Many-Criteria Evaluation of Infrastructure Investment Priorities for Distribution Network Planning

YIDONG CHEN[1,2], JINMING LI[1,2], KUN SHENG[3], TIANBIN YANG[4], XIAOLIN XU [5],
ZHIZHONG HAN[4], AND ZHUANG HU[5]

[1]State Grid Hunan Electric Power Company Limited Economic & Technical Research Institute, Changsha 410004, China
[2]Hunan Key Laboratory of Energy Internet Supply-Demand and Operation, Changsha 410004, China
[3]State Grid Hunan Electric Power Company Limited, Changsha 410000, China
[4]Hunan Hua Jie Engineering Consulting Co., Ltd., Changsha 410007, China
[5]College of Electrical and Information Engineering, Hunan University, Changsha 410082, China

Corresponding authors: Xiaolin Xu (847912441@qq.com) and Jinming Li (li407516762@163.com)

ABSTRACT With the liberalization of incremental distribution network investment business, more and more investment projects from various sources and diversified ownership are eligible for construction applications. This article proposes a many-criteria investment priorities evaluation method for incremental distribution network planning based on the hyperplane projection transformation. In the established many-criteria evaluation indicator system, the multi-grade indicators including economic and technical factors are adopted to comprehensively evaluate the distribution network infrastructure projects. Furthermore, the hyperplane projection transformation is applied to project the solutions from the many-objective hypercube to the normalized hyperplane. Then, the comprehensive distance quantifies the quality and balance of the distribution network infrastructure project indicators, and the investment priority rankings can be obtained. Finally, the performance of the proposed method is validated on six distribution network infrastructure projects with eleven evaluation indicators. The results show that the proposed many-criteria evaluation of infrastructure investment priorities is effective to recognize the non-dominance solutions with extremely good or extremely poor indicators.

INDEX TERMS Hyperplane projection transformation, investment priority, incremental distribution network, prosumer infrastructure, many-criteria evaluation.

I. INTRODUCTION

With the implementation of incremental distribution network planning, many problems in the distribution network, such as the poor quality of power supply and serious security risks, have been improved [1]. At the same time, more and more investment projects from various sources and diversified ownership are eligible to participate in the construction of incremental distribution network. Compared with the traditional distribution network investment, the incremental distribution network planning should not only guarantee the safety and reliability of the grid, but also take into account the economy and efficiency of the distribution network operation due to the participation of the social capital [1], and more evaluation indicators are needed when evaluating incremental

The associate editor coordinating the review of this manuscript and approving it for publication was Huai-Zhi Wang.

distribution network construction projects. Furthermore, there are plenty of prosumers who can both use electricity and generate electricity in the distribution network [2]–[4], which brings great uncertainty to the investment decision-making of the distribution network. Therefore, with many indicator factors, the comprehensive selection and priority ranking of distribution network investment projects is a challenge. The existing methods mainly use TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) or improved TOPSIS to prioritize distribution network infrastructure projects. However, with the increasing number of indicators involved, the performance of non-dominance will severely degrade and show inefficiency in solution searching and decision making, causing all the candidate infrastructure projects to become non-dominated [5]. That is, TOPSIS cannot recognize the extreme non-dominance solutions with extremely good or extremely poor indicators, and the distribution

network investment decision makers are more inclined to the overall optimal infrastructure project with balanced evaluation indicators. Consequently, this research aims to investigate the many-criteria investment priorities evaluation method for incremental distribution network planning considering both the quality and balance of the project indicators, which is based on the hyperplane projection transformation.

So far, extensive research on the evaluation of distribution network infrastructure projects have been investigated and studied [1], [6]–[15]. The indicator system has been established in [6] to comprehensively evaluate the infrastructure of distribution network. In [7], a comprehensive evaluation model is set up to assess the wind power accommodation ability of a power grid. Also, a decision support system is built in [8], [9] to select the optimal planning option for the distribution network planning and distribution feeders to be equipped with high-impedance fault detectors, respectively. In [10], a multiyear distribution network planning optimization model is put forward to assess the investment modes of incremental distribution network planning. An assessment model is developed in [11], [12] to evaluate the reliability and economic benefits of power systems. In [13], based on the best-worst method and TOPSIS, a hybrid decision-making framework is proposed to assess the operating performance of the power grid. Besides, several works in [14]–[17] have used fuzzy-TOPSIS to solve the problem of project ranking and sustainability evaluation. In [14], the TOPSIS combined with grey incidence analysis is used to assess the sustainability performance of power grid infrastructure projects. Also, the fuzzy-TOPSIS is adopted in [17] to rank the city investment projects in a participatory budget based on the similarity to the ideal point. Nevertheless, the authors did not take into account the balance of evaluation indicators and cannot recognize the extreme non-dominance solutions with extremely good or extremely poor indicators.

The remainder of this research is organized as follows: in Section II, the selection of the evaluation indicators is investigated and formulated. Section III studied the normalization of evaluation indicators. In Section IV, the hyperplane projection transformation is researched and the implementation steps of the proposed many-criteria evaluation of infrastructure investment priorities for incremental distribution network planning are presented. The case studies are implemented and analyzed in Section V. Finally, concluding remarks are drawn in the last Section.

II. SELECTION OF EVALUATION INDICATORS

The many-criteria investment decisions of infrastructure projects for incremental distribution network planning will be affected by many internal and external factors, such as economic factors and technical factors. Economic factors and technical factors can be further subdivided into multiple evaluation indicators to comprehensively evaluate the investment priority of each distribution network infrastructure project. The evaluation indicator system with multi-grade indicators adopted is shown in Figure 1.
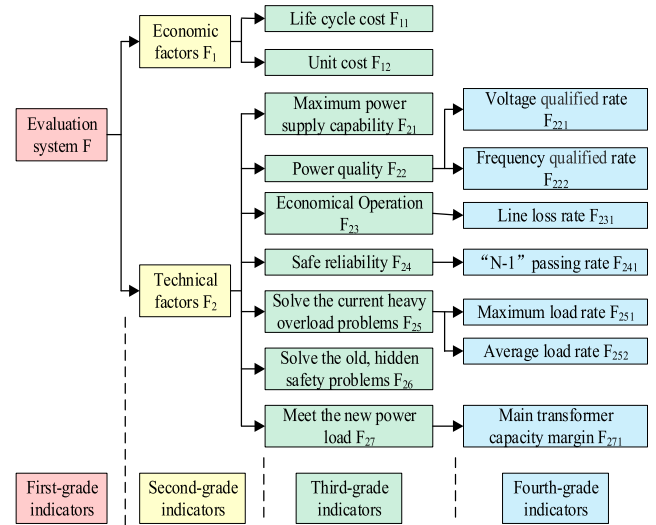

FIGURE 1. Evaluation indicator system of infrastructure projects for incremental distribution network planning.

A. ECONOMIC FACTORS
The investment demands of distribution networks are often greater than the investment capabilities of power grid enterprises. Thus, the economic factors should be considered first and can be evaluated by two indicators of the life cycle cost and the unit cost.

1) LIFE CYCLE COST
The life cycle cost of a distribution network infrastructure project is composed of initial investment costs, operation and maintenance costs, waste and environmental cost, and failure costs [18]:

$$LCC = C_I + C_O + C_F + C_D \qquad (1)$$

where LCC is the life cycle cost, C_I is the initial investment costs, C_O is the operation and maintenance costs, C_F is the failure costs, C_D is the waste and environmental costs.

2) UNIT COST
The unit cost of a distribution network infrastructure project can be obtained from the ratio of the total project cost to the rated capacity.

$$C_A = \frac{C_T}{P_{\text{rated}}} \qquad (2)$$

where C_A is the unit cost, C_T is the total project cost, P_{rated} is the rated capacity.

B. TECHNICAL FACTORS
The distribution network needs to ensure that users have a safe, economical and sustainable power supply. The new distribution network infrastructure projects need to be able to continuously improve the technical reliability of the distribution network. The technical factors in this patent mainly consider 7 indicators such as maximum power supply capability, power quality, economic operation, safety reliability, solving

the current heavy overload problems, solve the old, hidden safety problems, meet the new power load.

1) MAXIMUM POWER SUPPLY CAPABILITY

The "N−1" security constraints can be defined as the distribution network can still maintain stable operation and normal power supply under a certain component such as a line or transformer being disconnected due to a fault. Thus, the maximum power supply capability can be defined as the maximum load that the distribution network can supply when meeting the "N−1" security constraints.

2) POWER QUALITY

The voltage waveform distortion caused by impulsive and fluctuating loading in the distribution network can cause frequency excursion and voltage excursion. In severe cases, poor power quality can cause damage to precision and power quality-sensitive electrical equipment. The voltage qualified rate and frequency qualified rate are selected to evaluate the power quality of the distribution network, and can be obtained by the following formulas:

$$\sigma_U = \frac{T_{U,\text{pass}}}{T_{U,\text{total}}} \times 100\% \tag{3}$$

$$\sigma_f = \frac{T_{f,\text{pass}}}{T_{f,\text{total}}} \times 100\% \tag{4}$$

where σ_U is the voltage qualified rate. $T_{U,\text{pass}}$ is the sum of the time that the monitoring point voltage is within the qualified range, $T_{U,\text{total}}$ is the total voltage detection time, σ_f is the frequency qualified rate. $T_{f,\text{pass}}$ is the sum of the time that the monitoring point frequency is within the qualified range, $T_{f,\text{total}}$ is the total frequency detection time.

3) ECONOMICAL OPERATION

The economic operation can improve the profitability of the distribution network. The line loss rate is selected to evaluate the economics of the operation of the distribution network, and can be obtained by the following formula:

$$\eta_{\text{loss}} = \frac{Q_{\text{loss}}}{Q_{\text{total}}} \times 100\% \tag{5}$$

where η_{loss} is the line loss rate, Q_{loss} is the power loss caused by the distribution network lines and transformers, Q_{total} is the total power supplied by the distribution network.

4) SAFE RELIABILITY

The safe and reliable operation of the distribution network is the foundation of social development [19] and is conducive to the safety and stability of the entire power network. The "N−1" passing rate is the proportion of lines that meet the "N−1" security constraints and is selected to evaluate the safe reliability of the distribution network:

$$\eta_{\text{N-1}} = \frac{N_{\text{pass}}}{N_{\text{total}}} \times 100\% \tag{6}$$

TABLE 1. Score Ranges for Solving the Old, Hidden Safety Problems.

Number	0	1	2	3	>3
Score ranges	[0,2]	[2,4]	[4,6]	[6,8]	[8,10]

where $\eta_{\text{N}-1}$ is the "N−1" passing rate, N_{pass} is the number of lines meeting the "N−1" security constraints, N_{total} is the total number of lines.

5) SOLVING THE CURRENT HEAVY OVERLOAD PROBLEMS

The new distribution network infrastructure projects should be able to continuously solve the current heavy overload problems of the distribution network. The maximum load rate and average load rate are selected to evaluate whether the new distribution network infrastructure projects solve the current heavy overload problems, and can be obtained by the following formulas:

$$\eta_{\text{max,Load}} = \frac{L_{\text{max}}}{P_{\text{rated}}} \times 100\% \tag{7}$$

$$\eta_{\text{aver,Load}} = \frac{L_{\text{aver}}}{P_{\text{rated}}} \times 100\% \tag{8}$$

where $\eta_{\text{max,Load}}$ is the maximum load rate, L_{max} is the annual maximum load, P_{rated} is the rated capacity, $\eta_{\text{aver,Load}}$ is the average load rate, L_{max} is the annual average load.

6) SOLVING THE OLD, HIDDEN SAFETY PROBLEMS

Whether a new infrastructure project can solve the old, hidden safety problems is also used as an indicator to evaluate its investment priority. According to the number of old, hidden safety problems that have been solved, different score ranges from 0 to 10 are given for this indicator.

7) MEETING THE NEW POWER LOAD

The main transformer capacity margin is selected to evaluate the urgency of a new project to meet the new power load.

$$y = \frac{L_{\text{new}}}{P_{\text{rated}} - L_{\text{max,0}}} \times 100\% \tag{9}$$

where y is the main transformer capacity margin, L_{new} is the new power load, $L_{\text{max,0}}$ is the current maximum power load.

III. NORMALIZATION OF EVALUATION INDICATORS

Since each distribution network infrastructure project has its particularity, the projects cannot be compared only from the numerical value of the indicators. Each project should also be compared with previous distribution network infrastructure projects of the same type or scale that have been put into operation. At the same time, since the new distribution network infrastructure projects have not been implemented, some indicators of them are vague and uncertain, and the actual value cannot be obtained. Thus, to obtain the corresponding fuzzy interval of scores, this article organizes experts to evaluate and score each evaluation indicator of each distribution network infrastructure project. To simplify the
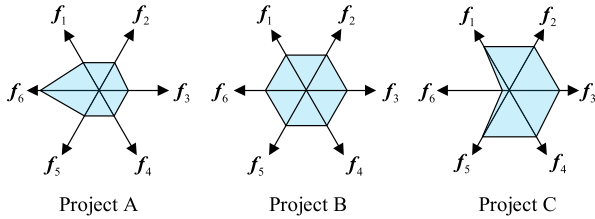
FIGURE 2. Score radar chart of three distribution network infrastructure projects with six evaluation indicators.

calculation, the median of the score fuzzy interval is used as the final score of the indicators.

For the indicator score evaluated by experts, the bigger the value, the higher the investment priority. Before the hyperplane projection transformation, the indicators need to be transformed by the following formula. After that, the smaller the indicator value, the higher the investment priority.

$$f_{i,h}^* = f_{h,\max} - f_{i,h} \qquad (10)$$

where $f_{i,h}^*$ is the hth transformed indicator of the ith project, $f_{h,\max}$ is the maximum value of the hth indicator among all infrastructure projects, $f_{i,h}$ is the hth untransformed indicator of the ith project. It should be noted that after the transformation, the ideal solution changes from $(f_{1,\max}, f_{2,\max}, \ldots, f_{H,\max})$ to $(f_{1,\min}^*, f_{2,\min}^*, \ldots, f_{H,\min}^*)$.

Then, the transformed indicators can be normalized by the following formula:

$$\bar{f}_{i,h} = \frac{f_{i,h}^* - f_{h,\min}}{f_{h,\max} - f_{h,\min}} \qquad (11)$$

where $\bar{f}_{i,h}$ is the hth normalized indicator of the ith project, $f_{h,\min}$ is the minimum value of the hth indicator among all infrastructure projects. It should be noted that after the normalization, the ideal solution changes from $(f_{1,\min}^*, f_{2,\min}^*, \ldots, f_{H,\min}^*)$ to $(0, 0, \ldots, 0)$.

IV. HYPERPLANE PROJECTION TRANSFORMATION AND IMPLEMENTATION STEPS

A. HYPERPLANE PROJECTION TRANSFORMATION

The hyperplane projection transformation is applied to project the solutions from the many-objective hypercube to the normalized hyperplane. Then, the comprehensive distance quantifies the quality and balance of the distribution network infrastructure project indicators to identify the overall best solution. Figure 2 illustrates the score radar chart of three distribution network infrastructure projects with six evaluation indicators. According to the preference of investment decision-makers, the investment priority of project B is superior to other projects when they have the same total scores.

For an infrastructure project evaluation system with H evaluation indicators, H extreme points consisting of the maximum value of each evaluation indicator in all projects can be obtained. Then, an H-1 dimensional hyperplane can be constructed with these extreme points [20], and its general
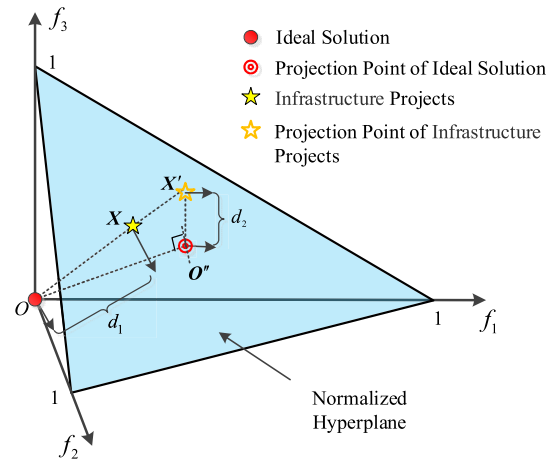

FIGURE 3. Normalized hyperplane composed of 3 indicators.

TABLE 2. Weight Coefficient of Second-Grade Indicator.

Indicators	Weight coefficient
Economic factors F_1	0.3
Technical factors F_2	0.7

expression is as follows [21]:

$$\gamma_1 \cdot f_1 + \gamma_2 \cdot f_2 + \ldots + \gamma_h \cdot f_h + \ldots + \gamma_H \cdot f_H = 1 \qquad (12)$$

where $(\gamma_1, \gamma_2, \ldots, \gamma_h \ldots, \gamma_H)$ is the unit normal vector of hyperplane, $(f_1, f_2, \ldots, f_h, \ldots, f_H)$ is the coordinates of extreme points.

It should be noted that after the normalization, the coordinates of all extreme points are 1. A normalized hyperplane with 3 evaluation indicators is shown in Figure 3. After the hyperplane projection transformation, the ith project X with normalized multi-dimensional vectors $(\bar{f}_{i,1}, \bar{f}_{i,2}, \ldots, \bar{f}_{i,h}, \ldots \bar{f}_{i,H})$ is projected to X' with $(f_{i,1}', f_{i,2}', \ldots, f_{i,h}', \ldots, f_{i,H}')$ on the normalized hyperplane, and the ideal solution O with $(0, 0, \ldots, 0)$ is projected to O'' with $(f_1'', f_2'', \ldots, f_h'', \ldots, f_H'')$ on the normalized hyperplane. The projection point coordinates of the ideal solution and the ith project can be obtained by the following formula:

$$f_{i,h}' = \frac{\bar{f}_{i,h}}{\bar{f}_{i,1} + \bar{f}_{i,2} + \cdots + \bar{f}_{i,h} + \cdots + \bar{f}_{i,H}} \qquad (13)$$

$$f_h'' = \frac{\bar{f}_h}{\bar{f}_1^2 + \bar{f}_2^2 + \cdots + \bar{f}_h^2 + \cdots + \bar{f}_H^2} \qquad (14)$$

where $f_{i,h}'$ is the coordinate of project i projected from many-objective hypercube to the normalized hyperplane, f_h'' is the coordinate of the ideal solution projected to the hyperplane, $\bar{f}_h$ is the normalized coordinates of extreme points.
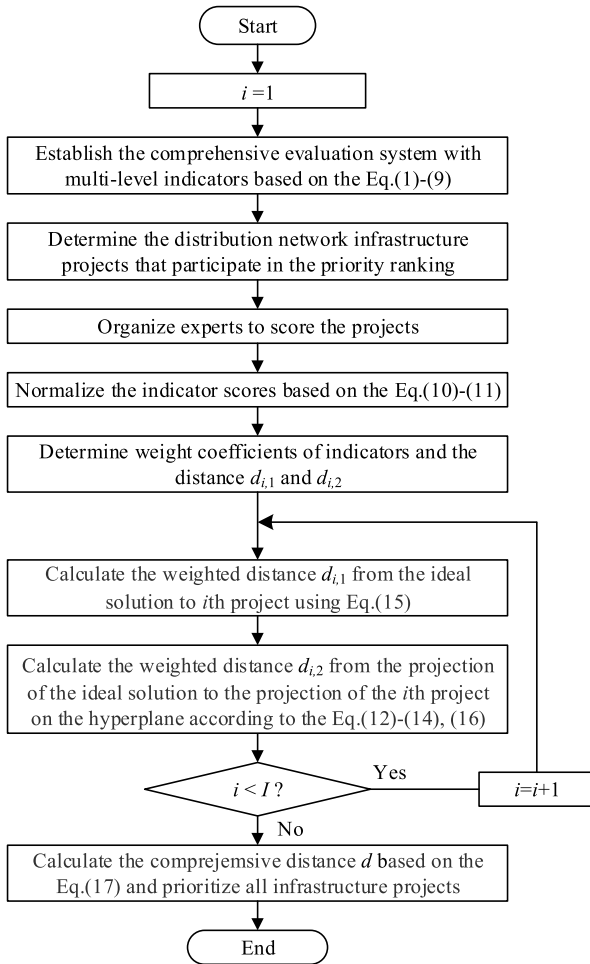
Two distances are used to evaluate the investment priority of the project: the distance from the ideal solution to ith project $d_{i,1}$ and the distance from the projection of the ideal solution to the projection of the ith project on the

TABLE 3. Weight Coefficient of Third-Grade Indicator.

Indicators	Weight coefficient	Indicators	Weight coefficient
Life cycle cost F_{11}	0.4	Safe reliability F_{24}	0.2
Unit cost F_{12}	0.6	Solving the current heavy overload problems F_{25}	0.2
Maximum power supply capability F_{21}	0.1	Solving the old, hidden safety problems F_{26}	0.16
Power quality F_{22}	0.2	Meeting the new power load F_{27}	0.04
Economical operation F_{23}	0.1	-	-

TABLE 4. Weight Coefficient of Fourth-Grade Indicator.

Indicators	Weight coefficient
Voltage qualified rate F_{221}	0.5
Frequency qualified rate F_{222}	0.5
Maximum load rate F_{251}	0.6
Average load rate F_{252}	0.4

FIGURE 4. Flowchart of proposed many-criteria investment priorities evaluation method for incremental distribution network planning.

hyperplane $d_{i,2}$:

$$d_{i,1} = \sqrt{\sum_{h=1}^{H} w_h \cdot (\bar{f}_{i,h})^2} \quad (15)$$

$$d_{i,2} = \sqrt{\sum_{h=1}^{H} w_h \cdot (f'_{i,h} - f''_h)^2} \quad (16)$$

where $d_{i,1}$ is the distance from the ideal solution to the ith project, $d_{i,2}$ is the distance from the projection of the ideal

solution to the projection of the ith project on the hyperplane, w_h is the weight coefficient of the hth evaluation indicator.

The smaller the distance $d_{i,1}$ is, the closer the ith project is to the ideal solution, and it means that the project is more suitable for investment. The projection point of the ideal solution on the normalized hyperplane is the most balanced point from each indicator. Thus, the distance $d_{i,2}$ is used to evaluate the balance of the project indicators. The smaller the distance $d_{i,2}$ is, the better the balance of the project indicators, and the extreme non-dominance solutions with extremely good or extremely poor indicators are not likely to appear in this project.

According to the investment preference of the investment decision makers, the appropriate distance weight coefficient is selected. After the normalization of the distance $d_{i,1}$ and $d_{i,2}$, the comprehensive distance of the ith project can be obtained by the following formula:

$$d = \omega_d \cdot \frac{d_{i,1} - d_{1,\min}}{d_{1,\max} - d_{1,\min}} + (1 - \omega_d) \cdot \frac{d_{i,2} - d_{2,\min}}{d_{2,\max} - d_{2,\min}} \quad (17)$$

where d is the comprehensive distance of the ith project, ω_d is the distance weight coefficient, $d_{1,\min}$ is the minimum distance from the ideal solution to projects, $d_{1,\max}$ is the maximum distance from the ideal solution to projects, $d_{2,\min}$ is the minimum distance from the projection of the ideal solution to the projection of projects on the hyperplane, $d_{2,\max}$ is the maximum distance from the projection of the ideal solution to the projection of projects on the hyperplane.

B. IMPLEMENTATION STEPS

The flowchart of the proposed many-criteria evaluation of infrastructure investment priorities for incremental distribution network planning is illustrated in Fig. 4. Before

**TABLE 5.** Evaluation Results of 6 Infrastructure Projects From Experts.

Indicators	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Life cycle cost F_{11}	[7.50,7.70]	[6.80,7.00]	[6.40,6.60]	[6.90,7.10]	[6.35,6.55]	[6.90,7.10]
Unit cost F_{12}	[7.70,8.10]	[8.10,8.50]	[7.50,7.90]	[7.77,8.17]	[7.70,8.10]	[8.20,8.50]
Maximum power supply capability F_{21}	[7.80,8.00]	[8.30,8.50]	[8.40,8.60]	[8.17,8.37]	[7.80,8.00]	[8.40,8.60]
Maximum power supply capability F_{221}	[8.70,8.90]	[8.45,8.75]	[8.50,8.70]	[8.57,8.77]	[8.40,8.60]	[8.57,8.77]
Frequency qualified rate F_{222}	[8.55,8.95]	[8.45,8.75]	[8.45,8.75]	[8.58,8.68]	[8.40,8.60]	[8.58,8.68]
Line loss rate F_{231}	[8.25,8.75]	[8.30,8.50]	[8.20,8.40]	[8.30,8.50]	[8.25,8.75]	[8.30,8.50]
"N-1"passing rate F_{241}	[8.40,8.80]	[8.55,8.85]	[8.50,8.90]	[8.62,8.72]	[8.40,8.80]	[8.62,8.82]
Maximum load rate F_{251}	[8.90,9.10]	[6.95,7.05]	[6.90,7.10]	[6.90,7.10]	[6.90,7.10]	[6.90,7.10]
Average load rate F_{252}	[6.90,7.10]	[8.90,9.10]	[8.90,9.10]	[8.50,9.50]	[6.90,7.10]	[8.50,9.50]
Meeting the new power load F_{27}	[7.50,8.50]	[7.80,8.20]	[7.80,8.20]	[7.50,8.50]	[7.50,8.50]	[0.00,2.00]
Solving the old, hidden safety problems F_{26}	[0.00,2.00]	[0.00,2.00]	[0.00,2.00]	[0.00,2.00]	[8.50,9.50]	[0.00,2.00]

the priority rankings of distribution network infrastructure projects, the evaluation indicators should be determined primarily. Then, based on the project scoring results from the experts, each indicator shall be normalized and projected on a normalized hyperplane constructed by H extreme points. Besides, calculate the distance from the ideal point to the infrastructure projects and the distance from the projection of the ideal solution to the projection of projects on the hyperplane. Thereafter, the comprehensive distance can be obtained by the product of these two distances and the distance weight coefficient respectively. Finally, based on the numerical value of the comprehensive distance, the investment priority rankings of the distribution network infrastructure projects can be obtained.

V. CASE STUDY

The proposed many-criteria investment priorities evaluation method for incremental distribution network planning based on the hyperplane projection transformation is tested through six distribute network infrastructure projects. The weight coefficients of the second-grade, third-grade, and fourth-grade indicators are listed in Table 2, Table 3, Table 4, respectively. The evaluation results of the six distribute network infrastructure projects from the expert group are listed in Table 5. In addition, the distance weight coefficient is set to 0.5.

To simplify the calculation, the median of the score fuzzy interval is used as the final score of the indicators. Then, the final score of the six distribute network infrastructure projects from the expert group is normalized using Eq. (10) and Eq. (11). Figure.5 shows the radar map of the normalized project indicators. It can be found that only the project 6 received an extremely bad score in the indicator "Meeting the new power load". The project 5 received an extremely good score in the indicator "Solving the old, hidden safety problems". Then, the indicators of the six distribute network
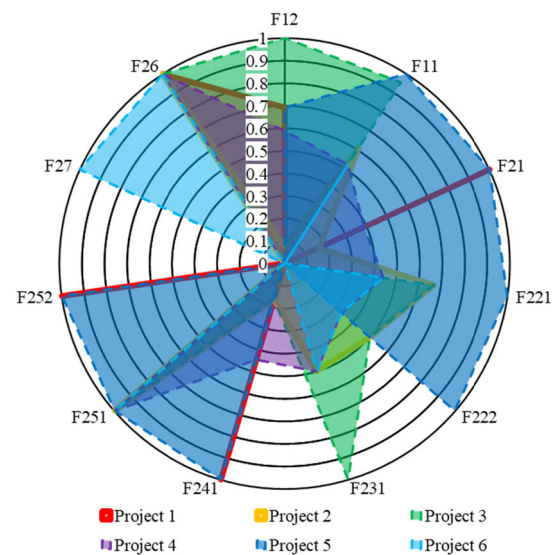
FIGURE 5. Radar map of normalized infrastructure project indicators.

infrastructure projects can be projected from the hypercube to the hyperplane, and the distance from the ideal point to the infrastructure projects and the distance from the projection of the ideal solution to the projection of projects on the hyperplane can be calculated. The results of the hyperplane projection transformation are shown in Table 6.

As shown in Table 6, it can be found that project 4 has the highest investment priority with a normalized comprehensive distance of 0.0798. Thus, project 4 is the most ideal investment project among the six distribution network infrastructure projects. The project 2 has the smallest distance to the ideal solution, which is only 0.4790, but the investment priority of project 2 is lower than that of project 4 due to its poor balance of indicators. As it can be seen from Figure 5, most of the indicator scores of the project 6 are better than those of project 2, but the project 6 received an extremely bad score in the indicator "Meeting the new power load". As a

TABLE 6. Results of the Hyperplane Projection Transformation.

Project	d_1	d_2	Normalized d	Rank
Project 1	0.6167	0.0965	0.6936	6
Project 2	**0.4790**	0.0715	0.2213	2
Project 3	0.7241	0.0686	0.5331	5
Project 4	0.5335	**0.0519**	**0.0798**	**1**
Project 5	0.8344	0.0517	0.5000	4
Project 6	0.5438	0.0828	0.4385	3

result, the comprehensive distance of project 6 is larger than that of project 2, and the investment priority of project 6 is lower than that of project 2. Besides, most of the indicator scores of the project 5 are worse than those of project 3, but the project 5 received an extremely good score in the indicator "Solving the old, hidden safety problems". Therefore, the case study verifies the effectiveness of the proposed methods to identify the extreme non-dominance solutions with extremely good or extremely poor indicators.

VI. CONCLUSION

In this article, a many-criteria investment priorities evaluation method for incremental distribution network planning based on the hyperplane projection transformation is proposed. Compared with TOPSIS, the proposed method can identify the non-dominance solutions with extremely good or extremely poor indicators due to the consideration of both the quality and balance of the indicators. The conclusions of this research are summarized as follows: 1) A four-grade indicator evaluation system including economic and technical factors is established to comprehensively evaluate the distribution network infrastructure projects; 2) For quantifying the quality and balance of the distribution network infrastructure project indicators, the hyperplane projection transformation is used to project the ideal solution and infrastructure projects from the many-objective hypercube to the normalized hyperplane; 3) By calculating the distance from the ideal solution to infrastructure projects and the distance from the projection of the ideal solution to the projection of projects on the hyperplane, the comprehensive distance can be obtained, and the investment priority of the project 6, which is closer to the ideal solution, is lower than the project 2 due to the consideration of the indicator balance.

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YIDONG CHEN received the B.S. degree in electrical engineering and automation from Hunan University, in 2012, and the M.S. degree in electrical engineering from Shanghai Jiao Tong University, in 2015. He is currently a Power Grid Engineer with the State Grid Hunan Company Limited Economic & Technical Research Institute, Changsha, China. His current research interests include power grid investment management and technical economy.

XIAOLIN XU received the B.S. degree in electrical engineering from Shihezi University, Shihezi, China, in 2018. He is currently pursuing the M.S. degree with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His current research interest includes the investment strategies of the power systems.

JINMING LI received the B.S. and M.S. degrees in electrical engineering from the South China University of Technology, Guangzhou, China, in 2011 and 2014, respectively. He is currently a Power Grid Engineer with the State Grid Hunan Economy Institute, Changsha, China. His current research interest includes power system planning and reliability.

ZHIZHONG HAN received the B.S. degree in engineering management from the Changsha University of Science and Technology, Changsha, China, in 2006. He is currently an Engineer with Hunan Hua Jie Engineering Consulting Co., Ltd., Changsha. His current research interests include power grid construction investment, cost management, and power grid project post-evaluation.

KUN SHENG received the B.S. and M.S. degrees in electrical engineering and the M.S. degree in electric power system and automation from Tianjin University, Tianjin, China, in 2001 and 2004, respectively, and the Ph.D. degree in electric power system and automation from the Institute of Electrical Engineering, Chinese Academy of Sciences. He is currently the Deputy Director of the Department of Investment Management, State Grid Hunan Electric Power Company Limited, Changsha, China. His current research interests include power system planning and investment strategies of the power grid.

TIANBIN YANG received the B.S. degree in civil engineering from Hunan University, Changsha, China, in 1991. He is currently an Engineer with Hunan Hua Jie Engineering Consulting Co., Ltd., Changsha. His current research interests include power grid construction investment and cost management, and power grid project post-evaluation.

ZHUANG HU received the B.S. degree in electrical engineering from the Hefei University of Technology, Hefei, China, in 2019. He is currently pursuing the M.S. degree with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His current research interest includes power system planning and operation.

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