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Optimal Bidding Strategy for a Power Producer Under Monthly Pre-Listing Balancing Mechanism in Actual Sequential Energy Dual-Market in China

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ABSTRACT At present, electricity transaction in China is mainly conducted by medium- and long-term market contracts, while the spot electricity market has not yet been implemented. An appropriate energy imbalance processing mechanism for medium- and long-term power transactions is highly demanded for maintaining the stability of market operation, since it is supposed to guide market participants to reduce system imbalances and actively provide balancing services. Given this background, a bi-level optimization model for developing optimal bidding strategies of power producer in the monthly sequential contract and balancing markets is proposed based on the currently implemented monthly pre-listing balancing mechanism in China. In the upper level of the model, the monthly utility which makes a tradeoff between revenues and risks produced by the bidding strategy of the producer in the monthly sequential energy dual-market is maximized, considering the uncertainties of the monthly energy imbalances in the power system and the bidding strategies of rivals. In the lower level, the dispatch cost is minimized by simulating the three-stage process of sequential system operation, which includes contract market clearing by power exchange (PX), energy decomposition and modification by the system operator (SO) and balancing market clearing by PX. The simulation results of an eastern provincial electricity market in China show that the presented model can assist power producers in adjusting their monthly bidding strategies with relevant factors, such as the minimum output level of each producer, risk preference, and forecast information including system energy imbalance status and bidding strategies of rivals. In addition, the proposed method is also helpful for market designers in setting market parameters, such as government-authorized contract energy proportion and settlement thresholds in the balancing market.

INDEX TERMS Bidding strategy, medium- and long-term market, imbalance processing mechanism, balancing market, monthly pre-listing balancing mechanism.

ABBREVIATIONS

AGC	Automatic Generation Control
BM	Balancing Market
BMU	Balancing Mechanism Unit
BRP	Balance Responsible Party
BS	Balancing Service
CM	Contract Market
EBSC	Electricity Balancing Significant Code
EIS	Energy Imbalance Service
FPN	Final Physical Notification
LMP	Locational Marginal Price
MCP	Marginal Clearing Price
MPBM	Monthly Pre-Listing Balancing Mechanism
NEM	National Electricity Market
NETA	New Electricity Trading Arrangement
NG	National Grid
Ofgem	Office of Gas and Electricity Markets

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PAB	Pay as Bid
PDF	Probability Distribution Function
PX	Power Exchange
RPM	Regulation Power Market
Rule MLT	Basic Rule of the Medium- and Long-term Market
SBP	System Buy Price
SO	System Operator
SPP	Southwest Power Pool
SSP	System Sell Price
TES	Transactive Energy System
UC	Unit Commitment
WPP	Wind-power Producer

I. INTRODUCTION

At present, electricity transaction in China is mainly conducted by medium- and long-term contracts. Since the new round of power industry reform in 2015, the trading electricity volume in China has been constantly increasing. In the first half of 2018, the total traded electrical energy reached over 800 TWh, experiencing an annual growth of 24.6%. Imbalances between the actual consumption and the contract volume are inevitable due to the fluctuation in both generation and demand [1]. In the case that the spot electricity market system has not yet been implemented in China, dealing with the imbalances to ensure the security and stability of the power system and safeguarding the interests of market participants is an important issue to be examined. It is worth to mention that power exchange (PX) and system operator (SO) are two separate organizations in China. PX is responsible for market clearing while SO is in charge of the real-time dispatch of power producers in each time period. In September 2016, Basic Rule of the Medium- and Long-term Market (Rule MLT) [2] was issued by National Development and Reform Commission and National Energy Administration of China. Rule MLT provides guidance for the processing of the electrical energy imbalances in medium- and long-term market of China, in which monthly pre-listing balancing mechanism (MPBM) is highly recommended. Several provinces issued their own implementation documents immediately following the recommendation to actively address the energy imbalances.

Generally, there is a wide range of balancing mechanisms concerning different time-scales and different participants during power system operation. On generation side, for instance, Automatic Generation Control (AGC) is responsible for maintaining the system frequency to the nominal value in response to real-time power balance [3]. Besides, both margins UP/DOWN from hydro-units and gas compression in gas supply pipes for thermal units are ultra-short-term control mechanism primarily for system security. As for the MPBM in China, it is set to address the monthly energy imbalance of the power system using a more market-oriented and economical method on a monthly timescale, so as to make a smooth transition before the spot electricity market is implemented in China. Apart from balancing mechanisms which focus on regulations of power generation, there are also balancing mechanisms such as load control at distribution level that results in contributions at transmission level. In [4], a new scheme of proactive building demand participation is presented, which enables buildings to express their energy consumption preferences to smart gird operators. A mixed integer second-order cone programming formulation for the security and chance-constrained unit commitment problem considering wind fluctuations is presented in [5]. A distributed computational approach for a distribution system market where participants play a role in determining bilateral transactions is presented in [6].

To address the energy imbalances through market-oriented ways, real-time market clearing to adjust real-time imbalances with day-ahead market using Locational Marginal Price (LMP) is applied in the PJM Market of the US [7]–[8]. Similarly, a combination of real-time market clearing and post-settlement is also applied in the National Electricity Market (NEM) of Australia [9]. On the other hand, the Regulation Power Market (RPM) of the Nord Pool [10], the Energy Imbalance Service (EIS) Market of the Southwest Power Pool (SPP) [11] and the Balancing Mechanism (BM) of the UK [12] specifically are balancing markets that are already established. The balancing market is operated after the year-ahead, month-ahead, day-ahead and intra-day markets to ensure power balance of the power system in short term [13]. Despite a small percentage of the transaction electricity volume in the RPM, EIS and BM (e.g., the volume in BM accounts for only about 3% of the total volume [14]), the mechanism designs and parameter settings of the balancing market play a crucial role in the stable operation of the power system. A three-layer system designed for the balancing market is proposed in [13], i.e., balancing planning, provision and settlement. The system is then applied to measure market conditions, performance and development of the European balancing market, indicating that the timing of the balancing market and the imbalance pricing mechanism have large impacts on the incentives of the Balance Responsible Party (BRP) to reduce imbalances. Based on a comprehensive review of the balancing market in Spain, policy recommendation on balancing products is given in [15], which includes the separation of capacity and energy products as well as upward and downward products. In [16], the settlement rule and scoring rule of the balancing market are analyzed, with the feasibility and superiority of uniform pricing and capacity cost plus energy cost that the German balancing market demonstrated. An agent-based model is established in [17] to evaluate the imbalance pricing mechanism. Analytical results show that the single pricing mechanism provides effective economic signals for the market as well as reduces imbalance costs of BRP. In [18], agent-based modelling is further explored to facilitate the design of Transactive Energy System (TES) framework, which permits the power to be efficiently balanced across the entire power system by demand response programs as well as flexible market-based provision of power and ancillary services. A market-based imbalance settlement model is developed in [19], demonstrating that compared with the exogenous penalty mechanism, the market-based mechanism achieves better trade-offs between resource efficiency and bid appropriateness.

Under different mechanism designs and parameter settings of the balancing markets, market behaviors and strategies of power producers are crucial to reflect the effectiveness of the rule. The phenomenon of "negative price" in the European balancing market is presented in [20], attributed to participation of the renewable energy in the low-load period, which is demonstrated as a market signal for the investment in flexible resources. By fully utilizing the regulation capacity to maximize the profit of the wind farm and energy storage system union, a coordinated strategy for balancing market bidding and real-time operation of the union is proposed in [21]. In order to realize the maximum economy of micro-grid aggregators in the sequential day-ahead and balancing markets, the optimal bidding and centralized self-scheduling strategy is proposed in [22]. In [23], coordinated bidding of the power producer in the sequential day-ahead and balancing markets is studied. The bidding process is formulated as a multi-stage stochastic program considering the sequential markets clearing and the price uncertainties. By modeling a multi-stage risk-constrained process of a wind-power producer (WPP) participating in the sequential day-ahead and balancing markets, the optimal offering strategy of WPP is developed in [24], demonstrating that WPP has limited market power and tends to behave as a price-taker in the balancing market.

At present, power transaction in China is mainly carried out in year-ahead and month-ahead markets, which are typical medium- and long-term power markets. Besides, spot market system is not formally introduced into China's electricity market. Since electrical energy remains the subject matter of the power transaction influenced by the traditional planned dispatch mode in China. Therefore, it is necessary for SO to decompose the electrical energy into electrical power of each period during real power dispatch. Accordingly, MPBM is specifically introduced to address the monthly energy imbalances using a more market-oriented way, serving as a transition to the establishment of spot market in the foreseeable future. MPBM is quite different from other balancing markets in terms of operation process and timescale for balancing service dispatch. Therefore, this paper is presented to provide a new tool to build bidding strategies for power producers under the monthly sequential energy dual-market mode in MPBM for Chinese wholesale power market. It is also aimed at providing basis for design of power markets which do not have a spot market system but intend to be deregulated gradually.

Given this background, the overall bidding problem of the power producer is constructed as a bi-level model with a two-stage optimization. It is assumed that the power producer builds its strategic bidding strategies including optimal bid in the monthly contract market (CM) and optimal bid/offer in the balancing market (BM) based on its expectations on rivals' behaviors and the monthly energy imbalance of the power system, while the SO will use the dispatch strategy that minimizes dispatch cost in the CM and the BM respectively. It is also supposed that all generation units that participate in the market are always on without considering unit commitment (UC). This is based on the fact that during current market transition period in China, there is no market-oriented unit commitment mechanism, and power dispatch is still based on the principle of "fair, open and just" by SO. Therefore, large scale units are seldom shut down except for scheduled maintenance. The aims and contributions of this paper are identified as follows:

1) The three-stage process of sequential system operation under MPBM is simulated to minimize the total generation cost, which better fits to the actual market operation without spot market system. The three-stage process is designed to begin with monthly contract market clearing by PX at the end of previous month, follow by scheduled energy decomposition by SO immediately afterwards, and end with balancing market clearing by PX at the end of current month.
2) A decision-making model of the optimal bidding strategy of the producer in actual sequential and coupling energy dual-market under MPBM in China is developed, which provides a new method not only for producers to adjust their optimal bidding strategy under the sequential energy dual-market environment, but also for market designers to improve overall performance of the market under MPBM by setting and adjusting market parameters.

The rest of the paper is organized as follows: the framework of the monthly sequential energy dual-market including the monthly contract and balancing markets in China is described in Section II. Next, a bi-level optimization model for optimal bidding strategies of the power producer in the monthly sequential energy dual-market is established and formulated in Section III. The solution procedure of the model is also presented in this section. Case studies are given in Section IV by using data of a provincial electricity market in China. Finally, conclusions are put forward in Section V.

II. MARKET BACKGROUND OF POWER PRODUCER'S BIDDING

A. ENERGY IMBALANCE PROCESSING MECHANISM IN CHINA

Energy imbalances in the medium- and long-term market of China are inevitable, since they are mainly generated from load forecast errors of SO as well as failure of producers to meet their obligation determined in the contract market. FIGURE 1 gives out the forecast and actual volume of the monthly power consumption of Anhui Province, China in 2017. To address the problem, four kinds of energy imbalances processing mechanisms are put forward in Rule MLT, namely MPBM, daily pre-listing balancing mechanism, equal proportion adjustment and rolling adjustment. Among them,

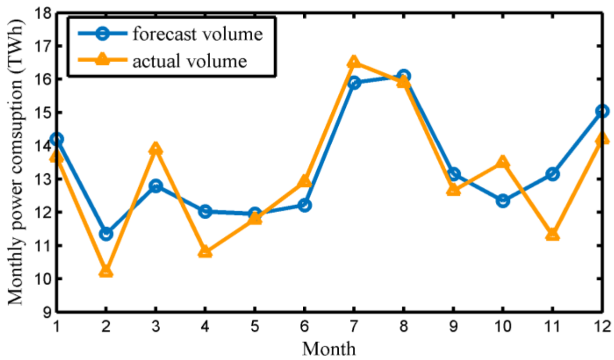

FIGURE 1. Forecast and actual volume of the monthly power consumption of Anhui Province, China in 2017.

the first two reflect the willingness of power producers to provide balancing services (BSs), while the last two depend more on the discretionary power of SO. Under MPBM, which is strongly recommended by Rule MLT, PX adjusts producers' outputs upward/downward according to their offers/bids in the last 7 days of every month, aiming at the minimum cost to handle the monthly energy imbalances of the power system. The timescale of the last 7 days allows PX to make a more precise week-ahead forecast for the total monthly demand.

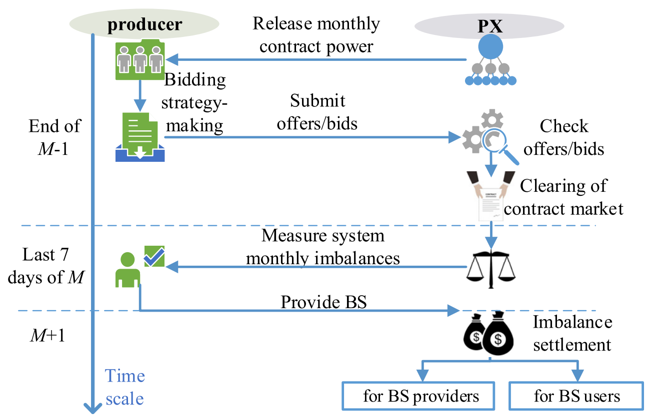

FIGURE 2. Process of the energy imbalances processing and settlement.

The monthly sequential energy dual-market is established with the introduction of MPBM, which includes the monthly CM and the BM. The process of handling and settling energy imbalances of the system in the current month M under MPBM is illustrated in FIGURE 2. At the end of month $M-1$, power producers submit their biddings to the dual-market. The two markets are sequential and coupled, since the CM is cleared at the end of month $M-1$ while the BM is cleared at the end of month M. Both the clearing results of the CM and the BM should be considered during the settlement period. The imbalance settlement consists of payments for BS providers and penalties for BS users. Note that the settlement threshold is set in the BM, for the purpose of damping unintended rewards and penalties due to stochastic variations, with the same effect as the dead zone in the performance-based regulation (PBR) [25]. This means that PX only pay/charge BSs provided/used beyond the threshold with its financial balancing account bilaterally regulated.

TABLE 1. Comparisons of Monthly Sequential Energy Dual-Market In China.

	Monthly contract market（CM）	Balancing market（BM）
Market participants	Producers/consumers	Producers
Total trading energy	Known before biddings	Unknown before biddings
Offer/bid	Offer	Offer & bid
Clearing objective	Minimum cost	Minimum cost
Clearing time	End of month *M*-1	Day *D*-6 of month *M*
Clearing mode	Energy clearing	Energy clearing
Settlement mode	Marginal clearing price（MCP）	Pay as Bid（PAB）
Settlement volume	Overall energy	Energy beyond threshold

Detailed characteristics of the monthly sequential energy dual-market in month M are compared in TABLE 1. D is the total number of days per month. Similar to California's power market in 1990s, PX and SO are two separate organizations in charge of the power transaction and the power dispatch respectively in China. Besides, total monthly electrical energy signed in the CM needs to be decomposed into electrical power of each time period according to the typical daily load curves by SO for the purpose of power dispatch [26]. Therefore, the monthly scheduled energy decomposition should be carried out immediately after the CM is cleared.

According to Rule MLT, the overall operation process of the monthly market under MPBM of China is shown in FIGURE 3 (a) and presented as follows:

a) At the end of month M-1, producers submit their biddings to both the CM and the BM. After the CM is cleared by PX in a centralized mode, the total monthly scheduled energy of each producer is given by PX and the specific scheduling for each hour is determined by SO based on energy decomposition algorithm.

b) From day 1 to day $D-7$ of month M, dispatch curves of all producers are adjusted with equal ratio by SO, which is a traditional non-economical method to realize real-time electrical power balance of the power system.

c) At the day $D-6$ of month M, the BM is cleared merely on the power producer's side, based on a more precise monthly imbalance determined a week in advance. In this way, dispatch curves of the last 7 days in month M are adjusted economically by SO based on the clearing results of the BM, so as to make up for the deficiency of the non-economic dispatch from day 1 to day $D-7$. It should be noted that the shapes of dispatch curves of all producers remain unchanged during the BS dispatch, since the BS dispatch is realized by electrical energy balance rather than electrical power balance.

d) After the BS dispatch in month M, imbalance settlement is performed both for BS providers and BS users. As for

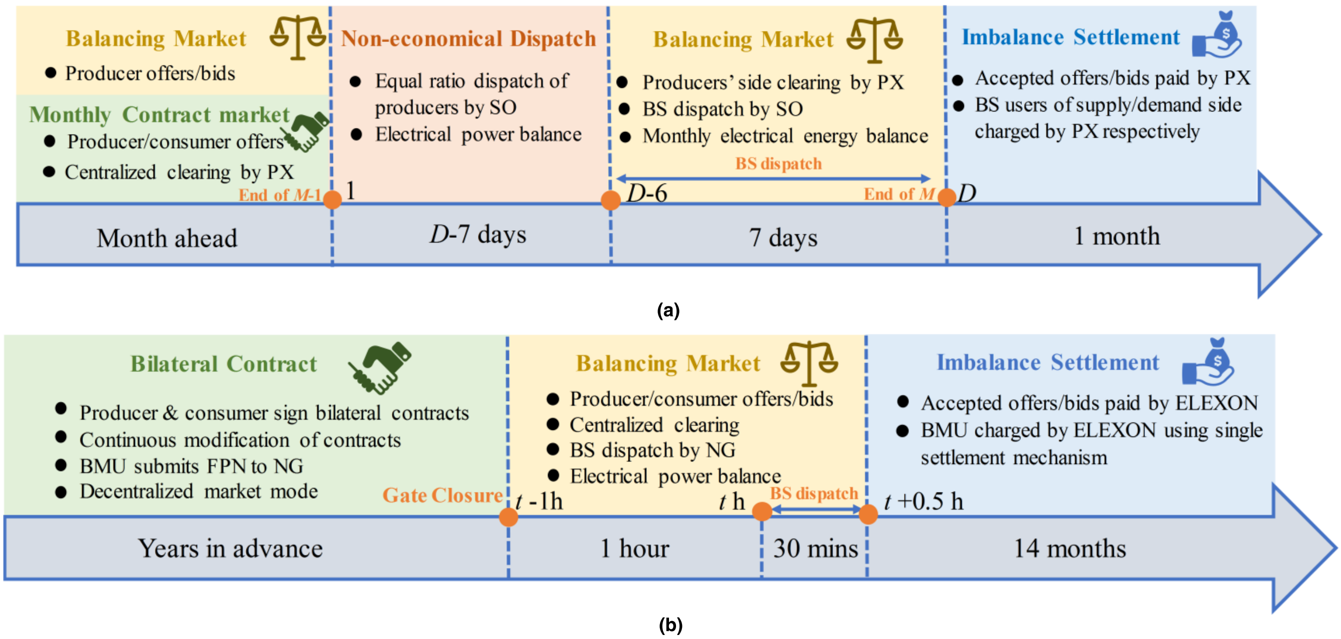

FIGURE 3. A comparison between the MPBM of China and the BM of the UK. (a) The MPBM of China. (b) The BM of the UK.

BS providers, i.e. power producers, accepted offers/bids are compensated by PX. As for BS users on both supply and demand side, penalties are charged by PX respectively.

B. COMPARISON OF THE BM IN THE UK AND THE MPBM IN CHINA

The MPBM has certain similarities with the BM of the UK. After the introduction of the New Electricity Trading Arrangement (NETA) in the UK, the BM is operated on the basis of bilateral contracts by National Grid (NG), and plays a vital role in keeping the balance of the system. The overall market operation process under the BM of the UK is shown in FIGURE 3 (b).

a) Bilateral contracts are signed by producers and consumers in a decentralized market mode years in advance. These contracts can be continuously modified until the Final Physical Notification (FPN) of each Balancing Mechanism Unit (BMU) is submitted to the NG.

b) After gate closure at $t - 1$ of each trading period, balancing services are purchased by NG based on FPN of BMU, aiming at the minimum BS dispatch cost [12]. Different from the MPBM in China, both producers and consumers can provide balancing services in the UK. One hour after the gate closure, BS dispatch is performed by NG, which lasts for 30 minutes.

c) After the power dispatch, the balancing settlement is conducted by ELEXON according to the Electricity Balancing Significant Code (EBSC). During the imbalance settlement, Pay as Bid mode is applied to BS providers while System Sell Price (SSP) and System Buy Price (SBP) were settlement prices for BS users. Office of Gas and Electricity Markets (Ofgem) has been making continuous assessment and innovation to the BM. In 2014, the EBSC Review (final draft) [27] was proposed, in which transformation from dual settlement into single settlement was put forward, aiming at providing more effective economic signals for the system and motivating market members to achieve system balance.

FIGURE 3 also shows a comparison between the MPBM of China and the BM of the UK. Despite some similarities in the bidding and settlement modes, there exist great differences with regard to time points of biddings, members of BS providers, units for imbalance settlement, etc. Note that one major difference lies in the timescale of the whole market operation process from bilateral contract to imbalance settlement. Furthermore, electrical power balance is realized in the UK while electrical energy balance for the whole month is realized in China.

III. DECISION FRAMEWORK OF POWER PRODUCER'S BIDDINGS UNDER MPBM IN CHINA

A. REVENUES AND RISKS OF PRODUCERS IN THE MONTHLY SEQUENTIAL ENERGY DUAL-MARKET

The bi-level decision framework of the optimal bidding of producer i in month M is shown in FIGURE 4, illuminating the complete process of biddings of producers, clearing and settlement of the dual-market. In the upper level, the optimal strategy-making process of producer i is given. First of all, information including transaction electrical energy issued by PX as well as the estimation of the biddings of rivals p_{-i} and the monthly energy imbalances of the power system ΔQ is collected by producer i. Next, both revenues and risks produced by the bidding strategy of producer i in the monthly contract and balancing markets are calculated based on the market settlement rule. Finally, the bidding strategy

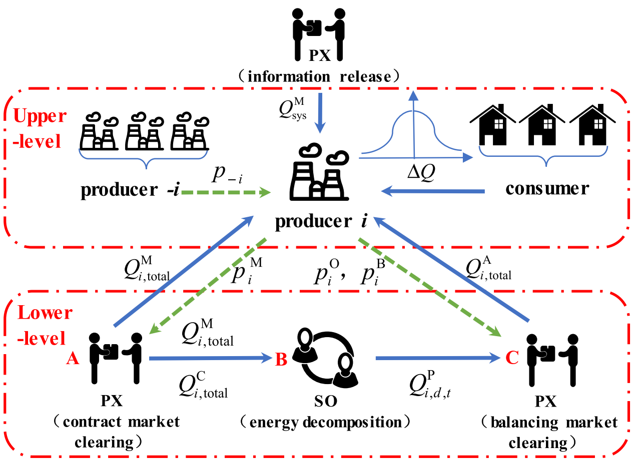

FIGURE 4. Framework of the optimal bidding strategy of power producer under monthly sequential energy dual-market.

of producer i which makes a trade-off between revenues and risks in the monthly sequential energy dual-market is made.

In the lower level, the three-stage process of real market operation including contract market clearing by PX (module A), scheduled energy decomposition by SO (module B) and balancing market clearing by PX (module C) is simulated in sequence. By transmitting producer's biddings p_i^{M}, p_i^{O} and p_i^{B} downward and market clearing results $Q_{i,\mathrm{total}}^{\mathrm{A}}$ and $Q_{i,\mathrm{total}}^{\mathrm{A}}$ upward, the two levels are closely bound.

For producer i, the monthly total scheduled energy $Q_{i,\mathrm{total}}^{\mathrm{P}}$ is composed of the monthly government-authorized contract energy $Q_{i,\mathrm{total}}^{\mathrm{C}}$ and the monthly contract energy $Q_{i,\mathrm{total}}^{\mathrm{M}}$ which is cleared by PX in module A. They are respectively presented as:

$$Q_{i,\mathrm{total}}^{\mathrm{P}} = Q_{i,\mathrm{total}}^{\mathrm{M}} + Q_{i,\mathrm{total}}^{\mathrm{C}} \tag{1}$$

$$Q_{i,\mathrm{total}}^{\mathrm{C}} = \gamma_i^{\mathrm{m}} \cdot Q_{i,\max}^{\mathrm{P}} \tag{2}$$

where $Q_{i,\max}^{\mathrm{P}}$ represents the maximum monthly scheduled generating capacity of producer i. The market openness index γ_i^{m} given indicates the proportion of government-authorized contract energy and is strictly under government regulations, which guarantees the basic generation output of each producer. China has been taken a prudent attitude since the electricity market-oriented reform in 2003. The setting of γ_i^{m} is a method for government to introduce a partial energy competition and reflects its attitude to open up the power market gradually.

For producer i, the total monthly revenue R_i is composed of three parts, which is presented as :

$$R_i = R_i^{\mathrm{C}} + R_i^{\mathrm{M}} + R_i^{\mathrm{A}} \tag{3}$$

where revenues of government-authorized energy R_i^{C}, contract energy R_i^{M} and balancing energy R_i^{A} including up-regulation R_i^{O} and down-regulation R_i^{B} are respectively expressed as:

$$R_i^{\mathrm{C}} = (\, p_i^{\mathrm{C}} - c_i\,) \cdot Q_{i,\mathrm{total}}^{\mathrm{C}} \tag{4}$$

$$R_i^{\mathrm{M}} = (\, p^{\mathrm{M}} - c_i\,) \cdot Q_{i,\mathrm{total}}^{\mathrm{M}} \tag{5}$$

$$R_i^{\mathrm{A}} = \begin{cases} R_i^{\mathrm{O}} & (\text{if } \Delta Q > 0) \\ R_i^{\mathrm{B}} & (\text{if } \Delta Q < 0) \end{cases} \tag{6}$$

$$R_i^{\mathrm{O}} = (p^{\mathrm{M}} - c_i) \cdot Q_{i,\mathrm{total}}^{\mathrm{A}} + (p_i^{\mathrm{O}} - p^{\mathrm{M}}) \cdot Q_{i,\mathrm{total}}^{\mathrm{Oc}} \tag{7}$$

$$R_i^{\mathrm{B}} = (p^{\mathrm{M}} - c_i) \cdot Q_{i,\mathrm{total}}^{\mathrm{A}} - p_i^{\mathrm{B}} \cdot Q_{i,\mathrm{total}}^{\mathrm{Bc}} \tag{8}$$

where c_i represents the generation cost of producer i, which is calculated by the average coal consumption of the producer [28]. p_i^{C} indicates the settlement price for government-authorized energy and p^{M} is the MCP in the CM. $Q_{i,\mathrm{total}}^{\mathrm{A}}$ denotes the total monthly balancing energy of producer i, and is defined as:

$$Q_{i,\mathrm{total}}^{\mathrm{A}} = \sum_{d=1}^{D}\sum_{t=1}^{T} Q_{i,d,t}^{\mathrm{R}} - \sum_{d=1}^{D}\sum_{t=1}^{T} Q_{i,d,t}^{\mathrm{P}} \tag{9}$$

where T means the total number of dispatch periods of each day. $Q_{i,d,t}^{\mathrm{P}}$ and $Q_{i,d,t}^{\mathrm{R}}$ represent the decomposed scheduled power and the actual generating power of producer i at time period t of day d, respectively. $Q_{i,\mathrm{total}}^{\mathrm{Oc}}$ and $Q_{i,\mathrm{total}}^{\mathrm{Bc}}$ denote the balancing energy settled for up-regulation and down-regulation services under corresponding market settlement thresholds β^{O} and β^{B}, and are respectively represented as:

$$Q_{i,\mathrm{total}}^{\mathrm{Oc}} = \begin{cases} 0 & (\text{if } Q_{i,\mathrm{total}}^{\mathrm{A}} \le \beta^{\mathrm{O}} \cdot Q_{i,\mathrm{total}}^{\mathrm{P}}) \\ Q_{i,\mathrm{total}}^{\mathrm{A}} - \beta^{\mathrm{O}} \cdot Q_{i,\mathrm{total}}^{\mathrm{P}} & (\text{if } Q_{i,\mathrm{total}}^{\mathrm{A}} > \beta^{\mathrm{O}} \cdot Q_{i,\mathrm{total}}^{\mathrm{P}}) \end{cases} \tag{10}$$

$$Q_{i,\mathrm{total}}^{\mathrm{Bc}} = \begin{cases} 0 & (\text{if } 0 < -Q_{i,\mathrm{total}}^{\mathrm{A}} \le \beta^{\mathrm{B}} \cdot Q_{i,\mathrm{total}}^{\mathrm{P}}) \\ Q_{i,\mathrm{total}}^{\mathrm{A}} - \beta^{\mathrm{B}} \cdot Q_{i,\mathrm{total}}^{\mathrm{P}} & (\text{if } -Q_{i,\mathrm{total}}^{\mathrm{A}} > \beta^{\mathrm{B}} \cdot Q_{i,\mathrm{total}}^{\mathrm{P}}) \end{cases} \tag{11}$$

where β^{O} and β^{B} are set diversely under rules of each province in China [2] (e.g., ±2% in Guangdong province and +6%,−2% in Shandong province).

Considering market uncertainties, the revenue R_i^{M} and R_i^{A} are defined as random variables. The monthly utility index U_i is introduced, so that a trade-off can be made between revenues and risks produced by the bidding strategy of producer i in the monthly dual-market. In the upper level, U_i is maximized for the optimal bidding strategy, thus the model is presented as:

$$\max_{p_i^{\mathrm{M}}, p_i^{\mathrm{O}}, p_i^{\mathrm{B}}} U_i = R_i - 0.5A_i \cdot \sigma_i \tag{12}$$

$$R_i = R_i^{\mathrm{C}} + E(R_i^{\mathrm{M}}) + E(R_i^{\mathrm{A}}) \tag{13}$$

$$\sigma_i = \mathrm{CVaR}(R_i^{\mathrm{M}}) + \mathrm{CVaR}(R_i^{\mathrm{A}}) \tag{14}$$

where σ_i represents the risk assessment index, and A_i represents risk-adverse parameter of producer i, which is generally set as a constant from 1 to 5 [29]. The bigger value of A_i, the more risk-averse producer i appears to be. $E(\cdot)$ and CVaR($\cdot$) represent expectation and Conditional Value-at-Risk (CVaR) of the random variables, respectively. CVaR, derived from VaR, refers to conditional mean of losses in excess of VaR. It overcomes the insufficiency of VaR in measuring the tail loss and thus can reflect the potential loss in market competitions better [30]. CVaR of R_i^{M} and R_i^{A} can be estimated as [31]:

$$\mathrm{CVaR}(R_i^{\mathrm{M}}) = -\mu^{\mathrm{M}} + \frac{1}{S^{\mathrm{M}} \cdot (1-\delta)} \sum_{l_1=1}^{S^{\mathrm{M}}} [\mu^{\mathrm{M}} - R_i^{\mathrm{M}}(l_1)]^+ \tag{15}$$

$$\mathrm{CVaR}(R_i^{\mathrm{A}}) = -\mu^{\mathrm{A}} + \frac{1}{S^{\mathrm{A}} \cdot (1-\delta)} \sum_{l_2=1}^{S^{\mathrm{A}}} [\mu^{\mathrm{A}} - R_i^{\mathrm{A}}(l_2)]^+ \tag{16}$$

where μ^{M} and μ^{A} represent the revenue thresholds in the monthly contract market and balancing market, respectively. S^{M} and S^{A} represent the total scenario numbers in the two markets, respectively. l_1 and l_2 indicate the specific scenario numbers in the two markets, respectively. δ indicates the confidence level. $[\mu^{\mathrm{M}} - R_i^{\mathrm{M}}(l_1)]^+ = \max\left\{0, \mu^{\mathrm{M}} - R_i^{\mathrm{M}}(l_1)\right\}$, and $[\mu^{\mathrm{A}} - R_i^{\mathrm{A}}(l_2)]^+ = \max\left\{0, \mu^{\mathrm{A}} - R_i^{\mathrm{A}}(l_2)\right\}$.

B. CLEARING MECHANISM CONSIDERING ENERGY DECOMPOSITION

Considering the characteristics of the MPBM, the three-stage process of real market operation is simulated in the lower level in chronological order.

1) MODULE A: CLEARING OF MONTHLY CONTRACT MARKET BY PX

At the end of month $M-1$, the monthly contract market is cleared by PX. Since the independent transmission and distribution prices have not yet been established in China, bidding prices of producers/consumers are prices relative to on-grid/catalog prices which are authorized by the government. In fact, owning to limited total market volume confined by the market openness index γ_i^{m}, the power supply and demand sides appear to be two independent markets, which clear respectively by ranking biddings of producers/consumers from low to high. Therefore, module A can be equated to single supply side bidding model. In module A, the objective of PX is to minimize the dispatch cost of I producers:

$$\min_{Q_{i,\mathrm{total}}^{\mathrm{M}}} \sum_{i=1}^{I} p_i^{\mathrm{M}} \cdot Q_{i,\mathrm{total}}^{\mathrm{M}} \tag{17}$$

$$\text{subject to} \ \sum_{i}^{I} Q_{i,\mathrm{total}}^{\mathrm{M}} = Q_{\mathrm{sys}}^{\mathrm{M}} \tag{18}$$

$$Q_{i,\mathrm{total}}^{\min} \leq Q_{i,\mathrm{total}}^{\mathrm{M}} \leq Q_{i,\mathrm{total}}^{\max} \tag{19}$$

Equation (18) keeps the balance of the total monthly contract, where $Q_{\mathrm{sys}}^{\mathrm{M}}$ is the total monthly contract energy issued by PX. Equation (19) limits the minimum monthly outputs $Q_{i,\mathrm{total}}^{\min}$ and maximum monthly outputs $Q_{i,\mathrm{total}}^{\max}$ of producer i, which are determined by producer's government-authorized contract energy, unit's minimum output and maintenance condition.

2) MODULE B: SCHEDULED ENERGY DECOMPOSITION BY SO

After contract market clearing, the total scheduled energy $Q_{i,\mathrm{total}}^{\mathrm{P}}$ is decomposed by SO according to the minimum output $Q_{i,d,t}^{\min}$ of producer i at time period t of day d. As mentioned above, it is assumed that all generation units that participate in the market competition are always on without considering unit commitment. This is based on the fact that in current market transition period, there is no market oriented UC mechanism. Due to power dispatch according to the principle of "fair, open and just" by SO, large scale units are seldom shut down except for scheduled maintenance. The traditional energy decomposition operation [26] is realized by following steps:

a) Initialize counting variable $w = 1$. Define $\mathbf{N}_C^{(w)}$ as the set of over-limit producers, and $\mathbf{N}_{\mathrm{C}}^{(0)} = \phi$. The total period scheduled power of the system is initialized as:

$$Q_{d,t}^{\mathrm{P}(0)} = \lambda_{d,t}^{\mathrm{P}} \cdot \sum_{i}^{I} Q_{i,\mathrm{total}}^{\mathrm{P}} \tag{20}$$

where $Q_{d,t}^{\mathrm{P}(w)}$ is the total undecomposed scheduled power of the power system at time period t of day d. $\lambda_{d,t}^{\mathrm{P}}$ represents the proportion of power demand of each period, which can be calculated by the typical daily load curves.

b) The scheduled period power of each producer before the modification of round w is allocated as:

$$Q_{i,d,t}^{\mathrm{P}(w)} = \omega_{i,d,t}^{\mathrm{P}(w)} \cdot Q_{d,t}^{\mathrm{P}(w-1)} \tag{21}$$

$$\omega_{i,d,t}^{\mathrm{P}(w)} = \frac{Q_{i,\mathrm{total}}^{\mathrm{P}}}{\sum\limits_{i=1,\{i,d,t\}\notin N_{\mathrm{C}}^{(w-1)}}^{I} Q_{i,\mathrm{total}}^{\mathrm{P}}} (\{i,d,t\} \notin N_{\mathrm{C}}^{(w-1)}) \tag{22}$$

where $\omega_{i,d,t}^{\mathrm{P}(w)}$ represents the allocation ratio of the scheduled period power of the producer before the modification of round w, and $Q_{i,d,t}^{\mathrm{P}(w)}$ denotes its corresponding scheduled power.

c) Scheduled period power of each producer is modified at the round w, i.e., if $Q_{i,d,t}^{\mathrm{P}(w)} \leq Q_{i,d,t}^{\min}$, let $Q_{i,d,t}^{\mathrm{P}(w)} = Q_{i,d,t}^{\min}$, where $\{i,d,t\} \in N_{\mathrm{C}}^{(w)}$.

d) Determine whether the modification is finished. If $N_{\mathrm{C}}^{(w)} - N_{\mathrm{C}}^{(w-1)} = \phi$, the process of energy decomposition and modification is terminated; otherwise, update $Q_{d,t}^{\mathrm{P}}$ by (23), let $w = w+1$ and return to step b).

$$Q_{d,t}^{\mathrm{P}(w)} = Q_{d,t}^{\mathrm{P}(0)} - \sum_{i=1,\{i,d,t\}\in N_C^{(w)}}^{I} Q_{i,d,t}^{\min} \tag{23}$$

3) MODULE C: CLEARING OF BALANCING MARKET BY PX

At day D-6, the balancing market is cleared by PX based on offers/bids of producers, aiming at the minimum cost for BS dispatch, which can be expressed as:

$$\min_{Q^R_{i,d,t}} \sum_{i=1}^{I} p_i^{\mathrm{O}} \cdot g(Q^{\mathrm{A}}_{i,\mathrm{total}}) + \sum_{i=1}^{I} p_i^{\mathrm{B}} \cdot g(-Q^{\mathrm{A}}_{i,\mathrm{total}}) \tag{24}$$

where p_i^{O} and p_i^{B} represent offers and bids for balancing service provided by producer i, respectively. Note that BS dispatch is based on the monthly energy imbalance in real operation, i.e., only up-regulation or down-regulation services are purchased by PX for each month. To describe this feature, piecewise function $g(x)$ is introduced:

$$g(x) = \begin{cases} x & (\text{if } x > 0) \\ 0 & (\text{if } x \leq 0) \end{cases} \tag{25}$$

To further solve the function $g(x)$, $\boldsymbol{Q}^{\mathrm{A}}_{i,\mathrm{total}} = \boldsymbol{u}_i^{\mathrm{A}} - \boldsymbol{v}_i^{\mathrm{A}}$ is defined, where $\boldsymbol{u}_i^{\mathrm{A}}$ and $\boldsymbol{v}_i^{\mathrm{A}}$ are two non-negative slack variables which indicate the total balancing energy of up-regulation and down-regulation substantially. In this way, function (24) is simplified as:

$$\min_{Q^R_{i,d,t}} \sum_{i=1}^{I} p_i^{\mathrm{O}} \cdot \boldsymbol{u}_i^{\mathrm{A}} + \sum_{i=1}^{I} p_i^{\mathrm{B}} \cdot \boldsymbol{v}_i^{\mathrm{A}} \tag{26}$$

$$\text{subject to: } \sum_{i=1}^{I} Q^{\mathrm{R}}_{i,d,t} = Q^{\mathrm{R}}_{d,t} \tag{27}$$

$$Q^{\mathrm{R}}_{i,d,t} = \alpha^{\mathrm{A}}_{i,d} \cdot Q^{\mathrm{P}}_{i,d,t} \tag{28}$$

$$\boldsymbol{u}_i^{\mathrm{A}} - \boldsymbol{v}_i^{\mathrm{A}} = \sum_{d=1}^{D-6} \sum_{t=1}^{T} r \cdot Q^{\mathrm{P}}_{i,d,t} + \sum_{d=D-6}^{D} \sum_{t=1}^{T} Q^{\mathrm{R}}_{i,d,t} - Q^{\mathrm{P}}_{i,\mathrm{total}} \tag{29}$$

$$Q^{\min}_{i,d,t} \leq Q^{\mathrm{R}}_{i,d,t} \leq Q^{\max}_{i,d,t} \tag{30}$$

$$\boldsymbol{u}_i^{\mathrm{A}} \geq 0 \,, \boldsymbol{v}_i^{\mathrm{A}} \geq 0 \tag{31}$$

According to Rule MLT, economic BS is only dispatched at the last 7 days of each month. Therefore, only $Q^{\mathrm{R}}_{i,d,t}$ from day $D-6$ to day D are decision variables of PX, hence in module C, $t = 1, 2 \ldots T$, and $d = D-6, D-5 \ldots D$.

The balance of the power system in each time period in the last 7 days is constrained by (27). Equation (28) indicates that BS dispatch is realized by translating dispatch curves of producers upward or downward, where $\alpha^{\mathrm{A}}_{i,d}$ is the translation ratio. Equation (29) defines the total BS provided by producer i, which includes the non-economic dispatch with equal unified ratio r from day 1 to day $D-7$ and the economic dispatch from day $D-6$ to D with $\alpha^{\mathrm{A}}_{i,d}$, where ratio $r = (\Delta Q + Q^{\mathrm{P}}_{\mathrm{sys}})/Q^{\mathrm{P}}_{sys}$. The minimum output $Q^{\min}_{i,d,t}$ and maximum output $Q^{\max}_{i,d,t}$ of producer i at each time period is constrained in (30).

C. SOLUTION PROCEDURE OF PRODUCER'S OPTIMAL BIDDING STRATEGY CONSIDERING MARKET UNCERTAINTIES

During the optimal bidding strategy-making process of the power producer, both monthly energy imbalances of the power system and bidding strategies of rivals are uncertain. Therefore, producers should build its bidding strategies subject to expectations on the monthly energy imbalance and its rivals' behavior. The bidding parameter of rivals can be estimated using certain mathematical methods based on historical data or assumption [32]–[35]. It is obvious that historical data take time to accumulate. However, the MPBM in China has just been put forward and it is still in the test stage, so there is a lack of abundant data for parameter fitting and prediction. Therefore, assumptions for rivals' behavior are made in the market simulation model in this paper.

The imbalance ΔQ is derived from random errors of load forecast, which satisfies a normal distribution [36]. Imbalance coefficient $k \sim N(\mu_k, \sigma_k)$ is introduced to describe ΔQ as:

$$\Delta Q = k \cdot Q^{\mathrm{P}}_{\mathrm{sys}} \tag{32}$$

Uncertainties of ΔQ are modeled using the scenario generation method, in which N samples are taken according to the Probability Distribution Function (PDF) of k.

Since the proposed bidding strategy is based on a non-game model, forecasted bidding strategies of the rivals are used to simulate market competitions. However, producers in the market competition are numerous, so it is difficult to estimate each of their biddings accurately. Therefore, biddings of rivals are normally simplified as single or several kinds. In this paper, rivals of producer i are accumulated as producer $-i$, and their equivalent bidding curves in the monthly contract and balancing markets are respectively presented as [37]:

$$p^{\mathrm{M}}_{-i} = c_{-i} + \mu^{\mathrm{M}}_{-i} \cdot Q_{-i} \tag{33}$$

$$p^{\mathrm{O}}_{-i} = p^{\mathrm{B}}_{-i} = c_{-i} + \mu^{\mathrm{A}}_{-i} \cdot (\Delta Q_{-i} + Q_{-i}) \tag{34}$$

where μ^{M}_{-i} and μ^{A}_{-i} represent slopes of the equivalent bidding curves in the monthly CM and BM, respectively. c_{-i} is a constant parameter of the bidding curves. Generally, probability method is employed to estimate the PDF of bidding parameters, which characterizes uncertainties of bidding strategies of rivals [38], and is also adopted in this paper. Solution procedure of the optimal bidding strategy for the producer i under the monthly sequential energy dual-market is presented in FIGURE 5.

According to the chronological order of the optimization for biddings in the dual-market, an iterative method is applied to determine producer's optimal bidding strategy $(p_i^{\mathrm{M}*}, p_i^{\mathrm{O}*}, p_i^{\mathrm{B}*})$. Besides, particle swarm optimization (PSO) is adopted to solve $p_i^{\mathrm{M}*}$, which can solve complex nonlinear optimization problem effectively and find the global optimal solution with a high probability [39]. In FIGUURE 5, the dotted line depicts the information flow, PP i refers to power producer i, a is the initial bidding value in the CM, $\mathbf{S}_i$ represents possible offers/bids set in the BM, K is the iteration number and $K_{\max}$ is the maximum number of iterations.

IV. CASE STUDIES

Actual data of Anhui Province in China are used to demonstrate the proposed model of bidding strategies of the

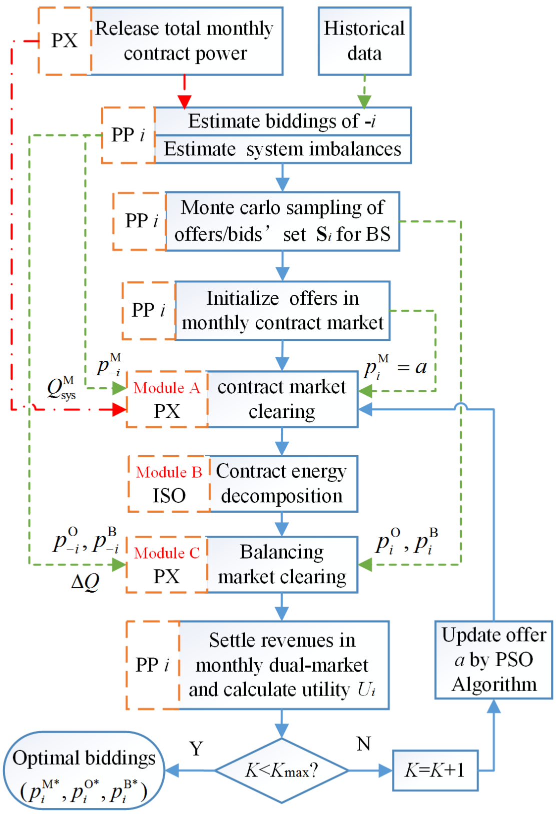

FIGURE 5. Solution procedure of producer's optimal bidding strategy under monthly sequential energy dual-market.

power producer. The market information including total monthly contract energy, power producers' generation cost and load statistics are from its Analysis Report on Power Transaction in Anhui Province in August, 2017, provided by Anhui Power Exchange Center Co. Ltd. The market has eight major power producers. According to the power transaction information in August 2017, the total monthly contract energy Q_{sys}^{M} is 14.654 TWh, which accounts for 15.86% of the total electrical energy consumption. The bidding strategy of the largest power producer with 683 MW installed capacity and generation cost of 0.039 USD/kWh is considered. The monthly scheduled energy decomposition is based on actual load statistics in August 2017 of Anhui Province.

In the benchmark case, the government-authorized contract energy proportion γ_i^m is 34.6% based on market statistics. In the simulation of market uncertainties, assume that the imbalance coefficient k satisfies $N(0, 0.03)$, and 1000 scenarios of the energy imbalances ΔQ are generated. The parameters of the equivalent bidding curves of other market rivals, namely c_{-i}, μ_{-i}^{M} and μ_{-i}^{A}, are set as 0.036, 1.27 and 1.27 respectively based on historical market data. Besides, thresholds for up-regulation and down-regulation are 0 and -2%, respectively, which are recommended value by Rule MLT. The risk preference coefficient A_i is set as 3 and the confidence coefficient δ is assumed as 95%.

The optimal bidding strategy for the benchmark case is (0.049, 0.053, 0.024), which indicates that under this circumstance, the producer should offer 0.049 USD/kWh in the CM, while offer 0.053 USD/kWh and bid 0.024 USD/kWh in the BM respectively, in order to maximize its monthly utility. However, the optimal strategy varies due to different parameters of both the producer and market conditions. Detailed cases are analyzed as follows.

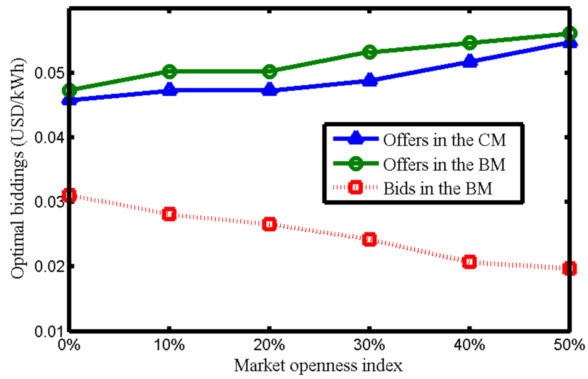

FIGURE 6. Dual-market bidding strategy of the producer under different market openness indexes.

A. IMPACTS OF MARKET OPENNESS INDEX ON THE BIDDING STRATEGY

It can be seen from FIGURE 6 that with the increase of the market openness index γ_i^m, i.e., the power market becomes less open, the optimal offers for both the CM and the BM tend to increase gradually; in contrast, the optimal bids in the BM tend to decrease gradually. This implies that when the monthly scheduled energy guaranteed by the government-authorized contract increased, initiatives of the producer to participate in the CM and to provide up-regulation service decline. Thus in order to encourage the power producers to participate more in the overall market competition both in the CM and the BM, market designers should gradually open up the market by limiting the proportion of government-authorized contract energy to certain level.

In addition, FIGURE 6 also shows that the optimal offers in the CM are always lower than in the BM. This is largely due to the greater uncertainty in the BM compared to the CM. It is widely acknowledged that with high risk comes the expectation of high return. This phenomenon is consistent with the empirical analysis that the offers in the day-ahead market are usually lower than that in the real-time market [40] in the case of typical spot market.

B. IMPACTS OF MINIMUM OUTPUT LEVELS OF THE PRODUCER ON THE BIDDING STRATEGY

Under the current market mechanism of contract energy decomposition, the optimal bidding strategy of the producer is affected by minimum output levels of the producer as well. FIGURE 7 reveals that when the minimum output varies from 35% to 55% of the rated capacity, the optimal offers of the producer in the CM trend upward, while the optimal offers/bids in the BM almost remain stable.

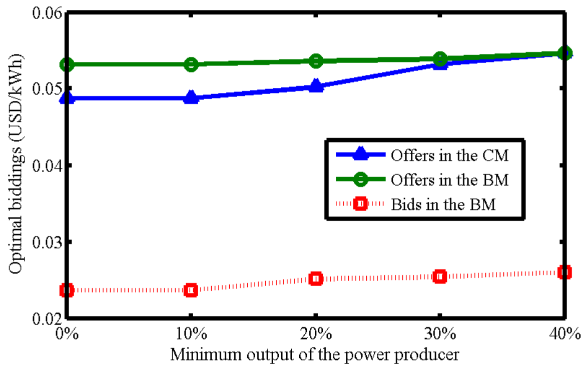

FIGURE 7. Dual-market bidding strategy of the producer under different minimum output levels.

The change of the optimal offers in the CM reflects the effect of the contract energy decomposition and modification in the three-stage system operation process between the clearing of the CM and the BM. With the increase of the producer's minimum output level, its monthly scheduled energy guaranteed by the contract energy decomposition increases at the same time, and this causes a decline of willingness of the producer to participate in the CM.

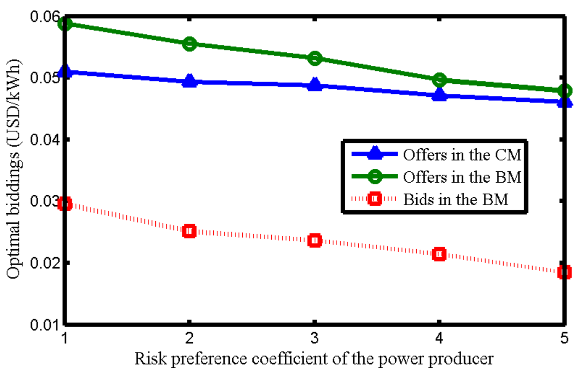

FIGURE 8. Dual-market bidding strategy of the producer under different risk preference coefficients.

C. IMPACTS OF RISK PREFERENCE OF THE PRODUCER ON THE BIDDING STRATEGY

The attitude towards the market risk of the producer is another important factor that influences its offers/bids. FIGURE 8 demonstrates that when the risk preference coefficient A_i varies from 1 to 5, i.e., when the producer becomes more risk-averse, its optimal offers/bids in both the CM and the BM decline. This tendency indicates that the producer becomes more aggressive on bidding, so as to acquire a certain market share. Besides, it is shown that the decline of optimal offers/bids in the BM is more obvious compared to that in the CM, since bidding in the BM has higher uncertainty level for the producer. As it is mentioned above, total trading energy of the producer is known in the CM while unknown in the BM before it submits its bid/offer to the PX.

TABLE 2. Biddings and revenues of the producer under different thresholds.

β^B	p_i^B (USD / kWh)	Expected revenues ($\times 10^6$ USD)	BS dispatch cost ($\times 10^6$ USD)
2%	0.024	13.312	77.660
3%	0.025	12.481	63.385
4%	0.025	11.715	49.110
5%	0.027	10.743	34.835

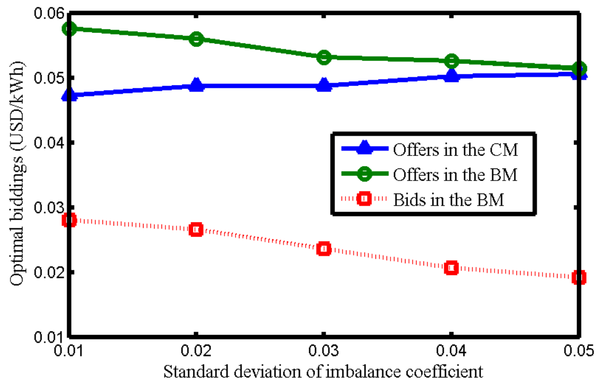

FIGURE 9. Dual-market bidding strategy of the producer under imbalance coefficients of different distributions.

D. IMPACTS OF SETTLEMENT THRESHOLDS ON THE BIDDING STRATEGY

As mentioned above, the settlement threshold is one of the distinctive characteristics of the BM in China. TABLE 2 shows that when the settlement threshold of down-regulation service varies from 2% to 5%, the optimal bids of the producer in the BM tend to increase gradually. However, the expected revenues of the producer tend to decrease, which leads to the decrease of the total BS dispatch costs of SO. It can be deduced that increase of the settlement threshold reduces the potential revenues of the producer by providing BSs, thus depressing its initiatives to participate in the BM. As mentioned above, the settlement threshold is specially set in the BM under MPBM, for the purpose of damping unintended rewards and penalties due to stochastic variations. Although the settlement threshold is conducive to reducing the impact on financial imbalance account of PX, BSs provided by power producers below the threshold cannot be compensated. On the long run, it will further lead to the increase of bids for BS and the decrease of valid regulation capacity of the power system. Therefore, it is important for market designer to make a tradeoff between initiatives of market participants and BS dispatch cost when setting settlement thresholds.

E. SENSITIVITY ANALYSIS OF UNCERTAINTY FACTORS ON THE BIDDING STRATEGY

As shown in FIGURE 9, when the standard deviation of the imbalance coefficient k's normal distribution increases, the optimal offers of the producer in the CM increase

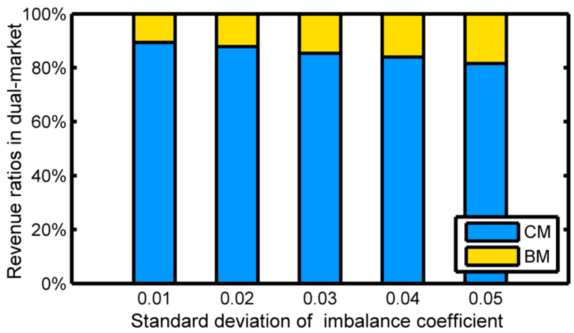

FIGURE 10. Dual-market revenue ratios of the producer under imbalance coefficients of different distributions.

gradually, while the optimal offers/bids in the BM decrease. This directly leads to the increase of revenue ratio of the producer in the BM as shown in FIGURE 10. It can be deduced that when uncertainty of the imbalances increases, preference of the producer for capacity allocation shifts from the CM to the BM. In this way, its utility can be maximized by providing more BSs.

TABLE 3. Bidding strategy of the producer under different bidding parameters of rivals.

Distribution	Producer's bids/offers		
	p_i^{M} (USD/kWh)	p_i^{O} (USD/kWh)	p_i^{B} (USD/kWh)
D_A	0.049	0.053	0.024
D_B	0.053	0.056	0.027
D_C	0.056	0.058	0.028

TABLE 3 provides the optimal bids/offers of the producer under different distributions of bidding parameters of rivals, namely μ_j^{M} and μ_j^{A}. In the following scenarios, the distributions of μ_j^{M} and μ_j^{A} are respectively set as: 1.27 constantly (denoted as D_A); 1.21, 1.24, 1.27, 1.30, 1.33, with 20% chance respectively (denoted as D_B); 1.15, 1.21, 1.27, 1.33, 1.39, with 20% chance respectively (denoted as D_C).

It can be seen from TABLE 3 that when the uncertainty of bidding strategies of the other market rivals increases, the optimal offers/bids of the producer increase in both the CM and the BM. This indicates that the producer becomes more conservative towards market participation when risk levels increase in both markets. In addition, it is also crucial for PX to consider information disclosure cautiously in order to encourage the market participation of power producers, including whether there is a time delay for disclosure and to which degree the information should be disclosed.

V. CONCLUSIONS

In this paper, a bi-level optimization model is innovatively proposed for the optimal bidding strategy of power producers in the monthly sequential energy dual-market in China for the first time. The three-stage process of real system operation under the sequential energy dual-market based on MPBM is simulated comprehensively, including the clearing of the CM, the contract energy decomposition and the clearing of the BM. A trade-off between revenues and risks produced by the bidding strategy of the producer under MPBM is considered using the utility index. Numerical examples are conducted based on real-world data in China's provincial electricity market.

Case studies indicate that the proposed model can be used by producers to adjust its bidding strategy according to various relevant factors. Besides, it can also be used by market designers to analyze impacts of different market parameters on market performance during market parameter setting. The results produced by the model are consistent with the common-sense knowledge, which illustrates the validity of the model, e.g., the more risk-adverse the producer is, the more preferable it tends to allocate its generation capacity in the CM; the increase of uncertainties of monthly energy imbalances of the system makes the producer shift its capacity allocation from the CM to the BM.

Apart from the common-sense knowledge, some conclusions that are specifically applied to the monthly sequential energy dual-market under MPBM for Chinese wholesale power market can also be obtained. Firstly, the increase of the producer's minimum output depresses its initiatives to participate in the CM due to the market operation process of contract energy decomposition by SO. Secondly, the increase of the market openness level, which is determined by the proportion of government-authorized contract energy, encourages the producer to participate in the CM and to provide up-regulation service in the BM. Thirdly, as one of the distinctive characteristics of the BM in China, if the settlement threshold is set too low, the producer's initiative to participate in the BM would be strongly depressed.

The proposed model can be further extended from the following aspects: a) Provincial BMs in China have different balance adjusting time (e.g., energy imbalances of the previous month are cleared on the first 5 days of the next month in Shandong province), thus a comparative analysis of bidding strategy can be made. b) Game theory can be applied to market equilibriums simulation to further analyze the influence of market mechanism designs on overall market performance.

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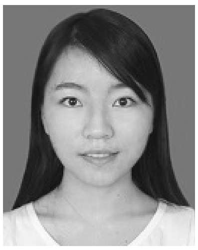

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