Bi-level Coordinated Optimal Dispatching Method of Power System Considering Renewable Energy Uncertainty and Flexible Load Aggregators

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Abstract. The increase of renewable energy penetration and the diversity of flexible loads in the customer side have posed new challenges to secure and economic dispatching of power system. Based on the concept of load aggregator (LA), we propose a bi-level optimal dispatching model for power system. In order to guarantee the security of power system operation, we propose a bi-level coordinated dispatching method to consider the aggregation of various flexible loads and the uncertainty of renewable energy generation, which can realize efficient and economic dispatch of power system. Numerical results in one test system demonstrate that our proposed dispatching model can reduce the total dispatch cost and LA’s electricity bill simultaneously.

1. Introduction

With the ongoing transformation of energy structure, the penetration of renewable energy, especially wind and solar power, is increasing. Owing to the intermittency and volatility of renewable resources which bring in the flexibility and economy problem, it’s difficult to achieve the balance of supply and demand of power system only by the regulation of generation side. At present, how to effectively utilize demand response (DR) technology to tap the dispatch potential from the user side, so as to increase the flexibility of power system has become a hot topic at home and abroad [1].

In the case of deteriorating load characteristics, electric vehicles (EV), air conditioning (AC) load, distributed energy station (DES) and other user side controllable loads can adjust their power demand in a short time, and do not affect or less affect the performance of the equipment itself and the user’s comfort [2]. Through reasonable controlling means, it can not only stabilize the intermittent net load fluctuations, reduce the peak valley difference of the system, but also increase the installed capacity of renewable energy which can reach low capital cost and good social and economic benefits.

The dispatch of the typical flexible loads mentioned above in a large scale to respond to the real-time demand has been investigated [3]. In [4], the optimal control model of AC load is proposed on the basis of considering user comfort and load adjustment space and a bi-level optimal scheduling and control model of direct load control (DLC) of AC load is established. An energy trajectory based behavioral boundary model for electric vehicles is designed to realize the orderly charging and discharging of electric vehicles in long time scale so as to participate in the dispatch of the power system [5]. In order to promote the effective participation of DES in power grid peak shaving, a
large-scale aggregation management and an optimization model of DES aggregator participating in power grid peak shaving scheduling in the form of bidding is established which not only utilizes the DES effectively but also performs well in peak load shifting [6].

Note that flexible loads are often difficult to be managed efficiently and be dispatched timely. As a result, load aggregators, one of the essential market players in the operation of distributed flexible resources participating in distributed electricity market emerge to integrate and manage all kinds of distributed generation, energy storage device and active load in the power market [7]. Its flexible demand response service can effectively solve the dispatching obstacles of the independent system operator to the distributed load side resources, and realize the source-load interaction [8]. In reference [9], from the perspective of load aggregators participating in the balance of power system interests, a bi-level optimal dispatch model with LA is constructed, which shows that LA has a stabilizing effect on the peak load of power system, thus promoting the economic operation of power system. In [10], by the use of load reduction, load transfer and energy storage devices, LA participates in the demand side response, and the article analyzes the impact of price mechanism on LA optimization model. [11] investigates from the price perspective as well with a bi-level optimization model for EV aggregators to participate in electricity market established, and the bidding strategy of EV aggregators is studied. Moreover, a double layer real-time dispatch model of independent microgrid based on LA dispatch priority is proposed, and the influence of different strategy’s degree of confidence on the operation cost and LA revenue of microgrid is analyzed [12].

Most researches on the joint optimal operation and dispatch of LA and power grid usually regard LA as a commercial entity, ignoring its network topology, focusing on the economy of LA participating in the market, and rarely consider the dispatch cost of power grid. In this work, we focus on ensuring the security and economy of power grid as well as guaranteeing LA’s benefits and we take renewable energy generation and multiple kinds of flexible loads into account.

The remainder of this paper is organized as follows. Section 2 introduces renewable energy generation uncertainty model and economic dispatch model of LA is proposed in Section 3. In Section 4, the bi-level optimal dispatch model of power system is proposed. Case studies to validate the effectiveness of the proposed model are presented in Section 5. The paper is concluded in Section 6.

2. Renewable energy generation model

In order to describe the uncertainty of renewable energy generation such as wind power and solar power, the output power models of wind turbine and photovoltaic (PV) are proposed in this section.

2.1. Wind power output model

The approximate relationship between wind turbine output power $P_{wt}(v)$ and wind speed $v$ can be expressed by the following piecewise function:

$$P_{wt}(v) = \begin{cases} 
0 & 0 \leq v \leq v_{ci} \\
\frac{P_{wt-rate}}{v_r - v_{ci}} (v - v_{ci}) & v_{ci} \leq v \leq v_r \\
\frac{P_{wt-rate}}{v_{co} - v_r} (v_{co} - v_r) & v_r \leq v \leq v_{co} \\
0 & v_{co} \leq v
\end{cases}$$

(1)

where $v_{ci}, v_{co}, v_r$ represent cut-in wind speed, cut-out wind speed and rated wind speed respectively; $P_{wt-rate}$ is the rated output power of wind turbine.

2.2 Solar power output model

The output power of PV array is affected by light intensity and ambient temperature, which can be formulated as follows:

$$P_{pv} = P_{STC} \frac{G_c}{G_{STC}} [1 + k(T_c - T_r)]$$

(2)

where $P_{pv}$ is the actual output power of PV module; $P_{STC}$ is the maximum output power of photovoltaic array under standard test conditions; $G_c$ is the actual irradiation intensity; $G_{STC}$ is the
irradiation intensity under standard test conditions; \( k \) is power temperature coefficient; \( T_c \) and \( T_r \) represent the battery temperature and reference temperature respectively.

3. Economic dispatch model of load aggregator

3.1. Objective function

According to the demand of the grid, load aggregators mainly transfer all kinds of internal adjustable load resources whose dispatch cost consists of the fee for purchasing power from power grid, the penalty fee for insufficient reduction of power supply and the compensation fee provided to the load users involved. The cost function of load aggregators is listed as follows:

\[
\min \left[ \sum_{u \in U} \left( \sum_{t \in T} p_{t,u}^{\text{buy}} \cdot y_t^{\text{buy}} + \sum_{t \in T} \left| p_{t,u}^{\text{plan}} - p_{t,u}^{\text{com}} \right| \cdot y_t^{\text{pen}} + \sum_{t \in T} \sum_{i \in I} \lambda_{i,t,u} y_{i,t,u}^{\text{com}} \right) \right]
\]

(3)

where \( p_{t,u}^{\text{buy}} \) is the power purchased from the grid with the electricity price denoted as \( y_t^{\text{buy}} \); \( p_{t,u}^{\text{plan}} \) is the day ahead plan power; \( y_t^{\text{pen}} \) represents the penalty price; \( \lambda_{i,t,u} \) is a binary variable the value of which is 1 if the user participate in and \( y_{i,t,u}^{\text{com}} \) is the compensate price.

3.2. Constraints

Load aggregators are able to dispatch air conditioning load, electric vehicle, distributed energy storage and large industrial load, based on this the related constraints of all kinds of loads dispatched are described as the following:

\[
t_{\text{off}} = \mu C \ln \left( \frac{T_{\text{out}} - T_{\text{min}}}{T_{\text{out}} - T_{\text{max}}} \right)
\]

(4)

\[
t_{\text{on}} = \mu C \ln \left( \frac{\mu P \psi_c + T_{\text{max}} - T_{\text{out}}}{\mu P \psi_c + T_{\text{min}} - T_{\text{out}}} \right)
\]

(5)

\[
p_{AC,\text{buy}} = \sum_{i \in I^{AC}} \lambda_{i,t,u} y_{i,t,u}^{\text{com}} \cdot k_{i,t,u} \cdot P \quad u \in U^{AC}, t \in T^{AC}, i \in I^{AC}
\]

(6)

\[
k_{i,t,u} \leq \frac{T}{t_{\text{on}}^{i,t,u} + t_{\text{off}}^{i,t,u}} \quad u \in U^{AC}, t \in T^{AC}, i \in I^{AC}
\]

(7)

\[
p_{\text{EV, buy}} = \sum_{i \in I^{EV}} \left( p_{i,t,u}^{\text{cha}} a_{i,t,u} - p_{i,t,u}^{\text{dis}} b_{i,t,u} \right) \quad u \in U^{EV}, t \in T^{EV}, i \in I^{EV}
\]

(9)

\[
\begin{cases}
0 \leq p_{i,t,u}^{\text{cha}} a_{i,t,u} \leq p_{\text{cha,max}}^{\text{max}} \\
0 \leq p_{i,t,u}^{\text{dis}} b_{i,t,u} \leq p_{\text{dis,max}}^{\text{max}} \\
a_{i,t,u} + b_{i,t,u} = 1 \\
a_{i,t,u}, b_{i,t,u} \in \{0, 1\}
\end{cases}
\]

(10)

\[
SOC_{i,t-1,u} + \frac{E_{i}^{\text{cap}}}{\eta_{\text{cha}}} \left( \frac{p_{i,t,u}^{\text{cha}} a_{i,t,u} - p_{i,t,u}^{\text{dis}} b_{i,t,u}}{\eta_{\text{dis}}} \right) \cdot \Delta T \quad t \geq 2
\]

(13)

\[
SOC_{i,\text{ini},u} + \frac{E_{i}^{\text{cap}}}{\eta_{\text{cha}}} \left( \frac{p_{i,t,u}^{\text{cha}} a_{i,t,u} - p_{i,t,u}^{\text{dis}} b_{i,t,u}}{\eta_{\text{dis}}} \right) \cdot \Delta T \quad t = 1
\]

(14)

\[
p_{\text{shift},i,t,u}^{\text{max}} - SOC_{i,t,u}^{\text{max}} \leq SOC_{i,t,u} \leq SOC_{i,t,u}^{\text{min}} \leq SOC_{i,t,u}^{\text{max}} \quad u \in U^{EV}, t \in T^{EV}, i \in I^{EV}
\]

(14)

\[
p_{t,u}^{\text{shift},i,t,u} = \sum_{i \in I^{\text{IU}}} \left( p_{t,u}^{\text{shift},i,t,u} + P_{\text{cut},i,t,u} \right) \quad u \in U^{IU}, t \in T^{IU}, i \in I^{IU}
\]

(15)

\[
\sum_{t = a^-}^{b^+} \lambda_{\text{shift},i,t,u} p_{\text{shift},i,t,u}^{+} = \sum_{t = a^-}^{b^+} \lambda_{\text{shift},i,t,u} p_{\text{shift},i,t,u}^{-} \quad u \in U^{IU}, t \in T^{IU}, i \in I^{IU}
\]

(16)
In the above formulation, constraints (4) and (5) describe the equivalent thermal parameters (ETP) model of AC. \( \tau_{off} \) and \( \tau_{on} \) are the downtime and cooling period. \( \mu \) and \( C \) are the thermal resistance and thermal capacity parameters of the room respectively, with \( \psi_{\text{COP}} \) denoting the refrigeration energy efficiency ratio of AC; \( P \) is the power of AC; Constraint (6) represents the aggregated power of AC while constraint (7) limits the start-stop number of AC and constraint (8) guarantees each user can only participate in one scheme.

Constraint (9) is the aggregated power of EV. \( a_{t}\) are charging and discharging binary variables which guarantee EV can only charge or discharge at a time by constraints (11) and (12). Constraint (10) limits the maximum charging and discharging power. Constraint (13) describes the state of charge (SOC) of EV battery with \( \eta_{\text{char}}, \eta_{\text{dis}}, E_{i}^{\text{cap}} \) representing charging efficiency, discharging efficiency and battery capacity respectively, and constraint (14) places restrictions on SOC conditions too. Moreover, constraints (9)-(14) can be formulated to describe DES model as well.

Industrial load can be divided into reducible loads denoted by \( P_{\text{cut},t,u} \) and shiftable loads denoted by \( P_{\text{shift},t,u} \). The aggregated power of industrial load is described by constraint (15). Constraint (16) indicates that the amount of shiftable loads doesn’t change after transfer. Constraint (17) and (18) restricts the maximum shifting power before shift and after shift respectively. The power after cut is described by constraint (19) and the reduced power is limited by constraint (20).

4. Bi-level optimal dispatch model of power system

4.1. Problem formulation

The proposed approach has two functionalities: (i) demand management of the power system, and (ii) electricity bill allocation among all load aggregators. Thus, the proposed approach is formulated as a bi-level programming model. The upper level explores dispatch decisions of power system with the target of minimizing the grid cost and allocate the power demand to each load aggregator who is going to schedule its’ output aiming to minimize the energy bill on the lower level. The framework of the proposed bi-level optimization model is shown in figure 1 with the model formulated as the following:

Objective function for the upper level

\[
\min \sum_{t \in T} \left( \sum_{g \in G} P_{g}(P_{\text{gt}}) + \sum_{n \in N} P_{n,t} \cdot \gamma_{n,t} \right)
\]

Constraints for the upper level

\[
\sum_{w \in W} P_{w,t} + \sum_{s \in S} P_{s,t} + \sum_{g \in G} P_{g,t} = \sum_{b \in B} P_{b,t} + \sum_{n \in N} P_{n,t}
\]

\[
\sum_{b \in B} K_{ib} \left( \sum_{g \in G(b)} P_{g,t} + \sum_{w \in W(b)} P_{w,t} + \sum_{s \in S(b)} P_{s,t} - \sum_{n \in N(b)} P_{n,t} - P_{\text{load}}^{\text{b,t}} \right) \leq c_{i}^{\text{max}}
\]

Objective function for the lower level

\[
\min \left[ \sum_{u \in U} \left( \sum_{t \in T} P_{u,t} \cdot \gamma_{t} + \sum_{t \in T} P_{\text{buy}}^{\text{u,t}} \cdot \gamma_{t}^{\text{buy}} + \sum_{t \in T} P_{\text{plan}}^{\text{t,u}} \cdot \gamma_{t}^{\text{plan}} + \sum_{t \in T} \sum_{i \in I} \lambda_{i,t,u} \gamma_{i,t,u} \right) \right]
\]
Constraints for the lower level

\[ P_{n,t}^b = \sum_{u \in U} P_{r,u}^{buy} \quad \text{s.t.} \quad (4) - (20) \quad (29) \]

The objective function (21) of the upper-level problem minimizes the total cost of power system consisting of the generation cost and the cost of dispatching load aggregators where \( F_g(.) \) represents the quadratic fuel cost function and \( y_{n,t} \) represents selling price from LA to grid. Constraint (22) describes the total power balance of power system. The transmission network security is guaranteed by constraint (23) which takes direct current (DC) power flow into account with \( K_{lb} \) and \( C_{max} \) denoting the sensitivity factor of line and the maximum transmission capacity of line. Constraints (24) and (25) make sure that the unit operates within the ramping rate limit between two consecutive period. The maximum and minimum power output of thermal units, wind generator and PV are limited by constraints (26) – (28) respectively. The lower-level problem’s objective function and constraints are the same as what are proposed in the last section. Constraint (30) indicates that the dispatch results of the upper level are transferred into the lower level.

4.2. Solution methodology

To jointly solve the upper-level problem and the lower-level problem, we firstly obtain the real time power demand of the load aggregators by minimizing the total cost of the power system in the upper level. Based on the dispatch results, load aggregators in the lower level aiming to reduce their electricity bill will allocate their internal loads. In addition, the solution flowchart of the proposed bi-level optimization model is presented by figure 2.

5. Case study

In this section, our proposed bi-level optimal dispatch model is tested via RTS-24 system, as shown in figure 3. The installation nodes of wind power and photovoltaic are 13,15 and 3,18 respectively. The inserting node of LA is 7. The load curve in one day is shown in figure 4. The basic load of LA is 1200 kW, involving AC load, EV, DES and large industrial load. The time-of-use tariff is adopted for the
cost of purchasing and selling electricity from LA to power grid which is shown in table 1 and the selling price of LA to power grid is set as 0.8 times of the purchasing price.

In this paper, the GAMS software is used to call solver to solve the model. The AMD Ryzen 5 3600 6-Core Processor CPU and 3.6 GHz personal computer are used to analyze the case on GAMS win64 24.1.3 platform.

![Figure 3. The RTS-24 testing system](image)

![Figure 4. Daily load variation curve](image)

| Table 1. The time-of-use tariff            |
|-------------------------------------------|
| **Type** | **Time division** | **Electricity price/(yuan/kWh)** |
| Peak period | 8:30-11:00,18:30-23:00 | 0.9531 |
| Normal period | 7:00-8:30,11:00-18:30 | 0.6512 |
| Valley period | 23:00-7:00 | 0.3494 |

5.1. Optimization results and analysis
In order to verify the feasibility and applicability of the proposed method, the following two schemes are designed, scheme1: LA participation in the market is not considered; scheme 2: The proposed bi-level optimal dispatch model.

5.1.1. Traditional dispatch model without LA participation. First of all, the economic improvement of renewable energy generation penetration to power system dispatch without considering LA is illustrated. By setting different penetration rate of renewable energy generation, the optimal dispatch model of power grid is solved repeatedly, the total cost of the power system is shown in table 2.

| Table 2. Dispatch cost with different renewable energy penetration rate |
|---------------------------------------------------------------|
| **Renewable energy penetration** | **Dispatch cost (yuan)** |
| 10% | 860211.38 |
| 20% | 769644.92 |
| 30% | 687622.34 |
It can be seen from the result that with the increase of renewable energy penetration, the total cost of power system dispatch is constantly decreasing.

5.1.2. Bi-level optimal dispatch model with LA participation. When LA participates in the market, it is necessary to consider the impact of its economic dispatch on the safety and economy of the power system operation. Naturally, we consider the scenario of renewable energy penetration rate of 10%. The results of the dispatch cost with and without LA participation are listed in table 3.

| Scenario    | Dispatch cost (yuan) |
|-------------|----------------------|
| With LA     | 756671.14            |
| Without LA  | 860211.38            |

It can be concluded from the table that the participation of LA can effectively reduce the dispatch cost on the premise of ensuring the security of power system, and at the same time, the electricity bill of LA can be cut down to only 11682.26 yuan which guarantees the cost of LA is the lowest during the dispatch. Additionally, the real time consumption curve of load aggregator is presented in figure 5. Compared with the daily load curve, we can notice that the energy consumption of LA increases in the low load period and decreases in the peak load period. Therefore, the participation of LA can not only reduce the cost of power system dispatch, but also effectively achieve the peak load shifting goal.

![Figure 5. The real time consumption curve of LA](image)

6. Conclusion
Under the market environment, with the growing number of renewable energy generation, the two-way interaction between users and power system is enhanced, which increases the complexity of power system optimal dispatch. In order to realize economic dispatch of LA on power system, a bi-level optimal dispatch model considering LA participation is proposed in this paper. Simulation results demonstrates the superiority of the proposed model which are able to reduce the dispatch cost, lower LA’s electricity bill and make better utilization of renewable energy generation simultaneously.
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