Optimal Active Power Dispatching of Microgrid and Distribution Network Based on Model Predictive Control

Yang Li, Xinwen Fan, Zhiyuan Cai, and Bing Yu

Abstract: First, a three-tier coordinated scheduling system consisting of a distribution network dispatch layer, a microgrid centralized control layer, and local control layer in the energy internet is proposed. The multi-time scale optimal scheduling of the microgrid based on Model Predictive Control (MPC) is then studied, and the optimized genetic algorithm and the microgrid multi-time rolling optimization strategy are used to optimize the datahead scheduling phase and the intra-day optimization phase. Next, based on the three-tier coordinated scheduling architecture, the operation loss model of the distribution network is solved using the improved branch current forward-generation method and the genetic algorithm. The optimal scheduling of the distribution network layer is then completed. Finally, the simulation examples are used to compare and verify the validity of the method.

Key words: microgrid; model predictive control; optimal active power dispatching; coordination control

1 Introduction

Energy internet is currently the theme of energy development. With the improvement of people’s awareness of environmental protection and the depletion of primary energy, the development and utilization of distributed renewable energy has become the main direction of the energy internet. In terms of technology, converting the distributed energy into electric energy and sending it to power grids is not anymore difficult. However, many distributed energies disordered access to distribution networks pose a huge challenge to the planning construction and operation management of relatively weak distribution networks. Microgrids are of importance as a link between the distributed power supply and the distribution network. The optimal scheduling based on a microgrid has also become a hot research topic at the present.

As regards the economic research of microgrid optimal scheduling, the cost model of the micro source was established in Ref. [1], and the improved particle swarm optimization was used to solve the model. In Ref. [2], the author put forward the design goal of the Microgrid Energy Management System (MGEMS) and architecture based on the economical optimization scheduling of microgrid added into the grid. From two time scales, (i.e., ahead-day and intra-day), the author realized the optimal scheduling of an independent micro-grid [3]. A three-level time-scale optimal scheduling method was proposed [4], which can realize the optimal scheduling of an independent power system and upgrade real-time optimization results. The authors in Refs. [4, 5] used the scheduling strategy based on the rolling optimization in the ahead-day to improve the anti-jamming capability of the model in real-time optimal scheduling within microgrid; however, the microgrid scheduling periodicity was not considered and the remaining intra-day capacity balance constraint of energy storage was not considered.

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Meanwhile, with the large-scale access of microgrids\footnote{6}, the optimization of microgrids and distribution networks is also receiving increasing attention. In view of the problems of operational safety and energy consumption in the operation control of the distribution network with high penetration distributed power access, scholars in various countries performed related research in the coordination and dismissal of the energy storage system\footnote{5, 7–9} and controllable load\footnote{4, 10, 11}. China Electric Power Research Institute performed a research on the optimal dispatching of the distribution network with distributed generation, where the model of dividing the active scheduling of the distributed power sources was established\footnote{12}.

The main contributions of this article are as follows:

1. A three-tier coordination scheduling framework of a distribution network and a micro-grid is proposed.
2. The operation characteristics of each micro-source and energy storage in the micro-grid are analyzed, and the cost model is established. In the ahead-day optimization, the improved genetic algorithm is used to realize economic optimization. Meanwhile, in the intra-day optimization, the intra-day operation plan of the dispatchable units in the microgrid is adjusted based on the microgrid rolling optimization and the correction strategy of the linear state space Model Predictive Control (MPC) algorithm to realize the smooth tracking of the power of the tie-line of the microgrid. Finally, the simulation example is used to verify the effectiveness of this method.
3. The coordinated dispatching of the distribution network and the microgrid is studied. The network loss of the distribution network is taken as the optimization objective. The constraint and the allocation of the set scenario is considered. The operation constraints of the power grid are also considered. The improved branch current forward-and-forward generation method and genetic algorithm are used to complete the optimal dispatching of the distribution network layer. The comparative analysis of the simulation example is used to verify the feasibility of the method.

2 System Model

2.1 Scheduling system architecture

Based on the traditional five-level scheduling system\footnote{13}, we proposed herein a three-tier coordinated scheduling architecture of the distribution network including a microgrid (Fig. 1). In this architecture, the local control layer realizes the local control of the micro-source and the load, and the centralized control layer realizes the data collection, coordination, and control among various micro-sources, prediction of the micro-source power and the load power, etc. The distribution network dispatch layer realizes the interaction between the microgrid and the distribution network.

2.2 Analysis and modeling of the micro-source characteristics in the micro-grid

2.2.1 Wind turbine

The output power of the wind turbine was different under different wind speeds. The relationship between the two\footnote{14} is presented as follows:

\[
P = \begin{cases} 
0, & 0 \leq v < v_i; \\
av^3 + bv^2 + cv + d, & v_i < v < v_r; \\
P_r, & v_r < v < v_o; \\
0, & v > v_o 
\end{cases} \tag{1}
\]

where \(v_i, v_o, \) and \(v_r\) is the cutting in speed, cutting out speed, and rated speed of the wind turbine, respectively. \(P_r\) is the rated power. The cost model is presented as

\[
C_{WT} = \sum_{t=1}^{24} K_{WT} \cdot P_{WT}(t) \tag{2}
\]

where \(K_{WT}\) is the operation and maintenance cost coefficient of the wind turbine, and \(P_{WT}(t)\) is the power generation of the wind turbine at moment \(t\).

2.2.2 Photovoltaic power generation system

The factors affecting the output of the photovoltaic power generation were the solar panel temperature, ambient temperature, and solar radiation intensity. The output of
the photovoltaic system is calculated as
\[
P_{PV} = P_{STC} \frac{G_{ING}}{G_{STC}} \left[ 1 + k(T_c - T_r) \right]
\] (3)
where \( P_{STC} \) is the maximum output power of the components under standard test conditions. \( k \) is the temperature coefficient of the component. \( T_c \) and \( T_r \) are the photovoltaic panel temperature and the reference temperature, respectively. \( G_{STC} \) and \( G_{ING} \) are the irradiance intensity under the standard test conditions and the estimated output, respectively. The cost model is presented as
\[
C_{PV} = \sum_{t=1}^{24} K_{PV} \cdot P_{PV}(t)
\] (4)
where \( K_{PV} \) is the operation and maintenance cost coefficient of the photovoltaic power generation system. \( P_{PV}(t) \) is the power generation of the photovoltaic power generation system.

2.2.3 Micro gas turbine
The cost model of the micro gas turbine is presented as
\[
C_{MT} = \sum_{t=1}^{24} \rho_{MT} \cdot P_{MT}(t)
\] (5)
where \( P_{MT}(t) \) is the power generation of the micro gas turbine at moment \( t \). \( \rho_{MT} \) is the unit operating cost coefficient of the micro gas turbine.

2.2.4 Fuel cell
The cost model of the fuel cell is presented as follows:
\[
C_{FC} = \sum_{t=1}^{24} \rho_{FC} \cdot P_{FC}(t)
\] (6)
where \( P_{FC}(t) \) is the power generation of the fuel cell at moment \( t \). \( \rho_{FC} \) is the unit operating cost coefficient of the fuel cell.

2.2.5 Storage battery
The remaining capacity of the battery is usually expressed by the State Of Charge (SOC) of the battery. Its charge and discharge model is presented as follows:
\[
SOC(t)= \begin{cases} 
SOC(t-1) - P_{bat}(t) \Delta t / E_{bat}\eta_{dis} & , P_{bat}(t) \geq 0 \\
SOC(t-1) - P_{bat}(t) \Delta t / E_{bat}\eta_{ch} & , P_{bat}(t) < 0 
\end{cases}
\] (7)
where \( SOC(t) \) is the corresponding state of charge of the battery at moment \( t \). \( P_{bat}(t) \) is charge and discharge power of the battery at moment \( t \). \( E_{bat} \) is the battery capacity. \( \eta_{ch} \) and \( \eta_{dis} \) are the efficiency of the battery charge and discharge, respectively. The cost model of battery is presented as
\[
C_{bat} = \sum_{t=1}^{24} \rho_{bat} \cdot |P_{bat}(t)|
\] (8)
where \( \rho_{bat} \) is the unit operating cost coefficient of a battery. We let \( \rho_{bat}(t) = 0.001 \).

3 Optimal Scheduling of the Micro Networks Based on Model Predictive Control
In this section, we used the multi-time-scale rolling optimization method based on the MPC to optimize the economic operation of the micro-grid. The optimization was divided into two parts to conduct the research: one part was the ahead-day economic optimization based on a short-term forecast of the wind, light, and load forecasting data; while the other part was the intra-day rolling optimization of coordinated control based on an ultra-short time forecast of the wind, light, and load forecasting data. The results showed that, this method considers the economy of the microgrid and the schedulability of the microgrid and the grid. Meanwhile, it saves the operating costs and makes the system more stable for the distribution network.

3.1 Day-ahead economic scheduling of the microgrid
The goal of the day-ahead optimal scheduling is to ensure the optimal operation economy of the microgrid system.

We set the time resolution of the day-ahead scheduling as 1 h. We can schedule the controllable units within the scope of each constraint, formulate the power generation plan for the next day, and release it in advance according to the day-ahead forecasting data of the wind power and the PV.

3.1.1 Day-ahead optimized objective function
\[
\min C = C_{PV} + C_{WT} + C_{MT} + C_{FC} + C_{grid}
\] (9)
where \( C_{grid} \) is the microgrid and grid integration costs. The other items correspond to the items in Section 2.
\[
C_{grid} = \sum_{t=1}^{24} \left( \rho_{price}(t) \cdot P_{grid}(t) + \rho_{grid}(t) \cdot P_{grid}(t) \right)
\] (10)
where \( \rho_{price}(t) \) is the interactive electricity prices of the microgrid and the grid. \( \rho_{grid}(t) \) is the pollution control costs coefficient of purchasing electricity in the microgrid.
and the grid. $P_{\text{grid}}(t) < 0$ represents selling electricity to the grid, and $P_{\text{grid}}(t) > 0$ represents purchasing electricity from the grid.

### 3.1.2 Restrictions

We need to meet the operating constraints of each micro-source of the micro-grid as follows when involving various energy supplies:

(a) Power balance constraints

$$P_{\text{PV}}(t) + P_{\text{WT}}(t) + P_{\text{MT}}(t) + P_{\text{FC}}(t) + P_{\text{bat}}(t) + P_{\text{grid}}(t) = P_{\text{load}}(t)$$

(b) Tie line power constraints

$$P_{\text{gridmin}} \leq P_{\text{grid}}(t) \leq P_{\text{gridmax}}$$

(c) Distributed power output constraints

$$P_{\text{DG}_{i}}, \text{min} \leq P_{\text{DG}_{i}}(t) \leq P_{\text{DG}_{i}}, \text{max}$$

(d) Climbing constraints

The climbing rate constraints of the micro gas turbine are presented as

$$P_{\text{MT}}(t) - P_{\text{MT}}(t-1) \leq P_{\text{MTup}};$$
$$P_{\text{MT}}(t) - P_{\text{MT}}(t-1) \leq P_{\text{MTdown}}$$

(e) Battery constraints

When the battery is normally working, the constraints of the charge state and the power interaction must be met.

$$P_{\text{bat}}, \text{min} \leq P_{\text{bat}}(t) \leq P_{\text{bat}}, \text{max}$$
$$SOC_{\text{bat}}, \text{min} \leq SOC(t) \leq SOC_{\text{bat}}, \text{max}$$

The microgrid scheduling is periodic; hence, the battery also needs to satisfy the start and end state constraints of the SOC:

$$SOC(0) = SOC(T)$$

where $SOC(0)$ and $SOC(T)$ are the start and end states of SOC battery within a scheduling cycle, respectively.

### 3.1.3 Optimization

The microgrid’s economic optimization scheduling is based on the goal of minimizing the total operating cost of the microgrid. The objective function is the running cost function, which is a combinatorial optimization problem with multivariate, nonlinear, and constraints\(^5\). Therefore, in the ahead-day optimal scheduling of the microgrid, we used the genetic algorithm to optimize the solution\(^15,16\). Figure 2 shows the overall process of genetic algorithm.

### 3.2 Scheduling optimal scheduling based on model predictive control in micro-grid intraday rolling

The deviation between the scheduling plans given by the ahead-day forecasting data and the actual intra-day situation was very large\(^17\). Therefore, we needed to correct the intra-day deviation of the actual dispatch according to the short-term forecasting data and the rolling schedule control method of the MPC.
3.2.1 Predictive model

The grid-connected micro-grid was selected herein as a research example. The micro-grid included wind power, photovoltaic, load, micro-gas turbines, fuel cells and batteries, where the output of the micro-gas turbine, fuel cell, and battery was controllable. We set the prediction period as TS. The state space model of the micro-grid is written as follows:

\[
\begin{bmatrix}
SOC(k+1) \\
P_{grid}(k+1) \\
P_{MT}(k) \\
P_{FC}(k) \\
P_{bat}(k)
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 & -\frac{T_s}{P_{bat}} \\
0 & -1 & -1 & -1 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
SOC(k) \\
P_{grid}(k) \\
P_{MT}(k-1) \\
P_{FC}(k-1) \\
P_{bat}(k-1)
\end{bmatrix} + \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
P_{load}(k) \\
P_{PV}(k) \\
P_{WT}(k)
\end{bmatrix} + \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
P_{grid}(k) \\
P_{MT}(k-1) \\
P_{FC}(k-1) \\
P_{bat}(k-1)
\end{bmatrix}
\] (19)

\[y(k) = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
SOC(k) \\
P_{grid}(k) \\
P_{MT}(k-1) \\
P_{FC}(k-1) \\
P_{bat}(k-1)
\end{bmatrix}
\] (20)

where

\[x(k) = [SOC(k) P_{grid}(k) P_{MT}(k-1) P_{FC}(k-1) P_{bat}(k-1)]^T\]

is state variables vector.

\[\Delta u(k) = \begin{bmatrix}
\Delta P_{MT}(k) \\
\Delta P_{PV}(k) \\
\Delta P_{bat}(k)
\end{bmatrix}
\]

is control variable vector.

\[r(k) = [P_{load}(k) P_{PV}(k) P_{WT}(k)]^T\]

is short-term prediction of the power composition of the disturbance vector.

\[y(k) = [P_{grid}(k) SOC(k) 0 0 0]^T\]

is output variables.

Substituting Eq. (19) into Eq. (20), we can obtain the estimated output vector \(Y_t(k)\) of the contact line power and the battery SOC at moment \(k+1-k+N\) when it is predicted at moment \(k\):

\[Y_t(k) = [P_{grid}(k+1) SOC(k+1)\cdots P_{grid}(k+N) SOC(k+N)]^T\] (21)

3.2.2 Optimization of the intra-day objective function

According to the results of the optimization in day-ahead, the tie line power and the day-ahead optimization value of the battery SOC at moment \(k+1-k+N\) constitute a tracking control target vector \(Y_{ref}(k)\):

\[Y_{ref}(k) = [P_{grid}(k+1) SOC_{ref}(k+1)\cdots P_{grid}(k+N) SOC_{ref}(k+N)]^T\] (22)

In the intra-day rolling optimization, we set the goal as eliminating the line power fluctuations caused by the ahead-day forecasting error; hence, the optimization objective function is expressed as follows:

\[\min J(k) = ||Y_t(k) - Y_{ref}(k)||_Q^2 + ||\Delta u(k)||_R^2 = (Y_t(k) - Y_{ref}(k))^T Q (Y_t(k) - Y_{ref}(k)) + \Delta u^T(k) R \Delta u(k)\] (23)

Using Eq. (23), we can obtain the optimal control sequence of all the controllable micro-source output adjustments from \(k-N_C\) to \(k\). However, we can only deliver the control sequence of the backward one cycle at the current \(k\) time. The above process is repeated when the time \(k+1\) comes.

3.2.3 Feedback correction

Feedback correction can further correct deviations and avoid the shift caused by a model mismatch and the environmental disturbances. The specific approach is to measure the current actual active output state of the online system and take this as the initial value of the rolling optimization at the current moment to form a closed-loop control, which can make the prediction model more accurate:

\[x(k) = x_{ref}(k)\] (24)

3.3 Case study

We used MATLAB 2014b version for the simulation. The simulation results are as follows.

3.3.1 Day-ahead economic scheduling

We made the battery, micro gas turbine, and fuel cell controllable. The time resolution was set as 1 h, under the abovementioned constraints. We used the improved genetic algorithm to solve. The optimization objective
was the lowest operating cost of the micro-grid. Figures 3–5 present the day-ahead optimized scheduling results. Figure 3 shows the output of the microgas turbine, fuel cell, battery and microgrid after ahead-day optimization. Figure 4 depicts the remaining capacity after the battery has been optimally scheduled. Figure 5 shows the tie line power of the microgrid and the grid. It was positive when the microgrid bought electricity from the grid and negative when selling to the grid. The three maps also showed something interesting:

1. After the optimal scheduling, the reasonable charging and discharging of the battery in various periods achieved the peak load and reduced the operating costs of the micro-grid.

2. By the optimization calculation, we found that when the microturbine and the fuel cell operated at the corresponding time and met the microgrid load, the microgrid gained sales by selling electricity, and the selling period was the peak period.

Table 1 shows the comparison of the operation cost of the micro-grid before and after the optimization, and the total operating cost of the microgrid in a day dropped from RMB3412.73 to RMB2622.90 after the optimization.

### 3.3.2 Intra-day rolling optimal scheduling

Based on the ahead-day optimized power of the tie line and the SOC of the battery, we took the predicted length as $N = 24$, control length as $N_C = 6$, and the rolling optimization period on a short time scale in a day as $T_S = 5$ min. Hence, the total rolling optimization frequency in a day was 288. Figures 6–8 depict the results of the intra-day rolling optimization scheduling. Figure 6 shows the operation of the microgas turbine, battery and fuel cell after the intra-day adjustment. The operation plan of the controllable micro-source in the microgrid was fixed in the intra-day stage to keep track of the planned ahead-day value of the tie line.

Figure 7 shows the contrast of the power control effect of the tie line after the model predictive optimization control. The power of the intra-day tie line after the model predictive optimization control was basically the same as the planned value given in the ahead-day, proving that the MPC was good for tracking control. In addition the time of each rolling optimization was 0.89 s, which met the needs
of real-time control. Figure 8 shows the tracking control of the battery SOC, in which case the battery had weight factors of 200 and 300. During the simulation, the larger the weight factor of the battery, the better the tracking effect. The tracking effect became worse when the weight factor was very small. The planning value of the ahead-day battery SOC had no reference value. Therefore, in the actual operation, the weight factor of the battery must be set according to the specific operational needs.

In addition, during the intra-day rolling optimization scheduling, the actual scheduling of each micro-source and energy storage was adjusted in different degrees, resulting in the change of the optimal running cost of the micro-grid. Table 2 shows the running cost of the micro-grid after the intra-day optimization scheduling.

The operating cost of the microgrid increased by 58.42 yuan after the predictive control optimization. However, in the intra-day model, 738.37 yuan was still saved compared with that before, and the total cost reduction rate was 21.64%, ensuring the economic operation of the microgrid.

4 Coordination and Optimization of Scheduling in Distribution Network with Microgrids

In this section, we took a modified example of the PE&G69 node distribution network in the United States as the research object and incorporated the microgrids consisting of the photovoltaic and energy storage into a high proportion of PVs. In addition, we implemented the centralized energy storage, and investigated the coordination and optimization of scheduling in the distribution network with microgrids.

<table>
<thead>
<tr>
<th>Table 2 Economic contrast between with and without the MPC optimization. (yuan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Normal network</td>
</tr>
<tr>
<td>Model subject to restrictions</td>
</tr>
</tbody>
</table>

Fig. 8 Battery SOC tracking.

4.1 Coordination and optimization scheduling strategy

Under the premise of not allowing the distribution network to appear over power dumping, strategy is presented as in the discussion that follows.

4.1.1 Distribution network scheduling layer

We regard the minimum network loss as the optimization objective, and solve the optimal power flow of the time series distribution network and issue ahead-day scheduling commands to the microgrid.

4.1.2 Microgrid centralized control layer

In the intra-day microgrid optimization scheduling, the microgrid centralized control layer needs to adjust the charging and discharging of the distributed energy storage according to the ahead-day scheduling instructions issued by the dispatch layer and the actual intra-day PV output.

4.2 Optimization scheduling model

4.2.1 Distribution network layer scheduling model

(1) The minimum network loss in the distribution network operation was regarded as the optimization goal, as shown in Eq. (25):

$$\min P_{\text{loss}} = \sum_{i=1}^{n} U_{b,i} I_{b,i}$$

(25)

where $P_{\text{loss}}$ is the active power loss of the distribution network; $U_{b,i}$ is the branch voltage of branch $i$ in the distribution network, $I_{b,i}$ is branch current of branch $i$ in the distribution network; and $n$ is the branch number of the distribution network.

(b) Power constraints of the root node injection

$$P_{\text{grid}}(t) = \sum_{i=1}^{n} P_{\text{load},i}(t) - \sum_{j=1}^{m} P_{\text{PV},j}(t) - \sum_{k=1}^{r} P_{\text{ESS},k}(t)$$

(26)

where $P_{\text{grid}}(t)$ is the active power when the external power grid injects the root node of the distribution network at moment $t$; $P_{\text{load},i}(t)$ is the load of node $i$ in the distribution network; $P_{\text{PV},j}(t)$ is the power generation of the photovoltaic power generation system at moment $t$ in the photovoltaic power storage micro-grid $j$; $P_{\text{ESS},k}(t)$ is the output of the centralized energy storage $k$ at moment $t$; $P_{\text{ESS},k}(t) > 0$ means discharging; and $n, m,$ and $r$ are the number of nodes outside the root node of the distribution network, the number of microgrids, and the amount of energy storage in a centralized configuration, respectively.

(b) Power constraints of the root node injection
\[ P_{d0}(t) \geq 0 \]  

(27)

The amount of photovoltaic power generation must be completely absorbed in the regional distribution network, and more power should not leapfrog back to the main grid to reduce the impact of distributed generation on the grid operation.

(c) Node voltage constraints

\[ V_{i_{\text{min}}} \leq V_i \leq V_{i_{\text{max}}} \]  

(28)

where \( V_i \) is the node voltage of the distribution network, \( V_{i_{\text{max}}} \) and \( V_{i_{\text{min}}} \) are the upper and lower node voltages, respectively.

From the requirements of ensuring the quality of the power supply and the safety of the power supply, we referenced the allowable voltage offset of the 10 kV voltage level and set the allowable voltage offset as \( \pm 7\% \).

(d) Storage constraints

\[ P_{\text{ESS}k_{\text{min}}} \leq P_{\text{ESS}k}(t) \leq P_{\text{ESS}k_{\text{max}}} \]  

(29)

where \( P_{\text{ESS}k_{\text{max}}} \) and \( P_{\text{ESS}k_{\text{min}}} \) are the upper and lower power of the centrally configured energy storage, respectively.

\[ \text{SOC}_{\text{ESS}k_{\text{min}}} \leq \text{SOC}_{\text{ESS}k}(t) \leq \text{SOC}_{\text{ESS}k_{\text{max}}} \]  

(30)

where \( \text{SOC}_{\text{ESS}k_{\text{min}}} \) and \( \text{SOC}_{\text{ESS}k_{\text{max}}} \) are the upper and lower energy storage SOCs of the centralized configuration of energy storage, respectively.

\[ \text{SOC}_{\text{ESS}k}(0) = \text{SOC}_{\text{ESS}k}(T) \]  

(31)

where \( \text{SOC}(0) \) and \( \text{SOC}(T) \) are the starting state and ending states of the battery SOC in a scheduling cycle, respectively.

(e) Distributed power output constraints

\[ P_{\text{PV}j_{\text{min}}} \leq P_{\text{PV}j}(t) \leq P_{\text{PV}j_{\text{max}}} \]  

(32)

where \( P_{\text{PV}j_{\text{max}}} \) and \( P_{\text{PV}j_{\text{min}}} \) are the upper and lower PVs in the photovoltaic storage.

4.2.2 Microgrid scheduling model

The microgrid scheduling was based on the MPC day-rolling optimization and the optimal dispatch strategy described in the previous section. With reference to the ahead-day plans formulated by the distribution network dispatch layer, we can stabilize the tie line power fluctuations between various micro-grids and distribution networks by adjusting the intraday charge and discharge plans of distributed energy storage in optical microcells\(^[18]\).

4.3 Model solution

Figure 9 shows the calculation flow chart. The genetic algorithm was used to solve the optimal power flow in the distribution network.

4.4 Case study

According to the scheduling strategy described earlier, the optimal power flow of the distribution network was solved under the premise of meeting various constraints.

Figure 10 illustrates the network loss comparison of the distribution network. After the photovoltaic grid, the grid loss of the distribution network increased compared with the original grid loss during the crossover period of the peak period of the photovoltaic power generation and the normal period of the load electricity consumption. The system loss can be reduced in the other periods of the photovoltaic generation. The system network loss was unchanged when the amount of photovoltaic power generation was zero.

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Fig. 9 Flow chart of the power flow calculation.
The overall system network loss dropped after the centralized energy storage was added into the grid. Meanwhile, the network loss increased in the period of 22:00-24:00. As shown in Figs. 11 and 12, this was caused by the energy storage requiring to meet the constraints of the remaining power in the start and the end. The load and the loss can increase when charging the energy storage during this time.

As shown in Fig. 13, the active power injected into the root node of the power distribution network was greater than zero during each period under the reasonable charging and discharging with centralized energy storage. Hence, the surplus power of the photovoltaic power generation can be completely absorbed in the distribution network and meet the constraints of the distribution network optimization operation.

Figure 14 shows the comparison chart of the voltage at each node of the distribution network. Table 3 presents the statistics of the voltage over-limit at the all-day node of the distribution network. The node voltage of the distribution network was low, especially at the peak load time, before the optical storage micro-grid and centralized energy storage were added into grid. The voltage of some nodes also dropped. The node voltage increased between 7:00 and 19:00 during the PV power generation period after PV was added into the grid. However, the gap between the PV output and the load became larger during the period of 12:00-13:00. The voltage rise also exceeded the operation constraint requirements, which was not conducive for the stable grid operation. The voltage stability was improved compared with the first two cases.
when the charge and discharge of the centralized energy storage were optimized, and the node voltage was within the range of 0.94–1.03 pu within the whole day, which met the voltage constraints for the safe system operation.

According to the “Notice of NDRC on Adjusting the Tariff of New Energy Targets (Draft)”, the benchmark electricity tariffs for photovoltaic grids will be reduced in 2017, and the on-grid tariffs for categories I, II and III resource zones will be adjusted to 0.55 yuan, 0.65 yuan, and 0.75 yuan, respectively. We took herein the highest price of photovoltaic electricity, (i.e., category III resource area) as a reference. We also took the Anhui province in the category III resource area as a reference for dividing peak and valley. Table 4 shows the time-sharing electricity price.

Table 5 lists the cost comparison, where the total operation cost of the optimized distribution network on that day dropped by 10,812.29 yuan. The network loss cost was 57.56% lower than that without optimization. In addition, the amount of the distribution network purchasing from the main network significantly dropped because of the photovoltaic power generation added into the grid. The pollution treatment costs decreased by 6449.39 yuan, thereby reducing the pressure of pollution control.

The installed capacity of the PV added into the grid was 400 kW in node 19, while the active load was only 32.43 kW. Taking the tie line power tracking status of the optical storage microgrid as an example, the simulation was performed as shown in Fig. 15. The distributed energy storage in the microgrid can achieve a smooth tracking of the power of the microgrid tie line by the rapid power response.

5 Conclusion

This study investigated the coordination and optimal scheduling of a distribution network with a microgrid and its related problems. First, a three-layer coordination control system of the distribution network and the micro-grid was established. Second, we analyzed the characteristics of the micro-source and the energy storage, and established the corresponding cost model. The optimal scheduling strategy of the micro-grid based on MPC was then studied to achieve economic optimization and a smooth output of the network operation. Finally, we studied the coordination and the optimal dispatch of the distribution network and the microgrid to improve the operation economy of the distribution network and reduce the impact of the distributed power on the operational stability of the distribution network.

In the future, we will consider studying the group control technology of the microgrid and the leapfrog transport of the distributed generation to improve the coordination and dispatch strategy of the distribution network and the microgrid.

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