Research on Power System Expansion Planning Considering Demand Response

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Abstract. In the future power system, the uncertainty of the load side will increase, and the planning of various demand resources in the system will affect the flexibility and economy of the power system. Excessive planning capacity of demand response resources will cause excessive investment, and insufficient planned capacity will affect the flexibility of the system. In order to obtain the investment decision plan for new demand-side resources within the planning period, this article adds demand resources such as energy storage systems and controllable loads based on thermal power units as the main flexible resources, establish an optimization model with the goal of minimizing the annual cost of the power system expansion plan. Based on the improved IEEE-RTS96 system, a numerical example is analysed, and the influence of different demand-side response resources on system planning is deeply explored. The results show that comprehensive planning of multiple types of demand-side response resources is more competitive than single resource planning in terms of system economy and operational flexibility.

1. Introduction

With the increasingly severe problems of energy shortage, global warming, and deterioration of the ecological environment, speeding up the development and utilization of renewable energy has become a general consensus of all countries in the world [1,2,3]. According to the National Bureau of Statistics of China, by the end of 2020, the grid-connected capacity of wind power and solar power has reached 280 million kW and 250 million kW, respectively, and non-fossil energy power generation accounts for 33.9% of electricity consumption[3]. However, wind power generation is different from traditional power sources. Its output is affected by multiple factors such as environment and weather, and large-scale wind power grid integration will increase the uncertainty of the power system, making the system's demand for flexible resources continue to rise[4]. Therefore, with the continuous development of renewable energy power generation, the flexibility of the power system should be fully tapped to meet the needs of safe and stable operation of the system. Demand response is an effective method to solve the randomness and intermittency of renewable energy power generation. With the rapid development of the Internet of Things technology, there are more and more types of resources responding to the demand side[5]. Grid companies can adjust the power demand on the user side to achieve peak shaving and valley filling, reducing the operating cost of the power system[6].

In recent years, domestic and international planning and research on power systems that take into account the demand-side response have been heating up, and there have been a large number of research
results. Literature [7] comprehensively considered the response characteristics of the controllable load at the same time and across the time period, established a wind power planning model based on demand response. Literature [8,9] constructed a coordinated planning model of source and network loads through overall planning of conventional units, grid lines and demand-side response resources. Literature [10] reveals the impact of demand-side response on system investment returns by establishing a sustainable planning model for energy hubs. Literature [11] quantified the proportional relationship between demand response, system revenue and peak shaving capacity, and proposed using load demand response to improve grid peak shaving capacity, expand the scale of wind power grid connection, and improve the economic benefits of the system. Literature [12] and Literature [13] proposed a coordination optimal model of energy storage in a power system which accommodated a high penetration of wind power to deal with the peak shaving problem of the system and increase the consumption of wind power.

Most studies only focus on deterministic demand-side resources, and do not consider the uncertain behaviour of loads in actual engineering applications. Based on this, this article aims to minimize the sum of system operating costs and investment costs, comprehensively considers system power balance constraints, investment constraints, power equipment operating characteristics and other constraints, and adds different demand-side resources to the planning model for comparative analysis. The analysis of calculation examples shows that the comprehensive planning of multiple types of demand-side response resources is more competitive than single resource planning in terms of system economy and operational flexibility.

2. Power system planning model considering demand response

With the massive access of demand-side resources, the development of power system planning that takes into account the demand-side response can meet the new economic and flexibility requirements of the power system. The planning objects in this chapter mainly include thermal power that can meet the demand for electric power, as well as demand-side resources such as energy storage and controllable load.

2.1. Objective Function

The power system expansion planning that takes into account demand-side resources mainly adds demand-side response resources on the basis of the original power system, and establishes an optimization model with the minimum cost of the entire power system expansion planning. The expansion planning cost of the power system includes the investment cost of new power equipment and the operation and maintenance cost of the system. The objective function of the model can be expressed by equation (1):

$$\min F = F_{in} + F_{op}$$

In the formula, represents the equivalent annual cost of the power system; represents the equivalent annual investment cost of energy storage and controllable load; is the annual operating cost of the power system.

The investment cost mainly includes the expansion planning cost of energy storage and controllable load. The specific expression is as follows:

$$F_{in} = F_{E_{in}} + F_{L_{in}}$$

In the formula, $F_{E_{in}}$ is the equivalent annual investment cost of the newly added energy storage, $F_{L_{in}}$ is the equivalent investment cost of the newly added controllable load. The specific accounting model is shown as follows:

$$F_{E_{in}} = \sum_{i \in \Omega_E} x_i (C_{P_i} P_i + C_{E_i} E_i) \delta_i (r, N_E)$$

$$F_{L_{in}} = \sum_{j \in \Omega_L} y_j Q_j (C_{P_j} P_j + C_{L_j} E_j) \delta_j (r, N_L)$$
In the formula, $\delta(r, N) = \frac{r(1+r)^N}{(1+r)^N - 1}$

In the formula, $\Omega_k$ and $\Omega$ represent the set of energy storage to be selected and the set of controllable loads respectively; $x_i$ and $y_j$ represent the state of construction of energy storage equipment and controllable load respectively, and its value is 1 for construction, and 0 for no construction; $C_{pc}$ and $C_{ee}$ are the unit power and unit capacity price of energy storage; $P_i$ and $E_i$ are the planned power and planned capacity of energy storage respectively; $\delta(r, N)$ is the coefficient of equivalent annual value, and its value is related to the discount rate $r$ and the operating lifetime $N$ of the power equipment.

The operating cost of the system includes energy consumption cost, start-up and shutdown cost, load loss penalty cost, load compensation cost, which can be expressed as follows:

$$F_{op} = C_G + C_S + C_A + C_{DR}$$

$$C_G = N_T \sum_{s=1}^{N_s} \rho_s \sum_{i=1}^{T} \left( \sum_{k=1}^{G} \left( a_k P_{ik,s,t}^G + b_k P_{ik,s,t}^G + c_k u_{ik,s,t}^G \right) \right)$$

$$C_S = N_T \sum_{s=1}^{N_s} \rho_s \left( \sum_{i=1}^{T} \left( \sum_{k=1}^{G} u_{ik,s,t}^G (1 - u_{ik,s,t}^G) S_{ik,s,t} \right) \right)$$

$$C_A = Q_{loss} \times N_T \sum_{s=1}^{N_s} \sum_{i=1}^{T} \rho_i P_{i,s,t}^{loss}$$

In those formulas, $N_T$ is the total statistical period; $\rho_s$ is the probability of the scene; $N_G$ is the number of original generator sets; $u_{ik,s,t}^G$ is the operating state of thermal power unit $k$ in the $s$-th scenario at the moment; $a_k$, $b_k$ and $c_k$ are the cost coefficients of thermal power unit $k$; $S_{ik,s,t}$ is the start and stop cost of thermal power unit $k$; $P_{L,s,t}^{loss}$ is the load loss of the system at time $t$ in the $s$-th scenario; $Q_{loss}$ is the penalty cost coefficient for loss of load; $P_{L,s,t}^{loss}$ is the interruptible load of user $n$ at time $t$ in the $s$-th scenario; $K_{iu}$ and $K_{iu}$ are the quadratic coefficient and the first coefficient of the compensation amount respectively.

2.2. Constraints

The power system expansion planning model that takes into account demand-side response resources, on the basis of satisfying system operation constraints, also includes conventional unit operation constraints, investment constraints, energy storage equipment operation constraints, and controllable load constraints. It can be expressed by formula (11) to formula (20).

(1) Power balance constraint:

$$\sum_{i \in \Omega_{ES}} P_{i,s,t}^E + \sum_{i \in \Omega_{LS}} P_{i,s,t}^{LS} + \sum_{n \in \Omega_{LS}} \mu_{n,s,t} P_{n,s,t}^{LS} = P_{L,s,t}^L + L_{In,s,t} - L_{Out,s,t}$$

In the formula, $\Omega_{GS}$ is the original thermal power unit assembly of the system; $P_{i,s,t}^E$ is the output of the $i$-th energy storage device at time $t$ in the $s$-th scene; $\mu_{n,s,t}$ is the interrupted state of the interruptible load $j$ at time $t$ in the $s$-th scenario; $P_{n,s,t}^{LS}$ is the corresponding interrupted power; $P_{L,s,t}^L$ is the load power of the system at time $t$; $L_{In,s,t}$ and $L_{Out,s,t}$ represent the transfer-in and transfer-out volume of the transferable load respectively.

(2) Investment constraint:
\[
\sum_{i \in \mathcal{I}_p} x_i (C_p + C_{\mathcal{E}_i}) + \sum_{j \in \mathcal{I}_k} y_j Q_j (C_p + C_{\mathcal{E}_j}) \leq C_{\text{max}}
\]  
(12)

In the formula, \(C_{\text{max}}\) is the upper limit of the total investment.

(3) Energy storage system operation constraints:

\[
\begin{align*}
E_{\text{min}} & \leq E_{\text{in},j} \leq E_{\text{max}} \\
P_{E,\text{max}} & \leq P_{E,\text{in},j} \leq P_{E,\text{min}}
\end{align*}
\]  
(13), (14)

(4) Controllable load constraint:

The newly-added controllable loads in the power system mainly include transferable loads and reducible loads. The transferable load constraint is mainly considered from two aspects of power balance and load transfer amount constraint, which can be expressed by equation (15) to equation (17).

\[
\sum_{i \in \mathcal{I}_p} L_{\text{in},i,s,t} = \sum_{i \in \mathcal{I}_p} L_{\text{out},i,s,t}
\]  
(15)

\[
L_{\text{in},i,s,t} \leq L_{\text{in},\text{max}}
\]  
(16)

\[
L_{\text{out},i,s,t} \leq L_{\text{out},\text{max}}
\]  
(17)

Interruptible load constraints are mainly considered from three aspects: load interruption amount constraints, interruption time constraints and interruption times constraints, which can be expressed by e.q. (18)-(20).

\[
P_{j,\text{min}} \leq P_{j,s,t} \leq P_{j,\text{max}}
\]  
(18)

\[
\begin{cases}
T_{j,s,t} \leq T_{j,\text{max}} \\
\left(T_{j,s,t} - T_{j,\text{min}} \right) \left(1 - \mu_{j,s,t} \right) \geq 0
\end{cases}
\]  
(19)

\[
\sum_{t=2}^{T} (1 - \mu_{j,s,t-1}) \mu_{j,s,t} \leq N_{j,\text{max}}
\]  
(20)

3. Case study

In order to deeply explore the impact of different demand-side response resources on system planning, this paper is based on the improved IEEE-RTS96 system and sets the following four scenarios to compare and analyse the planning results to verify the correctness and effectiveness of the model.

Scenario 1: Only consider the original 600MW thermal power unit in the system as a flexible response resource.

Scenario 2: Adding controllable load for planning based on scenario 1.

Scenario 3: Add energy storage device to plan on the basis of scenario 1.

Scenario 4: On the basis of scenario 1, the energy storage device and the controllable load are added at the same time for planning.

| Table 1. Added demand-side response resource parameters |
|--------------------------------------------------------|
| Demand resource type | Energy storage device | Controllable load |
|----------------------|-----------------------|-------------------|
| Capacity to be cast   | 20/60,50/150,100/300  | 30/90,60/180      |
| Annual value cost of  | 18000/23500           | 11000/100         |
| unit capacity investment ($/(MW)^1/$/(MWh)^1) |                       |                   |

The total installed capacity of the thermal power unit of the calculation example system is 3700MW, the maximum load is 3000MW, and the charging and discharging efficiency of battery energy storage
is 90%. The new energy storage and controllable load parameters of the system are shown in Table 1. Comprehensively considering the four factors mentioned in Chapter 2 of this article, it is estimated that the controllable load participates in the demand side response potential of 10% of the annual maximum load, and the discount rate of the power industry is 0.1. According to the results of the calculation examples, the planning results in each scenario are shown in Figure 1.

![Figure 1](image)

**Figure 1** New demand-side resource types and capacities in different scenarios

The economic indicators of the planning scheme in each scenario are shown in Table 2.

| Cost                  | Scene 2   | Scene 3   | Scene 4   |
|-----------------------|-----------|-----------|-----------|
| Total cost / (10^6$)  | 1360.8    | 1398.6    | 1289.9    |
| Cost of investment / (10^6$) | 45.2      | 33.4      | 52.8      |
| Cost of operation / (10^6$) | 1315.6    | 1365.2    | 1237.1    |

Combining Figure 1 and Table 2, it can be seen that with the addition of new energy storage and controllable loads, the proportion of thermal power that participates in flexible adjustment in the system decreases. This shows that the new energy storage and controllable load increase the flexibility of the system to adjust the resource capacity to a certain extent. In Scenario 2 and Scenario 3, the capacity of thermal power units participating in flexible adjustment is almost unchanged. Because the controllable load and the energy storage device have different operating characteristics, the capacity required for the controllable load as a demand-side response resource is significantly larger. Scenario 4 considers that the system adds two demand-side response resources, energy storage device and controllable load at the same time. Although the investment cost has increased, the overall economy of the system is the best due to the reduction in system operating costs. At the same time, as the addition of energy storage and controllable loads meets the demand side response requirements of the system, the operation of the system will be more stable. It can be seen that the comprehensive planning of multiple types of demand-side response resources is more competitive than single resource planning in terms of system economy and operational flexibility.

4. Conclusions

This paper optimized the capacity of the two demand-side response resources of the energy storage device and the controllable load, so as to make the system expansion plan the most economical. By analysing the results of different demand-side resources participating in the planning, it can be seen that comprehensive planning of multiple types of demand-side response resources is more competitive than single resource planning in terms of system economy and operational flexibility. In actual engineering...
applications, appropriate demand-side resources can be selected according to the actual needs of the power system to optimize the operating economy of the system.

5. References

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