Research on comprehensive performance evaluation model of multi-energy micro-grid based on prospect theory improved VIKOR technique

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Abstract: With the increasing energy shortage and ecological environment problems, the multi-energy micro-grid (MEMG) considering distributed new energy has attracted more attention. Scientific and comprehensive evaluation of the comprehensive performance of MEMG can provide guidance for the construction of micro-grid, which has high practical significance. In this paper, a comprehensive performance evaluation method of MEMG based on prospect theory improved VIKOR method is proposed. First of all, according to the development characteristics of MEMG, a comprehensive evaluation index system of MEMG performance considering economy, energy efficiency and environmental benefit is constructed. Secondly, considering the subjective risk tendency of the decision-maker, the prospect value function is established, and the best-worst-method (BWM) is used for index weighting. Then, the prospect value is introduced into the VIKOR framework to form the comprehensive performance evaluation model of MEMG. Finally, the simulation results show that the proposed method is reasonable and effective, and the annual operating cost of the PV-MEMG system is low, having relatively high energy saving and environmental protection benefits.

Keywords: Comprehensive performance, multi-energy micro-grid, prospect theory, VIKOR

1 INTRODUCTION

In recent years, with the development of economy and the continuous increase of energy consumption, energy shortages and ecological environmental problems have been triggered. Distributed new energy has high utilization efficiency and environmental protection performance, meeting the requirements of environmental protection and energy conservation. As a new power supply mode, multi-energy micro-grid (MEMG) can organically combine different distributed energy sources, which has higher environmental protection benefits and energy utilization efficiency, but also bears higher investment and maintenance costs [2, 9]. Therefore, it is necessary to establish a MEMG performance evaluation model to comprehensively evaluate the operation efficiency of MEMG, thus providing guidance for the construction and development of MEMG.

The present evaluation model for MEMG is mainly based on the fact that the decision-maker is completely rational [3]. However, the decision-maker often makes decisions based on his

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risk preference. It is necessary to consider the impact of the decision-maker's bounded rationality, so as to make the evaluation results more reasonable. In addition, the commonly used multi-criteria decision-making (MCDM) methods does not take into account the nonlinear relationship between the comprehensive evaluation value and indicators [5]. Based on this, this paper proposes an improved VIKOR evaluation method based on prospect theory to comprehensively evaluate the performance of MEMG with distributed new energy, which enriches and expands the existing research framework.

2 EVALUATION INDEX SYSTEM FOR MEMG

In order to accurately evaluate the comprehensive performance of MEMG, it is necessary to establish a comprehensive and accurate evaluation index system, and introduce appropriate evaluation criteria and methods. Compared with traditional power grid, MEMG has relatively high total investment cost, but high energy output efficiency and high environmental benefits. The established comprehensive evaluation index system is as shown in Figure 1, with three first-level indicators named economy, energy efficiency and environmental benefit. The economy dimension includes two secondary indicators: total investment cost and annual operating cost. The energy efficiency dimension includes two secondary indicators: primary energy efficiency and energy saving rate. The environmental benefit dimension includes three secondary indicators: CO2 emissions, NOx emissions and pollution penalty fees. Among all secondary indicators, primary energy efficiency and energy saving rate are benefit indicators, while other indicators are cost indicators.

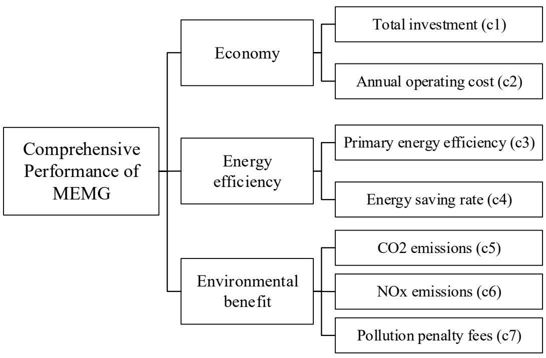

Figure 1. Comprehensive performance evaluation index system of MEMG.

3 MCDM MODEL BASED ON PROSPECT THEORY IMPROVED VIKOR

3.1 Determination of value function

Data preprocessing. Considering that the evaluation indicators include cost indicators and benefit indicators, and the dimensions of each indicator are different, it is necessary to normalize the values of each indicator. The calculation formula is:

$$x_{ij} = \begin{cases} \left(a_{ij} - a_{j,\min}\right)/\left(a_{j,\max} - a_{j,\min}\right), & \text{benifit indicator} \\ \left(a_{j,\max} - a_{ij}\right)/\left(a_{j,\max} - a_{j,\min}\right), & \text{cost indicator} \end{cases} \tag{1}$$

where $A = \left(a_{ij}\right)_{m\times n}$ is the original evaluation matrix, $X = \left(x_{ij}\right)_{m\times n}$ is the normalized evaluation matrix, and $a_{j,\min}$ and $a_{j,\max}$ are the minimum and maximum values of j-th column in A respectively

The prospect value of the MEMG scheme can be calculated according to the prospect theory. The comprehensive prospect value $V(f)$ is determined by the value function and weight. The specific calculation formula is [4]:

$$V(f) = V(f^+) + V(f^-) \tag{2}$$

$$V(f^+) = \sum_{i=1}^{k} w_i v(x_i) \tag{3}$$

$$V(f^-) = \sum_{i=k+1}^{n} w_i v(x_i) \tag{4}$$

where $V(f)$ is the comprehensive prospect value; $V(f^+)$ is the income prospect value; $V(f^-)$ is the loss prospect value; k is the number of indicators in the decision-making scheme that are revenue relative to the reference point; n is the number of evaluation indicators; w_i is the weight; $v(x_i)$ is the value function, and its calculation formula is as follows:

$$v(x) = \begin{cases} \Delta x^{\alpha}, & \Delta x \geq 0 \\ -\lambda(-\Delta x)^{\beta}, & \Delta x < 0 \end{cases} \tag{5}$$

where: α and β are risk preference and aversion coefficients, and there are $0<\alpha<1$ and $0<\beta<1$. λ is the loss avoidance coefficient, reflecting the degree of aversion of the decision-maker to the loss. Δx is the difference between the decision scheme x_{ij} and reference point x^*, that is, $\Delta x = x_{ij} - x^*$. Decision-makers' decision-making behaviour is bounded rational. They are risk-averse in the face of income, risk-prone in the face of loss, and more sensitive to loss.

3.2 Determination of weight function

The calculation of comprehensive prospect value needs to scientifically and reasonably determine the weight of indicators. This paper proposes a weighting method based on BWM method to ensure the reliability of the weighting results. The BWM method is a subjective weighting method, which is similar to the AHP and also based on the idea of pairwise comparison. However, it is not an arbitrary pairwise comparison, but a systematic comparison method. The specific steps are as follows [8]:

Step 1: Select an best criterion C_B and a worst criterion C_W from the index set $\{c_1, c_2, \dots, c_n\}$;

Step 2: All indicators are scored with a number between 1 and 9 to determine the preference of the indicator compared with the best indicator. If an indicator is equally important to the best indicator, assign a value of 1. If an indicator is very unimportant relative to the best indicator, assign a value of 9. Based on this, the best comparison vector $A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$ is constructed, where a_{Bi} represents the preference between the best criterion and criterion i, and there is $a_{BB} = 1$.

Step 3: Use 1 to 9 to indicate the importance of the indicator relative to the worst indicator. If an indicator is as important as the worst indicator, assign a value of 1. If an indicator is very important relative to the worst indicator, assign a value of 9. Then, a worst comparison vector $A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$ is constructed, where a_{iW} represents the preference between the worst criterion and criterion i, and there is $a_{WW} = 1$.

Step 4: Construct the mathematical model to obtain the optimal weight W:

$$\min k$$
$$s.t.\begin{cases} \left|\frac{w_B}{w_i} - a_{Bi}\right| \le k, \forall i \\ \left|\frac{w_i}{w_W} - a_{iW}\right| \le k, \forall i \\ \sum_i w_i = 1 \\ w_i \ge 0, \forall i \end{cases} \tag{6}$$

Compared with AHP method, BWM has the following advantages: for n indicators, BWM only needs $2n - 3$ comparisons, while AHP needs $n(n-1)/2$ comparisons. Meanwhile, for BWM, the comparison process is greatly simplified, the risk of inconsistency is reduced, and the reliability of the results is improved by the optimization model.

3.3 VIKOR method based on prospect theory

VIKOR is a MCDM method based on ideal point solution [1], which ranks the schemes according to the method of maximizing group utility and minimizing individual regret. The basic method is to compare the scheme to be evaluated with the ideal scheme, and prioritize it according to the difference between them, so as to obtain a reasonable and effective compromise solution, which can effectively avoid the generation of reverse order, and the result is more reasonable and easy to be accepted by decision makers.

The VIKOR method based on prospect theory uses the prospect value instead of the initial evaluation value of the index to carry out the comprehensive evaluation of the scheme. The steps are as follows.

Step 1: Obtain the prospect value f_{ij} of the index value of each decision scheme, and obtain the positive and negative ideal values of the prospect value f_i^+ and f_i^-.

Step 2: Calculate the maximum group utility S_j and the minimum individual regret R_j, that is:

$$S_j = \sum_{i=1}^{n} \left(w_i \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \right) \tag{7}$$

$$R_j = \max_i \left(w_i \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \right) \tag{8}$$

Step 3: Determine the comprehensive value of each evaluation object Q_j:

$$Q_j = \theta \frac{S_j - S^*}{S^- - S^*} + (1 - \theta) \frac{R_j - R^*}{R^- - R^*} \tag{9}$$

where $S^* = \max S_j$, $S^- = \min S_j$, $R^* = \max R_j$ and $R^- = \min R_j$. θ is the decision-making mechanism coefficient. if $\theta > 0.5$, decisions are made according to maximizing group utility; if $\theta < 0.5$, decisions are made based on minimizing individual regret; if $\theta = 0.5$, decisions are made according to the principle of balance. In this paper, $\theta = 0.5$. The smaller the S, R and Q values, the better the evaluation result of the decision scheme.

Step 4: Each evaluation scheme is ranked according to Q_j value from small to large. Let scheme A_i be the MEMG scheme ranked i. If scheme A_1 with the lowest comprehensive value meets two conditions: ① $Q_{A_2} - Q_{A_1} \geq 1/(1+m)$; ② A_1 also ranks first according to S_j or R_j, then A_1 is the best scheme. Otherwise, it can be divided into two situations: if condition ① is not met, a compromise solution can be obtained. Select any one of $A_1, A_2, \dots, A_t$, where A_t is the last MEMG solution that meets $Q_{A_t} - Q_{A_1} < 1/(m-1)$; If the condition ② is not met, select scheme A_1 or A_2.

4 CASE ANALYSIS

4.1 Case and data

In this paper, five different MEMG system design schemes for comprehensive intelligent building in a coastal city are used as simulation examples. The energy composition is shown in Table 1. The total building area is about 8700 m^2, and the roof area is 1200 m^2. The power generation capacities of photovoltaic (PV), internal combustion engine (ICE), fuel cell (FC) and gas turbine (GT) are all 140 kW, other equipment parameters are the same as that of Zhang et al. (2015), and the specific values of each evaluation index are shown in Table 2.

Table 1. System structure of different MEMG system

Scheme number	System type	System structure
A_1	Traditional MEMG	Grid+Electric air conditioner+Gas boiler
A_2	PV-MEMG	Grid+PV+ Electric air conditioner+Gas boiler
A_3	FC-MEMG	Grid+FC+Electric air conditioner
A_4	GT-MEMG	Grid+GT+Absorption refrigerator+Gas boiler
A_5	ICE-MEMG	Grid+ICE+Absorption refrigerator+Gas boiler

Table 2. Indicator data of different MEMG system

Evaluation indicator	A_1	A_2	A_3	A_4	A_5
c1/10000 Yuan	277	597	829	329	310
c2/10000 Yuan	189	137	159	159	153
c3/%	66.6	134.2	116.3	75.1	77.9
c4/%	17.6	59.0	52.7	26.8	29.4
c5/t	153.84	73.60	51.10	96.30	88.30
c6/t	4.21	1.97	1.52	1.54	1.33
c7/10000 Yuan	3.821	1.792	1.368	1.505	1.313

4.2 Evaluation results

(1) Determine the value function of prospect theory. Select the average value of the index as the reference point, that is, $x^* = \sum_{i=1}^{n} x_{ij}/n$. Then, use the average profit reference point to evaluate the optimal scheme of the MEMG. The value function $v(x_i)$ can be obtained by Equation (5). According to Zhang et al. (2016), set $\alpha = 0.88$, $\beta = 0.88$, $\lambda = 1.5$, respectively, then the value matrix under the average profit-type reference point can be obtained:

$$V_1 = \begin{bmatrix} 0.394 & -0.914 & -0.678 & -0.773 & -0.951 & -1.134 & -1.154 \\ -0.416 & 0.477 & 0.633 & 0.571 & 0.227 & 0.072 & 0.093 \\ -1.031 & 0.014 & 0.377 & 0.424 & 0.451 & 0.249 & 0.281 \\ 0.298 & 0.014 & -0.489 & -0.441 & -0.080 & 0.242 & 0.223 \\ 0.333 & 0.158 & -0.425 & -0.341 & 0.062 & 0.318 & 0.303 \end{bmatrix}$$

(2) Determine the comprehensive weight of each indicator. The BWM method is used to determine the index weight. According to expert opinions, the primary energy efficiency is set as the best indicator, and the NOx emission is the worst indicator. The corresponding optimal and worst judgment vectors are as follows:

$A_B = [2,4,1,3,6,7,5]$, $A_W = [6,4,7,5,2,1,3]$

According to formula (6), the index weight is calculated as follows:

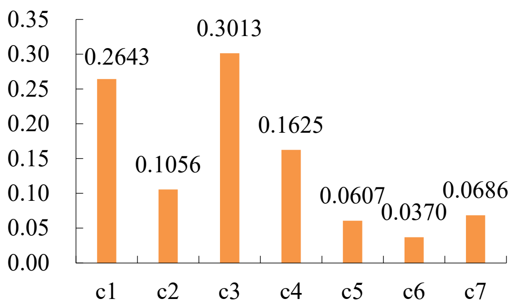

Figure 2. Indicator weighting results

(3) Using VIKOR method based on prospect theory, the S, R and Q values of each MEMG scheme can be obtained respectively, as shown in Table 3. It can be seen that the comprehensive ranking of each scheme by Q value is: $A_2 \succ A_5 \succ A_3 \succ A_4 \succ A_1$. There is a large gap between A_2 and A_5, and the test of $Q_{A_2} - Q_{A_5} < 1/(m+1)$ is passed. Meanwhile, the S value and R value of A_2 are also the best, and the conditions ① and ② are met at the same time, so the PV-MEMG (A_2) scheme is the best scheme.

Table 3. Evaluation results of VIKOR method based on prospect theory

Calculation results	A_1	A_2	A_3	A_4	A_5
S	0.8272	0.1479	0.2864	0.4044	0.3407
R	0.1991	0.0982	0.1727	0.1704	0.1606
Q	1.0000	0.0000	0.4711	0.5467	0.4513

After analyzing the evaluation results of all schemes, the PV-MEMG (A_2) ranks the first. Although its total investment and construction cost is slightly higher than that of the traditional system, due to the access of PV, its annual operating cost is reduced, the primary energy utilization efficiency is greatly improved, and the emission of pollutants is reduced. The ICE-MEMG ranks the second. Compared with other MEMG systems, its investment cost is low and environmental benefits are good, but the primary energy utilization efficiency is low. Although A_3 has high energy efficiency and environmental benefits, its total investment cost is much higher than other schemes. The energy efficiency and economy of A_4 are basically the same as that of A_5, but the environmental benefits are significantly lower than that of A_5. Compared with other MEMG systems, the traditional system in A_1 has the lowest investment cost, but its energy utilization efficiency and environmental benefits are low, so its comprehensive score is the lowest.

4.3 Comparative analysis of methods

The conventional VIKOR method without prospect value is used to evaluate the performance of the above MEMG schemes, and the evaluation results are shown in Table 4.

Table 4. Evaluation results of VIKOR method without prospect value

Calculation results	A_1	A_2	A_3	A_4	A_5
S	0.8272	0.1665	0.3233	0.4413	0.3755
R	0.1991	0.1001	0.1727	0.1741	0.1658
Q	1.0000	0.0000	0.4853	0.5815	0.4900

The evaluation results obtained by this method are different from those obtained by VIKOR method based on prospect theory. The ranking result is: $A_2 \succ A_3 \succ A_5 \succ A_4 \succ A_1$. Of the two methods, A_2 is the best and A_1 is the worst scheme, but the ranking of A_3 and A_5 is different. This is because the individual regret index of A_5 is relatively low, that is, A_5 is relatively balanced among all indicators, while A_3 has the lowest score on the economy index. In the VIKOR evaluation method based on the initial indicator value, the inferior indicators of A_3 are easily compensated by good indicators. In the VIKOR evaluation method based on the prospect theory, because the decision-maker is more sensitive to the loss, and the inferior indicators are more difficult to be compensated by good indicators, resulting that A_5 without obvious inferior indicators is better, which is also consistent with the actual project situation. Overall, it can be seen that the prospect theory comprehensively considers the impact of the decision-maker's bounded rationality on the decision results, and improves the accuracy and reliability of the evaluation results.

5 CONCLUSIONS

Aiming at the MEMG considering distributed new energy, this paper proposes a MEMG performance evaluation method based on prospect theory improved VIKOR method. Through the simulation analysis of the MEMG system of the integrated intelligent building, the results show that:

(1) The rationality and effectiveness of the evaluation results are improved by adopting the prospect theory, which considers the impact of the limited rationality of the decision-maker on the decision.

(2) The comprehensive performance of the MEMG system considering distributed new energy are better than that of the traditional MEMG system. Its advantages are mainly reflected in energy utilization efficiency and environmental benefits, but the total investment cost is relatively high. Among all MEMG schemes, the PV-MEMG system has the lowest annual operating cost, the highest energy utilization efficiency, less harmful gas emissions and the best comprehensive performance.

(3) The VIKOR method based on prospect theory is adopted to obtain a reasonable and effective compromise solution by comprehensively considering the maximization of group utility and the minimum of individual regret, so as to make the decision more reasonable and reliable.

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