A Game Theoretical Pricing Mechanism for Multi-Area Spinning Reserve Trading Considering Wind Power Uncertainty

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***Abstract*—The rapid development of wind power has led to an increased demand for spinning reserve in power systems today. However, one of the most severe challenges to China's power systems is the mismatch between wind power installation capacity and the capability for supplying spinning reserve within each independently operated provincial power system. Coordinating the spinning reserve across multiple areas would providentially improve the accommodation of wind power. This paper proposes a game-theoretical model for spinning reserve trading between provincial systems that treat spinning reserve as a commodity. Based on the incomplete information, the trading price is calculated by satisfying the Bayesian Nash equilibrium, and then the trading quantity is determined. This ensures that both the buyer and the seller are able to maximize their expected profit. Case studies are performed using a 2-bus interconnected system and a 3-area IEEE RTS system. The results show that the proposed model is valid and effective.**

***Index Terms*—Game theory, multi-area power system, spinning reserve trading, wind power uncertainty.**

NOTATION

The notation used is provided below.

1) *indices*

A, B, X	Indices for areas.
t	Index of time periods from 1 to T.
m, n, r	Indices for area buses.
up	Index for up SR.
down	Index for down SR.

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2) *Sets*

Ω_T	Set of time periods.
Ω_N^A	Set of internal buses in area A.
N_n^A	Set of internal buses connected to bus n in area A.
B_n^A	Set of buses from other areas connected to bus n in area A.
Ω_G^A	Set of generating units in area A.
G_n^A	Set of generating units on bus n in area A.
Ω_{W}^A	Set of wind farms in area A.
W_n^A	Set of wind farms on bus n in area A.
Ω_B^A	Set of border buses in area A connected to area B.
Ω_{L}^A	Set of inner branches in area A.
Ω_{TL}^A	Set of tie-lines in area A.

3) *Parameters*

$W_\omega^{A,\mathrm{inst}}$	Installed capacity of wind farm ω [MW].
$W_{\omega,t}^A, W_{\omega,t}'^A$	Forecasted and actual wind generation for wind farm ω in time period t [MW].
$L_{n,t}^A, L_{n,t}'^A$	Forecasted and actual load demand for bus n in time period t [MW].
$\overline{P_k^A}, \underline{P_k^A}$	Maximum and minimum output of unit k [MW].
$PR_k^{A,\max}$	Maximum ramping speed in one time period for unit k [MW].
$\overline{IU_k^A}, \overline{IV_k^A}$	Daily maximum startup and shutdown times of unit k.
$IU_{k,\mathrm{cost}}^A$	Startup cost of unit k [\$/MW].
$IV_{k,\mathrm{cost}}^A$	Shutdown cost of unit k [\$/MW].
$RU_k^{A,+}$	Maximum up SR that can be provided by unit k [MW].
$RU_k^{A,-}$	Maximum down SR that can be provided by unit k [MW].
$RD_{j,t}^{A,+}$	Maximum up SR demand for cost interval j in time period t [MW].
$RD_{j,t}^{A,-}$	Maximum down SR demand for cost interval j in time period t [MW].
$l_{nr}^{A,\max}$	Maximum transfer capacity of tie-lines or internal branches [MW].
$TL_{nm,t}^A$	Target power flow for tie-line nm in time period t [MW].

X_{nr}	Reactance of line nr [per unit].
$\pi_k^{A,+}$	Cost of unit k to serve up SR [$/MW].
$\pi_k^{A,-}$	Cost of unit k to serve down SR [$/MW].
π_l	Load shedding penalty [$/MW].
π_w	Wind curtailment penalty [$/MW].
$\pi_{v,\text{up}}^{A,\max}$	Maximum value of up SR [$/MW].
$\pi_{v,\text{up}}^{A,\text{mode}}$	Mode value of up SR [$/MW].
$\pi_{v,\text{down}}^{A,\max}$	Maximum value of down SR [$/MW].
$\pi_{v,\text{down}}^{A,\text{mode}}$	Mode value of down SR [$/MW].
$\pi_{c,\text{up}}^{B,\max}$	Maximum cost of up SR [$/MW].
$\pi_{c,\text{up}}^{B,\text{mode}}$	Mode cost of up SR [$/MW].
$\pi_{c,\text{down}}^{B,\max}$	Maximum cost of down SR [$/MW].
$\pi_{c,\text{down}}^{B,\text{mode}}$	Mode cost of down SR [$/MW].
$\alpha_{\text{up}}^A, \vartheta_{\text{up}}^A$	Coefficient and constant of the strategy function for buying up SR of buyer A.
$\beta_{\text{up}}^B, \xi_{\text{up}}^B$	Coefficient and constant of strategy function for selling up SR of seller B.

4) *Variables*

$I_{k,t}^A$	Binary decision variable: 1 if unit k in time period t is on; 0 otherwise.
$IU_{k,t}^A$	Binary decision variable: 1 if unit k starts up in time period t; 0 otherwise.
$IV_{k,t}^A$	Binary decision variable: 1 if unit k shuts down in time period t; 0 otherwise.
$P_{k,t}^A$	Output of unit k in time period t [MW].
$rs_{k,t}^{A,+}, rs_{k,t}^{A,-}$	Up and down reserve provision of unit k in time period t [MW].
$rd_{j,t}^{A,+}, rd_{j,t}^{A,-}$	Up and down reserve demand of period j in time period t [MW].
$C_{\omega,t}^A$	The curtailed wind power for wind farm ω in time period t [MW].
$S_{n,t}^A$	The load shed by bus n in time period t [MW].
$\delta_{n,t}^A$	Phase angle of bus n in time period t [rad].
$R_t^{A,\text{up}}$	Total up SR resource in time period t in area A [MW].
$R_t^{A,\text{down}}$	Total down SR resource in time period t in area A [MW].
v_{up}^A	Actual up SR value for buyer A [$/MW].
v_{down}^A	Actual down SR value for buyer A [$/MW].
c_{up}^B	Actual up SR cost for seller B [$/MW].
c_{down}^B	Actual down SR cost for seller B [$/MW].
$b_{\text{up}}^A, b_{\text{down}}^A$	Up and down SR price provided by buyer A [$/MW].
$s_{\text{up}}^B, s_{\text{down}}^B$	Up and down SR price provided by seller B [$/MW].
$p_{\text{up}}, p_{\text{down}}$	Up and down SR trading price [$/MW].
$P_t^{B\to A,\text{up}}$	Optimized up SR trade quantity for seller B in time period t [MW].
$P_t^{B\to A,\text{down}}$	Optimized down SR trade quantity for seller B in time period t [MW].
$Q_t^{B\to A,\text{up}}$	Total up SR trade quantity in time period t from area B to area A [MW].
$Q_t^{B\to A,\text{down}}$	Total down SR trade quantity in time period t from area B to area A [MW].

5) *Functions*

$Prob(\cdot)$	Probability of an event.
$E(\cdot)$	Expectation of an event.
$f(x)$	Probability density distribution of a normally distributed x.
$g(\cdot)$	Operating cost of generating units, in the form of a quadratic function.

I. Introduction

THE rapid development of wind power (WP) has led to an increasing demand for spinning reserve (SR) in China's interconnected power systems, which are composed of several provincial power systems [1], [2]. Currently, each provincial power system in China operates in an independent manner, with a limited amount of contracted tie-line energy exchange between neighboring systems. Few of the systems have cross-border reserve exchanges, and the reserve dispatch is only conducted within the control region. Therefore, when the up SR is insufficient in a provincial power system, some of the load must be shed to guarantee the reliability of the system; similarly, when the down SR is insufficient, WP generation must be curtailed. The increasing penetration of WP will intensify the problem. For example, the power system in Gansu province in China has a significant share of WP because of its naturally abundant wind resources [1]. However, its SR capability cannot match its high WP capacity. This results in a significant WP curtailment problem. In 2013, more than 16 TWh of WP was curtailed in China [3]. This situation has severely hindered the development of WP in China [3], [4]. Utilizing SR capacity over a broader area has been proposed as one of the promising solutions [5]. Because less SR is required by power systems with little or no WP generation, these systems could help neighboring power systems with significant WP generation counteract unpredictable power or load changes during system operation.

Ideally, a central operator with access to all data from the interconnected power systems could schedule the reserve globally, ensuring the minimum operating cost for the entire system. However, in most cases, provincial power systems are operated by different companies and the operation information of the power system is not sufficiently shared. Furthermore, the provincial systems usually behave in a selfish manner, seeking to maximize their profit instead of considering the whole system. For these reasons, the ideal central operation cannot be implemented, and a buyer-seller relationship exists between the provincial systems.

Generally, supplying SR will increase the operating costs of the SR provider because supplying SR may require units to deviate from their economically optimal operating point [5], [6]. However, the SR receiver will benefit from the SR by avoiding load shedding or WP curtailment. Therefore, the SR should be assigned a price and traded as a commodity with an incentive pricing mechanism [7], especially for the regions with a regulated electricity market.

With modern communication networking [8], the multi-area reserve dispatch has been widely studied. In [6], a two-stage decentralized algorithm for simultaneous energy and SR dispatch was proposed based on multiple scenarios of WP uncertainty and equipment failure. Additionally, [9] extended the work of [6] by incorporating unit commitment decision variables into the model. In [10], the SR was allocated among multiple systems using a penalty function-hybrid direct search method. Refernce [11] developed a multi-area security constraint unit commitment model including the problem of optimal SR provision based on the reliability criteria. These papers have focused on improving the technique for distributed optimization or optimizing the multi-area SR provision, aiming to maximize the global profit of the whole system, while assuming that all subsystems are willing to exchange information with each other. The design of market mechanism still left a challenge.

Among the limited studies on multi-area reserve trading mechanisms, most research has focused on single-area power system reserve pricing. A method was proposed in [12] for pricing energy and reserves using stochastic programming. Reference [13] incorporated the reserve shortage pricing into power generation scheduling based on multiple operation scenarios. Reference [14] analyzed reserve pricing in security-constrained electricity markets subject to transmission flow limits. All of these models have focused on system operation dispatching, in which the modeling of WP uncertainty is usually required [15]–[17]. Although these papers provide the basic ideas and methods for the design of multi-area reserve pricing and trading mechanisms, the multi-area economic dispatching problem continues to be a challenge.

Game theory, which has recently been applied to power systems [18]–[23], provides the capability to solve the two challenges described above at the same time. First, game theory is acknowledged to be an effective tool for market mechanism design in many different areas, especially finance and politics. Second, game theory investigates the problem from the perspective of multiple players, and thus naturally solves problems in a distributed manner. Finally, many mature mechanism design methodologies and game solving methods have been developed. Game-theoretical methods are not difficult to implement in practical applications. Equilibria can be found without the need for complex numerical algorithms or large computational efforts. Reference [20] proposes an equilibrium approach to model the interactions of the strategic producers in an oligopolistic electricity market with large-scale WP integration. Reference [21] studies on the bidding strategy to get maximum total system profits, and auction games are used to settle the reserve price between wind and conventional producers. References [22] and [23] study the problem of bidding strategy for wind farms in short-term electricity markets, and the mathematical program with equilibrium constraints is used to obtain strategic offering. These methods mainly focus on the single-area WP producer bidding strategies. However, in China, there is no day-ahead or real-time electricity markets, and the problem is how to consume the electricity produced by large-scale WP in a larger geography scope. Different regional or provincial power systems in China may belong to different upper-level power corporations, and they will seek for maximum personal profits. Therefore, in order to promote WP accommodation in multi-area noncooperative power systems, this paper proposes an alternative day-ahead multi-area SR trading mechanism to hold the SR capacity (power) trading between every two interconnected power systems. It is formulated as the double auction (DA), which is a type of static game between noncooperative traders with incomplete information [24]. The theory of Bayesian games is used to obtain a Bayesian Nash equilibrium (BNE) solution [25]. This new mechanism is designed to help organize SR exchanges between multi-area power systems and maximize both the seller's and buyer's expected profit. Note that the SR needed to compensate unit and branch outages is not considered in this paper.

The contributions of this paper are twofold:

1) The proposed mechanism provides a solution for the interconnected noncooperative power systems to trade SR for accommodating the increasing WP in a larger geography scope. The WP producer could benefit from the mechanism to produce more wind electricity.
2) The proposed SR trading mechanism is completely decoupled from the system dispatching process. This minimizes the changes to the existing optimal dispatching solution, and no decomposition technique is required.

The remainder of this paper is organized as follows. In Section II, the power system uncertainties are modeled. In Section III, the detailed mechanism formulation is provided. Section IV demonstrates the validity of the proposed SR trading mechanism using both 2-area 2-bus test system and the 3-area IEEE RTS benchmark system. Section V concludes the paper.

II. Power System Uncertainty Modeling

Uncertainty modeling is the basis for power system operation [26], and in this paper an empirical formula is firstly developed to consider uncertainties.

A. Wind Uncertainty

Generally, the WP prediction error is not normally distributed. However, the prediction error for the aggregated WP of widespread wind farms tends to be normally distributed, based on the central limit theorem [27]. Consequently, the prediction error for the total wind generation in area A, denoted by $\varepsilon_{W,t}^{A,z}$, can be formulated as a normal distribution, as in (1a)

$$\sum_{w\in\Omega_{\mathrm{W}}^{A}} W_{w,t}^{A} = \sum_{w\in\Omega_{\mathrm{W}}^{A}} W'^{A}_{w,t}+\varepsilon_{W,t}^{A,z}, \varepsilon_{W,t}^{A,z} \sim N\left(0, \sigma_{W,t}^{A,z}\right). \quad (1a)$$

The index z in $\varepsilon_{W,t}^{A,z}$ is the WP prediction horizon, and the standard deviation $\tau_{W,t}^{A,z}$ increases with z. In [28], $\rho_{W,t}^{A,z}$ is formulated as a linear function of the predicted WP (per unit) and the installed WP capacity, as in (1b). The coefficient γ does not vary with z, and equals 0.2; the coefficient η can be expressed as a function of z, as in (1c). In (1c), ρ and τ are parameters that can be extracted by statistical regression analysis based on historical data

$$\sigma_{W,t}^{A,z} = \gamma \sum_{w\in\Omega_{\mathrm{W}}^{A}} W_{w,t}^{A} + \eta \sum_{w\in\Omega_{\mathrm{W}}^{A}} W_{w}^{A,\mathrm{inst}}, \quad \gamma,\eta > 0 \quad (1b)$$

$$\eta = \rho(z/\tau + 1). \quad (1c)$$

The forecast error for the total WP for different prediction horizons and predicted values can be obtained using (1b), as shown in Fig. 1.

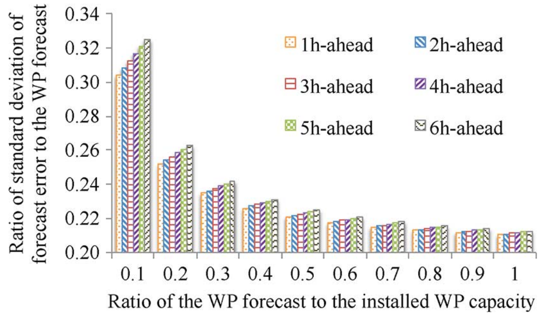

Fig. 1. Standard deviation of the prediction error for the total WP for different prediction horizons and predicted values.

Additionally, the effect of the maximum distance $x(10^3\ \mathrm{km})$ between pairs of wind farms in the same area on the standard deviation of the WP prediction error is discussed in [28]. Equation (1b) is based on a maximum distance of 140 km. With increasing x, $\tau_{W,t}^{A,z}$ decreases linearly, as in (1d)

$$\begin{aligned}\sigma_{W,t}^{A,z}\Big|_x &= \sigma_{W,t}^{A,z}\Big|_{x=0.14}[-0.3495(x-0.14)+1]\\ &= \sigma_{W,t}^{A,z}|_{x=0.14}\,(1.04893-0.3495x),\\ &\quad x\in[0.14,1.85].\end{aligned} \tag{1d}$$

B. Load Uncertainty

Many techniques have been developed for load prediction [29], and they are more mature than WP prediction techniques in obtaining a high prediction accuracy. In this paper, it is assumed that the load prediction error, denoted by $\varepsilon_{L,t}^{A,z}$, is normally distributed as in (2a), and the standard deviation $\tau_{L,t}^{A,z}$ is defined as in (2b) [27]. In (2b), κ is determined by the prediction accuracy, which varies from 0 to 100; a higher accuracy will result in a lower κ value. In this paper, κ is set to 1. Additionally, $L_t'^A$ is approximated as L_t^A because the load forecast error is usually very small:

$$\sum_{n\in\Omega_N^A\cup\Omega_B^A} L_{n,t}^A = \sum_{n\in\Omega_N^A\cup\Omega_B^A} L_{n,t}'^A + \varepsilon_{L,t}^{A,z}, \varepsilon_{L,t}^{A,z}\sim N\left(0,\sigma_{L,t}^{A,z}\right) \tag{2a}$$

$$\sigma_{L,t}^{A,z} = \kappa\%\cdot\sum_{n\in\Omega_N^A\cup\Omega_B^A} L_{n,t}'^A \approx \sum_{n\in\Omega_N^A\cup\Omega_B^A} L_{n,t}^A. \tag{2b}$$

C. Net Load Uncertainty

The net load is the load remaining in the total system load that is not served by WP. In this paper, it is assumed that the load demand and the wind generation are independent of each other. Therefore, the standard deviation $\tau_{D,t}^{A,z}$ of the net load prediction error $\varepsilon_{D,t}^{A,z}$ is defined as (3a) and (3b), and the average value is zero:

$$\begin{aligned}\sigma_{D,t}^{A,z}|_x &= \sqrt{\left(\sigma_{L,t}^{A,z}\right)^2+\left(\sigma_{W,t}^{A,z}|_x\right)^2}\\ &= \sqrt{\left[\kappa\%\cdot L_t^A\right]^2+\lambda_x^2\left[\gamma\sum_{w\in\Omega_W^A} W_{w,t}^A+\eta\sum_{w\in\Omega_W^A} W_w^{A,\mathrm{inst}}\right]^2}\end{aligned} \tag{3a}$$

$$\lambda_x = 1.04893-0.3495x, x\in[0.14,1.85]. \tag{3b}$$

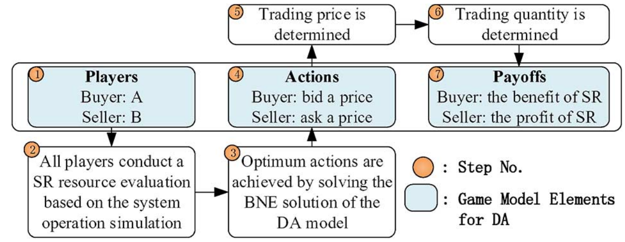

Fig. 2. Framework of the SR trading mechanism.

In this paper, the maximum up or down SR demand equals the positive or negative maximum net load prediction error, respectively. Because 99.7% of the error lies in the interval from $-3\tau_{D,t}^{A,z}$ to $3\tau_{D,t}^{A,z}$ in the normal distribution, $\pm3\tau_{D,t}^{A,z}$ is treated as the approximate maximum positive and negative net load prediction error. Therefore, the maximum up and down SR demands both equal $3\tau_{D,t}^{A,z}$.

III. Mathematical Formulation of the SR Trading Mechanism

The mechanism for SR trading is formulated in this section. The SR trading process is shown in Fig. 2. There are three steps for buyers and sellers to follow in the SR trading under the proposed mechanism: estimating the owned SR resources, estimating the actual SR *value* and *cost*, and bidding a price that will maximize the expected profit. Before going into the mechanism, the DA model, some definitions and assumptions will be firstly introduced.

A. Introduction of Double Auction and Some Definitions

DA is a process that buyers submit bids and sellers submit offers simultaneously, and the trade takes place at some clearing price p [24]. All the sellers who offered less than p sell and all buyers who bid greater than p buy at this price p. DA has been used as a tool to study the determination of prices in ordinary markets. There are five elements in the game model, namely trading objects, players, rules, actions and payoffs. In this paper, up and down SRs are the trading objects treated as commodities. Each provincial power system acts as a player, and follows the rules of DA to take actions seeking for the maximum payoff. Trading will take place successfully only when both conditions hold: the traded-in SR can bring benefit to the buyer; and the traded-out SR can bring profit to the seller. In this paper, the SR benefit for the buyer equals *SR value* minus *SR trading price*, and the *SR value* is the SR-resulting reliability incrementation, i.e., expectation of the reduced penalty of WP curtailment and load shedding; the SR profit for the seller equals *SR trading price* minus *SR cost*, and the *SR cost* is the extra operation cost for the SR provision. When traders take actions following the BNE solution of DA, the maximum benefit expectation (for the buyer) and profit expectation (for the seller) can be achieved simultaneously.

The actual SR value for the buyer and the actual SR cost for the seller at time t, as private information, is denoted as $v_{SR,t}^{buyer}$ (\$/MW) and $c_{SR,t}^{seller}$ (\$/MW), respectively. In this paper, $v_{SR,t}^{buyer}$ equals the expected resulting reduction in the buyer's loss. Quantitatively, $v_{SR,t}^{buyer}$ of 1 MW of up SR is the penalty expectation of shedding 1 MW of load, and $v_{SR,t}^{buyer}$ of 1 MW of down SR is the loss expectation for curtailing 1 MW of WP. $c_{SR,t}^{seller}$ is equal to the corresponding SR provision cost. In addition, there exists a distribution for $v_{SR,t}^{buyer}$ and $c_{SR,t}^{seller}$, the probability distribution function of which is denoted as $f(v_{SR,t}^{buyer})$ and $f(c_{SR,t}^{seller})$, respectively.

B. Assumptions of the SR Trading Mechanism

Although some historical data are published on their websites, provincial power systems maintain private data that they use to inform their bidding or trading decisions in electricity markets while seeking the maximum expected profit. Therefore, SR trading is based on incomplete information and is a type of Bayesian game [25]. The DA model in [30] is used in this paper to model the core trading process.

The assumptions of the proposed SR trading mechanism are as follows:

1) The $f(v_{SR,t}^{buyer})$ and $f(c_{SR,t}^{seller})$ for each provincial power system are public information, but the $v_{SR,t}^{buyer}$ and $c_{SR,t}^{seller}$ are private to the buyer and seller, respectively.
2) The seller's price $s_{SR,t}^{seller}$ and the buyer's price $b_{SR,t}^{buyer}$ at time t is a linear function (or action, strategy) of $v_{SR,t}^{buyer}$ and $c_{SR,t}^{seller}$, respectively.
3) The trading will be successful when and only when $s_{SR,t}^{seller} \geq c_{SR,t}^{seller}$, $b_{SR,t}^{buyer} \leq v_{SR,t}^{buyer}$, and $s_{SR,t}^{seller} \leq b_{SR,t}^{buyer}$. The trading price will be the arithmetic mean of $s_{SR,t}^{seller}$ and $b_{SR,t}^{buyer}$.
4) $f(v_{SR,t}^{buyer})$ and $f(c_{SR,t}^{seller})$ are assumed as triangular distribution. Usually, $v_{SR,t}^{buyer}$ and $c_{SR,t}^{seller}$ obey an unimodal function [5], e.g. normal distribution. Comparing with other simple distributions, the shape of triangular distribution is the most similar with normal distribution so the accuracy of the model is not heavily jeopardized. Additionally, other distributions can also be used in the proposed mechanism, and the mathematical formulation may be sophisticated but can at least be solved numerically.
5) The utility for the buyer is the benefit from the traded-in SR (the difference between $v_{SR,t}^{buyer}$ and the trading price); and the utility for the seller is the profit from the traded-out SR (the difference between the trading price and $c_{SR,t}^{seller}$).
6) The tie-lines have sufficient transfer capacity to deliver SR service between the provincial power systems, and the reserve deployment is not considered in this paper, which could be studied in the future work.

With the above assumptions, the SR trading mechanism is established and the price (i.e., an action or a strategy) that maximizes the utility expectation for both the seller and the buyer can be achieved based on the DA model using the incomplete information available.

C. Owned SR Resource Evaluation

Before trading with neighboring systems, each provincial power system should first evaluate its SR resources by simulating the operation of its system independently. If one power system does not trade with other systems and operates independently, SR provision is also required for its operation reliability. Usually, SR provision is determined by two curves:

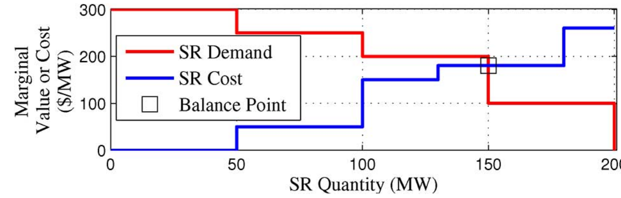

Fig. 3. Method to determine the SR requirements by the balance point at which the marginal SR value equals the marginal SR cost.

one is the SR supply curve, whose horizon axis is SR provision quantity in MW and vertical axis is corresponding marginal SR provision cost in $/MW; and the other one is the SR demand curve, whose horizon axis is also the SR provision quantity and vertical axis is corresponding marginal SR value. The SR provision requirements can be determined by the point at which the marginal SR value meets the marginal SR cost, shown as Fig. 3, in which the SR demand curve is discretized as a J-interval piecewise curve.

As mentioned above, a system operation simulation model is deployed to evaluate the SR resource. The method to find the balance point of SR provision is also embedded into the model. The optimized unit commitment and economic dispatch (UCED) and SR provision can be achieved by solving the model, which is presented as (4). Because this model is not the core work of the paper, the reserve deployment is not considered for simplicity:

$$\begin{aligned}
&\Bigg\{\min \pi_w \sum_{t=1}^{T} \sum_{w\in\Omega_{\mathrm{W}}^A} C_{w,t}^A + \pi_l \sum_{t=1}^{T} \sum_{n\in\Omega_{\mathrm{N}}^A\cup\Omega_B^A} S_{n,t}^A \\
&+\sum_{t=1}^{T}\sum_{k\in\Omega_{\mathrm{G}}^A}\left[g\left(P_{k,t}^A\right)+IU_{k,t}^A\cdot IU_{k,cost}^A+IV_{k,t}^A\cdot IV_{k,cost}^A\right] \\
&+\sum_{t=1}^{T}\Bigg[\sum_{k\in\Omega_{\mathrm{G}}^A}\left(\pi_k^{A,+}\cdot rs_{k,t}^{A,+}+\pi_k^{A,-}\cdot rs_{k,t}^{A,-}\right) \\
&-\sum_{j=1}^{J}\left(\pi_{\mathrm{v,up}}^{A,\max}\cdot rd_{j,t}^{A,+}+\pi_{\mathrm{v,down}}^{A,\max}\cdot rd_{j,t}^{A,-}\right)\Bigg]
\end{aligned}\tag{4a}$$

subject to

$$\begin{aligned}
&\Bigg\{\sum_{w\in \mathrm{W}_n^A}\left(W_{w,t}^A - C_{w,t}^A\right) + \sum_{r\in \mathrm{N}_n^A}\left[\left(\delta_{r,t}^A-\delta_{n,t}^A\right)/X_{rn}\right] \\
&-\sum_{m\in \mathrm{B}_n^A}\left[\left(\delta_{n,t}^A-\delta_{m,t}^B\right)/X_{nm}\right]+\sum_{k\in \mathrm{G}_n^A}P_{k,t}^A \\
&= L_{n,t}^A - S_{n,t}^A, \forall n\in\Omega_{\mathrm{N}}^A
\end{aligned}\tag{4b}$$

$$I_{k,t}^A \underline{P_k^A} + rs_{k,t}^{A,-} \leq P_{k,t}^A \leq I_{k,t}^A \overline{P_k^A} - rs_{k,t}^{A,+}, \forall k\in\Omega_{\mathrm{G}}^A \tag{4c}$$

$$IU_{k,t}^A \geq I_{k,t}^A - I_{k,t-1}^A, \forall k\in\Omega_{\mathrm{G}}^A \tag{4d}$$

$$IV_{k,t}^A \geq I_{k,t-1}^A - I_{k,t}^A, \forall k\in\Omega_{\mathrm{G}}^A \tag{4e}$$

$$\sum_{t\in\Omega_T} IU_{k,t}^A \leq \overline{IU_k^A}, \forall k\in\Omega_{\mathrm{G}}^A \tag{4f}$$

$$\sum_{t\in\Omega_T} IV_{k,t}^A \leq \overline{IV_k^A}, \forall k\in\Omega_{\mathrm{G}}^A \tag{4g}$$

$$0 \leq rs_{k,t}^{A,+} \leq RU_k^{A,+}, \forall k\in\Omega_{\mathrm{G}}^A \tag{4h}$$

$$0 \le rs_{k,t}^{A,-} \le RU_k^{A,-}, \forall k \in \Omega_{\mathrm{G}}^A \tag{4i}$$

$$0 \le rd_{j,t}^{A,+} \le RD_{j,t}^{A,+}, \forall j = 1,2,\ldots,J \tag{4j}$$

$$0 \le rd_{j,t}^{A,-} \le RD_{j,t}^{A,-}, \forall j = 1,2,\ldots,J \tag{4k}$$

$$\sum_{j=1}^{J} rd_{j,t}^{A,+} \le \sum_{k\in\Omega_{\mathrm{G}}^A} rs_{k,t}^{A,+} \tag{4l}$$

$$\sum_{j=1}^{J} rd_{j,t}^{A,-} \le \sum_{k\in\Omega_{\mathrm{G}}^A} rs_{k,t}^{A,-} \tag{4m}$$

$$\left|P_{k,t+1}^A - P_{k,t}^A\right| \le PR_k^{A,\max}, \forall k \in \Omega_{\mathrm{G}}^A \tag{4n}$$

$$\left(\delta_{n,t}^A - \delta_{m,t}^B\right)/X_{nm} = TL_{nm,t}^A, \forall (n,m) \in \Omega_{\mathrm{TL}}^A \tag{4o}$$

$$\left|\left(\delta_{n,t}^A - \delta_{r,t}^A\right)/X_{nr}\right| \le l_{nr,t}^{A,\max}, \forall (n,r) \in \Omega_{\mathrm{L}}^A \tag{4p}$$

$$0 \le C_{w,t}^A \le W_{w,t}^A, \forall w \in \Omega_{\mathrm{W}}^A \tag{4q}$$

$$0 \le S_{n,t}^A \le L_{n,t}^A, \forall n \in \Omega_{\mathrm{N}}^A \cup \Omega_B^A\} \,\forall t\} \,\forall A. \tag{4r}$$

The optimization variables for problem (4) are $\{I_{k,t}^A, IU_{k,t}^A, IV_{k,t}^A, P_{k,t}^A, rs_{k,t}^{A,+}, rs_{k,t}^{A,-}, \forall k; rd_{j,t}^{A,+}, rd_{j,t}^{A,-}, \forall j; \delta_{n,t}^A, S_{n,t}^A, \forall n; C_{w,t}^A, \forall w\}\forall t, \forall A$. The objective function (4a) is the individual system operating cost, including the WP curtailment penalty, the load shedding penalty, the operating cost and the reserve provision cost of the generating units. Constraints (4b) form the power eq-balance equation. Constraints (4c) guarantee that the scheduled power for the generating unit is not less than the minimum output or greater than the maximum output. Constraints (4d)–(4g) limit the maximum startup and shutdown times during one day. Constraints (4h)–(4k) put bounds on the reserve supply and demand variables. Constraints (4l)–(4m) enforce that the reserve supply must be no less than the reserve demand. Constraints (4n) enforce the ramp-up and ramp-down speed limits of the generating unit. Equations (4o) represent the power flow in the tie-lines, and ensure that each power system operates individually, where $TL_{nm,t}^A$ is specified by the power contract that defines a typical power flow curve for the tie-lines. Constraints (4p) ensure that the power flow in the branches will be less than the transfer capacity. Constraints (4q) and (4r) place bounds on the scheduled WP curtailment and the involuntary load shedding, respectively. After solving (4), the up and down SR resource of the power system is determined by (5a) and (5b), respectively

$$R_t^{A,\mathrm{up}} = \sum_{k\in\Omega_{\mathrm{G}}^A} rs_{k,t}^{A,+} \tag{5a}$$

$$R_t^{A,\mathrm{down}} = \sum_{k\in\Omega_{\mathrm{G}}^A} rs_{k,t}^{A,-}. \tag{5b}$$

D. Actual Value and Cost Estimation

The actual value to the buyer of receiving the SR, i.e. $v_{SR,t}^{buyer}$, is known only to the buyer. It is estimated as the average value of the potential loss, as shown in (6a) and (6b). In (6a), $[1 - 2\int_0^{\varepsilon_{D,t}^{A,z}} f(x)dx]$ is the probability that $d\varepsilon_{D,t}^{A,z}$ load is shed by x, and thus $\pi_{v,\mathrm{up}}^{A,\max}[1 - 2\int_0^{\varepsilon_{D,t}^{A,z}} f(x)dx]$ is the corresponding expected load shedding penalty. The numerator of (6a) is the uncovered remaining potential loss expectation caused by insufficient up SR. Hence, (6a) is the average value of the up SR for A at time period t. Similarly, (6b) is the average value of the down SR. The actual cost of supplying the SR that is known only to the seller, i.e. $c_{SR,t}^{seller}$, is estimated as the average cost to provide SR, as shown in (6c) and (5d)

$$v_{\mathrm{up},t}^A = \frac{\int_{R_t^{A,\mathrm{up}}}^{3\sigma_{D,t}^{A,z}} \left\{\pi_{\mathrm{v,up}}^{A,\max}\left[1 - 2\int_0^{\varepsilon_{D,t}^{A,z}} f(x)dx\right]\right\} d\varepsilon_{D,t}^{A,z}}{3\sigma_{D,t}^{A,z} - R_t^{A,\mathrm{up}}} \tag{6a}$$

$$v_{\mathrm{down},t}^A = \frac{\int_{-3\sigma_{D,t}^{A,z}}^{-R_t^{A,\mathrm{down}}} \left\{\pi_{\mathrm{v,down}}^{A,\max}\left[1 - 2\int_{\varepsilon_{D,t}^{A,z}}^{0} f(x)dx\right]\right\} d\varepsilon_{D,t}^{A,z}}{3\sigma_{D,t}^{A,z} - R_t^{A,\mathrm{down}}} \tag{6b}$$

$$c_{\mathrm{up},t}^B = \frac{\sum_{k\in\Omega_{\mathrm{G}}^B}\left(\pi_k^{B,+}\cdot rs_{k,t}^{B,+}\right)}{\sum_{k\in\Omega_{\mathrm{G}}^B} rs_{k,t}^{B,+}} \tag{6c}$$

$$c_{\mathrm{down},t}^B = \frac{\sum_{k\in\Omega_{\mathrm{G}}^B}\left(\pi_k^{B,-}\cdot rs_{k,t}^{B,-}\right)}{\sum_{k\in\Omega_{\mathrm{G}}^B} rs_{k,t}^{B,-}}. \tag{6d}$$

E. Game Model and the Optimized Strategies Derived From the BNE Solution

Using the estimated $R_t^{A,\mathrm{up}}$, $R_t^{A,\mathrm{down}}$, $v_{\mathrm{up},t}^A$, $v_{\mathrm{down},t}^A$, $c_{\mathrm{up},t}^A$, and $c_{\mathrm{down},t}^A$ derived from (5) and (6), every pair of power systems sharing a set of tie-lines will conduct an SR trade. The profit for each trader depends on the DA game for each time period t $(t = 1,2,\cdots,T)$ between each pair of interconnected power systems. The detailed game model is shown as follows:

- Buyers and sellers: The buyers and sellers are the provincial power systems. Each system will provide a buyer price and a seller price, and the role of each system is determined by the mechanism.
- Strategies: In each trade, $b_{SR,t}^{buyer}$ and $s_{SR,t}^{seller}$ is provided by the buyer and the seller, respectively.
- Utilities: The utility for the buyer and the seller are shown as below. The trade will be conducted only when $b_{SR,t}^{buyer} \ge s_{SR,t}^{seller}$, and the trading price is assumed as $(1/2)(b_{SR,t}^{buyer} + s_{SR,t}^{seller})$:

$$u_{SR,t}^{buyer} = \begin{cases} v_{SR,t}^{buyer} - \frac{1}{2}\left(b_{SR,t}^{buyer} + s_{SR,t}^{seller}\right) & \text{,if } b_{SR,t}^{buyer} \ge s_{SR,t}^{seller} \\ 0 & \text{,otherwise} \end{cases}$$

$$u_{SR,t}^{seller} = \begin{cases} \frac{1}{2}\left(b_{SR,t}^{buyer} + s_{SR,t}^{seller}\right) - c_{SR,t}^{seller} & \text{,if } b_{SR,t}^{buyer} \ge s_{SR,t}^{seller} \\ 0, & \text{otherwise.} \end{cases}$$

Based on the defined game model, each power system will bid following the optimal strategy to achieve the maximum utility, where the optimal strategy is derived from the BNE solutions. When multiple solutions exist, the solution with the maximum trade quantity will be selected as the final solution (the calculation of the trade quantity will be discussed in Section III-G).

$f(v_{SR,t}^{buyer})$ and $f(c_{SR,t}^{seller})$ are assumed as triangular distributions with a lower limit a, an upper limit b and a mode c ($a \le c \le b$, $a < b$), formulating the probability density function in (6e)

$$f(x|a,b,c) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & \text{for } a \le x \le c \\ \frac{2(b-x)}{(b-a)(b-c)} & \text{for } c \le x \le b. \end{cases} \tag{6e}$$

TABLE I
PARAMETERS OF TRIANGULAR DISTRIBUTIONS

SR	Type	
	a, c, b of Cost	a, c, b of Value
Up SR	$0,\ \pi_{c,\mathrm{up}}^{B,\mathrm{mode}},\ \pi_{c,\mathrm{up}}^{B,\max}$	$0,\ \pi_{v,\mathrm{up}}^{A,\mathrm{mode}},\ \pi_{v,\mathrm{up}}^{A,\max}$
Down SR	$0,\ \pi_{c,\mathrm{down}}^{B,\mathrm{mode}},\ \pi_{c,\mathrm{down}}^{B,\max}$	$0,\ \pi_{v,\mathrm{down}}^{A,\mathrm{mode}},\ \pi_{v,\mathrm{down}}^{A,\max}$

Assume that A is a buyer and B is a seller, and they are trading up SR service. The process for trading down SR service would be the same. The parameters of the triangular distributions for the SR cost and value are set as in Table I.

Based on assumption 2 in Section III-B, the strategies can be expressed according to (6f)

$$b_{\mathrm{up},t}^{A}=\alpha_{\mathrm{up},t}^{A}v_{\mathrm{up},t}^{A}+\vartheta_{\mathrm{up},t}^{A},s_{\mathrm{up},t}^{B}=\beta_{\mathrm{up},t}^{B}c_{\mathrm{up},t}^{B}+\xi_{\mathrm{up},t}^{B}. \quad (6f)$$

One BNE solution is $(b_{\mathrm{up},t}^{*A},s_{\mathrm{up},t}^{*B})$, if and only if conditions (6g) and (6h) hold. The strategies guarantee that both players A and B can receive the maximum expected profit. In (6g), $Prob(b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B})$ is the probability that the buyer's bidding price $b_{\mathrm{up},t}^{A}$ is no less than the seller's bidding price $s_{\mathrm{up},t}^{B}$, and $E(b_{\mathrm{up},t}^{A}|b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B})$ is the expectation of the buyer's bidding price when $b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B}$ holds. Then, $(1/2)[s_{\mathrm{up},t}^{B}+E(b_{\mathrm{up},t}^{A}|b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B})]$ is the trading price, and the difference between it and $c_{\mathrm{up},t}^{B}$ is the seller's utility when $b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B}$ holds. Then, (6g) is the expected utility of the seller. Equation (6h), which is the buyer's expected utility, is formulated similarly:

$$\max_{s_{\mathrm{up},t}^{B}}\left\{\frac{1}{2}\left[s_{\mathrm{up},t}^{B}+E\left(b_{\mathrm{up},t}^{A}|b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B}\right)\right]-c_{\mathrm{up},t}^{B}\right\} \cdot Prob\left(b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B}\right) \quad (6g)$$

$$\max_{b_{\mathrm{up},t}^{A}}\left\{v_{\mathrm{up},t}^{A}-\frac{1}{2}\left[b_{\mathrm{up},t}^{A}+E\left(s_{\mathrm{up},t}^{B}|b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B}\right)\right]\right\} \cdot Prob\left(b_{\mathrm{up},t}^{A}\geq s_{\mathrm{up},t}^{B}\right). \quad (6h)$$

The BNE solution could be achieved by solving the equation set composed of (6f)–(6h) to get the value of $\alpha_{\mathrm{up},t}^{A},\vartheta_{\mathrm{up},t}^{A},\beta_{\mathrm{up},t}^{B},\xi_{\mathrm{up},t}^{B}$. The first-order optimization condition of (6g) is shown as (6i) and (6j), and that of (6h) is shown as (6k) and (6l). The first-order optimization condition is different when $b_{\mathrm{up},t}^{A}$ or $s_{\mathrm{up},t}^{B}$ locates into different distribution internals. Therefore, totally four conditions exist shown as the second column in Table II, and the BNE solution corresponding to each condition could be obtained by solving the equation set composed of (6i)–(6l) shown at the bottom of the page.

TABLE II
BAYESIAN NASH EQUILIBRIUM SOLUTIONS

No.	Condition	Eq. Set	BNE Sol.
1	$b_{\mathrm{up},t}^{A}\leq\beta_{\mathrm{up},t}^{B}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}+\xi_{\mathrm{up},t}^{B}$ $s_{\mathrm{up},t}^{B}\leq\alpha_{\mathrm{up},t}^{A}\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}+\vartheta_{\mathrm{up},t}^{A}$	solve (6k)(6m)	Analytical Sol.: (6o)
2	$b_{\mathrm{up},t}^{A}\leq\beta_{\mathrm{up},t}^{B}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}+\xi_{\mathrm{up},t}^{B}$ $s_{\mathrm{up},t}^{B}>\alpha_{\mathrm{up},t}^{A}\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}+\vartheta_{\mathrm{up},t}^{A}$	solve (6k)(6j)	Analytical Sol.: (6p)
3	$b_{\mathrm{up},t}^{A}>\beta_{\mathrm{up},t}^{B}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}+\xi_{\mathrm{up},t}^{B}$ $s_{\mathrm{up},t}^{B}\leq\alpha_{\mathrm{up},t}^{A}\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}+\vartheta_{\mathrm{up},t}^{A}$	solve (6n)(6m)	Numerical Sol. with assigned distribution parameters
4	$b_{\mathrm{up},t}^{A}>\beta_{\mathrm{up},t}^{B}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}+\xi_{\mathrm{up},t}^{B}$ $s_{\mathrm{up},t}^{B}>\alpha_{\mathrm{up},t}^{A}\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}+\vartheta_{\mathrm{up},t}^{A}$	solve (6n)(6j)	

Taylor expansion of (6i) and (6l) to $c_{\mathrm{up},t}^{B}$ and $v_{\mathrm{up},t}^{A}$ is used as their appropriate expression, respectively, shown as (6m) and (6n) at the bottom of the following page.

The equation set is updated to be composed of (6j), (6k), (6m) and (6n). Four BNE solutions, corresponding to four different conditions obtained by solving the equation set, are shown in Table II. It should be noted that the No. 1 and No. 2 conditions could get analytical solutions, shown as (6o) and (6p), respectively, while No. 3 and No. 4 could only get numerical solutions. With the assigned value of $\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}$, $\pi_{v,\mathrm{up}}^{A,\max}$, $\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}$, and $\pi_{c,\mathrm{up}}^{B,\max}$, the BNE solutions of No. 3 and No. 4 could be achieved:

$$\begin{cases} b_{\mathrm{up},t}^{*A}=\frac{4}{5}v_{\mathrm{up},t}^{A}+\frac{\sqrt{6\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}\pi_{v,\mathrm{up}}^{A,\max}}}{30} \\ s_{\mathrm{up},t}^{*B}=\frac{4}{11}c_{\mathrm{up},t}^{B}+\frac{\sqrt{6\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}\pi_{v,\mathrm{up}}^{A,\max}}}{6} \end{cases} \quad (6o)$$

$$\begin{cases} b_{\mathrm{up},t}^{*A}=\frac{4}{5}v_{\mathrm{up},t}^{A}+\frac{\pi_{v,\mathrm{up}}^{A,\max}}{30} \\ s_{\mathrm{up},t}^{*B}=\frac{4}{5}c_{\mathrm{up},t}^{B}+\frac{\pi_{v,\mathrm{up}}^{A,\max}}{6}. \end{cases} \quad (6p)$$

Note that the whole solving process of BNE solutions does not depend on the $v_{\mathrm{up},t}^{A}$ and $c_{\mathrm{up},t}^{B}$. When both traders use linear bidding functions, the buyer (the seller) can formulate and solve the model without knowing the actual $c_{\mathrm{up},t}^{B}$ ($v_{\mathrm{up},t}^{A}$) of the seller (the buyer).

$$s_{\mathrm{up},t}^{B}=\frac{1}{5}\sqrt{4\left(c_{\mathrm{up},t}^{B}-\vartheta_{\mathrm{up},t}^{A}\right)^{2}+5\left(\alpha_{\mathrm{up},t}^{A}\right)^{2}\pi_{v,\mathrm{up}}^{A,\mathrm{mode}}\pi_{v,\mathrm{up}}^{A,\max}}+\frac{2}{5}c_{\mathrm{up},t}^{B}+\frac{3}{5}\vartheta_{\mathrm{up},t}^{A}\text{ , if }s_{\mathrm{up},t}^{B}\leq\alpha_{\mathrm{up},t}^{A}\pi_{\mathrm{v,up}}^{A,\mathrm{mode}}+\vartheta_{\mathrm{up},t}^{A} \quad (6i)$$

$$s_{\mathrm{up},t}^{B}=\frac{4}{5}c_{\mathrm{up},t}^{B}+\frac{1}{5}\vartheta_{\mathrm{up},t}^{A}+\frac{1}{5}\alpha_{\mathrm{up},t}^{A}\pi_{v,\mathrm{up}}^{A,\max}\text{ , if }s_{\mathrm{up},t}^{B}>\alpha_{\mathrm{up},t}^{A}\pi_{\mathrm{v,up}}^{A,\mathrm{mode}}+\vartheta_{\mathrm{up},t}^{A} \quad (6j)$$

$$b_{\mathrm{up},t}^{A}=\frac{4}{5}v_{\mathrm{up},t}^{A}+\frac{1}{5}\xi_{\mathrm{up},t}^{B},\text{if}b_{\mathrm{up},t}^{A}\leq\beta_{\mathrm{up},t}^{B}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}+\xi_{\mathrm{up},t}^{B} \quad (6k)$$

$$b_{\mathrm{up},t}^{A}=\frac{1}{5}\sqrt{4\left(v_{\mathrm{up},t}^{A}-\xi_{\mathrm{up},t}^{B}\right)^{2}+9\left(\pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^{B}\right)^{2}+8\pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^{B}\left(\xi_{\mathrm{up},t}^{B}-v_{\mathrm{up},t}^{A}\right)-5\pi_{c,\mathrm{up}}^{B,\max}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}\left(\beta_{\mathrm{up},t}^{B}\right)^{2}} +\frac{2}{5}v_{\mathrm{up},t}^{A}+\frac{3}{5}\xi_{\mathrm{up},t}^{B}+\frac{3}{5}\pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^{B},\text{if}b_{\mathrm{up},t}^{A}>\beta_{\mathrm{up},t}^{B}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}+\xi_{\mathrm{up},t}^{B} \quad (6l)$$

F. Determining the SR Trade Quantity

Since $v_{SR,t}^{buyer}$ is estimated as the minimum average value shown as (6a) and (6b), it means that the higher the trade quantity is, the lower the marginal value will be. With higher trading quantity, the marginal profit for the buyer will decrease, but the buyer could still achieve greater profit. For the seller, it suffers from the risk of encountering insufficient SR when more SR is required, and thus the seller must balance the SR requirement for its own power system reliable operation and the quantity of SR service supplied to the buyer. The seller's optimum SR trade quantity is the level at which the profit equals the marginal SR value to itself. In other words, the marginal benefit of supplying SR will be smaller than the marginal value for the seller itself if this trade quantity increases. Therefore, the trade quantity $P_t^{B\to A,\mathrm{up}}$ and $P_t^{B\to A,\mathrm{down}}$ can be obtained by solving (7a) and (7b), respectively. In (7a), $(p_{\mathrm{up},t} - c_{\mathrm{up},t}^B)$ is the average marginal profit, and the right side is the marginal up SR value for the seller itself. By solving this equation, $P_t^{B\to A,\mathrm{up}}$ can be obtained, and similarly, (7b) is for determining $P_t^{B\to A,\mathrm{down}}$:

$$\begin{cases} p_{\mathrm{up},t} - c_{\mathrm{up},t}^B = \dfrac{\pi_{\mathrm{v,up}}^{B,\max} \displaystyle\int_{R_t^{B,\mathrm{up}} - P_t^{B\to A,\mathrm{up}}}^{R_t^{B,\mathrm{up}}} h\left(\varepsilon_{D,t}^{B,z}\right) d\varepsilon_{D,t}^{B,z}}{P_t^{B\to A,\mathrm{up}}} \\ h\left(\varepsilon_{D,t}^{B,z}\right) = 1 - 2\displaystyle\int_0^{\varepsilon_{D,t}^{B,z}} f(x)dx \end{cases} \tag{7a}$$

$$\begin{cases} p_{\mathrm{down},t} - c_{\mathrm{down},t}^B = \dfrac{\pi_{\mathrm{v,down}}^{B,\max} \displaystyle\int_{-R_t^{B,\mathrm{down}}}^{-R_t^{B,\mathrm{down}} + P_t^{B\to A,\mathrm{down}}} h\left(\varepsilon_{D,t}^{B,z}\right) d\varepsilon_{D,t}^{B,z}}{P_t^{B\to A,\mathrm{down}}} \\ h\left(\varepsilon_{D,t}^{B,z}\right) = 1 - 2\displaystyle\int_{\varepsilon_{D,t}^{B,z}}^{0} f(x)dx. \end{cases} \tag{7b}$$

The final SR trade quantity $Q_t^{B\to A,\mathrm{up}}$ and $Q_t^{B\to A,\mathrm{down}}$ is determined by (7c) and (7d), respectively, and is the minimum level of the original trade quantity determined by (7a) and (7b), the owned SR resource and the maximum SR trade requirement

$$Q_t^{B\to A,\mathrm{up}} = \min\left\{P_t^{B\to A,\mathrm{up}}, R_t^{B,\mathrm{up}}, 3\sigma_{D,t}^{A,z}\right\} \tag{7c}$$

$$Q_t^{B\to A,\mathrm{down}} = \min\left\{P_t^{B\to A,\mathrm{down}}, R_t^{B,\mathrm{down}}, 3\sigma_{D,t}^{A,z}\right\}. \tag{7d}$$

1) Consider sellers $(s_1, s_2, \ldots, s_{SN})$, which are sorted in ascending order of the actual SR cost, and buyers $(b_1, b_2, \ldots, b_{BN})$, which are sorted in descending order of the actual SR value, where *SN* and *BN* are the numbers of sellers and buyers, respectively.
2) **X** is an *SN*×*BN* matrix. If s_i and b_j are connected, x_{ij} equals 1; otherwise, x_{ij} equals 0.
SP is an *SN*×*BN* matrix. If $x_{ij} = 1$, sp_{ij} equals the price bid of s_i for b_j; otherwise, sp_{ij} equals 0.
BP is an *BN*×*SN* matrix. If $x_{ij} = 1$, bp_{ij} equals the price bid of b_i for s_i; otherwise, bp_{ij} equals 0.
P is an *SN*×*BN* matrix; p_{ij} is the trade price between s_i and b_j.
Q is an *SN*×*BN* matrix; q_{ij} is the trade quantity between s_i and b_j.
All elements of **P** and **Q** are initialized with 0.
Set counter *i*=0.
3) If $i \neq SN$, set counter *i*← $i + 1$ and *j*=0, go to step 4. Otherwise, stop.
4) If $j \neq BN$, set counter *j*← $j + 1$, go to step 5. Otherwise, go to step 3.
5) If x_{ij} is 1 and $sp_{ij} \geq bp_{ji}$, go to step 6. Otherwise, go to step 4.
6) $p_{ij} = \frac{1}{2}(sp_{ij} + bp_{ji})$, and q_{ij} is determined by (7), go to step 4.

Fig. 4. SR trading process for multiple sellers and buyers.

G. Trading Between Multiple Buyers and Sellers

Because there is no central trader to collect price bids from the sellers and buyers and then provide a market price, SR trading takes place between every two power systems. A seller or buyer connected to multiple buyers and sellers could provide multiple price bids to different players. For multiple buyers and sellers, the trading will be conducted as shown in Fig. 4. Note that two non-neighboring areas cannot trade through a common neighboring area for the sake of simplicity, and this situation will be studied in the future work.

IV. Illustrative Examples and Case Studies

A 2-bus interconnected test system and the 3-area IEEE RTS test system are used as two examples to test the proposed SR trading mechanism.

A. 2-Bus Interconnected Test System

The 2-bus interconnected test system is composed of two buses and a tie-line, and each bus represents one area, denoted as S1 and S2. S1 has two generating units with the capacity of 100 MW (Gen 1) and 65 MW (Gen 2), respectively, and the minimum output of both units is as 50% of the capacity. S1 also has 160 MW WP integrated. S2 has a 250 MW generating unit (Gen 3), and its minimum output is 50 MW. All generating units have identical quadratic cost functions, i.e., $g(P) = 0.007P^2 + 10P + 200$. The startup cost and shutdown cost are all set as \$5000, and the maximum startup times and shutdown times are all only

$$s_{\mathrm{up},t}^B = \begin{cases} \frac{2}{5}\left(1 - \frac{2\vartheta_{\mathrm{up},t}^A}{\delta}\right) c_{\mathrm{up},t}^B + \frac{3}{5}\vartheta_{\mathrm{up},t}^A + \frac{\delta}{5} \\ \delta = \sqrt{4\left(\vartheta_{\mathrm{up},t}^A\right)^2 + 5\left(\alpha_{\mathrm{up},t}^A\right)^2 \pi_{v,\mathrm{up}}^{A,\mathrm{mode}} \pi_{v,\mathrm{up}}^{A,\max}} \end{cases}, \text{if } s_{\mathrm{up},t}^B \leq \alpha_{\mathrm{up},t}^A \pi_{\mathrm{v,up}}^{A,\mathrm{mode}} + \vartheta_{\mathrm{up},t}^A \tag{6m}$$

$$b_{\mathrm{up},t}^A = \begin{cases} v_{\mathrm{up},t}^A \left(\frac{2}{5} - \frac{4\xi_{\mathrm{up},t}^B + 4\pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^B}{5\omega}\right) + \frac{3}{5}\left(\xi_{\mathrm{up},t}^B + \pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^B\right) + \frac{1}{5}\omega \\ \omega = \sqrt{\left(2\xi_{\mathrm{up},t}^B + 3\pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^B\right)^2 - 4\pi_{c,\mathrm{up}}^{B,\max}\beta_{\mathrm{up},t}^B\xi_{\mathrm{up},t}^B - 5\pi_{c,\mathrm{up}}^{B,\max}\pi_{c,\mathrm{up}}^{B,\mathrm{mode}}\left(\beta_{\mathrm{up},t}^B\right)^2} \end{cases},$$
$$\text{if } b_{\mathrm{up},t}^A > \beta_{\mathrm{up},t}^B \pi_{c,\mathrm{up}}^{B,\mathrm{mode}} + \xi_{\mathrm{up},t}^B \tag{6n}$$

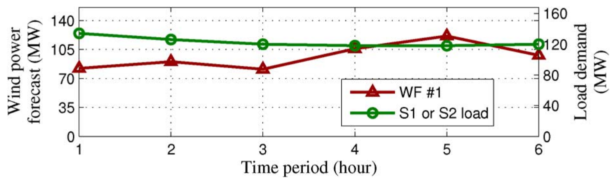

Fig. 5. Predicted wind power curve for the wind farms located in S1, and the system load demand of S1 and S2.

TABLE III
PARAMETERS OF THE TRIANGULAR DISTRIBUTIONS IN THE 2-BUS INTERCONNECTED TEST SYSTEM

Area	SR	a, c, b of $f(c_{SR,t}^{seller})$	a, c, b of $f(v_{SR,t}^{buyer})$
S1	Up	0, 0.2, 1	0, 10, 50
	Down	0, 0.2, 1	0, 2, 10
S2	Up	0, 0.2, 1	0, 5, 50
	Down	0, 0.2, 1	0, 1, 10

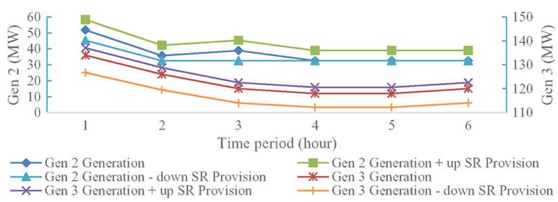

Fig. 6. 2-bus interconnected test system operation simulation results.

Fig. 7. SR trading quantities and prices for S1 to buy from S2.

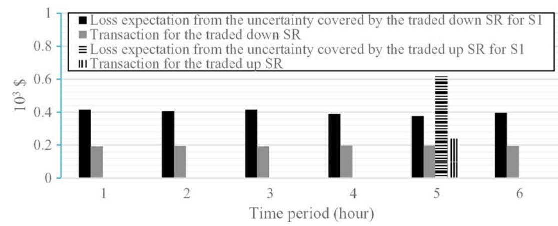

Fig. 8. Benefit analysis of the Up SR traded in time period 5.

TABLE IV
WIND FARMS LOCATED IN THE 3-AREA IEEE RTS TEST SYSTEM

No.	WF 1	WF 2	WF 3	WF 4	WF 5
Capacity (MW)	600	1200	600	600	900
Bus	118	121	123	213	218
Area	1	1	1	2	2

one.The ramping speed limit of each unit is set as 80% of its capacity. The maximum reserve a unit can supply is set as 10% of its capacity. The tie-line transfer capacity is set as large as possible. The first six time periods of the normalized load curve from the 352nd day of the IEEE RTS-79 [31] system is used to generate a 6-time-period daily load curve. The predicted WP curves and system load curves are shown in Fig. 5. In this paper, the price of energy transfer is set at 20 $/MWh. The load shedding penalty and WP curtailment penalty is set at 1000 and 100 $/MWh, respectively. Renewable energy policies could be implemented by adjusting this loss value. The enforced power flow $TL_{nm,t}^{A}$ is set to be 0 for simplicity.

The actual up and down reserve cost for each unit is set to be 10% of the first-order coefficient in the quadratic cost function. The detailed parameters of the triangular distributions are shown in Table III. Model (4) is solved using CPLEX [32].

During the SR resource evaluation process, the unit commitment results are: Gen 2 and Gen 3 are on for all time periods; and Gen 1 is off for all time periods. There is no load shedding for both S1 and S2, but S1 has 20, 36, and 10 MWh WP curtailment in time period 4, 5, and 6, respectively, approximately 11.5% of the total wind generation. The detailed results of unit generation and SR provision are shown in Fig. 6. The up SR provision of S1 has reached its maximum capability for all time periods, while S2 has remaining available up SR resource; S1 has severe WP curtailment from time period 4 to 6, so no down SR can be provided and more is required in these time periods. The achieved SR trade quantities and prices from S2 to S1 are shown in Fig. 7. Up SR is bought by S1 in time period 5; down SR is traded in all six time periods. S1 can get benefit in time period 5 from the up SR trading, show as Fig. 8. S1 pays $240 for the up SR transaction, which could cover the uncertainty leading to $620 loss expectation. Similarly, S1 can get benefit from down SR trading in all time periods.

B. 3-Area IEEE RTS

The proposed SR trading mechanism is further tested using the 3-area 73-bus IEEE RTS [33]. The system data and parameters are given in [33]. The slack bus is bus 113. The unit cost function is derived from he generation cost data of IEEE RTS 24-bus test system in Matpower 4.1 [34]. The up and down reserve provision cost for each unit in area 1, area 2, and area 3 is set to be 15%, 10%, and 5% of the first-order coefficient in the quadratic cost function, respectively. The transfer capacity of all internal branches is set to 600 MW. Five generating units are replaced by wind farms in the interconnected systems, as shown in Table IV. The load curve from the 352nd day is selected as the 24-h load curve. The maximum total load is 8550 MW, with a maximum of 2850 MW for each area. The predicted WP curves and the system load are shown in Fig. 9. The parameters of the triangular distributions are shown in Table V. The other parameters are the same as in the 2-bus interconnected test system. As a comparison, this case is carried out based on two different circumstances, i.e., 1) using the proposed SR trading mechanism without a centralized operator; 2) dispatching SR globally with a centralized operator.

1) Without a centralized operator

For this circumstance, the trading mechanism proposed in this paper is used. The trading results are: Area 1 buys SRs from both the other two areas, shown in Fig. 10; and area 2 buys 0.54 MW up SR from area 3 in time period 17. SR trading occurs between every two areas. Area 1 requires much more SR provision compared with the other two areas. Although area 2 has two wind farms, the WP prediction is relatively low (no more than 30%

TABLE V
PARAMETERS OF THE TRIANGULAR DISTRIBUTIONS IN THE 3-AREA IEEE RTS TEST SYSTEM

System	SR	Type	
		a, c, b of $f(c_{SR,t}^{seller})$	a, c, b of $f(v_{SR,t}^{buyer})$
Area 1	Up	0, 1.5, 5	0, 90, 100
	Down	0, 1.5, 5	0, 20, 30
Area 2	Up	0, 1, 5	0, 80, 100
	Down	0, 1, 5	0, 10, 30
Area 3	Up	0, 0.75, 5	0, 10, 100
	Down	0, 0.75, 5	0, 5, 30

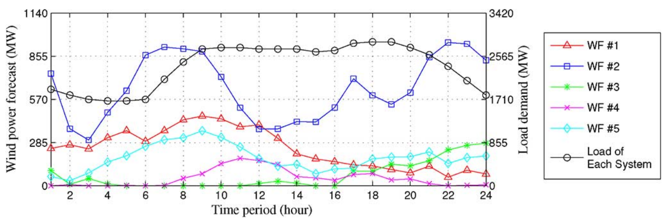

Fig. 9. WP forecasts and system load demand of each area for 3-area case.

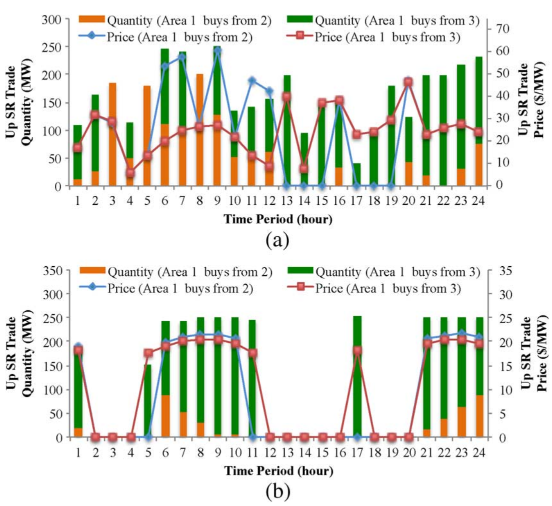

Fig. 10. SR trade quantity and price between areas. (a) Up SR Trade. (b) Down SR Trade.

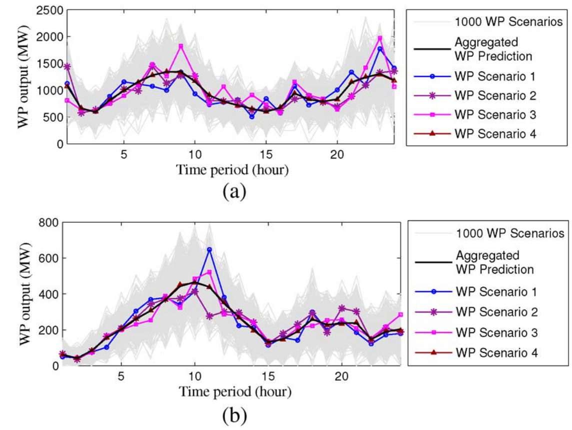

Fig. 11. Four WP scenarios extracted from the 1000 generated scenarios. (a) WP scenarios for area 1. (b) WP scenarios for area 2.

of the total installed capacity), and therefore the WP uncertainty is limited to a narrow range, as shown in Fig. 11(b).

To demonstrate the effect of the SR trading, one thousand equally potential WP scenarios are generated by randomly sampling the normally distributed total WP prediction error based on the original WP prediction curve. These scenarios are then reduced to four using the k-means clustering method [35], as shown in Fig. 11. The original WP prediction is called the base scenario, and the results of each WP scenario from running model (4) with the SR service are shown as the bold data in Table VI, and all scenarios have no load shedding. Note that all the scenarios have the same unit commitment as during the SR resource evaluation period. In addition, tie-lines can transfer the pre-traded SR service when it is deployed. In other words, the tie-line power flow limit is changed to allow the traded SR transferring. Comparing with the base scenario without SR trading, all scenarios with SR trading result in a reduced WP curtailment and a smaller total cost.

2) With a centralized operator

This circumstance is the case carried out as a comparison with the case that there is no centralized operator. The centralized operator will conduct the SR dispatching standing at the global point, considering the minimum global operating cost and SR provision cost. Each power system shares its owned SR resource in a non-selfish manner, both in day-ahead and real-time dispatching, following the operator's command. In order to carry out a comparison, the centralized operator will dispatch the units to have a global SR quantity equal to that in circumstance 1), and the tie-line power flow limit in each scenario is also set as same as that in circumstance 1). The simulation results are shown as the italic data in Table VI. The total cost of each area is lower than that of circumstance 1). On one hand, the global SR provision cost decreases when there exists a centralized operator: the SR provision is optimized from the overall power system perspective, and the area with lower SR provision cost would supply more SR than the area with higher SR provision cost. On the other hand, the unit with lower operation cost in the multi-area power system will be dispatched to generate more electricity than that with higher operation cost, and the load demand of each area is provided by the unit from the global power system instead of within its own system. However, the SR service is not considered in this circumstance, and the area who supplies SR to other areas will not benefit from the interaction, and get higher SR provision cost compared with circumstance 1), for example, area 2 and area 3. This circumstance works only when all regional power systems are not selfish, seeking for the maximum global benefit. Compared with circumstance 1), this circumstance with a central operator could obtain a lower global operation cost, but could not guarantee that the operation of each power system is optimized from its own perspective.

V. CONCLUSION

This paper focuses on the problem of SR exchange between areas for WP accommodation in an interconnected power system. For most systems today, there is still no a practical cross-border exchange mechanism for SR, especially in systems with a regulated market. Game theory is used in this paper to create a multi-area SR trading mechanism. First, instead of using scenario-based stochastic or robust optimization, an empirical formula is developed that takes into account the uncertainties in the total WP and the system load. The BNE solution of the DA model is used to determine the optimal

TABLE VI
SIMULATION RESULTS FROM THE WIND POWER SCENARIOS ON THE 3-AREA IEEE RTS TEST SYSTEM

Generated WP Scenarios	Area	Operation Cost (10^4\$)	Up SR Provision cost (10^4\$)	Down SR Provision cost (10^4\$)	SR Trade Cost (10^4\$)	Energy Transfer Benefit (10^4\$)	Wind Loss Penalty (10^4\$)	Area Total Cost (10^4\$)	Global Total Cost (10^4\$)
Base	1	141.43	2.40	2.53	0.00	0.00	56.71	203.08	
Scenario	2	129.29	1.83	2.09	0.00	0.00	11.76	144.98	489.65
w/o trading	3	140.19	0.47	0.52	0.00	0.00	0.41	141.59	
Base	**1**	**126.20**	**1.21**	**0.98**	**17.32**	**0.36**	**5.22**	**150.56**	
Scenario	**2**	**109.58**	**0.91**	**0.85**	**-4.05**	**3.72**	**0.16**	**103.74**	**364.39**
with trading	**3**	**122.37**	**0.53**	**0.46**	**-13.27**	**0.00**	**0.00**	**110.09**	
Base	*1*	*123.46*	*1.01*	*0.78*	*0.00*	*0.00*	*4.89*	*130.14*	
Scenario	*2*	*107.14*	*0.96*	*0.87*	*0.00*	*0.00*	*0.69*	*109.66*	*362.02*
with operator	*3*	*121.06*	*0.67*	*0.49*	*0.00*	*0.00*	*0.00*	*122.22*	
Scenario 1	**1**	**131.11**	**1.22**	**0.95**	**17.32**	**0.34**	**7.54**	**157.80**	
with	**2**	**113.01**	**1.11**	**0.89**	**-4.05**	**3.59**	**1.01**	**108.38**	**371.42**
trading	**3**	**117.57**	**0.49**	**0.45**	**-13.27**	**0.00**	**0.00**	**105.24**	
Scenario 1	*1*	*126.08*	*1.59*	*1.58*	*0.00*	*0.29*	*6.09*	*135.05*	
with	*2*	*114.11*	*1.67*	*1.45*	*0.00*	*3.36*	*0.70*	*114.57*	*369.40*
operator	*3*	*118.43*	*0.70*	*0.65*	*0.00*	*0.00*	*0.00*	*119.78*	
Scenario 2	**1**	**130.54**	**1.17**	**0.97**	**17.32**	**0.37**	**9.20**	**158.83**	
with	**2**	**110.10**	**1.03**	**0.88**	**-4.05**	**3.62**	**2.77**	**107.12**	**371.26**
trading	**3**	**117.61**	**0.52**	**0.44**	**-13.27**	**0.00**	**0.00**	**105.31**	
Scenario 2	*1*	*126.88*	*1.62*	*1.58*	*0.00*	*0.25*	*5.62*	*135.46*	
with	*2*	*111.66*	*1.47*	*1.39*	*0.00*	*2.83*	*0.95*	*112.65*	*367.89*
operator	*3*	*118.39*	*0.73*	*0.66*	*0.00*	*0.00*	*0.00*	*119.78*	
Scenario 3	**1**	**129.87**	**1.14**	**0.89**	**17.32**	**0.35**	**22.36**	**171.22**	
with	**2**	**109.87**	**1.02**	**0.89**	**-4.05**	**3.73**	**1.27**	**105.26**	**382.77**
trading	**3**	**118.55**	**0.55**	**0.44**	**-13.27**	**0.00**	**0.00**	**106.28**	
Scenario 3	*1*	*125.19*	*1.67*	*1.64*	*0.00*	*0.34*	*18.25*	*146.41*	
with	*2*	*110.22*	*1.53*	*1.36*	*0.00*	*2.14*	*1.13*	*112.10*	*379.14*
operator	*3*	*119.27*	*0.71*	*0.65*	*0.00*	*0.00*	*0.00*	*120.63*	
Scenario 4	**1**	**125.92**	**1.19**	**0.98**	**17.32**	**0.36**	**7.16**	**152.21**	
with	**2**	**109.52**	**0.92**	**0.84**	**-4.05**	**3.71**	**0.00**	**103.52**	**366.03**
trading	**3**	**122.59**	**0.51**	**0.46**	**-13.27**	**0.00**	**0.00**	**110.30**	
Scenario 4	*1*	*119.63*	*1.61*	*1.58*	*0.00*	*0.40*	*4.97*	*127.39*	
with	*2*	*110.63*	*1.51*	*1.37*	*0.00*	*3.61*	*0.00*	*109.90*	*362.87*
operator	*3*	*124.23*	*0.70*	*0.65*	*0.00*	*0.00*	*0.00*	*125.58*	

pricing strategy for the SR traders. Second, the proposed mechanism enables each interconnected power system to determine dispatching individually instead of solving a multi-area reserve dispatch problem using a distributed optimization algorithm. The proposed mechanism's performance is verified using a 2-area 2-bus test system and the 3-area IEEE RTS test system.

Future work will explore the following two aspects. First, the choice among multiple BNE solutions should be investigated in detail; in this paper, the BNE solution with the maximum SR trade quantity is selected as the optimal pricing strategy to promote SR exchange. Second, the proposed mechanism, which is based on a DA model, should be compared with other types of game-theoretical auction models, and the model with the maximum trading efficiency and effectiveness should be used in SR trading.

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