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Review and Prospects for Evaluating Power Grid Dispatching Service Quality

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ABSTRACT To reasonably evaluate the dispatching service quality of a power grid and comprehensively reflect the diversified demand satisfaction extent of the relevant stakeholders in the power system, it is imperative to construct an evaluation index system for power grid dispatching service quality, which should thoroughly consider the demand satisfaction of generation-side stakeholders, grid-side stakeholders, and load-side stakeholders. In this paper, the research status of the source-grid-load stakeholders' satisfaction indexes is overviewed from the perspective of their dispatching demand. The dispatching demand satisfaction indexes of the source-grid-load stakeholders and major evaluation methods in the literature are also summarized. According to current research progress, proposals for improving the rationality and efficiency of power grid dispatching service quality evaluation are also described. Finally, by combining the development demands of power grid dispatching service quality, we outline future research directions that involve dispatching demand satisfaction indexes evaluation for source-grid-load stakeholders in the power system.

INDEX TERMS Power grid dispatching, demand satisfaction, service quality, evaluation index system.

I. INTRODUCTION

With the continuous development of the power market and new innovations in power systems, power consumers have become a key factor in the competitiveness of power supply companies and an important force in determining market changes [1], [2]. The effective evaluation of power supply service quality is an important prerequisite for power supply companies to improve their service quality [3]. Power supply companies can evaluate their service quality level by analyzing the extent to which consumers' demands are satisfied. The higher the user's satisfaction degree is, the higher the quality of service provided by the power supply company is [4]. High-quality power supply services are important factors for power grid companies to expand market share and improve profitability [5]. Especially in the context of the high proportion of renewable energy penetration and the continuous advancement of the power market, through the interaction between users and the power grid, providing flexible and personalized services for relative stakeholders in the power system have become an inevitable requirement for the development of smart grids in the future [6].

The quality of service is traditionally considered to be a measure of the ability of the power system to continuously and reliably supply the electrical energy required by the load [7]. With the continuous innovations in the power market mechanism today and the changes in the roles of the relative stakeholders during power grid dispatching, the evaluation index for power grid dispatching service quality has been given a richer connotation [8]. The quality of service can fully reflect the extent of dispatching demand satisfaction for relatively diverse stakeholders on the power generation side, the power grid side, and the load side. Comprehensive evaluation of the power grid dispatching service quality is one of the important references for addressing the problems of high operating costs, high pollution emissions and users' poor power consumption experiences.

At the current stage, large-scale ultrahigh voltage alternating current and direct current channels as well as large-capacity energy bases are rapidly being constructed, the dispatching coupling degree is getting closer and closer [9], and the total amount of clean energy consumption keeps increasing. Through the scheduling of generation-transmission-utilization coordination, the differentiated demands of the relative stakeholders in the power system can be fully satisfied [10]. Constructing demand satisfaction indexes of source-network-load stakeholders,

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obviously, are conducive to find the weak links that are not valued by the dispatchers in power grid control centers, and improve the dispatching service quality of the power grid. Therefore, there is an urgent need to construct an evaluation index system of power grid dispatching service quality while considering the multi-stakeholders demands satisfaction, to reflect the deviation degree between the actual dispatching demand satisfaction and expected dispatching demand satisfaction of the relative stakeholders in the power system. In addition, this approach provides theoretical guidance for the power grid dispatchers to make decisions and formulate the corresponding dispatching plans.

In the literature, most metrics have been presented to evaluate the reliability, economics and cleanliness of power grid dispatching. However, to the best of our knowledge, comprehensive indexes that explicitly evaluate the dispatching service quality of power grids have not yet been proposed. Therefore, this paper intends to construct an evaluation index system of power grid dispatching service quality from the perspective of multi-stakeholders differentiated demand satisfaction. The research status on the dispatching demand satisfaction indexes evaluation of the source-network-load stakeholders is expounded, and then, we make some proposals for improving the rationality and efficiency of the power grid dispatching service quality evaluation. Last but not least, some challenging problems and future research directions are outlined.

The structure of this paper is organized as follows. In Section II, we overview the dispatching demand satisfaction indicators of the source-network-load stakeholders in the literature. The commonly used evaluation methods in the literature are exemplified in Section III. The evaluation process for assessing the power grid dispatching service quality is given in Section IV. Section V elaborates the key evaluation techniques, and Section VI concludes the existing shortcomings and the problems to be solved in future research.

II. EVALUATION INDEXES CONTENT

Overall, the dispatching service quality of power grids can be divided into three categories: generation side, grid side and load side. In this section, we overview the dispatching demand satisfaction indexes of generation-side stakeholders, grid-side stakeholders, and load-side stakeholders, respectively, to construct a comprehensive evaluation index system for power grid dispatching service quality.

A. DISPATCHING DEMAND SATISFACTION INDEXES OF THE POWER GENERATION SIDE

The fairness, clearness and economics of power generation are generally used as the critical dispatching demand satisfaction indexes for the generation-side stakeholders.

1) FAIRNESS INDICATORS

The satisfaction indexes of dispatching fairness demand on the power generation side are usually used to reflect the profit equity of generation-side stakeholders, which can be evaluated by the power generation plan progress, the ranking of power generation utilization hours, the load factor of power generation and daily plan adjustment rationality [11]. The statistical value of power generation plan progress is the cumulative value of the annual plan completed by each unit from January 1st to the present, which is used to evaluate the power generation plan progress of various types of power plants. The calculation formula of the index is shown below.

$$E_1 = \sum_i |D_i - D_{average}| \tag{1}$$

In (1), D_i represents the deviation of the average adjustable utilization rate of the power generation planning unit i, which is the difference between the average actual adjustable utilization rate and the average planned adjustable utilization rate of the power generation planning unit i. $D_{average}$ indicates the deviation of the average adjustable utilization rate of units in the province, which is the difference between the average actual adjustable utilization rate and the average planned adjustable utilization rate of the units in the province.

The utilization hours ranking index of power generation reflects the utilization hours ranking of each unit. The calculation formula is expressed as follows:

$$E_2 = \sum_i \left|\beta_i T_i - T_{average}\right| \tag{2}$$

In (2), β_i is a coefficient set, which can be adjusted according to the requirements for generation utilization hours of units with different rated output power. T_i represents the utilization hours of generator set i, and $T_{average}$ represents the average utilization hours of generator sets in the province.

The load factor of power generation reflects whether the load rate of a unit's power generation matches the load rate of power consumption within a day.

The reasonable degree of daily plan adjustment is used to evaluate the rationality of adjustments when the existing power generation progress of the unit is no longer reasonable. The calculation formula is shown below.

$$E_3 = \sum_i |S_{Mi} - S_{Ni}| \tag{3}$$

In (3), Ni represents the proportion of the annual power generation plan completed by the power generation planning unit i. Mi represents the ratio of the current day's power generation of the planning unit i to the current day's power generation capacity. S_{Mi} and S_{Ni} are the corresponding ranking results, respectively.

2) CLEANLINESS INDICATORS

The levels of pollutants' emissions produced by the generator set and the consumption level of renewable energy are usually used to evaluate the dispatching cleanliness demand satisfaction of generation-side stakeholders.

With multiple types of renewable energy penetration into the power grid, the grid-connected rate of renewable energy units, the proportion of electricity generated by renewable energy units, and the level of compliance with flue gas emissions are used as the dispatching cleanliness demand satisfaction indexes of generation-side stakeholders [12], which can be calculated by the following formulas:

$$C_{1\_1} = \sum_{i\in\Omega} P_i T_i / \sum_{i\in\Omega} W_i \times 100\% \tag{4}$$

$$C_{1\_2} = \sum_{i\in\Omega} P_i T_i / W^T \times 100\% \tag{5}$$

$$C_{1\_3} = C'_{1\_3} \times \frac{21 - O_2}{21 - O'_2} \tag{6}$$

In (4) and (5), P_i is the active output power of unit i; T_i is the grid-connected duration of unit i; and Ω represents the renewable energy unit commitment of the whole network. In (4), W_i is the total electricity generation of unit i during the statistical period, and in (5), W^T is the total electricity generation of the whole network during the statistics period. In (6), the level of compliance for the flue gas emissions is further expressed by the concentration of soot, sulfur dioxide and nitrogen oxides, which can be converted to the concentration value under the referenced oxygen content; C'_{1_3} represents the measured pollutants concentration, and its unit of measurement is mg/m^3; O_2 and O'_2 are the referenced oxygen content and measured oxygen content, respectively, and their units of measurement are %. Aiming at the power generation cleanliness evaluation issues of different dispatching modes with wind power penetration into the power grid, the dispatching cleanliness demand satisfaction indexes of generation-side stakeholders are evaluated through the environmental benefits of per unit wind power and the pollutants' emissions of per unit electricity generation [13], as shown below, respectively:

$$B_e = \frac{f_1 - f_0}{\sum_{t=1}^{T} P_{w,t}} \tag{7}$$

$$e_u = \frac{E_m}{E_a} \tag{8}$$

In (7), f_0 and f_1 are the total pollutant emissions generated by conventional units before and after the integration of wind power into the electric network during the dispatching period, respectively; $P_{w,t}$ is the output power of the wind farm at time t; T is the total duration of wind power connected to the power grid. In (8), E_m is the total pollutant emissions, and E_a is the total electricity generation of the unit.

3) ECONOMIC INDICATORS

The electricity generation cost of various types of units, peak shaving costs, renewable energy abandonment rate, and electricity sales revenue are usually used as the main indicators for evaluating the economic dispatching demand satisfaction of the generation-side stakeholders.

In the interconnected power grid dispatching model with large-scale renewable energy penetration, the output power of the tie-line can be adjusted to promote the accommodation of renewable energy, thereby reducing the cost of thermal power generation [14]–[16], and the renewable energy abandonment rate can reasonably reflect the dispatching economics of the power generation side. To evaluate the power generation economics of different dispatching modes with renewable energy integrated into the power grid, the literature [17] evaluates the generation-side dispatching economics from the perspective of operation economics of conventional thermal power plants and wind power plants. Coal consumption cost and peak shaving cost are used as the main economic dispatching indicators of thermal power plants, and the wind abandonment rate is used as the economic dispatching indicator of wind power plants, which are calculated as follows:

$$F = \frac{\sum_{i=1}^{N}\sum_{t=1}^{T} [F_i(P_i(t)) + S_i(t)]}{\sum_{i=1}^{N}\sum_{t=1}^{T} P_i(t)} \tag{9}$$

$$S_r = k_{ui} P_w(t) u_s\% / P_L \tag{10}$$

$$\eta = 1 - \sum_{i=1}^{N_w}\sum_{t=1}^{T} P_{wi}(t) / \sum_{i=1}^{N_w}\sum_{t=1}^{T} P^*_{wi}(t) \tag{11}$$

In (9), $P_i(t)$ and $S_i(t)$ are the output power and start-up cost of the conventional thermal generation unit i at time t, respectively; F_i is the coal consumption cost of the conventional thermal generation unit i; and N represents the total number of conventional thermal generation units. In (9) and (11), T represents the total dispatching periods. In (10), k_{ui} is the cost coefficient for spinning reserve; $P_w(t)$ is the output power of the wind farm at time t; $u_s\%$ represents the demand factor of the wind power forecast error for the positive reserve; and P_L is the total load. In (11), N_w represents the total number of wind farms; $P^*_{wi}(t)$ and $P_{wi}(t)$ are the maximal predicted dispatching power and actual dispatching power of the wind farm at time t, respectively.

B. DISPATCHING DEMAND SATISFACTION INDEXES OF THE POWER GRID SIDE

The safety, reliability and economics of the power grid operation are usually used as the referenced indicators for evaluating the key dispatching demand satisfaction of grid-side stakeholders.

1) SAFETY INDICATORS

Usually, the maximum load rate of the line is used to reflect the security extent of the power grid dispatching operation. However, there is a large number of lines on the power grid side, which cannot be easily expressed with unified equilibrium indicators. Therefore, the balance degree of the power grid operation is also used to evaluate the safety of the power grid dispatching operation [11]. The balance degree of the power grid operation is an important factor that reflects whether the power flow of line is balanced, i.e., at the same load level, the smaller the power grid operation balance degree is, the more even the power flow of the line is, and the more secure the power network dispatching operation is. The maximum load rate and the operation balance degree of the power grid are calculated as follows:

$$maximum\ load\ rate = \max_{96\ points\ per\ day}\left[\max_{i\in\Omega}\left(\frac{P_i}{P_{i\max}}\right)\right] \tag{12}$$

$$\begin{cases} operation\ balance\ degree = \sum_{j\in\Omega}\left(R_j - \frac{\sum_{k\in\Omega} R_k}{N}\right)^2 \\ R_j = P_{lj}/P_{lj\max} \end{cases} \tag{13}$$

In (12), P_i and $P_{i\max}$ are the actual load and maximum load of the $i-th$ line or section, respectively; and Ω represents the selected line or section set. In (13), R_j is the load rate of line j; P_{lj} is the active power flow of line j; $P_{lj\max}$ is the rated active capacity of line j; and N is the total number of statistical sections.

2) RELIABILITY INDICATORS

The reliability indicator of the power grid dispatching operation is usually used to reflect the operational reliability for the grid-side key equipment and the ability to continuously supply users' power demands [18].

At present, a number of indexes have been proposed to evaluate the dispatching operation reliability of the distribution network [19]. The conventional reliability indicators of the distribution network mainly include the system average interruption frequency and duration, the energy not supplied, the customer average interruption frequency and duration, and the average service availability [20]. However, it cannot fully reflect the reliability level of the power supply that users actually feel. To reflect the users' true perceptions of power supply reliability and provide personalized user services, [21] establishes a comprehensive evaluation index system of power supply reliability in distribution networks, which accounts for the user's experience of power consumption. In [22], the reliability indicators of the distribution network operation are expanded on the basis of conventional reliability indicators, the load shedding probability, the expected energy not supplied (EENS), and the overvoltage expectation, which are taken as the main indicators to reflect the multi-time scale reliability levels of the grid-side dispatching operation at different layers.

Aiming at the dispatching reliability issue of the power system with wind energy integration, the literature [23] takes the EENS as the grid-side operation reliability index, which would be calculated as follows:

$$E_{EENS}^{\mathrm{t}} = \sum_k \beta_k P_{dcur,k}^t \Delta t \tag{14}$$

In (14), β_k is the fault probability of the unit in scenario k, and $P_{dcur,k}^t$ is the amount of load shedding in scenario k at time t. In addition, from the perspective of power system interruption duration, [13] uses the EENS, loss of load expectation (LOLE), loss of load expectation probability (LOLP) and the line overload probability as the dispatching operation reliability evaluation indicators of the power grid with wind power penetration, which are calculated as follows:

$$EENS = \frac{\sum_{y=1}^{N} c_y}{N} \tag{15}$$

$$LOLE = \frac{\sum_{y=1}^{N} t_y}{N} \tag{16}$$

$$LOLP = \sum_{i\in F}\frac{t_i}{T} \tag{17}$$

$$P = \sum_{j\in S}\frac{t_j}{T} \tag{18}$$

In (15) and (16), N is the number of random samples. In (15), c_y is the total amount of load shedding. In (16), t_y represents the power shortage duration. In (17) and (18), T is the total simulation time. In (17), F is the load shedding state set of the power system; and t_i is the duration of state i. In (18), S represents the overrun state set of the line; and t_j is the duration of state j.

To improve the real-time dispatching reliability of the power grid side [24], the ability to regulate the peak load and the load-side demand satisfaction degree for the service quality can be used as critical indicators [25]–[27].

3) ECNOMIC INDICATORS

The operation and maintenance costs, transmission and distribution costs, and revenue levels of the power grid are usually used as referenced indicators to evaluate the grid-side dispatching operation economics.

In the demand-side management scheduling model, by effectively using the load-side resources, the investment costs of the power facilities and operation expenditures of the power grid can be reduced, thereby providing consumers with lower-cost energy services [8], [28]. By responding to the peak shaving demand of the power grid, the users reduce their demand for electricity consumption, thereby saving the investment cost of the power grid and improving the economic operation level of the power grid [29]. The formula for reducing the investment cost of the power grid is shown below.

$$F_h = \Delta N_y \cdot \frac{F_z}{N_r} \tag{19}$$

In (19), F_h indicates the reduced investment cost of the power grid side, ΔN_y indicates the reduction of the peak load capacity, F_z and N_r indicate the total grid-side investment cost and power capacity, respectively. In [30], the grid-side operating income function is defined as the difference between the sales of the electricity and the costs of purchasing electricity, as shown below.

$$U_d = (p_t - p_H)\sum_{i=1}^{N} x_{t,i} \tag{20}$$

In (20), p_t is the unit electricity sales price of power grid at time t, p_H is considered to be the fixed unit electricity purchasing cost of the power grid there, $x_{t,i}$ represents the power consumption of the $i-th$ user at time t, and N is the total number of users. In the economic dispatching problem of the power system with wind power penetration, the average power purchase cost is used as the grid-side economic dispatching evaluation indicator [17], which is calculated as follows:

$$C_e = \frac{W_G(t)C_G + W_W(t)C_W}{W_L(t)} \tag{21}$$

In (21), $W_G(t)$ and $W_W(t)$ are the grid-connected power of the thermal turbines and wind turbines at time t, respectively; C_G and C_W are the grid-connected power prices of the thermal turbines and wind turbines, respectively; and $W_L(t)$ represents the total power consumption of the load at time t.

C. DISPATCHING DEMAND SATISFACTION INDEXES OF THE LOAD SIDE

1) OVERVIEW OF THE USERS' SATISFACTION MODEL

The Fornell's American Customer Satisfaction Index (ACSI) model is one of the most widely used consumer satisfaction measurement models in the world [4], [31]. It uses a relationship model that consists of latent variables, which are consumer's expectations, perception of value, service quality, complaints, and loyalty, as shown in Figure 1:

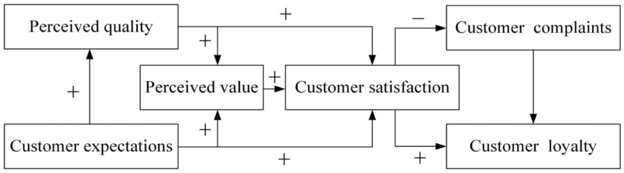

FIGURE 1. **Power consumer satisfaction model.**

Consumer satisfaction is the core index of power grid dispatching service quality evaluation [32]. However, the consumer satisfaction degree for electricity use is usually vague and subjective, and it must be converted into specific, objective and quantifiable functions. In the field of product configuration design, the ratio of product quality to cost is taken as the consumer satisfaction index [33]. In the field of economics, utility functions are often used to measure consumers' satisfaction degree with a set of goods and services [34], [35]. Power consumers participate in the power market and adjust their load demand based on different preferences, such as temperature changes, electricity prices, comfort, and then, the utility functions are used to reflect the users' satisfaction level after adjusting their own power consumption demand, thereby providing a theoretical reference for improving consumers' satisfaction and reducing their electricity costs [36]–[38]. References [30], [39], [40] use a function of the user's power consumption to represent the utility function, to reflect the satisfaction degree of user's power consumption after responding to the grid-side dispatching demand. The calculation formula of the utility function in [30] is shown below.

$$W_i(x_{t,i}, w_{t,i}) = w_{t,i}x_{t,i} - \frac{\alpha}{2}(x_{t,i})^2 \tag{22}$$

In (22), $\omega_{t,i} > 0$ is a parameter that varies with the user and time; α is a parameter given in advance; and $x_{t,i}$ is the power consumption of the $i-th$ user at time t.

2) USER DEMAND SATISFACTION IN DIFFERENT SCHEDULING MODELS

The dispatching demand satisfaction indicators of load-side stakeholders can usually be elaborated from multiple aspects. such as the power quality [41], reliability, cost, communication, and services quality [42]. This section will sort out the users' demand satisfaction evaluation indicators in different system scheduling models.

Load-side demand satisfaction indexes are usually used to reflect the user 's willingness to participate in demand-side responses [43]. The higher the demand satisfaction value is, the more users would respond to the dispatching demands of the power grid [44], thereby reducing the power generation costs and operational costs of the power grid [45], and improving the dispatching service quality of the power grid. At the same time, users can obtain economic compensation by signing load reduction contracts with the power grid, thereby reducing their own electricity expenditures. For users, the greater their demand gratification degree is, the more satisfied they are with their electricity consumption scheme [46], [47].

The existing literature on the demand response scheduling model mainly evaluates the satisfaction degree of users' power consumption from two aspects: the adjustment degree of the users' power consumption method and the power consumption expenditure [25], [35], [48]–[54]. Overall, the satisfaction degree of the users' power consumption method measures the comfort of the users' power consumption, and the satisfaction degree of the users' power consumption expenditure measures the economy of the users' power consumption. The satisfaction indexes of the users' power consumption method and the power consumption expenditures in [48], [52] are calculated as follows:

$$m = 1 - \frac{\sum_{t=1}^{24} |\Delta q_t|}{\sum_{t=1}^{24} q_t} \tag{23}$$

$$s = 1 - \frac{\sum_{t=1}^{24} |\Delta L_t|}{\sum_{t=1}^{24} L_t} \tag{24}$$

In (23), $\sum_{t=1}^{24} |\Delta q_t|$ is the total deviation in the power consumption after the price optimization, and $\sum_{t=1}^{24} q_t$ is the total power consumption before the price optimization. In (24), $\sum_{t=1}^{24} L_t$ is the total electricity expenditure of consumers before the price optimization, and $\sum_{t=1}^{24} |\Delta L_t|$ is the total reduction in the expenditure after the price optimization.

A demand-side management price decision model that considers consumer satisfaction is established in [55], it assumes that the maximum comfort curve for the power consumption is $S_i = [S_{i,1}, S_{i,2}, \ldots, S_{i,n}]$, where $S_{i,n}$ represents the power consumption of the $i-th$ user at time n in the most comfortable condition, and the load demand curve of the $i-th$ user changes from the original load demand curve $P_i^0 = [P_{i,1}^0, P_{i,2}^0, \ldots, P_{i,n}^0]$ to the load demand curve $P_i^1 = [P_{i,1}^1, P_{i,2}^1, \ldots, P_{i,n}^1]$ after adjustment of the electricity price, where $P_{i,n}^0$ and $P_{i,n}^1$ are the power consumption of the $i-th$ user at time n before and after the electricity price changes, respectively. $U_{i,s}$ is defined as the comfortability degree of power consumption in the following formula (25), where a value with an upper line represents its average value. The user's fullness degree of power consumption is $U_{i,q}$, which is shown in the following formula (26), it has a linear relationship with its load within a certain range. The fullness (the satisfaction degree of the users' total power demand) multiplied by the comfortability (the satisfaction degree of the users' electricity consumption habits) is used to represent the load satisfaction U_i, as shown in the following formula (27).

$$U_{i,s} = \frac{1}{2} \cdot \frac{\sum\limits_k (P_{i,k}^1 - \bar{P}_{i,k}^1)(S_{i,k} - \bar{S}_{i,k})}{\sqrt{\sum\limits_k (P_{i,k}^1 - \bar{P}_{i,k}^1)^2} \sqrt{\sum\limits_k (S_{i,k} - \bar{S}_{i,k})^2}} \tag{25}$$

$$U_{i,q} = \frac{\sum\limits_k P_{i,k}^1}{\sum\limits_k P_{i,k}} \tag{26}$$

$$U_i = U_{i,q} \times U_{i,s} \tag{27}$$

Considering the diversity of the load-side stakeholders, a certain type of demand satisfaction weighting coefficient is given according to a given rule. Therefore, the overall multi-users satisfaction index is defined as:

$$U_\Sigma = \sum_i \lambda_i U_i \tag{28}$$

In (28), λ_i is the $i-th$ user's satisfaction weight. In addition, by introducing the objective function weights μ, the optimization goals of minimizing the system peak load and maximizing the user's satisfaction are formulated as follows:

$$\min \left(\mu \times \max_t \left\{ \frac{\sum\limits_i P_{i,t}^1}{\max\limits_t \left\{ \sum\limits_i P_{i,t}^0 \right\}} \right\} - (1-\mu) \sum_i \lambda_i U_i \right) \tag{29}$$

This formula can be adapted to different dispatching objects according to diverse demands. For example, for consumers, an objective function that minimizes the electricity expenditure or maximizes the user's satisfaction can be used. For the grid-side stakeholders, load fluctuations in the power system can be reduced by minimizing the peak-to-valley differences. Operational decision-makers can flexibly choose the optimization targets according to the actual dispatching demands.

In the model of electric vehicle participation in power grid dispatching, there has been a considerable number of studies on electric vehicle users' demand satisfaction indicators. The demands of electric vehicle users' power consumption are satisfied by ensuring the normal service life of the power battery and completing the charging within the specified amount of time [56]. In references [57], [58], the charging cost of an electric vehicle, the loss cost of the power battery, the deviation between the scheduled output and actual output of the electric vehicle are used as users' demand satisfaction indicators, and then, they optimize the charging and discharging scheduling for the purpose of improving user's satisfaction, suppressing the fluctuation in the new energy output and load at the same time. Reference [59] uses the charging fees and initial charging time as the indexes of the electric vehicle users' demand satisfaction, to reduce the peak-to-valley difference in the power grid and improve the users' demand satisfaction. Reference [60] incorporates the charging time, charging cost, and charging convenience into the electric vehicle users' demand satisfaction indexes, thereby providing theoretical references for the scientific location and optimal capacity allocation of the charging stations. References [61] and [62] use the average waiting time and the probability of traffic jams as electric vehicle users' demand satisfaction indicators, to improve the service quality and profit of the charging stations. In [63], to improve the terminal service quality of the charging station, the driving distance to the charging station, the charging time, the charging energy and the charging cost are used as the electric vehicle users' demand satisfaction indicators, which are calculated as follows:

$$R_{CSD,1} = \left(1 - \frac{L}{L_M}\right)^2 \tag{30}$$

$$R_{CSD,2} = 1 - \frac{\max(|T_1 - T_1'|, |T_2 - T_2'|)}{\Delta T_{\max}} \tag{31}$$

$$R_{CSD,3} = \max\left(1, \frac{E_{prop}}{C_{EV} \frac{Q_{SOC,exp} - Q_{SOC}}{100\%}}\right) \tag{32}$$

$$R_{CSD,4} = e^{-\alpha \frac{c}{c_{exp}}} \tag{33}$$

In (30), $R_{CSD,1}$ is expressed as the satisfaction with the driving distance to the charging station; L is the walking distance between electric vehicle users and the charging station, and L_M is the maximum walking distance that can be accepted by electric vehicle users. In (31), $R_{CSD,2}$ is expressed as the charging time satisfaction; T_1 and T_1' are the actual inbound time and expected inbound time of the electric vehicles, respectively; T_2 and T_2' are the actual outbound time and expected outbound time of the electric vehicles, respectively; and $\Delta T_{\max}$ represents the maximum waiting time of the electric vehicle users. In (32), the satisfaction of charging energy is $R_{CSD,3}$; the bidding charge energy of the charging station is E_{prop}; Q_{SOC} and $Q_{SOC,exp}$ are the current state of charge and the expected state of charge, respectively; and C_{EV} is the effective energy storage capacity of the power battery. In (33), $R_{CSD,4}$ represents the satisfaction of the charging costs; α is the price impact factor; c_{exp} is the user's expectation charging cost of per unit electricity; and the charging station bidding price for the current charging request is c, where $c_{exp} > 0, c \geq 0$.

In the dispatching model of an active distribution network, the power consumption satisfaction and power utilization reliability are the crucial indexes for evaluating the users' satisfaction with grid-side dispatching service quality [51], [64]. Reference [65] evaluates the users' power consumption satisfaction through the number of consumers complaints in the distribution network, which is calculated as follows:

$$S_c = \left(1 - \frac{N_{uc}}{M}\right) \times 100\% \tag{34}$$

In (34), N_{uc} represents the total number of complaints received from consumers in the distribution network per year, and M represents the total number of users in the distribution network. Furthermore, in [65], [66], the reliability rate of power consumption and the voltage qualification rate are also taken as reference indicators to improve the reliability of the users' electricity consumption. The calculation formulas are given as follows:

$$R_{RSL} = \left(1 - \frac{\sum t_m}{M \times T}\right) \times 100\% \tag{35}$$

$$VER = \frac{\sum t_{vm}}{M \times T} \times 100\% \tag{36}$$

In (35) and (36), t_m and t_{vm} denote the total power outage time and voltage qualification hours of the $m-th$ consumer in the distribution network during the statistical time, respectively; M and T represent the total number of consumers and the statistics duration in the distribution network, respectively.

In residential energy management systems, the consumer demand satisfaction indexes can be quantitatively analyzed by the adjustment degree of users' usage habits for different electrical equipment [67], which can also be used as an objective function or constraint to motivate users to actively participate in demand response projects, on the basis of not causing inconvenience to users, reducing the cost of the electricity consumption for residential users and increasing the operational revenue of the power grid [68]. In [69], the dissatisfaction degree of power users in residential management systems is modeled by an exponential function of the load reduction, which is expressed as follows:

$$Dis = \left[\exp\left(\sum cur(t)\right)\right] - 1 \tag{37}$$

In (37), $cur(t)$ is the total load reduction of power consumers at time t. By using the cost of electricity consumption and dissatisfaction of electricity consumption method as the optimization scheduling goal of the residential energy management system, the cost of electricity consumption and dissatisfaction of electricity consumption method can be reduced at the same time. Moreover, the fatigue degree of the response can be quantitatively analyzed by the users' response frequency and duration, to continuously ensure that users participate in demand response projects, and to improve the profit of the power grid and users [70]. The calculation formula of the response fatigue degree is given as follows:

$$RFI = \sum_{w} \pi_w \left(\frac{\sum_i v_i^{App} \tau_{i,w}^{dissat}}{T \sum_i v_i^{App}} \right) \times 100\% \tag{38}$$

In (38), v_i^{App} is the inelastic parameter of the load, $\tau_{i,w}^{dissat}$ represents the duration of the $i-th$ user's unsatisfactory response in scenario w, π_w is the scenario probability, and T is the duration of users' participating in demand response projects.

In considering an integrated energy management system model with multiple energy sources penetration, [18], [71] use the system average fault outage duration to characterize the ability of regional integrated energy systems to maintain a reliable energy supply. The power quality is the crucial factor that affects the user's energy use experience, and to further improve the service quality of the integrated energy management system, the economy and comfort of electricity consumption can usually be used as users' demand satisfaction indexes. Reference [72] evaluates the service quality provided by an integrated energy system for users from the perspective of safety, economics, reliability, and cleanliness, to provide comprehensive conductive information and facilitate the decision-making of dispatchers.

In the optimal dispatching model of household microgrids, [54] takes the comfort and economy of power consumption as the objective function for preventing the price response measures from being too radical and ignoring the service quality, thereby ensuring the comfort and economy of users' power consumption while satisfying the grid-side peak shaving demand. In the island microgrid model, the ratio of total power generation to total load during all periods can be represented as the satisfaction index of users' power consumption [73], which is expressed as follows:

$$F = \frac{\sum_{t=1}^{T} \left(\sum_{n=1}^{M_G} P_{n,t}^{MT} + P_t^{RE} + P_t^{DC} - P_t^{CH} \right)}{\sum_{t=1}^{T} P_t^{L}} \times 100\% \tag{39}$$

In (39), $P_{n,t}^{MT}$ is the output power of microgenerators at time t; M_G is the number of microgenerator units; P_t^{RE} is the total output power of the wind turbine and photovoltaic generator unit at time t; P_t^{DC} and P_t^{CH} are the discharge power and charge power of the energy storage at time t, respectively, P_t^L is the total load at time t. When considering that multiple microgrids are interconnected and connected to the main power network, the load satisfaction can be ensured by maintaining a balance between the power generation and users' power consumption demand via the interactions among the microgrids and utility grid [74].

According to the reference overviewed above, a summary of the power grid scheduling service quality evaluation index system that accounts for source-network-load demand satisfaction is below.

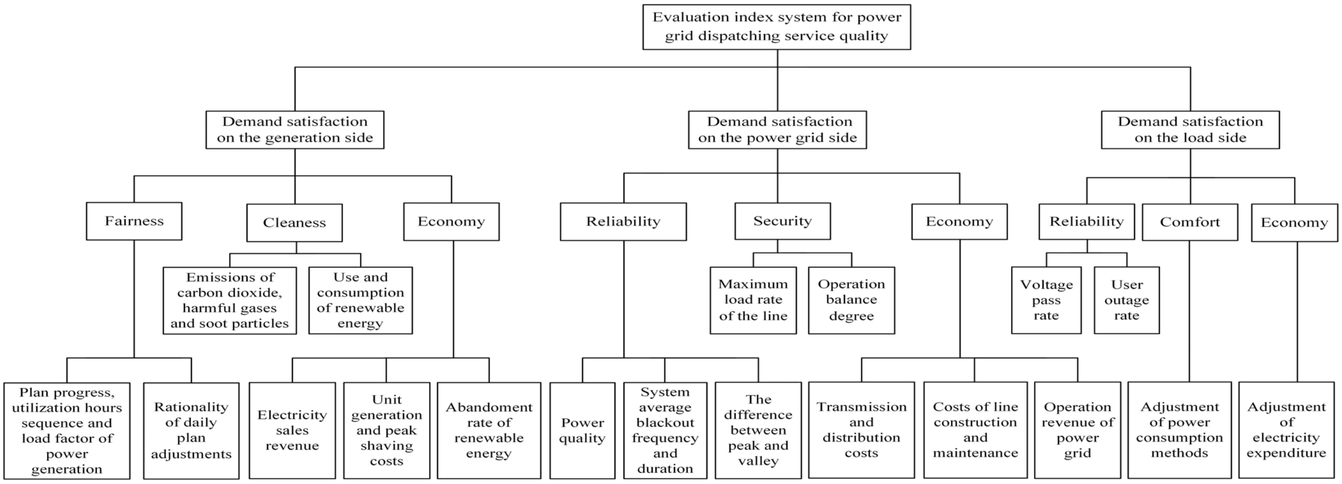

FIGURE 2. **The evaluation index system for power grid dispatching service quality.**

III. EVALUATION METHOD OF SATISFACTION INDICATORS

At present, the evaluation methods used for the dispatching demand satisfaction indexes of different stakeholders in the power system are similar to generally used evaluation methods. The most commonly used evaluation methods include the analytic hierarchy process [41], [75], [76], fuzzy evaluation method [1], [77], [78], neural network method [79]–[81], and entropy weight method [82].

The analytic hierarchy process can fully consider dispatchers' preferences, but it is significantly affected by the expert's professional level, engineering experience and subjective tendency, thereby causing the evaluation results to be too subjective. The fuzzy evaluation method can better solve fuzzy and uncertain problems, but it is also vulnerable to some subjective factors due to the determination of a membership function. The neural network method has a certain adaptive ability to address nonlinear evaluation problems. In [79], it is found that the teaching quality evaluation accuracy calculated by a BP neural network is 13.42% higher than using analytic hierarchy process due to its advantages of nonlinear modeling, however, the disadvantage of using a neural network evaluation method is that its convergence speed is slow and it can easily fall into a local optimum. These two problems can be overcome to some extent by combining the neural network method and other optimization algorithms [80], [81]. In [80], the power customer satisfaction is evaluated by using the BP neural network optimized by the fish swarm algorithm. This approach falls into a local optimum 10 times with a mean square error of 0.1 by using the optimized BP neural network evaluation, however, it traps into the same local optimum 130 times by adopting the BP neural network evaluation alone. Furthermore, the former approach reaches the global optimum with a mean square error of 0.001 after 88 iterations of training, while the latter approach reaches the target after 168 iterations of training. In [81], optimizing BP neural network evaluation by a genetic algorithm spends 739 epochs less than using a BP neural network evaluation merely reaching the target with a mean square error of 0.001. The weights determined by the entropy weight method will not be affected by power grid dispatchers, but using entropy weight alone could cause the given weights to be contrary to the actual situation when there is an increase in the samples. Therefore, assigning the weights is the key factor that affects the authenticity of the evaluation results.

In general, due to the complexity and diversity of the evaluation indexes, it is difficult to be in accordance with the actual situation by relying only on the subjective evaluation of decision makers or the weights given directly by objective evaluation. Adaptively adjusting the weights of the corresponding indexes according to the actual situation [83], and adopting the method of combining subjective weighting with objective weighting can effectively improve the reliability of the evaluation results. In [79], it is found that the teaching quality evaluation accuracy calculated by combining a BP neural network with the analytic hierarchy process is 11.13% and 24.55% higher than using neural network evaluation or analytic hierarchy process alone, respectively. Reference [82] uses the improved gray correlation method and the DEMATEL-ANP-entropy method to determine the subjective weight and objective weight of the corresponding power supply quality evaluation indicators, respectively, and the final evaluation result can be more able to reflect the true customers' preferences and power supply quality. In [84], a method of integrating the CRITIC and analytic hierarchy process is proposed to evaluate the satisfaction degree of high-voltage incremental power users in some Chinese provinces in 2016, and by combining the subjective weights of experts with objective weights based on the original data, it can make the evaluation results more objective and scientific for the decision makers of the power industry to formulate corresponding strategies. Furthermore, to address the problem that a great number of the same types of consumers participate in the process of power grid dispatching, the same types of consumers can be processed uniformly, thereby reducing the complexity of the problem. In [6], [85], load-side resources are aggregated and managed by the load aggregators. The load aggregators are used as intermediary to interact with the power grid on behalf of a cluster of consumers. This approach is more propitious for the distribution of benefits after consumers' participation in demand response scheduling. Reference [86] clusters electric vehicles based on 4 discriminative indicators, including the maximum delayed charging time, arrival time, departure time, and charging time. This cluster-based method preferably solves the problems that are caused by simply using the entire electric vehicle fleet or a single electric vehicle as the evaluation object in the process of power grid dispatching, and it shares the virtues of both a holistic model and a single model.

Electricity sales companies usually assess the level of service quality through the users' electricity consumption satisfaction indexes [61], [82]. However, the satisfaction degree of users' electricity consumption is usually vague and subjective. Therefore, the literature [1] uses interval-type fuzzy sets to make full use of the uncertain and fuzzy perception information of the power users themselves, to simplify the description of consumers' satisfaction with the service quality. Reference [78] uses the fuzzy comprehensive evaluation method to analyze the competitiveness of various types of electricity retailers, to provide constructive suggestions for different types of electricity retailers to formulate strategies and improve their service quality.

In the literature, the objective data about the users' electricity consumption satisfaction is usually obtained through offline means, such as questionnaire surveys, or online means, such as telephone hotlines or web apps. For example, in [4], the Henan Branch of the State Grid establishes an evaluation index system of power supply service quality based on the data from 95598 telephone hotline and questionnaire surveys, to improve users' power consumption satisfaction and the power quality. However, it does not account for the diversified demands of different types of power users, and the time variability of the service quality experienced by users. Reference [87] gives a real-time and dynamic evaluation method of power consumer satisfaction, which solves the problems that the raw data received from a questionnaire cannot reflect the changes in demand satisfaction in real time, compared with the traditional consumer satisfaction model, the final evaluation results can reflect the demand satisfaction degree of power users more truly.

IV. DISPATCHING SERVICE QUALITY EVALUATION PROCESS

The evaluation process of power grid dispatching service quality that accounts for the source-network-load demand satisfaction is shown in Figure 3:

1) Classification of indicators

According to the current research status, the dispatching demand satisfaction evaluation indexes of the source-network-load stakeholders are sorted out.

2) Construction of evaluation index system

The dispatching service quality evaluation indicators of the power grid in the literature are divided into three top-rank indicators: generation-side demand satisfaction, grid-side demand satisfaction, and load-side demand satisfaction. Then, the three top-rank indicators are further divided into nine second-rank indicators. Finally, the nine second-rank indicators are determined by nineteen third-rank indicators.

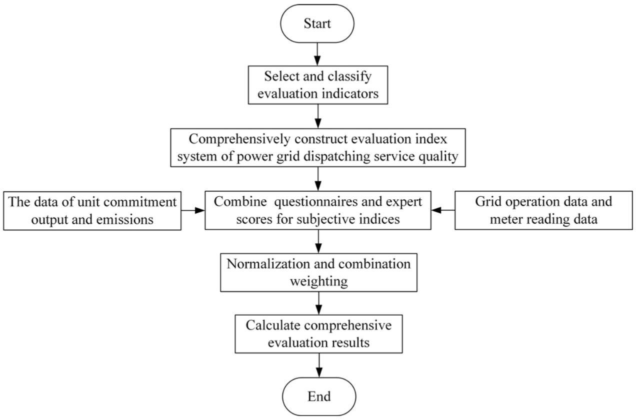

FIGURE 3. Evaluation flow chart of power grid scheduling service quality.

3) Combination weight and evaluation

In accordance with the well-organized evaluation index system of the power grid dispatching service quality, we can calculate subjective and objective evaluation results of the corresponding indexes, and then propose different evaluation methods to determine the subjective weight and objective weight of the corresponding indicators, respectively. Finally, calculate the comprehensive evaluation results.

V. KEY TECHNOLOGIES FOR EVALUATING SOURCE-NET-LOAD DISPATCHING SERVICE QUALITY

By sorting out and summarizing the evaluation indicators and evaluation methods for dispatching demand satisfaction on the power generation side, the power grid side, and the load side, it can be seen that most of the dispatching demand satisfaction indexes of the power grid are relatively isolated. An evaluation index system of power grid dispatching service quality that considers the multi-stakeholders demand satisfaction has not been proposed so far. Obviously, if the service quality indicators of power grid dispatching could not cover multi-stakeholders demand satisfaction, it would seriously affect the integrity and rationality of the evaluation, and the constructed evaluation index system could not meet the requirements of the current power grid dispatchers for analysis and decision-making. Therefore, it is of great urgency to establish an evaluation index system of the power grid dispatching service quality, to reflect the differential dispatching demand satisfaction of multiple stakeholders in the power system. The evaluation process for the power grid dispatching service quality can be improved in the following aspects.

1) Construct an evaluation index system for the power grid dispatching service quality: it is indispensable to build a comprehensive evaluation index system for the power grid dispatching service quality from the perspective of multiple stakeholders' demands. The evaluation index system should

cover the following aspects: the fairness, economy, and cleanliness of power generation; the operational safety, economy, and reliability of the power grid; the reliability, economy, and comfort of power consumption. Most evaluation indexes of the power grid dispatching service quality should meet the requirements of quantifiable analysis.

2) Multi-indexes comprehensive evaluation methods: by combining subjective evaluation methods, such as analytic hierarchy process, fuzzy evaluation, and objective evaluation methods based on data, such as entropy weight method, neural network evaluation method, it can not only reduce the uncertainty caused by subjective judgment, but can also effectively avoid insufficient connectedness with the characteristics of the power industry, which is caused by simply using objective analysis. In this way, the combination of weights can be more in conformity with the authentical service demand satisfaction of multiple stakeholders in the power system. Finally, the evaluation results can be more scientific and rational for power grid dispatchers to formulate the corresponding strategies.

VI. CONCLUSION

In 2017, State Grid and China Southern Power Grid proposed to develop the position of the power grid as an energy supplier into an energy service provider. The quality of service has become an indispensable evaluation indicator for power grid dispatchers. The multiple stakeholders' demand satisfaction index in the power system directly reflects the dispatching service quality level of the power grid, and it is an important reference for power grid dispatchers to analyze and formulate dispatching plans. At this stage, the researches on the evaluation indexes of power grid dispatching service quality mainly focus on the fairness, economic and cleanliness of power generation, the operational safety, reliability and economics of the power grid, as well as the reliability, economics and comfort of electricity use. The generally used evaluation methods mainly include subjective evaluation methods, such as analytic hierarchy process, expert scoring method, fuzzy evaluation, and objective evaluation methods, such as the entropy weight method and neural network method. However, it is noted that there is still room for improving the evaluation process of the power grid dispatching service quality, which is summarized as follows: most of the power grid dispatching service quality indexes are evaluated from the demand satisfaction of several stakeholders in the power system, the stakeholders it considers are not comprehensive enough. Most of the dispatching demand satisfaction indexes of the power grid are relatively isolated, and it has not fully considered to include the overall benefits brought by the source-network-load interaction and coupling. The constructed evaluation index system of the power grid dispatching service quality is not reasonable and comprehensive. The evaluation method of the power grid dispatching service quality can be easily affected by subjective factors and uncertain external factors, thereby causing the validity of evaluation results to be subject to the sample sizes, ambiguity and complexity of indexes.

Therefore, the future development direction of evaluating the power grid dispatching service quality is embodied in the following three aspects:

1) It is indispensable to suit the practical dispatching demand of multiple stakeholders in the power system on the basis of considering the interaction degree of the source-network-load stakeholders. We must establish an evaluation index system of power grid dispatching service quality that considers multi-stakeholders demand satisfaction.

2) We must establish a multi-time scale dispatching service quality evaluation index system of a multi-class power grid with large-scale renewable energy penetration.

3) We must continuously minimize the impact of subjective factors and uncertain factors on the evaluation results, and improve the rationality of the methods for evaluating the power grid dispatching service quality.

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