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An Analysis From the Perspective of Direct Power-Purchase for Industrial Users: Should the Power Grid Company Implement Incentive-Based Demand Response Management?

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ABSTRACT As a means for the power grid company to guide industrial users to reduce power consumption through economic compensation, incentive-based demand response management (IBDRM) plays an important role in the process that industrial users purchase power directly from power plants (direct power-purchase for short). Therefore, this paper studies the impacts of IBDRM on the power grid company, power plants, and industrial users from the perspective of industrial users' direct power-purchase, so as to analyze whether the power grid company should implement IBDRM in direct power-purchase. First, we model the interactions of the power grid company, the power plant, and the industrial user under different scenarios, including Case N (the power grid company does not implement IBDRM) and Case R (the power grid company implements IBDRM) by using Stackelberg game. Then, we solve the models to get equilibrium results. The primary contributions of this article include following parts: **1)** Compared with Case N, the power plant's power selling price and the industrial user's power-purchase quantity are higher under Case R, and both are negatively correlated with the compensation for the power plant. **2)** The power grid company should implement IBDRM in direct power-purchase. Because under Case R, the industrial user reduces the power consumption, the profits of the power grid company and the power plant are higher, and the social welfare is also greater. **3)** Under Case R, we also find that the social welfare is positively correlated with the compensation for the industrial user.

INDEX TERMS Direct power-purchase, incentive-based demand response management, industrial user, Stackelberg game.

I. INTRODUCTION

With the rapid development of the global economy, the power demand is gradually increasing. For example, Japan's power consumption has increased from 0.05 trillion kWh in 1950 to 1.10 trillion kWh in 2011.[1] The power consumption in the United States has risen from 1.71 trillion kWh in 1974 to 3.89 trillion kWh in 2010.[2] China's power consumption has increased from 0.25 trillion kWh in 1978 to 7.23 trillion kWh in 2019, with an increase of about 28.9 times [1], [2]. The rapid growth of power consumption poses great pressure on the power grid company. As an important means to realize the flexible interaction between power users and the power grid, incentive-based demand response management (IBDRM) can alleviate the pressure of the power supply [3], [4]. IBDRM means that when the reliability of the power system is threatened (e.g., the peak load period of the power grid), the power grid company will guide users to reduce their power consumption through economic compensation, so as to ensure the safety and stability of the power grid [5]–[7]. Practical results of major cities in China, such as Tianjin, Shanghai, and Inner Mongolia, show that IBDRM can effectively maintain the stability of the power system [8], [9]. At present, the smart grid develops rapidly. The characteristic

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[1]https://www.iea.org/
[2] https://www.globaldata.com/

of interaction between smart grid and power users is helpful to guarantee IBDRM [10], [11]. Moreover, since power plants need to reschedule their power generation plans and incur some costs during IBDRM, the power grid company will also provide power plants with economic compensation, such as peak load regulation compensation [12]. Compared with residential users, the load transfer of industrial users who have relatively high power consumption is more likely to occur in IBDRM [13], so the effect of power system balance regulation will be more significant if we encourage them to participate in IBDRM. The Economic and Information Commission of Guangdong Province of China points out that energy-intensive industrial users are enterprises with an annual power consumption above 80 million kWh .[3] In 2015, the State Council of China issued the policy (Zhongfa [2015] No. 9) to start the opening and reform of the power sales side market, which allowed power plants to carry out direct transactions with industrial users. As stated by [14], more and more industrial users choose to purchase power directly from power plants (direct power-purchase for short) rather than from power sales companies, since the cost of direct power-purchase is significantly lower [15]. According to the survey data from China Power Council, China's direct power-purchase trading volume in 2019 has reached 30.2% of its total power trading volume.[4] Therefore, in the current smart grid environment, it is necessary to study the impacts of IBDRM on different participants (i.e., the power grid company, power plants, and industrial users) in direct power-purchase transactions so as to provide guidance for future decisions.

IBDRM has different impacts on the transaction entities of direct power-purchase. From the standpoint of the power grid company, although the demand response compensation increases its costs, it can also reduce the operation and management costs of the power system, for instance, reducing the investment in capacity expansion of the transmission and distribution network (i.e., avoidable capacity cost) and the power loss in the process of transmission and distribution (i.e., avoidable power cost), etc., [16]. From the standpoint of power plants, as industrial users reduce power consumption during peak hours, their power generation plans are disrupted, and thus they have to bear the costs such as peak load regulation cost. However, power plants can also get compensation benefits provided by the power grid company, such as peak load regulation compensation [12]. From the standpoint of industrial users, they will cause the interruption cost due to load reduction, but they will also receive the demand response compensation from the power grid company [17]. Obviously, the impacts of IBDRM on the power grid company, power plants, and industrial users are still unclear. Therefore, we need to study the following questions.

1) Should the power grid company implement IBDRM in direct power-purchase? If the power grid company chooses to implement IBDRM, how does it formulate the optimal incentives to the power plant and the industrial user?

2) Under the case where the power grid company implements IBDRM, if the power plant and the industrial user choose to participate in IBDRM, how will the former's transaction price of direct power-purchase and the latter's power-purchase quantity be adjusted, respectively?

3) What are the impacts of IBDRM implemented by the power grid company on the actual power consumption of the industrial user, the profit of each direct power-purchase transaction entity (i.e., the power grid company, the power plant, and the industrial user), the consumer surplus, and the social welfare?

This paper seeks to answer the above questions from the perspective of operations management. Its purpose is to study the decisions of different direct power-purchase transaction entities, and provide managerial implications for the power grid company to implement IBDRM based on the practice in which industrial users participate in direct power-purchase transactions. In this paper, we consider a direct power-purchase transaction system consisting of a power grid company, a power plant, and an industrial user with high power consumption. For the direct power-purchase transactions between power plant and industrial user, first, under the case where the power grid company does not implement IBDRM (Case N), with the power plant as a leader and the industrial user as a follower, we construct a Stackelberg game model of the power plant and the industrial user. And we can obtain the equilibrium power selling price of the power plant and the equilibrium power-purchase quantity of the industrial user. Then, under the case where the power grid company implements IBDRM (Case R), with the grid company as a primary leader, the power plant as a secondary leader, and the industrial user as a follower, we construct a Stackelberg game model of the power grid company, the power plant, and the industrial user. And we can obtain the equilibrium compensation of the power grid company, the equilibrium power selling price of the power plant, and the equilibrium power-purchase quantity of the industrial user. On this basis, under Cases N and R, this paper compares the equilibrium power selling prices, the equilibrium power-purchase quantities, the equilibrium actual power consumptions, the equilibrium profits of each direct power-purchase transaction entity, and the equilibrium consumer surplus. And we analyze the impacts of IBDRM on the power grid company, the power plant, the industrial user, and consumers. Finally, this paper also verifies the main theoretical results through numerical analysis and compares the social welfare under the two cases.

The contributions of this paper mainly include the following two aspects. First, for the demand response compensation mechanisms of the power grid company, the existing literature only considers that the power grid company provides the compensation for industrial users, whereas we study that the power grid company provides the compensation for power plants and industrial users at the same time. This paper can

[3] www.gdii.gov.cn/index.html
[4] https://www.cec.org.cn/

make up the defects of existing researches and provide a theoretical basis for the power grid company to formulate a reasonable demand response compensation scheme. Second, through theoretical analysis, this paper obtains managerial implications. For example, the power grid company should carry out IBDRM to industrial users as soon as possible in direct power-purchase, especially when the stability of the power system is threatened. The power grid company should also specify the lower and upper limits of load reduction for industrial users. Moreover, in order to achieve a tripartite win-win for the power grid company, power plants, and industrial users under the implementation of IBDRM, the power grid company should strive to promote industrial users' enthusiasm for participating in IBDRM. Specifically, the power grid company should maintain a balanced compensation ratio between power plants and industrial users (i.e., the power grid company needs to make sure that it is profitable for industrial users to participate in IBDRM), the demand response compensation for industrial users should be improved as much as possible.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 gives the notations explanation and problem description. Under Cases N and R, Section 4 gives the equilibrium results of the decision variables and profits of each direct power-purchase transaction entity in the Stackelberg game, respectively. Section 5 analyzes the impacts of IBDRM on the direct power-purchase transaction entities and consumers. In Section 6, the main theoretical results are verified through numerical analysis, and the social welfare under Cases N and R is compared. Section 7 summarizes the main conclusions and managerial implications of this paper, and also gives future research prospects.

II. LITERATURE REVIEW

For the research problems that this paper focuses on, the existing studies which are closely related to them mainly involve two streams: one is the game strategy between power plants and industrial users in the direct power-purchase environment, the other is the compensation strategy for IBDRM of the power grid company.

At present, there are some representative achievements in the research of game strategy between power plants and industrial users in the direct power-purchase environment. For instance, Wen and David [18] study the bidding quotation of power plants and industrial users in the direct power-purchase market. They then solve the game model by using the Monte Carlo approach. They find that the bidding price of power plants and industrial users is mainly affected by their expectations of the competitors' bidding methods. Song *et al.* [19] combine the generation cost matrix of power generation companies and the willingness vector of industrial users to purchase power. After that, they discuss the bidding strategies of power generation companies in the bilateral market. Their results show that all Nash equilibria are equivalent to the revenue of generators. Zare *et al.* [20] solve the problem of how industrial users purchase power under the circumstance of price fluctuations in the direct power-purchase market. They propose a method for evaluating the power-purchase cost of industrial users based on the information gap decision theory. This method is helpful for industrial users with different risk preferences to obtain their optimal power-purchase strategies in the game process with power plants. Fang *et al.* [21] study the pricing mechanism of direct power-purchase. On the basis of considering the power transmission cost in the power wholesale market, they construct a double auction model of competitive power plants and industrial users. Then, they obtain an equilibrium pricing mechanism. This mechanism realizes incentive compatibility for risk-neutral participants. Tsitsiklis and Xu [22] analyze and solve the problem that changes in power demand of industrial users increase the power generation cost of power plants. They design a dynamic real-time power pricing method by building a dynamic game model. Compared with the marginal cost power pricing method, this method can better motivate industrial users to reduce their power consumption during the peak load period of the power system. Tang *et al.* [23] discuss the bilateral contract transaction between power plants and industrial users based on the game theory. Specifically, they build a Bayesian game model of multiple power plants, and a Stackelberg game model between power plants and industrial users. They verify that the established model can maximize the profits of power plants and minimize the power-purchase costs of industrial users. Abedinia *et al.* [24] adopt the robust optimization method and the stochastic method to study the optimal bidding strategy for an industrial user when purchasing power directly from a renewable energy power plant. The results show that the more uncertain parameters an industrial user considers in the transaction process, the higher the purchase price will be. Zhang *et al.* [25] want to improve the direct power-purchase trading mechanism, so they propose a two-stage bidding trading mechanism when power plants and industrial users are gaming. This mechanism not only ensures the fairness and efficiency of direct power-purchase transactions, but also helps to lower the average transaction price in the direct power-purchase market. When constructing the game models in the direct power-purchase environment, most of the above studies regard industrial users as consumers and consider the minimization of their power-purchase cost, but ignore the purpose of industrial users as enterprises to earn profits. Therefore, this paper analyzes the profitability of industrial users based on market factors, which makes up for the lack of existing research.

Some research results have also been obtained on the compensation strategy when the power grid company implements IBDRM. Fahrioglu and Alvarado [26] identify the interruptible load types of power users through power failure willingness factors. Then, they adopt a non-linear compensation pricing method to design a demand response contract with incentive compatibility. Vivekananthan *et al.* [27] combine the load transfer situation and the voltage improvement degree of residential users during IBDRM. They then study the demand response compensation strategies of residential users. These strategies can guarantee the users' power consumption satisfaction, and at the same time can also reduce their power demand during the peak period of the grid. Obrien *et al.* [28] model the demand response compensation pricing problem based on the game theory, and design a payment distribution mechanism based on the Shapley value method. After that, they adopt a reinforcement learning method which is similar to balanced stratified sampling to estimate the equilibrium solution. Yoo *et al.* [29] focus on the transaction between power generation companies that also sell power and residential users. Under the condition of maximizing the overall interests of both sides, they study how the power grid company formulates the optimal demand response compensation. They find that the implementation of IBDRM can reduce the market clearing price. Islam *et al.* [30] study the IBDRM compensation mechanism which aims at reducing the excess power generation of renewable energy. They build a relevant optimization model and solve it by using the particle swarm algorithm. What's more, the effectiveness of the designed compensation mechanism is verified by a numerical example. Wang *et al.* [31] explore the nonlinear demand response compensation pricing model from the perspective of load aggregators. They verify that the established model can promote the enthusiasm of the user side to participate in IBDRM. Ghorashi *et al.* [32] face the phenomenon that users' participation in IBDRM may lead to a peak rebound and the power transmission system congestion during low load periods, they study the design and optimization of demand response compensation mechanism by combining the smart grid technology. Moreover, the numerical analysis indicates that the proposed compensation mechanism can improve the operational characteristics of the power grid and reduce the peak rebound without increasing the costs of users. Liu *et al.* [33] consider the flexibility differences of power users when participating in the demand response to put forward a differentiated demand response compensation method. Compared with the unified compensation method, this method can well reduce the compensation cost of the power grid company. However, When analyzing the demand response compensation strategy of the power grid company, the existing studies only take industrial users as compensation targets, and fail to consider both power plants and industrial users as targets simultaneously. From this perspective, with the goal of maximizing the profit of the power grid company, we try to obtain the optimal subsidies set by the power grid company for power plants and industrial users. In addition, we also analyze the impact of IBDRM on social welfare, which is a supplement to the existing research.

III. NOTATIONS EXPLANATION AND PROBLEM DESCRIPTION

In order to describe the model established in this paper more clearly, the symbols involved are defined and explained, as shown in Table 1. Specifically, the subscripts $i = \{G, P, F\}$ represent variables related to the power grid company, the power plant, and the industrial user, respectively. The superscripts $j = N$ and $j = R$ represent Case N and Case R, respectively.

TABLE 1. Notations.

Variables	Descriptions
h	The total compensation amount that the power grid company pays to the power plant and the industrial user when implementing IBDRM (Decision variable).
p^j	The direct power-purchase transaction price of the power plant under Case j (Decision variable).
q^j	The direct power-purchase transaction quantity of the industrial user under Case j (Decision variable).
π_i^j	The profit for stakeholder i under Case j.
p_G	The wheeling cost charged by the power grid company to the industrial user.
k	The unit transmission and distribution cost of the power grid company in the process of power transmission.
λ_G	The unit income of the grid company through the development of IBDRM.
α	The proportional coefficient of compensation received by the power plant in the total IBDRM's compensation amount of the power grid company ($1-\alpha$ is the proportional coefficient of compensation received by the industrial user in the total IBDRM's compensation amount of the power grid company).
$C_P(q^j)$	The power generation cost function of the power plant under Case j.
a	The quadratic coefficient of the power generation cost function.
b	The first order coefficient of the power generation cost function.
c	The constant term of the power generation cost function.
ω_P	The unit peak load regulation cost of the power plant.
β	The proportional coefficient of product output corresponding to the unit power consumption of the industrial user.
z	The basic selling price of the industrial user's product when the market demand is zero.
Δq	The reduced load of the industrial user who participates in IBDRM.
r^j	The actual power consumption of the industrial user under Case j.
φ	The quadratic coefficient of the industrial user's interruption cost function.
μ	The first order coefficient of the industrial user's load reduction function.

In this paper, we consider a direct power-purchase trading system consisting of a power grid company, a power plant, and an industrial user who consumes a lot of power. And in this system, each entity plays the Stackelberg game. Specifically, under Case N, the power plant is the leader and the industrial user is the follower. And we assume that the power grid company is only a service organization responsible for power transmission and distribution under this case, and does not participate in the game process. At this time, the power flow and capital flow between entities can be shown in Fig. 1 (a). In the process of direct power-purchase transaction, the power transmission is realized by entrusting the power grid company to transmit and distribute power from the power plant to the industrial user, and the industrial user needs to pay both the wheeling cost to the power grid company and the power-purchase cost to the power plant. Under Case R, since the power grid company is the organizer of IBDRM and has a high initiative, therefore, the power grid company is the primary leader, the power plant is the secondary leader, and the industrial user is the follower. The power flow and capital flow between entities are shown in Fig. 1 (b). Different from Case N, under Case R, because the power grid company carries out IBDRM, it increases the demand response compensation costs, including the compensation of the power plant (for example, the peak load regulation compensation) and the demand response compensation of the industrial user.

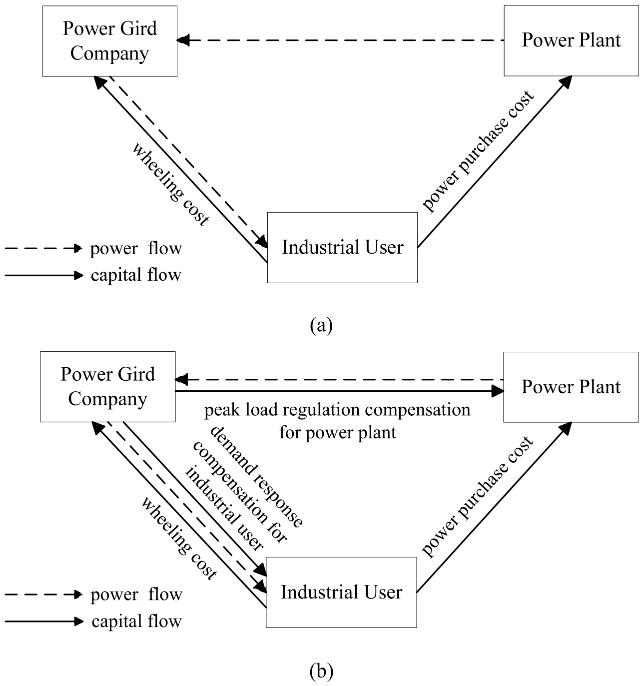

FIGURE 1. Direct power-purchase for industrial users under two cases. (a) Case N. (b) Case R.

Since industrial users are usually high-energy-consuming enterprises, their power bills can reach more than 50% of the total product production costs [34]. In this paper, we assume that the power costs can represent the total costs when the industrial user produces products. Moreover, because the power costs of the industrial user include the power-purchase cost p^j paid to the power plant and the wheeling cost p_G paid to the power grid company, combined with representing the power consumption of the industrial user when producing a unit product, thus, the unit product production cost of the industrial user can be expressed as $\sigma^j = \left(p^j + p_G\right)/\beta$. In addition, referring to the Cobb-Douglas production function [35], when the labor and capital input is constant, the output of the high-energy-consuming industrial user can be approximated as $\xi^j = \beta r^j$ [36]. Besides, in order to ensure that the power plant can obtain a positive profit when participating in IBDRM, we assume that the price of the direct power-purchase transaction meets $p^R > \omega_P + \left[\beta^4 \Delta q / \left(a + 2\beta^2\right)\right] - \alpha h$ and the load reduction of the industrial user meets $\Delta q > 0$.

IV. EQUILIBRIUM RESULTS UNDER CASES N AND R

In this section, we calculate the equilibrium results of each direct power-purchase transaction entity (i.e., the power grid company, the power plant, and the industrial user) under Cases N and R, respectively. On this basis, we also get the equilibrium profits of the power grid company, the power plant, and the industrial user.

A. EQUILIBRIUM RESULTS UNDER CASE N

Under Case N, this paper regards the power grid company as a social service organization without decision-making power. Meanwhile, the decision-making sequence of the other two members is as follows: The power plant takes the lead in deciding the transaction price p^N. Then, the industrial user reacts and decides its own power-purchase quantity q^N. Moreover, in the following text, we assume that under Case N, the industrial user's actual power consumption r^N is equal to its power-purchase quantity q^N.

For the power grid company, its profit is mainly composed of the income from wheeling cost, and the cost of transmission and distribution in the process of transmitting power. Hence, the profit function of the power grid company can be expressed as

$$\pi_G^N = p_G q^N - k q^N \tag{1}$$

For the power plant, its profit is mainly composed of the power sales revenue and the power generation cost. We follow [37] and [38], the power generation cost function of the power plant is expressed in the form of a quadratic function, that is, $C_P\left(q^N\right) = a\left(q^N\right)^2 + bq^N + c$. On this basis, the profit function of the power plant can be expressed as follows

$$\begin{aligned} \max_{p^N} \pi_P^N &= p^N q^N - C_P\left(q^N\right) \\ &= p^N q^N - \left[a\left(q^N\right)^2 + bq^N + c\right] \end{aligned} \tag{2}$$

For the industrial user, its profit is mainly composed of the product sales revenue and the product production cost. And we assume that the product sales price ρ^N is satisfied with $\rho^N = z - \xi^N = z - \beta q^N$ [39]. Therefore, the profit function expression of the industrial user is as follows

$$\max_{q^N} \pi_F^N = \xi^N\left(\rho^N - \sigma^N\right) = \beta q^N\left(z - \beta q^N - \frac{p^N + p_G}{\beta}\right) \tag{3}$$

By (2) and (3), adopting the backward induction method to solve the model, we can get the equilibrium power selling price of the power plant and the equilibrium power-purchase quantity of the industrial user under Case N, as shown in Lemma 1.

Lemma 1: Under Case N, the power plant's equilibrium power selling price is $p^{N*} = \frac{\left(a+\beta^2\right)\left(\beta z - p_G\right) + b\beta^2}{a + 2\beta^2}$, *the* *industrial user's equilibrium power-purchase quantity is* $q^{N*} = \frac{\beta z - b - p_G}{2(a+2\beta^2)}$.

From Lemma 1, it can be seen that under Case N, the power selling price decided by the power plant is related to the wheeling cost. Therefore, the pricing department can control the power price of direct power-purchase transactions by adjusting the wheeling cost. And for the industrial user, factors such as the production capacity and the market potential demand should be fully considered when deciding the power-purchase quantity.

According to Lemma 1, when IBDRM is not carried out, the equilibrium profits of the power grid company, the power plant, and the industrial user are $\pi_G^{N*} = \frac{(p_G-k)(\beta z-b-p_G)}{2(a+2\beta^2)}$, $\pi_P^{N*} = \frac{(\beta z-b-p_G)^2}{4(a+2\beta^2)} - c$, and $\pi_F^{N*} = \left[\frac{\beta(\beta z-b-p_G)}{2(a+2\beta^2)}\right]^2$, respectively.

B. EQUILIBRIUM RESULTS UNDER CASE R

Under Case R, the decision-making sequence of each member is as follows: First, the power grid company decides the total compensation amount h provided to the power plant and the industrial user, and the compensation received by the power plant and the industrial user can be adjusted through the distribution ratio coefficients α and $1-\alpha$. Second, the power plant decides the transaction price p^R of direct power-purchase considering the impact of IBDRM. Finally, the industrial user decides its own power-purchase quantity q^R. It should be noted that referring to [40], since the industrial user's load reduction Δq is positively correlated with its demand response compensation $(1-\alpha)h$, in order to simplify the model, this paper defines the load reduction of the industrial user as an endogenous variable, namely $\Delta q = \mu(1-\alpha)h - d$ $(\mu > 0)$. Moreover, this paper considers that the industrial user can reduce load when participating in IBDRM, which results in a part of the power being purchased but not used [17]. Therefore, under Case R, the industrial user's actual power consumption is the difference between the power purchased and the power reduced in IBDRM, namely $r^R = q^R - \Delta q$.

For the power grid company, its profit is mainly composed of the income of wheeling cost, the cost of power transmission and distribution, the expenditure of demand response compensation, and the income of IBDRM (for example, avoidable capacity cost, avoidable power cost, etc.). Consequently, the profit function of the power grid company can be specifically expressed as follows

$$\max_h \pi_G^R = p_G\left(q^R-\Delta q\right) - k\left(q^R-\Delta q\right) - h\Delta q + \lambda_G\Delta q \tag{4}$$

For the power plant, its profit is mainly composed of the power sales revenue, the power generation cost, the peak load regulation cost, and the peak load regulation compensation. Moreover, the power generation cost of the power plant is $C_P(r^R) = a(q^R-\Delta q)^2 + b(q^R-\Delta q) + c$. Ulteriorly, we can get the power plant's profit function expression is

$$\max_{p^R} \pi_P^R = p^R q^R - \left[a\left(q^R-\Delta q\right)^2 + b\left(q^R-\Delta q\right) + c\right] - \omega_P\Delta q + \alpha h\Delta q \tag{5}$$

For the industrial user, its profit is mainly composed of the product sales revenue, the product production cost, the demand response compensation income, the interruption cost, and the power-purchase cost corresponding to load reduction. Besides, the industrial user sets the product sales price ρ^R as $z-\beta\left(q^R-\Delta q\right)$, and the interruption cost function it needs to face when participating in IBDRM is $L_F(\Delta q) = \varphi(\Delta q)^2$ [29]. Therefore, the profit function of the industrial user can be expressed as

$$\max_{q^R} \pi_F^R = \beta\left(q^R-\Delta q\right)\left[z-\beta\left(q^R-\Delta q\right)-\frac{p^R+p_G}{\beta}\right] + (1-\alpha)h\Delta q - \varphi(\Delta q)^2 - p^R\Delta q \tag{6}$$

By (4)-(6), adopting the backward induction method to solve the model, we can get the equilibrium demand response compensation of the power grid company, the equilibrium power selling price of the power plant, and the equilibrium power-purchase quantity of the industrial user under Case R, as shown in Lemma 2.

Lemma 2: Under Case R, the power grid company's equilibrium demand response compensation is $h^* = \frac{\tau+2d}{2\mu(1-\alpha)}$, *the power plant's equilibrium power selling price is* $p^{R*} = \frac{(a+\beta^2)(\beta z-p_G)+b\beta^2+\beta^4\tau}{a+2\beta^2}$, *and the industrial user's equilibrium power-purchase quantity is* $q^{R*} = \frac{\beta z-b-p_G}{2(a+2\beta^2)} + \frac{(a+\beta^2)\tau}{2(a+2\beta^2)}$, *where* $\tau = \mu(1-\alpha)\left[-\frac{\beta^2(p_G-k)}{a+2\beta^2}\right] - d$.

It can be seen from Lemma 2 that the power grid company, as the executor of IBDRM, can maximize its own profit by setting the scientific compensation amount. Moreover, we can observe that when the power grid company determines the compensation amount, it should not only consider the conventional factors such as the income obtained through IBDRM and the load reduction capacity of the industrial user, but also analyze the influence of compensation ratios α and $1-\alpha$ between the power plant and the industrial user on the compensation formulation. In addition, compared with Case N, the equilibrium transaction price and the equilibrium transaction quantity of direct power-purchase under Case R are not only affected by p_G, β, and z, but also affected by the distribution ratio coefficients α and $1-\alpha$ of demand response compensation. Also, we can get the load reduction of the industrial user under Case R, i.e., $\Delta q^* = \frac{\tau}{2}$.

According to Lemma 2, the following corollary can be obtained.

Corollary 1: i) $\frac{\partial p^{R*}}{\partial \alpha} < 0$; *ii)* $\frac{\partial \Delta q^*}{\partial \alpha} < 0$ *and* $\frac{\partial q^{R*}}{\partial \alpha} < 0$.

Part i) of Corollary 1 shows that the transaction price p^{R*} decreases with the increase of α. This is because the power plant will lower its transaction price as the compensation income increases, so as to attract users through the price reduction measure. Part ii) of Corollary 1 indicates that q^{R*} is also inversely proportional to α. The reason is that with the increase of compensation proportion allocated to the power plant, even if the transaction price set by the power plant shows a decreasing trend, the benefits that the industrial user can get by participating in IBDRM is greatly discounted, which will reduce the industrial user's enthusiasm to take part in IBDRM. When the industrial user purchases power, the reserved power quantity Δq^* for IBDRM will be reduced. As a result, the power-purchase quantity of the industrial user shows a decreasing trend.

According to Lemma 2, when IBDRM is carried out, the equilibrium profits of the power grid company, the power plant, and the industrial user can be summarized as

$$\pi_G^{R*} = \frac{(p_G - k)(\beta z - b - p_G)}{2\left(a + 2\beta^2\right)} + \frac{\tau^2}{4\mu(1-\alpha)},$$

$$\pi_P^{R*} = \frac{(\beta z - b - p_G)^2}{4\left(a+2\beta^2\right)} + \frac{\beta^4\tau^2 + 2\left[\left(a+\beta^2\right)(\beta z - p_G) + b\beta^2\right]\tau}{4\left(a+2\beta^2\right)} + \left[\frac{\alpha(\tau + 2d)}{2\mu(1-\alpha)} - \omega_P\right]\frac{\tau}{2} - c,$$

and

$$\pi_F^{R*} = \left[\frac{\beta(\beta z - b - p_G)}{2\left(a+2\beta^2\right)}\right]^2 + \left\{\frac{2\left(a^2 + 3a\beta^2 + 3\beta^4\right)p_G - \beta^6\tau}{4\left(a+2\beta^2\right)^2} + \frac{(1-\mu\varphi)\tau + 2d}{4\mu} - \frac{\beta\left[2a^2 z + 2\beta\left(a+\beta^2\right)\left(b + 3\beta z + \beta^2\tau\right)\right]}{4\left(a+2\beta^2\right)^2}\right\}\tau,$$

respectively.

V. ANALYSIS AND DISCUSSION

In this section, the specific analyses are made on the impacts of IBDRM on the transaction price of direct power-purchase, the transaction quantity of direct power-purchase, the actual power consumption of the industrial user, the profits of each direct power-purchase transaction entity (i.e., the power grid company, the power plant, and the industrial user), and the consumer surplus. Based on this, we also put forward some managerial implications.

By comparing the transaction prices of direct power-purchase under Cases N and R, we generate the following proposition.

Proposition 1: $p^{R*} > p^{N*}$.

Proposition 1 indicates that compared with Case N, the transaction price of direct power-purchase under Case R is higher. This is because the industrial user who participates in IBDRM produces the power consumption fluctuation, and the power plant is affected by this and incurs additional costs (such as the peak load regulation cost). Therefore, the power plant will increase the transaction price to ensure that its own profit is not damaged. Whereas the power plant should be careful not to blindly pursue the high profit and set an excessively high power selling price, which will lead to the loss of users.

By comparing the transaction quantities of direct power-purchase under Cases N and R, we obtain the following proposition.

Proposition 2: $q^{R*} > q^{N*}$.

Proposition 2 indicates that compared with Case N, the transaction quantity of direct power-purchase under Case R is higher. This is because the industrial user will include the load reduction of IBDRM when planning the power-purchase quantity, so as to obtain the corresponding compensation benefit of this part of the load. But it is necessary for the industrial user to decide the reasonable load reduction. Because if the load reduction is too low, it will reduce the compensation that the industrial user can get through IBDRM. And if the load reduction is too high, it will cause the industrial user to bear relatively high costs, such as the product sales revenue reduction, the interruption cost, and so on.

By comparing the actual power consumptions of the industrial user under Cases N and R, we can get the following proposition.

Proposition 3: $r^{N*} > r^{R*}$ *and* $\frac{\partial r^{R*}}{\partial \alpha} > 0$.

Proposition 3 indicates that compared with Case N, the actual power consumption of the industrial user under Case R is lower. The reason for this phenomenon is that IBDRM can reduce the power consumption of the industrial user when the load of the power grid is at peak or when the power supply security is threatened. Also, r^{R*} decreases with the decrease of α. This is because the smaller α is, the larger $1-\alpha$ is, which means that the more demand response compensation the industrial user can obtain, the more incentive the industrial user is to participate in IBDRM, and the more obvious the reduction of the industrial user's actual power consumption is. Therefore, the power grid company can maintain the stability of the power grid by implementing IBDRM. The power grid company needs to balance the compensation between industrial users and power plants in order to improve the effectiveness of IBDRM. To be more specific, it is of vital importance to motivate industrial users' enthusiasm to participate in IBDRM by increasing their monetary incentives.

When exploring the willingness of direct power-purchase transaction entities to take part in IBDRM, since the power grid company, the power plant, and the industrial user pay more attention to whether IBDRM can increase their profits, this paper compares the equilibrium profits of each direct purchase transaction entity under Cases N and R, and obtains the following propositions.

Proposition 4: i)$\pi_G^{R*} > \pi_G^{N*}$*; ii)* $\pi_P^{R*} > \pi_P^{N*}$*; iii) when* $0 < \alpha < \bar{\alpha}$, $\pi_F^{R*} > \pi_F^{N*}$*; when* $\bar{\alpha} < \alpha < 1$, $\pi_F^{N*} > \pi_F^{R*}$, *where* $\bar{\alpha}$, as shown at the bottom of the next page.

Part i) of Proposition 4 indicates that the power grid company can improve its profit by carrying out IBDRM. The profit obtained by the power grid company is passive under Case N, and it turns into an active state in which the power grid company strives to maximize its own profit by setting the demand response compensation under Case R. We can see that the power grid company should implement IBDRM. IBDRM not only makes the power grid company provide the basic work of maintaining the stable operation of the power grid, but also further ensures the economic benefits of the power grid company. Part ii) of Proposition 4 shows that the profit of the power plant is improved because of the implementation of IBDRM. Under Case R, although the power plant has to bear a certain peak load regulation cost to cope with the load reduction of the industrial user, the cost expenditure of this part will be lower than the benefits (including obtaining the peak load regulation compensation, saving the power generation cost of load reduction, etc.) brought to the power plant by IBDRM. Part iii) of Proposition 4 indicates that in most situations, the development of IBDRM can increase the profit of the industrial user. The reason why the profit of the industrial user under Case R may be lower than that under Case N is that with the increase of compensation proportion allocated to the power plant, the compensation received by the industrial user is not enough to make up for the costs(including the reduction of product sales revenue, interruption cost, etc.) of participating in IBDRM. At this time, the industrial user is very likely not to participate in this activity, which is very detrimental to the development of IBDRM. Therefore, if the power grid company wants to ensure that its demand response compensation distribution proportion is reasonable, the distribution result should be able to promote the industrial user's willingness to participate in IBDRM, that is, the industrial user can improve its profit through IBDRM.

By comparing the consumer surplus under Cases N and R, the following proposition can be obtained.

Proposition 5: $CS^{N*} > CS^{R*}$.

Proposition 5 indicates that the consumer surplus under Case N is higher than that under Case R. This is because under Case R, as the industrial user participates in IBDRM, its power consumption will be reduced when producing products, resulting in a decrease in the product output. In order to protect its own profit, the industrial user will increase the sales price of products, which will reduce the consumer surplus. Hence, when organizing IBDRM, the power grid company should pay attention to control the load reduction of the industrial user. Otherwise, the industrial user may continue to increase its reduced load to obtain more demand response compensation. The excessive load reduction of the industrial user leads to a decrease in product output and an increase in product price, which will eventually destroy the stability of the industrial user's downstream market.

VI. NUMERICAL ANALYSIS

In this section, we use the numerical analysis to verify the above-mentioned main theoretical results and compare the social welfare under Cases N and R. In the process of numerical analysis, referring to [29], [40], and [41], the values of some parameters are: $a = 0.3$, $b = c = 0$, $p_G = 180$, $k = 135$, $\varphi = 2.5$, and $\mu = 0.055$. Referring to [29], [36], and [41] and based on the actual situation of our investigation, the values of other parameters are: $\omega_P = 400$, $\lambda_G = 2500$, $\beta = 2$, $z = 450$, and $d = 20$.

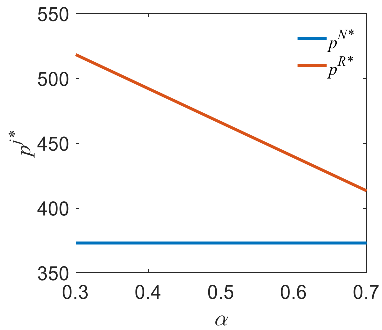

FIGURE 2. Comparison of the transaction prices of direct power-purchase under Cases N and R.

First, this paper compares the transaction prices p^{j*} of direct power-purchase under Cases N and R, as shown in Fig. 2. Compared with Case N, under Case R, the power plant increases its decision-making price. Moreover, under Case R, as the demand response compensation received increases, the power plant will continuously reduce its power selling price. This is consistent with the conclusion given in Proposition 1 and part i) of Corollary 1.

Second, this paper compares the transaction quantities q^{j*} of direct power-purchase under Cases N and R, as shown in Fig. 3. Compared with Case N, the decision-making power-purchase quantity of the industrial user is. higher under Case R. Moreover, under Case R, as the demand response compensation obtained decreases, the power-purchase quantity of the industrial user is also in a state of decreasing. This is consistent with the conclusion given in Proposition 2 and part ii) of Corollary 1.

$$\bar{\alpha} = 1 - \frac{\left(a+2\beta^2\right)\left[a^2\left(d-2\mu\beta z+d\mu\varphi\right)+2\left(a^2+3a\beta^2+3\beta^4\right)\mu p_G+\beta^6\varphi d\right]}{\mu\left[\left(1-\mu\varphi\right)\left(a+2\beta^2\right)^2-\beta^4\mu\left(2a+3\beta^2\right)\right]\left[\beta^2\left(p_G-k\right)-\left(a+2\beta^2\right)\lambda_G\right]} + \frac{\left(a+2\beta^2\right)\left\{2\beta^2\left(a+2\beta^2\right)\left[d\left(2+\mu\beta^2+2\mu\varphi\right)-\mu\left(b+3\beta z\right)\right]\right\}}{\mu\left[\left(1-\mu\varphi\right)\left(a+2\beta^2\right)^2-\beta^4\mu\left(2a+3\beta^2\right)\right]\left[\beta^2\left(p_G-k\right)-\left(a+2\beta^2\right)\lambda_G\right]}.$$

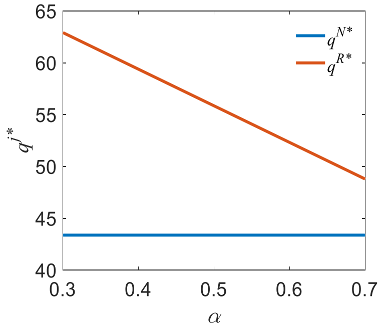

FIGURE 3. Comparison of the transaction quantities of direct power-purchase under Cases N and R.

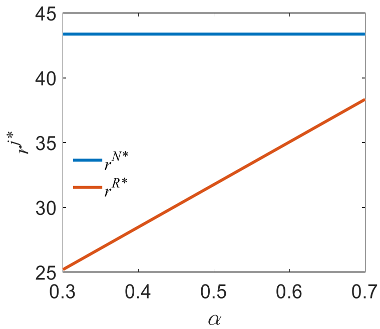

FIGURE 4. Comparison of the actual power consumptions of the industrial user under Cases N and R.

Next, we compare the actual power consumptions r^{j*} of the industrial user under Cases N and R, as shown in Fig. 4. Compared with Case N, under Case R, the industrial user will reduce power consumption during the peak load period of the power grid or the unstable period of the power system. Thus, the industrial user's final power consumption will be lower. Furthermore, the more compensation the industrial user receives, the higher its load reduction is, and the lower its final actual power consumption will be. This is consistent with the conclusion obtained in Proposition 3.

In addition, we also compare the profits of the power grid company, the power plant, and the industrial user under Cases N and R, as shown in Fig. 5. Compared with Case N, the profit of the power grid company will increase after organizing IBDRM, which is consistent with the conclusion given in part i) of Proposition 4. After the power plant participates in IBDRM, its profit will also increase, which is consistent with the conclusion given in part ii) of Proposition 4. When comparing the profit of the industrial user under Case R with that under Case N, the former is initially higher than the latter. As the compensation for the industrial user decreases, the former will eventually be lower than the latter. This is consistent with the conclusion given in part iii) of Proposition 4. In addition, under Case R, it can be found that the profit of the power grid company shows a decreasing trend with the increase of α, which is caused by the inhibition of the industrial user's enthusiasm to participate in IBDRM. The profit of the power plant increases at first and then decreases with the increase of α. This is because when the proportion of demand response compensation obtained by the power plant is small, the industrial user will receive high demand response compensation. At this time, the enthusiasm of the industrial user to participate in IBDRM is high, and the power generation cost that power plants can save due to load reduction is also high. But as the proportion of compensation received by the power plant continues to increase, the power plant will reduce its power selling price. Besides, the enthusiasm of the industrial user to participate in IBDRM is gradually reduced at this point, and the benefits brought by load reduction to the power plant are also reduced. Multiple negative effects lead to a downward trend in the profit of the power plant. Moreover, the profit of the industrial user shows a decreasing trend with the increase of α. This is because the benefits that the industrial user obtains through IBDRM are constantly declining, and even will eventually be lower than the participation cost of IBDRM borne by the industrial user.

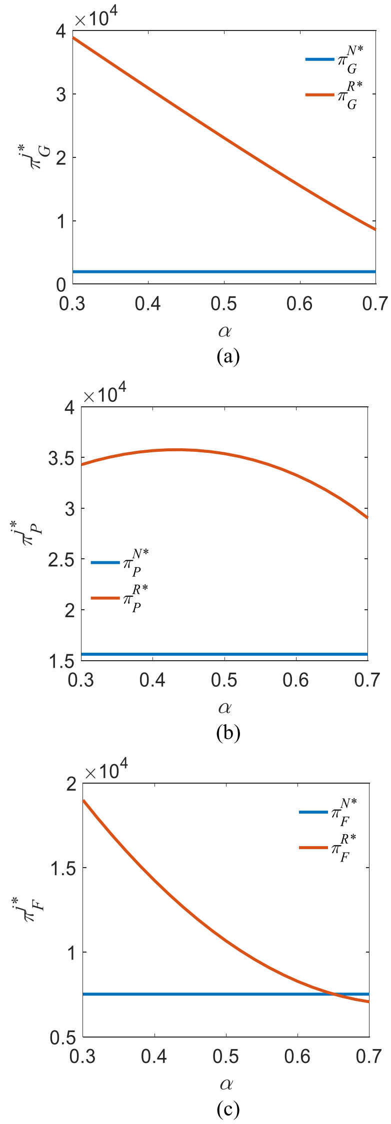

FIGURE 5. Comparison of the profits under Cases N and R. (a) The profit of the power grid company. (b) The profit of the power plant. (c) The profit of the industrial user.

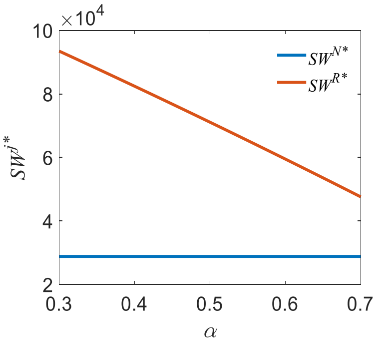

FIGURE 6. Comparison of the social welfare under Cases N and R.

Finally, because the analysis of the social welfare is complex, we performed a numerical simulation on it. We consider that the social welfare consists of four parts, namely, the profit of the power grid company, the profit of the power plant, the profit of the industrial user, and the consumer surplus in the downstream market of the industrial user. The impact of the compensation ratio α received by the power plant on the social welfare SW^{j*} is shown in Fig. 6. As can be seen from Fig. 6, IBDRM implemented by the power grid company improves the social welfare. The social welfare is inversely proportional to α, that is, it is proportional to the compensation ratio $1-\alpha$ received by the industrial user. The reason for this phenomenon is that the load reduction is ultimately sent by the industrial user. Therefore, the best way to improve the effect of IBDRM is to stimulate the industrial user's awareness of active participation. For this purpose, within a reasonable range, the power grid company should increase the compensation amount of the industrial user as much as possible.

VII. EXTENSIONS

In this section, we have two extensions: multiple industrial users and bursts of electricity demand.

A. MULTIPLE INDUSTRIAL USERS

Previously, the direct power-purchase trading system we studied consists of a power grid company, a power plant, and an industrial user. In order to study the scalability of the number of industrial users, we let the direct power-purchase trading system include a power grid company, a power plant, and T industrial users. Then, we reconstruct the profit models of each entity. Under Cases N and R, we consider that the average quantity of power purchased by each industrial user for product production is q_t^j $(t=1,\ldots,T)$ and satisfies $\sum_{t=1}^{T} q_t^j = Tq_t^j = q^j$. Moreover, under Case R, we use Δq_t to represent the average load reduction of each industrial user and satisfies $\sum_{t=1}^{T}\Delta q_t = T\Delta q_t = \Delta q$. Furthermore, under Cases N and R, we can express the profit functions of the power grid company, the power plant, and the industrial user group as follows

$$\pi_G^N = p_G\sum_{t=1}^{T} q_t^N - k\sum_{t=1}^{T} q_t^N \tag{7}$$

$$\max_{p^N} \pi_P^N = p^N\sum_{t=1}^{T} q_t^N - \left[a\left(\sum_{t=1}^{T} q_t^N\right)^2 + b\sum_{t=1}^{T} q_t^N + c\right] \tag{8}$$

$$\max_{q_t^N} \pi_F^N = \beta\sum_{t=1}^{T} q_t^N\left(z-\beta\sum_{t=1}^{T} q_t^N - \frac{p^N+p_G}{\beta}\right) \tag{9}$$

$$\begin{aligned}\max_{h} \pi_G^R &= p_G\left(\sum_{t=1}^{T} q_t^R - \sum_{t=1}^{T}\Delta q_t\right) - k\left(\sum_{t=1}^{T} q_t^R - \sum_{t=1}^{T}\Delta q_t\right)\\ &\quad - h\sum_{t=1}^{T}\Delta q_t + \lambda_G\sum_{t=1}^{T}\Delta q_t\end{aligned} \tag{10}$$

$$\begin{aligned}\max_{p^R} \pi_P^R &= p^R\sum_{t=1}^{T} q_t^R - \left[a\left(\sum_{t=1}^{T} q_t^R - \sum_{t=1}^{T}\Delta q_t\right)^2\right.\\ &\quad \left. + b\left(\sum_{t=1}^{T} q_t^R - \sum_{t=1}^{T}\Delta q_t\right) + c\right]\\ &\quad - \omega_P\sum_{t=1}^{T}\Delta q_t + \alpha h\sum_{t=1}^{T}\Delta q_t\end{aligned} \tag{11}$$

$$\begin{aligned}\max_{q_i^R} \pi_F^R &= \beta\left(\sum_{t=1}^{T} q_t^R - \sum_{t=1}^{T}\Delta q_t\right)\\ &\quad \times\left[z-\beta\left(\sum_{t=1}^{T} q_t^R - \sum_{t=1}^{T}\Delta q_t\right) - \frac{p^R+p_G}{\beta}\right]\\ &\quad + (1-\alpha)h\sum_{t=1}^{T}\Delta q_t - \varphi\left(\sum_{t=1}^{T}\Delta q_t\right)^2 - p^R\sum_{t=1}^{T}\Delta q_t\end{aligned} \tag{12}$$

By comparing the expressions in (7)-(12) with the expressions in (1)-(6) one by one, it can be seen that new equilibrium outcomes and thresholds can be obtained by replacing q^j with $\sum_{t=1}^{T} q_t^j$ and Δq with $\sum_{t=1}^{T}\Delta q_t$. Therefore, our main results still hold.

B. BURSTS OF ELECTRICITY DEMAND

The power consumed by the industrial user is mainly used to produce products [34]. Therefore, the quantity of electricity demanded by the industrial user depends on the number of products demanded by consumers in the downstream market. We divide the consumer demand for products into low demand and high demand, which are represented by subscripts L and H, respectively. Then, we use f_L and f_H to represent the probability of two situations, which meets $f_L + f_H = 1$. When the value of f_H is large, the power demand of the industrial user will burst. Furthermore, we express the profit function expressions of the industrial user under Cases N and R as

$$\begin{aligned}\max_{q^N} \pi_F^N &= f_L \beta q^N \left(z_L - \beta q^N - \frac{p^N + p_G}{\beta}\right) \\ &\quad + f_H \beta q^N \left(z_H - \beta q^N - \frac{p^N + p_G}{\beta}\right) \quad (13)\end{aligned}$$

$$\begin{aligned}\max_{q^R} \pi_F^R &= f_L \left\{\beta \left(q^R - \Delta q\right)\left[z_L - \beta\left(q^R - \Delta q\right) - \frac{p^R + p_G}{\beta}\right] \right. \\ &\quad \left. + (1-\alpha) h \Delta q - \varphi (\Delta q)^2 - p^R \Delta q\right\} \\ &\quad + f_H \left\{\beta \left(q^R - \Delta q\right)\left[z_H - \beta\left(q^R - \Delta q\right) - \frac{p^R + p_G}{\beta}\right] \right. \\ &\quad \left. + (1-\alpha) h \Delta q - \varphi (\Delta q)^2 - p^R \Delta q\right\} \quad (14)\end{aligned}$$

By comparing the expressions in (13) and (14) with the expressions in (3) and (6), respectively, it can be seen that new equilibrium outcomes and thresholds can be obtained by replacing z with $f_L z_L + f_H z_H$. Therefore, the main results still qualitatively hold.

VIII. CONCLUSION

This paper analyzes whether the power grid company should implement IBDRM from the perspective of direct power-purchase for industrial users, and discusses problems about the formulation of demand response compensation, the impact of IBDRM on the direct power-purchase transaction, the economic benefit evaluation of IBDRM, and so on. First, we build Stackelberg game models of direct power-purchase transaction entities (i.e., the power grid company, the power plant, and the industrial user), and solve the model by using backward induction. Then, we compare the equilibrium results under Cases N and R and draw the following conclusions.

First, compared with Case N, the price and the quantity of the direct power-purchase transaction under Case R both increase. Moreover, although the transaction price set by the power plant decreases with the increase of the compensation proportion, the planned power-purchase quantity of the industrial user still keeps decreasing.

Second, by implementing IBDRM, the power grid company can effectively induce the industrial user to reduce its power consumption.

Third, for the power grid company and the power plant, IBDRM increases their profits. For the industrial user, when its demand response compensation is high, its profit improves. But with the continuous decrease of compensation, the profit of the industrial user under Case R will eventually be lower than that under Case N. In addition, IBDRM also improves social welfare, so its implementation is very economical.

Based on the above conclusions, we can conclude that in the smart grid environment, the power grid company should implement IBDRM in direct power-purchase. Furthermore, the research in this paper can also provide the following managerial implications for the power grid company to carry out IBDRM in the direct power-purchase environment.

First, in the process of implementing IBDRM, the power grid company should propose the lower limit and upper limit of load reduction for industrial users. Specifically, first, by forecasting and analyzing some associated data, the power grid company sets a percentage value (that is, the proportion of load reduction of industrial users in their total power consumption). Then, the power grid company stipulates that the load reduction of industrial users shall not be lower or higher than this value.

Next, in the process of formulating IBDRM compensation, it is necessary for the power grid company to consider factors such as the benefits that can obtain through IBDRM, the capacity of industrial users to reduce load, the distribution proportion of demand response compensation between power plants and industrial users, and others.

Finally, to better promote the effect of IBDRM, the power grid company should motivate industrial users to participate in IBDRM more actively. Within the scope of reasonable compensation distribution (that is, there are no extreme situations in which all compensation is allocated to power plants or industrial users, and industrial users can be guaranteed to increase their profits by participating in IBDRM), the power grid company should increase the amount of demand response compensation set for industrial users.

In the future, our work can be extended in the following aspects. On one hand, this paper sets the load reduction amount of industrial users participating in IBDRM as an endogenous variable, which can be used as a decision variable of industrial users for further research in the future. On the other hand, this paper only considers that the direct power-purchase transaction occurs in one power plant and one industrial user. Whereas in reality, there are many power plants and industrial users in the direct power-purchase market. The decisions of power plants and industrial users will be affected by other power plants and industrial users, respectively. Therefore, future studies can explore the impacts of IBDRM of the power grid company when multiple power plants and industrial users conduct direct power-purchase transactions.

APPENDIX

Proof of Lemma 1: Adopting the backward induction method, first, by $\frac{d^2\pi_F^N}{d(q^N)^2} = -2\beta^2 < 0$, we can know that π_F^N is a concave function with regard to q^N, and there is a maximum value. Let $\frac{d\pi_F^N}{dq^N} = 0$, we can obtain the reaction function of the industrial user's power-purchase quantity as $q^N\left(p^N\right) = \frac{\beta z - p^N - p_G}{2\beta^2}$. Then, by substituting the reaction function of power-purchase quantity into (2) (namely,

$$\pi_F^{R*}-\pi_F^{N*}=\left\{\frac{2\left(a^2+3a\beta^2+3\beta^4\right)p_G-\beta^6\tau-2a^2\beta z}{4\left(a+2\beta^2\right)^2}-\frac{\beta^2\left(a+\beta^2\right)\left(b+3\beta z+\beta^2\tau\right)}{2\left(a+2\beta^2\right)^2}+\frac{\left(1-\mu\varphi\right)\tau+2d}{4\mu}\right\}\tau=0,$$

$$\bar{\alpha}=1-\frac{\left(a+2\beta^2\right)\left[a^2\left(d-2\mu\beta z+d\mu\varphi\right)+2\left(a^2+3a\beta^2+3\beta^4\right)\mu p_G+\beta^6\varphi d\right]}{\mu\left[\left(1-\mu\varphi\right)\left(a+2\beta^2\right)^2-\beta^4\mu\left(2a+3\beta^2\right)\right]\left[\beta^2\left(p_G-k\right)-\left(a+2\beta^2\right)\lambda_G\right]}+\frac{\left(a+2\beta^2\right)\left\{2\beta^2\left(a+2\beta^2\right)\left[d\left(2+\mu\beta^2+2\mu\varphi\right)-\mu\left(b+3\beta z\right)\right]\right\}}{\mu\left[\left(1-\mu\varphi\right)\left(a+2\beta^2\right)^2-\beta^4\mu\left(2a+3\beta^2\right)\right]\left[\beta^2\left(p_G-k\right)-\left(a+2\beta^2\right)\lambda_G\right]}.$$

the profit function of the power plant π_P^N), we can also prove the concavity of the function by $\frac{d^2\pi_F^N}{d(p^N)^2}=-\frac{a+2\beta^2}{2\beta^4}<0$. Let $\frac{d\pi_P^N}{dp^N}=0$, we can obtain the equilibrium transaction price of direct power-purchase under Case N is $p^{N*}=\frac{(a+\beta^2)(\beta z-p_G)+b\beta^2}{a+2\beta^2}$. Finally, by collating, we can obtain the equilibrium transaction quantity of direct power-purchase is $q^{N*}=\frac{\beta z-b-p_G}{2(a+2\beta^2)}$. Lemma 1 holds.

Proof of Lemma 2: Adopting the backward induction method, first, by $\frac{d^2\pi_F^R}{d(q^R)^2}=-2\beta^2<0$, we can know that π_F^R is a concave function with regard to q^R, and there is a maximum value. Let $\frac{d\pi_F^R}{dq^R}=0$, we can obtain the reaction function of the industrial user's power-purchase quantity as $q^R\left(h,p^R\right)=\frac{\beta z-p^R-p_G}{2\beta^2}+\mu\left(1-\alpha\right)h-d$. Then, by substituting the reaction function of power-purchase quantity into (5) (namely, the profit function of the power plant π_P^R), we can also prove the concavity of the function by $\frac{d^2\pi_P^R}{d(p^R)^2}=-\frac{a+2\beta^2}{2\beta^4}<0$. Let $\frac{d\pi_P^R}{dp^R}=0$, we can obtain the reaction function of the power plant's sales price as $p^R\left(h\right)=\frac{(a+\beta^2)(\beta z-p_G)+b\beta^2+2\beta^4[\mu(1-\alpha)h-d]}{a+2\beta^2}$. Next, by substituting the reaction function of the sales price into (4) (namely, the profit function of the power grid company π_G^R), we can also prove the concavity of the function by $\frac{d^2\pi_G^R}{dh^2}=-2\mu\left(1-\alpha\right)<0$. Let $\frac{d\pi_G^R}{dh}=0$, so the equilibrium demand response compensation of the power grid company is $h^*=\frac{\tau+2d}{2\mu(1-\alpha)}$. Finally, by collating, we can obtain under Case R, the equilibrium transaction price of direct power-purchase is $p^{R*}=\frac{(a+\beta^2)(\beta z-p_G)+b\beta^2+\beta^4\tau}{a+2\beta^2}$, and the equilibrium transaction quantity of direct power-purchase is $q^{R*}=\frac{\beta z-b-p_G+(a+\beta^2)\tau}{2(a+2\beta^2)}$. Lemma 2 holds.

Proof of Corollary 1: First, we prove i). From Lemma 2, we can know that $\frac{\partial p^{R*}}{\partial\alpha}=-\frac{\mu\beta^4}{a+2\beta^2}\left[\lambda_G-\frac{\beta^2(p_G-k)}{a+2\beta^2}\right]<0$. Then, we prove ii). Specifically, $\frac{\partial\Delta q^*}{\partial\alpha}=-\frac{\mu}{2}\left[\lambda_G-\frac{\beta^2(p_G-k)}{a+2\beta^2}\right]<0$, $\frac{\partial q^{R*}}{\partial\alpha}=-\frac{\mu(a+\beta^2)}{2(a+2\beta^2)}\left[\lambda_G-\frac{\beta^2(p_G-k)}{a+2\beta^2}\right]<0$.In summary, Conclusion 1 holds.

Proof of Proposition 1: Based on Lemmas 1 and 2, we can know that $p^{R*}-p^{N*}=\frac{\beta^4}{a+2\beta^2}\tau>0$. Proposition 1 holds.

Proof of Proposition 2: Based on Lemmas 1 and 2, we can know that $q^{R*}-q^{N*}=\frac{a+\beta^2}{2(a+2\beta^2)}\tau>0$. Proposition 2 holds.

Proof of Proposition 3: First, based on Lemmas 1 and 2, we can know that $r^{N*}=q^{N*}=\frac{\beta z-b-p_G}{2(a+2\beta^2)}$ and $r^{R*}=q^{R*}-\Delta q=\frac{\beta z-b-p_G}{2(a+2\beta^2)}-\frac{\beta^2}{2(a+2\beta^2)}\tau$. Then, we can get that $r^{N*}-r^{R*}=\frac{\beta^2}{2(a+2\beta^2)}\tau>0$, and $\frac{\partial r^{R*}}{\partial\alpha}=\frac{\mu\beta^2}{2(a+2\beta^2)}\times\left[\lambda_G-\frac{\beta^2(p_G-k)}{a+2\beta^2}\right]>0$. Proposition 3 holds.

Proof of Proposition 4: First, we prove i). The difference between the power grid company's profit under Case R and that under Case N is $\pi_G^{R*}-\pi_G^{N*}=\frac{\tau^2}{4\mu(1-\alpha)}>0$. Then, we prove ii). The difference between the power plant's profit under Case R and that under Case N is $\pi_P^{R*}-\pi_P^{N*}=\frac{\beta^4\tau^2+2[(a+\beta^2)(\beta z-p_G)+b\beta^2]\tau}{4(a+2\beta^2)}+\left[\frac{\alpha(\tau+2d)}{2\mu(1-\alpha)}-\omega_P\right]\frac{\tau}{2}>0$.

Finally, we proof iii). When the industrial user's profit under Case R is equal to that under Case R, that is $\pi_F^{R*}-\pi_F^{N*}$, as shown at the top of the page, we can obtain the critical value of α as $\bar{\alpha}$, as shown at the top of the page.

In summary, Proposition 4 holds.

The proof of Proposition 5: Based on Lemmas 1 and 2, we can know that the consumer surplus under Case N is $CS^{N*}=\int_{\rho^{N*}}^{z}\zeta^N\left(\rho^N\right)d\rho^N=\int_{\rho^{N*}}^{z}z-\rho^N d\rho^N=\frac{(z-\rho^{N*})^2}{2}=\frac{[z-(z-\beta q^{N*})]^2}{2}=\frac{\beta^2(q^{N*})^2}{2}=\frac{\beta^2(r^{N*})^2}{2}$, and the consumer surplus under Case R is $CS^{R*}=\int_{\rho^{R*}}^{z}\zeta^R\left(\rho^R\right)d\rho^R=\int_{\rho^{R*}}^{z}z-\rho^R d\rho^R=\frac{(z-\rho^{R*})^2}{2}=\frac{\{z-[z-\beta(q^{R*}-\Delta q^*)]\}^2}{2}=\frac{\beta^2(q^{R*}-\Delta q^*)^2}{2}=\frac{\beta^2(r^{R*})^2}{2}$. Combining $r^{N*}-r^{R*}>0$ of Proposition 3, we can obtain that $CS^{N*}-CS^{R*}>0$. Proposition 5 holds.

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