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A Dynamic Evaluation Method for High-Permeability New Energy Distribution Network Planning Considering Multistage Development Trends

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With the development of new power systems, high penetration of new energy (HPNE) will become a major feature of power systems in the future. In order to solve the problem that the traditional distribution network planning index makes it difficult to fully consider the impact of new energy access on the distribution network, this paper constructs a distribution network planning evaluation index system considering the characteristics of HPNE, and designs a set of static comprehensive evaluation methods of distribution network planning schemes based on the "over-average penalty" entropy weight method (EWM). At the same time, distribution network planning is a long-term dynamic process, and the static evaluation method makes it difficult to describe the actual situation of the multistage construction process of distribution networks. To this end, a dynamic evaluation method of distribution network planning is proposed, which realizes the comprehensive evaluation of multistage distribution network planning based on dual excitation control lines. Finally, an example of four 10 kV distribution network planning schemes of a power supply bureau are analyzed to prove the effectiveness of the proposed method.

Keywords: high permeability new energy distribution network, distribution network planning, comprehensive evaluation index system, multistage development dynamic evaluation, entropy weight method

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1 INTRODUCTION

Vigorously promoting the sustainable development of renewable energy, improving its penetration in the power grid, and achieving the goal of "carbon peaking and carbon neutralization" have become the new trends of building a green and clean power system (NDRC, 2015; Yang et al., 2018). However, high permeability new energy access brings new challenges to the distribution network, such as randomization of the operation state and the complexity of planning objectives (Kang and Yao, 2017; Zhang et al., 2021). Therefore, Zou et al. (2012), Jia et al. (2018), and Wang et al. (2019) used different methods to solve the problem of improving the randomness of distribution network operations after new energy access, and realized the robust planning of new distribution networks. Huang et al. (2016), Su et al. (2016), Sheng and Liu (2017), Wang et al. (2019), and Yao et al. (2019) incorporated economic benefit indicators, energy conservation and emission reduction indicators, power quality indicators, and other objectives into the planning of distributed resources accessing active distribution networks. It can be seen that a large number of distribution network planning studies focus on how to solve the highly stochastic robust planning problem with the penetration of new energy and the collaborative planning problem with different objectives. By contrast, in distribution network planning research, the index quantification and statistical analysis of the impact of HPNE on distribution networks is still in its infancy.

In the evaluation index system of distribution network planning schemes, the traditional distribution network planning indexes can be divided into three categories: economic indexes considering construction cost, reliability indexes considering power supply reliability, and other technical indexes similar to new energy consumption rates. In the context of high permeability new energy access, these traditional indicators make it difficult to fully consider the impact of new energy access on distribution networks. Therefore, some studies have been carried out.

Yan et al. (2018) made a preliminary exploration into the distribution network evaluation indexes of new energy characteristic access, and designed new indexes such as new energy output fluctuation. Zhang et al. (2010) considered various impacts of distributed resource access on distribution networks and put forward corresponding quantitative indexes. Chen et al. (2017) designed a new distribution network evaluation index, considering the voltage and frequency fluctuations of the bus with photovoltaic grid-connection. Considering the penetration of renewable energy, Ma et al. (2019) established a new evaluation index system for economic operation of distribution networks. In addition, many distribution network evaluation systems with different requirements have been established (Cui et al., 2013; Liu et al., 2013; Ou et al., 2014). The above studies have tried to include the impact of new energy on the distribution network evaluation. However, a complete evaluation index system for distribution network planning under the high permeability new energy has not been formed.

As for the comprehensive evaluation method of distribution network planning schemes, many scholars have studied and discussed it. Wang et al. (2018) comprehensively evaluated the intelligent planning schemes of distribution networks by using the analytic hierarchy process. Ding et al. (2015) introduced the utility risk model and fuzzy comprehensive evaluation method into the vulnerability assessment of distribution networks. Gang et al. (2007) attempted to establish a comprehensive Decision-Making System for distribution network planning schemes using the data envelopment method. In Jiang et al. (2021), a comprehensive evaluation system of distribution network indicators was established based on the analytic hierarchy process. These studies depend on the subjective evaluation of the importance of each index. And it is worth noting that every index in distribution network planning is of great significance, especially the reliability index. The disqualification of any index should be reflected in the final evaluation results. However, the current research used the weighted summation method to calculate the final evaluation value, which makes it difficult to reflect the impact of unqualified indicators. In addition, these studies on distribution network planning and evaluation focus more on the static evaluation at the end of distribution network planning, while distribution network planning is actually a multistage dynamic problem.

To sum up, this paper systematically explores the distribution network planning with the characteristics of HPNE, puts forward a distribution network planning index system, and designs a static comprehensive evaluation method for distribution network planning schemes. Furthermore, a dynamic evaluation method considering the characteristics of multistage distribution network planning is introduced to form a complete evaluation system of distribution network planning schemes. The main contributions of the article are as follows:

1) According to the actual impact of HPNE on the distribution network, the evaluation indexes considering the characteristics of HPNE are summarized. Combined with the existing evaluation index system of distribution network planning schemes, a comprehensive evaluation index system more suitable for distribution network planning in the future new power system is proposed in this paper.
2) In order to highlight the impact of unqualified indexes, this paper introduces an "over-average penalty" to improve the entropy weight method (I-EWM), and further puts forward the static comprehensive evaluation method of distribution network planning schemes under the HPNE.
3) Considering that distribution network planning is a multistage dynamic process, a dynamic evaluation method of distribution network planning schemes based on dual excitation control lines is proposed.

2 EVALUATION INDEX SYSTEM OF DISTRIBUTION NETWORK PLANNING SCHEMES UNDER HIGH PENETRATION OF NEW ENERGY

2.1 Characteristics of Grid Integration of New Energy

Grid integration indexes reflect the impact of the energy and distribution characteristics of new energy on the distribution network, including typical output fluctuation index C_{F}, dispersion index C_{D}, and line N−1 verification contribution rate index $C_{\mathrm{N-1}}$.

2.1.1 Typical Output Fluctuation Index C_{F}

The fluctuation and intermittence of the new energy output will interfere with the operation of the distribution network. Considering that new energy is changeable and highly random, this paper introduces the typical output fluctuation index to quantify the fluctuation of new energy. The typical output of new energy can be extracted by the hierarchical clustering method (Peng et al., 2015).

$$C_{\mathrm{F}} = \sqrt{\frac{\sum_{i=1}^{n} P\left(\left(i+1\right)\Delta T\right) - P\left(i\Delta T\right)}{n}} \Big/ P_N \tag{1}$$

where n refers to the number of time intervals; ΔT is the time interval; i represents the i-th time intervals; $P(i\Delta T)$ indicates the output of new energy at i; P_N represents the rated power.

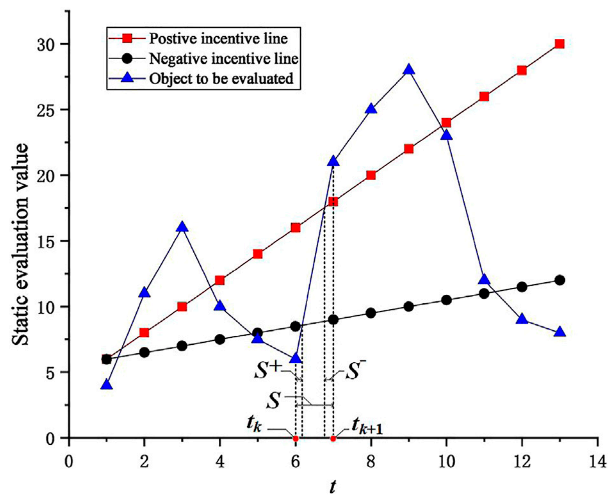

FIGURE 1 | Schematic diagram of dual excitation control lines.

2.1.2 Dispersion Index C_D

In the distribution network, the more dispersed the access of new energy, the more conducive to the local consumption of energy. Therefore, this paper proposes the dispersion index. The calculation formula is:

$$C_D = 1 - \max\left|\frac{P_{N,i} - P_{avg}}{P_{avg}}\right| \times 100\% \tag{2}$$

where P_{avg} refers to the average rated power of new energy at all access points connected to the distribution network; $P_{N,i}$ indicates the rated power of the i-th new energy.

2.1.3 Line $N-1$ Verification Contribution Rate Index C_{N-1}

Considering that the new energy can be considered as a standby resource (Pan et al., 2017), it contributes to improving the $N-1$ verification pass rate. So, the index is proposed as:

$$C_{N-1} = \frac{N_{DG} + N}{N_{all}} \times 100\% \tag{3}$$

where N_{DG} indicates the number of lines that have improved the line connection rate after the access of new energy; N refers to the lines in the distribution network that have passed the $N-1$ verification; N_{all} represents all lines running in the distribution network.

2.2 New Energy Acceptance Capacity

The specific contents of new energy acceptance capacity indexes include effective penetration rate index C_P and peak shaving contribution C_B.

2.2.1 Effective Penetration Rate Index C_P

Considering power flow reverse transmission will pose a threat to security (Chen et al., 2021; Hu et al., 2019), the effective penetration rate index is proposed to investigate the local consumption of new energy.

$$C_P = \frac{1}{N}\sum\frac{\overline{P_{DG}}}{\overline{P_{load}}} \times 100\% \tag{4}$$

where $\overline{P_{DG}}$ represents the average value of typical output of new energy connected to the distribution network; $\overline{P_{load}}$ refers to the average value of typical load of new energy access points in distribution network planning; N represents the number of new energy access points.

2.2.2 Peak Shaving Contribution Index C_B

In order to consider the contribution of new energy in peak shaving, this paper introduces the peak shaving contribution index as:

$$C_B = \min\left(\frac{\sum_{i=1}^{n} P_{DG}}{P_{M,peak}}, \frac{\sum_{i=1}^{n} P_{DG}}{P_{E,peak}}\right) \times 100\% \tag{5}$$

where $P_{M,peak}$, $P_{E,peak}$ represent the load at morning peak and evening peak, respectively.

2.3 Economy of New Energy Access

The economy of new energy access consists of direct and green economic benefits.

2.3.1 Direct Economic Benefits C_{save}

The direct economic benefit is calculated by subtracting the annual cost of new energy installation and operation from its own power generation income.

$$\begin{cases} C_{save} = C_{sal} - C_{cost} \\ C_{sal} = a \times W \\ C_{cost} = \sum_{i=1}^{n_e}\left((c_{tzi} + c_{azi})P_N f_{cr} + c_{whi}P_N\right) \\ f_{cr} = r\frac{(1+r)^{Lf}}{(1+r)^{Lf} - 1} \end{cases} \tag{6}$$

where C_{sal} represents the income brought by new energy power generation; a is the on-grid electricity price of new energy; W is the total annual power generation under the typical output of new energy; C_{cost} represents the total annual cost of new energy; c_{tzi} is the investment cost of new energy at node i; c_{azi} is the installation cost of new energy at node i; c_{whi} is the operation and maintenance cost of new energy at node i; P_N is the rated installation capacity of new energy; n_e is the total installed number of new energy; f_{cr} is the investment recovery coefficient; r is the discount rate; Lf refers to the service life of new energy.

2.3.2 Green Economic Benefits C_e

C_e is the environmental costs that are reduced after new energy replaces traditional energy. It generally includes environmental pollution cost and fines for the discharge of pollutants.

$$C_e = \sum_{i=1}^{n_p}(V_{ei}Q_i + V_i Q_i) \tag{7}$$

where V_{ei} is the environmental value of the i-th pollutant; Q_i is the discharge amount of the i-th pollutant; the fine amount of the i-th pollutant is denoted as V_i; n_p indicates the number of types of pollutants. The i-th pollutant emission is the number of pollutants emitted by coal-fired power generation when the power generation is the same as that of new energy.

2.4 Reliability Indexes

This paper selects the comprehensive power supply availability rate C_{RS-3} and the average household power outage time C_T.

2.4.1 Power Supply Availability Rate C_{RS-3}

The power supply availability rate index is obtained by the power outage time of users.

$$C_{RS-3} = \left(1 - \frac{\sum t_m}{T \times M}\right) \times 100\% \tag{8}$$

where t_m represents the total power outage time of the m-th billing user; M represents the total number of billing users in the distribution network; T represents the statistical time.

2.4.2 Average Household Power Outage Time C_T

The C_T is reflected by the user outage duration and the number of user outages.

$$C_T = \frac{\sum t_m}{\sum m_j} \tag{9}$$

where m_j represents the number of billed users affected by the j-th power outage.

2.5 Technical Evaluation Indexes

The technical indexes reflect the operation level of the distribution network, which include the voltage qualification rate C_U and the line loss rate C_{loss}.

2.5.1 Voltage Qualification Rate C_U

The new energy improves the problem of voltage drop at the end of the distribution network effectively. The larger C_U, the higher the overall voltage quality of the distribution network.

$$C_U = \left(1 - \frac{\sum t_{vm}}{T \times M}\right) \times 100\% \tag{10}$$

where t_{vm} represents the total time that the voltage of the m-th billing user in the distribution network exceeds the limit within the statistical time.

2.5.2 Line Loss Rate C_{loss}

Reasonable arrangement of the location and capacity of new energy can effectively reduce the line loss (Bai et al., 2015; Kang and Yao, 2017). Therefore, the line loss rate is introduced to quantify the impact of new energy on the operation of the power grid.

$$C_{loss} = \frac{W_p - W_s}{W_p} \times 100\% \tag{11}$$

where W_p and W_s respectively represent the power supply and electricity sales of the distribution network during the statistical period.

So far, the comprehensive evaluation index system for distribution network planning under HPNE has been established.

3 STATIC COMPREHENSIVE EVALUATION METHOD OF DISTRIBUTION NETWORK PLANNING SCHEMES BASED ON THE "OVER-AVERAGE PENALTY" ENTROPY WEIGHT METHOD

3.1 Standardized Processing Method

There are differences in the dimensions and attributes of each index in the comprehensive evaluation index system for distribution network planning under HPNE. The deviation standardization method is used to normalize the raw data, and all index values are converted into benefit-type values in the [0, 1] interval (that is, the larger the value, the better).

Assuming that m distribution network planning schemes are evaluated at a certain stage $S = \{S_1, S_2, \ldots, S_m\}$, and the evaluation index set of each scheme is set to $C = \{C_1, C_2, \ldots, C_{11}\}$ (which represent the indicators in order $\{C_F, C_D, C_{N-1}, C_B, C_{save}, C_e, C_{RS-3}, C_T, C_U, C_{loss}\}$), then the value of the j-th evaluation index C_j in the i-th distribution network S_i is recorded as c_{ij}, and the set $\{x_{ij}\}$ is obtained after normalization and dimensionless processing.

If the index C_j is a benefit index, the processing formula is:

$$x_{ij} = \frac{c_{ij} - \min\{c_{ij}\}}{\max\{c_{ij}\} - \min\{c_{ij}\}} \tag{12}$$

If the index C_j is a cost index, the processing formula is:

$$x_{ij} = \frac{\max\{c_{ij}\} - c_{ij}}{\max\{c_{ij}\} - \min\{c_{ij}\}} \tag{13}$$

3.2 "Over-Average Penalty" Entropy Weight Method

Considering that the hierarchical order relationship method and the AHP both rely on expert knowledge, their results contain subjective experience. So, this paper adopts the entropy weight method based on the entropy of data information for evaluation.

For the evaluation object x_{ij}, its characteristic proportion p_{ij} is calculated as:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{14}$$

The information entropy of the corresponding index X_j is:

$$E_j = -\frac{1}{\ln m}\left(\sum_{i=1}^{m} p_{ij} \ln p_{ij}\right) \tag{15}$$

TABLE 1 | Comprehensive evaluation results by I-EWM and EWM.

		Stage 1	Stage 2	Stage 3	Stage 4
I-EWM	Case 1	0.15391	0.09642	0.33815	0.00929
	Case 2	0.24704	0.10036	0.07224	0.28462
	Case 3	0.11024	0.30856	0.03387	0.19995
	Case 4	0.18724	0.15149	0.21977	0.19291
EWM	Case 1	0.37790	0.22463	0.38205	0.38658
	Case 2	0.42839	0.33471	0.33766	0.38103
	Case 3	0.27836	0.42248	0.22631	0.25328
	Case 4	0.31670	0.33181	0.38202	0.35265

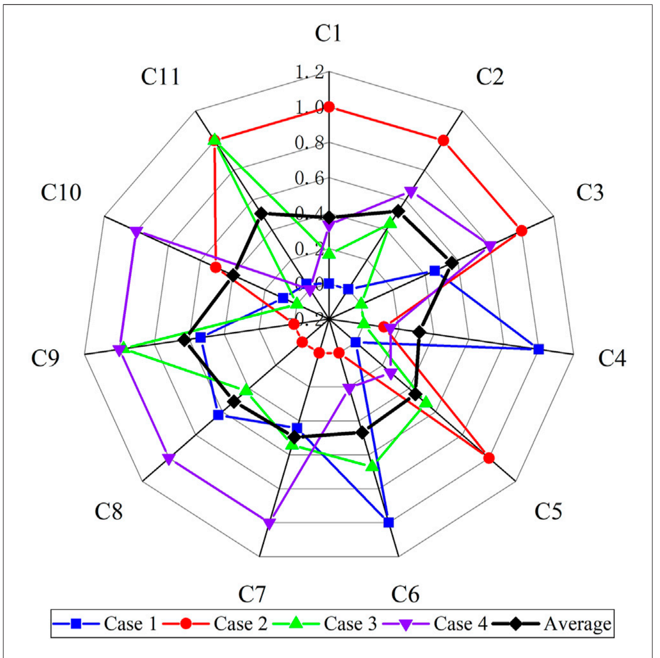

FIGURE 2 | Radar chart of indicators compared to the average for each option under planning stage 1.

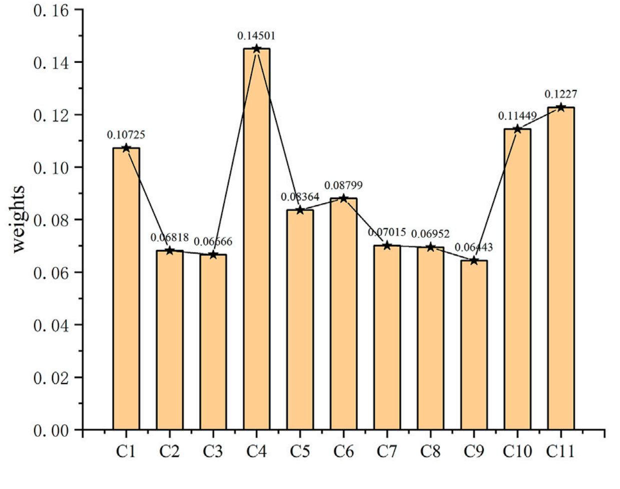

FIGURE 3 | Weight value of each index obtained by EWM in planning stage 1.

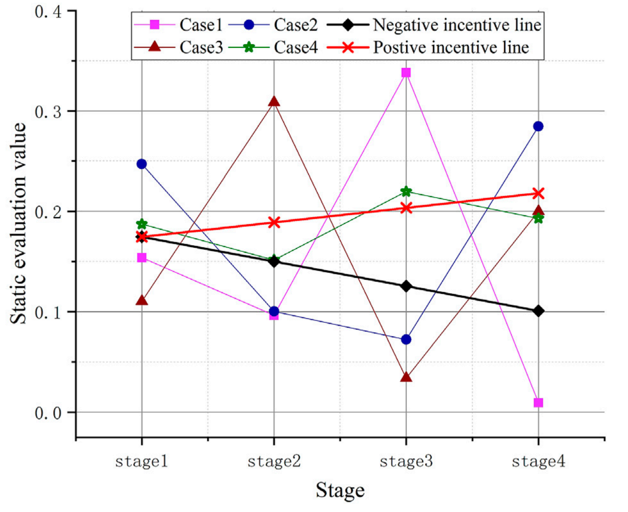

FIGURE 4 | Dynamic evaluation infographic under $V^+ = 0.5$, $V^- = 0.5$.

TABLE 2 | Dynamic comprehensive evaluation results of each planning case ($\boldsymbol{V^+} = 0.5$, $\boldsymbol{V^-} = 0.5$).

	Case 1	Case 2	Case 3	Case 4
DER	2.41677	1.90997	2.51372	**3.22673**
Average	0.14944	0.17607	0.16316	**0.18785**

Considering that each index has rich meanings, and the failure of any indicator should be reflected in the final evaluation result, this paper introduces the "over-average penalty." When weighting the evaluation value of each scheme, the corresponding weight of the element whose value is lower than the average value of the index is reset to zero.

$$\alpha_{ij} = \begin{cases} \dfrac{1 - E_j}{11 - \sum E_j} & x_{ij} \geq \overline{x_j} \\ 0 & x_{ij} < \overline{x_j} \end{cases} \tag{16}$$

where $\overline{x_j}$ represents the average value of the indicator C_j. From this, the final static evaluation result of each object can be calculated as:

$$y_i = \sum_{j=1}^{11} \alpha_{ij} \left| x_{ij} - \overline{x_j} \right| \tag{17}$$

4 DYNAMIC EVALUATION METHOD OF DISTRIBUTION NETWORK PLANNING SCHEMES BASED ON DUAL EXCITATION CONTROL LINES

This paper introduces a dynamic evaluation method based on dual excitation control lines, which considers the multistage construction process of the distribution network.

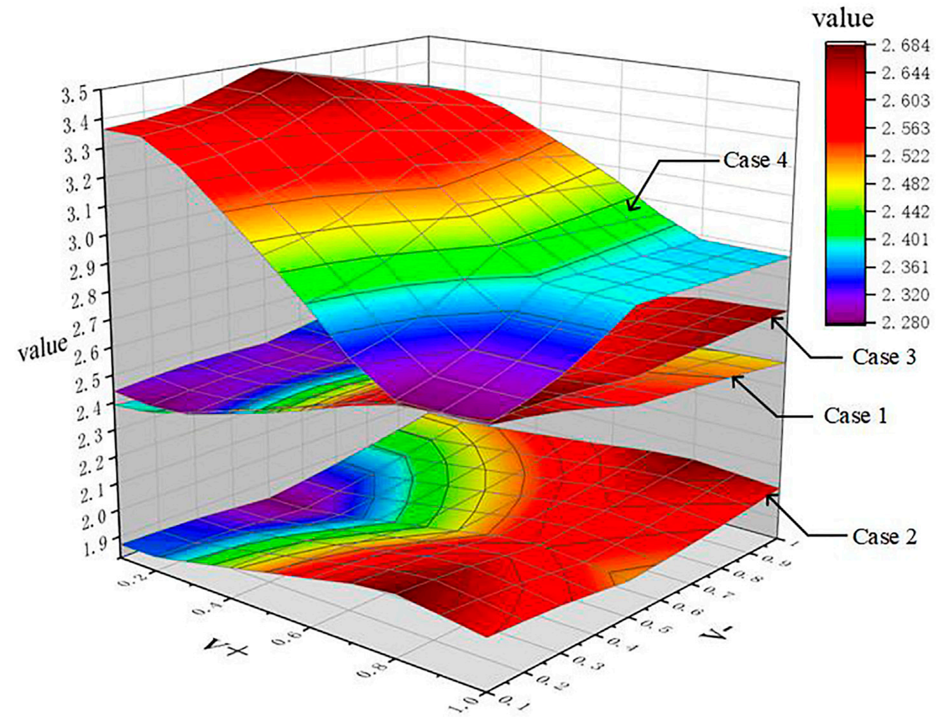

FIGURE 5 | Dynamic evaluation surfaces of each scheme under different V^+, V^-.

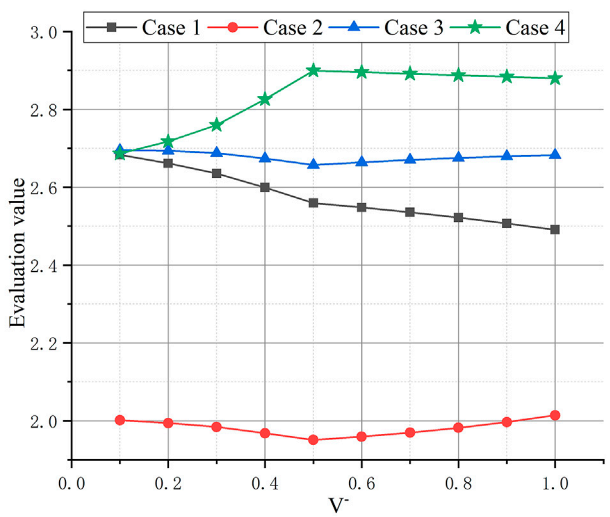

FIGURE 6 | The influence of different V^- on the dynamic evaluation results of each scheme when $V^+ = 1.0$.

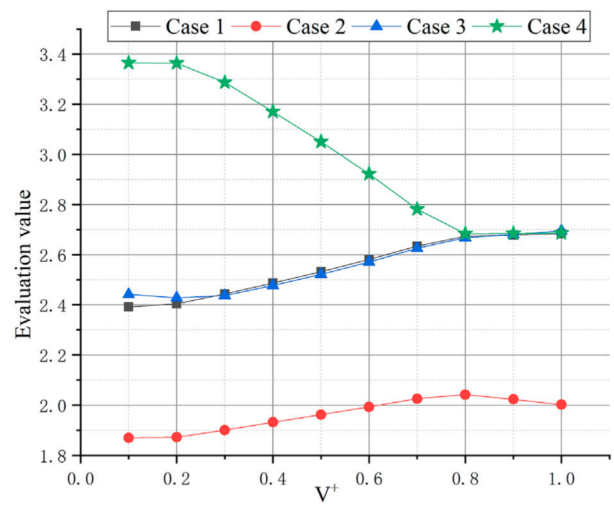

FIGURE 7 | The influence of different V^- on the dynamic evaluation results of each scheme when $V^+ = 1.0$.

4.1 Information Aggregation Algorithm Based on Dual Excitation Control Lines

Discrete evaluation points at different stages are transformed into continuous curves within a unit time period and are compared with positive and negative excitation lines. Appropriate rewards and punishments are given to the part above the positive incentive line and the part below the negative incentive line, respectively. The new evaluation value of each time period is obtained after weighted summation based on the positive and negative excitation coefficients. Finally, the new evaluation value is weighted and summed by the time factor to obtain the dynamic comprehensive evaluation value of the evaluation object. Dual excitation lines are usually expressed in linear form:

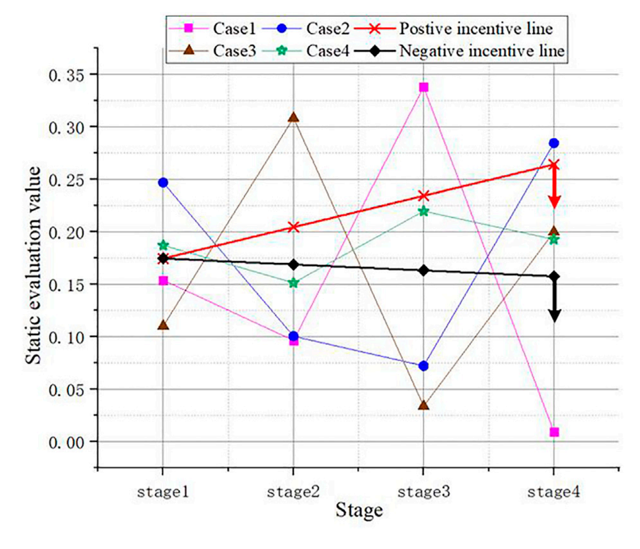

FIGURE 8 | Dynamic evaluation infographic under $V^{+} = 1.0$, $V^{-} = 0.1$.

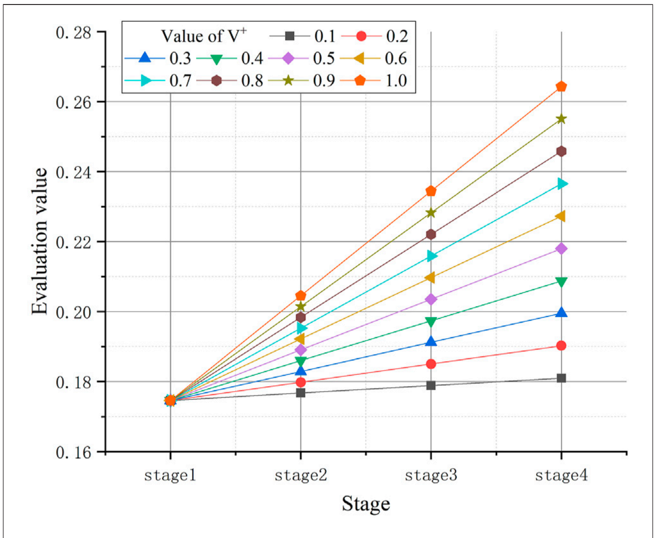

FIGURE 10 | Influence of different V^{+} on negative excitation line.

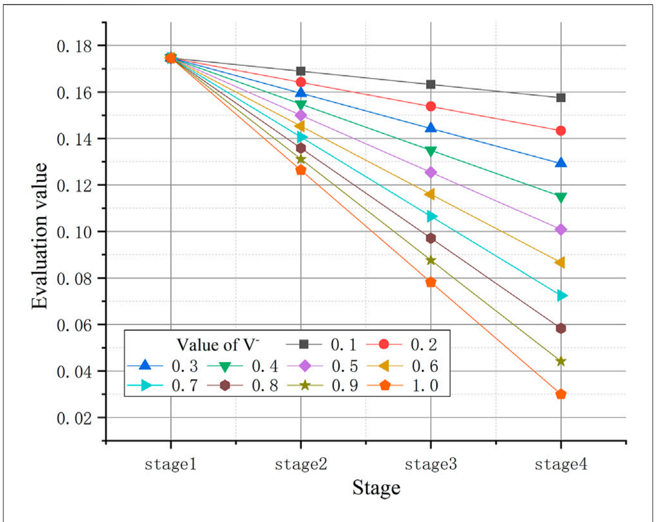

FIGURE 9 | Influence of different V^{-} on negative excitation line.

$$y - y_0^{\pm} = k^{\pm}(t - t_0) \tag{18}$$

where $y_0^{\pm}$ represents the ordinate value of the initial point of the positive and negative excitation lines, which is set as the average value of the initial stage evaluation value of each evaluation object for the sake of fairness (Diao et al., 2021; Yi et al., 2007); the slope of the double excitation line is denoted as $k^{\pm}$; t_0 is the initial stage of the evaluation; the calculation method of $k^{\pm}$ is as described in **Supplementary Appendix A**, in which it is necessary to determine the singular value and set the slope offset V^{+} and V^{-} for calculation.

The multistage evaluation value connecting line constitutes the development track of the evaluation object. The area enclosed by it and the horizontal axis reflect the overall condition of the evaluation object in the multi-stage. Therefore, the comprehensive evaluation value can be expressed by an integral. As shown in **Figure 1**, the area enclosed by the straight line $t_k y_{ik} y_{i,k+1} t_{k+1}$ and the horizontal axis reflects the overall condition of the evaluation object i in $[t_k, t_{k+1}]$. The underlying dynamic evaluation value is expressed in the form of an integral.

$$s_{ik} = \int_{t_k}^{t_{k+1}} \left[y_{ik} + (t - t_k) \frac{(y_{i,k+1} - y_{ik})}{(t_{k+1} - t_k)} \right] dt \tag{19}$$

Similarly, the comprehensive evaluation value of positive incentive s_{ik}^{+} and the comprehensive evaluation value of negative incentive and s_{ik}^{-} can be obtained, such as the area occupied by the S^{+} and S^{-} parts in **Figure 1**.

Due to the introduction of positive and negative excitation lines, the dynamic evaluation value includes rewards and punishments for the parts outside the positive and negative excitation lines. Let $s_{ik}^{\pm}$ be the dynamic comprehensive evaluation value of the evaluation object i with excitation in (t_k, t_{k+1}), then there are:

$$s_{ik}^{\pm} = \mu^{+} s_{ik}^{+} + s_{ik} - \mu^{-} s_{ik}^{-} \tag{20}$$

μ^{+}, μ^{-} ($\mu^{+}, \mu^{-} > 0$) are the positive and negative excitation coefficients, respectively.

Through the weighted synthesis of each time period in the whole process $[t_1, t_{T_N}]$, the total dynamic comprehensive evaluation value si± of the evaluation object i with excitation is obtained.

$$s_i^{\pm} = \sum_{k=1}^{N-1} h_k s_{ik}^{\pm} \tag{21}$$

where h_k ($h_k > 0, k = 1, 2, \ldots, N$) is the time factor, whose setting is adjusted according to the needs of decision makers. For example, to focus on recent developments, $\{h_k\}$ can be an increasing sequence.

To determine the positive and negative excitation coefficients μ^{+}, μ^{-} should follow the following two principles.

1) The principle of conservation of incentives.

For all m evaluation objects, the total number of positive and negative incentives is equal.

$$\mu^{+}\sum_{i=1}^{n}\sum_{k=1}^{N-1} s_{ik}^{+} = \mu^{-}\sum_{i=1}^{n}\sum_{k=1}^{N-1} s_{ik}^{-} \tag{22}$$

2) The principle of moderate incentives.

The sum of the positive and negative excitation coefficients is 1.

$$\mu^{+} + \mu^{-} = 1 \tag{23}$$

4.2 Multistage Dynamic Comprehensive Evaluation Steps

The basic data of the multistage dynamic comprehensive evaluation should be derived from the static comprehensive evaluation results of the distribution network planning scheme in **Section 3**. Before the multistage dynamic evaluation of the distribution network planning, the static comprehensive evaluation of each stage needs to be carried out. The evaluation idea of the entire dynamic comprehensive evaluation is shown in the following pseudo code.

Algorithm. 1A dynamic evaluation method of distribution network planning schemes based on dual excitation control lines

Step 1: Design a distribution network plan.
Initialize the number of planning stages N and m distribution network planning schemes.
Step 2: Simulation calculation of planning scheme indicators.
Use Monte Carlo and other simulation methods to calculate the index values of each planning scheme.
Step 3: Static evaluation of the distribution network planning.
for t in 1, 2, …, N
Normalize the index value $\boldsymbol{C}$= {C_1, C_2, …, C_{11}} in each distribution network planning scheme $\boldsymbol{S}$={S_1, S_2, …, S_m} at the current stage to obtain the dimensionless benefit index value {x_{ij}}.
Calculate the information entropy value E_j of each indicator in the planning stage.
for i in 1, 2, …, m
for j in 1, 2, …, 11
if $x_{ij} \ge \overline{x_j}$
$\alpha_{ij} = (1 - E_j)/(11 - \sum E_j)$
else
$\alpha_{ij} = 0$
Calculate the static evaluation value of the planning scheme i by $y_i = \sum_{j=1}^{11} \alpha_{ij} \left| x_{ij} - \overline{x_j} \right|$.
Step 4: Multi-stage dynamic evaluation of the distribution network planning scheme.
Initialize the slope offset V^{+}, V^{-}, and the time factor set $\{h_k\}$.
for t in 1, 2, …, N
Calculate the average μ_j and standard deviation σ_j of each indicator under each distribution network planning scheme $\boldsymbol{S}$={S_1, S_2, …, S_m} at the current stage, and set $\boldsymbol{S}^{*} = \boldsymbol{S}$.
while Ture
$\boldsymbol{S}^{*'} = \{S_i \in \boldsymbol{S}^{*} \mid \forall c_{i,j} \in [\mu_i - 3\sigma_i,\ \mu_i + 3\sigma_i]\}$
if $\boldsymbol{S}^{*'} \ne \boldsymbol{S}^{*}$
$\boldsymbol{S}^{*} = \boldsymbol{S}^{*'}$
else
break
Take the intersection of the set $\boldsymbol{S}^{*}$ of non-singularity plans in different stages, and then the final set of non-singular programming plans $\boldsymbol{S}^{*}$ can be obtained.
Calculate the global growth rate $r_{\max}^{a}, r_{\min}^{a}, \overline{r^{a}}$ to calculate the positive and negative excitation lines $y - y_0^{\pm} = k^{\pm}(t - t_0)$ under the non-singular scheme.
Calculate the basis, the comprehensive evaluation value of positive incentive and negative incentive s_{ik}, s_{ik}^{+} and s_{ik}^{-}.
Calculate the positive and negative excitation coefficients μ^{+}, μ.
Calculate the total dynamic comprehensive evaluation value $s_i^{\pm}$.
Output: $\{s_i^{\pm}\}$

5 CASE ANALYSIS

To verify the method proposed in this paper, we conducted an evaluation of four schemes of a 20-year 10 kV distribution network planning bureau in China. Each case is divided into four stages for planning. According to **Section 2**, the different index values of each case are shown in **Supplementary Appendix B**. The static evaluation result of I-EWM and EWM is shown in **Table 1**. The result of I-EWM is smaller than that of EWM, because each case is subject to the over-average penalty.

In order to analyze the "over-average penalty", we took the first stage as an example, and used the radar chart to compare the normalized indicators of each planning scheme with its average value as shown in **Figure 2**. The weight calculated by the EWM is displayed as shown in **Figure 3**. From **Figure 2**, most indicators of case 1 and case 3 are below the average in stage 1. So, they are punished by the average value. In **Figure 3**, it can be seen that compared to case 4, case 2 has a higher weight for the indicators that are not subject to the mean penalty. Therefore, the final evaluation of case 2 is better than that of case 4.

Further, the multistage dynamic evaluation method is used to realize the comprehensive evaluation of the four cases. V^{+} and V^{-} are set to 0.5. From the result shown in **Figure 4**, there are no singular cases. The average of static evaluation and the final dynamic evaluation results (DER) are shown in **Table 2**. Case 4 is suitable for each stage of distribution network development, whose evaluation values are relatively stable in the four stages. So, the result of case 4 is better than other cases as the bold values in **Table 2**. However, based on the static evaluation results at the end of the planning year, it is easy to conclude that case 2 is superior to other options. This obviously ignores the dynamic evolution of the grid throughout the planning period.

The dynamic evaluation results are closely related to the setting of positive and negative excitation lines. In order to explore the influence of excitation lines, this paper sets the combination of positive and negative slope offsets with an interval of 0.1. The dynamic evaluation surface is shown in **Figure 5**.

From **Figure 5**, case 4 is always superior to other cases, and case 2 is obviously inferior to other options. Simultaneously, the average value of static evaluation can also reflect the superiority of case 4, but it cannot reflect the disadvantage of case 2 during the overall planning period. In addition, the result of cases 1, 3, and 4 are close when V+ = 1.0, V− = 0.1. The positive and negative excitation lines make the evaluation results of the three case reach the same level. So, the results of the change of V^{-} when $V^{+} = 1.0$ and the change of V^{+} when $V^{-} = 0.1$ are discussed respectively, as shown in **Figure 6** and **Figure 7**.

From **Figure 6** and **Figure 7**, the results of each case show different trends with the change of V^{-}. According to (19), the basic dynamic evaluation value s_{ik} is fixed. Therefore, the result is related to the positive and negative incentives s_{ik}^{+}, s_{ik}^{+} and coefficient μ^{+}, μ^{-}. When $V^{+} = 1.0$, $V^{-} = 0.1$, the changes of V^{-} and V^{+} will cause the positive and negative excitation control lines to shift downward, as shown by the red and black arrows in **Figure 8**. The influence of V^{-} change on the negative excitation control line and the influence of V^+ change on the positive excitation control line are shown in **Figure 9** and **Figure 10**.

When V^- becomes larger, the negative excitation line will be shifted downward, which will reduce the negative excitation area. Because the negative excitation area decreases while the positive excitation area remains unchanged, the positive excitation coefficient decreases and the negative excitation coefficient increases according to the principle of excitation conservation. For case 4, before V^- increases to 0.5, the increase in the evaluation value brought by the reduction of the negative excitation area is greater than the reduction effect brought by the change in the excitation coefficient. However, when V^-—continues to increase after 0.5, the negative excitation area of case 4 does not change, only the negative influence of the excitation coefficient. Therefore, as shown in **Figure 6**, with the increase of V^-, case 4 shows a trend of increasing first and then decreasing. At the same time, since the negative excitation area of case 4 is zero at $V^- = 0.5$, the rate of reduction of the positive excitation coefficient will slow down with the increase of V^-. As a result, the change trend of other schemes has also changed after this. Among them, the downward trend of the dynamic evaluation results of case 1 has slowed down, while the downward trend of case 2 and 3 has changed from a downward trend to an upward trend.

From **Figure 7**, before V^+ drops to 0.8, case 4 has no positive excitation area, and it is only affected by the increase of the negative excitation coefficient due to the downward movement of the positive excitation line. Therefore, it shows decreasing trend with the decrease of V^+. After $V^+ = 0.8$, the benefit brought by the positive incentive area is greater than the negative impact brought by the incentive coefficient. The result of case 4 changes to a growth trend. Correspondingly, the decrease of the negative excitation coefficient is more severe at this time, which makes the dynamic evaluation values of other cases decrease more rapidly.

To sum up, the selection of the positive and negative slope offset V^+, V^- will affect the results of the positive and negative excitation control lines, and thus affect the final evaluation results. In general, the smaller the V^+, the larger the V^-, the lower the reward threshold, and the higher the penalty threshold. The results at this point are skewed towards incentives. Instead, a punishment mechanism is favored. The selection of this parameter needs to be considered in combination with the needs of the evaluator. When the needs cannot be clearly defined, the more conservative $V^+ = 0.5$ and $V^- = 0.5$ can be selected for evaluation.

6 CONCLUSION

In summary, this paper discusses the dynamic comprehensive evaluation of the multistage segment distribution network planning scheme under the characteristics of high permeability new energy. The main contributions are as follows:

1) The evaluation index considering the characteristics of HPNE is summarized and extracted. A comprehensive evaluation index system that is more suitable for the planning of distribution networks under the new power system in the future is proposed.
2) The entropy weight method is improved by introducing the “over-average penalty”. A static comprehensive evaluation method for the distribution network planning scheme under the HPNE is proposed.
3) A dynamic evaluation method based on the multistage development of the dual excitation control line distribution network planning is proposed to realize the dynamic evaluation of the multistage planning scheme of the distribution network.

It needs to be clarified that under the dynamic evaluation method in this paper, the development trend of the static evaluation results and the positive and negative incentives in each stage are fitted to a linear trend, which will make it difficult to accurately describe the distribution network changes in each stage of the planning scheme evaluation. The complex impact of the results and the inability to accurately represent the planner’s reward and punishment need improving, and how to improve them is a direction for further research.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JZ and CG put forward the basic idea of the article and completed the example analysis. TW and YD improved the idea of the article. MX and ZG completed basic data analysis and article polishing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.958892/full#supplementary-material

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