Study on Comprehensive Evaluation of Energy Saving Index System in Pumped Storage Power Station Based on Vertical Scatter Degree Method

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Abstract—The paper establishes an energy efficiency index system of pumped storage power station, and designs a dynamic comprehensive evaluation algorithm of energy efficiency levels for pumped storage power station based on comprehensive objective and subjective weighting method, which uses the historical data and achieves a comprehensive evaluation of the energy levels for pumped storage power station in a multi-period. Firstly, the paper introduces the energy flow structure and the operation characteristics of pumped storage power station and establishes an energy efficiency index system, and then the synthesized weights of each index are determined by G1 method and vertical scatter degree method. This paper proposes to set the index observation method margin and uses linear projection method to process the quantitative indicators dimensionlessly, and uses expert grading method to quantify the qualitative indicators. Finally, the linear weighted sum of indexes values in the energy level at each period for the pumped storage power station is figured out. The performance of this model and the reasonableness of evaluation are verified by an application in the dynamic evaluation of a pumped storage power station.

Keywords-pumped storage power station; energy efficiency index system; comprehensive objective and subjective weighting method; dynamic evaluation

I. INTRODUCTION

Recently, with the popularity of ecological civilization, power grid companies pay more attention to green, recyclable and low carbon development. Also, energy saving evaluation of power station and transformer substation draws more and more attention from people [1,2]. By far, both domestic and foreign studies focus on the external benefits of pumped storage station, while the study of energy saving evaluation to pumped storage station itself still on primary stage, which indicates the importance of this paper. Pumped Storage Power Station is responsible for exchanging peak load to fill valley load, Frequency and phase adjustment, emergency reserve and other special functions. The level of energy efficiency is directly related to the necessity of construction and the greening level of pumped storage power station. Therefore establishing an energy efficiency index system of pumped storage power station to evaluate comprehensively is of great significance for improving the comprehensive energy efficiency of pumped storage power plant and the awareness of energy saving.

Principle component analysis, fuzzy comprehensive evaluation are the common comprehensive evaluation methods, however, most of these methods are static, which only evaluate a certain period of power stations and dynamic information can't be used in the evaluation process. Compared with the traditional evaluation methods, dynamic evaluation can reflect the present and historical comprehensive energy levels, but the determination of weight coefficient will be the core problem of these methods. Subjective weight determination and objective weight determination are two main weight determination ways. Analytic hierarchy process (AHP), which belongs to the former one, can present valuator's knowledge structure and experience. However, constructing judgment matrix and consistency check leads to a large calculation quantity; G1-method is the improvement of AHP, can reduce calculation quantity as well as reflect expert's experience. Doubly weighting method, one of objective weight determination methods, can evaluate after uniting data from different period, which make no comparability between evaluation values in different periods; Other objective weight determination methods like vertical scatter degree method, will show the difference between evaluation objects. And this method only needs one determination operation so that evaluation values in different time can be compared[3].

A dynamic comprehensive evaluation algorithm of energy levels for pumped storage power station is designed in this paper based on vertical scatter degree method. The algorithm firstly establishes weight by G1-method and scatter degree method. Then the paper evaluates energy efficiency by linear weighted comprehensive assessment method based on one-year data of a pumped storage station, to prove the reasonability and efficiency of the algorithm.

II. CONSTRUCTION AND SELECTION OF INDEX SYSTEM

When index system being constructed, multi-factor feature, integrality and scientificity should be presented [4,5]. So considered the operation characteristic and energy loss structure, evaluation of pumped storage station can given from technical energy saving, management energy saving and comprehensive energy saving benefit. Raising comprehensive energy efficiency level, lowering comprehensive plant power consumption rate belong to technical energy saving. And management energy saving mainly contains precision of plant power consumption measurement and evaluation effort of energy consumption management, while coal saving benefit will be considered in comprehensive energy saving benefit. As a result, energy efficiency index system in this paper is shown in table 1.

TABLE I.   ENERGY EFFICIENCY INDEX SYSTEM

goal	symbol	First grade indexes	symbol	Second grade indexes	symbol
Energy efficiency index	Z	Comprehensive efficiency	Y1	Power generation quantity by natural inflow series	X1
				Water consumption of power generation	X2
				Power consumption of pumping	X3
				Comprehensive waterway head loss rate	X4
				Reservoir evaporation and leakage rate	X5
				Waterway leakage rate	X6
		Comprehensive plant power consumption rate	Y2	Direct plant power consumption rate	X7
				Power consumption rate of office and living quarter	X8
				Power consumption rate of other devices	X9
		Energy consumption management indexes	Y3	Precision of plant power consumption measurement	X10
				Evaluation effort of energy consumption management	X11
		Comprehensive energy saving benefit	Y4	Coal saving benefit	X12

III.   ALGORITHM DESIGN

Multi-objective Before design, all the evaluation parameters should be set. Assuming that there are N time intervals, constituting a time interval set, and two layers of indexes contained in the evaluation indexes. One is first grade indexes layer, the other is second grade indexes layer , and the overall goal layer Z. the value of index during is , the weight is .

Not only the sequence of evaluation in different time intervals can be acquired from the calculation results, but also the value of overall goal Z, which will reflect the extent of energy saving in a certain month. A fuzzy evaluation set of energy saving extent is defined, and a relative evaluation value set.

Procedure of algorithm in this paper:

a) Preprocessing of indexes. Unification and nondimensionalization of all the indexes.

b) Determining weight of second grade indexes. Progressed scatter degree method is used to calculate the weight of second grade indexes.

c) Obtaining evaluation value of first grade indexes. Using linear weighting method to obtain evaluation value of first grade indexes.

d) Determining weight of first grade indexes. Progressed scatter degree method is also used to calculate the weight of first grade indexes.

e) Based on linear weighting method to calculate evaluation value of energy saving level in different period, in order to get final dynamic evaluation value as well as analyze the develop trend and fluctuation of energy saving circumstance.

f) Judging the green degree and energy saving level of pumped storage station in a certain month on the basis of final evaluation value. In the meanwhile, analyzing the influence factors and improvements of evaluation results to guide energy saving project in the next month.

A.   Preprocessing of Indexes

1)   Nondimensionalization of quantitative indexes.

Considering the possibility of insufficient covering range and lack of data, a method to set index margin is raised. Simultaneously, nondimensionalize indexes with linear projection method, which is the observed value being projected to standard data area linearly and equally on the condition of leaving a certain margin. The data area in this paper is (50,100).

There are two types of indexes in the evaluation system, benefit type and cost type. In table 1, X1, X10, X11, X12 are all benefit type indexes, the remaining ones are cost type. Thus, all quantitative indexes can be transformed to data which locate in the area of 50 to 100 by using linear projection method[6].

$$a_{k,j}^* = k a_{k,j} + b \qquad (1)$$

The benefit indexes $a_{k,j}^* = \begin{cases} 50, & a_{k,j} = m_j \\ 100, & a_{k,j} = M_j \end{cases}$, so

$$a_{k,j}^* = 100 \times \frac{0.5 a_{k,j} + 0.5 M_j - m_j}{M_j - m_j} \qquad (2)$$

The cost indexes $a_{k,j}^* = \begin{cases} 50, & a_{k,j} = M_j \\ 100, & a_{k,j} = m_j \end{cases}$, so

$$a_{k,j}^* = 100 \times \frac{M_j - 0.5 m_j - 0.5 a_{k,j}}{M_j - m_j} \qquad (3)$$

In formula, $a_{k,j}^*$ is the observed data after process; M_j, m_j are the max and min in the data area respectively. M_j, m_j can be calculated with formula below, in which, Δm is the increment of extremum, s is the object number been evaluated.

$$\begin{cases} M_j = \max_k \{a_{k,j}\} + \Delta m \\ m_j = \begin{cases} \min_k \{a_{k,j}\} - \Delta m, & \min_k \{a_{k,j}\} > \Delta m \\ 0, & \min_k \{a_{k,j}\} \le \Delta m \end{cases} \\ \Delta m = \dfrac{\max_k \{a_{k,j}\} - \min_k \{a_{k,j}\}}{s-1} \end{cases} \quad (4)$$

2) Quantification of qualitative index.

Expert grading method is the common way to quantify qualitative indexes. Traditionally, qualitative indexes will be evaluated by an evaluation set, like "Excellent, Good, Average, Bad" and so on. Experts can determine the quantification value according to the corresponding evaluation set.

B. Calculation of Index Weight

1) G1-Method.

G1-method is a progressed subjective weight determination method based on AHP. Because of no need to construct judgment matrix and check consistency, a lot of calculation is decreased. Therefore, it's a method suitable for large sample capacity, especially when it's hard to quantify totally[3].

2) Vertical Scatter Degree Method.

Vertical scatter degree method can reflect the difference between evaluation objects as a whole. So the principle to determine weight of this method is to reflect differences between objects as much as possible [7,8]. Assume that evaluation objects are expressed with $O_i (i=1,2,...,p)$, discrete time points are express as $\{t_k\}(k=1,2,...,N)$. Moreover, the j index value of object O_i in time t_k is $x_{ij}(t_k)$. So $\{x_{ij}(t_k)\}$ is a time serial multidimensional data table. The problem supported by it can be show like $y_i(t_k) = f(\omega_1(t_k),...,\omega_m(t_k); x_{i1}(t_k),...,x_{im}(t_k))$, in the expression, m is index evaluation number, $y_i(t_k)$ is evaluation value of O_i at time t_k. Here, an assumption is made that $\{x_{ij}(t_k)\}$ is maximal index data after nondimensionalization. Accordingly, the comprehensive evaluation function at time t_k is shown below.

$$y_i(t_k) = \sum_{j=1}^{m} \omega_j x_{ij}(t_k)(k=1,2,\cdots,N; i=1,2,\cdots,p) \quad (5)$$

The difference between evaluation object is expressed as function (6), so the weight coefficient $\omega_j (j=1,2,...,m)$ can be got by its principle which mentioned earlier.

$$\sigma^2 = \sum_{k=1}^{N}\sum_{i=1}^{P}(y_i(t_k) - \overline{y})^2 = \omega^T \sum_{k=1}^{N} H_k \omega = \omega^T H \omega \quad (6)$$

In the expression, $\omega = (\omega_1, \omega_2, ..., \omega_m)^T$; $H = \sum_{k=1}^{N} H_k$ is an symmetric matrix; $H_k = A_k^T A_k (k=1,2,...,N)$ and

$$A_k = \begin{bmatrix} x_{11}(t_k) & \cdots & x_{1m}(t_k) \\ \cdots & & \cdots \\ x_{P1}(t_k) & \cdots & x_{Pm}(t_k) \end{bmatrix} (k=1,2,...,N) \quad (7)$$

If define $\omega^T \cdot \omega = 1$, when ω become the eigenvector corresponding to maximum eigenvalue $\lambda_{max}(H)$ of matrix H, σ^2 will be max, also, $\max \omega^T H \omega = \lambda_{max}(H)$. When $H_k > 0$, there must be $H > 0$, and the weight coefficient vector is positive. Therefore, the normalized eigenvector corresponding to $\lambda_{max}(H)$ is the calculated weight vector ω.

3) Calculation of index weight.

According to the advantages of subjective and objective analysis, a comprehensive weight determine method which combine the both advantages is come up with in this paper. Considering the subjective weight value w^1 and objective weight value w^2, comprehensive weight value is defined as $w = (w_1, w_2, \cdots, w_m)^T$ [9], thus

$$w_j = \frac{w_j^1 w_j^2}{\sum_{i=1}^{m} w_j^1 w_j^2}, \quad j=1,2,\cdots,m \quad (8)$$

C. Calculation of First Grade Indexes Evaluation Value

With the result of second grade indexes weight value and processing value, first grade indexes value can be calculated by formula (9) using linear weighting method.

$$Y_i^k = \sum_{j=1}^{m} w_j^{(2)} a_{k,j}, \quad i=1,2,\cdots,m_1; \quad k=1,2,\cdots,N \quad (9)$$

Y_i^k is the evaluation value of second grade index Y_i at time t_k; $w_j^{(2)}$ is weight value of second grade index.

D. Calculation of Evaluation Value During Every Time Interval

Weight value of first grade index is $w_i^{(1)} (i=1,2,\cdots,m_1)$, so get the overall goal function (10) with first grade evaluation result Y_i^k.

$$Z^{(k)} = \sum_{i=1}^{m_1} w_i^{(1)} Y_i^k, \quad k = 1, 2, \cdots, N \qquad (10)$$

$Z^{(k)}$ is the overall goal evaluation value of time interval k.

IV. CASE ANALYSIS

Based on the actual data of 12 months in 2013 of one pumped storage station, the paper evaluates energy saving level of the station and analyzes the result with the method designed in this paper.

A. Calculation of Case Data

According to the data of the pumped storage station, firstly, qualitative indexes X10, X11 are transformed to quantitative value, then nondimensionalized by the method mentioned earlier. The result is shown in table 2.

TABLE II. NONDIMENSIONALIZATION VALUE OF INDEXES

Mo-nth	X1 (10MWh)	X2 (m³/kWh)	X3 (kWh/m³)	X4 (%)	X5 (%)	X6 (%)	X7 (%)	X8 (%)	X9 (%)	X10	X11	X12 (10kt)
1	50.279	61.794	70.968	61.53	75.36	88.16	77.30	77.49	86.35	66.67	73.34	66.647
2	50.474	62.850	91.833	53.85	85.17	72.23	75.13	91.60	96.15	66.67	74.17	76.458
3	54.298	53.846	53.846	66.84	85.03	89.66	53.85	72.37	63.71	68.34	75.00	53.497
4	58.472	93.013	84.731	72.39	91.49	75.35	63.36	82.96	87.38	69.17	75.84	61.491
5	68.733	59.344	96.154	57.26	96.15	96.15	65.95	78.35	91.35	70.00	76.67	59.856
6	68.102	80.526	86.383	73.96	74.52	61.05	58.01	54.60	73.38	70.84	76.67	73.846
7	71.854	96.154	54.178	79.38	76.30	58.27	60.15	53.85	53.85	70.84	77.50	68.509
8	95.857	59.441	79.799	80.17	68.14	53.85	79.32	74.65	88.39	72.50	77.50	96.125
9	67.928	80.076	63.368	68.29	63.21	72.11	85.48	89.84	81.45	73.34	79.17	92.491
10	51.948	75.720	75.096	73.89	53.85	78.37	80.29	89.27	79.14	74.17	80.00	89.221
11	52.553	79.722	82.864	92.80	70.85	64.53	89.22	95.79	87.04	75.84	80.00	91.446
12	54.598	79.722	82.864	96.15	76.97	68.57	96.15	96.15	73.81	75.84	80.84	74.323

According to the energy flow and operation characteristic of the pumped storage station, the order relation between indexes can be settled, which is comprehensive waterway head loss rate >water consumption of power generation > power consumption of pumping >power generation quantity by natural inflow series> reservoir evaporation and leakage rate > waterway leakage rate; Direct plant power consumption rate > power consumption rate of other devices > power consumption rate of office and living quarter; Comprehensive energy saving benefit > comprehensive plant power consumption rate > comprehensive efficiency > energy consumption management indexes. Then the subjective weight of all indexes can be determined by G1-method. What's more, the precision of plant power consumption measurement and evaluation effort of energy consumption management have the same weight 0.5 because of the equivalent importance. In the next, objective weight shall be determined by vertical scatter degree method, which is shown in table 3.

The results of comprehensive evaluation can be obtained by weighted aggregation method according to the nondimensionalization value and the weight value of indexes, which are shown in table 4 and figure 1.

TABLE III. INDEXES WEIGHT VALUE

First grade indexes	Subjective weight	Objective weight	Comprehensive weight	Second grade indexes	Subjective weight	Objective weight	Comprehensive weight
Y1	0.2177	0.2411	0.2091	X1	0.1666	0.1425	0.1425
				X2	0.2000	0.1691	0.2029
				X3	0.2000	0.1771	0.2125
				X4	0.2400	0.1678	0.2416
				X5	0.1190	0.1759	0.1257
				X6	0.0744	0.1676	0.0748
Y2	0.2612	0.2603	0.2708	X7	0.3956	0.3158	0.3767
				X8	0.2747	0.3424	0.2836
				X9	0.3297	0.3418	0.3398
Y3	0.1554	0.2463	0.1526	X10	0.5000	0.4798	0.4798
				X11	0.5000	0.5202	0.5202
Y4	0.3657	0.2523	0.3675	X12	1	1	1

TABLE IV. THE RESULTS OF COMPREHENSIVE EVALUATION

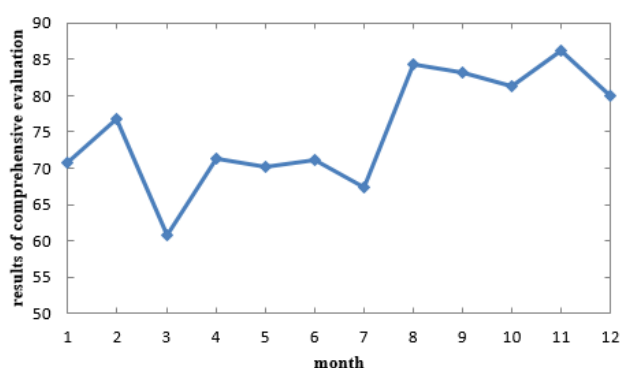| Month of 2013	Comprehensive efficiency	Comprehensive plant power consumption rate	Energy consumption management	Comprehensive energy saving benefit	Energy efficiency	Sequence
1	65.71	80.44	70.13	66.65	70.72	9
2	68.58	86.95	70.57	76.46	76.75	6
3	63.65	62.46	71.80	53.50	60.84	12
4	79.84	77.09	72.63	61.49	71.25	7
5	75.38	78.11	73.47	59.86	70.12	10
6	76.20	62.27	73.87	73.85	71.21	8
7	74.39	56.22	74.30	68.51	67.30	11
8	74.64	81.09	75.10	96.12	84.35	2
9	69.23	85.36	76.37	92.49	83.23	3
10	69.21	82.46	77.20	89.22	81.37	4
11	77.42	90.35	78.00	91.45	86.17	1
12	79.60	88.57	78.44	74.32	79.91	5

Figure.1 Drawing of the results of comprehensive evaluation

B. Result Analysis

a) The change of energy saving level is reflected by every months' evaluation value of the station. Looking from the whole year, the evaluation value is on the rise except March and July. However, the energy consumption indexes is increased by month, so the reason caused the two low energy saving level months can be analyzed from comprehensive energy saving benefit, comprehensive plant power consumption rate and comprehensive efficiency. After investigation, it turned out to be that the pumping power consumption and generation quantity was very little in March, but the power consumption of plant, office and living quarter didn't decrease, which made the increase of comprehensive efficiency and comprehensive plant power consumption rate, also lowered the energy saving level. While in July, due to the high temperature, power consumption of air conditions as well as of office and living quarter raised rapidly, leading to the increase of comprehensive plant power consumption rate and drop of energy saving level. Thus, the mode of operation should be optimized in order to reduce waterway loss. Also raise energy conversion efficiency by letting generator set work at high efficiency area. In the meanwhile, the plant power consumption management should be reinforced with optimizing ventilation, air condition and lighting system

operation mode, and reducing plant power consumption by means of technical reform. At last, strengthen power consumption management in office and living quarter to improve energy saving awareness.

b) Energy saving level of pumped storage station is not only embodied in comprehensive efficiency or comprehensive plant power consumption rate, but also related to energy saving function to power grid. The evaluation results of August and September show that despite of the low efficiency of station itself, the energy saving still remains in a high level because of the strong energy saving effect to power grid.

c) All comprehensive evaluation value locates 60 to 87, which means the energy saving level is low, common or high judging from the fuzzy evaluation set. So there is a large space of energy saving to improve, and the energy saving potential should be exploited to increase energy efficiency level, to make the station more green and energy-saving.

V. CONCLUSIONS

Based on the energy flow and operation characteristic, an energy saving index system of pumped storage power station is built. In the meantime, the paper approaches comprehensive evaluation to the index system by comprehensive weight method and relevant index preprocessing methods. The construction of the index system makes it possible to analyze the factors affect energy saving level from different aspects. Through evaluation, station's energy saving situation can be grasped dynamically, which means a lot to analyze station dynamic property, enhance energy saving level, exploit potentialities and achieve green station. Compared with the existing evaluation methods, the method designed in this paper comprehensively considered the subjective and objective effects to weight so as to make the weight process more reasonable. In the same time, linear projection and expert arranges method are applied to quantitative indexes and qualitative indexes respectively and the result reflects energy saving extent directly, which make the final evaluation result reasonable and direct. After comparison of evaluation value during every period of time, energy saving level trend can be got precisely so that will help to guide station's operation during the next period. Through case verification and analysis, the algorithm designed in this paper has excellent dynamic evaluation performance and the comprehensive evaluation value can directly reflect station's energy saving level.

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