Research on Regional Energy System Planning Considering Flexible Access of Electric Vehicles

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Abstract. The high proportion of renewable energy sources and intermittent loads pose challenges to the flexible operation of regional energy systems. To improve the flexible operation level of regional energy system, this paper considers the uncertainty of energy storage charging and discharging, demand-side management, and V2G of electric vehicles, and establishes a flexible resource supply capacity and cost model. With the goal of minimum flexibility demand and economic optimization, the implementation of flexible supply and demand balance constraints is added. The advantages and disadvantages of the traditional resource scheduling scheme and the unified flexible resource scheduling method are compared from the net load volatility, the maximum operating volatility and the whole time scale flexible supply and demand balance index. The algorithm analysis proves the advantages of the proposed scheduling scheme in improving the flexibility of the regional energy system, which can describe the flexibility of the regional energy system well and can be quantitatively characterized.

Keywords: Flexible access; Regional energy system; Regulatory ability; Net load fluctuation rate.

1. Introduction

Under the "two-carbon" goal, the proportion of photovoltaic in the regional energy system has gradually increased, and the volatility of photovoltaic output has caused a certain degree of impact on the stable operation of the regional energy system[1].

The power system plays an increasingly important role in the energy system due to the easy transmission and transformation of electrical energy and the fact that it is cleaner than other forms of energy use[2]. Uncertainty factors in power system are generally divided into random factors that can be simulated by statistical data, fuzzy factors that cannot be accurately predicted due to lack of information, and subjective uncertainty factors that are difficult to be quantitatively analyzed by mathematical methods, covering distributed power output, power load, multiple load characteristics, economic parameters, laws and regulations, etc.[3,4]. Traditional regional energy system planning is based on deterministic power supply and load scenarios to plan the regional energy system grid, power supply location and other issues, in the power system with increasing random factors, it is urgent to supplement and improve new theoretical methods. At present, domestic and foreign researches on uncertain factors in power system have been relatively mature, among which multi-scenario analysis, stochastic programming, robust optimization and fuzzy programming have been widely applied in regional energy system planning[5].

The multi-scenario analysis method usually uses mathematical tools to describe the uncertain variables in the problem quantitatively. Reference [6] generates many deterministic scenarios through Monte Carlo method, Latin hypercube sampling and other methods, and turns uncertain planning into a general planning problem to improve the efficiency of the algorithm. Reference [7] uses probability density function to fit the uncertainty of landscape load, and uses sampling method to generate scene. Reference [8，9] uses Kmeans method for clustering to optimize the location of grid and power supply. Robust optimization does not need to obtain the specific probability distribution of uncertain variables, the constraint conditions are strictly established, and the planning scheme is conservative, which has strong robustness.

Based on the above literature research, this paper first takes electric vehicles as the research object, conducts a quantitative analysis of the flexibility of electric vehicles, describes the up-and-down backup capacity of electric vehicles, and takes it as the upper and lower limit of adjustable power of demand-side flexibility resources in regional energy system planning.

2. Flexibility evaluation indicators

Flexible scheduling resources should respond to the system's flexible demand quickly and timely, and realize the real-time flexible supply and demand balance while taking into account the economy. In regional energy systems, the main sources of flexibility demand lie in the large-scale access of distributed power sources, the increasing load of electric vehicles and the primary load of the system, which can be defined as the change of the net load composed of these three on a fixed time scale.

$$FL_t = NL_{t+1} - NL_t, t = 1, \ldots, T \tag{1}$$

Where: FL_t is the flexibility demand of the system at the t moment, NL_t is the net load at the t moment, and T is the number of periods divided according to a certain time scale.

2.1 Real-time flexible supply and demand balance evaluation indicators

Considering the flexible supply and demand balance in the planning operation simulation of regional energy system, it is necessary to establish a set of indicators to measure the flexible real-time supply and demand balance. Two indexes, net load volatility and maximum allowable net load volatility, are proposed in this paper to evaluate the system's ability to support uncertain fluctuations and its flexibility in direction and time.

Real-time flexibility demand rate refers to the ratio of flexibility demand and net load per unit time, which represents the strength of flexibility demand, as shown in Formula (2).

$$F_{FRNL}^{t} = \frac{|FL_t|}{NL_t} \times 100\% \tag{2}$$

Where: NL^t indicates the net load of the current period.

Real-time flexibility allows the demand rate to represent the ability of the system to respond to the demand for flexibility in a relatively short time, as shown in Formula (3).

$$F_{FRNL,M}^{t} = \frac{\sum_{i=1}^{N_{flexS}} flexS_i^t}{NL^t} \times 100\% \tag{3}$$

Where: N_{flexS} indicates the number of flexible resources, $flexS_i^t$ is the flexible adjustment capability of the i flexible resource in the current period When $F_{FRNL}^t \le F_{FRNL,M}^t$, it indicates that flexibility resources and requirements are balanced at this time. Otherwise, the flexibility balance is not satisfied.

2.2 Network operation flexibility evaluation indicators

Line load ratio refers to the ratio of the actual value of line transmission and the maximum allowed transmission capacity at a certain time, and describes the flexibility of the network to withstand net load fluctuations.

$$F_{l.CM,i}^{t} = \frac{P_{li}^{t}}{P_{max,li}} \times 100\% \tag{4}$$

Where: $F_{l.CM,i}^t$ is the load rate of the i distribution line at the time ; $P_{\max,li}$ is the maximum transmission capacity of line i ; P_{li}^t is the actual transmission power of line i at time t .

The maximum value of the line equilibrium index corresponding to all the operation modes of the distribution network is taken as the index F_{NS} to measure the flexibility of the grid operation, that is,

$$F_{NS} = max\,(E_1, E_2) \quad (5)$$

Where: E_1 and E_2 represent the range and standard deviation of the load rate of each line of the regional energy system.

3. Flexibility resource analysis and index construction

3.1 Energy storage model

The mechanism of " high-low-charging " energy storage technology realizes peak shaving and valley filling, smooth load, reduces power supply cost, improves operation stability, and improves frequency.

Table 1. Various types of energy storage flexibility parameters

Storage mode	Response time	Efficiency /%	Investment (CNY/kWh)	Life /A
Battery energy storage	<1s	70-90	600-34000	20-25
Pumped storage	10s-30min	87	320-600	25
Flywheel energy storage	<1s	90-93	1200-3000	2025
Power storage by air compression	1-10min	80	85-600	25

However, the installation cost and operation subsidy cost of energy storage equipment are high. In the optimal allocation and operation of flexible resources, economic factors should be further considered to comprehensively evaluate its cost performance. The operating cost expression of the energy storage facility is :

$$C_{ESS} = C_{ESS,O} + C_{ESS,P} \quad (6)$$

$$C_{ESS,P} = \sum_{i=1}^{T} \sum_{j=1}^{N_{ESS}} (P_{ESSC,j}(i) e_E(i) + P_{ESSD,j}(i)(e_E(i) + e_S)\tau \quad (7)$$

$$F_{NS} = max\,(E_1, E_2) \quad (8)$$

Where: e_{ESS} is the purchase cost of energy storage, M_{ESS} is the number of charge and discharge cycle life of energy storage, $P_{ESSC,j}(i)$ is the discharge power of the i-th energy storage at the moment, and tt is the charging power of the j-th energy storage at the moment. e_E is the unit price of purchasing electricity in each period, and e_S is the unit subsidy price of purchasing electricity from the grid to the energy storage.

3.2 Energy storage model

Both the load-side response demand and the load cut by the system fault are load uncertainties. In this paper, the load-side flexibility demand mainly considers the latter, which determines the load loss through the real-time operation state of the regional energy system. The system loses part of the load, and the flexibility demand is downward. The specific mathematical model is :

$$F_L(t) = P_{LOAD} - P_{L,F}(t) \quad (9)$$

$$F_L(t) = P_{LOAD} L_{OLP} \quad (10)$$

$$F_{down}^{N}(t,\tau) = P_{L,F}(t) \quad (11)$$

Where: $F_L(t)$ is the system load ; P_{LOAD} is the total load of the system ; $P_{L,F}(t)$ is the amount of load loss at time t ; ll is the probability of load loss ; $F_{down}^{N}(t,\tau)$ is the downward flexibility requirement.

3.3 Energy storage model

With the gradual popularization of EV, after many EVs are connected to the power grid, because of the randomness and intermittence of their charging time, they will have unknown effects on user-side load, power grid planning and operation, power quality monitoring, flexibility and other scenarios.

The upward or downward flexible adjustment ability of electric vehicles is expressed as :

$$\begin{cases} flexS_{EV,i,+} = min\,(P_{EV,d}(i), \frac{SOC_{EV}(i)-SOC_{EV,min}}{\tau} \\ flexS_{EV,i,-} = min\,(P_{EV,c}(i), \frac{SOCEV_{EV,max}-SOC_{EV}(i)}{\tau} \end{cases} \quad (12)$$

Where: $flexS_{EV,i,+}$ and $flexS_{EV,i,-}$ are the upward and downward adjustment capabilities of a single electric vehicle during the i period ; $P_{EV,d}(i)$ and $P_{EV,c}(i)$ are the discharge power and charging power of the electric vehicle battery in i period, respectively. $SOC_{EV,\max}$ and $SOC_{EV,\min}$ are the upper and lower limits of the battery power of the electric vehicle ; $SOC_{EV}(i)$ is the current stored power of the electric vehicle battery device.

The cost of invoking electric vehicles as a flexible resource is

$$C_{EV} =- \sum_{n}^{N_{EV}} \sum_{i \in H_C} h_{EV}^{n}\,(i) P_{EV} \tau e_E(i) \quad (13)$$

4. Flexible resource scheduling strategy and solving model

4.1 Objective function

The total cost of flexible resource scheduling includes : interruptible load interruption cost, energy storage operation cost and subsidy cost. The objective function 1 is as follows :

$$C_1(\boldsymbol{X}) = \Delta t \sum_{t=1}^{T} \sum_{i=1}^{N_{ESS}} \left[\left(C_{i,t}^{ep} + \frac{C^{ESS}}{M^{ESS}} \right) P_{i,t}^{ESS,C} + (C_{i,t}^{ep} + C^{sp} + \frac{C^{ESS}}{M^{ESS}}) P_{i,t}^{ESS,D} \right] + \sum_{t=1}^{T} \sum_{i=1}^{N_{CL}} C_{i,t}^{CL} P_{i,t}^{CL} \quad (14)$$

Where: N_{ESS} is the number of energy storage, $C_{i,t}^{ep}$ is the time-of-use electricity price at time i, C^{sp} is the subsidy price given by the power grid to the energy storage discharge, $P_{i,t}^{ESS,C}$ and $P_{i,t}^{ESS,D}$ are the charging and discharging power at the i th energy storage time respectively ; N_{CL} is the number of interruptible loads ; $C_{i,t}^{CL}$ is the contract price of interruptible load ; $P_{i,t}^{CL}$ is the interrupt amount at time t of the i interruptible load ; C^{ESS} is the capacity cost coefficient of energy storage ; M^{ESS} is the number of cycle life of energy storage.

4.2 Objective function

By improving the crossover probability and mutation probability of the GA algorithm, and introducing the crossover and mutation operations of the improved GA algorithm into the PSO algorithm, the elite strategy is used to expand the sample space and select the best. Finally, the GAPSO algorithm with better performance than the GA algorithm and the PSO algorithm is obtained. The steps are as follows :

(1) Input network data, electric vehicle load, photovoltaic output, energy storage equipment parameters and other raw data ;

(2) Set parameters such as particle swarm acceleration factor, inertia factor, convergence accuracy, maximum number of iterations, boundary values of position and velocity, initialize individual optimal value and global optimal value, initialize position and velocity of particles, and form initial population.

(3) Sorting the individuals and performing crossover and mutation operations ;

(4) Update the velocity and position of the particles, check the constraints ;

(5) Calculate the flexibility demand and flexibility resource supply capacity, and calculate the fitness according to the objective function ;

(6) Global search, update the individual optimal value and global optimal value ;

(7) to determine whether the convergence accuracy or the maximum number of iterations is reached. If it is satisfied, turn (7), not satisfied (3) ;

(8) Output the optimal flexibility resource scheduling results, calculate the flexibility evaluation index, and end ;

5. Example analysis

In this paper, the improved IEEE33 distribution system with high permeability DG is used to optimize the scheduling of energy storage and interruptible load under two scheduling strategies, improve the flexibility index of regional energy system, and compare the improvement effect of the two schemes.

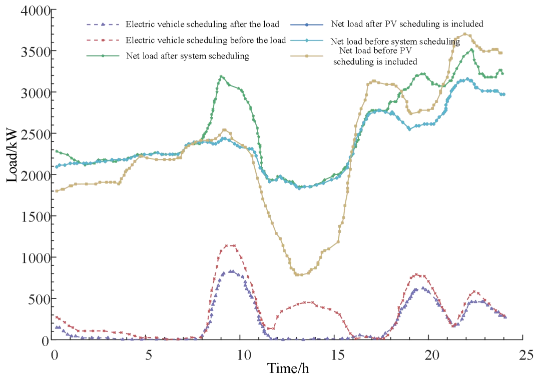

Fig. 1 The change of each load curve before and after strategy 1 scheduling

Observing the net load curve under the two scheduling schemes in Fig.2, after optimizing the scheduling flexibility resources, the volatility of the net load curve is significantly reduced. Especially in the two time periods of 9 : 00-11 : 00 and 20 : 00-23 : 00, and the trough period from 11 : 00 to 15 : 00, the optimal scheduling has brought obvious improvement. The net load curve of scheme 2 after scheduling is smoother, and the effect of reducing peak-valley difference is more significant.

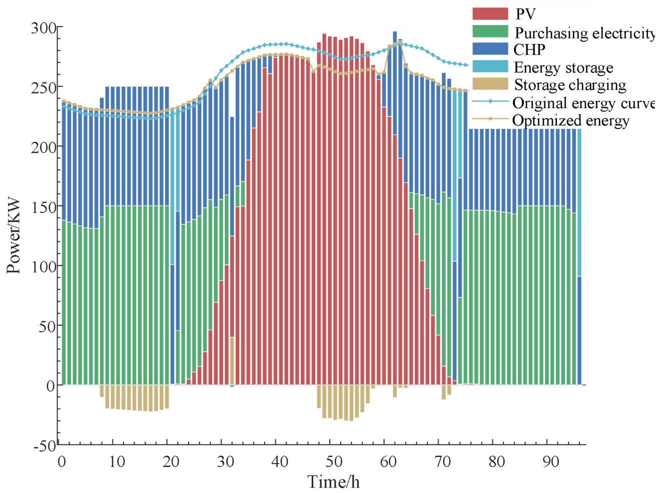

Fig. 2 The system flexibility demand rate of the two schemes

Table 2 is the comparison of the overall flexibility evaluation indicators of the two schemes. After the scheduling of the two strategies, the average flexibility demand of the strategy 1 is 41.70 % lower than that before the scheduling, and the average flexibility demand index of the strategy 2 is 61.26 % lower than that before the scheduling. The up-and down-regulation capabilities provided by the flexibility resources of the two schemes are quite sufficient relative to the demand of the system. In general, the flexibility of the distribution system after the scheduling of the strategy 2 is better than that of the scheme 1 on the whole time scale.

Table 2. Comparison of flexibility adequacy of two scheduling strategies

	Before scheduling	Strategy 1	Strategy 2
Average flexibility requirement	6.452	3.376	2.512
Average Flexibility Allows Demand Degree	/	142.351	147.745

Average flexibility sufficiency	/	138.334	139.522

6. Summary

This paper summarizes the flexible resources existing in the regional energy system, summarizes the characteristics of flexible scheduling resources, and establishes a model of flexible resource supply capacity and cost. With the goal of minimum flexibility demand and optimal economy, a flexibility optimization scheduling model is established by adding real-time flexibility supply and demand balance constraints.

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