Real-time dispatch strategy of microgrid based on fuzzy control of energy storage

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Abstract. Microgrid (MG) is effective to absorb the distributed renewable energy source (RES). Considering the uncertainty of RES and load, this paper proposes a fuzzy rule of energy storage system (ESS) and gets its output by anti-fuzzification in the real-time dispatch stage after receiving the actual load and RES value. Based on the envelope principle and fuzzy control, a grid-connected MG scheduling model is established. Considering the ultra-short-term forecasted data at the beginning of an hour, a receding-horizon scheduling model which includes the constraints of ladder price, ESS, RES, etc. and aims at the lowest operating cost, is established to correct the day-ahead scheduling error as the basic value of real-time scheduling at subsequent times. Taking a MG in Shaanxi Province as an example, the proposed strategy ensures the rapid and economic operation of MG.

1. Introduction

MG is viewed as an effective form to integrate large-scale RES, which not only can keep the reliable power supply to the local customers, but also self electricity to main grid at the Point of Common Coupling (PCC). Due to RES and load fluctuating quickly in short time scale, MG real-time dispatch is acquired to maintain power balance. Besides, to keep the balance between economic benefit and safety, how to manage ESS, controllable units (CG) and the transaction with main grid become a mutual constraint question during real-time dispatch. There are several literature investigating the scheduling model of MG. MG day-ahead scheduling model is presented based on the depreciation cost of battery [1]. To convert depreciation cost, rain-flow method is used by calculating the depth of charge and discharge state, which is converted into the number of cycles. However, the rain-flow method is not only complicated but is also used when given the existing operational data. In [2], a two-layer real-time scheduling model is established based on ESS cost. The top layer distributes the output of ESS and CG, and the bottom layer calculates the ESS cost based on the Lagrange equation for ultra-short-term forecast of real-time scheduling problems. ESS is optimized scheduling with lowest cost without considering power quality. In [3], a multiple time-scale cooperative optimization is proposed to fulfill the minimization of total operation cost based on model predictive control, but there is a lack of real-time scheduling research of ESS for a single period. In [4], considering day-ahead scheduling results, the real-time dispatching model is established based on values of RES and load updated by ultra-short-term forecast. However, the rolling schedule does not change the CG output decided by day-ahead scheduling, resulting in strongly dependence on day-ahead scheduling. The accuracy of the system is not guaranteed.
According to the ultra-short-term forecasted value of load and RES, [5] establishes a PCC power optimization model on multi-period, which can smooth PCC power fluctuations and reduce change rate of ESS. However, it weakens the function for ESS to clip peak and fill valley, and increases solving time. In [6], a multi-time MG optimization scheduling strategy is proposed with high practicability, which combines with day-ahead scheduling and real-time dispatch. However, when the day-ahead result deviates largely from the real value, climbing insufficiently will occur, resulting in the adjustment of PCC difficulty at that moment. According to day-ahead scheduling of ESS capacity, [7] establishes a real-time MG dispatch model based on network flow model with the goal of minimum equivalent cost. However, the calculation speed is slower than the heuristic algorithm. In [8], an active and reactive power joint real-time dispatch approach for MG is presented to reduce voltage deviation from reference value with voltage constraints. Compared with the active and reactive power independent scheduling, it cannot react to real-time power fluctuation of load and RES in time. In [9], power dispatching control utilizing mobile-commander scheme is proposed in “pyramid solar microgrid” with individual hybrid PV systems, which reduces power generation loss. It concentrates on the relation between hybrid PV systems. However, this method is lack of the control rule of ESS. Based on the day-ahead scheduling plan, an envelope principle is proposed to deal with PCC real-time deviations from plan in this paper. Combined with current state of ESS charge (SOC) and power fluctuations, a fuzzy control strategy is established to adjust the output of ESS with adequate reserve capacity, which utilizes fuzzy logic and approximate inference in order to quantify the human control experience. Considering the ultra-short-term forecasted data at the beginning of an hour, a receding-horizon scheduling model which includes the constraints of ladder price, ESS life, RES output, etc. and aims at the lowest operating cost, is established to correct the day-ahead scheduling error as the basic value of real-time scheduling at subsequent times [10]. Taking a MG in Shaanxi Province as an example, the proposed dispatch strategy verifies the rapidity and economy.

2. MG real-time dispatch model

2.1. PCC envelope principle

The uncertainties of RES and load in MG bring instantaneous fluctuation, resulting in the PCC power deviation from the planned operation point. Therefore, based on day-ahead scheduling results, an envelope is proposed to deal with power fluctuation as shown in figure 1. PCC power is controlled within the certain range, which is beneficial to reduce the triggering frequency of the device.

![Figure 1. An envelope of PCC day-ahead scheduling](image)

2.2. Units modeling for real-time dispatch

1) ESS modeling for real-time dispatch

Considering the limitation of capacity and maximum charging and discharging power, the upward and downward reserve power for real-time dispatch is shown in (1) and (2).

\[
P_{\text{up},k}^{ST}(t) = \min(P_{\text{dis},k}^{\text{max}} - P_{\text{dis},k}(t) + P_{\text{ch},k}(t), (SOC_k(t) - SOC_{k,\text{min}}) \eta_{\text{dis},k} / T_{\text{real}} - P_{\text{dis},k}(t)))
\]

\[
P_{\text{down},k}^{ST}(t) = \min(P_{\text{ch},k}^{\text{max}} - P_{\text{ch},k}(t) + P_{\text{dis},k}(t), (SOC_k^{\text{max}} - SOC_k(t)) / (\eta_{\text{ch},k} T_{\text{real}}) - P_{\text{ch},k}(t)))
\]
Where $P_{ch,k}(t)$, $P_{dis,k}(t)$ represent the charging and discharging power of ESS $k$, $P_{ch,k,max}$, $P_{dis,k,max}$ are the maximum charging and discharging power of ESS $k$, $SOC_{k,max}$, $SOC_{k,min}$ are the upper and lower bounds of SOC $k$, $\eta_{ch,k}$, $\eta_{dis,k}$ are charging and discharging efficiencies of ESS $k$.

2) CG modeling for real-time dispatch

The upward and downward reserve power of CG for real-time dispatch is shown in (3) and (4).

$$P_{CG,i,up}(t) = P_{CG,i,max} - P_{CG,i,real}(t)$$  \hspace{1cm} (3)

$$P_{CG,i,down}(t) = P_{CG,i,real}(t) - P_{CG,i,min}$$  \hspace{1cm} (4)

Where $P_{CG,i,min}$, $P_{CG,i,max}$ are the minimum and maximum technical output of CG $i$.

3) Operational constraints

Real-time dispatch keeps the power balance and maintains enough reserve power to deal with emergencies in MG at all times. In the case of multiple ESSs, its output must be allocated reasonably by its SOC to avoid excessive charging and discharging of a certain ESS. In this paper, PCC power exceed day-ahead plan is distributed to every ESS at the beginning, gradually accumulated residual value, which not only reduces the unbalance of ESS output, but also avoids excessive charging and discharging.

2.3. Fuzzy control strategy of ESS

Fuzzy control formalizes the expert knowledge of the controlled object domain through fuzzy logic and approximate reasoning, and establishes a mathematical model, which is effectively solved by the computer in real time. The fuzzy mathematics method is used to describe the fuzzy concepts of input variables and output variables and their corresponding functional relationships. How to design fuzzy principles is the core [11].

It is a fuzzy concept to control where PCC power lies in the envelope. Besides, fuzzy control prefers center position to boundary. Thus, the deviation degree of PCC power is divided into three fuzzy states: zero (Z), positive (P), and negative (N), then the membership function is established as shown in figure 2.

![](image)

**Figure 2.** Membership function of PCC power

The output of ESS is closely related to the safe operation of MG, and directly affects the life loss of ESS. When SOC or output is near the bounds, the life of ESS is severely damaged. According to fuzzy analysis, SOC is divided into three states: low (L), moderate (M), and high (H); the output of ESS is divided into three states: moderate (CD), big charge (BC), big discharge (BD). Finally, the membership function is established as shown in figure 3.

![](image)

**Figure 3.** Membership function: (a) SOC and (b) ESS’s output.
2.4. Real-time dispatch process

Power sources involved in real-time dispatch include: RES, ESS, CG, and controllable load. MG should supply reliable power to meet the load demand. Meanwhile, the RES is fully utilized. In order to reduce the operating cost, the output of CG should be cut down as much as possible. If PCC power is higher than planned value, real-time dispatch will sequentially increase the output of RES, ESS, CG, and controllable load. Otherwise, it will sequentially reduce the output of CG, ESS, and RES [13]. ESS is scheduled by fuzzy control, rule base of which is shown in Table 1.

Table 1. Fuzzy control rule of PCC power.

| Target of PCC power | L | M | H |
|---------------------|---|---|---|
| BC                  | Z | N | N |
| CD                  | N | Z | Z |
| BD                  | P | P | Z |

According to SOC and output power of ESS before scheduling, the target of PCC power is obtained by fuzzy inference. Then, the output of each device is further calculated. Based on fuzzy control, real-time dispatch strategy of MG is demonstrated in figure 4.

![Flowchart of real-time dispatch based on fuzzy control](image)

**Figure 4.** Flowchart of real-time dispatch based on fuzzy control
3. Real-time receding-horizon scheduling model for MG

3.1. Object function

\[
\min C = \sum_{j=1}^{J} \sum_{i=1}^{J} (C_{OM,j}(P_i(t)) + C_{DP,j}(P_i(t))) + \sum_{i=1}^{J} [C_i(P_i(t)) + C_{open,i}(t) + C_{OM,i}(P_i(t)) + C_{DP,i}(P_i(t))] + \sum_{j=1}^{J} [C_{env}(t) + P_{env}(t)] \Delta T - C_{sell}(t) + P_{sell}(t) \Delta T]
\]

Where \( A \) is the output power of ESS \( k \), \( C_{OM,k}(P_i(t)) \) is the maintenance cost of ESS \( k \), \( C_{DP,k}(P_i(t)) \) is the depreciation cost of ESS \( k \), \( P_i(t) \) is the output power of CG \( i \), \( C_i(P_i(t)) \) is the energy cost of CG, \( C_{open,i} \) is the start-up cost of CG \( i \). \( C_{OM,i}(P_i(t)) \) is the maintenance cost of CG \( i \). \( I_{open,i}(t) \) is the state of start-up time, 1 means starting up at this time. \( C_{buy}(t) \) is the purchase price of MG, \( P_{buy}(t) \) is the power purchase from main grid, \( C_{sell}(t) \) is the selling price, \( P_{sell}(t) \) is the selling power.

The maintenance cost and depreciation cost of ESS [12] are converted as follows:

\[
C_{OM,k} = K_{OM,k} \times |P_i(t)| \Delta T
\]

\[
C_{DP,k}(P_i(t)) = (E_{rated,k} \times C_{E,k}) \times L_{loss,k}
\]

Where \( K_{OM,k} \) is the maintenance cost coefficient of ESS \( k \); \( E_{rated,k} \) is the rated capacity of the ESS \( k \), \( C_{E,k} \) is the installation cost of the ESS \( k \); \( L_{loss,k} \) is the life loss factor of ESS \( k \).

3.2. Constraints

Constraints of receding scheduling include: maximum of purchase and sale power, maximum output of RES, minimum output times of CG, ESS and reserve constraints, etc. Due to space limitations, this paper focuses on the constraints of ESS [14]:

\[
SOC_k(t) = SOC_k(t-1) + (P_{sh,k}(t) \times \eta_{sh,k} / P_{dis,k}(t) \times \eta_{dis,k}) \Delta T
\]

\[
SOC_{k,min} \leq SOC_k(t) \leq SOC_{k,max}
\]

\[
I_{dis,k}(t) + I_{sh,k}(t) \leq 1
\]

\[
SOC_k(T) = SOC_k(0)
\]

4. Case Studies

4.1. Structure of the MG

The grid-connected MG in Shaanxi Province is shown in figure 5. The MG contains ESS, PV, CG and loads. ESS consists of two batteries whose capacity is 500kWh. The available range of SOC is from 10% to 90%. Parameters of ESS are listed in Table 2. The capacity of PV is 2MW. The maximum load of the MG is about 1500kW. Resolution of real-time dispatch is 5 minutes.
Forecast and actual value of load and PV power are shown in figure 6. PCC power of day-ahead scheduling and the ladder price are shown in figure 7.

Figure 5. Single line diagram of the MG

Table 2. Parameters of ESS

| Parameters     | Value  | Parameters | Value |
|----------------|--------|------------|-------|
| Rated capacity | 500 kWh| $\eta_{ch}$ | 0.99  |
| $P_{\text{dis,max}}$ | 500 kW  | $\eta_{dis}$ | 0.98  |
| $P_{\text{ch,max}}$ | 50 kW   | $K_{OM}$    | 0.2 ¥/kWh |
| Cycle life     | 5000   | $C_E$      | 1700 ¥/kWh |

4.2. Real-time dispatch results

As shown in figure 8(a), we can see that real-time dispatch keeps power balance the whole day. The real-time output is adjusted based on day-ahead scheduling in figure 8(b). Forecasted value is smaller than the actual value due to the load fluctuation. Therefore, ESS is charged in low electricity price, and discharged in high price, which serves to cut the peak and fill the valley. Moreover, SOC of two batteries are consistent nearly all the time, which could increase the average life. As shown in figure 8(c), the actual purchased power follows the day-ahead plan and satisfies the constraints of main grid. Due to huge error between the forecasted and actual load, the purchased power is generally higher than plan.
Figure 8. Real-time dispatch results: (a) power balance, (b) SOC and (c) PCC power.

There are 288 periods in the real-time dispatch. Due to the forecasted error, the initial value of the PCC often exceeds the envelope. Thus, the real-time dispatch is triggered 243 times to correct the day-ahead scheduling. The results show that PCC power is approximated to the shape of the day-ahead which proves the importance of real-time dispatch. The RES utilization rate was 100%. There is no load shedding in MG all day. The solving time of proposed model is within 5 seconds. ESS is dispatched to discharge at peak and charge at valley, which plays an important role in reduce operating costs for MG.

4.3. Comparison with no fuzzy control dispatch

The ESS is dispatched without fuzzy control, which is discharged in the peak of the electricity price and charged in the valley. The scheduling results are shown in Fig. 9. It can be seen from the Table 3 that the operating cost of MG real-time scheduling has been decreased by 7.69%, from 3401.330 yuan to 3071.056 yuan through fuzzy control. Besides, the actual PCC power curve is more approximate to the day-ahead plan, which means that MG is a friendly part of main grid.

Table 3. Comparison of operating costs

| Cost                | Fuzzy control (¥) | No fuzzy control (¥) |
|---------------------|-------------------|----------------------|
| Electricity purchase| 3695.162          | 4048.129             |
| ESS cost            | 357.231           | 312.578              |
| Electricity Sales   | 624.106           | 646.799              |
| Sum                 | 3428.287          | 3713.908             |

5. Conclusion

In this paper, a real-time dispatch strategy based on fuzzy control of ESS is proposed. Moreover, a receding-horizon scheduling model which aims at the lowest operating cost is established to correct the day-ahead scheduling error. Based on the updated optimization scheduling plan, an envelope principle is proposed to deal with PCC deviations from plan and to dispatch units in real-time. The PCC power is controlled within the envelope of the plan power, which makes the MG be controllable as seen from the main grid. This paper combines heuristic algorithm with optimization algorithm, in
order to meet the requirements of economic operation and calculation speed. The ESS can be reasonably dispatched to absorb the power fluctuations by fuzzy control.

6. References
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