Distributed Optimization Dispatch Strategy for Multi-agent System Based Isolated Microgrid

Tao Rui12, Cungang Hu 23, Weixiang Shen4, Jin Zhang3
1School of Computer Science and Technology, Anhui University, Hefei 230601, China
2Engineering Research Center of Power Quality, Ministry of Education, Anhui University, Hefei 230601, China
3School of Electrical Engineering and Automation, Anhui University, Hefei 230601, China
4Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne 3122, Australia

Abstract
This paper proposes a distributed optimization dispatch strategy for an isolated microgrid (MG) using multi-agent system (MAS). The isolated MG consists of suppliers, consumers and energy storage operators which are considered as agents. Based on the self-interest motivation market, a real-time price mechanism is proposed to optimize energy supply and demand, aiming to maximize the social welfare of each agent in the isolated MG. To achieve market equilibrium among all agents in the isolated MG, an asynchronous Alternating Direction Method of Multipliers (ADMM) algorithm is designed to provide market clearing price and solve power balance, where each agent only needs to exchange a small amount of information with its neighboring agents. Simulation results demonstrate the validity of the proposed strategy.

Keywords: microgrid, multi-agent system, distributed optimal, price mechanism, ADMM

Nomenclature
- \( P_i, P_j, P_k \): The Power of unit \( i, j, k \).
- \( Y_i, Y_j, Y_k \): The power loss coefficient of the branch \( i, j, k \)
- \( P_i^{\min}, P_i^{\max} \): The lower and upper limits of unit \( i \)
- \( P_j^{\min}, P_j^{\max} \): The lower and upper limits of unit \( j \)
- \( P_k^{\min}, P_k^{\max} \): The lower and upper limits of unit \( k \)
- \( P_{\text{loss}} \): The power loss of whole MG system.
- \( \theta \): The price whole MG system.
- \( \theta^a \): The average price of past.
- \( \theta^f \): The average price of future.

\( \theta_n \): The expected price of agent \( n \).
\( \theta^{\min}, \theta^{\max} \): The lower and upper limits system price.
\( P_n \): The power from agent \( n \) to agent \( m \).
\( P_n^{\text{trad}} \): The trading power of agent \( n \).
\( d_{nm} \): The communication state between agent \( n \) and agent \( m \).
\( CON_n \): The set of local constrains of agent \( n \).

1. Introduction
In the past few decades, wind power, photovoltaic and other forms of renewable generations (RGs) have shown explosive growth in conventional power grids due to the flexible access characteristics and good scalability of RGs. However, the increasing penetration of renewable energy resources (RESs) in distribution network poses great influence on conventional power grids [1], [2]. To fully exploit the benefits of distributed RGs and conventional generations (CGs), the deployment of energy storage systems (ESSs) and shiftable loads in MGs has been investigated to effectively improve the reliability and economic benefits of conventional power grids integrated with RESs [3].

The integration of various types of distributed generators (DGs), ESSs and load demand responses (DRs) brings challenges to the economic operation in MGs. This can be solved through the formulation of energy optimization problem by the establishment of energy trading market in MGs [4]. Since the participants in the energy market are usually self-interested, the benefits of both supply and demand sides should be considered [5]. As a common method, price incentive mechanism has been studied by many researchers. In [6], a distributed day-ahead primal-dual price strategy is adopted in MGs, where the operator generates prices to the consumers and suppliers, and the participants independently choose the schedules to
their best operational and economic interests. An energy auction market model is formulated in [7], where both buyers and sellers can always benefit more from participating in market than directly trading with power grids. In [8], both pay-at market clearing price and locational marginal price-based settlement mechanisms are employed to minimize electricity cost of market participants and maximize the voltage stability of MGs. The price-based demand response strategy is used in [9] to effectively adjust load demands to RESs while maximizing the benefits of MGs. In [10], a two-stage economic operation framework is proposed for an EV parking MG, and the marginal electricity price is adopted to improve the benefits of the MG operator and reduce the battery charging cost of EV users. In [11], a fully distributed price mechanism is proposed for energy trading among multiple MGs, which can maximize the payoff of all MG participants. In the abovementioned methods, since reasonable price mechanisms are adopted, the relationship between supply and demand is effectively improved and the social benefit of a whole system is increased. However, their price mechanisms are dependent on the day-ahead forecast information or the optimization results of the previous stage, and their common drawback is lack of real-time price mechanism in energy trading market.

In this paper, a distributed optimization strategy is designed for economic dispatch of an isolated MG, which can maximize the total social welfare of the whole MG through adopting the real-time price mechanism. The model is achieved with the distributed MAS concept, which has been widely applied in various distributed control problems, such as voltage regulation, energy management and power control. Comparing with centralized methods, the proposed method based on MAS is more flexible and reliable, and can better protect the privacies of participants. In addition, each agent can negotiate the price for energy transaction with neighboring agents to reach the market equilibrium, where the negotiation among all the agents achieves a collective consensus. Therefore, the optimal objective can be realized by adopting asynchronous Alternating Direction Method of Multipliers (ADMM), which is suitable to solve distributed consensus optimization problems [12].

The construction of the paper is as follows. Section 2 introduces the typical structure of a MG system and the distributed communication network. In Section 3, the social welfare models of MGs are proposed together with their contraints. The distributed algorithm based on ADMM is applied to maximize social welfare in Section 4. Finally, Section 5 gives the conclusions of this paper.

2. Operation model of MAS-based MG

2.1 System structure

The typical structure of an isolated MG is shown in Figure 1. The MG is connected to the power grid at the point of common coupling (PCC) through fast switch, which determines the state of the MG which can be isolated or grid-connected. There are various terminals on the PCC, which consists of $n_p$, DGs, $n_l$, ESSs, and $n_l$ loads. The DGs mainly consists of RGs and CGs. It is assumed that all the terminals are located closely so that the bus impedance is neglected. The terminals of RGs and ESSs are connected to the PCC through power electronic converters, the terminal of the CGs and loads are connected to the PCC through Electric control cabinet and load aggregators, respectively. Each branch has an independent local agent, which is responsible for branch energy optimization control and external communications. Moreover, the agents can exchange information with each other through an internet. Considering the building cost of infrastructure and communication reliability, each agent only establishes links with their nearby agents.

2.2 Social welfare maximization model

The social welfare of a whole system in this paper is regarded as the sum of the operation utilities of all agents. Thus, maximizing social welfare can be represented as

$$\max \left( \sum_{i=1}^{n_p} U_{DG,i}(P_i, \theta) + \sum_{j=1}^{n_l} U_{ESS,j}(P_j, \theta) + \sum_{k=1}^{n_l} U_{L,k}(P_k, \theta) \right)$$

(1)

where $U_{DG,i}(P_i)$, $U_{ESS,j}(P_j)$ and $U_{L,k}(P_k)$ are the utility function of DG agent $i$, ESS agent $j$, and load agent $k$, respectively. $P_i$, $P_j$ and $P_k$ are power supply, energy storage and load demand of $i$ th, $j$ th and $k$ th units, respectively, where $P_i, P_j, P_k > 0$ indicate they supply power and $P_i, P_j < 0$ indicate they consume power. $\theta$ is electricity price, which should be limited by

$$\theta^{\min} \leq \theta \leq \theta^{\max}$$

(2)

In the market environment, DGs are energy suppliers, which benefits from selling energy. Its utility function can be expressed as

$$U_{DG,i}(P_i, \theta) = \theta P_i (1 - \gamma_i) - C_{DG,i}(P_i)$$

(3)

$$P_i^{\min} \leq P_i \leq P_i^{\max}$$

(4)

where $\gamma_i$ is the percentage of power loss at the branch $i$. $C_{DG,i}(P_i)$ is a cost function of DG $i$. $P_i^{\min}$ and $P_i^{\max}$ are the lower and upper bounds of DG $i$, respectively. The operation cost of RGs is assumed to be zero because energy taken from RGs is free, i.e. PV
The future price can be predicted by the historical price information stored in the system server. Thus, the utility function can be modeled as

$$U_{ESS,j}(P_j) = \begin{cases} \frac{1}{2} (1 - \gamma_j)(\theta - \theta' - a_j P_j^2 - b_j P_j, P_j > 0 \\ \frac{1}{2} (1 - \gamma_j)(\theta - \theta' + a_j P_j^2 + b_j P_j, P_j < 0 \end{cases}$$ (8)

where \( \gamma_j \) is the percentage of the power loss at the branch \( j \) , \( a_j \) , \( b_j \) are the parameters of the unity function. The load capacity and power should be bounded by

$$P_j^{\text{min}} \leq P_j \leq P_j^{\text{max}}$$ (9)

The power balance of the whole system should be satisfied

$$\sum_{j=1}^{n_{\text{d}}}(P_j - \gamma_j | P_j |) + \sum_{j=1}^{n_{\text{d}}}(P_j - \gamma_j | P_j |) + \sum_{j=1}^{n_{\text{d}}}(P_j - \gamma_j | P_j |) = 0$$ (10)

where \( | \cdot | \) is the absolute value.

3. Power optimization based on ADMM

3.1 Formulation of distributed optimization

We denote the collection of all agents as \( N = n_0 \cup n_c \cup n_e \). For each agent \( n \in N \), we denote the expected energy from one agent \( n \) to another agent \( m \) as \( P_{nm} \), where \( m \in N \) and \( m \neq n \) . Thus, the trading power of agent \( n \) can be defined as

$$P_{nm}^{\text{trad}} = \sum_{m \in N \setminus n} d_{nm} P_{nm}$$ (12)

where \( d_{nm} \) indicates the communication state between the agent \( n \) and agent \( m \) , and \( d_{nm} = 1 \) while the communication link exists, otherwise \( d_{nm} = 0 \). Moreover, if \( P_{nm}^{\text{trad}} > 0 \)

$$P_{nm}^{\text{trad}} = (1 - \gamma_n) P_n$$ (13)

If \( P_{nm}^{\text{trad}} < 0 \)

$$P_{nm}^{\text{trad}} = (1 + \gamma_n) P_n$$ (14)

In addition, the expected price of each agent is defined as \( \theta_n \) , the objective function of social welfare maximization can be remodeled as

$$\max \sum_{n \in N} U_n(P_n, P_{nm}, \theta_n)$$ (15)

s.t. \( (P_n, P_{nm}, \theta_n) \in \text{CON}_n, \forall n \neq m \)

where \( \text{CON}_n \) is a set of the local constrains for the agent \( n \) , which includes (2), (4), (7), (9) and (12)-(14).

It is known from (15) that each agent \( n \) has the local variables \( P_{nm} \) and \( \theta_n \) to be optimized. However, a successful transaction negotiation between the agent \( n \) and agent \( m \) requires that the two agents need to reach consensus for the expected energy \( P_{nm} \) at the prices of \( \theta_n \) and the expected energy \( P_{nm} \) at the
price of $\theta_m$. From this point of view, the problem (15) can be re-expressed as
\[
\min \sum_{n \in N} -U_n(P_n, P_m, \theta_n)
\]
\[
\text{s.t. } [P_n, P_m, \theta_n] \in \text{CON}_n, \forall n \neq m
\]
\[
d_{mn}P_m = -d_{mn}P_m
\]
\[
d_{mn}\theta_m = d_{mn}\theta_m
\]
This can be considered as a distributed optimization problem with coupling constraints, which can be solved by ADMM.

3.2 Implementation based on ADMM

In order to simplify (16), we define the coupling variables of the agent $n$ as a vector $x_n = [P_m, \theta_n]^T$. Thus, the augmented Lagrangian function for the agent $n$ can be written as
\[
L_n(x_n, x_m, \lambda_n) = -U_n(P_n, x_n) + \sum_{m \in N, n \neq m} \left( \lambda_n^T (Ax_n + Bx_m) + \frac{\rho_n}{2} \|Ax_n + Bx_m\|^2 \right)
\]
where $\lambda_n$ is the vector of Lagrange multipliers. $A = [d_{mn}, d_{mm}]$, $B = [-d_{mn}, d_{mm}]$. $\rho_n$ is the penalty parameter.

Considering the fact that distributed synchronous operation is difficult to realize in the actual system, we adopt asynchronous consensus ADMM to update the parameters, which can be expressed as follows:
\[
x_n^{(t+1)} = \arg \min_{x_n} L(x_n, x_n^{(t)}, \lambda_n^{(t)})
\]
\[
x_m^{(t+1)} = \arg \min_{x_m} L(x_n^{(t+1)}, x_m, \lambda_n^{(t)})
\]
\[
\lambda_n^{(t+1)} = \lambda_n^{(t)} + \rho_n(Ax_n + Bx_m)
\]
Equations (18)-(20) can be solved iteratively until the primal residuals satisfies the following convergence condition.
\[
\|Ax_n + Bx_m\|^2 \leq \varepsilon
\]
where $\varepsilon$ is a threshold of convergence, then the variables $P_n$, $x_n$ and $\lambda_n$ can be considered to converge to the optimal solution. In order to ensure the convergence of the proposed model, the penalty parameter of each agent should be relatively large. The analysis of the penalty parameter on the convergence of the objective function optimization can be found in [14].

4. Case study

4.1 Simulation tool and parameters

The simulation is implemented by using Matlab2016a yalmip with CPLEX solver. The simulation of the isolated MG as shown in Figure 1, which includes one PV, one Wind generator (WG), one CG, one ESS and two loads, is carried out. The communication link states between different agents are listed in Table 1.

In order to improve the convergence and convergence speed of the proposed method, the penalty parameter is set as $\rho_n = 1.5$, and the convergence threshold is set as $\varepsilon_n = 10^{-5}$. The power loss coefficient of branch is set as $\gamma_n = 0.02$. The energy price is bounded by [0.3, 1.3], which is the range of electricity price adopted in most parts of China. Besides, the simulation parameters of units in MG are listed in Table 2.

### Table 1 Communication Link State

<table>
<thead>
<tr>
<th>Agent</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2 Parameters

<table>
<thead>
<tr>
<th>Units</th>
<th>$a_{i,j,k}$</th>
<th>$b_{i,j,k}$</th>
<th>$c_{i,j,k}$</th>
<th>Power(kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>WG</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>CG</td>
<td>0.003</td>
<td>0.005</td>
<td>0.18</td>
<td>300</td>
</tr>
<tr>
<td>ESS</td>
<td>0.0008</td>
<td>0.012</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>Load1</td>
<td>0.002</td>
<td>3.0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Load2</td>
<td>0.011</td>
<td>2.2</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

### Figure 2 Primal Residuals of ADMM

4.1 Results

4.2.1 Primal Residuals of ADMM

In the proposed MG system, the powers of the RGs are considered to be un-schedulable and always operate at its maximum power. The powers of the other schedulable units are initially set to their minimum power. The simulation results are shown as follows.
The convergence process of the primal residuals are shown in Figure 2. Obviously, the primal residuals continue to converge until all the residuals are less than $10^{-3}$, where the number of iterations is 110. The process indicates that the proposed distributed optimization method can make the optimization variables to converge to the target values very quickly, which is suitable for practical applications. The convergence curves of prices and powers are shown in Figures 3 and 4, respectively. The utility functions of different units indicate that the suppliers always prefer to sell more energy at high prices, while the consumers always prefer to create more benefits by consuming more power at relatively lower electricity costs. As shown in Figure 3, the prices of energy suppliers are always at the highest price at the beginning of the iteration, and the prices of energy consumers always begin at the lowest prices. As the number of iterations increases, the prices of suppliers and consumers gradually move closer to each other until the convergence conditions are satisfied. In the iteration process, the coupling power and price are mutually stimulating. The coupling powers in Figure 4 are all expressed by absolute values. It can be seen that when a number of iterations increase the curves of the neighboring agents approach each other rapidly and overlap each other in about the 40th iteration. The coincidence of coupling power indirectly indicates the realization of system power balance.

To better illustrate the realization of power balance, the power mismatch based on the power supplied, power consumed and power loss is shown in Figure 5. The power mismatch reaches zero in about the 40th iteration, and keeps it at zero in the iterations from 40 to 110. Although the power mismatch is rapidly reaching zero, energy supply and consumption still show an increasing trend in the iterations of 40 to 110. This is because the prices of different units are not completely convergent, and the power of some units is still adjusting, as shown in Figure 6.

### 4.2 Comparison with centralized strategy

In order to further demonstrate the validity of proposed distributed model in maximizing social welfare, the results of centralized optimization are compared with those of the proposed model in Table 3. The difference of social welfare obtained by the two models is only 0.2% while the difference of optimal prices is 0.6%. Besides, the differences of optimal power of different units are all listed in Table 3, which are all less than 1%. The results show the validity of the proposed distributed optimization strategy for economic dispatch in the isolated MG.
<table>
<thead>
<tr>
<th>results</th>
<th>centralized</th>
<th>distributed</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (CNY/kWh)</td>
<td>0.718</td>
<td>0.712</td>
<td>0.6%</td>
</tr>
<tr>
<td>Social Welfare (CNY)</td>
<td>472.3</td>
<td>471.8</td>
<td>0.2%</td>
</tr>
<tr>
<td>$P_{pv}$ (kW)</td>
<td>90.0</td>
<td>90.0</td>
<td>0</td>
</tr>
<tr>
<td>$P_{W2}$ (kW)</td>
<td>60.0</td>
<td>60.0</td>
<td>0</td>
</tr>
<tr>
<td>$P_{cv}$ (kW)</td>
<td>109.2</td>
<td>110.0</td>
<td>0.7%</td>
</tr>
<tr>
<td>$P_{ESS}$ (kW)</td>
<td>20.1</td>
<td>21.2</td>
<td>0.5%</td>
</tr>
<tr>
<td>$P_{load1}$ (kW)</td>
<td>-155.1</td>
<td>-154.6</td>
<td>0.3%</td>
</tr>
<tr>
<td>$P_{load2}$ (kW)</td>
<td>-128.2</td>
<td>-127.8</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

5. Conclusions

In this paper, a distributed power optimization strategy is proposed for isolated MGs based on MAS. The asynchronous ADMM is used to realize the equilibrium of energy market by optimizing the expected prices and trading energy. The simulation results show that the proposed strategy can effectively obtain the optimization objectives, which are the same as those achieved by centralized optimization methods. Besides, the convergence rate of the proposed strategy is fast, which indicates that the proposed strategy can be easily extended to the economic dispatch of the grid-connected MG and distribution network.

Acknowledgement

This work was supported by the National Key R&D Program of China (Nos. 2016YFB0900400) and the National Natural Science Foundation of China (Nos. 51777001, 51507001).

Reference

[9] Cuo Zhang, Yan Xu, Zhao Yang Dong and Kit Po Wong. ‘Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids.’ IEEE Transactions on Smart Grid, 2018, 9, (5), pp.4236-4247