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How to reduce the impact of distributed energy on power grid—a three-level game model with community energy transaction

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ABSTRACT

Reducing the fluctuations of distributed energy grid connection, improving power grid stability together with the effective utilization of energy, is a key issue that needs to be solved urgently in the large-scale development of renewable energy. This paper establishes a three-level game model of a distributed energy trading network, including Nash bargaining game, cooperative game and Stackelberg game, to study the energy trading mechanism between prosumers within and between energy communities. At the same time, based on the Shapley value and Core value methods via the cooperative game theory, a profit distribution model for the cooperation of multiple energy communities alliance has been established. Further, two power grid stability indicators are proposed to quantitatively measure the role of the three-level game model in improving power grid stability. Furthermore, this study uses three distributed energy communities of Jiangsu Province in China as study cases to verify the effectiveness of the three-level game model. The results show that the establishment of a three-level game model in the distributed energy trading network can not only reduce the impact of distributed energy grid connection on the grid, improve the stability of the power grid and the effective utilization of energy, but also bring economic and environmental benefits to all prosumers and the whole distributed energy system. In addition, under the profit distribution mechanism of the alliance, the participants of the alliance can obtain the greatest economic benefits, ensuring the stability of the alliance and the fairness of the income distribution.

Keywords: distributed energy, Nash bargaining game, cooperative game ,Stackelberg game, power grid stability indicators

NONMENCLATURE

Abbreviations

VRE	Variable renewable electricity
CEM	Community energy manager
AM	Alliance manager of energy communities
LCOE	Levelized cost of electricity
LCOS	Levelized cost of storage
PGC	Power grid company

Symbols

ρ_{LCOE}	levelized cost of electricity of distributed energy generation
$P_{p,i,j}(t)$	the output power of the distributed energy generation component of the prosumer j in the community i at time t
ρ_B	levelized cost of storage
$P_{dis,i,j}(t)$ $P_{cha,i,j}(t)$	the discharge and charging power of the energy storage battery of the prosumer j in the community i at time t
$\rho_{sell,i}^{cem}(t)$ $\rho_{buy,i}^{cem}(t)$	the electricity sale and purchase price of the CEM i to the prosumers in the community at time t
$P_{buy,i,j}^{u}(t)$ $P_{sell,i,j}^{u}(t)$	the power sold and purchased by the CEM i to the prosumer j in the community at time t
γ_1	the upper and lower limits of CEM electricity price changes
c	the carbon dioxide generated by 1kWh coal-fired power generation
c_0	the indirect carbon dioxide produced by distributed energy power generation components for every 1kWh output
ρ_C	the price per ton of carbon dioxide
$D_j^i(t)$	the power load of the prosumer j in the community i at time t
$P_{bat,i,j}(t)$	the energy storage battery power of the prosumer j in the community i at time t
n_i	the number of prosumers in the community i
m	the number of energy communities, CEMs
$P_{bat,i,j}^{rated}$	the rated maximum power of the energy storage battery of the prosumer j in the community i
$\varepsilon_1(t),\ \varepsilon_2(t)$	0-1 variables of energy storage battery operation state
δ	0-1 variable of distributed energy system operation state
$\theta_{cs,i}(t)$ $\theta_{cb,i}(t)$	the price coefficient of electricity sales and electricity purchase of CEM i at time t
$\rho_{gs}(t)$ $\rho_{gb}(t)$	the price of electricity sold by the PGC and the distributed energy feed-in tariff at time t
$\rho_{sell,i}^{am}(t), \rho_{buy,i}^{am}(t)$	the selling and purchase price of electricity from AM to the CEM i
γ_2	the upper and lower limits of AM electricity price changes
$P_{buy,i}^{cem}(t), P_{sell,i}^{cem}(t)$	the power purchased and sold by the CEM i from AM at time t
$\theta_{s,i}(t)$ $\theta_{b,i}(t)$	the power sale price coefficient and power purchase price coefficient of AM to CEM i at time t
$\rho_{gs,am}(t)$, $\rho_{gb,am}(t)$	the selling and purchase price of electricity from PGC to AM at time t
$P_{buy}^{am}(t), P_{sell}^{am}(t)$	the power purchased and sold by the AM to PGC at time t
γ_3	the upper and lower limits of power price changes for PGC
$\theta_{s,am}(t)$ $\theta_{b,am}(t)$	the price coefficient of power sales and distributed energy on grid of PGC for AM

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1. INTRODUCTION

As the world's largest energy consumer, China is committed to adopting more effective policies and measures to achieve carbon neutrality by 2060 [1]. Relevant research has recently proved that it is feasible to vigorously develop renewable energy solutions to alleviate environmental problems such as climate change [2].However, the natural characteristics of random fluctuations concerning solar and wind energy bring uncertainty to the load and power generation side of the power grid[3]. Hence, with the rapid development of distributed renewable energy, the volatility brought to the power grid is increasing whereas the power grid stability is getting extremely worse with increasing.

Many researches have been analyzed from an economic point of view. Considering the integration cost of variable renewable electricity(VRE) in power sector planning, as the optimal share of wind and photovoltaic power generation significantly decreases, the social welfare effect generated by VRE will become smaller or even negative [4][5]. Moreover, from the perspective of energy trading, a two-level game optimization scheduling model for an industrial park distributed energy system is proposed based on Stackelberg game and cooperative game[6]. However, the existing literature seldom considers energy transactions between distributed energy systems in communities, and quantitatively measures the impact of distributed energy grid connection on grid stability.

In order to solve the above problems, this paper establishes a three-level game model of a distributed energy trading network to research the energy trade between prosumers within and between energy communities. The main contributions of this article are as follows:

(1) A three-level game optimization model of distributed energy trading network is established to reduce the impact of distributed energy grid connection on the grid and improve the stability of the power grid.

(2) From the perspective of energy trading, two indicators are proposed to quantitatively measure the stability of the power grid.

(3) From the perspective of life cycle, the indirect carbon dioxide emission cost of distributed energy equipment and the environmental benefits of distributed energy power generation are considered.

2. THREE LAYER GAME FRAMEWORK AND POWER GRID STABILITY INDICATORS

This article assumes that all prosumers in the distributed energy system have installed distributed energy-energy storage power devices. The output power of the prosumers the distributed energy power generation system first meets its own power needs. The energy storage battery is then charged according to the charging state of the energy storage battery. The remaining power is finally sold to the community energy manager (CEM). Moreover, in order to reduce the computational complexity, the following assumption is made.

Hypothesis: the capacity will not affect the levelized cost of the distributed energy systems and energy storage batteries.

2.1 Three-level game model framework

2.1.1 Nash bargaining game framework

The bottom game of the three-level game is a cooperative game based on Nash bargaining theory between all prosumers in the community and their corresponding CEM[7]. The Nash bargaining game structure is shown in Fig. 1. The CEM can adjust its electricity sales and purchase prices. All prosumers in the community adjust the purchase and sale of electricity with CEM according to the price set by CEM.

2.1.2 Cooperative game framework

The cooperative game is conducted among all CEMs in adjacent areas. CEM is equipped with micro-grid and other infrastructure, which can conduct electricity transactions between different CEM. The specific structure is shown in Fig. 1. The basic assumptions are as follows:

(1) CEM in neighboring regions have the purpose of forming alliances.

(2) There will be no discounts or incentives for the electricity sales price and the distributed energy grid-connected price of the grid company if CEM does not participate in the alliance.

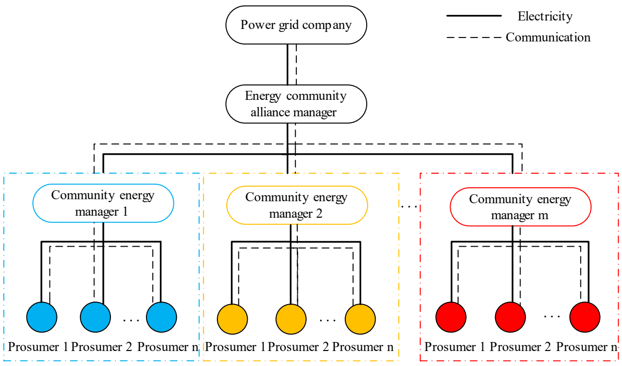
(3)The PGC will only give preferential treatment and rewards to the alliance in terms of price of electricity sales and price of distributed energy grid-connected connection if CEM participates in the alliance.

(4) The prosumers in the alliance can take the carbon emissions reduced by distributed energy system power generation to participate in the carbon trading market in adjacent areas, and the income obtained is regarded as part of the income of the prosumers.

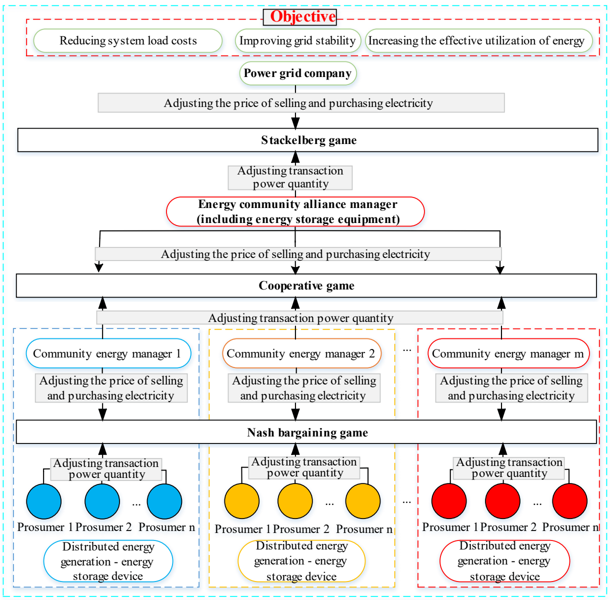
Based on cooperative game, CEM conducts electricity trading between different energy communities to balance the power supply and demand of all prosumers. When CEM's own power is insufficient, it first purchases power from other CEMs in the alliance. Further, when other CEMs cannot meet the power demand, the CEM then purchases power from the PGC through alliance manager of energy communities(AM). On the contrary, after the internal energy transaction of CEM in the alliance, if CEM still has surplus, the surplus is sold to the PGC through AM.

2.1.3 Stackelberg game framework

The top-level Stackelberg game is played between AM and PGC, where PGC is the dominant party and AM is the game follower. The Stackelberg game structure is shown in Fig. 1. The PGC can adjust the price of power transactions with AM. The AM adjusts its electricity trading volume with PGC according to the electricity transaction price of PGC. Electricity trading between energy communities under the management of AM can reduce the peak load and improve the stability of power grid. Therefore, the PGC will give the AM power purchase and distributed energy feed-in tariff concessions and rewards. At this time, the operation cost of AM is minimized.



(a) Energy transmission and information exchange of system



(b) Components and integration layout of system

Fig. 1. Three layer game model framework

2.2 Power grid stability indicators

In order to quantitatively measure the role concerning the three-level game optimization model in reducing power grid fluctuations, two power grid stability indicators, average value indicator AVE_w and variance indicator $S_{vol,w}$,are proposed. First, three scenarios and an assumption are defined, of which scenario 1 is used as the reference scenario. All the scenarios are explained as follows:

Scenario 1:all prosumers conduct energy transactions directly with the PGC.

Scenario 2: CEM will conduct energy transactions with the PGC after the prosumers in the community have conducted energy transactions with CEM.

Scenario 3: establish a three-level game model of distributed energy-trading network.

Hypothesis: under the three scenarios, the distributed energy generation equipment of all prosumers generates the same electricity at time t.

$S_w(t)$ represents the ratio of the distributed energy grid connected power to the power generation in the distributed energy system at time t under scenario w, as shown in Eq. (1),where $P_w(t)$ denotes the distributed energy on grid power of the distributed energy system at time t under scenario w, $P_e(t)$ represents the power generation of the distributed energy system at time t, where $P_e(t)$ ≥0. By definition, the smaller $S_w(t)$ is, it mean means that the smaller the power of distributed energy grid connection at time t under the scenario w.

From Eq. (2),AVE_w is the average value of $S_w(t)$ in the time period from 0 to T, representing the average on grid power of distributed energy system at each time under scenario w. From Eq. (3) , $S_{ave,w}$ indicates the expected power of distributed energy grid connection of the whole energy system under scenario w. Because the less the power of distributed energy grid connection, the smaller the fluctuation caused to the power grid and the better the stability of the power grid, the expected power of distributed energy grid connection under the three scenarios is set as 0 kWh.

Notably, the variance of data can reflect the stability of data and quantitatively describe the deviation between data and expectation. From Eq.(4), $S_{vol,w}$ represents the variance between the distributed energy on grid power $S_w(t)$ and the expected power $S_{ave,w}$ of the distributed energy system in the time from 0 to T under scenario w. Hence, the smaller AVE_w and $S_{vol,w}$ means that the smaller the fluctuation caused by distributed energy on the power grid, the more stable the power grid is. Mathematically, $S_w(t)$ together with AVE_w and $S_{vol,w}$ are correspondingly formulated as:

$$S_w(t) = \begin{cases} \frac{P_w(t)}{P_e(t)} & ,if\ P_e(t) > 0, w = 1,2,3 \\ 0, if\ P_e(t) = 0 & \end{cases} \quad (1)$$

$$AVE_w = \frac{1}{T}\sum_{t=1}^{T} S_w(t) \quad ,w = 1,2,3 \quad (2)$$

$$S_{ave,w} = 0, w = 1,2,3 \quad (3)$$

$$S_{vol,w} = \frac{1}{T}\sum_{t=1}^{T}\left(S_w(t) - S_{ave,w}\right)^2, w = 1,2,3 \quad (4)$$

3. THREE LAYER GAME MODEL OF DISTRIBUTED PHOTOVOLTAIC ENERGY TRADING NETWORK

Concerning the energy optimization of the three-level game model of distributed energy trading network, the 24 hour time of a day is divided into 24 segments, taking $t = \{1,2,\ldots,T\}$, where $T = 24$.

3.1 Nash bargaining game between CEMs and prosumers

3.1.1 Income analysis of prosumer

The cost of prosumer j in the community i in the 0-T period is calculated as follows:

$$Cost_{i,j}^{u} = \sum_{t=1}^{T}(C_{i,j}^{u}(t) - R_{i,j}^{u}(t)) \quad (5)$$

where $C_{i,j}^{u}(t)$ and $R_{i,j}^{u}(t)$ respectively represent the expenditure and income of the prosumer j in the community i at time t. Mathematically $C_{i,j}^{u}(t)$ is computed using the relation:

$$C_{i,j}^{u}(t) = \rho_{LCOE}P_{p,i,j}(t) + \rho_{B}\left[|P_{dis,i,j}(t)| + P_{cha,i,j}(t)\right] + \rho_{sell,i}^{cem}(t)P_{buy,i,j}^{u}(t) \quad (6)$$

From Eq. (6),the first part is the distributed energy module power generation cost of the prosumer j in community i at time t; the second part is the charge and discharge cost of the energy storage battery at time t; and the third part is the electricity purchase cost of the prosumer j in CEM i at time t. On the other hand, $R_{i,j}^{u}(t)$ is also estimated using the formula:

$$R_{i,j}^{u}(t) = \rho_{buy,i}^{cem}(t)P_{sell,i,j}^{u}(\mathrm{t}) + MP_{p,i,j}(t) \quad (7)$$

$$M = (c - c_0)\rho_c \quad (8)$$

Also from Eq. (7),the first part represents electricity sales revenue of prosumer j whereas the second part is the environmental benefits per 1kWh generated by the distributed energy power generation system of the prosumers. Considering the supply-demand balance of prosumers together with the upper and lower limits of power, there are constraints (9)-(13) in $\forall t \in \{1,2,\ldots,T\}, \forall i \in \{1,2,\ldots,m\}, \forall j \in \{1,2,\ldots,n_i\}$expressed respectively as:

$$D_j^i(t) + P_{bat,i,j}(t) = P_{p,i,j}(t) + P_{buy,i,j}^{u}(t) + P_{sell,i,j}^{u}(\mathrm{t}) \quad (9)$$

$$P_{bat,i,j}(t) = \varepsilon_1(\mathrm{t})P_{cha}(t) + \varepsilon_2(t)P_{dis}(t) \quad (10)$$

$$P_{p\_min,i,j}(t) \le P_{p,i,j}(t) \le P_{p\_max,i,j}(t) \quad (11)$$

$$P_{buy\_min,i,j}^{u}(t) \le P_{buy,i,j}^{u}(t) \le P_{buy\_max,i,j}^{u}(t) \quad (12)$$

$$P_{sell\_min,i,j}^{u}(\mathrm{t}) \le P_{sell,i,j}^{u}(\mathrm{t}) \le P_{sell\_max,i,j}^{u}(\mathrm{t}) \quad (13)$$

The electricity sales and purchase prices of CEM are calculated according to Eq.(14)-(17). When the distributed energy generation system is running, setting $\delta = 1$, otherwise $\delta = 0$.

$$\rho_{sell,i}^{cem}(\mathrm{t}) = \rho_{gs}(t) - \left(1 - \theta_{cs,i}(t)\right)\left|\rho_{gs}(t) - \rho_{gb}(t)\right| \quad (14)$$

$$\rho_{buy,i}^{cem}(t) = \rho_{gb}(t) + \left(1 - \theta_{cb,i}(t)\right)\left|\rho_{gs}(t) - \rho_{gb}(t)\right| \quad (15)$$

$$\theta_{cs,i}(t) = \frac{\sum_{j=1}^{n_i} P_{buy,i,j}^{u}(\mathrm{t})}{\sum_{j=1}^{n_i}\left(D_j^i(t) + P_{bat,i,j}^{rated}\right)} \quad (16)$$

$$\theta_{cb,i}(t) = \begin{cases} \delta \cdot \frac{\sum_{j=1}^{n_i} P_{sell,i,j}^{u}(\mathrm{t})}{\sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated})} + (1-\delta), \sum_{j=1}^{n_i} P_{sell,i,j}^{u}(\mathrm{t}) \le \sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated}) \\ \delta \cdot \frac{\sum_{j=1}^{n_i} P_{sell,i,j}^{u}(\mathrm{t})}{\sum_{j=1}^{n_i} P_{p,i,j}(t)} + (1-\delta), \sum_{j=1}^{n_i} P_{sell,i,j}^{u}(\mathrm{t}) > \sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated}) \end{cases} \quad (17)$$

Considering the CEM income and the stability of the power market, the restrictions are as follows (18)-(19).

$$0 \le \theta_{cs,i}(t) \le 1, 0 \le \theta_{cb,i}(t) \le 1 \quad (18)$$

$$0 \le \frac{|\rho_{sell,i}^{cem}(\mathrm{t}) - \rho_{gs}(t)|}{\rho_{gs}(t)} \le \gamma_1, 0 \le \frac{|\rho_{buy,i}^{cem}(t) - \rho_{gb}(t)|}{\rho_{gb}(t)} \le \gamma_1 \quad (19)$$

Therefore, the objective function is to minimize the power load cost of all prosumers of the community energy system:

$$\min F_{user} = \sum_{i=1}^{m}\sum_{j=1}^{n_i} Cost_{i,j}^{u} \quad (20)$$

In $\forall t \in \{1,2,\ldots,T\}, \forall i \in \{1,2,\ldots,m\}, \forall j \in \{1,2,\ldots,n_i\}$, all meet the operation constraints of energy storage battery[8] and (9)- (19).

3.1.2 Nash bargaining game model

The electricity trading price of CEM and the electricity trading quantity of prosumers at time t are determined. Suppose $\{\rho_{sell}^{cem*}, \rho_{buy}^{cem*}, P_{buy}^{u*}, P_{sell}^{u*}\}$ is the equilibrium solution obtained, which minimizes the power load cost of all prosumers of the community energy system, then the condition (21) is satisfied:

$$F_{user}\{\rho_{sell}^{cem*}(t), \rho_{buy}^{cem*}(t), P_{buy}^{u*}(t), P_{sell}^{u*}(t)\} \le F_{user}\{\rho_{sell}^{cem}(t), \rho_{buy}^{cem}(t), P_{buy}^{u*}(t), P_{sell}^{u*}(t)\} \quad (21)$$

3.2 Cooperative game between CEMs

3.2.1 CEM revenue analysis

The revenue calculation of AM in 0-T is shown in Eq.(22), where $R_i^{cem}(t)$ and $C_i^{cem}(t)$ are the income and expenditure of the CEM i at time t respectively.

$$Cost_i^{cem} = \sum_{t=1}^{T}\left(R_i^{cem}(t) - C_i^{cem}(t)\right) \quad (22)$$

Specifically, $R_i^{cem}(t)$ is expressed as:

$$R_i^{cem}(t) = \rho_{buy,i}^{am}(t)P_{sell,i}^{cem}(t) + \sum_{j=1}^{n_i}\rho_{sell,i}^{cem}(t)P_{buy,i,j}^{u}(t) \quad (23)$$

The first part of Eq. (23) denotes the electricity sales revenue from CEM i to AM at time t whereas the second part is the electricity sales revenue from CEM i to all prosumers in the community i at time t. In addition, $C_i^{cem}(t)$ can be obtained as formula:

$$C_i^{cem}(t) = \rho_{sell,i}^{am}(t)P_{buy,i}^{cem}(t) + \sum_{j=1}^{n_i}\rho_{buy,i}^{cem}(t)P_{sell,i,j}^{u}(t) \quad (24)$$

From Eq. (24), the first part is the electricity purchase expenditure from CEM i to AM at time t; while the second part is the electricity purchase expenditure from CEM i to all prosumers in the community i at time t.

Similarly, the formula and constraint conditions of power price coefficient of AM can be obtained, as shown in Eq. (25)-(26) and (29).

$$\theta_{s,i}(t) = \frac{P_{buy,i}^{cem}(\mathrm{t})}{\sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated})} \quad (25)$$

$$\theta_{b,i}(t) = \begin{cases} \delta \cdot \frac{P_{sell,i}^{cem}(\mathrm{t})}{\sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated})} + (1-\delta), P_{sell,i}^{cem}(\mathrm{t}) \le \sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated}) \\ \delta \cdot \frac{P_{sell,i}^{cem}(\mathrm{t})}{\sum_{j=1}^{n_i} P_{p,i,j}(t)} + (1-\delta), P_{sell,i}^{cem}(\mathrm{t}) > \sum_{j=1}^{n_i}(D_j^i(t) + P_{bat,i,j}^{rated}) \end{cases} \quad (26)$$

At this time, the calculation formulas and constraints of AM on CEM's power sales price $\rho_{sell,i}^{am}(t)$ and power purchase price $\rho_{buy,i}^{am}(t)$ are Eq. (27)-(28) and (29).

$$\rho_{sell,i}^{am}(t) = \rho_{gs}(t) - \left(1 - \theta_{s,i}(t)\right)\left|\rho_{gs}(t) - \rho_{gb}(t)\right| \quad (27)$$

$$\rho_{buy,i}^{am}(t)=\rho_{gb}(t)+\Big(1-\theta_{b,i}(t)\Big)\left|\rho_{gs}(t)-\rho_{gb}(t)\right| \quad (28)$$

$$\begin{cases} 0\le\theta_{s,i}(t)\le 1, 0\le\theta_{b,i}(t)\le 1 \\ 0\le\frac{\left|\rho_{sell,i}^{am}(t)-\rho_{gs}(t)\right|}{\rho_{gs}(t)}\le\gamma_2, 0\le\frac{\left|\rho_{buy,i}^{am}(t)-\rho_{gb}(t)\right|}{\rho_{gb}(t)}\le\gamma_2 \end{cases} \quad (29)$$

Taking into account the upper and lower limits of power of CEM i, as shown in Eq. (30).

$$\begin{cases} P_{buy\_min,i}^{cem}(\mathrm{t})\le P_{buy,i}^{cem}(\mathrm{t})\le P_{buy\_max,i}^{cem}(\mathrm{t}) \\ P_{sell\_min,i}^{cem}(\mathrm{t})\le P_{sell,i}^{cem}(\mathrm{t})\le P_{sell\_max,i}^{cem}(\mathrm{t}) \end{cases} \quad (30)$$

Therefore, the objective function is to maximize the sum of the benefits of all CEMs of the energy system:

$$\max F_{cem}=\sum_{i=1}^{m} Cost_i^{cem} \quad (31)$$

In $\forall t\in\{1,2,\dots,T\},\forall i\in\{1,2,\dots,m\},\forall j\in\{1,2,\dots,n_i\}$, all meet the operation constraints of system Eq. (25)-(30).

3.2.2 Profit distribution model of alliance

Suppose the system has three CEMs, which are composed of cooperative game $G=<N,v>$,collection of participants $N=\{CEM1,CEM2,CEM3\}$, abbreviated as $N=\{1,2,3\}$. S represents the alliance, $S\subset N$, and the characteristic function $v(S)$ represents the daily cost reduced by forming an alliance. The vector $X=\{x_1,x_2,x_3\}$ represents the result of the cooperative game of income distribution. The basic assumption of alliance establishment is that CEM is a rational participant in the cooperative game, who will choose to participate in the alliance that can maximize its own benefits.

Regardless of the empty set, three participants can form seven sets, {1}, {2}, {3}, {1,2}, {1,3}, {2,3}, {1,2,3}. For the income distribution of the alliance, it should not only consider the stability of the alliance, but also consider the fairness of income distribution. Therefore, applying Core value and Shapley value method to distribute the income of the cooperative alliance [9].

3.3 Stackelberg game between PGC and AM

3.3.1 AM revenue analysis

The AM income in the 0-T time is calculated as follows Eq.(32), where $C^{am}(t)$ and $R^{am}(t)$ are the income and expenditure of the AM at time t respectively. Thus the relationship amid the AM income and $C^{am}(t)$ are expressed as:

$$Cost^{am}=\sum_{t=1}^{T}\left(C^{am}(t)-R^{am}(t)\right) \quad (32)$$

$$C^{am}(t)=\rho_{gs,am}(t)P_{buy}^{am}(t)+\sum_{i=1}^{m}\rho_{buy,i}^{am}(t)P_{sell,i}^{cem}(t) \quad (33)$$

From Eq. (33), the power purchase expenditure from the AM to the PGC at time t; while the second part is signifies the power purchase expenditure from the AM to all CEMs at time t. Moreover, $R^{am}(t)$is computed using the relation:

$$R^{am}(t)=\rho_{gb,am}(t)P_{sell}^{am}(t)+\sum_{i=1}^{m}\rho_{sell,i}^{am}(t)P_{buy,i}^{cem}(t) \quad (34)$$

Also in the case of Eq.(34), the first part is the power sales revenue from the AM to the PGC at time t whereas the second part is the power sales revenue from AM to all CEMs at time t. The sales price and purchase price of electricity from PGC to AM are calculated as Eq.(35)-(38).

$$\rho_{gs,am}(t)=\rho_{gs}(t)-\Big(1-\theta_{s,am}(t)\Big)\left|\rho_{gs}(t)-\rho_{gb}(t)\right| \quad (35)$$

$$\rho_{gb,am}(t)=\rho_{gb}(t)+\Big(1-\theta_{b,am}(t)\Big)\left|\rho_{gs}(t)-\rho_{gb}(t)\right| \quad (36)$$

$$\theta_{s,am}(t)=\frac{P_{buy}^{am}(\mathrm{t})}{\sum_{i=1}^{m}\sum_{j=1}^{n_i}(D_j^i(t)+P_{bat,i,j}^{rated})} \quad (37)$$

$$\theta_{b,am}(t)=\begin{cases} \delta\cdot\frac{P_{sell}^{am}(\mathrm{t})}{\sum_{i=1}^{m}\sum_{j=1}^{n_i}(D_j^i(t)+P_{bat,i,j}^{rated})}+(1-\delta), P_{sell}^{am}(\mathrm{t})\le\sum_{i=1}^{m}\sum_{j=1}^{n_i}(D_j^i(t)+P_{bat,i,j}^{rated}) \\ \delta\cdot\frac{P_{sell}^{am}(\mathrm{t})}{\sum_{i=1}^{m}\sum_{j=1}^{n_i}P_{p,i,j}(t)}+(1-\delta), P_{sell}^{am}(\mathrm{t})>\sum_{i=1}^{m}\sum_{j=1}^{n_i}(D_j^i(t)+P_{bat,i,j}^{rated}) \end{cases} \quad (38)$$

Similarly ,the constraints are as follows(39)-(40):

$$\begin{cases} 0\le\frac{\left|\rho_{gs,am}(t)-\rho_{gs}(t)\right|}{\rho_{gs}(t)}\le\gamma_3, 0\le\frac{\left|\rho_{gb,am}(t)-\rho_{gb}(t)\right|}{\rho_{gb}(t)}\le\gamma_3 \\ 0\le\theta_{s,am}(t)\le 1, 0\le\theta_{b,am}(t)\le 1 \end{cases} \quad (39)$$

$$\begin{cases} P_{buy\_min}^{am}(\mathrm{t})\le P_{buy}^{am}(\mathrm{t})\le P_{buy\_max}^{am}(\mathrm{t}) \\ P_{sell\_min}^{am}(\mathrm{t})\le P_{sell}^{am}(\mathrm{t})\le P_{sell\_max}^{am}(\mathrm{t}) \end{cases} \quad (40)$$

Therefore, the objective function of the AM is to minimize the operation of the alliance:

$$\min Cost^{am} \quad (41)$$

In $\forall t\in\{1,2,\dots,T\},\forall i\in\{1,2,\dots,m\},\forall j\in\{1,2,\dots,n_i\}$, all meet the operation constraints of system Eq. (35)-(40).

3.3.2 Stackelberg game model

The PGC can adjust the electricity transaction price with AM to $\{\rho_{gs,am}(t),\rho_{gb,am}(t)\}$,while AM adjusts its trading electricity with the PGC to $\{P_{buy}^{am}(t),P_{sell}^{am}(\mathrm{t})\}$. $\{\rho_{gs,am}(t)^*,\rho_{gb,am}(t)^*,P_{buy}^{am}(t)^*,P_{sell}^{am}(\mathrm{t})^*\}$ is the obtained equilibrium solution, then the condition (42) is satisfied:

$$Cost^{am}\{\rho_{gs,am}(t)^*,\rho_{gb,am}(t)^*,P_{buy}^{am}(t)^*,P_{sell}^{am}(\mathrm{t})^*\}\le Cost^{am}\{\rho_{gs,am}(t),\rho_{gb,am}(t),P_{buy}^{am}(t)^*,P_{sell}^{am}(\mathrm{t})^*\} \quad (42)$$

4. CASE ANALYSIS

Numerical simulation is to conducted to verify the effectiveness of the three-level game model. The actual case is composed of three distributed energy communities in Jiangsu Province, China. The three energy communities are composed of six prosumers, three CEMs. All prosumers have installed wind power-photovoltaic power-energy storage devices.

4.1 Optimization results of three-level game model

Firstly, considering the stability of the alliance, the Core value method is used to solve the core set of the stable alliance. Secondly, considering the fairness of income distribution, Shapely value method is applied to the set of stable alliances. The final alliance to be solved is the set {1,2,3}. Under this distribution mechanism, the alliance {1,2,3} income of CEM1, CEM2 and CEM3 are 35.0104%(2590.7479 ¥),39.0883%(2892.5113 ¥) and 25.9013%(1916.6796¥) respectively.

The economic, environmental benefits and total power transaction volume under different alliances are compared, as shown in Fig.2. Compared with the independent operation of each CEM, the total cost, total electricity trading volume, carbon dioxide emission and total distributed energy grid connected of major alliance have been reduced by 16.9611%,49.5640 %,46.2234%

and 53.2011 % respectively.

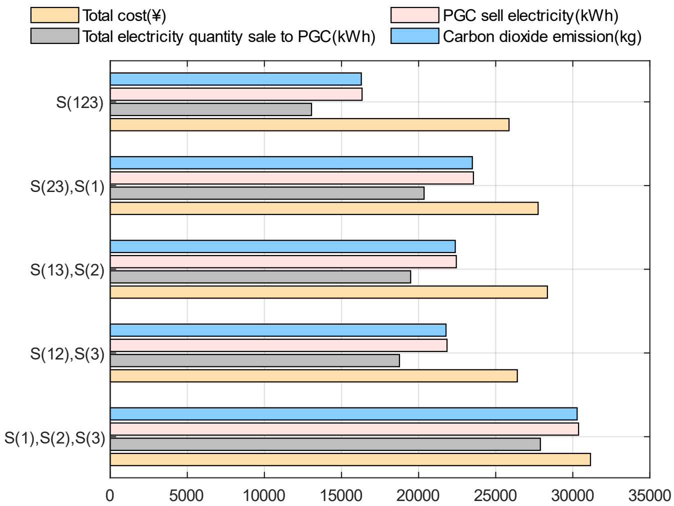


Fig.2. Performances of distributed energy network system under each alliance

4.2 Power grid stability analysis

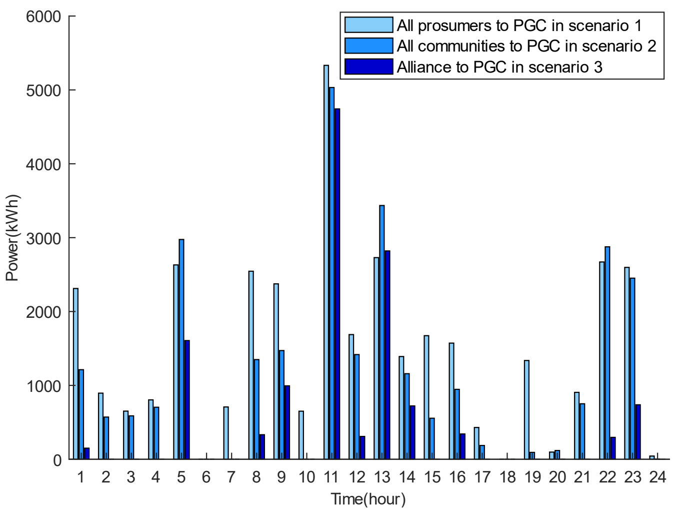


Fig.3. Electricity sales to PGC under three scenarios

Scenario 1, scenario 2 and scenario 3 are defined in Section 2.2. Results from the electricity sales to PGC under three scenarios are illustrated in Fig.3. The stability indicators of power grid under three scenarios are calculated by formulas (1)-(4) in Section 2.2, where $(AVE_1, AVE_2, AVE_3) = (0.2574, 0.1911, 0.0667)$ and $(S_{vol,1}, S_{vol,2}, S_{vol,3}) = (0.0902, 0.0681, 0.0166)$. Obviously, the grid stability indicators of scenario 3 is the smallest. Hence, scenario 3 has the best power grid stability.

5. CONCLUSION

In general, this paper proposes a three-level game model of distributed energy trading network from the perspective of economy and power grid stability. On the other hand, from the perspective of energy trading, two power grid stability indicators that include mean and variance indicators are proposed. Moreover, taking three distributed energy communities in Jiangsu Province of China as an example, the following conclusions are drawn:

(1) Compared with the independent operation of each CEM, the total cost, total electricity trading volume, carbon dioxide emission and total distributed energy grid connected of system have been reduced by 16.9611 %, 49.5640 %, 46.2234% and 53.2011 % respectively in the three-level game model. Consequently, the three-level game model can not only improve energy utilization efficiency and bring economic benefits to prosumers and energy system, but also produce environmental benefits.

(2) The mean and variance indicators under the three-level game model scenario are 0.0667 and 0.0166 , which is much better than others scenarios. Thus, the three-level game model can effectively improve power grid stability.

(3) Under the alliance's income distribution mechanism, CEM1, CEM2 and CEM3 have the largest proportions of alliance income being 35.0104%, 39.0883% and 25.9013% respectively. Hence, the income distribution model can ensure the stability and fairness of the alliance.

Further research in the future can build an model from the perspective of user-side real-time demand response base on three-level game model.

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