Research on Coordination Planning Model of Source-Grid-Load-Storage Considering Demand Response Uncertainty

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Abstract: With the integration of wind power, photovoltaic, and other new energy into the grid, the growth of carbon emissions has been effectively suppressed, which greatly contributes to the realization of the "Carbon peak, Carbon neutral''. However, the randomness and instability of new energy generation also greatly affect the stable operation of the power grid. At present, the combination of demand response and power system can give full play to the maximum potential of new energy. This is an effective method to realize stable and optimal operation of power system. Based on this, this paper first constructs the SOC output characteristic model of energy storage and considers the DLC and time-of-use price as well as different demand response types. The robust optimization method is used to deal with the uncertainty of demand response. Secondly, a multi-objective function and constraint conditions are constructed to minimize the system planning cost, operation cost, and pollution emission. Finally, the genetic algorithm is used to analyze an example in a certain area of Fujian. In the example, the economy of planning schemes under different robust control parameters is compared and analyzed. The results show that the model and calculation method in this paper are beneficial to delaying the investment in power systems, and can provide decision-making reference for mining and utilizing demand response resources, reducing system planning costs and improving operation efficiency.

Keywords: Demand response; robust optimization; planning method; uncertainty analysis.

1. Introduction

The ' 14th Five-Year ' period is a critical period for China to move from building a well-off society in an all-around way to building a socialist modernization country in an all-around way. The energy industry will also enter a critical period of transformation and change. With the deepening of the energy revolution, the demand for high-quality energy development is more prominent, and the supply and demand pattern of the power system will be profoundly changed[1]. The energy supply security and optimal scheduling of the power system are still facing multiple challenges. Carrying out demand response is becoming an important direction in the optimization planning and dispatching operation of the power system.

At present, there are some studies on demand response and power system optimization planning methods in the academic circle. Reference [2] focuses on the optimal dispatch of interruptible load and direct load control, and the demand response of the power system based on incentive is studied. Reference [3] studied the optimal allocation of microgrid power supply capacity based on cooperative game and demand response, which effectively improved the revenue of the microgrid. Reference [4] studied the power grid dispatching decision-making method combining the comprehensive energy demand response of electricity-gas coupling. Reference [5] studied the multi-objective optimization model of microgrids considering demand response and wind-solar uncertainty. Reference [6-7] studied the optimal scheduling of microgrids considering the comprehensive demand response. Reference [8] aiming at the problem that the grid capacity is difficult to adapt to the increased power generation, a comprehensive evaluation method is proposed to evaluate the application benefit of demand response in a smart power system. Reference [9] studied the optimization method and application of power system grid reconfiguration. Reference [10] used multi-objective optimization technology to study the optimization method of economic dispatch of power system environmental integration. Reference [11] analyzed the evolution process of the energy internet and its influence on the power system and proposed the power system planning method for the energy internet from the time dimension, space dimension, and multi-energy system dimension. Reference [12] studied the planning and operation optimization of power systems considering frequency security. The frequency security characteristics of the power system were expounded from the frequency transient process, the frequency security index, and the frequency analysis method. The principle of various types of frequency response modes and their application in power system optimization was combed from different links of source-network-load-storage. Reference [13] proposed a distribution system optimization planning model considering the network transfer capacity. The model took the minimum sum of investment and operation costs as the objective function and solved the model by using the joint strategy of improved differential evolution algorithm and primal-dual interior point method. The obtained planning scheme realized the coordinated optimization of distributed generation and distribution network, which effectively reduced the planning cost and future operation risk. Reference [14] proposed the optimal operation model of electric-thermal integrated energy system considering the comprehensive demand response of load, introduced the distribution network dispatching mechanism as the middle layer, and established a three-layer optimal dispatching structure including load aggregator, distribution network dispatching mechanism, and main network dispatching mechanism to realize the transmission of load side flexibility to the system side. Reference [15] conducted in-depth research on the power system uncertainty modeling method and its application in multi-scenario optimization with the uncertainty model as the main line and different subjects as scenarios.

In summary, there are still few studies on the combination of demand response and power system planning, especially how to rationally allocate capacity to avoid load shedding. Therefore, it is necessary to conduct in-depth research on this issue. Based on this purpose, this paper first constructs the SOC output characteristic model of energy storage and considers the DLC and time-of-use price as well as different demand response types. The robust optimization method is used to deal with the uncertainty of demand response. Secondly, a multi-objective function and constraint conditions are constructed to minimize the system planning cost, operation cost, and pollution emission. Finally, the genetic algorithm is used to carry out an example analysis in a certain area of Fujian, so as to verify the reliability of the model method.

2. SOC Characteristic Modeling of Energy Storage

Here, the state-of-charge (SOC) of the energy storage device O in the period t is set as $Q_{SOCo,t}$, and the relationship between the SOC of the energy storage device and the charging and discharging power is as follows :

$$Q_{SOCo,t} = Q_{SOCo,t\text{-}1} + c_{con,o}\lambda \frac{q_{o,t}t_{o,r}\theta_o}{S_{\max}^o} \quad (2\text{-}1)$$

where, $q_{o,t}$ represents the charge and discharge power of the energy storage device O , which is positive at charging and negative at discharging; $t_{o,r}$ is the charging and discharging period of the energy storage device O ; $S_{\max}^o$ represents the maximum capacity of energy storage equipment; θ_o represents charge and discharge efficiency; λ is a variable indicating whether the energy storage equipment is enabled, and the value of this variable is 0 or 1. When the output of photovoltaic power generation or wind power decreases sharply (or the load increases suddenly), and according to the climbing rate requirements, the diesel engine group cannot increase the output to meet the load, the system will dispatch the energy storage equipment to discharge to meet the user's electricity demand. At this time, the λ value is 1. When the system load is too low and the output of wind power and photovoltaic power is too high, the system will call the energy storage equipment to charge to increase the load and consume distributed renewable energy. At this time, the λ value is also 1. When the energy storage equipment is not called, the λ value is 0. $c_{con,o}$ is the control variable of energy storage equipment, which represents the control behavior of the system on charge and discharge of energy storage equipment. The specific value of $c_{con,o}$ is :

$$c_{con,o} = \begin{cases} \max[(1-e^{\Delta}),0], q_{o,t} > 0 \\ 1, q_{o,t} < 0 \end{cases} \quad (2\text{-}2)$$

$$\Delta = \frac{Q_{SOCo,t} - Q_{SOCo,\max}}{-\dfrac{q_{o,t}}{\gamma R_{o,\max}} + \dfrac{\mu}{\gamma}} \quad (2\text{-}3)$$

In the formula, $Q_{SOCo,\max}$ and $R_{o,\max}$ are the maximum charge state and rated charge and discharge power of energy storage equipment, and γ and μ are the charging and discharging process parameters of energy storage equipment. According to the research results of energy storage-related References at home and abroad, the values of γ and μ are 20.52 and 0.55, respectively.

3. Uncertainty Analysis of Demand Response

In the process of power system operation, the implementation of demand side response measures will change the user's electricity load, make it change compared with the system prediction load, and achieve the role of peak load shifting, so as to reduce the maximum load of the system. Since the system power planning and transmission and distribution planning are planned according to the maximum load, the decrease of the maximum load will have an impact on the system planning. The most direct impact is to reduce the power supply capacity and transmission and distribution capacity, thereby reducing the planning cost. However, the load change caused by the implementation of demand-side response measures is uncertain. Here, this uncertain load change is defined as the demand-side response uncertainty, which is directly related to the value range of user demand-side response elasticity, and the value range of user demand-side response elasticity can be large or small, so the demand-side response elasticity is also uncertain. In summary, before constructing the optimization planning model, we should first describe the demand-side response elasticity of users, and design the robust optimization constraint conditions considering the demand-side response elasticity.

Therefore, this paper will draw on the commonly used method of Reference to describe the range of demand side response elasticity. The range of electricity demand elasticity e_j for user j is :

$$e_n \le e_j \le e_m \tag{3-1}$$

In the formula, e_m and e_n are the maximum and minimum of elasticity respectively.

In the actual operation of the system, the probability of all users' e_j taking the upper or lower limit at the same time can be ignored. Therefore, Formulas (3 – 5) can be designed to represent the set of values of elasticity e_j. Here Γ is introduced, and this parameter represents the uncertainty of the system :

$$\Pi = \{e_j = e_z + \lambda_j e_a, |\lambda_j| \le 1; \sum_j |\lambda_j| \le \Gamma\} \tag{3-2}$$

$$e_z = 0.5(e_n + e_m) \tag{3-3}$$

$$e_a = 0.5(e_m - e_n) \tag{3-4}$$

In this paper, formula (3-2) is called' budget constraint', where Γ denotes the uncertainty constraint for demand side response. According to Formulas (3 – 2), when Γ is small, the model will approach the deterministic model; when the value of Γ increases, the range of elasticity e_j value set Π expands, and the range of demand-side response elasticity of the model expands. At this time, the model will be transformed into an uncertain model, and the uncertainty of demand-side response elasticity increases. Thus, the value of Γ is very important for the robustness analysis and model uncertainty description of the system. The value of Γ here can be determined by Formulas (3 – 5) according to the central limit theorem.

Suppose $\varphi_j = \dfrac{|e_j - e_z|}{e_a}$, and ω is the expected value of φ_j, and η is the variance, then :

$$\lim_{j \to \infty} \sum_{j=1}^{J} \frac{\varphi_j - J\omega}{\sqrt{J\eta}} \to N(0,1) \tag{3-5}$$

In formula (3-5), J is the total number of users or the number of user classes in the system ; $N(0,1)$ is the standard normal distribution. Further :

$$\Gamma = J\omega + \Phi^{-1}(\alpha)\sqrt{J\eta} \tag{3-6}$$

In Formula (3 – 6), α is the confidence level, and $\Phi(\alpha)$ is the cumulative probability distribution function of normal distribution. Here, the value range of Γ can be obtained :

$$\sum_j \frac{|e_j - e_z|}{e_a} \le \Gamma \tag{3-7}$$

From formula (3-2) and formula (3-7), Γ can only take integers. When the system has the worst case, the e_j of Γ users takes the minimum or maximum value, so the uncertainty of the model can be limited by the value of Γ. When the value of Γ is the largest and the system can still ensure safe and stable operation, the system is robust, which can reflect the idea of ' worst case consideration ' in robust optimization.

In this paper, we mainly analyze the influence of demand-side response strategies of DLC and TOU price on the change of user load under the condition of uncertain demand-side response elasticity.

3.1 Demand-side response uncertainty analysis considering DLC

Figure 3 - 1 shows the relationship between user load reduction and the amount of compensation paid to users under the implementation of DLC strategy.

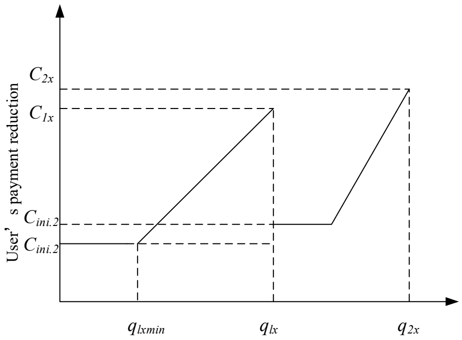

Figure 3-1 Relationship between user load reduction and compensation

$c_{ini,j}$ is the initial load reduction payment of user j, q_{jx} is the load reduction of user j, $q_{jx\min}$ is the minimum load reduction of user j, $c_{ini,j} \cdot q_{jx\min}$ is no matter how the DLC payment changes, q_{jx} always remains the same interval, similar to the fixed cost in economics.

When the demand-side response elasticity is a fixed value, q_{jx} can be obtained according to the general economic principle when the load payment amount is known to be reduced. However, when the value range of the elasticity is known and the specific value is unknown, the specific value of q_{jx} cannot be obtained, so the value of load variation is uncertain.

c_{jx} is the amount of load reduction payment for user j, the slope of the line is ξ_j, then $(c_{jx} - c_{ini,j}) = \xi_j (q_{jx} - q_{jx\min})$, the cost directly paid to a single or class of users can be calculated by calculating the triangle area under the line and the fixed cost. The formula is :

$$c_{jx}(q_{jx}) = c_{ini,j} \cdot q_{jx} + 0.5\xi_j q_{jx}{}^2 + c_{ini,j} \cdot q_{jx\min} \tag{3-8}$$

Therefore, the total load reduction payments for users are :

$$\sum_j c_{jx}(q_{jx}) = \sum_j c_{ini,j} \cdot q_{jx} + \sum_j 0.5\xi_j q_{jx}{}^2 + \sum_j c_{ini,j} \cdot q_{jx\min} \tag{3-9}$$

The value range of ξ_j is :

$$\xi_j = \frac{c_{jx} - c_{ini,j}}{q_{jx} - q_{jx\min}} \tag{3-10}$$

According to the general economic principle, the elasticity of electricity price and user load is defined as :

$$e_j = \frac{\dfrac{d_{j,t}}{q_{\mathrm{int},j,t}}}{\dfrac{\Delta p_{j,t}}{p_{\mathrm{int},j,t}}} = \frac{d_{j,t}}{\Delta p_{j,t}} \cdot \frac{p_{\mathrm{int},j,t}}{q_{\mathrm{int},j,t}} \tag{3-11}$$

Here, $\Delta p_{j,t}$ and $d_{j,t}$ are the changes of price and demand of users in t period, $p_{\mathrm{int},j,t}$ and $q_{\mathrm{int},j,t}$ are the initial price and initial demand respectively. In this paper, the demand-side response elasticity under the influence of DLC strategy also has a similar relationship. Considering the initial load reduction and the initial load reduction payment, the formula (3-11) under DLC strategy can be changed into :

$$e_j = \frac{q_{jx} - q_{jx\min}}{c_{jx} - c_{ini,j}} \cdot \frac{c_{ini,j}}{q_{jx\min}} = \frac{c_{ini,j}}{\xi_j q_{jx\min}} \tag{3-12}$$

Therefore, ξ_j is the specific expression of elasticity e_j on the slope of the straight line. Since the elasticity e_j of the user is uncertain, the slope ξ_j is also uncertain. During system operation, the DLC cost of calling user load reduction is :

$$\begin{aligned} C_{DLC} &= \sum_j [c_{ini,j} + 0.5(\xi_j + \Delta\xi_j)(c_{ini,j} + c_{ini,j+1})] q_{jx} \cdot \sigma_{jx} \\ &+ \sum_j c_{ini,j} \cdot q_{jx\min} \cdot \sigma_{jx} - \sum_j 0.5(\xi_j + \Delta\xi_j) \cdot q^2{}_{jx\min} \cdot \sigma_{jx} \end{aligned} \tag{3-13}$$

Among them, σ_{jx} is the variable whether the load reduction is enabled and $\Delta\xi_j$ is the slope variation. The formula (3-13) can be transformed into :

$$\begin{aligned} C_{DLC} &= \sum_j (c_{ini,j} \cdot q_{jx} + c_{ini,j} \cdot q_{jx\min}) \cdot \sigma_{jx} \\ &+ \sum_j (\xi_j + \Delta\xi_j) \cdot [\frac{q^2{}_{jx}}{2} + \sum_j \frac{q_{jx}(c_{ini,j} + c_{ini,j+1})}{2}] \cdot \sigma_{jx} \end{aligned} \tag{3-14}$$

Here we can set :

$$B_{jx} = (\xi_j + \Delta\xi_j) \cdot [\frac{q^2{}_{jx}}{2} + \sum_j \frac{q_{jx}(c_{ini,j} + c_{ini,j+1})}{2}] \tag{3-15}$$

$$A = \frac{q^2{}_{jx}}{2} + \sum_j \frac{q_{jx}(c_{ini,j} + c_{ini,j+1})}{2} \tag{3-16}$$

When the formula (3-7) is established :

$$B_{jx} = \max_{\left\{\sum_j |\lambda_j| \le \Gamma\right\}} \frac{q_{jx\min}}{c_{ini,j}} \sum_j \frac{\Delta\xi_j \cdot A}{e_j} \tag{3-17}$$

$$\sum_j B_{jx} = \max_{\left\{\sum_j |\lambda_j| \le \Gamma\right\}} \left\{ \sum_j \Delta\xi_j \cdot A \cdot \theta_{jx} \right\} \tag{3-18}$$

where, $\theta_{jx} = \dfrac{q_{jx\min}}{c_{ini,j} \cdot e_j}$, when $\sum_j |\lambda_j| \le \Gamma$ holds and takes the maximum value, let θ_0 be the dual variable of $\sum_j \theta_{jx}$, θ'_{jx} be the dual variable of θ_{jx}, and a_{jx} be the Lagrange coefficient. The A in Formulas (3 – 17) is split and recombined, and the parameter Γ of uncertainty constraint condition is introduced. Then, the principle problem can be transformed into the problem of solving the minimum value.

$$\sum_j B_{jx} = \min \left\{ \sum_j \theta'_{jx} + \theta_0 \Gamma \right\} \tag{3-19}$$

Thus, the formula (3-19) is consistent with the standard polynomial of mixed quadratic integer programming, where :

$$\theta_0 + \theta'_{jx} \geq \Delta\xi_j \cdot a_{jx} \tag{3-20}$$

$$\theta'_{jx} \geq 0 \tag{3-21}$$

$$\theta_0 \geq 0 \tag{3-22}$$

$$a_{jx} \geq 0 \tag{3-23}$$

Considering the general situation of power system planning and operation, DLC mainly affects the scheduling operation cost of the system. Formula (3 – 19) to (3 – 23) are the uncertainty constraints of DLC.

3.2 Demand-side response uncertainty analysis considering time-of-use price

After the implementation of the TOU price strategy, the relationship between the user ’ s load change and the TOU price is shown in Figs. 3 – 2. In the figure, $q_{\text{int},j}$ is the load of user j when the TOU price is not implemented, $p_{\text{int},j}$ is the electricity price at this time, $p_{end,j}$ is the electricity price after implementation, $q_{\text{int},j} - q_{if}$ is the user load after implementation, and q_{if} is the peak load reduced by the TOU price.

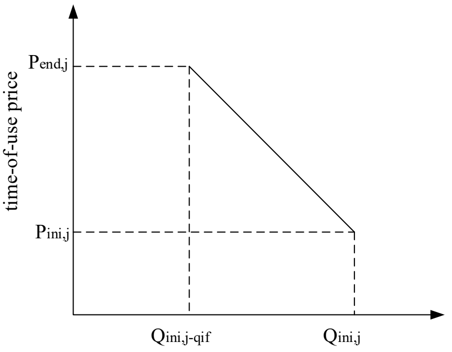

Figure 3 - 2 The relationship between user load reduction and TOU price

Here, the slope of the straight line is set as ζ_j, and $\Delta\zeta_j$ is the slope variation. According to Fig. 3 - 2, there is :

$$\begin{aligned}\sum_j q_{jf} &= \sum_j \frac{1}{\zeta_j + \Delta\zeta_j} \cdot \frac{p_{\text{int},j} + p_{\text{int},j+1}}{2} \cdot \left|p_{end,j} - p_{\text{int},j}\right| + \frac{1}{\zeta_j + \Delta\zeta_j} \cdot \frac{p^2{}_{end,j}}{2} \\ &= \sum_j q_{\text{int},j} - \frac{1}{\Delta\zeta_j} \cdot [\frac{p^2{}_{end,j}}{2} + \sum_j \frac{(p_{\text{int},j} + p_{\text{int},j+1})\left|p_{end,j} - p_{\text{int},j}\right|}{2}]\end{aligned} \tag{3-24}$$

Set $L = \frac{p^2{}_{end,j}}{2} + \sum_j \frac{(p_{\text{int},j} + p_{\text{int},j+1})\left|p_{end,j} - p_{\text{int},j}\right|}{2}$,

when the formula (3-7) holds :

$$\sum_j q_{jf} = \max_{\left\{\sum_j |\lambda_j| \leq \Gamma\right\}} \frac{\varepsilon_{jx}}{\Delta\xi_j} L \tag{3-25}$$

In the formula, $\varepsilon_{jx} = \frac{\sum_j q_{\text{int},j}}{\zeta_j}$, we can get :

$$\sum_j q_{jf} = \min\left\{\sum_j q_{\text{int},j} + \frac{\varepsilon_0}{\Gamma}\right\} \tag{3-26}$$

where ε_0 is the dual variable of $\sum_j q_{end,j}$, and the auxiliary variable in the transformation process is b_{jx}, so the constraint condition is :

$$\varepsilon_0 + q_{\text{int},j} \geq \Delta\xi_j \cdot b_{jx} \tag{3-27}$$

$$q_{\text{int},j} \geq 0 \tag{3-28}$$

$$\varepsilon_0 \geq 0 \tag{3-29}$$

$$b_{jx} \geq 0 \tag{3-30}$$

Therefore, the constraint conditions of demand-side response uncertainty caused by TOU price are Formula (3 – 26) to (3 – 30).

4. Construction of power system optimization planning model considering demand response

4.1 Model objective function

The power system optimization planning model considering demand response has three objective functions : system planning cost minimization, operation cost minimization and pollution emission minimization.

(1) System operation cost function

The objective function of the system operation cost only considers the minimization of the generation cost and the payment of the user ' s load reduction. The implementation of the time-of-use price strategy will affect the user ' s electricity expenditure, and will not increase or reduce the system operation cost. Therefore, the operation cost function here does not consider the time-of-use price. In this paper, the demand side is the key research object. Therefore, the renewable energy generation access is not considered, and only the thermal power units are considered. Therefore, the system operation cost function in this paper is based on the unit optimal combination cost function, and takes into account the DLC cost and the influence of DLC on user load, and the objective function of system operation cost can be obtained :

$$C_Y = \sum_t \sum_g \delta_g c_g(q_{g,t}) + \sum_j (c_{ini,j} \cdot q_{jx} + c_{ini,j} \cdot q_{jx\min}) \cdot \sigma_{jx} + (\sum_j \theta'_{jx} + \theta_0 \Gamma)) \cdot \sigma_{jx} \tag{4-1}$$

In the formula : C_Y is the total cost of system operation for a typical scheduling day, δ_g is the variable indicating whether unit g is enabled, when the value is 1, the unit is enabled, and 0 is not enabled. $c_g(q_{g,t})$ is the fuel cost of generating units, and its calculation formula is :

$$c_g(q_{g,t}) = a_g + b_g q_{g,t} + c_g q_{g,t}^2 \quad (4\text{-}2)$$

$q_{g,t}$ is the output of thermal power units, a_g , b_g , c_g is the cost coefficient of thermal power units, and the start-stop cost of units is ignored when calculating the power generation cost of thermal power units.

(2) Planning and construction cost function

System planning costs mainly include the investment and construction costs of power supply and transmission and distribution systems. The implementation of DLC and time-of-use pricing strategies will achieve peak load shifting or load reduction, thereby reducing the peak load in the region, achieving the goal of reducing power generation capacity and substation capacity, thereby reducing power generation and substation investment. Considering that the investment cost of transmission lines and information communication is less affected by user load, the influence of these two parts is ignored when constructing the initial function of planning cost. The initial cost function of the system planning is :

$$C_{pp} = \sum_g C_{gp} \cdot Q_g + \sum_b C_b \cdot Q_b \quad (4\text{-}3)$$

Formula C_{gp} is the unit capacity unit investment cost ; Q_g is the investment capacity of thermal power units ; C_b is the unit capacity substation investment construction cost ; Q_b is the substation capacity.

The total peak load reduced by TOU price is $\sum_j q_{jf}$, and the total load reduced by DLC is $\sum_j q_{jx}$, which can be taken as $\sum_j q_{jx} + \sum_j q_{if} = A_{pp}$.

Considering the influence of time-of-use price and DLC, there is :

$$C'_{pp} = \sum_g C_{gp} \cdot (Q_g - A_{pp}) + \sum_b C_b \cdot (Q_b - A_{pp}) \quad (4\text{-}4)$$

By bringing formulas (3-19) and (3-26) into formula (4-4), the total cost function of system planning considering uncertainty of demand side response can be obtained :

$$\begin{aligned} C_P &= \sum_g C_{gp} \cdot Q_g + \sum_k c_k \cdot l_k + \sum_b C_b \cdot Q_b \\ &-[C_{gp} + C_b][\sum_j q_{\text{int},j} + \frac{\varepsilon_0}{\Gamma} + (\sum_j \theta'_{jx} + \theta_0 \Gamma)) \cdot \sigma_{jx}] \end{aligned} \quad (4\text{-}5)$$

where c_k is the investment and construction cost of transmission lines and their auxiliary communication systems, l_k is the length of transmission lines and communication cables, and c_k is less affected by the maximum load of users.

(3) Pollution emission function

The pollution emission of typical scheduling day system is the third objective function of this model, and its expression is :

$$A = (e_{CN} + e_{CS} + e_{CY}) \cdot \sum_g U_g \quad (4\text{-}6)$$

In the formula, e_{CN} , e_{CS} and e_{CY} represent the emission coefficients of nitrogen oxides, SO_2 and soot respectively. U_g is the generating capacity of the unit.

Therefore, the objective function of this paper can be obtained by combining formula (4-1), formula (4-5) and formula (4-6) :

$$\min C_Y, C_P, A \quad (4\text{-}7)$$

4.2 Model constraining conditions

The constraints of this model include :

(1) System power balance constraint

$$\sum_g q_{g,t} - q_{LOSS,t} = D_{total,t} - \sum_j q_{jf,t} - \sum_j q_{jx,t} \quad (4\text{-}8)$$

In the formula, $q_{g,t}$ is the output power of the unit g in the period t , $q_{LOSS,t}$ is the power loss of the system, and $D_{total,t}$ is the predicted total load of the system in the period t .

$$\sum_g q_{gx,t} = \sum_{n_z} V_{xy}(\sigma_{x,t} - \sigma_{y,t}) + D_{x,t} \quad (4\text{-}9)$$

Formula (4-9) is the node power balance constraint, where $q_{gx,t}$ is the unit output of node x , n_z is the number of surrounding nodes of node x , $\sigma_{x,t}$ and $\sigma_{y,t}$ are the voltage phase angles of node x and surrounding node y . $D_{x,t}$ is the load at node x .

(2) Uncertain constraint conditions of q_{jx} and q_{jf}

Formula (3-2) to formula (3-7), formula (3-20) to formula (3-23) and formula (3-27) to formula (3-30) are constraints representing q_{jx} and q_{jf} uncertainties. These constraints are mainly used to limit the range of parameters that introduce demand-side response uncertainty into the robust optimization model.

(3) Transmission constraint

$$\sum_g q_g \le q_l \quad (4\text{-}10)$$

where, q_l is the transmission line capacity.

(4) Distribution constraint

$$\sum_g q_g \le Q_b \tag{4-11}$$

(5) Unit output constraints

$$q_{g\min} \le q_{g,t} \le q_{g\max} \tag{4-12}$$

$$-v_{g,d} \cdot \Delta t_{gud} \le \Delta q_{g,t} \le v_{g,u} \cdot \Delta t_{gud} \tag{4-13}$$

In the formula, $q_{g\min}$ and $q_{g\max}$ are the lower and upper limits of the unit output power, and formula (4-12) is the constraint condition of the unit output range. $\Delta q_{g,t}$ is the output variation of unit g in time period Δt_{gud} , and $v_{g,d}$ and $v_{g,u}$ are the maximum increase and decrease rates of unit output in unit time. Formula (4-13) represents that the output change of the unit in any time period should be kept between its maximum rising and falling rates.

(6) Reducing load constraints

$$q_{jx\min} \le q_{jx} \le q_{jx\max} \tag{4-14}$$

Formula (5-14) indicates that the load reduction of user j should be between upper and lower limits.

5. Example analysis

5.1 Example Analysis of Experimental Data

In this paper, the NSGA-II multi-objective genetic algorithm is used to solve the example. Before solving the actual data along the river in Fujian Province, the model is first introduced into the IEEE13 node system to do a preliminary example analysis. Because this example requires all the units connected to the diesel engine group, without considering distributed renewable energy generation, the IEEE13-bus system is modified. The modified example system is shown in Figure 5-1 :

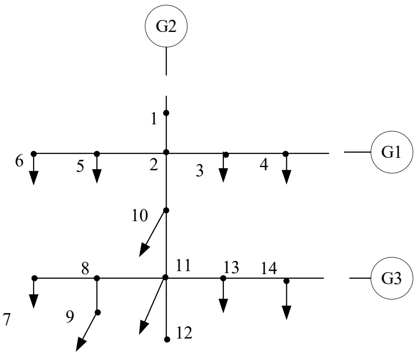

Figure 5-1 Improved IEEE13-bus system diagram

The power cost function of diesel engine group is the same as the calculation method of thermal power unit. The data of diesel engine group are shown in table 5-1.

Table 5-1 Diesel Engine Parameters

Type of diesel engine	Cost parameters			Upper limit of output /kW	Lower limit of output /kW	(v_g/v_d) /(kWh)	Cost / yuan
	a_g	b_g	c_g				
G-I	4.3	0.021	0.0025	15	0	10	15000
G-II	3.5	0.012	0.0011	10	0	7	10000

In terms of system load, users are not reclassified. Interruptible load data are shown in Table 5-2 :

Table 5 - 2 Interruptible load data of system

Nodal point	Upper limit of interruptible load /kW	Lower limit of interruptible load /kW
6	4	0
7	5	0
9	7	0

Here the user is set according to the elastic range of industrial users, the budget constraint Γ is still Γ = 2,3,4,6. In order to simplify the calculation process, the calculation of load reduction scheme is no longer divided by time, only one load reduction payment is obtained by calculation. At the same time, only solve the power planning scheme, other equipment in the system is still calculated according to the original example data.

Therefore, taking the system does not appear load shedding as the basic condition, after calculation, we can get three different time-of-use electricity price schemes and the corresponding load reduction scheme see table 5-3. At the same time, we can get the planning cost and operation cost of each scheme under different values of Γ see table 5-4, table 5-5, table 5-6.

Table 5-3 Time-of-use Pricing Scheme

Scheme	Valley time / (Yuan / kWh)	Normal time / (Yuan / kWh)	Peak time / (Yuan / kWh)	Load reduction payment / (yuan / kWh)
Option 1	0.42	0.50	0.55	0.92
Option 2	0.40	0.49	0.56	0.87
Option 3	0.37	0.48	0.63	0.84

Table 5 - 4 Combination Scheme 1

ΓValue / Indicator	Planning cost / million yuan	Operating costs / million yuan
2	14.33	1.90
3	14.12	1.87
4	13.91	1.85
6	13.82	1.82

Table 5-5 Combination Scheme 2

ΓValue / Indicator	Planning cost / million yuan	Operating costs / million yuan
2	14.02	1.85
3	13.78	1.82
4	13.51	1.79
6	13.25	1.75

Table 5-6 Combination Scheme 3

ΓValue / Indicator	Planning cost / million yuan	Operating costs / million yuan
2	13.55	1.76
3	13.21	1.72
4	12.95	1.69
6	12.89	1.67

Under the framework of combination scheme 3, the maximum load of each node is shown in Tables 5 – 7.

Table 5-7 Maximum load of each node

Nodal point	Load /kW	Nodal point	Load /kW
4	6.2	10	3.5
5	5.8	11	12.3
6	5.2	13	5.4
7	5.1	14	12.1
9	2.6		

According to the above table, the power planning is solved again. When Γ = 6, the combination scheme 3 is the optimal time-of-use price and DLC scheme. The corresponding power planning scheme is as follows : two G-IIs are connected at G1, two G-Is and one G-II are connected at G3, and one G-I is connected at G2.

From the above calculation results, the calculation method in this paper can be used to obtain the optimal combination scheme of system planning (Scheme 3) and the planning cost and operation cost under this scheme. The above simplified examples prove the effectiveness of the model and method in this paper, which is conducive to delaying the mining and utilization of power system investment and demand response resources.

6. Conclusions

Firstly, this paper constructs the SOC output characteristic model of energy storage, and considers two situations of DLC and TOU price as well as different demand response types. The robust optimization method is used to deal with the uncertainty of demand response. Secondly, a multi-objective function and constraint conditions are constructed to minimize the system planning cost, operation cost and pollution emission. Finally, the genetic algorithm is used to analyze an example in a certain area of Fujian. In the example, the economy of planning schemes under different robust control parameters is compared and analyzed. The results show that the optimal combination scheme of system planning is obtained by using the model and calculation method in this paper, which is conducive to delaying the investment of power system, and can provide decision-making reference for the mining and utilization of demand response resources, reducing the cost of system planning and improving the operation efficiency.

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