A Comprehensive Value Evaluation Model of Energy Storage in Frequency Modulation Market Based on Matter-Element Extension Theory

Su Yibo(✉), Jia Na, Zhou Xuyan, Wang Penglei, Wang Lin, and Yue Bo

Institute of Science and Technology, China Three Gorges Corporation, Beijing, China
1503113774@qq.com, {Ja_na,zhou_xuyan,wang_penglei,wang_lin18,
yue_bo}@ctg.com.cn

Abstract. With the "double carbon" goal proposed, the application of renewable energy with clean and low-carbon characteristics in the power grid has been paid more and more attention. Firstly, the value evaluation system of independent energy storage participating in frequency modulation is proposed for compressed air energy storage, lithium iron phosphate battery energy storage and all-vanadium flow battery energy storage. Secondly, the proposed value evaluation system is designed based on the least square method to assign weights to subjective and objective indicators, which is more objective and reasonable. After that, the matter-element extension theory is used to evaluate the proposed index system. By establishing the correlation between "pollutant reduction" and "renewable energy consumption contribution" and other indicators, this paper obtains the comprehensive value of independent energy storage participating in the frequency modulation market from multiple perspectives. Finally, according to the actual operation data of Mengxi power grid, the results show that the method can accurately measure the value of independent energy storage participation in frequency modulation, and can accurately measure the advantages and disadvantages of various types of energy storage participation in frequency modulation market indicators.

Keywords: Energy storage system · Frequency Modulation market · Comprehensive evaluation · Matter-element extension theory

1 Introduction

Aiming at the participation of energy storage system in frequency modulation of power grid, literature [1] studies the participation of battery energy storage in secondary frequency modulation of power grid, proposes a control strategy of secondary frequency modulation of power grid and verifies its feasibility. Literature [2] describes the randomness of frequency modulation demand of hybrid energy storage through Markov chain, and proposes a stochastic model predictive control method for effective energy management of hybrid energy storage. Literature [3] proposes a dynamic proportional

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AGC signal allocation control strategy to enhance the influence of rapid response of battery energy storage system on the basis of guaranteeing the performance of AGC. Literature [4] establishes an optimization model with the goal of improving the economy of energy storage participating in frequency modulation, and realizes the power control between energy storage with different media according to the state of energy storage charge. Literature [5] studies the control strategy of battery energy storage participating in primary frequency modulation of power system on the basis of considering the charging and discharging efficiency of energy storage.

In terms of the evaluation of energy storage participation in frequency modulation, literature [6] established an energy storage evaluation index including development trend and market state. Literature [7] proposed an evaluation method based on improved weight factors to evaluate the regulation performance of combined fire storage frequency modulation. Literature [8] established an evaluation model including energy storage technology, economic and social indicators based on multi-criteria decision model, and sorted the performance of energy storage system considering investors' risk preference. Literature [9] established the efficiency evaluation index system of battery energy storage participating in frequency modulation, and selected load tracking rate, contribution electricity and frequency modulation comprehensive deviation for efficiency comparative analysis. Literature [10] considered the cost, benefit and performance of frequency modulation, and established a comprehensive evaluation system of energy storage's participation in frequency modulation performance.

The existing research only analyzes the mode and performance of energy storage power stations participating in frequency modulation, and cannot comprehensively reflect the advantages of different energy storage in many aspects. Therefore, this paper proposes a comprehensive evaluation method of independent energy storage participation in FM market from multiple perspectives. Based on the characteristic advantages of independent energy storage power stations, the subjective and objective evaluation index weighting method is adopted, and the correlation between "unit footprint" and "contribution degree of renewable energy consumption" is established to obtain the comprehensive value of independent energy storage participating in the FM market from multiple perspectives. According to the actual operation data of Mengxi Power Grid, the advantages and disadvantages of compressed air energy storage, lithium iron phosphate battery energy storage and vanadium flow battery energy storage in economic, technical and environmental protection indicators were calculated.

2 Construction of Comprehensive Value Evaluation Index System

In order to improve the regulation ability of the system, a comprehensive evaluation method of independent energy storage participating in FM market by self-scheduling mode was proposed, taking the transaction mechanism of independent energy storage participating in FM market as the research object. The simulation operation data show that the participation of energy storage devices in the FM market plays an important role in promoting the consumption of new energy and enhancing the power supply guarantee ability. Based on this, this paper constructs an evaluation index system of independent energy storage participating in the FM market based on three first-level indicators, namely economy, technology and environmental protection, among which there are 14 second-level indicators, as shown in Table 1.

Among the above indicators, the levelling energy storage costs includes power loss, operation and maintenance cost, installed cost and lifetime cycle number; Frequency-modulation compensation rate of return represents the ratio of total income and total investment of an independent energy storage station participating in frequency-modulation during its whole life cycle; Generally speaking, the faster the adjustment speed, the less time required to reach the specified power adjustment, the faster the frequency regression speed of the system, representing the better the adjustment performance of the energy storage station; The smaller the adjustment accuracy difference, the better the performance; The smaller the response time, the better the response performance. At present, most auxiliary service markets usually set a standard adjustment time, and reflect the response time performance indicators of energy storage power stations through the ratio of the actual adjustment time to the standard adjustment time and reverse processing; Frequency modulation duration represents the discharge time of the energy storage station participating in the system frequency modulation; Failure rate represents the probability of accidents occurring in the annual operation time of the energy storage power station; Due to the increase of environmental protection pressure, it is more difficult to acquire land for power grid construction. The unit area of energy storage power station is the ratio of the area of energy storage power station to the rated energy.

Table 1. Index system of energy storage participating in frequency modulation evaluation

First-order index	**Secondary index**
A1 Economic index	A11 Levelling energy storage costs
	A12 Dynamic payback period
	A13 FM yield
B1 Technical indicators	B11 Adjust the speed
	B12 Adjustment accuracy
	B13 Response time
	B14 Energy storage loss rate of power station
	B15 Energy conversion efficiency of charging and discharging
	B16 FM duration
	B17 Failure rate
C1 Environmental protection index	C11 Floor area per unit
	C12 Carbon dioxide emission reduction
	C13 Contribution to renewable energy consumption
	C14 Benefits of pollutant reduction

3 Comprehensive Evaluation Model

3.1 Improved Analytic Hierarchy Process

The specific calculation process of the improved analytic hierarchy process is as follows:

Construct a judgment matrix.

First, experts use the proportional scale method to score the relative importance of the indicators successively, and construct a judgment matrix $R = \left(r_{ij}\right)_{n*n}$, where r_{ij} represents the relative importance of the given object to be described, and then compare the importance between r_i and r_j, $r_{ij} \geq 0$, $r_{ij} = 1/r_{ji}(i, j = 1, 2, \ldots, m)$.

The judgment matrix is transformed into a measure matrix.

$$p_{ij} = \begin{cases} \frac{l}{l+1}, & r_{ij} = l \\ \frac{1}{l+1}, & r_{ij} = 1/l \\ 0.5, & r_{ij} = 1, i \neq j \\ 0, & r_{ij} = 1, i = j \end{cases} \tag{1}$$

Thus, the comparison measure matrix $P = \left(p_{ij}\right)_{m*m}$ is obtained.

Calculated weight.

$$Z = \frac{2}{m(m-1)} \sum_{j=1}^{m} r_{ij}, (i = 1, 2, \ldots, m) \tag{2}$$

So we get the weight vector $Z = (z_1, z_2, \ldots, z_m)$.

3.2 Objective Evaluation Index Weighting Based on Entropy Weight Method

Assuming that there are X evaluation objects and I evaluation indicators, the steps to determine the weights by using entropy weight method are as follows:

Deterministic evaluation matrix.

According to the original data, the evaluation matrix $P = (p_{xi})_{X \times I}$, r_{xi} is determined as the value of the ith index of the XTH evaluation object. Among them, $x = 1, 2, \ldots, X$; $i = 1, 2, \ldots, I$. The matrix form is as follows:

$$P = \begin{pmatrix} p_{11} & \cdots & p_{1I} \\ \vdots & \ddots & \vdots \\ p_{X1} & \cdots & p_{XI} \end{pmatrix} \tag{3}$$

Index standardization.

The elimination index has different reduction, so the evaluation matrix is consistent and standardized, and the standardized matrix $S = (s_{xi})_{X \times I}$ is obtained. Indicators standardization methods are as follows:

$$s_{xi} = p_{xi} / \sum_{x=1}^{X} p_{xi} \tag{4}$$

Calculate the entropy of each evaluation index.

$$E_i = -\frac{\sum_{x=1}^{X} s_{xi} \text{In} s_{xi}}{\text{In} X} \tag{5}$$

When $s_{mi} = 0$, let's say $s_{xi}\text{In}s_{xi} = 0$.

Define the difference coefficient of the i-th evaluation index.

$$\alpha_i = 1 - E_i (i = 1, 2, \ldots, I) \tag{6}$$

The formula for calculating the entropy weight of the evaluation index.

$$R_i = \frac{\alpha_i}{\sum_{i=1}^{I} \alpha_i} (i = 1, 2, \ldots, I) \tag{7}$$

The entropy weight R_i is the amount of information contained in the indicator, and the larger the value, the more important and useful the indicator is.

3.3 Least Square Optimization Model

Suppose that the weights obtained by the subjective weighting method of the improved analytic Hierarchy process are as follows

$$Q = \left[Q_1, Q_2, \ldots, Q_K\right]^T \tag{8}$$

The weights obtained by using the objective weighting entropy weight method are as follows

$$S = [S_1, S_2, \ldots, S_K]^T \tag{9}$$

In order to consider the subjective experience preference and the authenticity of objective data information, and realize the unity of subjective and objective, the deviation between the final comprehensive weight and the subjective and objective weight should be as small as possible. To this end, the least square optimization model is established as follows. The established least squares decision model is shown in the following equation.

$$\begin{cases} \min H(W) = \sum_{m=1}^{M} \sum_{k=1}^{K} \left\{[(X_k - W_k)s_{mk}]^2 + [(V_k - W_k)s_{mk}]^2\right\} \\ \text{s.t.} \sum_{k=1}^{K} W_k = 1 \\ W_k \geq 0, k = 1, 2, \ldots, K \end{cases} \tag{10}$$

where: W_k is the comprehensive weight; Q_k is the subjective weight; S_k is the objective weight; s_{mk} indicates the indicator after standardization.

3.4 Matter-Element Extension Theory

Matter-element analysis is an important method to solve some complex and difficult problems, which cannot be successfully solved by conventional methods in some incompatible problems, and it combines qualitative and quantitative problems of analysis. "Object, feature and magnitude" is the central idea of matter-element extension theory, which takes these three elements as the basic analysis element to study the relationship between their changes. Matter-element is the basis of this theory. Every evaluation index is equivalent to matter-element, and the change of index can be clearly shown through the change of matter-element, which is convenient and intuitive. This change process is the extension of matter-element.

Matter-element is a triplet, its basic composition is the object to be evaluated, the characteristics of the object to be evaluated and the specific value of each characteristic of the object to be evaluated. Assuming that there are multiple characteristics of a certain object to be evaluated N, then the classical domain matter-element of N-dimension is:

$$R_j = \left(N, C, q_{ij}\right) = \begin{pmatrix} N_j & c_1 & q_{1j} \\ & c_2 & q_{2j} \\ & \vdots & \vdots \\ & c_n & q_{nj} \end{pmatrix} = \begin{pmatrix} N_j & c_1 & \left(g_{1j}, f_{1j}\right) \\ & c_2 & \left(g_{2j}, f_{2j}\right) \\ & \vdots & \vdots \\ & c_n & \left(g_{nj}, f_{nj}\right) \end{pmatrix} \tag{11}$$

In the formula, q_{ij} is the value range of index c_i at the JTH level, namely the upper and lower limits (g_{ij}, f_{ij}).

Identify node matter element.

$$R_p = (T, C, q_{iP}) = \begin{pmatrix} T & c_1 & q_{1p} \\ & c_2 & q_{2p} \\ & \vdots & \vdots \\ & c_n & q_{np} \end{pmatrix} = \begin{pmatrix} T & c_1 & \left(g_{1p}, f_{1p}\right) \\ & c_2 & \left(g_{2p}, f_{2p}\right) \\ & \vdots & \vdots \\ & c_n & \left(g_{np}, f_{np}\right) \end{pmatrix} \tag{12}$$

where: T is the range of all levels of the matter element to be evaluated; q_{ip} was the value range of index c_i, and the upper and lower limits of all grades of c_i (g_{ij}, f_{ij}).

Determine the indicator domain to be evaluated.

$$R_0 = (T, C, Q) = \begin{pmatrix} T & c_1 & q_1 \\ & c_2 & q_2 \\ & \vdots & \vdots \\ & c_n & q_n \end{pmatrix} \tag{13}$$

where: T is the matter element to be evaluated; $q_1, q_2, \ldots, q_n$ refers to the specific data obtained from T_0's detection of $c_1, c_2, \ldots, c_n$.

Establish correlation function.

$$R_j\left(q_j\right) = \begin{cases} \frac{-\rho\left(q_i, q_{ij}\right)}{\left|E_{ij}\right|}, \left(e_i \in E_{ij}\right) \\ \frac{\rho\left(q_i, q_{ij}\right)}{\rho\left(q_i, q_{ip}\right) - \rho\left(q_i, q_{ij}\right)}, \left(e_i \notin E_{ij}\right) \end{cases} \tag{14}$$

$$\rho\left(q_i, q_{ip}\right) = \left|v_i - \frac{g_{ip} + f_{ip}}{2}\right| - \frac{1}{2}\left(g_{ip} - f_{ip}\right) \tag{15}$$

$$\rho\left(q_i, q_{ij}\right) = \left|q_i - \frac{g_{ij} + f_{ij}}{2}\right| - \frac{1}{2}\left(g_{ij} - f_{ij}\right) \tag{16}$$

where: $R_j\left(q_j\right)$ is the correlation function value between index i and grade j; $\rho\left(q_i, q_{ij}\right)$ is the distance between the matter-element value of index i to be evaluated and the classical domain; $\rho\left(q_i, q_{ip}\right)$ is the distance between the matter element value to be evaluated and the node domain of index i; $\left|E_{ij}\right|$ is the distance between index i and the classical domain of grade j.

Determine evaluation level.

Set the weight of evaluation index c_i as α_i, then the comprehensive correlation degree of the matter element T to be evaluated is:

$$R_j(T) = \sum_{i=1}^{n} \alpha_i R_j(q_i) \tag{17}$$

Calculate the grade evaluation eigenvalues.

$$\overline{R_j}(T) = \frac{R_j(T) - \min R_j(T)}{\max R_j(T) - \min R_j(T)} \tag{18}$$

$$k^* = \frac{\sum_{j=1}^{m} j \cdot \overline{R_j}(T)}{\sum_{j=1}^{m} \overline{R_j}(T)} \tag{19}$$

The grade evaluation characteristic value reflects the degree of deviation from the grade of the index.

4 Example Analysis

4.1 Index System Weight

The Mongolian region is an important clean energy base, which is rich in clean energy and has great potential for development. The comprehensive evaluation index system and model constructed in this paper are applied to three energy storage power stations A, B and C in this region to evaluate and rank their frequency modulation performance. There are three independent energy storage power stations A, B and C, of which A is a compressed air energy storage power station, B is a lithium iron phosphate battery energy storage power station, and C is a vanadium flow battery energy storage power station. The basic information of each power station is shown in Table 2.

According to the basic data of 3 independent energy storage power stations, the method described in this paper is applied to comprehensively evaluate them, and the results are compared and analyzed. The weights of the index system based on the combination of subjectivity and objectivity are shown in Table 3.

Table 2. Basic parameters of energy storage power station

Power station	A	B	C
Rated power /MW	100	100	100
Rated capacity /MWh	200	200	200
Annual cycle life/times	350	350	350
Operating life/year	30	12	25
Initial investment (Yuan /kW)	4500	7000	5000
Discharge time (h)	8	4	8
Charging and discharging efficiency	55	90	85

Table 3. Index system weight

First-order index	weight	Secondary index	weight
A1 Economic index	0.352	A11 Levelling energy storage costs	0.415
		A12 Dynamic payback period	0.283
		A13 FM yield	0.301
B1 Technical indicators	0.315	B11 Adjust the speed	0.106
		B12 Adjustment accuracy	0.125
		B13 Response time	0.178
		B14 Energy storage loss rate of power station	0.101
		B15 Energy conversion efficiency of charging and discharging	0.091
		B16 FM duration	0.153
		B17 Failure rate	0.246
C1 Environmental protection index	0.333	C11 Floor area per unit	0.252
		C12 Carbon dioxide emission reduction	0.170
		C13 Contribution to renewable energy consumption	0.317
		C14 Benefits of pollutant reduction	0.261

4.2 Comprehensive Evaluation by Matter-Element Extension Method

In this paper, the first-level index "economy" has three second-level indexes; "Technical" has 7 second-level indicators; The first-level indicator "environmental protection" has 4 second-level indicators, that is, a total of 14 evaluation characteristics. According to its characteristics, the evaluation level is divided into four levels: "excellent", "good",

Table 4. Index evaluation of independent energy storage power station

Secondary index	Excellent (Y1)	Good (Y2)	Middle (Y3)	Difference (Y4)	Yp
A11 (yuan /kWh)	0–0.25	0.25–0.50	0.50–0.75	0.75–1.00	0–1
A12 (year)	0–5	5–10	10–15	15–20	0–20
A13	10–15	5–10	10–5	-5–0	-5–15
B11(s)	0–0.25	0.25–0.5	0.5–0.75	0.75–1	0–1
B12(s)	0–0.25	0.25–0.5	0.5–0.75	0.75–1	0.5–1
B13(s)	0–0.25	0.25–0.5	0.5–0.75	0.75–1	0.5–1
B14	0–25	25–50	50–75	75–100	0–100
B15	75–100	50–75	25–50	0–25	0–100
B16(h)	6–8	4–6	2–4	0–2	0–8
B17	0–5	5–10	10–15	15–20	0–20
C11(m^2/MWh)	0–25	25–50	50–75	75–100	0–100
C12(t)	135–180	90–135	45–90	0–45	0–180
C13	15–20	10–15	5–10	0–5	0–20
C14 (ten thousand Yuan)	750–1000	500–750	250–500	0–250	0–1000

"middle" and "poor", namely, four evaluation matter elements Q = (Q1, Q2, Q3, Q4). At the same time, the classical matter-element matrix Y1, Y2, Y3, Y4 and section domain interval Yp are obtained by referring to relevant standards and literature, as shown in Table 4.

4.3 Result Analysis

According to Eqs. (14) and (19), all the primary and secondary indexes of power station B and the overall evaluation results of the power station are obtained. The correlation degree of independent energy storage station B is 0.111, which indicates that the evaluation grade of the power station is "excellent", indicating that most of the indexes have reached the expected goals. In terms of the first level indicators, the final evaluation is "excellent", indicating that the three first level indicators of the power station not only have excellent performance, but also relatively balanced performance. In terms of secondary indicators, there are 7 indicators of "excellent" evaluation grade and 6 indicators of "good" evaluation grade. In particular, the contribution rate of new energy consumption promoted by environmental protection has reached "excellent", which just meets the national "two-carbon" policy. This indicates that station B is an ideal independent energy storage station. As above, the evaluation results of first-level indicators and overall indicators of three independent energy storage power stations A, B and C are obtained respectively, as shown in Table 5.

Table 5. Index evaluation results of independent energy storage power station

Evaluation index		**Excellent (Y1)**	**Good (Y2)**	**Middle (Y3)**	**Difference (Y4)**	**j***	**grade**
Power station A	A1 Economic index	-0.107	0.039	-0.298	-0.538	1.904	good
	B1 Technical indicators	-0.349	-0.034	0.007	-0.365	2.897	Middle
	C1 Environmental protection index	-0.324	-0.043	0.134	-0.379	2.749	Middle
	population	-0.259	0.050	-0.112	-0.428	2.762	Middle
Power station B	A1 Economic index	0.069	-0.483	-0.035	-0.633	3.289	Excellent
	B1 Technical indicators	0.180	-0.659	-0.447	-0.756	3.269	Excellent
	C1 Environmental protection index	0.090	-0.519	-0.038	-0.679	3.628	Excellent
	population	0.111	-0.550	-0.162	-0.687	3.391	Excellent
Power station C	A1 Economic index	-0.523	0.029	-0.292	-0.206	3.155	Excellent
	B1 Technical indicators	-0.486	0.007	-0.241	-0.168	3.287	good
	C1 Environmental protection index	-0.585	0.092	-0.378	-0.161	3.283	good
	population	-0.534	0.045	-0.307	-0.178	3.269	good

Table 5 shows the horizontal comparison results of the three power stations. Through the evaluation and analysis of the economic, technical and environmental indicators, it can be seen that the scores from high to low are lithium iron phosphate battery power station, all-vanadium flow battery energy storage station and compressed air energy storage station. By comparing the comprehensive evaluation result with the horizontal score of the established evaluation grade, it can be concluded that the evaluation grade of the lithium iron phosphate battery power station is excellent, and the performance is the best. The all-vanadium flow battery energy storage power station is good, and the evaluation grade of the three aspects is “good”. The power station is similar to the power station B, with balanced performance and “good”. It needs to strive to reach the level of the power station B in terms of economy, technology and environmental protection.

The compressed air energy storage station is medium, and only reaches “good” in terms of economy, while the other two indicators are only “medium”. This power station has the worst performance among the three power stations, so it needs to give full play to its advantages and try to improve its various capabilities.

5 Conclusion

In this paper, a total of 14 indicators are selected as the comprehensive evaluation index system from the three aspects of economy, technology and environmental protection of independent energy storage power stations participating in frequency modulation. The introduction of environmental protection indicators makes the comprehensive evaluation system more practical and objective. In this paper, a subjective and objective evaluation index weighting - mature-element extension theory method is proposed to evaluate the comprehensive value of independent energy storage power stations participating in FM market, which makes the comprehensive evaluation system more objective and fair. In the selection of indicator weights, the method of combining subjective and objective is adopted to make the selection of weights more reasonable and effective. The final result of the comprehensive evaluation index system accords with the understanding of the power station, indicating that the model established in this paper has good evaluation performance, and the evaluation results can reflect the strength of the power station in terms of technology, economy and environmental protection, and can make targeted improvements to the weak points of the power station, which has reference value for the development of the power station. Moreover, this paper quantifies the technical and environmental effects of independent energy storage power stations, which can provide support for the comprehensive evaluation of independent energy storage under the dual-carbon background.

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