A BI-LEVEL AND COMPREHENSIVE DECISION-MAKING METHOD OF SMART DISTRIBUTION NETWORK PLANNING UNDER ELECTRICITY MARKET ENVIRONMENT

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ABSTRACT

Under the background of open electricity market and low carbon economy development, the goals for smart distribution network (SDN) planning are guaranteeing reliable power supply, taking into account the interests of all sides, as well as improving efficiency of investment. Based on the analysis of uncertainty factors of SDN construction under electricity market environment, a bi-level and comprehensive decision-making method for SDN planning is proposed. Firstly, upper reliability constraint evaluation is built on the premise of reliable power supply, safeguarding people's livelihood. Then, with the application of AHP/CE-DEA method, lower comprehensive evaluation index system and its specific model were presented for the target of covering the interests of all parties and improving investment efficiency. Finally, the proposed bi-level and comprehensive decision-making model is verified to be effective and feasible, providing useful guidance for SDN development under the electricity market environment.

KEY WORD: *Smart Distribution Network Planning, Index System, Comprehensive Decision-Making, Electricity Market Environment.*

INTRODUCTION

As the fundamental industry in national economy, one of the important social responsibilities for distribution network is reliable power supply. Meanwhile, the deepening of the el1ectric power market reform and the development of the smart distribution network (SDN) technology affect the distribution network markedly [1]-[3].The external environment for investment of distribution network construction changes a lot in the market, decision-making is affected by amounts of factors such as urban planning, policies, regulatory and so on. Meanwhile, the participation of power grid, end-users, distributed generation (DG) operators and the public raises new requirements for SDN in the fields of operational stability, acceptance ability for DG as well as economic and environmental benefits and low carbon benefit [4]. Taking into account the interests of all sides is another important task of SDN.

Focusing on above problems, aiming at guaranteeing the reliability, improving investment efficiency and covering the interests of all parties, a bi-level and comprehensive decision-making method for SDN planning under electricity market is proposed. Firstly, upper reliability constraint evaluation is built to guarantee the reliable power supply. On the basis, a lower comprehensive evaluation index system and its specific model were proposed for the target of covering the interests of all parties and improving investment efficiency. Finally, the evaluation values of planning schemes are obtained by the AHP/CE-DEA method. Test examples are used to verify the efficiency and effectiveness of the method.

THE IDEA OF COMPREHENSIVE DECISION-MAKING FOR SDN IN POWER MARKET ENVIRONMENT

Under the new electricity market environment, the decision-makers of SDN planning need to analyze the key factors of reliability and the core demand among multiple stakeholders, identify the technical relationship and internal logical connection between them, and then build a comprehensive index system, so as to implement multi-stage and multi-objective decision-making. Only in that case can the SDN coordinate the benefit demands of different competitors since the open competition, and guarantee the power supply reliably.

Existing researches are mainly reflecting the development level of smart grid and the single evaluation index system for comprehensive benefit of evaluation or decision [5], which are unable to meet the demand among reliability and the core interests of multi-participants. So they are difficult to support the SDN benign development in open market. For the reason above, the idea of bi-level and comprehensive decision-making for SDN planning in electricity market is proposed in this paper. That is, constraints are based upon reliability, and decision objective is the optimal return on investment combing the benefit demands in multi-participants. Only taking the reliability constraints into the process of evaluation, cannot the insufficient reliability be offset by other too much better attributes, and then the deterministic objective as reliability can be implemented in the stage of planning, Moreover, the investment and benefit analysis covers the demands of stakeholders, provides an important way to meet the requirements of comprehensive decision and improve the efficiency of investment.

Based on the above analysis, this paper propose a frame of bi-level and comprehensive decision-making for SDN planning (see Fig.1). Two parts in comprehensive decision-making are contained, the upper level is reliability constraints and the lower level is comprehensive decision on investment and benefit. The upper level is the precondition for the decision-making while the lower level represents the market's choices. The specific ways to build the index system combing the demand of multi-stakeholders under the market and decision-making methods are introduced in subsequent chapters.

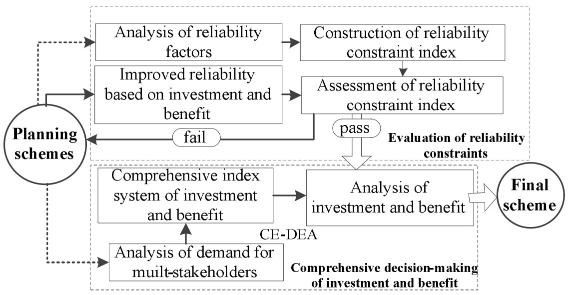

Fig.1 Decision-making method for SDN planning

THE UPPER LEVEL: RELIABILITY CONSTRAINTS EVALUATION

The key role of the upper reliability constraints evaluation is to build constraint indices and evaluation standards, and then check, modify and constrain the reliability level of SDN.

Construction of reliability constraint index

The reliability constraint is the basis of the upper evaluation, in order to reflect the reliable level of the SDN planning quickly and precisely.

Indices reflecting the level of reliability directly or indirectly are various, including the scientific of the network structure, the abundance of the power supply ability, the safety of operation and the reliability of power supply, and so on. Ref. [5] analyses the correlation factors, while parts of the indices cannot be obtained in the planning scheme. On this basis, we did further research: important attributes affecting the reliability in the planning scheme are extracted, decoupled as the key technological factors, and then turned into key indices of reliability constraints that are easily to be calculated and measured. The built reliability constraint index system is showed in Fig.2.

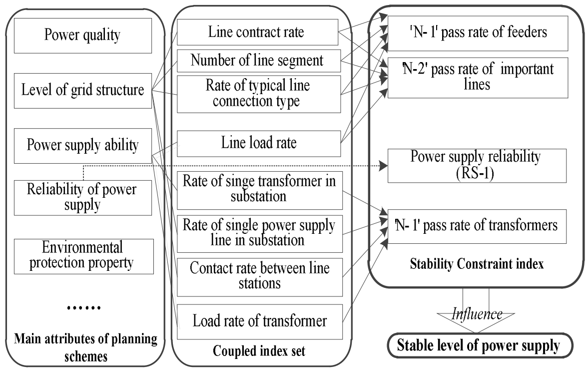

Fig.2 Reliability constraint index and its construction process

Evaluation and modification

The assessment of reliability constraint indices is to evaluate the planning scheme according to the assessment value of each index. If all the indices of the planning scheme pass through the evaluation, the reliability of the planning scheme meets the requirement. The evaluation goes into the lower level to make a comprehensive decision. During the process, the reasonability of the evaluation criteria affects the upper constraint evaluation greatly in the fields of scientific, accuracy and operability. Meeting the requirements of planning guidelines, adapting the regional development and improving the weak part are important principles that should be followed in the process of SDN. The settlement of the evaluation criteria should be coordinated with such principles and rules to build criteria presented in this paper are displayed in Table.1

Table.1 Evaluation Criterion of reliability constraint indexes

Index	**Evaluation Criterion**	
	Guide^{a,b}	***Regional Characteristic***
'N-1'passrate of feeders	Middle/High voltage lines: 100%	The area of important load accumulated: evaluation Criterion can be improved on the basis of regulations appropriate based on the regional characteristics and the status quo.
'N-1'passrate of important lines	Allow some of the lines do not meet the 'N-2'standard	
'N-1'passrate of transformer	'N-1'checking should be 100% satisfied.	
RS-1^{a,b}	City: ≥ 99.9% Provincial capital:≥99.98%	

a. State Grid Guide of China; b. China Southern Power Grid

For SDN construction projects with multi-plans (≥3), "prefer ring good and discarding bad" selection principle is applied for decision makers. However, since the distribution network in China has the characteristic of lots of points, wide area, long lines and complex structures, there are few plans to be selected. Data will be wasted if eliminating simply. For the reason, modification-evaluation step is presented, showed in Fig.1. In order to avoid unchecked investment, modification step uses the improved reliability method based on cost-benefit [6]. Due to the limitation motioned, specific introduction is omitted in this paper.

THE LOWER LEVEL: COMPREHENSIVE DECISION-MAKING ON INVESTMENT AND BENEFIT

The decision-making places emphasis on cost-benefit analysis of a SDN project under the market environment. And benefit is the statement for satisfying the demand, while the benefit of SDN is the statement for satisfying all the participants' demand. Thus, the essence of the decision-making in the lower level is to obtain the optimal solution through checking the degree of satisfaction of the planning scheme.

The stakeholders of SDN and their demand

The SDN is the advanced stage of the traditional distribution network, both grid corporation and end users as the main participants in traditional distribution network are contained. Meanwhile, the opening up of electric power market and the development of low carbon economy spur the DG which mostly transfer clean energy into electric power connect grid in large scale, supported by smart grid technology. That situation makes the DG operator become a new participant. In addition, distribution network bonds the transmission system, power supply and end users, so it obtains high attention from the state and society. In conclusion, the stakeholders of SDN include power grid, end users, DG operators as well as the state and society. Demand varies among different stakeholders, as shown in Fig.3

Different stakeholders have different demand for power grid, as the main investors and policymakers of power grid, the Power Grid Corp need to ensure reliable power supply and to achieve higher efficiency; end users demand more reliable and secure power supply; DG operators require a higher permeability of DG;the country and society is concerned about the safety and reliability of power network, but also on the environmental benefits of the power grid.

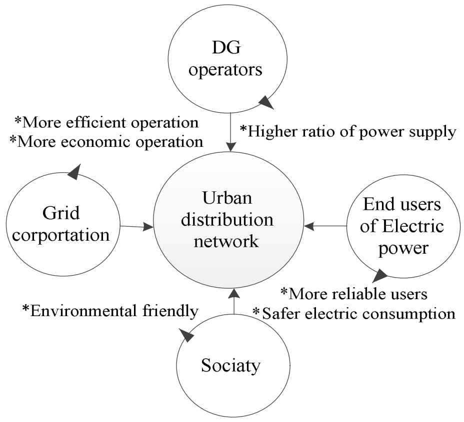

Fig.3 Reliability constraint index and its construction process

Comprehensive decision-making index system of investment and benefit

In order to satisfy the demand of investment and benefit analysis, the lower comprehensive decision-making indices system is divided into 2 parts as the input index and the output index. For SDN planning, input indices are easily to be built, as the different forms of investment can be converted into economic cost. The core demand among different stakeholders vary and overlap. They are converted into output index set, combined with the internal relationship of SDN operational characteristic on the basis of comprehensiveness and avoiding coupled effect.

Table.2 The interconnection relations of core requirements of stakeholders and operation characteristics of power grid

Property	Participants/ Beneficiaries	First-grade Index
Input	All Stakeholders	Life cycle cost of SDN construction
Output	End Users, Grid Company	Power supply reliability
	End Users, Grid Company	Power quality
	Society	Environmental benefits
	DG Operators	Acceptant ability for DG
	Grid Company	Efficiency of power supply

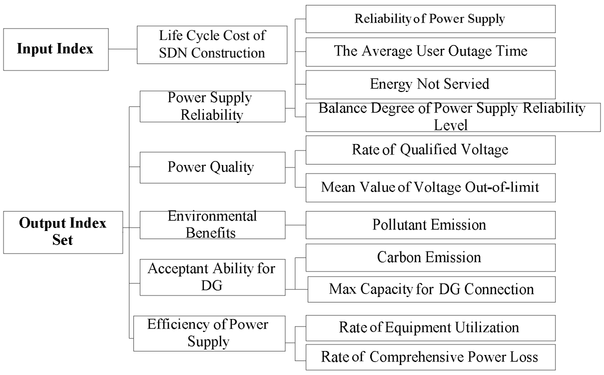

Fig.4 The system of comprehensive decision-making index balancing multi stakeholders

Through above analysis, the core demand of stakeholders are summarized as five independent operational characteristic indices from the side of grid in this paper. The five indices are set as the first level of input index, as showed in Table.2. On the basis, eleven indices which are easily calculated as the second index are proposed, refining the operation effects of each type of index. And then they are built as comprehensive decision-making index system of investment and benefit, as showed in Fig.4.

Comprehensive decision-making model of investment and benefit based on modified AHP/CE-DEA

In order to accurate assess the investment efficiency of different plans, the data envelopment analysis (DEA) and cross efficiency (CE) evaluation model are applied to analyse the investment efficiency, while compare different plans [7]. Meanwhile, since various stakeholders have different impact on decision-making process, we introduce Analytic Hierarchy Process (AHP) preference restraints to impose subjective limit on weight in the evaluation mode. According to the above steps, the comprehensive decision-making model of investment and benefit based on modified AHP/CE-DEA is eventually built. Specific steps are demonstrated as below.

1) Standardization of the original data. Input indices are converted to cost indexes $[x_1,x_2,x_3,\ldots,x_m]$, output indices are converted to benefit indexes $[y_1,y_2,y_3,\ldots,y_s]$.

2) The importance among input index x_i and output index y_r is respectively evaluated according to the expertise by AHP. Then the input/output judgment matrixes $\boldsymbol{A}_n$ and $\boldsymbol{B}_s$ are built. At last, the normalized weight set of input and output indices obtained by means of the consistency check as $[\gamma_1,\gamma_2,\gamma_3,\ldots,\gamma_m]$ and $[w_1,w_2,w_3,\ldots,w_n]$.

3) Build the AHP constraint cone matrixes of input and output indices as $M_{m\times m}=P_{m\times m}-\lambda_{max1}\times k\times E_{m\times m}$ and $N_{n\times n}=Q_{n\times n}-\lambda_{max2}\times k\times E_{n\times n}$, $0\le k\le 1$, where $P_{ij}=\gamma_i/\gamma_j$, $Q_{ij}=w_i/w_j$ and $\lambda_{max1,2}$ are the maximum Eigen value of **P** and **Q** respectively, **E** is a unit matrix, k is the relaxation factor to restrict the subjectivity and objectivity of the weight, restricting the subjectivity and objectivity in a contradictory way. If $k=0$, it represents fully discounting AHP preference restraints. If $k=1$, it represents fully accounting AHP preference restraints. The subjective restriction of weight goes up and the objective one goes down when k is greater.

4) Furthermore, the polyhedral closed convex cones as $MV\ge 0$ and $NU\ge 0$ are constructed according to the preference con constraint matrix $\mathbf{N}_{q\times q}$, adding up restriction on the weight of DEA. C^2R model with AHP constraint cone is as (1).

$$
\begin{aligned}
&\max \quad h_j = U^T y_j = \sum_{r=1}^{s} u_r y_{rj} \\
&s.t. \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} \ge 0,\ j=1,2,\cdots,n \\
&\quad \sum_{i=1}^{m} v_i x_{ij} = 1 \\
&\quad MV \ge 0,\ NU \ge 0 \\
&\quad V=[v_1,v_2,v_3,\cdots,v_m]^{\mathrm{T}},\ U=[u_1,u_2,u_3,\cdots,u_s]^{\mathrm{T}}
\end{aligned}
\tag{1}
$$

Where h_j is the efficiency index of the jth decision-making unit (DMU_j). Higher value of h_j implies that the DMU_j obtains relatively more output data with relatively few input data, compared with other plans. **V** and **U** are input weight set and output weight set. Then, the planning scheme's efficiency of self-evaluation and optimal weight of each index are obtained.

5) CE evaluation is applied to avoid the problem of multiple effective DMUs in C^2R model. The plan has the optimal value of cross efficiency, which is said to be the optimal plan. Calculation of the cross efficiency is presented as below.

$$
E_{kj} = \frac{\sum_{r=1}^{s} u_{rk} y_{rj}}{\sum_{i=1}^{m} u_{ik} y_{kj}}, \quad k,j=1,2,3,\ldots,n \tag{2}
$$

$$
e_j = \frac{1}{n}\sum_{i=1}^{n} E_{ij} \tag{3}
$$

Where E_{kj} ($k\neq j$) is the efficiency value when DMU_j is evaluated by the optimal weight obtained by self-assessment of DMU_k. E_{kk} is the self-assessment value of DMU_k. e_j is the mean value of the efficiency value evaluated by all the other optimal weights for DMU_j, as the cross efficiency value of DMU_j.

CASE STUDY

To assess the effectiveness of bi-level and comprehensive decision-making Method, Medium voltage in smart distribution network of a science park is chosen for the case study [8]. Planning area covers about 355.9 hectares area and future annual load can reach about 404 MW and the load is about 377 MW. Average load density is 105.93 MW/km2. What's more, the load is concentrated with high density and high demands on reliability of power supply. According to the characteristics of this region, E1~E7 eight alternatives of SDN are laid down, System wiring diagram is shown in Fig.5 .

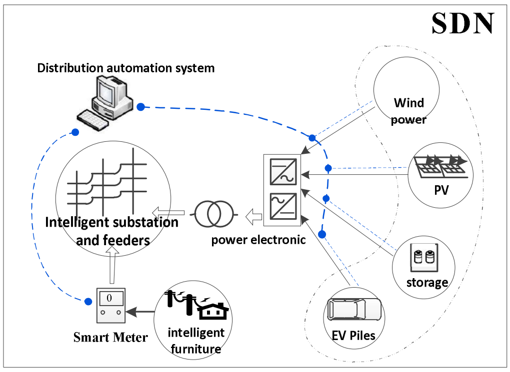

Fig.5 Planned area of SDN wiring diagram

The upper level: reliability constraints

According to the requirements of the demonstration area planning function and consulting the planning guide, evaluation criterion in constraint layer is set: the reliability rate of power supply has reached 99.98% and the pass rate of 'N-1' check and 'N-2' check have reached 100% and 60% respectively. Plan 4,5,7,8 does not meet the constraint condition, therefore they shall be modified.

The lower upper level: investment benefit comprehensive decision-making

The plan passing upper constraint evaluation is analyzed by investment benefit decision-making at the lower level. First of all, according to the index system of Fig.2, the index weight in output layer is obtained by AHP under preference of decision makers [0.5418 0.2050 0.1769 0.0242 0.2050]. According to the index weight, AHP/CE-DEA model containing is built, the relaxation factor $k=0.9$ is set. According to (1), optimal weights self-evaluation and self-assessment efficiency value of every plan are calculated. Cross efficiency of every unit is evaluated by (2)-(3) and the self-assessment efficiency value and cross efficiency values of every plan are shown in Table.3.

Table.3 Self-assessment and cross efficiency values

Property	E1	E2	E3	E4	E5	E6	E7	E8
SA Efficiency	1	0.94	0.86	0.87	0.96	0.86	0.90	1
Cross efficiency	0.93	0.85	0.80	0.81	0.87	0.77	0.83	0.90

According to the comprehensive classification, cross efficiency value can be set for: E1 > E8 > E5 > E2 > E7 > E4 > E3 > E6. Therefore, decision makers can choose the third plan with the highest investment yields as the implementation scheme of SDN.

CONCLUSION

Through a thorough analysis of market environment and internal technology features faced in the construction of SDN in China, a bi-level and comprehensive decision-making method for SDN is proposed in this paper, which can cover the interests of all parties. Upper reliability constraint evaluation is built in this method on the premise of reliable power supply. On this basis, in order to improve investment efficiency, balance the interests of all parties and realize a sustainable development of SDN, a comprehensive decision-making at the lower level model for SDN is now established and in research, containing both a comprehensive index system balancing the interests of multi stakeholders and AHP/CE-DEA comprehensive decision method. At last, the case analysis indicates that this decision method is accurate and objective with strong maneuverability, the result of which is credible. It is effective auxiliary decision-making method in the process of the smart distribution network planning under the market environment.

Acknowledgments

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