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A credit-based incentive mechanism for electrolytic aluminum enterprise participation in electricity market demand response [#]

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ABSTRACT

With the growth of renewable energy installed capacity, power systems urgently require flexible resources to participate in demand response, and electrolytic aluminum enterprises possess excellent load regulation potential. However, traditional demand response mechanisms suffer from poor execution effectiveness and singular incentives, making it difficult to fully mobilize enterprise participation enthusiasm. This paper establishes a comprehensive decision-making model for electrolytic aluminum enterprise participation in electricity markets to provide demand response. First, a user credit evaluation model based on improved subscription performance indicators is proposed, and a subsidy mechanism combining credit incentives with segmented assessment is constructed, linking credit scores with subsidy prices to form positive incentives. Then, considering production stability, an electrolytic aluminum load model incorporating power, temperature, and daily production constraints is established. Finally, case study analysis demonstrates that after adopting the proposed method, the electrolytic aluminum enterprise's credit value increases by 22.3% and overall revenue grows by 24.6%, validating the effectiveness of the proposed model.

Keywords: electrolytic aluminum load; demand response； high energy-intensive industry; flexibility resource

NONMENCLATURE

Symbols	
X	credit score
P	power
t	time period
l	electrolytic cell series
T_{e}	temperature of electrolytic cell series
J	compensation price
γ_{SPI}	subscription performance indicator value
C_{et}	demand response participation revenue
E_{d}	Daily aluminum production
A	product revenue
f_m	operation and maintenance costs of various equipment
f_{i}	electricity purchase cost
B_{grid}	electricity purchase amount of the electrolytic aluminum enterprise
E_{es}	state of charge of the battery

1. INTRODUCTION

With the rapid growth of renewable energy generation capacity, the power system's demand for flexibility resources is increasingly growing [1]. High energy-intensive industrial loads, as an important component of electricity consumption, have enormous electricity demand and account for a continuously rising proportion of total social electricity consumption. High energy-intensive industries such as electrolytic aluminum have large single-unit installed capacity and high load density, possessing tremendous adjustable space and response potential [2]. Compared to traditional demand response resources, the response capacity of high energy-intensive loads can reach megawatt levels, serving as an important supplement to the power system's flexibility resources [3].

At present, several studies have investigated the adjustable potential of electrolytic aluminum loads. In the electrolytic aluminum production process, due to substantial electricity consumption, enterprises possess certain demand elasticity and can adjust production schedules according to market prices to reduce overall production costs. Reference [4] proposed a unit commitment model considering electrolytic aluminum enterprises providing demand response; Reference [5] utilized electrolytic aluminum loads as new peak-shaving resources, combining them with deep peak regulation of thermal power units for system dispatch optimization;

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Reference [6] proposed a method for electrolytic aluminum participation in grid frequency stability control considering static voltage stability constraints; Reference [7] analyzed the adjustable capacity of electrolytic aluminum loads by considering the electrothermal energy conversion principle of electrolytic cells.

However, existing demand response mechanisms suffer from problems such as poor execution effectiveness and singular incentive measures, making it difficult to fully mobilize the participation enthusiasm of electrolytic aluminum enterprises and constraining the effective utilization of demand response resources [8]. Furthermore, although high energy-intensive loads possess advantages of large response capacity and flexible regulation, existing research is mostly limited to technical feasibility analysis, lacking in-depth exploration of how to fully stimulate and utilize this enormous potential.

Against this background, this paper addresses the challenges of electrolytic aluminum enterprises participating in demand response by innovatively proposing a user credit evaluation model based on improved subscription performance indicators. The model evaluates the deviation between actual response quantities and contractually agreed quantities, combined with exponential smoothing methods to dynamically track enterprises' historical credit performance. The model fully considers the impact of production costs and electricity price fluctuations on enterprises' total revenue and demand response revenue, establishing a multi-dimensional economic assessment model that includes energy consumption costs, operational costs, and demand response participation benefits. Power, temperature, and daily production constraints are incorporated to ensure production stability and safety when enterprises participate in demand response.

2. MATHEMATICS MODEL

2.1 User credit evaluation model

To more accurately reflect the alignment between the actual response quantity provided by electrolytic aluminum enterprises in demand response and the contracted response quantity agreed upon with the grid company, this paper adopts the deviation between actual response quantity and contracted response quantity as the subscription performance indicator to evaluate the response execution performance of electrolytic aluminum enterprises.

$$\gamma_{\mathrm{SPI}} = 1 - \frac{\sum_{t=1}^{T_{\mathrm{N}}}\sum_{l=1}^{N_{\mathrm{ea}}} | P_l - P_{l,t} - P_{l,t,\mathrm{tar}} |}{\sum_{t=1}^{T_{\mathrm{N}}}\sum_{l=1}^{N_{\mathrm{ea}}} P_{l,t,\mathrm{tar}}} \tag{1}$$

Where: γ_{SPI} is the subscription performance indicator value; P_l is the baseline operating power of the electrolytic cells; $P_{l,t}$ is the actual operating power of electrolytic cell series l in the enterprise at time t; $P_{l,t,\mathrm{tar}}$ is the contracted power reduction amount between the electrolytic aluminum enterprise and the grid company for time period t; T_{N} is the total time scale; N_{ea} is the total number of electrolytic cell series.

To reflect long-term demand response performance, an exponential smoothing method is employed to construct a comprehensive credit evaluation mechanism that incorporates historical credit records into the assessment. Differentiated weights are applied to credit values from different rounds, with higher weights assigned to the current round to emphasize the latest performance.

$$X_t = \begin{cases} 100 r_1 \gamma_{\mathrm{SPI}} + (1 - r_1) X_{t-1}, \gamma_{\mathrm{SPI}} < \gamma_0 \\ 100 r_2 \gamma_{\mathrm{SPI}} + (1 - r_2) X_{t-1}, \gamma_{\mathrm{SPI}} \geq \gamma_0 \end{cases} \tag{2}$$

Where: X_t is the updated credit score for time period t; X_{t-1} is the credit score calculated in the previous time period; γ_0 is the baseline response grade; r_1 and r_2 are evaluation coefficients.

2.2 Enterprise revenue model for demand response participation

To promote continuous and efficient participation of electrolytic aluminum enterprises in demand response, the grid company has established a subsidy mechanism that combines incentive pricing with segmented assessment. The incentive pricing includes basic subsidies and credit incentive subsidies, achieving differentiated incentives. Meanwhile, a lenient segmented assessment mechanism is implemented to mitigate the impact of uncertainties on enterprises.

$$J = J_0 + \varepsilon X \tag{3}$$

$$P_{\mathrm{act}} = \sum_{t=1}^{T_{\mathrm{N}}}\sum_{l=1}^{N_{\mathrm{ea}}} (P_l - P_{l,t}) \tag{4}$$

$$P_{\mathrm{tars}} = \sum_{t=1}^{T_{\mathrm{N}}}\sum_{l=1}^{N_{\mathrm{ea}}} P_{l,t,\mathrm{tar}} \tag{5}$$

$$C_{et} = \begin{cases} 0 & P_{\text{act}} < 0.5P_{\text{tars}} \\ 0.8JP_{\text{tars}} & 0.5P_{\text{act}} \le P_{\text{tars}} < 0.5P_{\text{act}} \\ JP_{\text{tars}} & 0.8P_{\text{act}} \le P_{\text{tars}} < 0.5P_{\text{act}} \\ 0.24JP_{\text{act}} + 0.8JP_{\text{tars}} & 1.2P_{\text{act}} \le P_{\text{tars}} < 0.5P_{\text{act}} \\ 1.44JP_{\text{act}} & P_{\text{tars}} \ge 1.5P_{\text{act}} \end{cases} \tag{6}$$

Where: J is the compensation price for electrolytic aluminum enterprises providing demand response; P_{act} is the actual response quantity of the enterprise; P_{tars} is the contracted response quantity of the enterprise; C_{et} is the actual subsidy value obtained by the enterprise.

2.3 Electrolytic aluminum load model

1) Power model

$$\begin{cases} P_{l,\min} \le P_{l,t} \le P_{l,\max} \\ I_{l,\min} \le I_{l,t} \le I_{l,\max} \quad ,\forall l,t \\ P_{l,t} = I_{l,t}{}^2 R_{l,t} + I_{l,t}E_{l,t} \end{cases} \tag{7}$$

Where: $P_{l,\max}$ and $P_{l,\min}$ are the maximum and minimum values of electrolytic cell power, respectively; $R_{l,t}$ and $E_{l,t}$ are the equivalent resistance and electromotive force, respectively; $I_{l,t}$ is the current intensity supplied to electrolytic cell series.

2) Temperature model

$$\begin{cases} \left(P_{l,t} - P_{l,t-1}\right)\Delta t = cm\left(T_{\text{e},l,t} - T_{\text{e},l,t-1}\right) \\ T_{\text{e,min}} \le T_{\text{e},l,t} \le T_{\text{e,max}} \end{cases} ,\forall l,t \tag{8}$$

Where: $T_{\text{e},l,t}$ represents the temperature of electrolytic cell series; $T_{\text{e,max}}$ and $T_{\text{e,min}}$ are the upper and lower limits of electrolytic cell temperature; c is the specific heat capacity of the electrolyte; m is the mass of the electrolyte.

3) Daily aluminum production model

$$E_{\text{d,min}} \le \sum_{t=1}^{T_{\text{N}}} \sum_{l=1}^{N_{\text{ea}}} P_{l,t} \le E_{\text{d,max}} \tag{9}$$

Where: $E_{\text{d,min}}$ and $E_{\text{d,max}}$ represent the minimum and maximum values of daily energy consumption of the electrolytic aluminum enterprise, respectively.

2.4 Objective

This paper analyzes a specific electrolytic aluminum enterprise as an example, assuming that the enterprise is equipped with photovoltaic systems, wind turbines, and energy storage devices. Therefore, this paper takes the maximization of total revenue as the objective function, which consists of the electrolytic aluminum enterprise's product revenue $A_{l,t}$, demand response participation revenue C_{et}, electricity purchase cost f_i, and operation and maintenance costs of various equipment f_m:

$$\max f = \max(A_{l,t} + C_{et} - f_m - f_i) \tag{10}$$

$$A_{l,t} = \sum_{t=1}^{T_{\text{N}}} \sum_{l=1}^{N_{\text{ea}}} B_l P_{l,t} \tag{11}$$

$$f_{\text{m}} = \sum_{1}^{T_{\text{N}}} \begin{pmatrix} \alpha_{\text{WT}} P_{\text{WT},t} + \alpha_{\text{PV}} P_{\text{PV},t} \\ +\alpha_{\text{es}} \left| P_{\text{cha},t} + P_{\text{dis},t} \right| \end{pmatrix} \Delta t \tag{12}$$

$$f_{\text{i}} = \sum_{t=1}^{T_{\text{N}}} \left(\alpha_{\text{buy}} B_{\text{grid},t}\right) \Delta t \tag{13}$$

Where: B_l is the aluminum product production profit price coefficient for electrolytic cell series l; α_{WT} is the unit operation and maintenance cost of wind turbines; $P_{\text{WT},t}$ is the power generation of wind turbines at time t; α_{PV} is the unit operation and maintenance cost of photovoltaic units; $P_{\text{PV},t}$ is the power generation of photovoltaic units at time t; α_{es} is the unit operation and maintenance cost of batteries; $P_{\text{cha},t}$ and $P_{\text{dis},t}$ are the charging and discharging power of batteries at time t, respectively; α_{buy} is the unit electricity purchase price; $B_{\text{grid},t}$ is the electricity purchase amount of the electrolytic aluminum enterprise at time t.

2.5 Other Constraints

1) Electric Power Balance Constraint

$$\begin{aligned} & B_{\text{grid},t} + P_{\text{WT},t} + P_{\text{PV},t} + P_{\text{dis},t} \\ & = \sum_{l=1}^{N_{\text{ea}}} P_{l,t} + P_{\text{cha},t} \end{aligned} \tag{14}$$

2) Battery Operation Constraints

$$0 \le P_{\text{cha},t} \le P_{\text{es,max}} \times P_{\text{cha,sign}} \tag{15}$$

$$0 \le P_{\text{dis},t} \le P_{\text{es,max}} \times P_{\text{dis,sign}} \tag{16}$$

$$P_{\text{cha,sign}} + P_{\text{dis,sign}} = 1 \tag{17}$$

$$E_{\text{es},t} = E_{\text{es},t-1} + \Delta t\left(\eta_{\text{cha}} P_{\text{cha},t} - P_{\text{dis},t} / \eta_{\text{dis}}\right) \tag{18}$$

$$E_{\min} \le E_{\text{es},t} \le E_{\max} \tag{19}$$

Where: $P_{\text{es,max}}$ is the maximum charging and discharging power of the battery; $P_{\text{cha,sign}}$ and $P_{\text{dis,sign}}$ are charging and discharging flags, both are 0-1 variables; $E_{\text{es},t}$ is the state of charge of the battery at time t; η_{cha} is the charging efficiency; $P_{\text{cha},t}$ is the charging power of the battery at time t; η_{dis} is the discharging efficiency; $P_{\text{dis},t}$ is the discharging power of the battery at time t; $E_{\min}$ is the minimum value of state of charge; $E_{\max}$ is the maximum value of state of charge.

3. CASE STUDY

The initial credit score of this electrolytic aluminum enterprise is assumed to be 70. The evaluation coefficients r_1 and r_2 are set to 0.3 and 0.1, respectively. The baseline response grade γ_0 is set to 0.8. The case study is configured with a 24-hour demand response participation period. The results of 10 demand response events are analyzed.

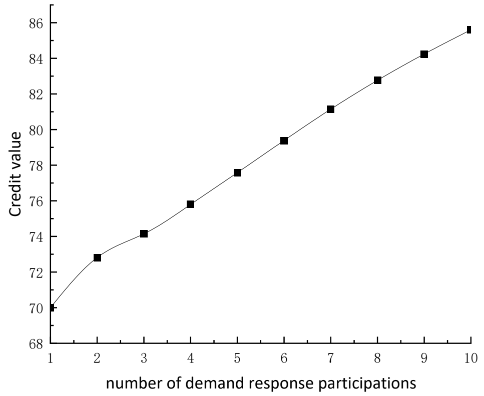

Fig.1 Credit value changes of enterprise by number of demand response participations

As shown in Figure 1, the credit value of the electrolytic aluminum enterprise continuously increases with the number of demand response events. The enterprise's credit value rises from the initial score of 70 to 85.6 after experiencing ten rounds of demand response, representing an increase of approximately 22.3%. It can be observed that the electrolytic aluminum enterprise continuously optimizes its demand response participation performance to enhance the revenue from demand response participation. This demonstrates the advantage of the credit value-based assessment approach proposed in this paper for evaluating the effectiveness of enterprise participation in demand response.

Tab.1 Financial performance of electrolytic aluminum enterprise in 10 demand response programs

Number of demand response participations	C_{et} （¥）
1	1301418.65
2	1346764.39
3	1366081.74
4	1390070.97
5	1415978.30
6	1442179.64
7	1467716.81
8	1491149.42
9	1512640.69
10	1532342.72

As shown in Figure 2, the overall revenue of the electrolytic aluminum enterprise also continuously increases. After participating in 10 demand response events, the enterprise's overall revenue increases by approximately 24.6% compared to the revenue after participating in only 1 demand response event. Combined with Table 1, it can be observed that the subsidy revenue obtained by electrolytic aluminum participation in demand response also shows an upward trend, with the revenue from the 10th participation increasing by approximately 17.8% compared to the revenue from the 1st participation. This demonstrates that by using the execution effectiveness of enterprise demand response provision as the assessment standard to evaluate enterprise creditworthiness and providing different incentive subsidies accordingly, the enthusiasm of enterprises for demand response participation is significantly enhanced. This approach not only substantially improves the revenue from enterprise demand response participation but also increases the overall revenue of the enterprise.

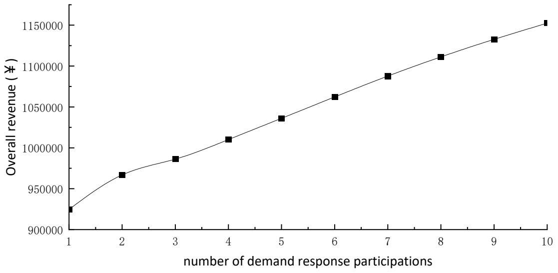

Fig.2 Overall revenue variation of enterprise

4. CONCLUSION

This paper proposes a comprehensive decision-making model for electrolytic aluminum enterprise participation in electricity market demand response, featuring a credit evaluation system based on improved subscription performance indicators and a subsidy mechanism that links credit scores with incentive pricing. The model incorporates production constraints including power, temperature, and daily output limits to ensure operational stability during demand response participation. Case study results demonstrate that the proposed approach significantly enhances enterprise participation effectiveness, with credit value increasing by 22.3% and overall revenue growing by 24.6%.

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REFERENCE

[1] QIU Y, LU S, LU H, et al. Flexibility of Integrated Energy System: Basic Connotation, Mathematical Model and Research Framework. Automation of Electric Power Systems 2022; 46(17): 16-43.

[2] XU J, YU Q, LIAO S, et al. Industrial park tie-line power smoothing strategy considering production safety. Journal of Shanghai Jiao Tong University 2024; 58(6): 941-953.

[3] YAO M, HAN X, ZHENG Y, et al. Ponder on promoting the participation of high energy-intensive industries in power ancillary service market. Energy of China 2018; 40(2): 22-26.

[4] LIU J, ZENG K, WANG C, et al. Unit Commitment Considering Electrolytic Aluminum Load for Ancillary Service. 2019 International Conference on Intelligent Green Building and Smart Grid(IGBSG2019); Yichang China: IEEE, 2019: 608-611.

[5] YUE X, LIAO S, FU L, et al. Hierarchical optimization strategy of high-penetration wind power system considering electrolytic aluminum energy-intensive load regulation and deep peak shaving of thermal power. Power System Technology 2024;48(08): 3186-3196.

[6] LIAO S, ZHANG M, XU J, et al. Frequency stability control method for electrolytic aluminum participation in power grid considering the static voltage stability constraints. Proceedings of the CSEE 2022; 42(18): 6727-6740.

[7] GONG F, REN K, ZHANG A, et al. Review of electrolytic aluminum load participating in demand response to absorb new energy potential and methods. 2021 IEEE 2nd International Conference on Big Data, Artificial Intelligence and Internet of Things Engineering (ICBAIE); Nanchang, China: IEEE, 2021: 1015-1019.

[8] TANG Z, WANG K, ZHAO J, et al. A study on incentive mechanisms for air-conditioning loads participating in demand response. Zhejiang Electric Power 2025; 44(02): 32-41.