Research on optimal dispatching method of power systems with high proportion of clean energy based on multi-energy complementarity

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Abstract. The rapid development and large-scale utilization of clean energy is not only conducive to alleviate the global fossil energy crisis, but also brings huge economic and environmental benefits. However, the uncertainty of new energy represented by wind power and photovoltaic power brings a lot of impact on the operation and dispatching of the power system. Hence, it’s urgent to explore a new dispatching mode adapted to the power system with high proportion of clean energy. The optimal dispatching method of power system with high proportion clean energy based on multi-energy complementarity is explored with goal of making full use of clean energy and reducing the operating cost. Particle swarm optimization algorithm and branch and bound method are used to solve the cascade hydropower optimal dispatching problem and the wind, photovoltaic, thermal power joint optimal dispatching problem respectively. Finally, the feasibility of the model is verified by an example.

1. Introduction

Since the global industrialization, the traditional fossil energy has been widely developed and utilized, and the limited reserves and a large number of environmental problems seriously threaten the sustainable development of human economy and society. Countries all over the world are actively developing the exploration and utilization of renewable clean energy represented by wind energy and solar energy. At present, under the condition that the installed capacity of IPS (Intermittent Power Source) accounts for a small proportion, there has been a serious curtailment of clean energy in China. In order to realize sustainable development, complete the replacement of renewable energy to traditional fossil energy, and effectively improve the consumption of IPS, there is an urgent need to explore the optimal dispatching mode to adapt to the power system with high proportion of clean energy.

When modelling the economic dispatch of the power system with large-scale IPS, the random variable representing the output of IPS is introduced on the basis of the original DED (Dynamic Economic Dispatch) model. How to deal with random variables is a key problem. The existing research on dealing with the random variables in the model are mainly divided into three categories. One is the interval number model based on interval prediction information of IPS. A two-layer robust interval unit commitment model is established by introducing discrete decision variables of conventional units and energy storage system into the robust interval economic dispatching model in...
literature [1]. In literature [2], a nonlinear dual optimization method for interval economic dispatching is proposed, the wind power is described as interval number, and a two-layer nonlinear economic dispatching model is established. One is the probability model based on probability of the output of IPS. In literature [3], the equality constraint of power balance is relaxed to inequality constraint, and the power balance constraint is transformed into a related opportunity programming model to maximize the probability of random event occurrence in uncertain environment. A multi-scenario optimization model considering wind power and load fluctuation is established in literature [4]. Based on the previous research, the probability density function of deviation of the output of wind power is established in literature [5], and the spanning reserve acquisition model is constructed based on the opportunity constraint programming method. In addition, there is a method to establish the fuzzy number model based on the credibility measure of the output of IPS. In literature [6], a robust fuzzy model is established by considering the uncertainty of both sides of power generation and consumption. In literature [7], the fuzzy confidence is set to an incremental vector considering the change of prediction accuracy of IPS under different time scales. A multi-time-scale fuzzy chance constrained dispatching model is established.

However, the proportion of clean energy in the power system involved in the existing research is still low, especially it is difficult to realize the optimal dispatching of the system with high proportion of IPS. In this paper, an optimal dispatching method based on multi-energy complementarity is proposed, which is suitable for system with high proportion of IPS. The different characteristics of various energy forms are analyzed. Appropriate adjustment of model parameters can be applied to the actual power grid dispatching according to the development direction of the actual power grid in the future.

Firstly, the optimal dispatching model of power system with high proportion clean energy is established and simplified, then the problem is decoupled, and the hydropower and thermal/wind and photovoltaic power are optimized respectively. Finally, the effectiveness of the model is verified by numerical simulation. The model takes into account the thermal power, hydropower, wind power and photovoltaic power, makes use of the peak regulation ability of the system as much as possible, promotes the consumption of wind power and photovoltaic power on the premise of ensuring the safe operation of the system, and improves the economy of the system operation at the same time.

2. Optimal dispatching model based on multi-energy complementarity

2.1. Objective function

In order to achieve the goal of reducing the generation cost of thermal units as much as possible on the basis of fully absorbing clean energy in a power system with high proportion of clean energy. The objective function of the optimal dispatching model is the sum of the total generation cost of thermal units and the penalty cost of curtailed wind power and photovoltaic power:

$$\min \sum_{s \in S} p(s) \sum_{t=1}^{T} [F^t_r (t) + F^t_r (t)]$$

(1)

Here, $s$ is the scenario with different prediction error of load, wind power and photovoltaic power, $S$ is the collection of all possible scenarios, $p(s)$ is the probability of the scenario $s$, and $\sum p(s) = 1$, $T$ is the number of dispatching periods, take $T = 24$ hours; $F^t_r (t)$ is the total generation cost of thermal unit $t$ in scenario $s$, and $F^t_r (t)$ is the penalty cost of IPS curtailment in scenario $s$.

Furthermore, the generation cost can be divided into the coal consumption cost and the start-up/shutdown cost.

$$F^t_r (t) = F^t_g (t) + F^t_q (t)$$

(2)

$$F^t_g (t) = \sum_{m=1}^{m} u_{mt,j} (a_{mt} + b_{mt} P_{mt,j} + c_{mt} P_{mt,j}^2)$$

(3)
\[ F_q(t) = F_{q1}(t) + F_{q2}(t) \]
\[ = \sum_{m=1}^{M} u_{m,t} \cdot (1-u_{m,t-1} \cdot \left[ K_{m} + B_{m} \cdot \left( 1-e^{X_{m,off}} \right) \right]) + \sum_{m=1}^{M} u_{m,t-1} \cdot (1-u_{m,t})G_{m,t} \]  

(4)

Where \( M_t \) represents the collection of thermal units, and \( F_q(t) \) represents the cost of coal consumption, \( F_{q1}(t) \) and \( F_{q2}(t) \) correspond to start-up cost and shutdown cost respectively, \( a_m, b_m, \) and \( c_m, \) are the cost coefficient of coal consumption of unit \( m_t; \) \( K_m \) and \( B_m \) are fixed cost coefficient and variable cost coefficient in the process of unit start-up, respectively; \( X_{m,off} \) is the length of time that the unit \( m_t \) has been shut down continuously before time \( t, \) \( \tau_m \) is the cooling time constant of unit \( m_t, \) \( G_{m,t} \) is the shutdown cost of unit \( m_t. \)

And the penalty cost of IPS curtailment can be expressed as follow:

\[ F_2(t) = \mu_w \sum_{m=1}^{M_w} \sum_{t=1}^{T} (\bar{P}_{mv,w,t} - P_{mv,w,t}) + \mu_p \sum_{m=1}^{M_p} \sum_{t=1}^{T} (\bar{P}_{mp,p,t} - P_{mp,p,t}) \]  

(5)

Here, \( \mu_w \) and \( \mu_p \) are the coefficient of wind power curtailment and photovoltaic power curtailment, respectively. \( M_w, M_p \) are the collections of wind farms and photovoltaic farms, respectively. \( \bar{P}_{mv,w,t} \) and \( P_{mv,w,t} \) are the expected and actual wind power output of wind farm \( m_w, \) and the subscript \( m_p \) for photovoltaic farms.

Although the two parts of the objective function are both nonlinear, they can be linearized according to literature [8].

2.2. Constraints

2.2.1. Minimum start and stop time constraint

\[ u_{m,t} = 1, t \in \left[ I_{on,m}, I_{off,m} \right], I_{on,m} = \min \{ T, (T_{on,m} - X_{on,m,0})u_{m,0} \} \]
\[ \sum_{n=1}^{y} u_{m,n} \geq T_{on,m}(u_{m,t} - u_{m,t-1}), t \in \left[ I_{on,m} + 1, T - T_{on,m} + 1 \right] \]  

(6)

\[ \sum_{n=1}^{y} \left[ u_{m,n} - (u_{m,t} - u_{m,t-1}) \right] \geq 0, t \in \left[ T - T_{on,m} + 2, T \right] \]

\[ u_{m,t} = 0, t \in \left[ I_{off,m}, D_{off,m} \right], D_{off,m} = \min \{ T, (T_{off,m} + X_{off,m,0})(1-u_{m,0}) \} \]
\[ \sum_{n=1}^{y} (1-u_{m,n}) \geq T_{off,m}(u_{m,t} - u_{m,t-1}), t \in \left[ D_{off,m} + 1, T - T_{off,m} + 1 \right] \]  

(7)

\[ \sum_{n=1}^{y} \left[ 1 - u_{m,n} - (u_{m,t} - u_{m,t-1}) \right] \geq 0, t \in \left[ T - T_{off,m} + 2, T \right] \]

Here, \( I_{on,m} \) and \( D_{off,m} \) denote the periods during which the unit \( m_t \) must be open and off at the beginning of the dispatching cycle, respectively; \( X_{on,m,0} \) indicates the time that the unit \( m_t \) has been turned on or down continuously at the beginning of the dispatching cycle, a positive number indicates online-time, and a negative number indicates off-time; \( U_{on,m,0} \) is the state of the unit \( m_t \) at the beginning of the dispatching cycle; \( T_{on,m} \) and \( T_{off,m} \) are the minimum continuous online-time and off-time of the unit \( m_t, \) respectively.

2.2.2. Constraint on the output of the units. The output of thermal units should not exceed the maximum output at any time, and the change of output in adjacent period should be less than the
maximum climbing capacity. The planned output of wind power farms and photovoltaic farms should be less than the expected value of predicted power.

$$\max \left\{ -P_{\text{mt}}^{\text{down}}, \bar{P}_{\text{mt}} - P_{\text{mt},t} \right\} \leq P_{\text{mt},t+1} - P_{\text{mt},t} \leq \min \left\{ R_{\text{mt}}^{\text{up}}, \bar{P}_{\text{mt}} - P_{\text{mt},t} \right\}$$

$$P_{\text{mt}} \leq P_{\text{mt},t} \leq \bar{P}_{\text{mt}}$$
$$0 \leq P_{\text{mt},t} \leq \bar{P}_{\text{mt},t}$$

(8)

Here, $\bar{P}_{\text{mt}}$ and $P_{\text{mt}}$ are the capacity and minimum technical output power of unit $\text{mt}$, respectively, and the subscript $\text{mh}$ is corresponding to hydropower units; $R_{\text{mt}}^{\text{up}}$ and $R_{\text{mt}}^{\text{down}}$ are the upward and downward climbing capacity of unit $\text{mt}$, respectively.

For hydropower stations, there are some additional constraints on storage capacity and generating flow.

$$P_{\text{mh},t} = c_1 \bar{V}_{\text{mh},t} + c_2 V_{\text{mh},t}^2 + c_3 Q_{\text{mh},t} + c_4 \bar{Q}_{\text{mh},t} + c_5 \bar{Q}_{\text{mh},t} + c_6$$

$$Q_{\text{mh},t}^{\min} \leq Q_{\text{mh},t} \leq Q_{\text{mh},t}^{\max}$$

$$V_{\text{mh},t}^{\min} \leq V_{\text{mh},t} \leq V_{\text{mh},t}^{\max}$$

(9)

$$Q_{\text{mh},t} = V_{\text{mh},t+1} - V_{\text{mh},t} + I_{\text{mh},t} + \sum_{i=1}^{S_{\text{mh}}} Q_{\text{mh},t-i}$$

Here, $c_1$ and $c_2$ are hydropower conversion coefficients of hydropower station $\text{mh}$; $Q_{\text{mh},t}$ is the generating flow of hydropower station $\text{mh}$ in the period $t$, which should be between the maximum value $Q_{\text{mh},t}^{\max}$ and the minimum value $Q_{\text{mh},t}^{\min}$; $V_{\text{mh},t}$ is the storage capacity of hydropower station $\text{mh}$ at the end of the period $t$, which should be between the maximum value $V_{\text{mh},t}^{\max}$ and the minimum value $V_{\text{mh},t}^{\min}$; $\bar{V}_{\text{mh},t}$ is the average storage capacity of the reservoir $\text{mh}$ for the period $t$ used in the hydropower conversion relationship, take the mean value of the storage capacity at both ends of the period; The generating flow $Q_{\text{mh},t}$ of hydropower station $\text{mh}$ in the period $t$ should be the sum of the change of storage capacity of reservoir $\text{mh}$ and the natural water inflow $I_{\text{mh},t}$ in the period $t$. If there are $S_{\text{mh}}$ hydropower stations superior to the hydropower station $\text{mh}$, then the generating flow of all the upper hydropower stations considering lag time $\tau_{\text{mh},n}$ should be added. $V_{\text{mh},T}$ is the storage capacity of reservoir $\text{mh}$ at the end of dispatching cycle, which should be equal to the planned value $V_{\text{mh},\text{end}}$.

2.2.3. Power balance constraint

$$L_t = \sum P_{\text{mt},t}^s + \sum P_{\text{mh},t}^s + \sum P_{\text{mp},t}^s + \sum P_{\text{mp},t}^s$$

(10)

Here, $L_t$ is the sum of the load and prediction error of wind power and photovoltaic power of scenario $s$, which is referred to as load for short in the following text.

2.2.4. Maximum power of transmission line constraint

$$-P_{f_t}^{\max} \leq P_{f_t} \leq P_{f_t}^{\max}$$

(11)

Here, $P_{f_t}$ represents the transmission power on line $l$ during the period $t$, which is positive when it flows in the same direction as the positive direction and is negative on the contrary. $P_{f_t}^{\max}$ is the maximum forward transmission capacity of line $l$. 
3. Model solving
Because the optimal dispatching problem of power system with high proportion of clean energy is a complex nonlinear and non-convex mixed integer optimization problem, it will be very difficult to solve it directly. Therefore, it is divided into two sub-problems, including cascade hydropower optimal dispatching problem and thermal-wind-photovoltaic power joint dispatching optimization problem. Because of the nonlinear constraints in the joint optimal dispatching problem of cascade hydropower stations, the particle swarm optimization algorithm can be used to solve the problem. Because the unit combination scheme formulated day ahead is very difficult to change in the actual dispatching, the unit combination scheme should meet the needs of each scenario. After a series of linearization, the subproblem is a typical mixed integer programming problem, which can be solved effectively by using the branch and bound method.

4. Example analysis
In order to verify the effectiveness of the model, a numerical analysis is carried out with the modified IEEE standard 24-bus system, which includes 25 thermal units, 2 hydropower stations, 2 photovoltaic farms and 2 wind farms.

Because the generation of various scenarios is not the focus of this paper, it is assumed that forecasting errors of wind power, photovoltaic power and system load all satisfy the normal distribution. The sampling method and scenario reduction method can be used to generate the required number of typical load scenarios.

4.1. Unit commitment scheme of thermal units
After deducting the hydropower power in each load scenario, the residual load can be distributed among thermal units, wind farms and photovoltaic farms by branch and bound method. The solution is carried out through the CPLEX toolkit.

Figure 1 shows the optimal unit commitment scheme. The more economical units 1-6 remain open for 24 hours, the less economical units 23-25 remain closed for 24 hours, and the rest of the units are turned on when needed. There are some exceptions, such as the opening of unit 22 instead of unit 21 in order to meet the remaining load demand for the period 18, which is actually related to the capacity of the two units. When the residual load is greater than the capacity of unit 21, the frequent start-up and shutdown of the units can be avoided by this scheme, and the online unit can be operated in a more economical state.

4.2. Result of load distribution
Take the result of load distribution under scenario 1 as an example, as shown in Figure 2:
It can be seen that because the incoming water is relatively fixed and the hydropower is optimized separately, the change of the output of hydropower is relatively small, and the output of wind farms and photovoltaic farms presents a certain complementary characteristic. The large thermal units bear the base load and the smaller ones is responsible for peak regulation at the same time.

4.3. Analysis of sensitivity of simulation parameters.

4.3.1. The influence of the penalty cost coefficient of IPS curtailment. In order to test the influence of the penalty cost coefficient of IPS curtailment on the result of the model, the penetration ratio of wind power and photovoltaic power is adjusted to 1.8 times of the initial value, so that the curtailment has to appear in the dispatching result. The penalty cost coefficient is set from 0 to $30/MWh, then observe the change of the result of dispatching. The curve shown in Figure 3 is obtained.

As can be seen from Figure 3, the change trend of the two curves show a strong complementary relationship, indicating that with the increase of the punishment of IPS curtailment, the amount of curtailed IPS in the dispatching cycle is effectively controlled. However, the price paid is the increase in the generation cost of the thermal units.

4.3.2. The influence of permeability of IPS. In order to study the influence of permeability of IPS on the dispatching result of the system, the prediction expectation and prediction error of IPS are adjusted according to a certain proportion (called specific permeability), and the corresponding optimal operation cost and penalty cost are recalculated respectively, and the curve shown in Figure 4 is obtained.
Specific permeability

Total operating cost of The system /$
\times10^5$

Penalty cost of IPS curtailment/$
\times10^4$

Figure 4. Variation of operating cost and penalty cost with specific permeability.

It can be seen that the IPS curtailment will appear when the specific permeability is 1.3, and the curtailed IPS will get more and more with the increase of the specific permeability. In this example, the total operating cost of the system does not increase until the specific permeability reaches 1.7. It shows that in the case of the continuous increase of the permeability of IPS, the model comprehensively considers the power generation cost saved by increasing the amount of the consumption of IPS and the penalty cost caused by curtailing IPS to determine the total amount of IPS to be absorbed, both of which jointly promote the consumption of IPS. On the other hand, other kinds of constraints restrict the consumption of IPS, and finally the two kinds of factors reach a balance, that is, the optimal dispatching result, which also reflects the role of the penalty cost coefficient of IPS curtailment in the dispatching model.

5. Conclusions
In order to alleviate the global fossil energy shortage crisis, clean energy industry is booming, the power system with high proportion of clean energy has emerged. However, the large-scale clean energy assessed to the power grid has greatly increased the uncertainty of the operation of power system. In order to solve this problem, the optimal dispatching power system with high proportion of clean energy is studied in this paper, the main contents and conclusions are as follows:

1st, in order to maximize the utilization of clean energy and reduce operating cost, an optimal dispatching model based on multi-energy complementary is established.

2nd, the original problem is divided into optimal dispatching problem of hydropower station group and joint optimal dispatching problem of thermal units, wind farms and photovoltaic farms. The improved PSO algorithm is used to solve subproblem of hydropower stations with nonlinear constraints, and the branch-bound method is adopted to solve the subproblem of the simplified joint dispatching of thermal units, wind farms and photovoltaic farms.

3rd, the feasibility of the model is verified through the analysis of a numerical example. The result shows that this model can effectively improve the consumption of clean energy while realizing reasonable arrangement of thermal units. The sensitivity analysis is used to verify the role of the penalty cost of IPS curtailment in promoting the absorption of clean energy, and the influence of the permeability of IPS on the dispatching result is also verified.

In the follow-up work, this model can be extended in the following aspects: 1) Consider the impact of the system on the environment after access of IPS, introducing the emission characteristics of inits into the objective function. 2) Taking into account the impact of energy storage devices on the optimal dispatching of the system to further improve the model.
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