Incentive strategies for responders of electric vehicle virtual energy storage based on comprehensive contribution evaluation

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Abstract. The user-side demand resources of electric vehicles are integrated by load aggregators to respond to grid dispatch, which will bring many value-added benefits to the grid and other entities in the market. This article analyzes and constructs evaluation indicators from the two aspects of power contribution and response rate contribution to analyze the contribution of electric vehicle operators and electric vehicle users. The TOPSIS-grey correlation evaluation model is established and divided into four stages: state determination, reward and punishment analysis, peak-valley combination, and incentive distribution to analyze the comprehensive contribution of electric vehicle users. This is conducive to determining the amount of electricity and the response range of response speed when electric vehicles participate in the market to obtain rewards or punishments, and then distribute the compensation value and value-added benefits obtained when electric vehicle users participate in the regulation operation.

1. Introduction

The disorderly charging and discharging operations of electric vehicles cause voltage and harmonic problems to the distribution network. However, as a distributed energy storage, it has both source and load characteristics, can respond to grid dispatching needs, is a high-quality resource for providing auxiliary power services, and can give full play to its mobile energy storage characteristics[4], which will vigorously promote the intelligent and interactive development of energy supply and exchange.

As an important flexible load for the demand response of the distribution network, electric vehicles are conducive to peak shaving and valley filling after aggregator concentration, and improve the security and stability of the grid. The incentive method for electric vehicles to connect to the distribution network and participate in grid dispatch has gradually become a research hotspot. Literature[1] considers the peak-valley price difference, quantitatively analyzes the upper and lower limits of the electric vehicle charging and discharging prices, and constructs an optimal and orderly charging and discharging sequential control strategy model considering price incentives. Literature[2] considers the electric vehicle discharge mode to design a user-oriented charging and discharging dual incentive mechanism and proposes a semi-trusted user response method. Literature[3] studies how electric vehicle aggregators decide the optimal economic incentive value to maximize the revenue of charging. Literature
[5] combined the analytic hierarchy process and the approaching ideal point sorting method to evaluate the operation of electric vehicle charging network.

Based on the above background, this article analyzes the contribution of electric vehicle operators and users in terms of power and response rate. It is divided into a judgment stage and a reward and punishment stage to calculate its contribution, and uses the TOPSIS-grey correlation evaluation model to conduct a comprehensive contribution analysis and incentive distribution to electric vehicle users.

2. Evaluation index system for the contribution of electric vehicle operators

2.1. Power contribution

For electric vehicle operators, their main contribution can be analyzed and constructed from two aspects: power contribution and response rate contribution. To calculate the contribution of electricity, we must first calculate the planned completion rate \( \lambda_\alpha \), which is the planned completion of peak shaving and valley filling by electric vehicle operators, and the planned completion of peak shaving is represented by \( \alpha_i \), the completion of the valley filling plan is represented by \( \beta_i \), the peak cutting contribution is represented by \( \lambda_\alpha \), and the valley filling contribution is represented by \( \lambda_\beta \).

\[
\alpha_i = \frac{p_i - p_0}{p_0} \quad \beta_i = \frac{v_i - v_0}{v_0}
\]

(1) (2)

Among them, \( p_i \) represents the actual monthly peak shaving of operator i; \( p_0 \) represents the monthly planned peak shaving of operator i; \( v_i \) is the actual monthly valley filling volume of operator i; \( v_0 \) is the monthly planned valley filling volume of operator i. The calculation process is divided into two stages: the judgment stage and the reward/penalty stage.

Judgment stage: If \(-20\% \leq \alpha_i \leq 20\%\), it means that the operator has actively participated in the peak shaving response and entered the reward stage to analyze the operator’s response attributes and rewards. Similarly, if \(-20\% \leq \beta_i \leq 20\%\), it means that the operator actively participates in the valley filling response and enters the reward stage to analyze the operator's response attributes and rewards.

Reward/punishment phase: Reward stage:

\[
\bar{\alpha}_i = \frac{\sum_{i=1}^{N} a_i}{N}, \quad \bar{\beta}_i = \frac{\sum_{i=1}^{N} \beta_i}{N}
\]

(3) (4)

Among them, \( \bar{\alpha}_i \) and \( \bar{\beta}_i \) represent the average planned completion rates of N operators in terms of peak cutting and valley filling.

By comparing the average completion rate of operator i and all operators, we can get the sum of the relative completion levels of operator i in peak cutting \( s_{i,1} \) and valley filling \( l_{i,1} \). A value greater than zero indicates a positive contribution, and a value less than zero indicates a negative contribution.

\[
s_{i,1} = \frac{a_i - \bar{a}_i}{\bar{a}_i} \quad l_{i,1} = \frac{\bar{\beta}_i - \beta_i}{\bar{\beta}_i}
\]

(5) (6)

The value range of \( s_{i,1} \) and \( l_{i,1} \) is \(-200\% \leq s_{i,1}, l_{i,1} \leq 200\%\). According to the linear regression formula, the function that maps the current numerical interval to the target interval can be obtained.

\[
y = y_{\min} + \frac{y_{\max} - y_{\min}}{x_{\max} - x_{\min}} \times (x - x_{\min})
\]

(7)

Among them, \( y_{\max} \) indicates the maximum value of the target interval to be mapped, \( y_{\min} \) indicates the minimum value of the target interval to be mapped, \( x_{\max} \) indicates the maximum value of the current data, and \( x_{\min} \) indicates the minimum value of the current data. x is any value in the hypothetical current data, and y is the value after normalization mapping.
According to the idea of periodic settlement, taking 7 days as a settlement cycle, the contribution of all peak-shaving responses and valley-filling responses that the operator participated in within 7 days will be:

\[
\overline{\lambda}_{i,a} = \frac{\sum_{t=1}^{7} \lambda_{a}}{7}
\]  

(11)

\[
\overline{\lambda}_{i,b} = \frac{\sum_{t=1}^{7} \lambda_{b}}{7}
\]  

(12)

Punishment stage: For operator i, its penalty is recorded as \( m_{p} \):

\[
m_{p} = \left[ \left( |\alpha_{i} | - 20\% \right) \cdot p_{0} + \left( |\beta_{i} | - 20\% \right) \cdot v_{0} \right] \cdot P_{TOU} \cdot k_{p}
\]

(13)

Among them, \( |\alpha_{i} | - 20\% \) represents the electricity exceeding the allowable deviation during peak shaving, \( |\beta_{i} | - 20\% \) represents the electricity exceeding the allowable deviation during valley filling, \( P_{TOU} \) represents the time-of-use electricity price corresponding to this demand response stage, and \( k_{p} \) represents the penalty coefficient. Taking 7 days as a settlement cycle, it is possible to record the compensation paid by the operator each time due to failure to perform the contract, and sum and output it on the settlement day.

2.2. Response rate contribution

Response rate contribution \( \lambda_{2} \) is whether electric vehicle operators can participate in the completion of the response in a timely manner. To calculate the response rate contribution, the response rate must first be calculated. The response rate of peak clipping is denoted by \( d_{i} \), the response rate of valley filling is denoted by \( e_{i} \), the contribution of rate clipping is denoted by \( \lambda_{d} \), and the contribution rate of valley filling is denoted by \( \lambda_{e} \).

\[
d_{i} = \frac{t_{a} - t_{i}}{t_{a}}
\]

(14)

\[
e_{i} = \frac{t_{a} - t_{i}}{t_{a}}
\]

(15)

Among them, \( t_{i} \) represents the operator’s actual peak shaving/valley filling response time; \( t_{0} \) represents the operator’s promised peak shaving/valley filling response time, and \( t_{m} \) represents the latest effective peak shaving/valley filling response time.

The calculation process is divided into two stages: the judgment stage and the reward/penalty stage.

Judgment stage: Judge whether the operator responds effectively: If \( t_{i} < t_{m} \), it means that the operator is actively involved in the peak shaving response and enters the reward phase, and analyzes the operator’s contribution to the response rate and the reward. If \( t_{i} \geq t_{m} \), it means that the operator has not actively participated in the response and enters the penalty stage to analyze the operator’s penalty.

Reward/punishment phase: Reward stage: The value range of \( d_{i} \) and \( e_{i} \) is:

\[
\frac{t_{0} - t_{m}}{t_{0}} \leq d_{i} \leq -1
\]

\[
\frac{t_{0} - t_{m}}{t_{0}} \leq e_{i} \leq -1
\]

According to the linear regression formula, the function that maps the current numerical interval to the target interval can be obtained.

\[
y = y_{min} + \frac{y_{max} - y_{min}}{x_{max} - x_{min}} \cdot (x - x_{min})
\]

(16)

\[
y = 0\% + \frac{100\%-0\%}{t_{0} - t_{m}} \cdot \left( x - \frac{t_{0} - t_{m}}{t_{0}} \right) = \frac{t_{0}}{t_{m}} (x - 1) + 1
\]

(17)

\[
\lambda_{i,d} = \frac{t_{0}}{t_{m}} (d_{i} - 1) + 1 = \frac{t_{0}}{t_{m}} t_{p} + 1
\]

(18)
According to the idea of periodic settlement, taking 7 days as a settlement period, the rate contribution of all peak-shaving responses and valley-filling responses that the operator participated in within 7 days will be:

\[ \lambda_{i,e} = \frac{t_e}{t_m} (e_i - 1) + 1 = \frac{-t_f}{t_m} + 1 \]  \hspace{1cm} (19)

Punishment stage: \( \frac{t_1 - t_0}{t_0} \) is the ratio of actual time exceeding the latest effective response time to the promised response time.

3. Evaluation Method of Comprehensive Contribution of Electric Vehicle Users

3.1. Evaluation model
Combining the TOPSIS method and the grey relational analysis method to establish an evaluation model. By replacing the traditional Euclidean distance with the grey relational degree, the relative closeness of each evaluation scheme to the ideal scheme is constructed as the basis for ranking the schemes.

The basic idea of the method is: firstly, standardize the data matrix of the evaluation plan to obtain a standardized decision matrix, and calculate the positive ideal plan and the negative ideal plan according to the formula. Then, according to the gray correlation analysis method, the gray correlation degree between each evaluation plan and the positive and negative ideal plan is calculated, and the relative closeness of each plan is calculated. Finally, sort according to the relative closeness, which can be compared and analyzed. This model is suitable for evaluation research of multi-factor decision-making programs, and it is applied to the evaluation of user contribution.

The specific process of TOPSIS method and grey relational analysis method can be found in literature [10].

3.2. Incentive distribution method considering comprehensive contribution
Calculate the gray correlation degree between each evaluation object and the positive ideal solution \( Y^+ \). On the basis of the weighted standardized matrix \( Y \), calculate the gray correlation coefficient \( g_{ij}^+ \) between the \( i \)-th object and the positive ideal solution with respect to the \( j \)-th index. The calculation formula is:

\[ \zeta_i(k) = \frac{\min_{j} \min_{i} |x_0(k) - x_i(k)| + \rho \max_{j} \max_{i} |x_0(k) - x_i(k)|}{\max_{i} \max_{j} |x_0(k) - x_i(k)| + \rho \max_{i} \max_{j} |x_0(k) - x_i(k)|} \]  \hspace{1cm} (22)

Among them, \( k \) corresponds to \( j \), \( x_0(k) \) corresponds to \( y_j^+ \), and \( x_i(k) \) corresponds to \( y_{ij} \), so:

\[ g_{ij}^+ = \frac{\min_{j} |y_j - y_{ij}| + \rho \max_{j} |y_j - y_{ij}|}{\max_{j} |y_j - y_{ij}| + \rho \max_{j} |y_j - y_{ij}|} = \frac{\rho w_j}{w_j - z_{ij} + \rho w_j} \]  \hspace{1cm} (23)

Among them, \( i = 1,2,\ldots,m; j = 1,2,\ldots,n; \rho \) is the resolution coefficient, generally 0.5. Then the gray correlation degree between the evaluation object and the positive ideal solution, that is, the comprehensive contribution degree of the evaluation object is:

\[ \lambda_i = p_1 = \sum_{j=1}^{n} w_j g_{ij} \]  \hspace{1cm} (24)

Among them, \( w_j \) is the weight of the \( j \)-th index.

Through the above steps, the comprehensive contribution \( \lambda_i \) of operator \( i \) can be obtained. Assuming that in a settlement cycle, there are a total of \( N \) operators participating in the response, and the total reward money obtained by all operators through participating in peak shaving and valley filling is \( M \). The number of responses that the operator participated in is recorded as \( n_i \), then for operator \( i \), the reward it receives is recorded as \( m_h \):
5

\[ m_b = M \times \frac{\lambda_i}{\sum_{i=1}^{N} \lambda_i} \times n_i \]  \hspace{1cm} (25)

4. Evaluation and Incentive Strategies of Electric Vehicle User Contribution under Peak-shaving Auxiliary Service

4.1. Phase 1: State determination

For a single electric vehicle user's contribution \( \phi \), its main contribution can be analyzed from the difference between a single user's response power and the average response power, and an evaluation index can be constructed. The peak clipping contribution is represented by \( \phi_{\alpha} \), and the valley filling contribution is represented by \( \phi_{\beta} \).

\[ \phi_{\alpha,i} = \frac{pc_i - \bar{pc}}{|\bar{pc}|} \]  \hspace{1cm} (26)

\[ \phi_{\beta,i} = \frac{vc_i - \bar{vc}}{|\bar{vc}|} \]  \hspace{1cm} (27)

Among them, \( pc_i \) is the amount of users participating in peak shaving, and \( vc_i \) is the amount of users participating in valley filling. The positive values of \( \phi_{\alpha} \) and \( \phi_{\beta} \) indicate that the contribution is positive and rewards are given; If their value is negative, the contribution is negative, and no reward or even punishment is given.

According to the idea of periodic settlement, taking 7 days as a settlement period, the contribution of all peak-shaving responses and valley-filling responses that the user participated in within 7 days will be:

\[ \bar{\phi}_{\alpha,i} = \frac{\sum_{t=1}^{t=7} \phi_{\alpha,t}}{7} \]  \hspace{1cm} (28)

\[ \bar{\phi}_{\beta,i} = \frac{\sum_{t=1}^{t=7} \phi_{\beta,t}}{7} \]  \hspace{1cm} (29)

If \( \bar{\phi}_{\alpha,i} \geq 0\% \), it means that the user actively participates in the peak-shaving response, is rewarded, and enters the reward stage for further analysis. If \(-20\% \leq \bar{\phi}_{\alpha,i} \leq 0\% \), it means that the user has not actively participated in the peak-shaving response, but it is still within the allowable range, so there is no reward or penalty. If \( \bar{\phi}_{\alpha,i} \leq -20\% \), it means that the user is negatively responding to peak clipping and will be punished, and enter the punishment stage for further analysis. The same is true for the determination of the valley filling response \( \phi_{\beta,i} \).

4.2. Phase 2: Reward/Punishment Analysis

Reward stage: users who enter the reward stage have a contribution greater than 0.

Punishment stage: For user \( i \), the penalty is recorded as \( m_p \):

\[ m_p = \left[ (|\bar{\phi}_{\alpha,i}| - 20\%) \times \frac{p_i}{k} \right] + \left( |\bar{\phi}_{\beta,i}| - 20\% \right) \times \frac{v_i}{k} \times P_{T0U} \times k_p \]  \hspace{1cm} (30)

Among them, \( (|\bar{\phi}_{\alpha,i}| - 20\%) \times \frac{p_i}{k} \) represents the amount of electricity exceeding the allowable deviation when the user cuts the peak, and \( (|\bar{\phi}_{\beta,i}| - 20\%) \times \frac{v_i}{k} \) represents the amount of electricity exceeding the allowable deviation when the user fills the valley. Taking 7 days as a settlement cycle, you can record the compensation that the user has to pay for each failure to perform the contract, and sum and output it on the settlement day.

4.3. Stage 3: Peak and valley combination

According to the obtained contributions \( \bar{\phi}_{\alpha,i} \) and \( \bar{\phi}_{\beta,i} \) of the peak-shaving response and valley-filling response of the user \( i \) in a settlement cycle, the power contribution \( \phi_i \) of the operator \( i \) can be obtained.
4.4. Stage 4: Incentive Distribution

Through the above steps, the power contribution \( \Phi_i \) of all users of an operator can be obtained. Assuming that in a settlement cycle, there are a total of \( k \) users participating in the response, and the total reward money obtained by all users through participating in peak shaving and valley filling is \( M_c \). Assuming that \( M_c \) is \( s\% \) of \( M_a \), that is, the operator uses all the rewards \( s\% \) to motivate its users, and the number of responses of user \( i \) is recorded as \( n_{c_i} \), then for operator \( i \), the reward it receives is recorded as \( m_{c_i} \):

\[
m_{c_i} = M_c \frac{\Phi_i}{\sum_{i=1}^{k} \Phi_i} \times n_{c_i} = k\% \times M_a \frac{\Phi_i}{\sum_{i=1}^{k} \Phi_i} \times n_{c_i}
\]

(32)

5. Conclusion

As more and more electric vehicle loads are connected to the grid, its load characteristics have a great negative impact on the safe and stable operation of the system, flexible and adjustable resources on the user side of electric vehicles participate in demand response, after being aggregated, it can provide auxiliary services and develop good interactions between the car and the network. This article studies the contribution of electric vehicle users. First, this article analyzes the power and response rate of electric vehicle operators who aggregate the controllable resources of electric vehicles to participate in peak and valley response, and builds a contribution model based on the two stages of judgment, reward or punishment. Secondly, the TOPSIS method and the gray correlation analysis method are combined to establish an evaluation model to conduct a comprehensive analysis of user contribution. Finally, on the basis of the comprehensive contribution model, periodic settlement and incentive distribution are carried out on the contribution of users under an operator.

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