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Comprehensive evaluation method for tidal current power generation device

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Abstract There are many types of tidal current power generation devices, and it is necessary to make comprehensive evaluation of tidal current power generation devices in order to provide valuable reference for the improvement of their performance indexes. On the basis of the analysis of the tidal current power generation device performance indexes, the hierarchical model for comprehensive evaluation of device performance is given in this paper. By normalizing the membership matrix elements based on fuzzy comprehensive evaluation model, all the values of the matrix elements are restrained in the range of 0.0 to 1.0, hence the complexity of the calculations is reduced. Vector similarity is used to determine the expert weights which reflect the knowledge and experience of the experts. This paper presents an improved method for rank correlation analysis, and calculates the comprehensive weight value and the final evaluation results of tidal current power generation devices. The presented method improves the credibility of the evaluation. In the end, measured data of two units of tidal current power generation devices are evaluated in the paper, and the effectiveness of the presented method is verified.

Keywords Tidal current power generation device, Analytic hierarchy process, Rank correlation analysis, Similarity, Comprehensive evaluation

1 Introduction

Along with the advancement of science and technology and the development of social industrialization, the problem of energy shortage is becoming more and more serious. One important way to settle the energy shortage is to develop new energy power generation technology. There are abundant energies in the ocean, including wave energy, tidal current energy, salinity energy and thermal energy. In order to promote the development of ocean energy, at least sixty countries had structured policies for their ocean industries [1, 2]. As a country of wide ocean areas, China has just begun to develop the technology for marine resources utilization. Wave and tidal current power generation technologies in China can only be applied to engineering prototype and demonstration experiment, and are not able to satisfy the demand of power generation on a large scale. At present, no testing site has been built to provide a platform for experiment, test, and evaluation of wave or tidal current power generation devices in China [3]. The ocean renewable energy project fund has supported a series of projects about offshore testing site construction of wave and tidal current energy utilization, which will carry forward the development of ocean energy

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generation technology in China [4]. Among them, the study on the comprehensive evaluation method for tidal current power generation device considered an important part of offshore testing site construction, offering valuable reference for improving the performance of tidal current power generation device.

There are various comprehensive evaluation methods, mainly including analytic hierarchy process (AHP), probabilistic method, fuzzy comprehensive evaluation, intelligent evaluation and grey integrative evaluation. Proper evaluation methods should be chosen to get rational evaluation results, in allusion to different study objects. During the calculation of AHP, what highly affects the results is the subjective judgment. Once the number of indexes is larger than 9, it will be hard to ensure the accuracy because the consistency check of judgment matrix adds the calculation difficulty [5]. Probabilistic method applies vector algebra to get evaluation results, and uses probability statistics characteristics to draw the main features of the indexes. Even though the subjective index influence is small, the accuracy of this method will be affected by the selection of basic value in quantization process [6]. Fuzzy comprehensive evaluation judges the grade according to maximum membership degree principle. Its deficiency is too much subjective judgment on human [7]. Capable of removing the artificial effected by weight, intelligent evaluation can assure the validity and practicability of the weights. However, the implicity of intelligent evaluation model makes it difficult to explain the output weights, and the convergence speed greatly influences the evaluation efficiency [8]. Grey integrative evaluation describes the strength, magnitude, and sequence of relationship between indexes with grey relational degree. Although it manages to solve the index quantification problem and eliminate the subjective impact, the weight distribution influences the final results directly [9].

It can be seen from the above introduction that simplex comprehensive evaluation method can hardly assure the reliability of the evaluation results. Besides, there is few study on comprehensive evaluation method for the performance of tidal current power generation device in China, and the evaluation of the performance indexes is made mainly on the basis of setting parameters, measured data, and expert experience. In order to ensure the accuracy and reliability of the evaluation results, this paper presents noteworthy evaluation indexes of tidal current power generation device, establishing the index system of comprehensive evaluation by using AHP. On the basis of trapezoid and semi-trapezoid distribution, the subordinating degree function is given. By normalizing the forward characteristics of indexes, element values of the membership matrix are assigned in the range of 0.0 to 1.0, and the complexity of the calculations is reduced. To improve rank correlation analysis, vector similarity is used to determine the expert weight, thus the comprehensive weight value with multiple indexes are calculated and the final assessment results are synthesized.

2 Analysis on performance indexes of tidal current power generation device

The measured data of tidal current power generation devices mainly include the real-time tidal current speed and the device power output (normally calculated by the instantaneous voltage u and the instantaneous current i of the generation system output). The data measurement of the two parts must be synchronized and the sample frequency is set as 2 Hz and or even higher. The test period is 15 days and 144 groups of continuous working data are recorded every day. The continuous measured duration of each group is 10 minutes [10, 11].

2.1 Power output characteristic

As an important performance index to evaluate the tidal current power generation device, power output characteristic reflects the device capability of absorbing tidal current energy and has a direct influence on the annual electricity output. The tidal current speed determines the power output of the generation device. Only when the speed is higher than 1 m/s will the tidal current energy be worth using. The output power of tidal current power generation device is given by

$$P = \frac{1}{2}\rho S v^3 C_p \tag{1}$$

where P is the output power of tidal current energy generation device; ρ is the current density and $\rho = 1.025 \times 10^3$ kg/m^3; S is the cross sectional area swept by the hydro turbine blade; v is the tidal current speed; C_p is the utilization factor of the first transformation of the device.

During the data acquisition, all the speed data of tidal current should correspond to the power data collected in the same period of time, and the data that does not meet the analysis need should be screened out and removed. Analysis bin interval of the data is determined, and the arithmetic mean values v_{cn} and p_{gn} corresponding to the bin interval is calculated. Then the power output characteristic curve of the device can be acquired by numerical fitting.

During the analysis of power output characteristic, the width of the bin interval and the number of the data points in the interval determine the representation of the data, which are the basis of curve fitting of power characteristic. Therefore, in order to determine the optimized selection scheme of the interval width that associates the rated working speed range of the device, it is necessary to analyze the error values caused by different selection schemes of the interval width according to statistical method as well as the measured data.

Meanwhile, the fitting result should be compared with continuous observation data in more than one month, so that the curve fitting scheme of the power output characteristic can be obtained in terms of the reliability, stability, and the error value of the fitting term. Usually the least square method is a good option for curve fitting.

2.2 Annual energy output

Annual energy output (AEP) [12] is calculated according to power output characteristic curve of tidal current power generation device and the distribution of tidal current speed. The total electric energy output of the device can be estimated within a year, and it is an important index to measure the economic performance of tidal current power generation device. On the basis of the above-mentioned analysis, the annual energy output can be calculated by

$$AEP = h_{AE} \sum_{i=1}^{N} \frac{a_i}{n} \overline{p}_{gi} \tag{2}$$

where h_{AE} is the power generation time of the year; N is the number of the analysis bin interval; n is the total sampling times; a_i is the number of v_{cn} corresponding to the dot (v_{cn}, p_{gn}) in the i^{th} bin interval; $\overline{p}_{gi}$ is the output power corresponding to the i^{th} bin interval.

2.3 Capacity coefficient

Capacity coefficient F is the index that represents the energy output of tidal current power generation device [13]. It is the ratio of the average output power P_A to the rated power P_N in a test period (a year, a season or a month).

$$F = \frac{P_A}{P_N} \tag{3}$$

F may also be represented by the equivalent full-load generation time during the test period, and is used to weigh the gross generation of the device, which is usually calculated by the accumulation of the power sequences obtained by the average current speed and average power in a period of time.

2.4 Ratio of average power to maximum power

Ratio of average power to maximum power reflects the ability to output the maximum electric power. It is defined as the ratio of the average power of the generation device P_a to the maximum power $P_{\max}$ in a test period, being symbolized by $\theta_{\max}$.

$$\theta_{\max} = \frac{P_a}{P_{\max}} = \frac{\sum_{i=1}^{N} \overline{p}_{gi}}{\max\{p_{g1}, p_{g2}, \ldots, p_{gn}\}} \tag{4}$$

2.5 Energy conversion efficiency

The energy conversion efficiency η of tidal current power generation device is defined as the ratio of the net electric power output P to the actual tidal current power input P_{KE}.

$$\eta = \frac{P}{P_{KE}} \times 100\% \tag{5}$$

In the actual test, the value is usually derived from accumulating three-level energy conversion efficiency, which is shown as

$$\eta = C_p \eta_d \tag{6}$$

where C_p is the energy utilization coefficient; η_d is the mechanical generation efficiency.

2.6 Stable working time

The flow cycle of tidal current is in accordance with the cycle of tidal, which is usually 12 hours or 24 hours. In the whole test period, the whole time that the device output stable electric power is recorded as the stable working time of the device, symbolized by T_s. The average value is used as the index of the stable working time.

2.7 Utilization rate

Utilization rate, symbolized by A_v, is usually indicated as the percent which the normal working time T_w (removing the time during which the generation system stops operating for normal maintenance and system faults) accounts for of the total time in the period T. In actual computation, the power characteristic function of the tidal current power generation device $P_W(v)$ is often used to calculate the utilization rate.

$$A_v = \int_{v_{ci}}^{v_{co}} P_W(v) \mathrm{d}v \tag{7}$$

3 Construction of comprehensive evaluation model

3.1 Conformation of index set and evaluation set

According to the above index analysis of tidal current power generation device, AHP is used to decompose the performance indexes of the device, and the comprehensive index evaluation system of tidal current power generation device is established, as shown in Table 1.

In order to reduce the calculation work and the complexity of the comprehensive evaluation as well as to guarantee the accuracy and reliability of the result, each index is divided into five levels of 'very poor', 'poor', 'qualified', 'good', and 'excellent'.

3.2 Construction of membership functions

Figure 1 shows the diagram of the membership functions of trapezoidal distribution. The membership function expressions corresponding to the levels 'very poor', 'poor', 'qualified', 'good' and 'excellent' are shown successively in (8)–(12). Based on the membership functions with the evaluation levels, the membership matrix $\boldsymbol{R}$ can be composed by using index data to calculate the index membership values.

$$u_1=\begin{cases}1 & 0<x_r\le x_1\\ \dfrac{x_2-x_r}{x_2-x_1} & x_1<x_r\le x_2\\ 0 & x_r>x_2\end{cases}\tag{8}$$

$$u_2=\begin{cases}\dfrac{x_r-x_1}{x_2-x_1} & x_1<x_r\le x_2\\ \dfrac{x_4-x_r}{x_4-x_3} & x_3<x_r\le x_4\\ 1 & x_2<x_r\le x_3\\ 0 & x_r\le x_1 \text{ or } x_r>x_4\end{cases}\tag{9}$$

$$u_3=\begin{cases}\dfrac{x_r-x_3}{x_4-x_3} & x_3<x_r\le x_4\\ \dfrac{x_6-x_r}{x_6-x_5} & x_5<x_r\le x_6\\ 1 & x_4<x_r\le x_5\\ 0 & x_r\le x_3 \text{ or } x_r>x_6\end{cases}\tag{10}$$

$$u_4=\begin{cases}\dfrac{x_r-x_5}{x_6-x_5} & x_5<x_r\le x_6\\ \dfrac{x_8-x_r}{x_8-x_7} & x_7<x_r\le x_8\\ 1 & x_6<x_r\le x_7\\ 0 & x_r\le x_5 \text{ or } x_r>x_8\end{cases}\tag{11}$$

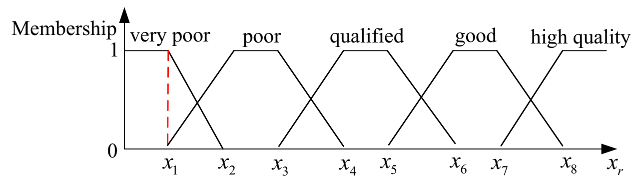

Fig. 1 Trapezoidal distribution of membership functions

$$u_5=\begin{cases}0 & x_r\le x_7\\ \dfrac{x_r-x_7}{x_8-x_7} & x_7<x_r\le x_8\\ 1 & x_r>x_8\end{cases}\tag{12}$$

3.3 Normalization of membership value

By normalizing the influence factors of the membership matrix, all the element values of the matrix are restrained in the range of 0.0 to 1.0. The evaluation result of a certain index's membership matrix is poorer if the elements are closer to 0.0, whereas the result is better if the elements are closer to 1.0. As the performance index values of tidal current power generation device are all positive and forward, the normalization processing can be carried out by

$$r'_{ij}=\frac{r_{ij}-r_{ij\min}}{r_{ij\max}-r_{ij\min}}\tag{13}$$

Hence the membership matrix is shown as

$$\boldsymbol{R}=\begin{bmatrix} r'_{11} & r'_{12} & \dots & r'_{1n}\\ r'_{21} & r'_{21} & \dots & r'_{2n}\\ & & \dots & \\ r'_{m1} & r'_{m1} & \dots & r'_{mn}\end{bmatrix}\tag{14}$$

4 Determination of index weight

4.1 Improved method for rank correlation analysis

The principle of improved method for rank correlation analysis and the calculation steps are as follows:

1) The importance degree given by relevant experts of the indexes can be received to confirm the rank correlation, according to Table 1. If the indexes are $u_1, u_2, \dots, u_K$ and the number of the experts is L, the ranking correlation

Table 1 Comprehensive index system of tidal current power generation device

Target layer	Criterion layer	Index layer
Output characteristics of tidal current power generation device	Electric power characteristics	Power output characteristic, capacity coefficient, ratio of average power to maximum power
	Energy efficiency	Annual energy output, energy conversion efficiency
	Run time	Utilization rate, stable working time

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given by the i^{th} expert can then be denoted by $u_i > u_j > \cdots > u_k$.

2) Let r_{ik} be the relative importance degree between adjacent indexes u_{k-1} and u_k of the i^{th} expert, so r_{ik} is defined by $w_2^{(2)} = 0.7$, and the values are shown in Table 2.

3) Determination of expert weight: r_i and r_j denote the rational valuation vectors about the evaluation indexes of the i^{th} and j^{th} experts, respectively, so the equations are $r_i = (r_{ik})$ and $r_j = (r_{jk})$. Let $\cos(r_i,\ r_j)$ be the cosines of angle between r_i and $r_j,$ and s_i be the similarity between values given by the i^{th} expert and other experts. s_i can be denoted by

$$s_i = \sum_{j=1, i\neq j}^{L} \cos(r_i,\ r_j) \quad (i = 1, 2, \cdots L) \tag{15}$$

By standardizing the similarity s_i, the weight a_i of the i^{th} expert can be obtained as

$$a_i = \frac{s_i}{\sum_{i=1}^{L} s_i} \quad (i = 1, 2, \cdots L) \tag{16}$$

4) Determination of index weight: let r_k^* be the rational valuation of the importance degree ratio of u_{k-1} to u_k given by L experts. The weight average of r_{ik} can be calculated according to the expert weight a_i, from which r_k^* is denoted as

$$r_k^* = \sum_{i=1}^{L} a_i r_{ik} \tag{17}$$

Hence calculation of the k^{th} index's weight w_k is shown in (18) and (19).

$$w_k^* = \left(1 + \sum_{j=2}^{m} \prod_{k=j}^{m} r_k^*\right)^{-1}$$

$$w_k^* = \left(1 + \sum_{j=2}^{m} \prod_{k=j}^{m} r_k^*\right)^{-1} \tag{18}$$

$$w_{k-1}^* = r_k^* w_k^* \quad (k = 2, 3, \cdot \cdot \cdot, m) \tag{19}$$

4.2 Synthesization of evaluation results

Multiplying the revised weight vector $\boldsymbol{W}$ in Section 4.1 by the membership matrix $\boldsymbol{R}$, the evaluation matrix $\boldsymbol{B} = (b_i)$ may be received, as shown in (20). Since the weight vector $\boldsymbol{W}$ and the membership matrix $\boldsymbol{R}$ have been standardized, there is no need to standardize the vector of the fuzzy comprehensive evaluation result. On the basis of maximum membership principle, the comprehensive level of tidal current power generation device can be acquired. The valuation level corresponding to $b_i = \max\{b_i\}$ is chosen as the comprehensive evaluation result of the performance of the device.

$$\boldsymbol{B} = \boldsymbol{W}\boldsymbol{R} \tag{20}$$

5 Case study

Two tidal current power generation devices are introduced here, one with a dome (Device 1), the other without a dome (Device 2). The output power ratings of both devices are given as 20 kW and the curves of the output power of Device 1 and Device 2 are shown in Fig. 2. After testing the two devices on the spot and standardizing the data, the devices' performance indexes are shown in Table 3. Since the devices indexes are positive, and the index values are restrained in the range of 0.0 to 1.0 after standardizing all, the reference values are 1.0. And the closer the values get to 1.0, the more qualified the performance of the device will be.

According to (8)–(13), the fuzzy comprehensive evaluation matrix $\boldsymbol{R}_1$ after the standardization of the criterion layer is calculated. Take the power characteristic as an example, the corresponding index layer evaluation matrix $\boldsymbol{R}_{11}$ is shown as

$$\boldsymbol{R}_{11} = \begin{bmatrix} 0 & 0 & 0.197 & 0.324 & 0.479 \\ 0 & 0 & 0.201 & 0.298 & 0.501 \\ 0 & 0 & 0.121 & 0.206 & 0.673 \end{bmatrix}$$

The same procedure can be adapted to obtain the index layer evaluation matrix $\boldsymbol{R}_{12}$ corresponding to energy conversion efficiency, and matrix $\boldsymbol{R}_{13}$ corresponding to working time.

$$\boldsymbol{R}_{13} = \begin{bmatrix} 0 & 0.252 & 0.613 & 0.135 & 0 \\ 0 & 0.264 & 0.544 & 0.192 & 0 \end{bmatrix}$$

The weight matrix $\boldsymbol{W}_1$ of criterion layer to goal layer is known as

$W_1 = (0.5,\ 0.4,\ 0.1)$.

There are 4 experts responsible for grading. By the improved method for rank correlation analysis mentioned above, the grade weight matrix $\boldsymbol{A}$ of the four experts is

Table 2 Proportional scale

$\frac{u_{k-1}}{u_k}$	Equal	Slightly strong	Strong	Obviously strong	Extreme	Median
r_{ik}	1.0	1.2	1.4	1.6	1.8	1.1, 1.3, 1.5, 1.7

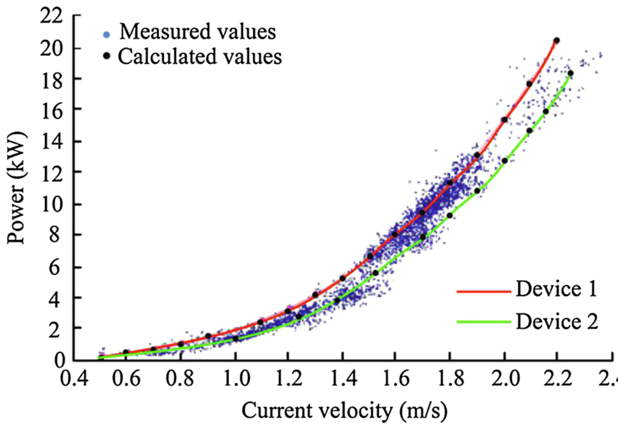

Fig. 2 Curves of output power of Device 1 and Device 2

Table 3 Initial data of performance indexes in tidal current power generation device

Evaluation parameters	Device 1	Device 2
Average power (kW)	16.685	17.344
Capacity coefficient	0.8464	0.8531
Ratio of average power to maximum power	0.9327	0.8977
Annual energy output (kWh)	59982.6	58968.6
Energy conversion efficiency	0.3633	0.3869
Stable working time (hour)	10.58	8.76
Utilization	0.4587	0.3898

$$\mathrm{A} = (0.198,\ 0.347,\ 0.265,\ 0.190)$$

Hence the weights of criterion layer to goal layer of Device 1 are

$$w_1^{(1)} = 0.6,\ w_2^{(1)} = 0.2,\ w_3^{(1)} = 0.2$$
$$w_1^{(2)} = 0.3,\ w_2^{(2)} = 0.7$$
$$w_1^{(3)} = 0.6,\ w_2^{(3)} = 0.4$$

The weight matrix $\boldsymbol{W}$ of criterion layer to goal layer can be compounded by the weight matrixes $\boldsymbol{W}_1$, $\boldsymbol{W}_2$, and the expert grading weight $\boldsymbol{A}$, which is

$$\boldsymbol{W} = (0.271,\ 0.195,\ 0.157,\ 0.143,\ 0.110,\ 0.053,\ 0.071)$$

By fuzzy transforming of the index layer $\boldsymbol{W}$ and the fuzzy evaluation matrix, the comprehensive evaluation matrix $\boldsymbol{B}$ can be obtained as

$$\boldsymbol{B} = \boldsymbol{WR} = (0.0708,\ 0.208,\ 0.2136,\ 0.325,\ 0.174)$$

According to the maximum membership degree principle, we know that the comprehensive evaluation matrix $\boldsymbol{B}$ of Device 1 is $b_4 = \max\{b_1,\ b_2,\ b_3,\ b_4,\ b_5\} = 0.325$. The corresponding evaluation level is 'good'. So the comprehensive performance evaluation result of Device 1 is 'good'. The comprehensive performance evaluation result of Device 2 is 'qualified' following the above way.

If using the traditional method of rank correlation analysis, we can get the weight matrix $\boldsymbol{W}_1{}'$ of criterion layer to goal layer which is:

$$\boldsymbol{W}_1{}' = (0.17, 0.215, 0.153, 0.194, 0.112, 0.055, 0.101)$$

By fuzzy transforming of the index layer $\boldsymbol{W}_1{}'$ and the fuzzy evaluation matrix, the comprehensive evaluation matrix $\boldsymbol{B}'$ can be obtained as follows:

$$\boldsymbol{B}' = \boldsymbol{W}_1{}'\boldsymbol{R} = (0.062,\ 0.314,\ 0.216,\ 0.265,\ 0.195)$$

According to the maximum membership degree principle, we know that the comprehensive evaluation matrix $\boldsymbol{B}'$ of Device 1 is $b_2 = \max\{b_1,\ b_2,\ b_3,\ b_4,\ b_5\} = 0.314$. The corresponding evaluation level is 'poor'. So the comprehensive performance evaluation result of Device 1 is 'poor'. The comprehensive performance evaluation result of Device 2 is 'qualified' following the above way.

By comparing the objective operation of the two devices, it is obvious that the performance of Device 1 is superior to the performance of Device 2. Therefore, the method presented in this paper is relatively practical.

6 Conclusion

Since China has just begun to develop ocean energy power generation technology, no testing site for the experiment, test and evaluation of wave or tidal current power generation devices has been built yet. According to the project requirement of 'first stage construction of the comprehensive system of ocean testing site comprehensive test and evaluation', this paper gives performance indexes of tidal current power generation. On the basis of the fuzzy comprehensive evaluation model, it presents an improved method for rank correlation analysis to determine the index weight. The improved method for rank correlation analysis meets the allocation requirement of subjective and objective weights. It offers each expert rational valuation vector about the evaluation indexes, which ensures objective assignment of the index weights when the experts hold different opinions. The improved method for rank correlation analysis is suitable for computer analysis, and provides theory basis for subsequent implementation of the comprehensive testing and evaluation system.

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