Region-to-Region Energy Sharing for Prosumer Clusters in Distribution Network: A Multi-Leaders and Multi-Followers Stackelberg Game

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***Abstract*—With the extensive integration of the distributed energy resources, the energy scheduling among multiple sharing entities has been complicated by prosumer-based-regions and their interaction with regional prosumers. This article proposes an energy sharing scheme considering the region-to-region (R2R) energy sharing process and demand response (DR) simultaneously, which is formulated as a multi-leaders and multi-regions Stackelberg game. Regions are formulated by prosumer clusters with same geographical locations, where the regional energy-sharing providers serve as the leaders conducting the R2R energy sharing, while prosumers within the region are the followers implementing the DR. A R2R energy sharing model among regions is formulated where a novel dynamical pricing scheme is designed based on the unbalanced energy in R2R energy sharing process. Besides, a fair and stable allocation mechanism is introduced according to prosumers' contribution for the R2R energy sharing, which is nested into prosumers' DR model with dynamical regional prices. The multi-leaders and multi-followers Stackelberg equilibrium can be obtained through a distributed iterative algorithm, which implements between the regions and prosumers. Finally, the practical case study shows the effectiveness of improving local energy consumption and the regions' economic interests.**

***Index Terms*—Region-to-region, multi-leaders and multi-followers Stackelberg game, price mechanism, prosumers, demand response.**

NOMENCLATURE

Parameter/Variable

T	Number of time slots of the energy-sharing process.
N	Number of prosumers in a region.
M	Number of regions in the distributed network.
M	Number of buyer regions in the distributed network.
$\boldsymbol{M^S}$	Number of seller regions in the distributed network.
S	Possible sub region configurations.
$\mathcal{N}$	Grand region consists with all the prosumers in the same transformers.
i	Index for prosumers.
m,n	Index for regions.
τ	Index for time slot (h).
$\lambda_{gb}^{\tau}, \lambda_{gs}^{\tau}$	Selling and buying prices of utility grid (CNY/kWh).
$\lambda_{b}^{m,\tau}, \lambda_{s}^{m,\tau}$	Dynamic internal buying and selling prices of region *m* (CNY/kWh).
$\lambda_{\text{R2R}}^{\tau}$	Region-to-region (R2R) energy sharing price (CNY/kWh).
λ_{loss}	Transmission power losses coefficient.
λ_{pv}	Subsidy coefficient of photovoltaic (PV) energy (CNY/kWh).
ρ_{m}^{τ}	Unbalanced rate of region *m*.
a_0, b_0	Dynamic regional prices parameters.
$E_{\text{pv}\ i}^{m,\tau}$	Energy production by the PV of prosumer *i* in the region *m* (kWh).
$E_{\text{flx}\ i}^{m,\tau}, E_{\text{flx},i}^{m,\tau}$	Flexible load and fix load of prosumer *i* in the region *m* (kWh).
$E_{\text{nt}\ i}^{m,\tau}, E_{i}^{m,\tau}$	Netload and total consumption of prosumer *i* in the region *m* (kWh).
$E_{\text{ini}\ i}^{m,\tau}$	Initial total consumption of prosumer *i* in the region *m* (kWh).
$E_{\text{flx}\ \min i}^{m,\tau}, E_{\text{flx}\ \max\ i}^{m,\tau}$	Lower and Upper bounds of prosumer *i*'s energy consumption in the region *m* (kWh).
$E_{\text{nt}}^{m,n,\tau}$	Netload of region *m* (kWh).
$E_{\text{R2R}}^{m,n,\tau}$	R2R sharing energy between region *n*, *m* (kWh).
Q^{mn}	The reactive power transmitted between region *n*, *m* (kW).
$E_{\text{loss}}^{m,\tau}$	Transmission power losses of region *m* (kWh).
$S_{\min},\ S_{\max}$	Minimal and maximal apparent power of capacity of the transmission power line (kW).
U_m	Node voltage of region *m* (kV).

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$U_{\min}, U_{\max}$	Lower and upper bounds of node voltage (kV).
$R^{m,n}$	Transmission line resistance between region *n*, *m* (Ω).
$I^{m,n}$	Transmission line current between region *n*, *m* (A).
$k^{\tau}_{m,n}$	Match coefficient between region m, n.
m_i	Contribution of prosumer *i*.
$\varsigma_i^{m,\tau}$	Contribution rate of prosumer *i*.
x_i	Allocation obtained by prosumer *i*.
$\omega_i^{m,\tau}$	Preference parameter for prosumer *i*.

Acronyms

R2R	Region-to-region.
DERs	Distributed energy resources.
DR	Demand response.
PV	Photovoltaic.
UEMS	User energy management system.
SE	Stackelberg equilibrium.
ESPs	Energy-sharing provider.

I. Introduction

RECENTLY, the proliferation of distributed energy resources (DERs) has drastically changed the way electricity generated and consumed. Consequently, consumers equipped with distributed generators and demand response (DR) program is regarded as prosumers, which have gradually emerged and played an important role in the energy management problems [1]. With the ability to produce and consume energy, proactive prosumers have incentives to participate in the energy sharing, which leads to a transformation from producer-centric to consumer-centric energy sharing structure [2]. In the consumer-centric energy sharing structure, an efficient energy sharing model is required to coordinate the transactions between prosumers. In [3], direct energy trading among individual prosumers is allowed for maximizing the DERs' usage, which facilitates a kind of energy sharing mode, named peer-to-peer (P2P) energy sharing. With the effective performances, this energy sharing approach becomes a popular research topic among the emerging energy management techniques [4], [5], [6]

A number of researches have been conducted in P2P energy sharing in recent years. In general, the P2P energy sharing can be conducted in two methods: (i) decentralized method and (ii) centralized method. Under a decentralized P2P energy sharing framework, prosumers share with others directly without any supervisory agents [7]. A bilateral energy trading [8] and a multi-bilateral economic dispatch formulation [9] are introduced to realize the maximum social welfare both allowing for product and price differentiation. Because interaction exists among prosumers, the game theory is indicated efficient for solving the prosumer-based P2P sharing problems [10]. Considering the self-interested nature of prosumers, the non-cooperative game is developed to coordinate prosumers interests' conflict, and the Nash equilibrium can be obtained in the regions integrated energy system joint market established in [11].

In the centralized P2P energy sharing scheme, managers are essential for the optimal regulation of energy sharing, where the energy-sharing providers (ESPs) always act as managers to coordinate the sharing process [12]. In recent researches, the Stackelberg game has been widely used to model the interactive relationships between prosumers and managers, where prosumers are generally defined as followers responding to the managers' actions who always act as leaders [13], [14]. Moreover, prosumers are motivated to participant in the P2P energy sharing community, and the individual preferences are combined with the game theory to maximize the prosumers' profits [15], [16]. However, the non-cooperative game only focuses on prosumers' personal interests but ignores the overall interest of the whole system consist of all prosumers.

To further promote the consumption of the DERs, distributed photovoltaic (PV) is encouraged to insert into the whole county (city, district) in China [17]. With the increasing integration of the DERs, formulating prosumers as multi-regions provides a new approach to manage the energy sharing among large-scale prosumers [18], [19]. Some studies focus on the formulation rules of multi-region, designing cooperative Stackelberg game framework with double auction mechanism [2], proposing a clustering-based method considering prosumers' personal preference [20], building non-cooperative Stackelberg game model with prosumers' switching decisions [21], to construct the prosumer based-regions. However, the energy sharing mechanism between regions and the coordination of prosumers' interactions within regions are rarely mentioned in the energy sharing problems with multi-region.

Based on the multi-region formulation rules mentioned in the aforementioned research, interactions exist in three aspects: i) between regions and prosumers, ii) inter-regions, iii) between prosumers inside a region. Thus, the energy scheduling among multiple sharing entities (prosumers and regions) is complex. Besides, with interest competing, prosumers within the regions should obtain a fair allocation according to their regional contribution. However, existing researches scarcely mention a motivating allocation mechanism considering the regions and prosumers' interests interactions coordinately. Challenges are presented for the designing of multi-region energy sharing framework considering diversified interactions and fair allocation mechanisms. The motivation behind this work is to propose a region-to-region (R2R) energy sharing scheme for prosumer clusters in distribution network under a multi-leaders and multi-followers Stackelberg game model, which includes the following detailed characteristics:

1) An energy sharing framework is proposed based on a multi-leaders and multi-followers Stackelberg game. The ESPs act as leaders implement R2R energy sharing and a dynamical pricing scheme is designed to guide prosumers' DR. While prosumers are the followers gathering as a cooperative way inside regions, and conduct DR which affecting R2R energy sharing process by changing regional load distribution.
2) A R2R energy sharing scheme is designed based on the geographical-formed prosumer clusters. Besides, a dynamic pricing scheme is presented with an unbalance rate,

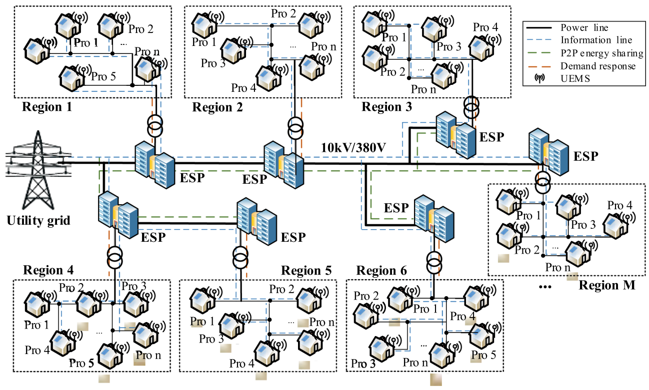


Fig. 1. Architecture of the energy-sharing system.

which is defined as the unbalanced energy in R2R energy sharing process.

3) Accompanied with dynamic pricing scheme from R2R energy sharing process, a fair allocated mechanism is derived in prosumers' DR model. The extra profits of R2R contributed by the prosumers' DR process are regarded as a reward for the prosumers, which affects prosumers' load regulations and facilitates the R2R energy sharing.

II. Framework

A. System Structure

The architecture of the energy sharing system is depicted in Fig. 1. Prosumers equipped with PV panel and the user management system (UEMS) access to the 380V side of the transformer. The optimization of prosumers is implemented through the UEMS. The region is a geographically-distributed multi-prosumers cluster with the transformer covered range in the 10 kV side. Energy can be shared in the regions by prosumers with in a region. Meanwhile, regions can conduct the R2R energy sharing cross different voltage levels to realize the local energy consumption. The R2R process is conducted based on the wireless channels in private 4G/5G network with virtual private network. In the physical system topology, the network losses caused by R2R energy sharing should be taken by both traders since they shared the network resources equally in the R2R energy sharing process.

B. Energy Sharing of Regions and Prosumers

As shown in Fig. 1, there are three participants in the energy-sharing system which are prosumers, ESP, and the utility grids. The ESP act as an intermediary between prosumers and the utility grids. Two optimization processes are conducted through ESPs and prosumers as: i) R2R energy sharing among ESPs; ii) DR conducted by prosumers based on the regional prices.

The ESP serve as buyers or sellers represent the regions selecting R2R traders and optimizing R2R sharing energy with the purpose of maximum region profits. Considering for the unbalanced trading energy in the R2R sharing process, the regional prices are set by the ESPs to promote prosumers' load consumption and optimize the R2R energy sharing, which is the input data for prosumers' DR optimization. Besides, ESP server as a central agent coordinate energy sharing among users within the region.

Prosumers conduct the DR in the region, which is affected by the regional prices transmitted by ESP. With higher prices, prosumers prefer to selling energy among prosumers, while with lower prices, prosumers prefer to buying energy. The energy sharing in the region dynamically change the regions' netload, resulting in different R2R trading energy and partners. The changing optimal R2R energy trading result will allot to each prosumer within a region, which is reflected as the contribution revenue for prosumers.

C. Formation of the Regions

With the transmission power losses in the actual network topology, the regions are formed based on prosumers' geographical locations. Meanwhile, the dynamic regional prices are set in the region, which applies incentives compared to the utility grid prices. Therefore, the rational prosumers are not willing to leave the region and do not share energy directly with the utility grid [22]. Since prosumers have contributions to the region's R2R energy sharing, prosumers can obtain profits allocated from ESP which are considered as the reward for changing their load distribution. In China, the allocations should be differential according to the influence of participants' load shifting on regional profits [23]. The balance among prosumers can be obtained when the regional internal stability is formed with a fair allocation mechanism.

III. R2R Energy Sharing Among Regions

A. Basic Model

Let a group of N prosumers in a nearby region form a region m indexed by: $i \in m := \{1, 2, \ldots, N\}$. For the PV prosumers, there always exist a certain proportion of the flexible load $E^{m,\tau}_{\text{flx } i}$, which can be satisfied in a shiftable time scale. Meanwhile, there are fix load $E^{m,\tau}_{\text{fix } i}$ denote to the compulsive demand in a certain time slot τ. The total consumption and netload are expressed as follows:

$$E_{\mathrm{i}}^{\mathrm{m},\tau} = E_{\mathrm{flx,i}}^{\mathrm{m},\tau} + E_{\mathrm{fix,i}}^{\mathrm{m},\tau} \tag{1}$$

$$E_{\mathrm{nt,i}}^{\mathrm{m},\tau} = E_{\mathrm{i}}^{\mathrm{m},\tau} - E_{\mathrm{pv,i}}^{\mathrm{m},\tau} \tag{2}$$

Prosumers in a nearby region formed a region, and the region's netload is constitute of prosumers' netload. The total consumption of prosumers and regions in the whole-time horizon should satisfied the constraints as follows:

$$\mathrm{E}_{\mathrm{flx.mini}}^{\mathrm{m},\tau} \le E_{\mathrm{flxi}}^{\mathrm{m},\tau} \le \mathrm{E}_{\mathrm{flx.maxi}}^{\mathrm{m},\tau} \tag{3}$$

$$\sum_{\tau \in \mathrm{T}} E_{\mathrm{i}}^{\mathrm{m},\tau} = \sum_{\tau \in \mathrm{T}} \mathrm{E}_{\mathrm{inii}}^{\mathrm{m},\tau} \tag{4}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{N}} E_{\mathrm{nt,i}}^{\mathrm{m},\tau} = E_{\mathrm{nt}}^{\mathrm{m},\tau} \tag{5}$$

B. R2R Energy Sharing Model for Regions

When $E^{m,\tau}_{\text{nt}\,i} > 0$, the region acts as a buyer $m \in M^B$, and purchase the short energy from other regions which is expressed as $E^{m,\tau}_{\text{R2R}} > 0$; whereas when $E^{m,\tau}_{\text{nt}\,i} < 0$, the region is a seller $m \in M^S$, and sell the surplus energy to other regions which is expressed as $E^{m,\tau}_{\text{R2R}} < 0$.

The R2R energy sharing are conducted among ESPs, and the trading objective are proposed for ESPs, which containing the prosumers sharing profits $P^{m,\tau}_{\text{pro}}$, region sharing profits $P^{m,\tau}_{\text{coa}}$. The mathematical formulation of R2R energy sharing model in time slot τ is given as follows:

$$\max P^{\tau}_{\text{m}}(E^{\text{m},1,\tau}_{\text{R2R}}, E^{\text{m},2,\tau}_{\text{R2R}}, \ldots, E^{\text{m},\text{M},\tau}_{\text{R2R}}) = P^{\text{m},\tau}_{\text{pro}} + P^{\text{m},\tau}_{\text{coa}} \quad (6)$$

$$P^{\text{m},\tau}_{\text{pro}} = \sum_{\text{i}=1}^{\text{N}} (\lambda^{\text{m},\tau}_{\text{b}} \cdot \max(E^{\text{m},\tau}_{\text{nt,i}}, 0) + \lambda^{\text{m},\tau}_{\text{s}} \cdot \min(E^{\text{m},\tau}_{\text{nt,i}}, 0)) \quad (7)$$

$$P^{\text{m},\tau}_{\text{coa}} = \begin{cases} -\lambda^{\tau}_{\text{gb}}(E^{\text{m},\tau}_{\text{nt}} - \sum_{\text{n}\in\text{M}^{\text{S}}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}}) \\ -\lambda^{\tau}_{\text{R2R}} \cdot \sum_{\text{n}\in\text{M}^{\text{S}}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}} - \lambda_{\text{loss}} E^{\text{m},\tau}_{\text{loss}}/2, \text{m} \in \text{M}^{\text{B}} \\ -\lambda^{\tau}_{\text{gs}}(E^{\text{m},\tau}_{\text{nt}} - \sum_{\text{n}\in\text{M}^{\text{B}}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}}) \\ -\lambda^{\tau}_{\text{R2R}} \cdot \sum_{\text{n}\in\text{M}^{\text{B}}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}} - \lambda_{\text{loss}} E^{\text{m},\tau}_{\text{loss}}/2, \text{m} \in \text{M}^{\text{S}} \end{cases} \quad (8)$$

where $P^{m,\tau}_{\text{pro}}$ is the prosumers sharing profits, defined as the profits ESP obtained by the prosumers' DR process. We assume that ESPs undertake the role of regional energy manager and region electricity retailers. Prosumers who would like to participant in the region are trading with ESPs, and accept the inner prices broadcast by ESPs. $P^{m,\tau}_{\text{coa}}$ is the profits ESP obtained through the regional energy sharing process. $E^{m,\tau}_{nt\,i}$ is the netload of prosumer i in the region m. $E^{m,\tau}_{\text{nt}}$ is the netload of region m. $k^{\tau}_{m,n}$ is the match coefficient between region m, n, and equal to 1 if the trade can be achieved. $E^{m,n,\tau}_{\text{R2R}}$ is the R2R trading energy. λ^{τ}_{gb}, λ^{τ}_{gs} are the feed-in-tariff of PV energy.

The first and second terms in $P^{m,\tau}_{\text{coa}}$ are the profits obtained by trading with the utility grid and the ESPs' profits obtained by the R2R energy sharing, respectively. To maximize local energy consumption, a trader can conduct the R2R sharing with multiply traders is considered. The match coefficient $k^{\tau}_{m,n}$ between traders m, n equals to 1 when the surplus energy of the sellers and deficit energy of buyers reach to a balance in time slot τ. Since the regions' netload cannot be totally balanced in the R2R energy sharing, the unbalanced energy must be traded with the utility grid with λ^{τ}_{gb}, λ^{τ}_{gs}. Meanwhile, $\lambda^{\tau}_{\text{R2R}}$ are used to denote the R2R sharing prices among regions. To facilitate the implementation of R2R energy sharing, $\lambda^{\tau}_{\text{R2R}}$ is set as: $\lambda^{\tau}_{\text{R2R}} = \frac{\lambda^{\tau}_{gs}+\lambda^{\tau}_{gb}}{2}$, which is beneficial for both buyers and sellers compared with sharing to the utility grid directly [24].

The third term in $p^{m.\tau}_{\text{coa}}$ is the network loss costs in the R2R energy sharing processes. The transmission power losses cannot be ignored (9), as the R2R energy sharing processes are considered conducts in the 10 kV power line. The energy transmission losses can be considered as a cost in the profits function, which is proportional to the transmission power losses with the losing coefficient λ_{loss} [25].

$$E^{\text{m},\tau}_{\text{loss}} = (I^{\text{m,n}})^2 \cdot R^{\text{m,n}} \quad (9)$$

where $I^{\text{m,n}}, R^{\text{m,n}}$ are the transmission line current and resistance between region n and m.

During the R2R energy sharing process, there are some constraints should be satisfied. To guarantee the profitability of the ESP, the total R2R trading energy should be less than the regions' netload which restrict the region can only present as either a buyer or a seller (10). The R2R energy trading can be conducted when selling energy matches with the buying energy (11) [26]. It is assumed that the matching pairs are reached when the energy reported by buyers and sellers different within a small number ε. The system power flow can be expressed as (12). On the time unit of 1h, the transformation of energy and power in node m is expressed as (13). To avoid the congestion and overload in the transmission line, the apparent power should satisfy the power line transmission limitation (14) [27]. Assuming that the bus voltage should fit in with working requirements (15).

$$\left| \sum_{\text{n}\neq\text{m}}^{\text{M}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}} \right| \leq |E^{\text{m},\tau}_{\text{nt}}| \quad (10)$$

$$\left| k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}} + k^{\tau}_{\text{n,m}} E^{\text{n,m},\tau}_{\text{R2R}} \right| \leq \varepsilon \quad (11)$$

$$\begin{cases} P_{\text{m}} = U_{\text{m}} \sum_{\text{n}=1} U_{\text{n}}(G_{\text{mn}} \cos\theta_{\text{mn}} + B_{\text{mn}} \sin\theta_{\text{mn}}) \\ Q_{\text{m}} = U_{\text{m}} \sum_{\text{n}=1} U_{\text{n}}(G_{\text{mn}} \sin\theta_{\text{mn}} - B_{\text{mn}} \cos\theta_{\text{mn}}) \end{cases} \quad (12)$$

$$P^{\text{m}} = \begin{cases} (\sum_{\text{n}\in\text{M}^{\text{S}}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}} + E^{\text{m},\tau}_{\text{nt}}) \cdot \Delta t, \text{m} \in \text{M}^{\text{B}} \\ (\sum_{\text{n}\in\text{M}^{\text{B}}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}} - E^{\text{m},\tau}_{\text{nt}}) \cdot \Delta t, \text{m} \in \text{M}^{\text{S}} \end{cases} \quad (13)$$

$$\text{S}_{\text{min}} \leq \sqrt{P^2_{\text{mn}} + Q^2_{\text{mn}}} \leq \text{S}_{\text{max}} \quad (14)$$

$$\text{U}_{\text{min}} \leq U_{\text{m}} \leq \text{U}_{\text{max}} \quad (15)$$

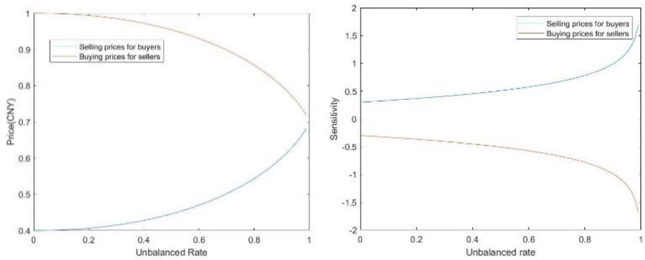
C. Pricing Scheme

In this article, it is expected to achieve the maximum energy self-balance within an area formed by multi regions under different transformers through R2R trading process. In order to maximize the prosumers' DR potential a regional pricing scheme is proposed, where the regional prices are the connection between the R2R energy sharing and prosumers' optimization process, and are determined by the ESP. The price can stimulate prosumers to regulate their load distribution and promote the energy balance. The unbalanced rate ρ^{τ}_{m} is defined as the ratio between the grid trading energy and regions' netload in time slot τ, which can be expressed as follows:

$$\rho^{\tau}_{\text{m}} = \frac{\sum_{\text{i}\in\text{N}} E^{\text{m},\tau}_{\text{nt,i}} - \sum_{\text{n}\in\text{M}} k^{\tau}_{\text{m,n}} E^{\text{m,n},\tau}_{\text{R2R}}}{\sum_{\text{i}\in\text{N}} E^{\text{m},\tau}_{\text{nt,i}}} \quad (16)$$

The regional price model is defined based on the unbalance rate which are formulated as:

$$\lambda^{\text{m},\tau}_{\text{s}} = \begin{cases} \lambda^{\tau}_{\text{gs}} + 2\text{a}_0\rho^{\tau}_{\text{m}} + \text{a}_0(1-\rho^{\tau}_{\text{m}})\ln(\text{b}_0 - \text{b}_0\rho^{\tau}_{\text{m}}), \text{m} \in \text{M}^{\text{B}} \\ \lambda^{\tau}_{\text{gs}}, \qquad \text{m} \in \text{M}^{\text{S}} \end{cases} \quad (17)$$



(a) (b)

Fig. 2. (a). Relationships between the selling and buying prices an unbalanced rate ρ_m^τ; (b). Relationships between the selling and buying prices sensitivities to ρ_m^τ.

$$\lambda_{\rm b}^{\rm m,\tau} = \begin{cases} \lambda_{\rm gb}^{\tau} - 2{\rm a}_0\rho_{\rm m}^{\tau} - {\rm a}_0(1-\rho_{\rm m}^{\tau})\ln({\rm b}_0 - {\rm b}_0\rho_{\rm m}^{\tau}), & {\rm m}\in{\rm M^S} \\ \lambda_{\rm gb}^{\tau}, & {\rm m}\in{\rm M^B} \end{cases} \tag{18}$$

where a_0 and b_0 are the parameters set by the operators.

When $\rho_m^\tau = 1$, which means the region is not involved into the R2R energy trading. Then the selling price and buying price are assumed to be equal in this situation. Then the following equations can be obtained for buyers and sellers, respectively:

$$\lambda_{\rm gb}^{\tau} = \lambda_{\rm b}^{\rm m,\tau} = \lambda_{\rm s}^{\rm m,\tau} = \lambda_{\rm gs}^{\tau} \tag{19}$$

Then $\rm a_0$ can be obtained as follows:

$$\rm a_0 = (\lambda_{gb}^{\tau} - \lambda_{gs}^{\tau})/2 \tag{20}$$

$\rm b_0$ is the sensitivity of regional prices to the unbalanced energy. According to (21) and (22), $\rm b_0$ is calculated through the first-order derivative of $\lambda_s^{m,\tau}$ and $\lambda_b^{m,\tau}$ to ρ_m^τ. From Fig. 2, it is obvious that regions with lower $\rm b_0$ are easier affected by the unbalanced energy. That means the regional prices have a great change when the unbalanced energy dynamically changed.

$$\frac{\partial\lambda_{\rm s}^{\rm m,\tau}}{\partial\rho_{\rm m}^{\tau}} = {\rm a}_0 - {\rm a}_0\cdot\ln({\rm b}_0 - {\rm b}_0\rho_{\rm m}^{\tau}) \tag{21}$$

$$\frac{\partial\lambda_{\rm b}^{\rm m,\tau}}{\partial\rho_{\rm m}^{\tau}} = -{\rm a}_0 + {\rm a}_0\cdot\ln({\rm b}_0 - {\rm b}_0\rho_{\rm m}^{\tau}) \tag{22}$$

Generally, to promote prosumers' local PV consumption, the internal buying prices are greater than the internal selling prices [1]. Besides, the regional prices are set within the utility prices to encourage the participant of internal energy sharing [12].

IV. Fair Allocated Mechanism Under Dynamic Pricing Scheme Within Regions

A. Prosumers' Demand Response

Affected by the regional prices, the demand response implements between prosumers and the ESP for maximum prosumers' utility. The region formed by the nearby prosumers can be defined as $(\mathcal{N}, v)$, where $\mathcal{N} = \{1, 2, \ldots, N\}$ represents a finite and nonempty set of all prosumers. In the region, there are many sub-regions $\{S|S\in\mathcal{N}\}$ which can be obtained with multiple prosumers. $v(\mathcal{N})$ is the characteristic function of the region expressed as: $v(\mathcal{N})$: $2^N \to R^N,\ v(\emptyset) = 0$. The characteristic function $v(\mathcal{N})$ is the value region which can obtain through the trading. So $v(\mathcal{N})$ can be defined as the region sharing profits $P_{coa}^{m,\tau}$ in (8) [18].

Definition 1 (Contribution): The extra profits region obtained through the prosumer *i*'s optimization is defined as its contribution:

$$m_i = v(N) - v(N_{-i}) - v(i) \tag{23}$$

where $v(\mathcal{N}_{-i})$ is the region's value obtained except prosumer *i*, and $v(i)$ is the value prosumer *i* received from trading with the utility grid. $v(i)$ is shown as follows:

$$v_i^{m,\tau} = \begin{cases} -\lambda_{\rm loss}(E_{\rm nt,i}^{\rm m,\tau})^2\cdot{\rm R^{m,grid}}/{\rm U_m^2} - \lambda_{\rm gb}^{\tau}E_{\rm nt,i}^{\rm m,\tau}, & {\rm m}\in{\rm M^B} \\ -\lambda_{\rm loss}(E_{\rm nt,i}^{\rm m,\tau})^2\cdot{\rm R^{m,grid}}/{\rm U_m^2} - \lambda_{\rm gs}^{\tau}E_{\rm nt,i}^{\rm m,\tau}, & {\rm m}\in{\rm M^S} \end{cases} \tag{24}$$

From the perspective of the marginal prosumers (i.e., the last one joining into the region), the load distributions affect the region's netload profile $E_{\rm nt}^{m,\tau}$. Meanwhile, other prosumers' load strategies $E_{{\rm nt}\,\mathcal{N}-i}^{m,\tau}$ can also be affected by the marginal prosumers. The reason is that the regional prices are decided by the R2R energy trading, which relates to the region's netload profile. Thus, prosumer's contribution rate is defined as the joint contribution of the marginal prosumer *i* and the original prosumers ($\mathcal{N}_{-i}$):

Definition 2 (Contribution rate): Prosumer *i*'s contribution rate can be defined as the proportion of all prosumers' contributions:

$$\varsigma_{\rm i}^{\rm m,\tau} = m_i / \sum_{\rm i\in N} m_i \tag{25}$$

To stimulate prosumers conducting the DR and improving the region load profile, the contribution rate $\varsigma_i^{m,\tau}$ is considered into prosumers' utility function. The utility function of prosumers can be defined as follows:

$$\begin{aligned} \max U_{\rm i}^{\rm m,\tau}(E_{\rm i}^{\rm m,\tau}) = & -\lambda_{\rm b}^{\rm m,\tau}\cdot\max(E_{\rm nt,i}^{\rm m,\tau}, 0) \\ & -\lambda_{\rm s}^{\rm m,\tau}\cdot\min(E_{\rm nt,i}^{\rm m,\tau}, 0) \\ & +\lambda_{\rm PV}\cdot E_{\rm PV,i}^{\rm m,\tau} + \omega_{\rm i}^{\rm m,\tau}\cdot\ln(1+E_{\rm i}^{\rm m,\tau}) \\ & +\varsigma_{\rm i}^{\rm m,\tau}\cdot\ln(1+|E_{\rm i}^{\rm m,\tau} - E_{\rm inii}^{\rm m,\tau}|) \end{aligned} \tag{26}$$

The utility function is divided into four parts. The first part $-\lambda_{\rm b}^{\rm m,\tau}\cdot\max(E_{\rm nt,i}^{\rm m,\tau}, 0) - \lambda_{\rm s}^{\rm m,\tau}\cdot\min(E_{\rm nt,i}^{\rm m,\tau}, 0)$ is the energy sharing profits/costs with the ESP. When the PV generation is greater/shorter than the total consumption, the prosumers act as sellers/buyers to maximize the profits or minimize their cost. The second part $\lambda_{\rm PV}\cdot E_{\rm PV,i}^{\rm m,\tau}$ is the subsidy for generating $E_{\rm PV,i}^{\rm m,\tau}$ PV energy. The third part $\omega_{\rm i}^{\rm m,\tau}\cdot\ln(1+E_{\rm i}^{\rm m,\tau})$ is prosumer *i*'s utility of consuming energy $E_{\rm i}^{\rm m,\tau}$, where $\omega_{\rm i}^{\rm m,\tau}$ is the preference parameter for prosumer *i* in time slot τ. Prosumers with high $\omega_{\rm i}^{\rm m,\tau}$ prefer to consuming more energy to obtain the maximum utility compared with prosumers with lower $\omega_{\rm i}^{\rm m,\tau}$.

The last part $\varsigma_{\rm i}^{\rm m,\tau}\cdot\ln(1+|E_{\rm i}^{\rm m,\tau} - E_{\rm inii}^{\rm m,\tau}|)$ is prosumers' comfort level deviating from the initial energy consumption habits. Prosumers with higher contribution to region's R2R energy trading should obtain higher feedback from the consumption habit deviation [18]. It is noted that ln(·)function have been widely used to reflect prosumers' preference order in economics [28], and it has been shown that suitable for reflecting the energy consumption utility recently [29]. To avoid the case of the negative utility, ln(1+ ·)have been adopted.

B. Fair Allocation Mechanism

Considering for the stability of the region formed based on the geographical location, a fair allocation mechanism is proposed to ensure that no more prosumers would secede from the region.

Definition 3 (Allocation): $X \in \mathbb{R}^{1\times N}$ is defined as the allocation vector within a region when X satisfies axioms as follows:

1) (Efficiency): The allocation mechanism is efficient if $x(N) = \sum_{i\in\mathcal{N}} x_i = \sum_{i=1}^{N} x_i = v(N), \forall X \in \mathbb{R}^{1\times N}$, which means the sum of all prosumers' allocation is the region's value.
2) (Individual rational): The allocation $\boldsymbol{X}$ is said to be individual rational if $x_i \geq v(i), \forall i \in \mathcal{N}$

Considering the profitability of the ESP, the allocation value should not be included into prosumer's utility function. However, a fair and stable allocation balance should be achieved among interactive prosumers. Therefore, the fair and stable allocation is reflected into the contribution rate and included into prosumer's utility function.

Then the allocation obtained by prosumers can be formulated as:

$$x_{\mathrm{i}}^{\mathrm{m},\tau} = \varsigma_{\mathrm{i}}^{\mathrm{m},\tau} \cdot v(N) \tag{27}$$

Definition 4 (core): The core is a set of stable allocation solutions that any interests cannot be further obtained by splitting off the region:

$$C(v) \equiv \left\{ x \in \mathrm{R}^{\mathrm{N}} \middle| \begin{array}{c} \sum_{\mathrm{i\in N}} x_i = v(N) \\ \text{for } \forall \mathrm{S} \in 2^N, \sum_{\mathrm{i\in N}} x_i \geq v(S) \end{array} \right\} \tag{28}$$

Theorem 1: The allocation obtained by the prosumers is stable if the allocation solutions are in the core.

Proof: There are two kinds of possible sub region formation in the proposed region model. For the first one, the region is formed by a prosumer (e.g., S = {1},{2},{3},…,{N}). The netload profile of region S is $E_{\mathrm{nt}}^{s,\tau} = E_{\mathrm{nt}\ i}^{s,\tau}$. For the second one, the sub-region is formed by multiple prosumers (e.g., S = {12,3,r}, r∈$\mathcal{N}$). It can be regard as a prosumer in the region $\mathcal{N}$ and still in the management of the ESP in the region m [18]. The netload profile of region S is $E_{\mathrm{nt}}^{s,\tau} = \sum_{i\in S} E_{\mathrm{nt}\ i}^{s,\tau}$.

If the sub region S deviating from the region m,the profits can be calculated as:

$$\begin{aligned} u^g(S) = &-\lambda_{\mathrm{loss}}(E_{\mathrm{nt}}^{\mathrm{s},\tau})^2 \cdot \frac{\mathrm{R}^{\mathrm{m,grid}}}{\mathrm{U_m^2}} - \lambda_{\mathrm{gb}}^{\tau} \max(E_{\mathrm{nt}}^{\mathrm{s},\tau}, 0) \\ &- \lambda_{\mathrm{gs}}^{\tau} \min(E_{\mathrm{nt}}^{\mathrm{s},\tau}, 0) \end{aligned} \tag{29}$$

Considering the sub region S as a prosumer in the region m, the profits can be expressed based on the prosumer utility function (26):

$$\begin{aligned} u^c(S) = &-\lambda_{\mathrm{b}}^{\mathrm{m},\tau} \cdot \max(E_{\mathrm{nt,i}}^{\mathrm{m},\tau}, 0) - \lambda_{\mathrm{s}}^{\mathrm{m},\tau} \cdot \min(E_{\mathrm{nt,i}}^{\mathrm{m},\tau}, 0) \\ &+ \varsigma_{\mathrm{i}}^{\mathrm{m},\tau} \cdot \ln(1 + |E_{\mathrm{i}}^{\mathrm{m},\tau} - E_{\mathrm{inii}}^{\mathrm{m},\tau}|) \end{aligned} \tag{30}$$

Comparing $u^g(S)$ and $u^c(S)$, the following equations can be obtained:

$$\begin{aligned} u^g(S) - u^c(S) = &\begin{pmatrix} -\lambda_{\mathrm{gb}}^{\tau} \max(E_{\mathrm{nt}}^{\mathrm{s},\tau}, 0) - \lambda_{\mathrm{gs}}^{\tau} \min(E_{\mathrm{nt}}^{\mathrm{s},\tau}, 0) \\ -\lambda_{\mathrm{loss}}(E_{\mathrm{nt}}^{\mathrm{s},\tau})^2 \cdot \frac{\mathrm{R^{m,grid}}}{\mathrm{U_m^2}} \end{pmatrix} \\ &- \begin{pmatrix} -\lambda_{\mathrm{b}}^{\mathrm{m},\tau} \cdot \max(E_{\mathrm{nt,i}}^{\mathrm{m},\tau}, 0) - \lambda_{\mathrm{s}}^{\mathrm{m},\tau} \cdot \min(E_{\mathrm{nt,i}}^{\mathrm{m},\tau}, 0) \\ +\varsigma_{\mathrm{i}}^{\mathrm{m},\tau} \cdot \ln(1 + |E_{\mathrm{i}}^{\mathrm{m},\tau} - E_{\mathrm{inii}}^{\mathrm{m},\tau}|) \end{pmatrix} \\ &= -\lambda_{\mathrm{loss}}(E_{\mathrm{nt}}^{\mathrm{s},\tau})^2 \cdot \frac{\mathrm{R^{m,grid}}}{\mathrm{U_m^2}} - \varsigma_{\mathrm{i}}^{\mathrm{m},\tau} \cdot \ln(1 + |E_{\mathrm{i}}^{\mathrm{m},\tau} - E_{\mathrm{inii}}^{\mathrm{m},\tau}|) \\ &-(\lambda_{\mathrm{gb}}^{\tau} - \lambda_{\mathrm{b}}^{\mathrm{m},\tau}) \cdot \max(E_{\mathrm{nt,i}}^{\mathrm{m},\tau}, 0) - (\lambda_{\mathrm{gs}}^{\tau} - \lambda_{\mathrm{s}}^{\mathrm{m},\tau}) \cdot \min(E_{\mathrm{nt,i}}^{\mathrm{m},\tau}, 0) \end{aligned} \tag{31}$$

It is obvious that $u^g(S) - u^c(S) \leq 0$ is tenable in both possible sub region formation. Therefore, for the sub region S, the profits directly obtained from trading with the utility grid is less than in the region $\mathcal{N}$. For the rational prosumers, the sub region is nonexistent according to the *individual rational* property in Definition 3.

Therefore, the allocation solution is always in the core, and the allocation mechanism for all the prosumers in the region $\mathcal{N}$ is stable.

V. Stackelberg Game for Regions and Prosumers

A. Game Formulation

Conflicting interests exists between prosumers and regions, and the game theory can be applied to analyze the decision-making process [30]. The Stackelberg game is used in this article to formulate the interactions between regions and prosumers [31]. To coordinate the R2R energy sharing among the regions and prosumers' DR within the regions, the multi-leaders and multi-followers Stackelberg game is applied, where ESPs act as leaders conducting the R2R energy sharing and prosumers act as followers conducting the DR. During the process, ESP optimize the R2R traders and trading energy, set the regional prices, while prosumers respond to the regional prices by adjusting the flexible load strategies. The multi-leaders and multi-followers Stackelberg game models can be expressed as follows:

$$G = \{(\mathrm{N} \in \mathrm{M}), \{\mathbf{E}^{\tau}\}, \{\boldsymbol{\lambda}_{\mathrm{b}}^{\tau}\}, \{\boldsymbol{\lambda}_{\mathrm{s}}^{\tau}\}, \{\mathbf{E}_{R2R}^{\tau}\}, \{\mathbf{U}^{\tau}\}, \{\mathbf{P}^{\tau}\}\} \tag{32}$$

where $\{\boldsymbol{E}^{\tau}\}$ are the set of prosumers' flexible load strategies set; $\{\boldsymbol{\lambda}_b^{\tau}\}, \{\boldsymbol{\lambda}_s^{\tau}\}$ are the internal buying and selling prices set according to the R2R unbalanced trading energy; $\{\boldsymbol{E}_{R2R}^{\tau}\}$ are the R2R sharing energy strategies which are consist of the trading energy and traders; $\{\boldsymbol{U}^{\tau}\}$ and $\{\boldsymbol{P}^{\tau}\}$ are the prosumers' utility and region's profits which are defined as (6) and (26). Since interaction between the ESPs and their prosumers are the same, we only consider the case in a particular region *m*.

The interaction relationship between ESPs and the prosumers are depicted in Fig. 3. The regional prices are determined by the ESP in the R2R energy sharing process through (17) and (18). Based on the regional prices, prosumers conduct the DR

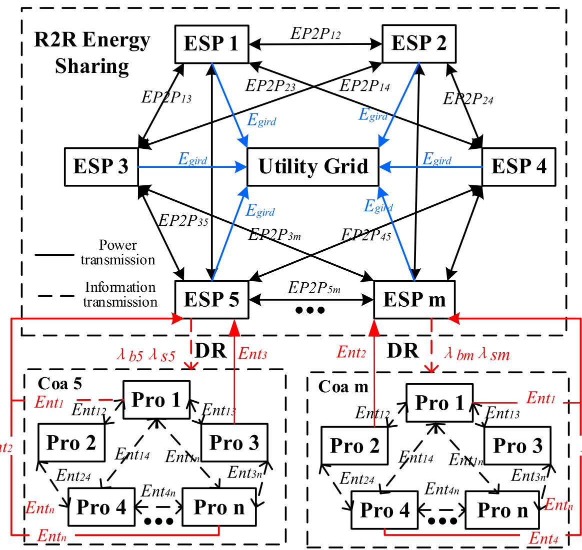


Fig. 3. Interaction relationship between ESPs and prosumers.

under the promise of the maximum utilities. Prosumers' netload distributions would affects the R2R energy sharing strategies.

B. Stackelberg Equilibrium

Definition 5 (Stackelberg equilibrium (SE)): For game G defined in (32), the unique SE (i.e., strategy set $(\boldsymbol{E}^{m,\tau*}, \boldsymbol{\lambda_b^{m,\tau*}}, \boldsymbol{\lambda_s^{m,\tau*}}, \boldsymbol{E}_{\mathrm{R2R}}^{\tau*})$) exists if and only if it satisfies the following set of inequalities:

$$\begin{aligned} &U_i^{m,\tau}(E_i^{m,\tau}, \boldsymbol{E_{-i}^{m,\tau*}}, \boldsymbol{\lambda_b^{m,\tau*}}, \boldsymbol{\lambda_s^{m,\tau*}}, \boldsymbol{E_{R2R}^{\tau*}}) \\ &\leq U_i^{m,\tau}(\boldsymbol{E^{m,\tau*}}, \boldsymbol{\lambda_b^{m,\tau*}}, \boldsymbol{\lambda_s^{m,\tau*}}, \boldsymbol{E_{R2R}^{\tau*}}), \\ &\forall i \in N, \forall E_i^{m,\tau} \in \boldsymbol{E^{m,\tau}} \end{aligned} \tag{33}$$

$$\begin{aligned} &P_m^{m,\tau}(\boldsymbol{E^{m,\tau*}}, \boldsymbol{\lambda_b^{m,\tau}}, \boldsymbol{\lambda_S^{m,\tau}}, \boldsymbol{E}_{R2R}^{m,n,\tau}, \boldsymbol{E}_{R2R}^{m,-n,\tau}) \leq \\ &P_m^{m,\tau}(\boldsymbol{E}^{m,\tau*}, \boldsymbol{\lambda_b^{m,\tau*}}, \boldsymbol{\lambda_S^{m,\tau*}}, \boldsymbol{E}_{R2R}^{\tau*}), \forall n \in M_{-m}, \\ &\forall E_{R2R}^{m,n,\tau} \in \boldsymbol{E}_{R2R}^{\tau*} \end{aligned} \tag{34}$$

where $\boldsymbol{E}_{-\mathrm{i}}^{\mathrm{m},\tau*} = [E_1^{\mathrm{m},\tau*}, E_2^{\mathrm{m},\tau*}, \ldots, E_{\mathrm{i-1}}^{\mathrm{m},\tau*}, E_{\mathrm{i+1}}^{\mathrm{m},\tau*}, \ldots, E_{\mathrm{N}}^{\mathrm{m},\tau*}]$, $\boldsymbol{E}_{\mathrm{R2R}}^{\mathrm{m},-\mathrm{n},\tau*} = [E_{\mathrm{R2R}}^{\mathrm{m},1,\tau}, E_{\mathrm{R2R}}^{\mathrm{m},2,\tau}, \ldots, E_{\mathrm{R2R}}^{\mathrm{m},\mathrm{m}-1,\tau}, E_{\mathrm{R2R}}^{\mathrm{m},\mathrm{m}+1,\tau}, \ldots, E_{\mathrm{R2R}}^{\mathrm{m},\mathrm{M},\tau}]$.

The maximum profits obtained for both prosumers and the ESP when game *G* reach to SE. Prosumers cannot increase their utility by adjusting their flexible load consumption strategies. Meanwhile, regions cannot improve their profits by changing the R2R sharing energy, R2R traders, and the regional prices.

In the proposed Stackelberg game *G* between prosumers and ESP, the SE can always be obtained based on the Theorem 2.

Theorem 2: The SE can be obtained only if the following conditions are satisfied:

1) Both leaders' and followers' strategies sets are nonempty, compact, and convex.
2) The followers have unique optimal solutions with the given leaders' strategies.
3) The leaders have unique solutions with the given followers' strategies.

Proof: Constrains (1–5) and (10–15) are all linear constrains and regions' profit function (6) and prosumers' utility function (26) are both nonempty, convex, and compact, the first condition in Theorem 2 can be proved to be tenable.

Assuming that the regional prices $\lambda_b^{m,\tau}$ and $\lambda_s^{m,\tau}$are given, and prosumers' contribution rate $\varsigma_i^{m,\tau}$ are constant, prosumers feasible strategy region can be divided into two regions based on the sign of $(E_i^{m,\tau} - E_{\mathrm{ini}\ i}^{m,\tau})$. For $E_i^{m,\tau} \geq E_{\mathrm{ini}\ i}^{m,\tau}$, $E_{i1}^{m,\tau} \in \Psi_1$; $E_i^{m,\tau} \leq E_{\mathrm{ini}\ i}^{m,\tau}$, $E_{i2}^{m,\tau} \in \Psi_2$. It is easy to find that:

$$\psi_1 \cup \psi_2 = \psi, \psi_1 \cap \psi_2 = \emptyset \tag{35}$$

For both region Ψ_1 and Ψ_2, the Hessian matrix of $U_i^{m,\tau}$ to $E_i^{m,\tau}$ is formulated as:

$$H_u = diag\left\{\begin{array}{l} -\frac{\omega_{\mathrm{i}}^{\mathrm{m},1}}{(1+E_{\mathrm{i}}^{\mathrm{m},1})^2} - \frac{\varsigma_{\mathrm{i}}^{\mathrm{m},1}}{(1-\mathrm{E}_{\mathrm{i}}^{\mathrm{m},1}+E_{\mathrm{ini i}}^{\mathrm{m},1})^2}, \\ -\frac{\omega_{\mathrm{i}}^{\mathrm{m},2}}{(1+E_{\mathrm{i}}^{\mathrm{m},2})^2} - \frac{\varsigma_{\mathrm{i}}^{\mathrm{m},2}}{(1-\mathrm{E}_{\mathrm{i}}^{\mathrm{m},2}+E_{\mathrm{ini i}}^{\mathrm{m},2})^2}, \\ \ldots, \\ -\frac{\omega_{\mathrm{i}}^{\mathrm{m},\mathrm{T}}}{(1+E_{\mathrm{i}}^{\mathrm{m},\mathrm{T}})^2} - \frac{\varsigma_{\mathrm{i}}^{\mathrm{m},\mathrm{T}}}{(1-\mathrm{E}_{\mathrm{i}}^{\mathrm{m},\mathrm{T}}+E_{\mathrm{ini i}}^{\mathrm{m},\mathrm{T}})^2}, \end{array}\right\} \tag{36}$$

Cause $w_i^{m,\tau} > 0$, $\varsigma_i^{m,\tau} > 0$ $\forall i \in N$, $\forall m, n \in M, \forall \tau \in T$, the *Hessian matrix* of $U_i^{m,\tau}$ is a negative definite matrix and $U_i^{m,\tau}$ is strictly concave with respect to $E_i^{m,\tau}$. Therefore, the optimal flexible load $E_{i1}^{m,\tau*}$ and $E_{i2}^{m,\tau*}$ exist and are unique in the feasible regions Ψ_1 and Ψ_2, and the second condition is satisfied in Theorem 1.

The regional prices are the connections between the ESPs and prosumers, and the R2R unbalanced energy are regarded as variables for the ESPs. Thus, the Hessian ma*trix* of P_m^{τ} to $\boldsymbol{E}_{\mathrm{R2R}}^{\tau}$ is formulated as:

$$H_p = diag\left\{\begin{array}{l} \frac{-\lambda_{\mathrm{loss}}\left(k_{\mathrm{m},1}^{\tau}\right)^2 \mathrm{R}^{\mathrm{m},1}}{\mathrm{U}_{\mathrm{m}}^2}, \\ \frac{-\lambda_{\mathrm{loss}}\left(k_{\mathrm{m},2}^{\tau}\right)^2 \mathrm{R}^{\mathrm{m},2}}{\mathrm{U}_{\mathrm{m}}^2}, \\ \ldots, \\ \frac{-\lambda_{\mathrm{loss}}\left(k_{\mathrm{m},\mathrm{n}}^{\tau}\right)^2 \mathrm{R}^{\mathrm{m},\mathrm{n}}}{\mathrm{U}_{\mathrm{m}}^2} \end{array}\right\} \tag{37}$$

where $\lambda_{\mathrm{loss}} > 0$, $\boldsymbol{k}_m^{\tau} = \{0, 1\}$, $\boldsymbol{R}^m > 0$, $U_m^2 > 0$ $\forall m, n \in M$, $\forall \tau \in T$. Therefore, the *Hessian matrix H* is always negative definite, the optimal R2R trading energy and traders are unique, and P_m^{τ} is strictly concave with respect to $\boldsymbol{E}_{\mathrm{R2R}}^{\tau}$.

Because prosumers' utility functions $\boldsymbol{U}^{\tau}$ and ESP' profit functions $\boldsymbol{P}^{\tau}$ are both strictly concave with respect to $\boldsymbol{E}^{m,\tau}$ and $\lambda_b^{m,\tau}$, $\lambda_s^{m,\tau}$, $\boldsymbol{E}_{\mathrm{R2R}}^{\tau}$, $\forall i \in N$, $\forall m \in M$ respectively, the maximum profits can achieve for both ESP and prosumers. Thus, Theorem 1 has been proved and a unique SE always exists in the proposed Stackelberg game *G*.

C. Solution Algorithm

A distributed iterative algorithm is adopted to solve the proposed Stackelberg Game *G*, where three iterative processes are implemented among the regions, within the regions, and between the ESPs and prosumers respectively.

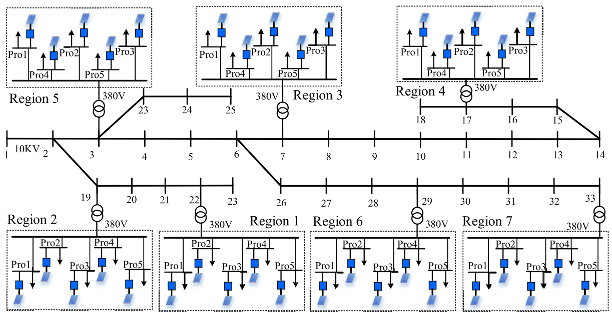


Fig. 4. IEEE 33-bus test network.

With the initial data collected in step 1, the Stackelberg iteration conducts between region and prosumers in step 2, which nested the region iteration and prosumer iteration process.

The R2R energy sharing iterations conducted among regions in step 3. The optimal trading energy is transmitted to the corresponding optimal traders and regional R2R sharing strategies are dynamically changed based on the optimal traders' sharing energy. The R2R energy sharing among regions reach a balance until all the regions' profits cannot be further increased through changing their strategies. Because regional netload cannot be totally balanced through R2R energy sharing process, regional prices are set based on the unbalanced energy, which is calculated in the step 4.

The iteration among prosumers is conducted simultaneously for each ESP with the dynamic regional prices in step 5. The DR process is conducted with the UEMS prosumers equipped. The ESP calculates prosumers' contribution rate through the optimal strategies obtained in the DR process. In each iteration process, the prosumers' optimal strategies are recalculated with the dynamic contribution rate. The final load distribution is decided if all the prosumers' strategies cannot be adjusted anymore.

The prosumers' strategies are dynamically affected by the R2R energy sharing strategies, while the optimal R2R sharing energy are also obtained based on the prosumers' load distribution. The SE can be achieved with the iterative process.

Besides, the internal-point optimization method is applied in the R2R energy sharing and prosumers' energy sharing process for each ESP and prosumer. The specific solution process is illustrated as follows:

Algorithm 1: Iterative Algorithm for Game G.

1. Input initial data

Input price parameters $a_0,\ b_0,\ \boldsymbol{\lambda}_{\text{R2R}},\ \lambda_{\text{loss}}, \lambda_{\text{pv}}$ and $\boldsymbol{\lambda}_{gb},\ \boldsymbol{\lambda}_{gs}$, which are set as the initial regional prices.

Collect prosumers' initial value: $\boldsymbol{E}_{\text{ini}}, \boldsymbol{E}_{\text{pv}}$

2. Iterations between ESPs and prosumers

For iteration $\omega = 1$

3. Iterations among regions

For iteration $r = 1$

For region $m = 1$

ESP optimizes $\boldsymbol{E}_{\text{R2R}}^{m,\tau}$ and selects the R2R traders through (6). Each ESP transmits the optimal R2R trading energy $\boldsymbol{E}_{\text{R2R}}^{m,\tau*}$ to the corresponding traders for R2R matching.

If $m = M$

End for region

If $\sum_{m=1}^{M} |\boldsymbol{E}_{\text{R2R}}^{m,\tau,r*} - \boldsymbol{E}_{\text{R2R}}^{m,\tau,r-1*}| \le \varepsilon 1$

End for region iteration

4. Regional dynamical prices calculation

ESP calculates the regional prices according to (17) and (18), and sets the initial contribution rate $\boldsymbol{\varsigma}^{m,\tau}$ for each prosumer based on (25).

5. Iterations among prosumers

Parfor region m = 1:M

For iteration $l = 1$

For prosumer $i = 1$

Prosumers obtain the optimal strategies $E_i^{m,\tau}$ through (26), and submit $E_i^{m,\tau*}$ to the ESP to calculate contribution rate.

If $i = N$

End for prosumer

ESP recalculates each prosumers' contribution rates based on their optimal strategies set $\boldsymbol{E}^{m,\tau*}$ according to (26).

If $|\boldsymbol{E}^{m,\tau,l*} - \boldsymbol{E}^{m,\tau,l-1*}| \le \varepsilon 2$

End for prosumer iteration

End for region

If $\sum_{m=1}^{M} |\boldsymbol{E}^{m,\tau,w*} - \boldsymbol{E}^{m,\tau,w-1*}| \le \varepsilon 3$

End for Stackelberg iteration

VI. Case Study

A. Basic Data

The IEEE 33-bus test network is used as the network topology for the case study, which structure is shown in Fig. 4. An industrial park data in Guangdong Province, China is used, where 35 numbers of PV prosumers are concerned and grouped into 7 regions according to the transformers they access. The data of prosumers' load strategies, PV generation is collected by the smart meter equipped in prosumers. The regional price parameters and grid trading prices are constant, which are set as $a_0 = 0.6,\ b_0 = 2,\ \lambda_{gb} = 1.0\frac{\text{CNY}}{\text{kWh}},\ \lambda_{\text{gs}} = 0.4\frac{\text{CNY}}{\text{kWh}}$, respectively. Thus, the R2R trading price is $\lambda_{\text{R2R}} = (\lambda_{gb} + \lambda_{gs})/2 = 0.7\text{CNY/kWh}$. The network losses and PV subsidies are set as $\lambda_{\text{loss}} = 0.45\text{CNY/kWh}$, $\lambda_{\text{pv}} = 0.378\text{CNY/kWh}$, respectively. The matching parameter ε is set to be 10 kWh.

B. Results of Prosumers' DR Process

The load distributions of all the regions with DR process are obtained, and the region 3 is taken for example to illustrate the prosumers' DR. The load distributions of region 3 with DR are shown in Fig. 5. According to Fig. 5, the utility grid trading energy is generated by both positive and negative netload, which is greatly reduced due to prosumers' DR process in time slots 8–10 and 11–13 and 14–17. In time slot 12, The peak load of region 3 is 8.38 MW. Motivated by the low internal buying prices,

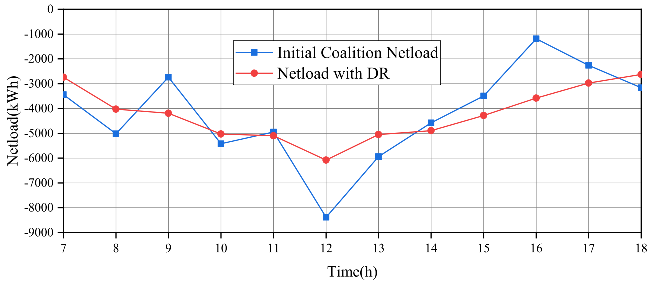


Fig. 5. Load distribution of region 3 with DR.

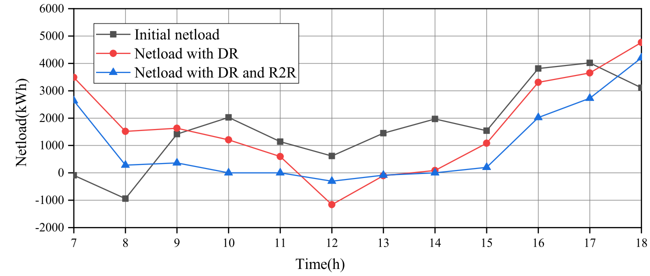


Fig. 7. Load distribution of region 7 with R2R and DR.

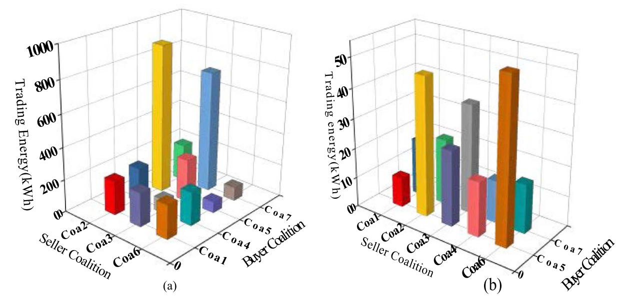


Fig. 6. Prosumers' R2R energy sharing results (a) $\tau = 8$ (b) $\tau = 14$.

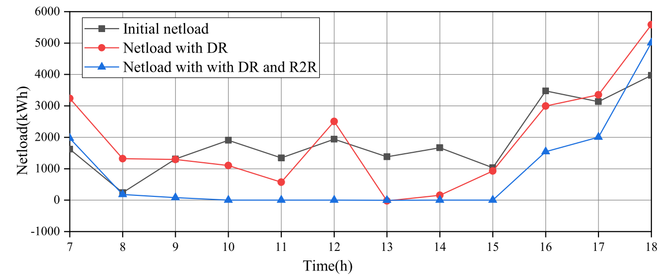


Fig. 8. Load distribution of region 5 with R2R and DR.

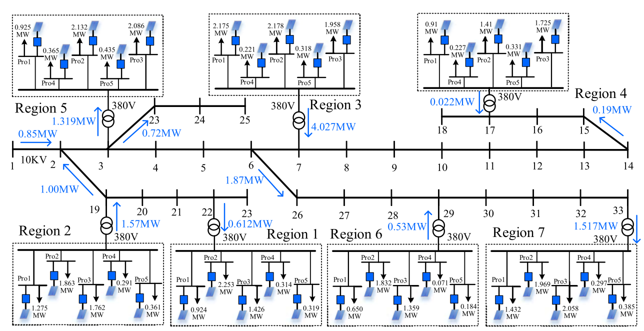


Fig. 9. Load distribution and power flow in time slot 8.

prosumers shift the flexible load from time slots 9 and 14–17 to the time slot 11–13, and the peak load in time slot 12 is reduced to 6.08 MW. Thus, the utility grid trading energy is reduced with prosumers' DR process.

C. Results of Regions' R2R Energy Sharing Combined DR

To demonstrate the effectiveness of considering the R2R energy trading in the energy sharing model, comparison is conducted between the DR sharing and the R2R combined DR sharing.

1) Results of the R2R Trading Energy: Through the R2R energy sharing combined with DR process, the optimal R2R trading energy in all the time slots are obtained. The results of the R2R energy sharing in time slot 8 and 14 are taken for example, which are shown in Fig. 6.

In time slot 8, the regions 2, 3, 6 are act as sellers, while the other regions are buyers. Because the R2R trading energy is limited by the regions' netload, with great PV energy surplus, region 2 can reach the most R2R trading energy with other regions. Besides, the optimal R2R trading energy is also determined by the resistance between regions. Taking region 5 for example, the R2R trading energies with sellers 2, 3, 6 are 914.52, 266.50, 68.82 kWh and the power losses are 0.014, 0.070, 0.108MW, respectively. The R2R energy sharing is mainly conducted between the region 2 and 5 due to the minimum network losses. With minor surplus energy in time slot 14, regions 5 and 7 conduct the R2R energy trading as the only two buyers. Consequently, the total R2R trading energy is significantly less than the energy traded in time slot 8.

2) Results of Region's Load Distribution: The optimal load distribution and netload of region 7 and region 5 are shown in Figs. 7 and 8 respectively. The result of load distribution and power flow in time slot 8 are shown in Fig. 9. It is obviously to find that, under the energy sharing mode with DR, the prosumers energy can be balanced inside the region, which leads to a great shaving of utility grid trading energy. For the proposed energy sharing with R2R and DR, the region energy can be further shared among the regions through the R2R trading, which further increase the local energy consumption.

From the perspective of region 7, the PV generation energy has surplus in all time slots. The flexible load in time slots 8–10 and 14–17 are shifted to the time slot 10–15 with low internal buying prices. Meanwhile, the surplus PV energy can also be balanced through the R2R energy in time slot 7–10 and 15–18. In time slot 8, the region 7 act as a buyer who decrease the grid side buying energy from 1513.85 kWh to 282.95 kWh through R2R trading. Besides, in time slot 14, region 7 also act as buyers in the R2R trading, who buys 19.08 kWh, 22.19 kWh, 36.60 kWh, 14.17 kWh, 16.34 kWh from region 1, 2, 3, 4, 6 respectively.

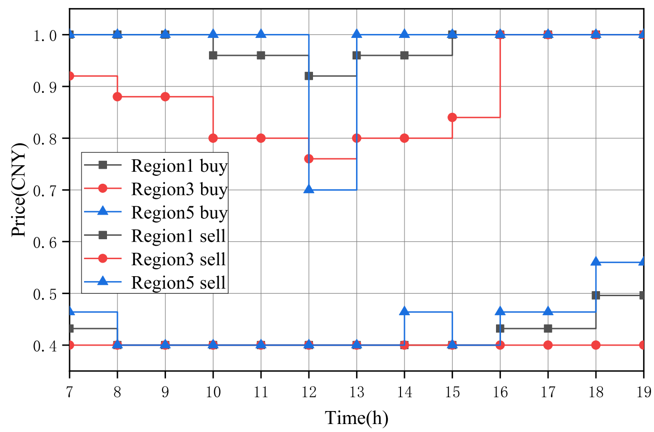


Fig. 10. Regional prices set by ESPs.

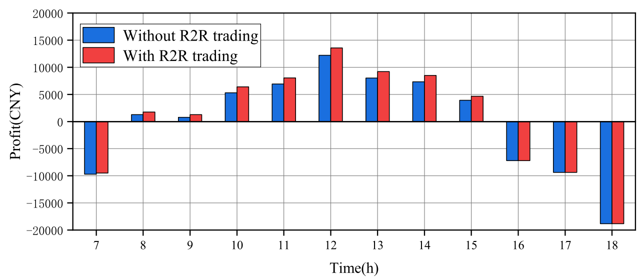


Fig. 11. Comparation results of the prosumers' profits.

Prosumers in region 5 implement the load shifting from time slot 9–11 and 13–15 to time slot 14, which increases the R2R trading energy and shaves the grid trading energy. In time slot 8, the region 5 act as a buyer who decrease the grid side buying energy from 1318.82 kWh to 177.51 kWh through R2R trading. Besides, in time slot 14, region 5 also act as buyers in the R2R trading, who buys 10.04 kWh, 46.45 kWh, 25.29 kWh, 18.23 kWh, 53.86 kWh from region 1, 2, 3, 4, 6 respectively.

3) Results of the Regional Prices and Prosumers' Profits: The regional prices for all the regions are obtained through the proposed dynamic prices mechanism. For clearly illustrating, the regional prices result for regions 1, 3, 5 are analyzed which is shown in Fig. 10. According to (17) and (18), the regional prices are determined by the R2R unbalanced energy. In time slot 10–14, prosumers are stimulated to buying more energy with the lower internal buying prices. Meanwhile, in time slots 7–8 and 16–19, prosumers are prone to reduce the load consumption for selling the surplus PV energy with higher internal selling prices, which achieving the region' peak load shifting.

In order to analyze the effectiveness of the dynamic internal prices we set for the economic improvement of prosumers, we compared the income of prosumers with or without R2R transaction, and the results are shown in Fig. 11 . According to Fig. 11, ESP's profit under R2R trading is higher than the without R2R trading mode in all periods except time slot 7. In addition, in the time slot 10–15, the prosumers gain income by selling electricity. At this time, the profit difference between prosumers with or without R2R is obviously large. Because the electricity selling price within the region is higher than the time-of-use price, the income gap is large when the prosumers sell electricity.

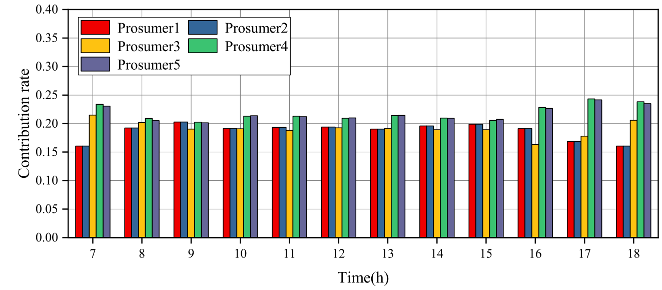


Fig. 12. Contribution rates of 5 prosumers in region 3.

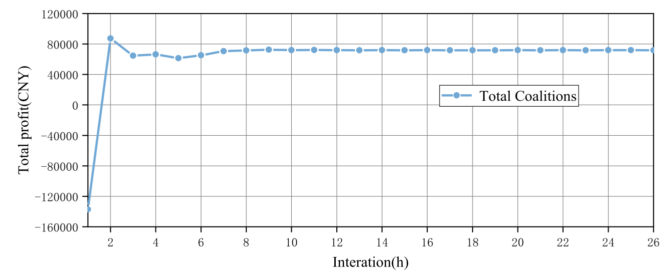


Fig. 13. Regional profit iterations convergency curve.

4) Results of the Contribution Rate: The contribution rates of 5 prosumers in region 3 are shown in Fig. 12. According to Fig. 12, each prosumer's contribution rates are uniformly distributed among 0.15–0.25 in all time slots. Prosumers 4 and 5 have higher contribution compared to other prosumers, because the roles i.e., seller) they act are consistent with the region in all the time slots. It would result in a further local energy consumption for the region 3.

D. Analysis of the Practical Realization

The distributed iterative algorithm is implemented by a computer with inter core i5-1135G7 CPU 2.40 GHz, 16 G memory, and MATLAB 2017a was used as the test environment. There are three iterations contained in the proposed algorithm. The first is the Stackelberg iteration conducted between ESP and prosumers, which will go through 40 iterations and the regional profit convergency curve is shown in Fig. 13. The second is the R2R energy sharing with 3 times of iterations. The third is the prosumers iteration process which conducted among the prosumers, the iterations number is 3. The optimization and data transmission are realized by the UEMS equipped in prosumers and the R2R energy sharing process is realized through the servers ESP equipped.

The distributed iterative algorithm proposed in this article is scalable and can be used in a distribution network with large nodes. The calculation process of the proposed method includes two parts: (i) DR between ESPs and prosumers and (ii) R2R trading. For the DR trading process, each prosumer will distributed conduct the DR process in their UEMS. The

TABLE I
CALCULATION TIME IN LARGE-SCALE APPLICATION

Number of regions	7	14	28	56	112
Calculation time (s)	28.25	56.68	113.19	278.45	550.35

calculation time will not increase with the increment of prosumers numbers because the number of UEMS will also increase with the prosumers number. Therefore, no matter how many prosumers, the calculation time of the DR process is almost 30s, which is fully enough for the energy scheduling.

For the R2R trading process, the calculation time will increase with the buyer regions number and seller regions number, where R2R trading is conducted between buyers and sellers. The computation complexity is $O[\min(n_{\text{sellers}}, n_{\text{buyers}})]$. Cause the trading process can be parallel conducted among the buyers or sellers. The calculation process for the R2R trading process is fast, as the current version of the manuscript shows, 5 seller and 2 buyer regions in time slot 14 conduct R2R require 28.25 s. We have increased the number of regions to implement the R2R, the time consumption is listed in Table I.

VII. Conclusion

In this article, we present a multi-leader and multi-followers Stackelberg game-based energy sharing framework considering for the R2R energy sharing among regions and the DR conducted by prosumers. The simulation case conducted in 33-bus test network with the realistic data reveals that prosumers incentive by the regional prices, will shift the peak load to high PV generation time slots. Meanwhile, regions' utility grid trading energy under the proposed R2R energy sharing model is reduced by 72.04% and 37.73% compared with the initial trading model and DR energy sharing model. Based on the motivation of the proposed R2R energy sharing model, more profits (e.g., 7.89kCNY) are obtained by the prosumers compared to the without R2R energy sharing. Thus, the effectiveness and economic efficiency are proved for the proposed R2R energy sharing model. The future work can be conducted in the following aspects: an energy storage combined model will be considered in the energy sharing framework, and the region will be built based on the prosumers' common interests.

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