Yang, Jiajia, Zhao, Junhua, Qiu, Jing, and Wen, Fushuan (2019) ***A Distribution Market Clearing Mechanism for Renewable Generation Units With Zero Marginal Costs.*** **IEEE Transactions on Industrial Informatics, 15 (8) pp. 4775-4787.**

A Distribution Market Clearing Mechanism for Renewable Generation Units with Zero Marginal Costs

Jiajia Yang, *Member, IEEE*, Junhua Zhao, *Senior Member*, *IEEE*, Jing Qiu, *Member*, *IEEE*, and Fushuan Wen, *Senior Member*, *IEEE*

Abstract **A key feature of an electricity distribution market is that it may be dominated by renewable generation with zero marginal cost. Existing market mechanisms are likely to fail in this context since it cannot generate a reasonable price signal to compensate for the investment cost of renewable generators. Given this background, a double-sided auction market mechanism is presented for pricing the zero marginal cost renewable generation in the distribution system. Honesty is proved to be a dominant strategy for participants, which would enable the proposed mechanism to develop into a set-and-forget bidding market. The proposed market mechanism is also shown to be compatible with the nodal pricing system. Finally, case studies are carried out and the results show that under the proposed market mechanism, the problem of always bidding a zero price by renewable generators in some existing markets can be avoided. Even when only renewable generation units with zero marginal costs participate in the bidding, the proposed mechanism can still produce a reasonable market clearing price (MCP). When adopting the average pricing market (APM) mechanism, merits of nodal pricing can still be retained and contribute to the enhancement of the operating efficiency of the distribution network.**

***Index Terms*—Electricity distribution market, renewable generation, zero marginal cost, honesty, dominant strategy, nodal price.**

I. Introduction

MOTIVATED by the concerns on climate change, air pollution and security of supply, renewable energy (RE) technologies are favoured by many countries during the past decades through establishing various supportive policies. As a result, the global penetration level, capital investment, and installed capacity of renewable energy generation have been increasing steadily. In particular, there are already plenty of publications on the transition towards a future 100% renewable energy system [1, 2]. Meanwhile, at the demand side, there is also a fast deployment of distributed renewable generation systems. For example, nearly one out of every four households in Australia has already installed rooftop solar panels [3].

Trading electricity in the distribution market is different from that in the wholesale market. Firstly, participants are mostly prosumers with small-scale renewable generators. The bid or offered transaction volume of electricity from each prosumer is usually small. Secondly, the traded energy in the distribution market may be 100% generated by renewable generation. Compared with fossil-fuelled power, the fuel cost of the renewable generation is zero. Thirdly, the distribution market participants are usually unable to develop optimal bidding strategies through sophisticated computation. Therefore, the set-and-forget method of setting bid parameters is preferred when participating in the distribution market. In summary, a new market mechanism which can properly meet all these requirements is urgently needed.

However, these special characteristics of trading in the distribution market have largely been neglected by researchers, especially the zero marginal cost of renewable generations. In some existing publications such as [4, 5], the quadratic cost function is still adopted for renewable energy generators, similar to the cost function of traditional thermal generators. In [6-10], the distribution market is modelled as an intermediate entity between the wholesale market and customers in the distribution system. The distribution market operator (DMO) communicates with the independent system operator (ISO) in the wholesale market and proactive customers to enable participations of customers in the wholesale market. Usually, the DMO receives the demand bids from customers in the distribution system, aggregates the bids and submits a single aggregated bid to the ISO. After market clearing by the ISO, the DMO distributes the cleared power among the participated customers. In order to conduct market clearing and settlement, the distribution locational marginal prices (DLMPs) are proposed and adopted in [7, 8, 10], which are similar to the concept of the well-established locational marginal price (LMP) in the wholesale market. Due to the higher percentage of power losses, voltage volatility, and phase imbalance in the distribution system, the determination of the DLMP is challenging. Therefore, a three-phase alternating current (AC) optimal power flow (OPF) based approach is developed to define and calculate the DLMP in [11].

Existing publications on the participation of renewable generations in the electricity market usually regard renewable

This work is partially supported by Australian Research Council Discovery Projects (DP170103427 and DP180103217), a National Natural Science Foundation of China grant (91746118), Shenzhen Municipal Science and Technology Innovation Committee Basic Research project (JCYJ20170410172224515), and State Key Laboratory of Smart Grid Protection and Control.

J. Yang is with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: yangjia.zju@gmail.com).

J. Zhao is with the School of Science and Engineering, Chinese University of Hong Kong, Shenzhen 518100, China (e-mail: zhaojunhua@cuhk.edu.cn).

J. Qiu is with the School of Electrical and Information Engineering, The University of Sydney, Sydney, NSW 2006, Australia (e-mail: feremy.qiu@sydney.edu.au).

F. Wen is with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China (e-mail:fushuan.wen@gmail.com).

generators as price-takers [12]. The researchers mainly focus on the scheduling problem associated with the output uncertainty of renewable generation units [13]. The other publications addressing the future 100% renewable energy scenario mainly focus on potential challenges, technical requirements, and economic benefits.

In existing marginal cost based electricity markets, MCP is determined by the marginal units regardless of its bidding generation output. When competing with generators that have a non-zero marginal operating cost, renewable generators with zero marginal costs are not motivated to bid at a non-zero price. In particular, when the penetration level of renewables in the power system is low, traditional thermal units usually act as marginal units. Bidding at zero can bring renewable generation units a high priority in the dispatch list while being paid by the same MCP. On the other hand, in a 100% renewable energy scenario, renewable generators that bid at a non-zero price can only decrease its own priority of being dispatched but help rise the MCP for other units if the other units choose to bid at zero. More importantly, marginal cost based market is designed to efficiently price the short-term operation cost of power systems [14], but renewable generators make decision mainly based on their long-term costs, such as their capital and maintenance costs. Therefore, marginal cost based market mechanism would fail to reveal the real market value and generation cost of renewables.

In this paper, an average pricing market mechanism is proposed for pricing the zero marginal cost renewable generation. In the proposed one, participants are motivated to set bidding parameter based on their own estimations of the generation costs (for producers) or electricity utilities (for consumers), which is defined as honesty. Honesty is proved to be a dominant strategy for participants in such a market. Using the proposed market mechanism, the problem of always bidding at a zero price by renewable generators in existing markets can be avoided. Even in a scenario where only renewable generation units with zero marginal costs participate in the bidding, the proposed mechanism can still produce a reasonable price signal.

The main contributions of this paper are summarized as below:

Firstly, a market mechanism for renewable generators with zero marginal cost is proposed. As most existing electricity markets are designed based on the marginal cost and marginal revenue theory, in the scenario of a 100% renewable generation bidding, these market mechanisms will fail to price the renewable energy generation properly. The proposed market mechanism in this paper is designed to solve this problem.

Secondly, honesty is proved to be a dominant strategy for participants under the proposed market mechanism. On this basis, participants can set bidding parameter based on their own estimations of the generation costs (for producers) or electricity utilities (for consumers). Therefore, participants' need for a set-and-forget method of setting bid parameters is satisfied.

Thirdly, the proposed distribution market pricing method is compatible with the nodal pricing system. The nodal pricing method has an advantage in pricing the impacts of various buses on line congestion and losses. In this paper, it is verified that the proposed pricing algorithm can be integrated with the nodal pricing method.

The rest of the paper is structured as follows. Section II elaborates failure of the marginal cost based electricity market. Then cost analysis for transactions in the distribution market is carried out in section III. Section IV presents the proposed market clearing mechanism for zero marginal renewable generations and section V provides case study results and discussions. Finally, the paper is concluded in section VI.

II. Failure of the Marginal Cost Based Electricity Market

Existing electricity markets can be broadly categorized into two types: the power pool (centralized market); the bilateral contract model (decentralized market) [15, 16]. The power pool is used to find the price signal for market participants and achieve the power balance in the power system concerned. The power pool market also helps provide a price reference for bilateral contract market trading, which is mainly utilized by participants to manage trading risk.

In the power pool market, the market operator (MO) receives energy offers from producers and energy bids from consumers for specified trading periods, and determines the power production of every producer, the consumption level of every consumer, and the price at which every producer / consumer is paid / charged for its energy production / consumption [17]. The objective of market is to pass the generation cost to consumers in a fair and efficient way [14]. The objective function is to maximize the net social welfare when both consumers and producers participate in the market while it becomes the minimization of electricity purchase cost when only producers participate. This process is known as market clearing and can be expressed as follows.

Objective function

$$\max \sum_{i=1}^{N} p_i^{\text{cb}} \cdot r_i^{\text{b}} - \sum_{j=1}^{M} p_j^{\text{cs}} \cdot r_j^{\text{s}} \text{ (double-sided auction)}$$

$$\text{or } \min \sum_{j=1}^{M} p_j^{\text{cs}} \cdot r_j^{\text{s}} \text{ (single-sided auction)} \tag{1}$$

where p_i^{cb} / p_j^{cs} indicates the dispatched demand / output of the i^{th} consumer / j^{th} producer; r_i^{b} / r_j^{s} is the bidding/offer price of the i^{th} consumer /j^{th} producer.

Generation and demand constraints

(1) Balance between generation offers and demand bids.

$$\sum_{i=1}^{N} p_i^{\text{cb}} = \sum_{j=1}^{M} p_j^{\text{cs}} \tag{2}$$

(2) The participation of producers and consumers in the electricity market is restricted to their production and consumption limits.

$$p_i^{\text{b,min}} \le p_i^{\text{cb}} \le p_i^{\text{b,max}} \tag{3}$$

$$p_j^{\text{s,min}} \le p_j^{\text{cs}} \le p_j^{\text{s,max}} \tag{4}$$

where $p_i^{\text{b,min}}$ / $p_i^{\text{b,max}}$ represents the lower / upper demand limit of the i^{th} consumer; $p_j^{\text{s,min}}$ / $p_j^{\text{s,max}}$ represents the lower / upper generation limit of the j^{th} producer.

Branch constraints

$$\sum_{i\in N} p_i^{\text{cb}} \cdot \rho_{l,i} + \sum_{j\in M} p_j^{\text{cs}} \cdot \rho_{l,j} \le P_l^{\max} \quad \forall l \in L \tag{5}$$

where $P_l^{\max}$ is the power limit of branch l; L is the set of branches in the distribution network; $\rho_{l,j}$ denotes the power transfer distribution factor (PTDF) which is used to indicate the relative change of the active power that occurs on a particular branch l due to actual power change at node j.

Besides, when adopting the AC OPF nodal pricing model, nodal voltage constraints can also be incorporated into the model. Fig.1 (*a*) and Fig.1 (*b*) show the market clearing mechanism for the single- and double- sided auction electricity markets, respectively.

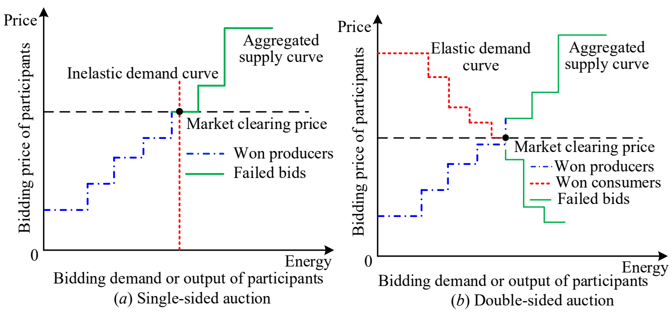


Fig. 1 Market clearing mechanism for single- and double-sided auction electricity markets.

The marginal cost based power pool works well for the thermal generation units, since they are controllable. But with the rising public concerns on carbon emission and the fast development of renewable generation technologies, the power industry is experiencing a transformation from centralized fossil fuel dominated generation to distributed renewable energy generation. This change of energy mix brings challenges to the existing market mechanisms due to the following characteristics of renewable energy generation [16]: (1) intermittent supply; (2) no (or limited) inertia; (3) zero marginal cost. The challenges (1) and (2) can be solved with ancillary services provided by conventional generators, battery storage and demand response technologies, while the challenge (3) would need a new market mechanism.

In reality, the zero bid price or even negative bid price has already appeared in some operating electricity markets. These electricity markets concerned still work well because of several reasons. Firstly, there is only a moderate share of renewable energy generation in current power systems and there is some subsidy from governments for renewable energy generation. Secondly, considering the non-zero marginal operating cost and huge fixed cost of a thermal power plant, when competing with renewable generators, the thermal power plant would not bid a zero price. Consequently, the marginal generation unit is usually a fossil-fueled generator, and the MCP is acceptable for renewable generators.

Due to the intermittence and uncertainty of renewable energy, outputs of renewable generation units are less controllable comparing with thermal generators. In the distribution market, bidding outputs of renewables would be determined based on generation forecasting results. The intermittence of renewable generation is considered to be eliminated through the following ways. Firstly, the proposed market mechanism can be organized in a flexible way, which can be operated as half-hourly, or hourly ahead market instead of a day-ahead market. Under this circumstance, the forecasting results for renewables can be quite accurate. Secondly, more and more end-users in the power system are equipped with energy storage systems and this can also help eliminate the intermittence and uncertainty of renewable energy.

Besides, the bidding output changes frequently since renewable generation is uncertain. Distribution market participants would prefer a set-and-forget method of setting bidding prices because this could prevent them from revising bids when renewable output changes. The proposed market mechanism is proved to motivate honest bidding behaviours. Participants' bidding strategies are mainly determined by their self-estimated generation cost (for producers) or electricity utility (for consumers). Consequently, such a mechanism enables participants to set their bidding prices in a set-and-forget way, despite changes of their demand or generation outputs.

III. Cost Analysis for Transactions in the Distribution Market

When developing their bids or offers in the distribution market, participants need to evaluate the renewable generation cost. Therefore, before establishing the market mechanism, cost analysis for renewable generation should first be carried out. The cost of electricity generation is usually determined by several aspects such as the upfront investment, operating expenses, and capacity factors. When analysing the cost of various generation technologies, their costs can be broadly classified into two categories: fixed and variable costs. The fixed costs are those that remain at a fixed amount no matter how much electricity is produced, including the capital cost, labour cost, and land involved in the construction of power plants. The variable costs are those that change with power output from generators, including the fuel cost, labour cost, material cost, start-up / shut down cost, emission cost, as well as O&M cost. Besides, other basic cost concepts are also used in the economics of power plants, such as the average cost of energy, the average cost of capacity, and marginal cost of energy.

Different from traditional generation technologies, renewable generation is capital-intensive but has zero fuel cost [18]. To the best of our knowledge, detailed analysis of renewable generation costs for pricing purpose is not available in existing publications. In existing studies which compare the renewable generation cost with other technologies (e.g., geothermal or hydro), the levelized cost of energy (LCOE) is usually adopted [19]. LCOE measures the average cost of each unit of electricity that a generator is expected to produce over its lifetime. The LCOE can also be defined as the electricity price when the net present value of the project investment is zero. The LCOE of renewable energy technologies can be calculated by

$$c^{\text{LCOE}} = \sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t} \Bigg/ \sum_{t=1}^{T} \frac{Q_t}{(1+r)^t} \tag{6}$$

where c^{LCOE} indicates the value of LCOE; I_t / M_t / F_t represents the investment / O&M / fuel expenditures in year t; r is the discount rate; T is the lifetime of the project; Q_t is the quantity of electricity generation in year t.

In addition to being used to measure the cost of renewable generation, LCOE can also be regarded as an indicator of electricity price for a project where revenues would equal costs, namely LCOE indicates the break-even price of generation for the project over its lifetime [19]. In [19], it is reported that the global weighted LOCE has declined to about 0.05 \$/kWh for onshore wind generation and 0.06 \$/kWh for solar photovoltaic (PV) based on the latest data in 2017. But these results are for utility-scale projects (>1MW for solar PV, >5MW for onshore wind generation). The projects below these size levels have higher costs than those reported. For participants in the distribution market, the cost of renewable generation s and the utility of electricity b can be estimated based on the LCOE, while the utility of electricity can also be estimated by referring to the retail price and the participant's willing to consume electricity.

IV. Proposed Market Clearing Mechanism

A. An Average Pricing Market Mechanism

The proposed market mechanism is a double-sided bidding one where the i^{th} (i =1,2, to N) consumer bids a price-demand pair (r_i^{b} , p_i^{b}) and the j^{th} (j =1,2, to M) producer offers a price-output pair (r_j^{s}, p_j^{s}) to the market. Once winning the auction, the consumer will purchase electricity from the distribution market at the MCP, otherwise, the consumer will need to purchase electricity at the incumbent retail price from the grid. Similarly, a producer will sell electricity to the distribution market at the MCP if winning the auction, otherwise will have to sell electricity into the grid at the feed-in tariff. By contrast, if consumers demand less or producers generate less energy than they bid, then their self-equipped energy storage system can be adopted for compensation. Or else, when the energy storage system is unavailable, financial penalties will be applied by requiring participants still to pay for the same amount of energy as they bid, since they did not accurately implement the market transaction outcomes and then the money can be used to compensate their counterparts. Besides, the advent of smart home technologies nowadays has enabled households to control their electricity consumption activities flexibly. With all these measures, it can be expected that participants will try to implement market clearing outcomes in an accurate way.

In the proposed market clearing mechanism, both consumers and producers have dominant strategies. A strategy is a dominant one if it maximizes the agent's expected utility for all possible strategies of other agents [20, 21]. In the proposed mechanism, the dominant strategies of participants will be honestly reporting their true utilities/costs. The market clearing mechanism is depicted in Fig.2.

In Fig.2, the weighted average $\bar{r}$ of participants' bid prices is adopted as the MCP, where the weighting factors are their bid quantities. Since it is the average price that acts as the MCP, the proposed market clearing mechanism is named as the average pricing market (APM).

$$\bar{r} = \left(\sum_{i=1}^{N} r_i^{\text{b}} \cdot p_i^{\text{b}} + \sum_{j=1}^{M} r_j^{\text{s}} \cdot p_j^{\text{s}} \right) \Bigg/ \left(\sum_{i=1}^{N} p_i^{\text{b}} + \sum_{j=1}^{M} p_j^{\text{s}} \right) \quad (7)$$

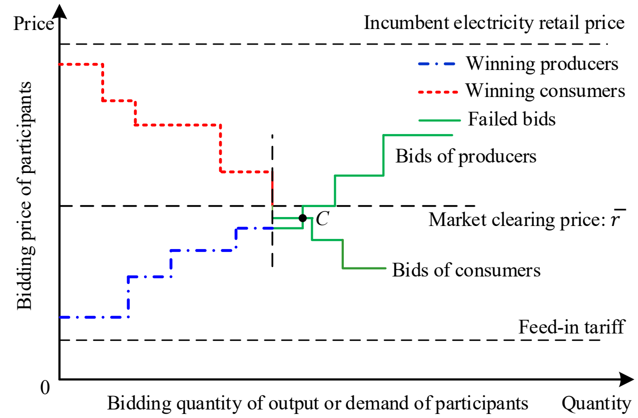


Fig. 2 Schematic diagram of the proposed market mechanism.

Market rules are elaborated as follows. It is assumed that the i^{th} consumer bids to the market at (r_i^{b}, p_i^{b}) (i=1, 2, to N).

$$(r_i^{\text{b}}, p_i^{\text{b}}) \begin{cases} \text{if} \quad r_i^{\text{b}} > \bar{r} & \text{win the bidding} \\ \text{if} \quad r_i^{\text{b}} < \bar{r} & \text{lose the bidding} \\ \text{if} \quad r_i^{\text{b}} = \bar{r} & \text{uncertain} \end{cases} \quad (8)$$

The j^{th} producer bids to the market at (r_j^{s}, p_j^{s}) (j=1, 2, to M).

$$(r_j^{\text{s}}, p_j^{\text{s}}) \begin{cases} \text{if} \quad r_j^{\text{s}} > \bar{r} & \text{lose the bidding} \\ \text{if} \quad r_j^{\text{s}} < \bar{r} & \text{win the bidding} \\ \text{if} \quad r_j^{\text{s}} = \bar{r} & \text{uncertain} \end{cases} \quad (9)$$

The i^{th} consumer wins the auction only when its bid price r_i^{b} is larger than $\bar{r}$. On the contrary, the j^{th} producer wins the auction only when its bid price r_j^{s} is smaller than $\bar{r}$. Besides, when a participant bids at a price that equals to $\bar{r}$, there is a possibility for this participant to be excluded from trading because the market needs to reach equilibrium between demand and supply. For instance, the MCP in Fig.2 under the APM is slightly higher than the crossing point C of demand and supply curves which is namely the MCP in the marginal cost based (double – sided auction) market. Instead of having the last winning consumer as a marginal participant in the marginal cost based market, the last winning producer acts as the marginal one under APM. Besides, it can be found in Fig.2 that even there is a producer bids at $\bar{r}$, this producer still lose the bidding. If the bid quantity of the last consumer increases, the producer who bids at $\bar{r}$ could possibly become the marginal unit, namely there is a possibility for the participant to be excluded from trading due to the necessity of equilibrium between demand and supply.

Considering that re-bidding will be permitted in the proposed market, there will be two different scenarios faced by participants. Scenario 1: before the re-bidding, all participants submit bids simultaneously and no market information is available. Scenario 2: during the re-bidding, market information such as current clearing price and total trading volume will be released and participants re-bid based on these known information.

It is defined as honesty if a participant will bid at his/her self-estimated generation cost / electricity utility when no market information is available. Once the current market clearing price and total trading volume is released, it is defined as honesty when the bidding behaviour truly reflects the relationship between a participant's self-estimation of generation cost/electricity utility and the MCP. In other words, being honest, a participant tends to submit a bid that is greater than/less than/equal to the observed MCP if the self-estimated generation cost/electricity utility is greater than/less than/equal to the MCP, respectively.

Theorem 1: *Honesty is a dominant strategy for participants in the proposed market mechanism.*

Proof: It is assumed that when a consumer submits a bid r_i^{b} to the electricity market, he/she is aware of his/her true utility of using electricity, which is represented by b. Without loss of generality, it can also be assumed that the bids of other participants except consumer i can be ordered and plotted as in Fig.2. After the participation of consumer i, the MCP would change from $\bar{r}$ to $\bar{r}_{\mathrm{new}}$. Then, the net utility of consumer i through consuming a unit of electricity can be expressed by $b-\bar{r}_{\mathrm{new}}$. But if the consumer i loses the auction, the attained utility will be 0.

In the proposed market mechanism, the bidding strategies of consumer i are analysed under different scenarios of utility b, as shown in Table I.

TABLE I ANALYSIS OF BIDDING STRATEGIES FOR CONSUMER UNDER DIFFERENT SCENARIOS

Scenarios of b	Bidding strategy	Values of $\bar{r}_{\mathrm{new}}$	Utility of consumer i
$b>\bar{r}$	if $r_i^{\mathrm{b}}>\bar{r}$	$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}$	$b-(1+\theta)\cdot\bar{r}$
	if $r_i^{\mathrm{b}}=\bar{r}$	$\bar{r}_{\mathrm{new}}=\bar{r}$	0
	if $r_i^{\mathrm{b}}<\bar{r}$	$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}$	0
$b=\bar{r}$	if $r_i^{\mathrm{b}}>\bar{r}$	$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}$	$b-(1+\theta)\cdot\bar{r}<0$
	if $r_i^{\mathrm{b}}=\bar{r}$	$\bar{r}_{\mathrm{new}}=\bar{r}$	0
	if $r_i^{\mathrm{b}}<\bar{r}$	$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}$	0
$b<\bar{r}$	if $r_i^{\mathrm{b}}>\bar{r}$	$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}$	$b-(1+\theta)\cdot\bar{r}<0$
	if $r_i^{\mathrm{b}}=\bar{r}$	$\bar{r}_{\mathrm{new}}=\bar{r}$	0
	if $r_i^{\mathrm{b}}<\bar{r}$	$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}$	0

Where θ is a parameter and indicates the change of market clearing because of the bids of consumer i.

Thus, when no available market information, to bid at $r_i^{\mathrm{b}}=b$ is the only choice that can be the best strategy for the consumer under all possible conditions.

In the re-bidding process, when $b>\bar{r}$ and consumer i chooses to bid at $r_i^{\mathrm{b}}>\bar{r}$, the consumer needs to ensure $b-(1+\theta)\cdot\bar{r}>0$. Let p_{-i}^{b} denote the total bids of other participants except consumer i, the MCP when consumer i bids at r_i^{b} can be expressed as follows.

$$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}=\left(r_i^{\mathrm{b}}\cdot p_i^{\mathrm{b}}+\sum\bar{r}\cdot p_{-i}^{\mathrm{b}}\right)\Big/\left(p_i^{\mathrm{b}}+\sum p_{-i}^{\mathrm{b}}\right) \quad (10)$$

$$b-(1+\theta)\cdot\bar{r}>0 \ \Rightarrow \bar{r}<r_i^{\mathrm{b}}<b+\left[(b-\bar{r})\cdot\sum p_{-i}^{\mathrm{b}}\right]\Big/p_i^{\mathrm{b}} \quad (11)$$

Therefore, when $b>\bar{r}$ and $r_i^{\mathrm{b}}>\bar{r}$, the price bid of consumer i can be determined by Eqn. (11).

To summarize, once the current market clearing price and total trading volume is released, the best strategy for consumer i when $b>\bar{r}$ is to bid $r_i^{\mathrm{b}}>\bar{r}$. Meanwhile, the analysis in Table I shows that when $b=\bar{r}$ and $b<\bar{r}$, consumer i cannot do better than bidding at $r_i^{\mathrm{b}}=\bar{r}$ and $r_i^{\mathrm{b}}<\bar{r}$, respectively.

Similarly, for the j^{th} producer, under the proposed market mechanism, the bidding strategies of producer j are analysed under different scenarios of its evaluation s, as shown in Table II. A producer obtains the utility of $\bar{r}_{\mathrm{new}}-s$ by selling a unit of electricity to consumers at the price of $\bar{r}_{\mathrm{new}}$. Besides, if a producer loses the bidding, the obtained utility will also be 0.

TABLE II ANALYSIS OF BIDDING STRATEGIES FOR PRODUCER UNDER DIFFERENT SCENARIOS

Scenarios of s	Bidding strategy	Values of $\bar{r}_{\mathrm{new}}$	Utility of producer j
$s>\bar{r}$	if $r_j^{\mathrm{s}}>\bar{r}$	$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}$	0
	if $r_j^{\mathrm{s}}=\bar{r}$	$\bar{r}_{\mathrm{new}}=\bar{r}$	0
	if $r_j^{\mathrm{s}}<\bar{r}$	$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}$	$(1-\theta)\cdot\bar{r}-s<0$
$s=\bar{r}$	if $r_j^{\mathrm{s}}>\bar{r}$	$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}$	0
	if $r_j^{\mathrm{s}}=\bar{r}$	$\bar{r}_{\mathrm{new}}=\bar{r}$	0
	if $r_j^{\mathrm{s}}<\bar{r}$	$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}$	$(1-\theta)\cdot\bar{r}-s<0$
$s<\bar{r}$	if $r_j^{\mathrm{s}}>\bar{r}$	$\bar{r}_{\mathrm{new}}=(1+\theta)\cdot\bar{r}$	0
	if $r_j^{\mathrm{s}}=\bar{r}$	$\bar{r}_{\mathrm{new}}=\bar{r}$	0
	if $r_j^{\mathrm{s}}<\bar{r}$	$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}$	$(1-\theta)\cdot\bar{r}-s$

Where θ is a parameter and indicates the change of market clearing because of the bids of producer j.

Thus, when no available market information, to bid at $r_j^{\mathrm{s}}=s$ is the only choice that can be the best strategy for the producer under all possible conditions.

In the re-bidding process, when $s<\bar{r}$ and producer j chooses to bid at $r_j^{s}<\bar{r}$, the producer needs to ensure $(1-\theta)\cdot\bar{r}-s>0$. Let p_{-j}^{s} denote the total bids of other participants except producer j, the MCP when producer j bids at r_j^{s} can be expressed as follows.

$$\bar{r}_{\mathrm{new}}=(1-\theta)\cdot\bar{r}=\left(r_j^{\mathrm{s}}\cdot p_j^{\mathrm{s}}+\sum\bar{r}\cdot p_{-j}^{\mathrm{s}}\right)\Big/\left(p_j^{\mathrm{s}}+\sum p_{-j}^{\mathrm{s}}\right) \quad (12)$$

$$(1-\theta)\cdot\bar{r}-s \ \Rightarrow s-\left[(\bar{r}-s)\cdot\sum p_{-j}^{\mathrm{s}}\right]\Big/p_j^{\mathrm{s}}<r_j^{\mathrm{s}}<\bar{r} \quad (13)$$

Therefore, when $s<\bar{r}$ and $r_j^{s}<\bar{r}$, the price bid of producer j can be determined by Eqn. (13).

Thus, once the current market clearing price and total trading volume is released, the best strategy for producer j when $s<\bar{r}$ is to bid $r_j^{s}<\bar{r}$. Meanwhile, the analysis in Table II shows that when $s=\bar{r}$ and $s>\bar{r}$, producer j cannot do better than bidding at $r_j^{s}=\bar{r}$ and $r_j^{s}>\bar{r}$, respectively.

In other words, when making decision to maximize their own utilities, both a consumer and a producer cannot do better than bidding honestly in the proposed market mechanism. Hence, Theorem 1 is proved.

The market clearing model of the proposed mechanism is formulated as follows.

$$\max \quad \sum_{i=1}^{N}p_i^{\mathrm{cb}}\cdot r_i^{\mathrm{b}}-\sum_{j=1}^{M}p_j^{\mathrm{cs}}\cdot r_j^{\mathrm{s}} \quad (14)$$

$$\text{s.t.} \quad \bar{r}=\Big(\sum_{i=1}^{N}r_i^{\mathrm{b}}\cdot p_i^{\mathrm{b}}+\sum_{j=1}^{M}r_j^{\mathrm{s}}\cdot p_j^{\mathrm{s}}\Big)\Big/\Big(\sum_{i=1}^{N}p_i^{\mathrm{b}}+\sum_{j=1}^{M}p_j^{\mathrm{s}}\Big) \quad (15)$$

$$\forall i\in N, p_i^{b}=0 \text{ if } r_i^{b}\le\bar{r} \quad (16)$$

$$\forall j\in M, p_j^{\mathrm{s}}=0 \text{ if } r_j^{\mathrm{s}}\ge\bar{r} \quad (17)$$

$$\sum_{i=1}^{N} p_i^{\mathrm{cb}} - \sum_{j=1}^{M} p_j^{\mathrm{cs}} = 0 \tag{18}$$

$$-P_l^{\max} \le \sum_{i\in N} p_i^{\mathrm{cb}} \cdot \rho_{l,i} + \sum_{j\in M} p_j^{\mathrm{cs}} \cdot \rho_{l,j} \le P_l^{\max} \quad \forall l \in L \tag{19}$$

$$0 \le p_i^{\mathrm{cb}} \le p_i^{\mathrm{b}},\ 0 \le p_j^{\mathrm{cs}} \le p_j^{\mathrm{s}} \tag{20}$$

where Eqn. (14) is to maximize the social welfare; Eqn. (15) calculates the MCP; Eqn. (16) and Eqn. (17) ensure that participants be dispatched only when they win the bidding; Eqn. (18) means that market clearing ends at an equilibrium state; Eqn. (19) represents transmission constraints; Eqn. (20) is constraint on decision variables.

B. Compatibility of the Proposed APM with Nodal Pricing

The nodal pricing method has been widely employed after being first proposed in [22], since it can provide appropriate price signal for reflecting the short-term operation cost of a given power system. Nodal pricing has an advantage in identifying the impacts of the injected power of each node on various line congestions and system power losses. Up to now, several forms of nodal pricing have been implemented in actually operating electricity markets including New York, New England, and PJM in USA, New Zealand, Argentina, as well as Chile. In [23], the nodal pricing mechanism is also introduced to price generation resources in the distribution network, but network congestion is not considered and nodal prices are derived based on the contribution of each distributed generation unit to the reduction of network losses.

The existing nodal pricing mechanism is based on marginal costs. Here it will be manifested that the proposed APM mechanism can also be integrated into the nodal pricing method.

In the PJM market, the adopted nodal price is composed of three components, namely system energy price, transmission congestion price and the marginal loss price [24] as expressed by Eqn. (21).

$$r^{\mathrm{np}} = r^{\mathrm{smp}} + r^{\mathrm{cp}} + r^{\mathrm{mlc}} \tag{21}$$

where r^{np} is the nodal price at a certain node; r^{smp} is the system marginal energy price derived from market clearing while ignoring branch congestion and losses; r^{cp} represents the congestion price and is calculated using the shadow price of binding constraints and the PTDF; r^{mlc} is the marginal loss price and is calculated using the system energy price and the penalty factor.

$$r^{\mathrm{cp}} = r^{\mathrm{sdp}} \cdot f^{\mathrm{PTDF}} \tag{22}$$

$$r^{\mathrm{mlc}} = r^{\mathrm{smp}} \cdot \left(1/f^{PF} - 1\right) \tag{23}$$

$$f^{PF} = 1\Big/\left[1-\left(\Delta P^{\mathrm{loss}}/\Delta P^{\mathrm{inj}}\right)\right] \tag{24}$$

where r^{sdp} denotes the shadow price of a binding constraint; f^{PTDF} indicates the PTDF; f^{PF} is penalty factor and measures the sensitivity of the transmission losses due to the injected power change at a certain bus; ΔP^{loss} / ΔP^{inj} is the change in system loss and power injection at a certain bus, respectively.

In order to integrate the proposed APM with the nodal pricing mechanism, the system marginal energy price r^{smp} in the nodal price needs to be replaced by $\bar{r}$ which is calculated using the APM. The shadow price r^{sdp} of a binding constraint can be calculated using the proposed market clearing model.

$$r^{\mathrm{apm,np}} = \bar{r} + r^{\mathrm{cp}} + r^{\mathrm{mlc}} \tag{25}$$

where $r^{\mathrm{apm,np}}$ is the nodal price after incorporating the MCP that is derived by the APM mechanism.

C. Analysis of the Game Equilibrium Considering Bidding Behaviours of Participants

Each rational participant in the distribution market will try to maximize its utility. Meanwhile, according to the previous discussion in Part A of this section, consumers / producers will bid to the market based on their self-evaluation of electricity utility / generation cost. Considering that participants are allowed to revise their bids in the electricity distribution market before the deadline, the bidding behaviours of participants can also be analysed in an iterative way.

After the k^{th} round of bidding, each participant needs to evaluate the market outcomes so as to determine its action in the k+1$^{\mathrm{th}}$ round of bidding. Let $\bar{r}_k$ denote the MCP after the k^{th} bidding. As discussed in the proof of Theorem 1, the best strategy for consumer i when $b>\bar{r}$ is to bid $r_i^{\mathrm{b}}>\bar{r}$. Meanwhile, when $b=\bar{r}$ and $b<\bar{r}$, consumer i bids at $r_i^{\mathrm{b}}=\bar{r}$ and $r_i^{\mathrm{b}}<\bar{r}$, respectively.

Then, the action space of the i^{th} consumer is given as follows.

$$\text{if } \bar{r}_k \ge b \begin{cases} \text{if } r_{k,i}^{\mathrm{b}} \le \bar{r}_k, \text{then } r_{k+1,i}^{\mathrm{b}} = r_{k,i}^{\mathrm{b}}; \\ \text{if } r_{k,i}^{\mathrm{b}} > \bar{r}_k, \text{then } r_{k+1,i}^{\mathrm{b}} = r_{k,i}^{\mathrm{b}} - \Delta < \bar{r}_k; \end{cases} \tag{26}$$

$$\text{if } \bar{r}_k < b \begin{cases} \text{if } r_{k,i}^{\mathrm{b}} > \bar{r}_k, \begin{cases} \text{if } p_{k,i}^{\mathrm{cb}} = p_i^{\mathrm{b}}, \text{then } r_{k+1,i}^{\mathrm{b}} = r_{k,i}^{\mathrm{b}}; \\ \text{if } p_{k,i}^{\mathrm{cb}} < p_i^{\mathrm{b}}, \text{then } r_{k+1,i}^{\mathrm{b}} = r_{k,i}^{\mathrm{b}} + \Delta; \end{cases} \\ \text{if } r_{k,i}^{\mathrm{b}} \le \bar{r}_k, \text{then } r_{k+1,i}^{\mathrm{b}} = r_{k,i}^{\mathrm{b}} + \Delta; \end{cases} \tag{27}$$

where Eqn. (26) and Eqn. (27) give the action space of the i^{th} consumer; $r_{k,i}^{\mathrm{b}}$ / $r_{k+1,i}^{\mathrm{b}}$ is the bid price of the i^{th} consumer in the k^{th} / k+1$^{\mathrm{th}}$ bidding; Δ is the step length in the iterative bidding; Δ represents the adjustment on bidding price made by a certain participant. In practice, the value of Δ will be determined by each decision-maker and can be an arbitrary value. The distribution market operator can set a threshold for the minimum adjustment in order to eliminate trivial adjustments. Besides, if limitation on times of re-bidding is enforced, market participants will automatically chose a proper value for re-bidding prices, in order to make the re-bid price meaningful.

Considering a rational consumer bids to maximize its utility, thus in Eqn. (26), when $\bar{r}_k \ge b$ and $r_{k,i}^{\mathrm{b}} > \bar{r}_k$, $r_{k+1,i}^{\mathrm{b}}$ needs to respect the following constraint.

$$r^{\mathrm{fdt}} < r_{k+1,i}^{\mathrm{b}} < \bar{r}_k \tag{28}$$

where r^{fdt} is the feed-in tariff.

In Eqn. (27), when $\bar{r}_k < b$ and $r_{k,i}^{\mathrm{b}} \le \bar{r}_k$, $r_{k+1,i}^{\mathrm{b}}$ needs to respect the flowing constraint.

$$\bar{r}_k < r_{k+1,i}^{\mathrm{b}} < \arg F(r_{k+1,i}^{\mathrm{b}}) = b - (1+\theta)\cdot \bar{r}_k = 0 \tag{29}$$

Eqn. (29) means that when re-bidding a consumer needs ensure its utility be non-negative after the k+1$^{\mathrm{th}}$ bidding, if the bidding strategies of other participants keep unchanged.

Likewise, the best strategy for producer j when $s<\bar{r}$ is to bid $r_j^{s}<\bar{r}$. Meanwhile, when $s=\bar{r}$ and $s>\bar{r}$, producer j bids at $r_j^{s}=\bar{r}$ and $r_j^{s}>\bar{r}$, respectively. The action space of the j^{th} producer is given as follows.

$$\text{if } \bar{r}_k \le s \begin{cases} \text{if } r^{s}_{k,j} \ge \bar{r}_k, \text{then } r^{s}_{k+1,j} = r^{s}_{k,j}; \\ \text{if } r^{s}_{k,j} < \bar{r}_k, \text{then } r^{s}_{k+1,j} = r^{s}_{k,j} + \Delta > \bar{r}_k; \end{cases} \tag{30}$$

$$\text{if } \bar{r}_k > s \begin{cases} \text{if } r^{s}_{k,j} \ge \bar{r}_k, \text{then } r^{s}_{k+1,j} = r^{s}_{k,j} - \Delta; \\ \text{if } r^{s}_{k,j} < \bar{r}_k, \begin{cases} \text{if } p^{cs}_{k,j} = p^{s}_{k,j}, \text{then } r^{s}_{k+1,j} = r^{s}_{k,j}; \\ \text{if } p^{cs}_{k,j} < p^{s}_{k,j}, \text{then } r^{s}_{k+1,j} = r^{s}_{k,j} - \Delta; \end{cases} \end{cases} \tag{31}$$

where Eqn. (30) and Eqn. (31) give the action space of the j^{th} producer. $r^{s}_{k,j}$ / $r^{s}_{k+1,j}$ is the bid price of the j^{th} producer in the k^{th} / $k+1^{\text{th}}$ bidding. Δ is the step length in the iterative bidding.

Similarly, considering each producer also bids to maximize its utility, in Eqn. (30), when $\bar{r}_k \le s$ and $r^{s}_{k,j} < \bar{r}_k$, $r^{s}_{k+1,j}$ needs to respect the following constraint.

$$\bar{r}_k < r^{s}_{k+1,j} < r^{\text{retail}} \tag{32}$$

where r^{retail} is the incumbent electricity retail price.

In Eqn. (31), when $\bar{r}_k > s$ and $r^{s}_{k,j} \ge \bar{r}_k$, $r^{s}_{k+1,j}$ needs to respect the following constraint.

$$\arg F(r^{s}_{k+1,j}) = (1-\theta)\cdot \bar{r}_k - s = 0 < r^{s}_{k+1,j} < \bar{r}_k \tag{33}$$

Eqn. (33) means that when re-bidding each producer needs ensure its utility be no-negative after the $k+1^{\text{th}}$ bidding, if the bidding strategies of other participants keep unchanged.

Due to the re-bidding of participants, the market clearing will experience a dynamic process until the deadline of re-bidding is reached or a gaming equilibrium attained. In reality, the re-bidding process is a re-order of the priority sequence among participants in the market clearing outcomes. As a result, a consumer with a relatively higher utility *b* and a producer with a relatively smaller cost *s* would get a higher priority through their re-bidding.

Theorem 2: *In the proposed market mechanism, when consumers appear in a descending order by their utility b and producers appear in an ascending order by their cost s, the bidding reaches a gaming equilibrium.*

Proof: Assume that in a gaming equilibrium, there exists a pair of purchasing bids from consumer i-1 and consumer i, where $b_{i-1} < b_i$ and $r^{b}_{i-1} > r^{b}_{i}$, then during the dynamic process of the market clearing, once $\bar{r}_{\text{dyn}}$ falls in (b_{i-1}, b_i), consumer i-1 and consumer i would re-bid by decreasing ($r^{b}_{i-1} \le \bar{r}_{\text{dyn}}$) and increasing ($r^{b}_{i} > \bar{r}_{\text{dyn}}$) their bid prices, respectively. It is the same with the bidding from producers, namely if $s_{j-1} > s_j$, once $\bar{r}_{\text{dyn}}$ falls in (s_j, s_{j-1}), producer j and producer j-1 would re-bid by decreasing ($r^{s}_{j} \le \bar{r}_{\text{dyn}}$) and increasing ($r^{s}_{j-1} > \bar{r}_{\text{dyn}}$) their bid prices, respectively. After re-bidding, the priority of participants being cleared will be re-ordered.

Once consumers are re-ordered in a descending order by their utility b, it can also be assumed that the MCP $\bar{r}_{\text{dyn}}$ falls between b_{i-1} and b_i, but here $b_{i-1} > b_i$ and $r^{b}_{i-1} > r^{b}_{i}$. Then consumer i-1 and consumer i are not motivated to re-bid anymore, because re-biding a higher price of $r^{b}_{i-1} > \bar{r}_{\text{dyn}}$ (due to $b_{i-1} > \bar{r}_{\text{dyn}}$) and a smaller price of $r^{b}_{i} < \bar{r}_{\text{dyn}}$ (due to $b_i < \bar{r}_{\text{dyn}}$) can no longer promote their priority in the market clearing process. The same analysis applies to the bidding of producers. Thus, theorem 2 is proved.

V. Case Study and Discussions

A. Data Specifications in the Case Study

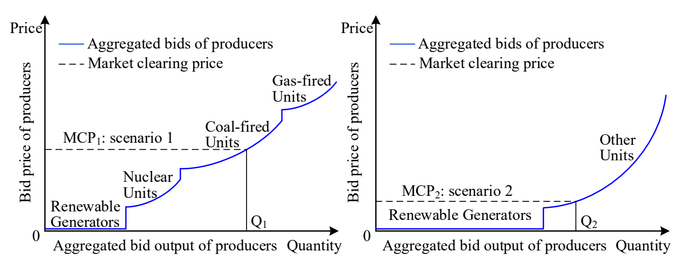
In the case study, it is assumed that there are 100 consumers and 100 producers in total. As discussed in Section III, the LOCE of renewable generation *s* and the self-estimated utility of electricity *b* are assumed to fall within the range between 0.05 and 0.5 \$/kWh. The step length Δ of adjusting biding prices for both consumers and producers is set as 0.05. During market simulation, there is no limitation on how many times these participants can re-bid into the distribution market. Besides, actual residential solar data in the Australian distribution system are presented in [25], with the majority of household solar panels having a generation capacity ranging from 1 kW to 5 kW. Therefore, the bid quantities of participants are assumed to fall within the range between 1 and 5kW. The initial biding parameters of participants are generated randomly.

In order to manifest problems brought by the marginal cost based market, various types of generation units are assumed to exist in the market discussed in part (1) of section V-B. Then, in part (2) of section V-B, another test case which consists of 100 customers and 100 producers is adopted to manifest the efficiency and feasibility of the proposed market mechanism in a distribution system without congestion. All these producers are renewable generation units. Furthermore, in order to show the compatibility of the proposed APM mechanism with the nodal pricing algorithm, the 33-bus distribution system with renewable generators is adopted in part (3) of section V-B and different scenarios of network congestion are considered.

B. Results and Discussions

(1) Market clearing under marginal cost based mechanism

Under the marginal cost based mechanism, the MCP is determined based on the merit order curve. After receiving the bids from participants, the market operator will aggregate the bids and rank the bids with the increasing price order for producers and the decreasing price order for consumers, which are namely the merit order curves. The intersection of the aggregated demand curve and the aggregated supply curve determines the MCP and the clearing volume, as shown in Fig.1. In reality, renewable generators usually bid at the price floor in existing electricity markets [26]. Fig.3 shows the market clearing outcome when a renewable generator bids a zero price in the marginal cost based market.



(*a*) Market with low penetration level of renewables (*b*) Market with high penetration level of renewables

Fig. 3 MCP determined by the merit order curve in the marginal cost based market.

Fig. 3(*a*) shows the scenario when the penetration level of renewables is low in the electricity market and various types of generators bid into the market. From Fig.3 (*a*), it can be found that the MCP is always determined by the marginal unit regardless of each unit's actual bidding quantity, where Q_1 is the total system demand. Therefore, the MCP can be determined by a non-zero bidding price even with a small bidding output, such as in scenario 2 of Fig.3 (*b*) where there is a high penetration level of renewables. As long as there exists any other unit with the marginal cost higher than the LCOE of renewable generation, renewable generators will bid a zero price. Therefore, renewable generators are not motivated to bid honestly according to their self-evaluated generation costs.

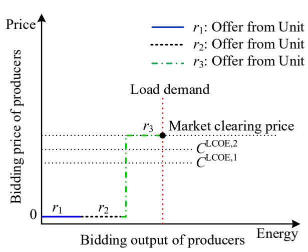
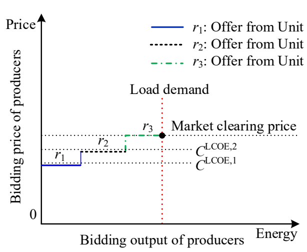
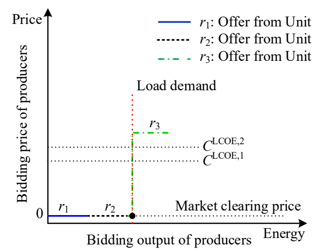
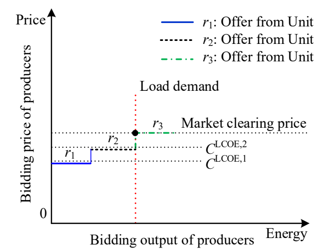
A power system with three generation units is taken as an example to further elaborate shortcomings of the conventional uniform clearing mechanism when pricing zero marginal cost generations, where details about end-users are omitted for simplification. As is known, generation costs can be divided into two categories, namely long-term and short-term costs. LCOE is a measurement of long-term generation cost for renewables while marginal cost measures the short-term generation cost. Details of generation units in the assumed power system are given in Table III.

TABLE III Details of Generation Units in the Assumed Power System

Unit #	Long-term Generation Cost	Short-term Generation Cost
	LCOE	Marginal Cost
1	$C^{LCOE,1}$	$C_1^{mgl}=0$
2	$C^{LCOE,2}$	$C_2^{mgl}=0$
3	$C^{LCOE,3}$	$C_3^{mgl}>0$

The marginal cost based market is designed to efficiently price the short-term operation cost of power systems where market participants make bidding decisions based on their short-term generation costs [14] [22]. In practice, the historical bidding data from the Australian National Electricity Market (NEM) suggests that generators tend to bid at its short-run marginal cost. Many generators in NEM bid at zero or negative prices in the energy market. The logic behind this is that, generators will bid at their short-run marginal cost or even lower prices is because they hope to ensure their power outputs and they expect that some other generators will be the marginal unit setting a higher price. In Table IV, comparisons between market clearing outcomes of the marginal cost based market and the proposed APM mechanism in this paper are presented.

TABLE IV Comparison Between the Marginal Cost Based Market and the Proposed APM Mechanism

Marginal cost based market	**APM mechanism**
Scenario 1: high load demand	Scenario 1: high load demand
	
Analysis of MCP	Analysis of MCP
Under the uniform clearing mechanism, the market clearing price will be acceptable for units 1 and 2, even though they would offer zero prices. Because the MCP is determined only by the marginal unit and offers from units 1 and 2 have no impact on MCP.	Under the APM mechanism, if units 1 and 2 still offer zero prices then the final MCP could be lower than their acceptable values. Therefore, in order to have an acceptable MCP, units 1 and 2 would choose non-zero offer prices since each offer has impacts on the final MCP. According to Theorem 2, the gaming equilibrium of the APM mechanism is a state where producers appear in an ascending order by their self-estimated generation cost *s*.
Scenario 2: low load demand	Scenario 2: low load demand
	
Analysis of MCP	Analysis of MCP
Due to the uncertainty of electricity consumption activities of end-users, renewable generators are also likely to become marginal units when load demand of power systems is low. The zero prices of offers from renewable generators result in the zero MCP, which would fail to reveal the genuine non-zero value of renewable generations.	Units 1 and 2 are no longer offering zero prices to the market under the proposed APM mechanism. Under this circumstance, even when only generation units with zero marginal costs participate in the bidding, the proposed mechanism can still produce a reasonable MCP.
Conclusion	Conclusion
Decisions of participants are made based on their short-term generation costs. Generation units with zero marginal costs will still offer zero prices to the market, even though they have non-zero LCOE.	The offer from each participant will impact the final MCP. The unique gaming equilibrium state enables participants to submit offers by considering their long-term generation cost LCOE.

From the comparison in Table IV, it can be found that the problem of always bidding a zero price by renewable generators in the marginal cost based market cannot be overcome if decision-making is based on the short-term generation cost, since MCP is only determined by the marginal unit and offers smaller than the marginal unit have no impact on it. In contrast, under the proposed APM mechanism, MCP is designed to be the weighted average of participants' bid prices, where the weighting factors are their bid quantities. The MCP is therefore determined by offers from all participants, thus it motivates participates to submit non-zero offers or even by taking into account their long-term generation cost LCOE. In a word, although the long-term generation cost LCOE is introduced to denote the generation cost of renewables, the failure of uniform clearing mechanism may still exist, namely generation units with zero marginal costs will still offer zero prices to the market. However, the proposed APM mechanism enables renewable generators to develop non-zero offers and they can also take into account their LCOE when setting parameters.

(2) Market clearing using the proposed APM mechanism

In Section IV, it has been proved that honesty is a dominant strategy for participants under the proposed APM mechanism. Market simulations are carried out under the proposed market mechanism. In order to examine the proposed market mechanism, it is assumed that the self-evaluated costs / utilities of all producers (from No. 1 to No. 100) / consumers (from No.1 to No.100) appear in a descending / ascending order, as shown in Fig.4. Since the output of a renewable generator is mainly determined by the natural condition, such as the wind and solar strength. In the case study, the bid quantity of generation output (for producers) and demand (for consumers) is generated randomly in each time of market simulation. Therefore, participants adjust their bidding strategies only through changing their bidding prices in the distribution market. Besides, the number of participants is also generated randomly in order to simulate the changing market condition.

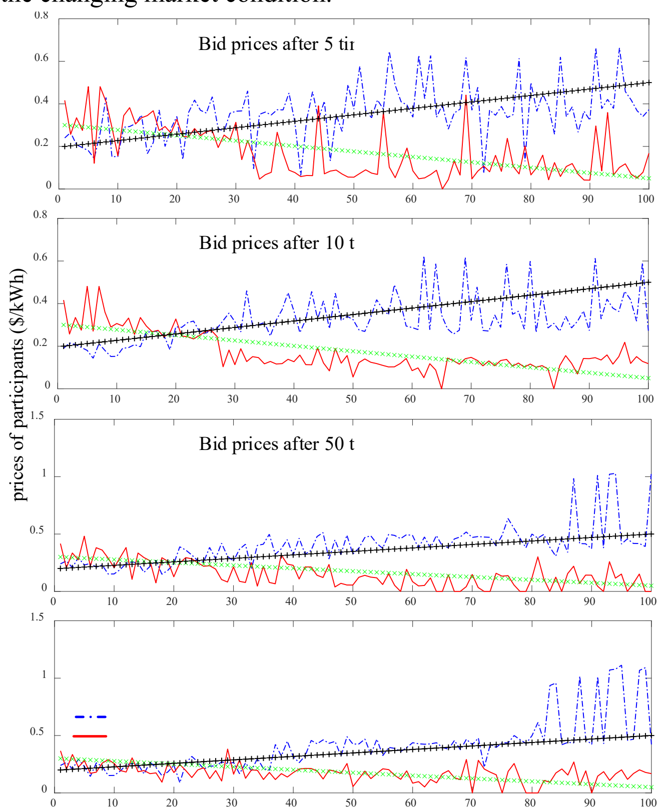


Fig. 4 Bid prices of participants in the market simulation.

As shown in Fig.4, with the increasing number of market simulations, from 5, 10, 50, to 70 times, the bidding prices of participants evolved from the initial random values into an ordered sequence. This is because after a large number of market simulations are carried out, various market conditions have been experienced by participants. Multiple games between participants with different LCOEs result in consumers' appearing in a descending order by their utility *b* and producers' appearing in an ascending order by their estimated cost *s*, as stated in Theorem 2. Market participants learnt from historical transactions that honesty which is defined for Theorem 1 is their dominant bidding strategy. Under the proposed APM mechanism, the bid prices of all participants finally fluctuate around their real self-evaluated electricity costs / utilities, namely each participant finally tends to submit a bid based on its own self-evaluated cost / utility. This result verifies the honesty dominant feature of the proposed market mechanism.

Compared with the marginal cost based mechanism, market participants will determine bidding prices according to their real self-evaluated generation costs (for producers) and utilities of electricity (for consumers) under the proposed APM mechanism. Consequently, the problem of always bidding a zero price by renewable generators in some existing markets can be avoided. Especially, when only renewable generators with a zero marginal cost participate in the bidding, the marginal cost based mechanism may fail to work since all participants only tend to bid at the price floor while expecting another unit will act as the marginal unit, but the proposed APM mechanism can still produce a reasonable MCP.

In addition, as participants are all bidding based their own self-evaluated costs / utilities, the setting of bidding parameters will be less affected by the behaviors of the opponents. Therefore, the proposed market mechanism has the potential of developing into a set-and-forget bidding market.

(3) The compatibility of the proposed APM mechanism with nodal pricing

The IEEE 33-bus distribution system [27] is adopted for testing the compatibility of the proposed APM mechanism with the nodal pricing mechanism. Because detailed modelling of the power flow problem is out of the scope of this paper, the distribution network here is treated as a lossless one. For simplification, it is assumed that the distribution network is a three-phase balanced one. Thus, the distribution network can be modelled as a single-phase (positive sequence) one. It is also assumed that end-users 1 to 32 are connected to feeders 2 to 33 sequentially, with end-users 1 to 16 to be consumers and end-users 17 to 32 to be producers. Besides, node 1 is selected as the slack bus.

In order to calculate nodal prices under the APM mechanism, the PTDFs are firstly calculated using the data from [27]. Then, the shadow price of each transmission constraint is calculated. Table V gives the assumed congestions and corresponding shadow prices of constraints.

TABLE V ASSUMED CONGESTIONS AND THE SHADOW PRICES OF CONSTRAINTS

Branch #	Connected nodes	Shadow price ($/kWh)
1	10 to 11	-0.0389
2	15 to 16	-0.0405
3	20 to 21	-0.7246
4	26 to 27	-0.0457

As mentioned in part B of Section IV, the nodal pricing algorithm has an advantage in identifying the impacts of the injected power of each node on various line congestions and system power losses. In Table V, four branches in the 33-bus distribution system are randomly chosen where congestion is considered to happen. Their shadow prices represent the marginal increasing of social welfare which is measured by money if the binding constraint is relaxed by 1kW. Since the difference of social welfare between before and after relaxing the binding constraint is negative, shadow prices are therefore negative values.

The calculation results of penalty factors are presented in Table VI. The congestion and network loss components of the final nodal price are calculated using the method introduced in part B of Section IV. Table VI shows the distribution network nodal prices attained by the proposed APM mechanism. Since node 1 is selected as the slack bus, nodal price of node 1 indicates the system marginal price, which is the incremental price of energy for the system without losses and congestions. As for the other nodes, their nodal price is determined by their contribution to network congestions and system power losses. To be specific, when a node is upstream of a binding constraint, its power injection would increase the branch congestion and thus have a positive PTDF corresponding to this constraint. After multiplying negative shadow prices shown in Table V, its congestion component in Eqn. (25) will be negative and finally results in negative revenues to generation units. If the bus is downstream of a binding constraint, its power injection would help relieve congestion with a negative PTDF. Together with the negative shadow prices, it will lead to positive revenues to generators.

In Table VI, the penalty factor is used to measure sensitivity of system power losses to power injection in each node. If the penalty factor is larger than 1, it means the corresponding node is electrically distant from system load and power injection of this node would increase system power losses. Consequently, the corresponding marginal loss component as expressed by Eqn. (23) will be negative and brings negative revenues to generators. In contrast, power injection of a node with a penalty factor less than 1 can help reduce system losses and would bring positive revenues to generation. As calculation results in Table VI comply with above analysis, it verified the compatibility of the proposed APM mechanism with the nodal pricing system. Therefore, in the distribution market with the APM mechanism employed, merits of nodal pricing can still be retained and contribute to the enhancement of the operating efficiency of the distribution network.

TABLE VI CALCULATION RESULTS OF NODAL PRICES IN THE IEEE 33-BUS DISTRIBUTION SYSTEM

Node	PTDF of each branch				Penalty factor	Nodal price ($/kWh)
	1	2	3	4		
1	0	0	0	0	1.00000	0.6371
2	0.000	0.000	0.000	0.000	0.99999	0.6371
3	0.011	-0.008	-0.050	-0.005	1.00003	0.6734
4	0.018	-0.006	-0.076	0.024	1.00009	0.6906
5	0.026	-0.003	-0.104	0.053	1.00015	0.7091
6	0.055	0.007	-0.206	0.162	1.00025	0.7764
7	0.092	0.056	-0.307	0.109	1.00032	0.8485
8	0.106	0.075	-0.346	0.089	1.00059	0.8762
9	0.222	0.137	-0.371	0.045	1.00092	0.8891
10	0.451	0.150	-0.402	0.030	1.00120	0.9026
11	-0.529	0.152	-0.405	0.028	1.00125	0.9429
12	-0.491	0.154	-0.410	0.026	1.00132	0.9450
13	-0.294	0.209	-0.382	-0.004	1.00156	0.9161
14	-0.173	0.243	-0.365	-0.022	1.00162	0.8984
15	-0.083	0.268	-0.352	-0.035	1.00168	0.8851
16	-0.073	-0.670	-0.334	-0.070	1.00174	0.9112
17	-0.042	-0.476	-0.276	-0.182	1.00180	0.8652
18	-0.031	-0.411	-0.256	-0.220	0.99808	0.8517
19	-0.007	0.005	0.031	0.003	1.00003	0.6146
20	-0.065	0.051	0.299	0.030	1.00021	0.4194
21	-0.085	0.067	-0.607	0.040	1.00024	1.0755
22	-0.215	0.095	-0.544	0.035	1.00027	1.0340
23	0.011	-0.023	-0.066	-0.058	1.00001	0.6881
24	0.013	-0.057	-0.104	-0.181	1.00009	0.7225
25	0.015	-0.091	-0.142	-0.303	1.00011	0.7569
26	0.052	0.001	-0.204	0.186	0.99979	0.7745
27	0.049	-0.009	-0.201	-0.779	0.99987	0.8169
28	0.030	-0.070	-0.183	-0.557	1.00012	0.7967
29	0.016	-0.115	-0.169	-0.390	1.00029	0.7812
30	0.011	-0.144	-0.177	-0.373	1.00037	0.7876
31	-0.006	-0.253	-0.210	-0.310	1.00050	0.8136
32	-0.013	-0.294	-0.222	-0.287	1.00053	0.8232
33	-0.022	-0.354	-0.240	-0.252	1.00055	0.8374

C. Further Analysis on Electricity Distribution Market

In existing electricity markets where generators usually submit an offer including prices and corresponding output levels, generators are required to fix at the output level determined by the market clearing process during the real-time operation of power systems. Under this circumstance, if re-bidding without any penalty is permitted, participants would be motivated to conduct gambling behaviours in order for higher profit without any cost. In the electricity distribution market of this paper, although intermittence and uncertainty of renewable energy can be controlled through organizing the electricity market in a flexible way and adopting energy storage systems, there are still uncertainties in renewable generation outputs and electricity consumption behaviours of end-users. Consequently, the final market clearing outcomes are subject to impacts of these uncertainties and are determined by the real-time conditions. In this paper, participants are permitted to re-bid without any penalty, but if they try to re-bid by deviating far from their self-estimated electricity utility, they are risking themselves by losing the bidding in the final market clearing process. Therefore, the uncertainty of renewable generations prohibits participants from conducting gambling behaviours. Besides, according to the definition of honesty in the paper, it is possible that generators will offer a price higher than its self-estimated generation cost s, but this will not change the final equilibrium state of the market, as given by Theorem 2.

In practical, a number of trials and projects on peer to peer (P2P) electricity trading in the distribution network have been implemented in some countries, including the Power Ledge in Australia, the Lo3 Energy in New York, USA, and the Piclo in UK. Ref. [28] surveyed the major P2P electricity trading projects worldwide and reviewed the potential development and future challenges. These projects are featured by promoting transactions between renewable energy suppliers and renewable energy preferred consumers in distribution markets. Although they aim to expand small-scale distributed resources and creating new markets, they all neglect the core problem associated with renewable energy trading: how to establish a proper pricing mechanism for renewable generation with a zero marginal cost.

Electricity trading in the distribution market is different from that in the wholesale market. Firstly, participants are almost all prosumers installed with small-scale renewable generators. The bid or offered transaction volume of electricity from each prosumer is usually small because of the limited generation capacity. Secondly, transactions are carried out between almost 100% renewable generations. Thirdly, participants will mainly be distributed small-scale energy prosumers. Unlike participants in electricity wholesale markets, distribution system prosumers are usually not able to develop bidding decisions through sophisticated optimization computation. Therefore, the set-and-forget method of setting bid parameters is preferred when participate in the distribution market.

Due to features of transaction in the distribution market, the proposed market mechanism differs from existing uniform-pricing and pay-as-bid markets in the following aspects. In the proposed one, all bidding prices and quantities are used when determining the market clearing price, while under uniform-pricing and pay-as-bid mechanisms it only the winning bids matters. A dominant bidding strategy is proved to exist in the proposed market, which enables the proposed mechanism to develop into a set-and-forget bidding market but is impossible under other market mechanisms.

Besides, existing research has shown that the increasing penetration level of renewable energy in the distribution system is extending the provision of ancillary services even to wind and photovoltaic systems [29]. However, this would incur additional costs associated with necessary infrastructures such as the installation of power converters. Therefore, the research of this paper mainly focused on the electricity energy market. The market clearing mechanism is designed for pricing the energy from renewable generations.

In practices, many coal-fired generators participate in both energy and ancillary markets simultaneously. As mentioned before, the historical bidding data from the Australian NEM suggests that the incomes gained from the ancillary market will not affect the generators' incentive to bid at its short-run marginal cost. For instance, many generators in NEM bid at zero or negative prices in the energy market, while providing frequency regulation services simultaneously. The logic behind this is that, generators will bid at their short-run marginal cost or even lower prices is because they hope to ensure their power outputs and they expect that some other generators will be the marginal unit setting a higher price. According to our analysis in the paper, we believe this logic is applicable in the distribution level market as well. Our novel clearing mechanism therefore would be helpful even if the distributed generation takes part in ancillary markets as well.

The further increasing integration of renewable resources in the distribution system could impact the distribution market in several different ways. Because enough reserve capacity will be needed to compensate the real-time deviation of renewable generations, especially the fast regulation services. Firstly, if impacts of the intermittence of renewables are considered to be eliminated in a way similar to this paper, namely through organizing the distribution market close to real-time and each participant can compensate for the deviation of renewable outputs using their self-equipped energy storage systems, then the proposed market mechanism can still be applied without establishing a separate ancillary market. Secondly, if participants would be penalized for deviation of outputs and modelled to purchase regulation services through market-based mechanisms, then the ancillary market which may be jointly or separately optimized with the energy market will be indispensable. At this point, not only distributed generators but also energy storage systems [30] should be taken into account when designing the ancillary market. Meanwhile, further research on the quantitative analysis of regulation services and pricing of energy storage capacity will also be needed to ensure the operation security and guarantee the power supply within a distribution network.

VI. Conclusions

The electricity distribution market, in particular the P2P electricity trading, has attracted world-wide interests. A variety of trials on P2P electricity trading have been carried out in countries around the world during the past years. However, until now, there is no market mechanism which can efficiently settle the transactions in the distribution market dominated by renewable generation. On the one hand, mainly small-scale renewable generation facilities are installed in the distribution network. Some market participants could be small prosumers. Therefore, they would prefer the set-and-forget method in building bidding strategies. On the other hand, the marginal costs of renewable generators are almost zero. Therefore, a new market mechanism is needed which differs from the traditional marginal cost based market mechanism. This paper proposed a double-sided auction mechanism for renewable generators with a zero marginal cost in the distribution network. An average price clearing mechanism is designed for distribution market competition. Notably, the honesty bidding behavior is proved to be a dominant strategy for participants in the proposed market, which enables the proposed mechanism to develop into a set-and-forget bidding market. In addition, the proposed APM mechanism is compatible with the nodal pricing system. Merits of the nodal pricing can still be retained when adopting the proposed mechanism in the distribution market.

In terms of future research, the purchase of regulation services through market-based mechanisms will be studied, which may be jointly or separately optimized with the energy market. Notably, energy storage systems as an essential provision of ancillary service in the distribution system should also be taken into account when designing the ancillary market mechanism. It will focus on quantitative analysis of regulation services and pricing of energy storage capacity to ensure the operation security and guarantee the power supply within a distribution network. Besides, uncertainty of implementing the market clearing outcomes is neglected in the proposed mechanism. Another direction of further work will be the impacts of uncertain trading behaviours on the market operation, since the implementation of market clearing outcomes cannot be guaranteed under certain occasions, such as when the energy storage capacity is insufficient.

References

[1] A. Blakers, B. Lu, and M. Stocks, "100% renewable electricity in Australia," *Energy*, vol. 133, pp. 471-482, Aug. 2017.

[2] B. V. Mathiesen, H. Lund, and K. Karlsson, "100% Renewable energy systems, climate mitigation and economic growth," *Applied Energy*, vol. 88, no. 2, pp. 488-501, Feb. 2011.

[3] Roy Morgan, "Solar Electric Panels hot items in Queensland & South Australia," July 06 2017. http://www.roymorgan.com/findings/7262-solar-energy-electric-panels-march-2017-201707061419

[4] N. Li, "A market mechanism for electric distribution networks," *Proceedings of the 2015 IEEE 54th Annual Conference on Decision and Control (CDC)*, Osaka, Japan, 15-18 Dec. 2015.
[5] Y. Liu, L. Guo, C. Wang, and X. Li, "Strategic bidding optimization of microgrids in electricity distribution market," *Proceedings of the 2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, USA, 16-20 Jul. 2017.
[6] T. Lu, Z. Wang, J. Wang, Q. Ai, and C. Wang, "A Data-Driven Stackelberg Market Strategy for Demand Response-Enabled Distribution Systems," *IEEE Trans Smart Grid*, vol. PP, no. 99, pp. 1-1, Jan. 2018.
[7] M. N. Faqiry, A. K. Zarabie, F. Nassery, H. Wu, and S. Das, "A day-ahead market energy auction for distribution system operation," *Proceedings of 2017 IEEE International Conference on Electro Information Technology (EIT)*, Lincoln, NE, USA, 14-17 May 2017.
[8] S. Parhizi, A. Khodaei, and S. Bahramirad, "Distribution market clearing and settlement," *Proceedings of the 2016 IEEE Power and Energy Society General Meeting (PESGM)*, Boston, MA, USA, 17-21 Jul. 2016.
[9] S. Parhizi, and A. Khodaei, "Investigating the necessity of distribution markets in accommodating high penetration microgrids," *Proceedings of the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Dallas, TX, USA, 3-5 May 2016.
[10] S. Parhizi, A. Majzoobi, and A. Khodaei, "Net-Zero Settlement in Distribution Markets," *Proceedings of the 2017 IEEE Power and Energy General Meeting (PESGM)*, Chicago, IL, USA, 16-20 Jul. 2017.
[11] R. Yang, and Y. Zhang, "Three-phase AC optimal power flow based distribution locational marginal price," *Proceedings of the 2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 23-26 Apr. 2017.
[12] V. Pakka and R. Rylatt, "Design and Analysis of Electrical Distribution Networks and Balancing Markets in the UK: A New Framework with Applications," *Energies*, vol. 9, no. 2, pp. 1-20, Feb. 2016
[13] S. M. Nosratabadi, R.-A. Hooshmand, and E. Gholipour, "A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 341-363, Jan. 2017.
[14] P. Pikk and M. Viiding, "The dangers of marginal cost based electricity pricing," *Baltic Journal of Economics*, vol. 13, no. 1, pp. 49-62, Jun. 2014.
[15] L. Barroso, T. Cavalcanti, P. Giesbertz and K. Purchala, "Classification of Electricity Market Models Worldwide," *2005 CIGRE/IEEE PES International Symposium*, 5–7 October 2005, New Orleans, Louisiana USA.
[16] P. Cramton, "Electricity market design," *Oxford Review of Economic Policy*, vol. 33, no. 4, pp. 589-612, Nov. 2017.
[17] A. J. Conejo, M. Carrión, and J. M. Morales, "Decision making under uncertainty in electricity markets," *Springer*, New York, USA, 2010.
[18] B. Elliston, J. Riesz, and I. MacGill, "What cost for more renewables? The incremental cost of renewable generation – An Australian National Electricity Market case study," *Renewable Energy*, vol. 95, pp. 127-139, Sept. 2016.
[19] International Renewable Energy Agency, "Renewable Power Generation Costs in 2017," Jan. 2018. http://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017
[20] D.C. Parkes, "Iterative com*binatoria*l auctions: achieving economic and computational efficiency," *University of Pennsylvania*, 2001.
[21] R. P. McAfee, "A dominant strategy double auction," *Journal of Economic Theory*, vol. 56, no. 2, pp. 434-450, Apr. 1992.
[22] F. C. Schweppe, M. C. Caramanis, R. D. Tabors, and R. E. Bohn, "Spot Pricing of Electricity," *Springer*, US, 1988.
[23] P. M. Sotkiewicz and J. M. Vignolo, "Nodal Pricing for Distribution Networks: Efficient Pricing for Efficiency Enhancing DG," *IEEE Trans. Power Systems*, vol. 21, no. 2, pp. 1013-1014, May 2006.
[24] PJM electricity market. Training Material. http://pjm.com/training/training-material.aspx
[25] Ausgrid. Solar home electricity data. https://www.ausgrid.com.au/Common/About-us/Corporate-information/Data-to-share/Solar-home-electricity-data.aspx
[26] B. A. Frew, "Revenue Sufficiency and Reliability in a Zero Marginal Cost Future," *Proceedings of the 15th International Workshop on Large-Scale Integration of Wind Power*, Vienna, Austria, 15-17 Nov. 2016.
[27] M. E. Baran, and F. F. Wu, "Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing," *IEEE Trans. Power Delivery*, vol. 4, no. 2, Apr. 1989.
[28] C. Park, and T. Yong, "Comparative review and discussion on P2P electricity trading," *Energy Procedia*, vol. 128, pp. 3-9, Sept. 2017.
[29] B. Olek and M. Wierzbowski, "Local Energy Balancing and Ancillary Services in Low-Voltage Networks With Distributed Generation, Energy Storage, and Active Loads," *IEEE Trans Industrial Electronics*, vol. 62, no. 4, Apr. 2015.
[30] M. Farrokhabadi, B. V. Solanki, C. A. Canizares, K. Bhattacharya, S. Koenig, , P. S. Sauter, T. Leibfried and S. Hohmann, "Energy Storage in Microgrids: Compensating for Generation and Demand Fluctuations While Providing Ancillary Services," *IEEE Power and Energy Magazine*, vol. 15, no. 5, Sept.-Oct. 2017.

Jiajia Yang (STM'15-M'18) received his B.E. degree from Northeast Electric Power University, China, M.E. degree from Zhejiang University, China, and Ph.D. degree from the University of New South Wales, Australia, in 2011, 2014 and 2018 respectively, all in electrical engineering. He is currently a Research Associate in electrical engineering at the University of New South Wales, Australia. His research interests include electricity retailing, data mining in smart grid, renewable energy integration, and power markets.

Junhua Zhao (M'07-SM'17) received his Ph.D. degree from the University of Queensland, Australia. He is currently an Associate Professor and the Assistant Dean of the School of Science and Engineering, the Chinese University of Hong Kong, Shenzhen, Guangdong, China. He is also a "National 1000 Talents Program" Young Scholar of China. His research interests include power system analysis and computation, smart grid, energy Internet, electricity market, data mining, and artificial intelligence. He is an Editorial Board Member of *Electric Power Components and Systems* and *Journal of Modern Power System and Clean Energy*.

Jing Qiu (M'14) is currently a lecturer in electrical engineering at the University of Sydney, Australia. He obtained his B.Eng. degree in control engineering from Shandong University, China, M.Sc. degree in environmental policy and management, majoring in carbon financing in the power sector, from The University of Manchester, U.K., and Ph.D. in electrical engineering from The University of Newcastle, Australia, in 2008, 2010 and 2014 respectively. His areas of interest include power system operation and planning, power economics, electricity market modeling, and risk management.

Fushuan Wen received the B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 1985 and 1988, respectively, and the Ph.D. degree from Zhejiang University, Hangzhou, China, in 1991, all in electrical engineering.

He joined the faculty of Zhejiang University in 1991, and has been a full professor and the director of the Institute of Power Economics and Information since 1997, and the director of Zhejiang University-Insigma Joint Research Center for Smart Grids since 2010. He had been a university distinguished professor, the deputy dean of the School of Electrical Engineering and the director of the Institute of Power Economics and Electricity Markets in South China University of Technology, Guangzhou, China, from 2005 to 2009. From May 2014 to May 2017, he had been a professor with Universiti Teknologi Brunei, Brunei. His research interests lie in power industry restructuring, power system alarm processing, fault diagnosis and restoration strategies, as well as smart grids and electric vehicles.

Prof. Wen is an Editor of the IEEE TRANSACTIONS ON POWER SYSTEMS and the IEEE POWER ENGINEERING LETTERS, a Subject Editor on power system economics of the *IET Generation, Transmission and Distribution*, an Associate Editor of the *Journal of Energy Engineering* (ASCE) as well as the *Journal of Modern Power Systems and Clean Energy* (Springer).