distributed control among multiple microgrids, with no central controller for the MGC, and the lower layer uses a central controller for each microgrid. Based on flexible communication links among microgrids, the optimal iterative information are exchanged among microgrids, thus HICOS would gradually converge to the global optimal solution. While some microgrids plug-in or plug-out, communication links will be changed, so as to unsuccessfully reach optimal solution. Differing from changeless communication links in traditional communication networks, HICOS redefines the topology of flexible communication links to meet the requirement to reach the global optimal solutions.

Simulation studies show that HICOS could effectively reach the global optimal dispatch solution with non-MGC center. Especially, facing to microgrids plug-in or plug-out states, HICOS would also reach the global optimal solution based on refined communication link topology.

Keywords Microgrid Cluster (MGC), Plug-in/plug-out dispatch optimization, hybrid interactive communication optimization solution(HICOS), Flexible communication

1 Introduction

With the continuing growth of energy consumption and growing attention to environmental pollution, the value of distributed generation (DG) is becoming more and more important. Effectively managing a large amount of DG connected to the grid is a significant challenge.

Microgrids are a mechanism to meet this challenge in their role as independent control systems containing DG, loads and energy storage devices [1, 2]. Large-scale application of microgrids in distribution power grids will require efficient integration of multiple microgrids [3–5]. In this paper we propose that a Microgrid Cluster (MGC), as an aggregator of microgrids, would help to achieve optimal dispatch of DG and enhance power system reliability and power quality [6, 7].

Microgrids are usually capable of both islanded and grid-connected operation, and being autonomous to switch between these states, which is called as—plug-in or plug-out [8]. It is a difficult problem how to deal with microgrid plugs in and plugs out in MGC in real operating time. Chen proposed microgrid economic scheduling and developed a mathematical model [9], based on the integration of plug-in hybrid electric vehicles (PHEVs), that may be solved using a

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3 Mathematic model of hierarchical hybrid optimization

In MGC hierarchical architecture, the upper layer operates in accordance to distributed coordinated mode, without an upper control center. The aim of the upper model is to minimize the total costs of energy supply in the MGC, with the constraints of power exchange constraints and transmission lines constraints. Meanwhile, in the lower layer each microgrid manages its own distributed generators using a centralized controller. The objectives of the lower layer are to minimize costs for each microgrid with the operating constraints of distributed generations and the energy storage units.

3.1 Upper layer distributed optimization of a MGC (ULDOM)

The optimization model for the MGC is defined as follows.

3.1.1 Objective function

$$\min C = \min \sum_{i=1}^{I_{MG}} f_i(P_{ex}^i) = \min \sum_{i=1}^{I_{MG}} a_i (P_{ex}^i)^2 + b_i P_{ex}^i + c_i \quad (1)$$

where C is the total costs of multiple microgrids; I_{MG} the number of microgrids controlled by distributed dispatch; f_i the cost function of microgrid i , which is often a quadratic function, whose coefficients of the quadratic term, linear term and constant term are a_i , b_i and c_i respectively; P_{ex}^i the exchange power between microgrid i and the main grid, where $P_{ex}^i > 0$ indicates that the main grid transfers energy to microgrid i ; and $P_{ex}^i < 0$ means microgrid i transfers energy to the main grid.

3.1.2 Constraints

The upper and lower bound constraints of the power exchanged between the main power grid and microgrid i are:

$$P_{ex,min}^i \leq P_{ex}^i \leq P_{ex,max}^i \quad i = 1, 2, \dots, I_{MG} \quad (2)$$

where $P_{ex,min}^i$, $P_{ex,max}^i$ are the lower and upper bounds of the exchanged power, which are decided by the transmission constraints of power lines connecting the microgrid to the main power grid.

The power demand constraint is:

$$\sum_{i=1}^{I_{MG}} P_{ex}^i = P_{demand} \quad (3)$$

where P_{demand} is the power generation command from the power system dispatch center, which requires the MGC to have a total power consumption of P_{demand} .

3.2 Lower layer optimization of each microgrid (LLOM)

Taking microgrid i for instance, the optimization problem for each microgrid is stated as follows.

3.2.1 Objective Function

$$\begin{aligned} C_F^i &= \min \sum_{j=1}^{J_i} C_j^i(P_j^i) \\ &= \min \left(C_{wind-om}^i P_{wind}^i + C_{pv-om}^i P_{pv}^i + C_{mt}^i P_{mt}^i + C_{mt-om}^i P_{mt}^i \right. \\ &\quad \left. + C_{bs-om}^i (P_{BT-dis}^i + |P_{BT-ch}^i|) \right) \end{aligned} \quad (4)$$

where C_F^i is the total cost of operating microgrid i ; P_j^i the planned generation of the j^{th} distributed generator in i^{th} microgrid; $C_j^i(P_j^i)$ the generation cost function of generator j in microgrid i ; J_i the number of distributed generators in microgrid i ; P_{wind}^i the output of wind generation in microgrid i ; $C_{wind-om}^i$ the operation and maintenance cost factor of wind power equipment; P_{pv}^i the output of photovoltaic generation in microgrid i ; C_{pv-om}^i the operation and maintenance cost factor of photovoltaic power equipment; C_{mt-om}^i the operation and maintenance cost factor of microturbine generation; P_{mt}^i the output of microturbine generation in microgrid i ; C_{mt}^i the fuel cost factor of microturbine generation; C_{bs-om}^i the operation and maintenance costs factor of storage; $P_{BT-ch}^i/P_{BT-disch}^i$ the charge/discharge power of the storage, which is positive while discharging and negative while charging.

3.2.2 Constraints

The power flow constraints are:

$$\sum_{j=1}^{J_i} P_j^i - P_{BT-ch}^i \cdot \eta_{BT-ch}^i - P_d^i = P_{ex}^i \quad (5)$$

$$\sum_{j=1}^{J_i} P_j^i + P_{BT-dis}^i \cdot \eta_{BT-dis}^i - P_d^i = P_{ex}^i \quad (6)$$

where $\eta_{BT-ch}^i/\eta_{BT-dis}^i$ is the charge/discharge efficiency of storage devices in microgrid i ; P_{ex}^i the exchange power of microgrid i and the main grid; P_d^i the loads of microgrid i .

The distributed generator constraints in microgrid i are:

$$P_{j,\min}^i \leq P_j^i \leq P_{j,\max}^i \quad j = 1, 2, \dots, J_i \quad (7)$$

where $P_{j,\min}^i$ and $P_{j,\max}^i$ are the upper and lower bounds of distributed generator j .

The energy storage constraints of microgrid i are:

$$P_{\text{BT-ch},\min}^i \leq P_{\text{BT-ch}}^i \leq P_{\text{BT-ch},\max}^i \quad (8)$$

$$P_{\text{BT-dis},\min}^i \leq P_{\text{BT-dis}}^i \leq P_{\text{BT-dis},\max}^i \quad (9)$$

$$B_{\min}^i \leq B^i \leq B_{\max}^i \quad (10)$$

where $P_{\text{BT-ch},\min}^i$, $P_{\text{BT-ch},\max}^i$ are the upper and lower charging power and $P_{\text{BT-dis},\min}^i$, $P_{\text{BT-dis},\max}^i$ are the upper and lower discharging power in microgrid i ; B^i the battery storage state of charge in microgrid i ; $B_{\min}^i$ and $B_{\max}^i$ the upper and lower limits of battery storage state of charge respectively.

4 Hybrid interactive communication optimization solution (HICOS)

This paper proposes the hybrid interactive communication optimization solution (HICOS) method to solve the mathematic model ((1)–(10)), which integrates upper-layer distributed optimization ((1)–(3)) and lower-layer centralized optimization ((4)–(10)).

Constraints (2) can be realized by projection operation [21], and the Lagrangian function of upper-layer optimization can be written as:

$$L(\mathbf{P}_{\text{ex}}) = \sum_{i=1}^{I_{\text{MG}}} f_i(\mathbf{P}_{\text{ex}}^i) - \mu \left(\sum_{i=1}^{I_{\text{MG}}} P_{\text{ex}}^i - P_{\text{demand}} \right) \quad (11)$$

where μ is the Lagrangian multiplier of the power demand constraint (3).

The optimization problem can be solved by distributed optimization iterations based on the sub-gradient [21]:

$$\mathbf{P}_{\text{ex}}^i(k+1) = PR_{\mathbf{P}_{\text{ex}}^i} \left\{ \sum_{j \in \Gamma_i} a_{ji} \mathbf{P}_{\text{ex}}^j(k) - \alpha(k) \times \frac{\partial L}{\partial \mathbf{P}_{\text{ex}}^i} \right\} \quad (12)$$

$$\mu_i(k+1) = PR_{\mu_i} \left\{ \sum_{j \in \Gamma_i} a_{ji} \mu_j(k) - \alpha(k) \times \frac{\partial L}{\partial \mu_i} \right\} \quad (13)$$

where $\mathbf{P}_{\text{ex}}^i$ and μ_i are the primal and dual variables stored in node i ; Γ_i the neighbor node set of node i ; $\alpha(k)$ the step size at iteration k ; L the Lagrangian function (11); $PR_{\mathbf{P}_{\text{ex}}^i}$ the projection operation towards feasible solution space determined by (2); PR_{μ_i} the projection operation to area $\mu_i \geq 0$ [21]; and a_{ji} an element in row j and column i of the communication connection matrix $\mathbf{A}$, which denotes the communication link topology among microgrids.

If there is no communication connection between node i and j , a_{ij} would be zero; otherwise, a_{ij} means the weight influence from node j to i . Using HICOS to solve the distributed optimization, $\mathbf{A}$ should meet the requirement of a doubly-stochastic matrix. That means the sum of all a_{ij} (matrix elements in the same row i or in the same column j) must be 1 [21], which can be written as

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1I_{\text{MG}}} \\ \vdots & \ddots & & \vdots \\ \vdots & & a_{ij} & \vdots \\ a_{I_{\text{MG}}1} & \cdots & \cdots & \ddots \end{bmatrix} \quad (14)$$

and satisfied by

$$\begin{cases} \sum_{i=1}^{I_{\text{MG}}} a_{ij} = 1 & j = 1, 2, \dots, I_{\text{MG}} \\ \sum_{j=1}^{I_{\text{MG}}} a_{ij} = 1 & i = 1, 2, \dots, I_{\text{MG}} \end{cases} \quad (15)$$

HICOS incorporates distributed optimization in the upper layer and centralized optimization in the lower layer. Meanwhile, the microgrid plugs in and plugs out could be modelled by changes in the communication connection matrix $\mathbf{A}$. The algorithm for HICOS is shown by the steps below:

- ① If starting iteration, set $k = 0$; else $k = k + 1$;
- ② Calculate iteratively $\mathbf{P}_{\text{ex}}^i(k+1)$ and $\mu_i(k+1)$ according to (12) and (13) after receiving information from neighbors $\mathbf{P}_{\text{ex}}^j(k)$ and $\mu_j(k)$ via communication links;
- ③ Send $\mathbf{P}_{\text{ex}}^i(k+1)$ to the lower-layer optimisation as the power exchange constraint of microgrid i (shown in (4));
- ④ Solve the lower-layer control problem (shown in (4)–(10)) in each microgrid via centralized optimization;
- ⑤ Achieve the microgrid optimal results $\mathbf{P}_{\text{ex}}^j$, which is the planned generation output of the j^{th} distributed generator in i^{th} microgrid;
- ⑥ Update $\mathbf{P}_{\text{ex}}^i(k)$ as the iteration results of step k ;
- ⑦ Transfer $\mathbf{P}_{\text{ex}}^i(k)$ to neighbor microgrids as exchange information using the communication links;
- ⑧ If microgrid j plugs in or plugs out, change the connection matrix $\mathbf{A}$ according to flexible communication;
- ⑨ Judge whether convergence has been achieved; if not, go to ①.

Iterations continue until the termination conditions of the hybrid hierarchy optimal model is met. This kind of algorithm has been widely applied in distributed optimization problem [21, 22]. The flowchart of the iterative algorithm is shown in Fig. 2.

Fig. 2 Flowchart of HICOS

5 Numerical simulations

Taking a MGC containing 10 microgrids as an example for simulation, MGC dispatch optimization considering microgrid plug-in and plug-out is solved by HICOS as proposed by this paper. The communication topology among microgrids is represented by the connection matrix A , which should be a doubly stochastic matrix [22, 23], so as to guarantee convergence of the distributed optimization algorithm.

Fig. 3 Communication link topology of MGC

5.1 Case I: HICOS solution

MGC, non-control-center, would realize multiple microgrids coordinated operation based on flexible communication. The communication links among microgrids would fully apply the existing communication channels in the distribution power grid, which includes different mode, such as fiber-optic, wireless, power line carrier, and so on. The communication topology of the simulated MGC containing 10 microgrids is shown in Fig. 3.

The connection topology matrix A , denoting the communication links among microgrids, should be a doubly-stochastic matrix. The communication connection matrix of the MGC containing 10 microgrids is shown in (16).

$$A_0 = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.8 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.1 & 0.5 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.6 & 0.1 & 0.1 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.1 & 0.8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0.6 & 0.1 & 0.1 & 0.1 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0.1 & 0.8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0.9 \end{bmatrix} \quad (16)$$

In stable conditions, the MGC, organized by 10 microgrids, operates coordinately based on the communication links among microgrids. Hierarchical hybrid optimization mathematic model ((1)–(10)) is solved by the hybrid interactive communication optimization solution(HICOS) method, according to the iterative steps (shown in Fig. 2). The optimization results for the simulated MGC are illustrated in Fig. 4. Each microgrid exchanges its state information via communication links with the connection topology matrix A_0 . The iterations will ultimately converge to the globally optimal solution.

 Fig. 4 Optimization results based on communication topology A_0

Fig. 5 Flexible communication topology when one or more microgrids plug out

5.2 Case II: HICOS considering microgrid plugs out

When one or more microgrids plug out from MGC, the topology of communication will undoubtedly be changed. Based on the original topology shown in Fig. 5, the communication links from the 7th node to the 5th, 8th, 9th, and 10th nodes will be dropped when microgrid 7th plugs out. Therefore, the original connection topology matrix A_0 would be changed into $A'_{\text{plug-out}}$, shown in (17).

$$A'_{\text{plug-out}} = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.8 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.1 & 0.5 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.6 & 0.1 & 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.1 & 0.8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9 \end{bmatrix} \quad (17)$$

Fig. 6 Optimization results of communication topology $A'_{\text{plug-out}}$

After reaching optimization results based on connection topology A_0 , microgrid 7th plugs out at the time T_c . The connection matrix A_0 is changed into $A'_{\text{plug-out}}$ (17), which is no longer a stochastic matrix, so the optimization results decrease to zero, as shown in Fig. 6.

To maintain communication connectivity among microgrids in the MGC, communication links between the nodes 4th and 9th node 5th and 10th are constructed. The connection topology matrix is therefore changed to $A^{\text{modified}}_{\text{plug-out}}$, shown in (18).

$$A^{\text{modified}}_{\text{plug-out}} = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.8 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.1 & 0.5 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.8 & 0 & 0 & 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.6 & 0.1 & 0.1 & 0 & 0.1 & 0 \\ 0 & 0 & 0.1 & 0 & 0.1 & 0.8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0.9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0.9 \end{bmatrix} \quad (18)$$

While microgrid 7th plugs out at the time T_c , the connection matrix A_0 is changed into $A^{\text{modified}}_{\text{plug-out}}$, which is also a doubly-stochastic matrix. The optimization algorithm would begin converging again and would converge to a new globally optimal solution, as shown in Fig. 7.

5.3 Case III: HICOS considering microgrid plugs in

When some microgrids plug in, new communication links should be constructed between the new microgrids and the existing microgrids. In the simulation there are new microgrids 11th and 12th plug into the MGC, so the new communication node 11th and 12th are connected with the existing node 2nd, 5th and 6th, as shown in Fig. 8.

Then the connection matrix A_0 would be changed according to the new communication links, maintaining the characteristics of a doubly-stochastic matrix, shown in Eq. 19.

Fig. 7 Optimization results based on connection topology $A^{\text{modified}}_{\text{plug-out}}$

Fig. 8 Flexible communication topology when microgrids plug in

Fig. 9 Optimization results based on communication topology $A_{\text{plug-in}}$

$$A_{\text{plug-in}} = \begin{bmatrix} 0.8 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & 0.7 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 \\ 0.1 & 0.1 & 0.5 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0.9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.5 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0.1 & 0 & 0.1 & 0.7 & 0 & 0 & 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0.6 & 0.1 & 0.1 & 0.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0.1 & 0.8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0.9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0.8 \\ 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9 \end{bmatrix} \quad (19)$$

At time T_c in the simulation, the new microgrids plug into the MGC. Based on the refreshed connection matrix $A_{\text{plug-in}}$, the optimization results solved by HICOS are illustrated as Fig. 9.

6 Conclusion

To support largescale integration of microgrids into power grids, a MGC (Microgrid Cluster) with distributed control is an effective solution to consider microgrids plug in or plug out. This paper constructs a MGC hierarchical hybrid optimization model, including upper-layer distributed optimization and lower-layer centralized optimization of each microgrid. HICOS (hybrid interactive communication optimization solution) is proposed as a novel solution to this optimization problem based on the flexible communication topology. The simulation cases testify the effectiveness of HICOS. The novel optimization model and methods in this paper, accustomed to plug-in and plug-out dispatch optimization in MGC based on flexible communication, are suitable for challenging and constructive experiments that demonstration practical operation of microgrids in a MGC.

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