Power Generation Efficiency Assessment of Distributed Photovoltaic by Improved Fuzzy- Gray Structure

MA Chunyan[1, 2], JIANG Shiying[3*]

[1]College of Electrical and Information Engineering
University of Hubei Automotive Technology
Shiyan, 442002, China

[2]College of Information Science and Engineering
University of Wuhan Science and Technology
Wuhan, 430081, China

[3]College of Econnomy and Management
University of Hubei Automotive Technology
Shiyan, 442002, China
{mcyjsy@126.com}

ABSTRACT: *For the current lack of generation efficiency assessment of distributed photovoltaic, we construct the evaluation system from three aspects covering input, process and output. Fuzzy Mathematics and Gray System Theory are introduced to carry out quantized assessment. First, the Analytic Hierarchy Process is applied to determine the weights of various indicators, and point gradation is used to express the exact evaluation information. On this basis, the Experts Coefficient Method is used to determine the membership of the evaluation index. We establish the Fuzzy-Gray relation matrix, and use* $M(\bullet, +)$ *operator and* $M(\square, +)$ *operator to calculate the mold propotion and gray propotion of relation matrix.To solve the problem that point gradation of the evaluation result is too large, we use the weighted average type operator* $M(\bullet, \oplus)$ *to optimize the evaluation result. Example shows that the improved Fuzzy-Gray method in the generation efficiency evaluation of distributed photovoltaic power, is good to overcome the problems that the assessment information is not clear and inaccurate. And this assessment system has certain significance for investment of distributed photovoltaic power stations and improving the power generation efficiency.*

Keywords: Distributed Photovoltaic, Power Generation Efficiency Assessment, Fuzzy Mathematics Theory, Gray System Theory, Analytic Hierarchy Process

Received: 10 December 2019, Revised 2 March 2020, Accepted 11 March 2020

DOI: 10.6025/jes/2020/10/2/63-71

1. Introduction

Distributed photovoltaic power generation is a system with the characteristics of clean, efficient and local. Compared with thermal power, it can better alleviate the problems of energy shortage and environmental pollution[1].Currently, more than 65 countries around the world use a variety of policy tools to encourage the development of distributed photovoltaic power industry[2].

Currently, the main research on distributed photovoltaic power generation focuses on: forecasting of distributed photovoltaic power generation[2,3], grid-benefit-cost analysis on distributed photovoltaic [4], distributed feed-in tariff and regulatory policy [5], distribution photovoltaic subsidy policy [6], and reliability assessment of grid-connected photovoltaic power station[7], quality assessment of distributed power [8] and so on. So we can conclude that it lacks research on generation efficiency assessment of distributed photovoltaic, and it is meaningful to carry out this research field.

Currently, distributed photovoltaic has become an important part of renewable energy in China. But there are large upfront investment and siting difficulties for distributed photovoltaic [9-10]. In addition, when photovoltaic power plant fully operate in the future , how to make full use of geographical advantages and solar energy, to achieve maximum conversion of solar energy ,is also an important problem. Therefore, assessment the generation efficiency of distributed photovoltaic power, and finding the key factors affecting the power generation efficiency is a better way to solve these problems [11].There are two main effects for assessment the generation efficiency of distributed photovoltaic power. Firstly, when making investment choice about photovoltaic power plant address, we should consider which region is sunny, and more suitable for photovoltaic power generation[9]; Secondly, in the process of photovoltaic power generation operation, how to adjust the characteristics of the unit, to adapt to the natural environment and sunlight, thereby improving the power generation efficiency.

The remainder of this paper is organized as follows: In the next section, we present the frame structure of Fuzzy-Grey Method modeling. We present the establishment of weight set and establishment of fuzzy-gray relation matrix in Section 3 and Section 4. In Section 5, we present the fuzzy-gray evaluation and result optimization. We also present a numerical example in Section 6. Finally, we summarize our key results and point out the further research directions in Section 7.

2. Frame Structure of Fuzzy-Grey Method Modeling

Fuzziness refers to that the ownership and state of objective things are not clear. Many evaluation factors, often lead to great ambiguity of comprehensive evaluation, and fuzzy mathematical method can compensate for the lack of statistical mathematics [12]. Gray refers to the uncertainty Figure 1. Frame Structure of Modeling of recognization. Many factors are difficult to be described in precise mathematical terms, so the information is inaccurate. That is, the evaluation information is gray [13]. The two characteristics are present at assessment the generation efficiency of distributed photovoltaic power, so we considerthe fuzziness and gray in the same time. Fuzzy-Grey Method modeling steps are as follows Figure 1.

Let us define the evaluation factors set $D = \{d_1 d_2, d_3, ... d_n\}$, $(i = 1, 2, ... n)$, thereby these evaluation factors form a hierarchical index system, which are divided into three levels: the target level, the main criterion layer and the criteria layer. And the next level of factor ,that is $D_i = \{d_{i1}, d_{i2}, ... d_{il}\}$, $(i = 1, 2, ... n)$. Of course, it can also extend to four and more levels.

According to the actual operating condition, the comment set are divide into 3 ratings, namely the collection of comment is $y = [y_1, y_2, y_3]$, which corresponds to comment rating: excellent, good, and general.

3. Establishment of Weight Set

In this section, we apply Analytic Hierarchy Process to establish the weight set.

3.1. Establishment of Judgment Matrix

If we use a_{ij} to indicate the importance ratio of u_i with respect to u_j, then by comparison we can obtain the judgment matrix [14], it is denoted by $A = (a_{ij})_{nxn}$.

Suppose there are n primary evaluation criterion level under the target $X^1{}_1, X^2, \Lambda, X^n$, $(I = 1, 2, ..., n)$ the importance degree of index X^1 to X^1 is W_I, and $\sum_{I=1}^{n} W_I = 1$; Here take $X^I (I = 1, 2, \Lambda, n)$ for example, calculate the importance degree of the next level indicators W_i^I. According to the mathematical principle of AHP, and the pairwise comparison of these indicators, the relationship matrix shows the relative importance degree of indicators:

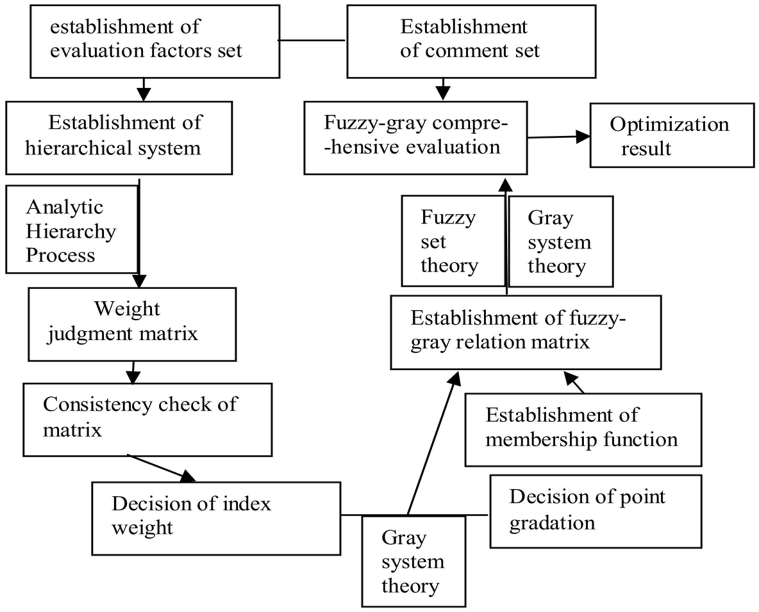

Figure 1. Frame Structure of Modeling

$$A^I = \begin{bmatrix} w_1^I/w_1^I & w_1^I/w_2^I & \Lambda\ w_1^I/w_m^I \\ w_2^I/w_1^I & w_2^I/w_2^I & \Lambda\ w_2^I/w_m^I \\ & M & \\ w_m^I/w_1^I & w_m^I/w_2^I & \Lambda\ w_m^I/w_m^I \end{bmatrix} = (a^I_{ij})_{m\times m} \tag{1}$$

Typically, you can take $w_i^I / w_j^I = \partial(\partial = 1, 2, \Lambda, 9; i = j = 1, 2, \Lambda, m)$ (2)

3.1. Consistency Check of Judgment Matrix

For the matrix A, if the relationship satisfies $a_{ij} = \frac{a_{ik}}{a_{jk}}$, then we call the matrix have complete consistency. When the matrix is not consistent, the largest eigenvalues of matrix is λ_{max}, and the weight vector after normalization is ω [16]. There is a relationship between the weight vector and the largest eigenvalues. According to fuzzy matrix operation, then the following result is :

$$A^I W^I = \begin{bmatrix} w_1^I/w_1^I & w_1^I/w_2^I & \Lambda\ w_1^I/w_m^I \\ w_2^I/w_1^I & w_2^I/w_2^I & \Lambda\ w_2^I/w_m^I \\ & M & \\ w_m^I/w_1^I & w_m^I/w_2^I & \Lambda\ w_m^I/w_m^I \end{bmatrix} \begin{bmatrix} w_1^I \\ w_2^I \\ M \\ w_m^I \end{bmatrix} = \begin{bmatrix} mw_1^I \\ mw_2^I \\ M \\ mw_m^I \end{bmatrix} = \lambda_{max} W^I \tag{3}$$

Here $\bar{a}^I_{ij} = a^I_{ij} \Big/ \sum_{q=1}^{m} a^I_{qj} = w^I_i \Big/ \sum_{q=1}^{m} w^I_q \left(i,j=1,2,\Lambda,m\right)$

$$\bar{w}^I_i = \sum_{j=1}^{m} \bar{a}^I_{ji} \left(i=1,2,\Lambda,m\right) w^I_i = w^I_i \Big/ \sum_{q=1}^{m} w^I_q \left(i=1,2,\Lambda,m\right) \tag{4}$$

$$W^I = \left[\bar{w}^I_1, \bar{w}^I_2, \Lambda, \bar{w}^I_m\right]^T$$

This is the weight of each index evaluation $x^I_{i\ (i = 1, 2, \Lambda, m)}$ under the object X^I. Similarly, you can find other weight vectors of the object-level indicators. The ω can or not represent individual elements accounted for in the proportion of object, depending on the extent of the inconsistency of matrix A. The more λ_{max} is larger than n, the greater the degree of inconsistency[14]. We commonly use consistency index to measure, and it is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

Consistency is furtherly defined ratio CR:

$CR = CI/RI$. Among them, the Random Consistency Index RI can be obtained by look-up table.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Table 2. Value range of *RI*

Typically, the judgment matrix is considered satisfactory consistency, if $CR \leq 0.1$. Otherwise you will need to adjust the judgment matrix, so that it has the satisfactory consistency.

3.3. Decision of Point Gradation

Because it is difficult to measure the amount of weight information with a value, so point gradation is used to express this characteristic [17]. For example, in view of clarity of the information, the information can be divided into: {very full, full, general, poor, very poor}. The corresponding point gradation of these descriptive language are {0~0.20, 0.21~0.40, 0.41~0.60, 0.61~0.80, 0.81~1.00}.

Evaluation factors weight set includes two parts, such as weights and point gray. So we get the evaluation factors weight set $\tilde{W}_{\otimes} = [(W_1, V_1), (W_2, V_2), (W_3, V_3), \ldots, (W_n, V_n)]$.

4. Establishment of Fuzzy-Gray Relation Matrix

4.1. Establishment of Membership Function

Firstly, we should membership function. According to the positive and negative of indicators, we can calculate membership[16].

For positive indicators, the membership function can be constructed as follows:

$$u_A(u) = ae^u + b \quad (6)$$

Here, a, b as a determined coefficient.

The membership function can be constructed for negative indicators:

$$u_B(u) = cu^{-1} + d \quad (7)$$

Here, c, d as a determined coefficient.

Maximum indicators (including positive and negative indicators) is M, the minimum is m. Then for the positive indicators, when $u = M$, $u_A(u) = 1$; when $u = m$, $u_A(u) = 0$. The we can find:

$$\begin{cases} ae^M + b = 1 \\ ae^m + b = 0 \end{cases} \quad (8)$$

Then according to the solution of equations, we can obtain a membership function of final positive indicator is:

$$u_A(u) = \frac{1}{e^M - e^m} e^u - \frac{e^m}{e^M - e^m} \quad (9)$$

For negative indicators, when $u = M$, $u_B(u) = 0$; when $u = m$, $u_B(u) = 1$. and there are

$$\begin{cases} cM^{-1} + d = 0 \\ cm^{-1} + d = 1 \end{cases} \quad (10)$$

After solution of the above equation, the membership function of negative indicators is:

$$u_B(u) = \frac{Mm}{M-m} u^{-1} - \frac{m}{M-m} \quad (11)$$

4.2. Fuzzy-gray Relation Matrix

The fuzzy-gray relation matrix shows the fuzzy and gray relationship between the evaluation factors set and comment set. Fuzzy-gray judgment matrix is consisted of mold portion and gray portion. Mold portion uses fuzzy membership to characterize fuzzy relations, and membership refers to degree of factors set affiliating to comment set. The gray portion uses the point gradation to characterize the fuzzy affiliation. Let set evaluation matrix:

$$\underset{\otimes}{\tilde{R}} = \begin{bmatrix} (u_{11}, v_{11}) & (u_{12}, v_{12}) & \dots (u_{1m}, v_{1m}) \\ (u_{21}, v_{21}) & (u_{22}, v_{22}) & \dots (u_{2m}, v_{2m}) \\ \dots & \dots & \dots \quad \dots \\ (u_{n1}, v_{11}) & (u_{n2}, v_{n2}) & \dots (u_{nm}, v_{nm}) \end{bmatrix} \quad (12)$$

Here u_{ij} represents membership, V_{ij} represents point gradation.

5. Fuzzy-Gray Evaluation and Result Optimization

Because the fuzzy-gray evaluation matrix consists of two parts, there is a very different nature between the gray portion and the mold portion, so each of them should be calculated differently [16]. Mold portion in this paper is calculated by algebraic product operator $M(\bullet, +)$, and gray portion is calculated by $M(\odot, +)$ operator calculates.

In the fuzzy synthesis operation, the information often lost a lot, and this causes that the results are not easily distinguishable and unreasonable[17]. To solve this problem, we use weighted average and fuzzy composite operator $M(\odot, +)$ to calculate. Its formula is:

$$f^* = \sum_{i=1}^{n} \mu(v_i) \cdot s_i^k / \sum_{i=1}^{n} s_i^k \quad (13)$$

Here, $\mu(v_i)$ is the value of grade i of comment set. s^k_i is fuzzy gray vector of the indicator k. Therefore, we need to give comment rating assignment $\mu(v_1)$, $\mu(v_2)$, $\mu(v_3)$, ..., $\mu(v_4)$. Finally, we determine the results of the evaluation according to f^*.

6. Numerical Example

6.1. Evaluation System

We establish evaluation system based on [9-11]as shown in Table 1.

6.2. Weight Set

We apply Analytic Hierarchy Process to seek the relative weight of each index. First, we invite the power industry expert and asked him, to make judgments on the relative importance of indicators based on personal experience. For example, the input

	first level d_i	weight set (ω_i, ν_i)	second level d_{ij}	weight set (ω_{ij}, ν_{ij})
objective	output index d_1	(ω_1, ν_1)	photovoltaic power generation and use d_{11} generation quantity d_{12}	(ω_{11}, ν_{11}) (ω_{12}, ν_{12})
	process index d_2	(ω_2, ν_2)	inverter efficiency d_{21} operational efficiency d_{22}	(ω_{21}, ν_{21}) (ω_{22}, ν_{22})
	input index d_3	(ω_3, ν_3)	sunshine hours d_{31} geographic latitude d_{32} dip adjustment d_{33}	(ω_{31}, ν_{31}) (ω_{32}, ν_{32}) (ω_{33}, ν_{33})

Table 1. Evaluation system

index d_3, he needs to do pairwise comparison of three indicators with each other,then make a judgment. After a pairwise comparison, the matrix A^I can be get.

According to matrix theory, for the judgment matrix, there is a formula $A^I W^I = \lambda_{max} W^I$. The W^I can or not represent individual elements accounted for in the proportion of Q, depending on the extent of the inconsistency of A. The more λ_{max} is larger than n, the greater the degree of inconsistency. We commonly use consistency index to measure, and it is:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \frac{3.10486 - 3}{2} = 0.05243$$

In this article $n = 3$, we take 0.58. So we can conclude that

$$CR = \frac{CI}{RI} = 0.05243 \ / \ 0.58 = 0.0904$$

The $CR \leq 0.1$, so the judgment matrix is considered satisfactory consistency. Otherwise you will need to adjust the judgment matrix. So we can get the weight of result index factor d_3 is $\tilde{W}_{d3} = [0.24, 0.68, 0.08]$. Then the evaluation weight of output index factor d_1 can be also obtained $\tilde{W}_{d1} = [0.45, 0.55]$. The weight of process index factor d_2 can be obtained $\tilde{W}_{d2} = [(0.27, 0.10), (0.73, 0.00)]$, and the weight of object is $\tilde{W} = [0.18, 0.34, 0.48]$.

6.3. Evaluation Factors Weight Set

According to AHP method, we get the weight set, and determine its gray point according to the adequacy of the information. Then the evaluation weight set of output index factor d_1 can be obtained $\tilde{W}_{\otimes d_1} = [(0.45, 0.30), (0.55, 0.60)]$, the evaluation weight set of process index factor d_2 can be obtained $\tilde{W}_{\otimes d_2} = [(0.27, 0.10) (0.73, 0.00)]$, the evaluation weight set of result index factor d_3 can be obtained $\tilde{W}_{\otimes d_3} = [(0.24, 0.70), (0.68, 0.00), (0.08, 0.10)]$.

The evaluation weight set of object can be obtained $\tilde{W}_{\otimes} = [(0.18, 0.20), (0.34, 0.10), (0.48, 0.30)]$.

6.4. Fuzzy-gray Relation Matrix

According to the membership function, we can get the fuzzy-gray relation matrix.

The fuzzy gray relation matrix of output indicators is:

$$\tilde{R}_{\otimes d_1} = \begin{bmatrix} (0.31,\ 0.10) & (0.29,\ 0.30) & (0.40,\ 0.20) \\ (0.36,\ 0.50) & (0.14,\ 0.60) & (0.50,\ 0.10) \end{bmatrix}$$

The fuzzy gray relation matrix of output indicators is:

$$\tilde{R}_{\otimes d_2} = \begin{bmatrix} (0.17,\ 0.10) & (0.08,\ 0.00) & (0.75,\ 0.20) \\ (0.43,\ 0.30) & (0.15,\ 0.90) & (0.42,\ 0.10) \end{bmatrix}$$

The fuzzy gray relation matrix of process indicators is:

$$\tilde{R}_{\otimes d_3} = \begin{bmatrix} (0.26, 0.60) & (0.57, 0.10) & (0.17, 0.00) \\ (0.18, 0.80) & (0.64, 0.10) & (0.18, 0.40) \\ (0.55, 0.10) & (0.41, 0.90) & (0.01, 0.20) \end{bmatrix}$$

6.5. Gray-fuzzy Comprehensive Evaluation

According to the weight set $\tilde{W}_{\otimes d_i}$ $(i = 1, 2, 3)$ of evaluation factors obtained by computing previously, as well as fuzzy-gray matrix of three indicators, the following results can be obtained.

The fuzzy-gray comprehensive evaluation results of output indicators is:

$$\tilde{B}_{\otimes d_1} = \tilde{W}_{\otimes d_1} \tilde{R}_{\otimes d_1} = [0.45,\ 0.30),\ (0.55,\ 0.60)] o \begin{bmatrix} (0.31,0.10) & (0.29,0.30) & (0.40,0.20) \\ (0.36,0.50) & (0.14,0.60) & (0.50,0.10) \end{bmatrix} = [(0.3375,\ 0.60),\ (0.2075,\ 0.90),\ (0.4550,\ 0.30)]$$

In the same way, the fuzzy-gray comprehensive evaluation results of process indicators d_2 is:

$\tilde{B}_{\otimes d_2}$ = [(0.3598, 0.10), 0.1311, 0.00), 0.5091, 0.10)]

In the same way, the fuzzy-gray comprehensive evaluation results of process indicators d_3 is:

$\tilde{B}_{\otimes d_2}$ = [(0.2288, 0.70), 0.1311, 0.00), 0.2600, 0.10)]

Based on the above results, the final evaluation matrix can be obtained as follows:

$\tilde{B}_{\otimes} = \tilde{W}_{\otimes} \tilde{R}_{\otimes}$ = [(0.292906, 0.50), (0.144852, 0.20), (0.37976, 0.50)]

Now we make choice in accordance with the principle of maximum membership, then the end result is 0.37976.It shows the generation efficiency of distributed photovoltaic power is general.

6.6. Result Optimization

In the fuzzy synthesis operation, the information often losts a lot, and this causes the results are not easily distinguishable and unreasonable. According to the (13), the calculation can be obtained as $f^* = 1.79352$, and it is closely to good. Therefore, the evaluation results can be considered as well. At this the point gradation is 0.20, so the information is sufficient and it shows a strong reliability of the conclusion. If we make choice in accordance with the principle of maximum membership, then the end result is general. At this time, the point gradation is 0.50. So the point gradation is high, and it shows the information is not sufficient, the conclusion also has weak reliability. Therefore, based on the fuzzy-gray assessment, the conclusion is more credible.

6. Conclusion

When photovoltaic power plant fully operation in the future , how to make full use of geographical advantages and solar energy, to achieve maximum conversion of light energy ,is also an important problem. In this paper, the improved fuzzy-gray comprehensive evaluation is used, input, process and outcome evaluation system covering three areas is established, and we conduct a comprehensive assessment. The research results show that:

(1) The application of fuzzy evaluation method can compensate for the lack of statistical mathematics, can handle system with many more evaluation factors and complex hierarchy, and solve problem that state assessment is not clear;

(2) In the process of assessment index weight, and indicators membership, there is inevitably incomplete information and inaccurate situation. Using gray evaluation method, make up incomplete and no certainty understanding;

(3) Fuzzy-Gray method which based on the theory of fuzzy and gray theory, preferably combines strengths of fuzzy and gray theory, while avoiding the non-clear and inaccuracies, and it can more accurately reflect the true situation.

The next step we could consider using non-linear form or trigonometric functions to characterize the membership, which will be further research direction.

Acknowledgment

This paper received support of hubei province science and technology plan items (item number: B2015122. JIANG Shiying is corresponding author, his E-mail is jiangshing@126.com. We show deep gratitude to them.

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