Received 6 October 2022, accepted 21 October 2022, date of publication 26 October 2022, date of current version 4 November 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3217540

RESEARCH ARTICLE

A Prosumer-Based Energy Sharing Mechanism of Active Distribution Network Considering Household Energy Storage

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This work was supported by the Science and Technology Project of State Grid Hebei Electric Power Company Ltd., under Grant kj2021-061.

ABSTRACT The proliferation of distributed renewable energy and the extensive use of household energy storage have gradually transformed the users of active distribution network (ADN) from traditional consumers to prosumers. The flexible resources of prosumers on the demand side need a suitable trading mechanism to realize the optimal allocation of resources. Unlike the traditional electricity market with high entry threshold, this paper proposed an energy sharing mechanism based on prosumers with household energy storage devices. Firstly, taking into account the charge and discharge utility of household energy storage equipment as well as the production and consumption utility of prosumers, a transaction decision model of prosumers is established. Then, based on the centralized social welfare maximization energy sharing problem, a distributed energy sharing mechanism of ADN is constructed through alternating direction method of multipliers (ADMM) algorithm. Finally, an illustrative example of two prosumers and a prosumer network of the ADN with 10 nodes are calculated and analyzed respectively. The results show that the proposed energy sharing mechanism can maximize social welfare and improve the local accommodation degree of renewable energy from 84.85% to 85.27%. The social welfare increases with the growth of the number of prosumers with household energy storage.

INDEX TERMS Energy sharing, active distribution network, alternating direction method of multipliers, household energy storage, prosumer.

I. INTRODUCTION

Active distribution network (ADN) is a control system containing a series of distributed resources such as controllable power generation, energy storage devices, flexible loads, and electric vehicles [1]. It can maintain the stable operation of distribution network by actively participating in the regulation process using the distributed resources above according to the current status of the system. The construction and development of ADN have led to a large number of distributed power generation devices being continuously connected to the distribution network [2]. Rooftop photovoltaic [3], [4] and small wind turbines [2] are the most prevalent ones. However, on the one hand, the random and intermittent nature of distributed renewable energy generation devices may cause serious abandonment of wind and photovoltaic power. On the other hand, distributed renewable energy generation can also bring problems such as reverse power and network congestion. Some countries have introduced relevant policies to allow the grid to charge for PV feed-in power in case of network congestion [5]. In such a circumstance, there is an increasing demand for energy storage devices, especially for household energy storage.

The associate editor coordinating the review of this manuscript and approving it for publication was Chandan Kumar.

The distributed generation devices endow the user with the function of producing electricity. The role of users changes from unilateral energy consumer to prosumer who can interact with the grid in both directions [6]. The participation of household energy storage makes the production and consumption behavior of the prosumer more flexible and controllable. The quadratic coordination framework of ''source-grid-load-storage'' can be formed between prosumers to jointly promote the flexible and stable operation of the ADN. However, without a suitable market transaction mechanism, it is difficult to fully utilize the distributed flexible resources.

Some scholars have studied the centralized trading mechanism in ADN. A trading model of distribution network was established based on Stackelberg game in [7] and [8]. An optimal model for trading between distribution network operator (DNO) and microgrids was constructed according to the game relationship among them. In [9], the security constraints were considered while establishing the market clearing model of ADN, which included microgrids operating in silos. However, on the one hand, the optimization results are difficult to realize the optimal allocation due to the limitations of various constraints and the trading mechanism [10]. On the other hand, the centralized trading mechanism involves the problem of users' privacy. Obtaining all electricity consumption-related information of users is difficult.

The energy sharing mechanism draws on the concept of sharing economy [11], [12]. Unlike traditional trading mechanisms such as electricity wholesale market, it allows idle electricity to be reallocated by ceding the right to use to achieve optimal allocation of resources [10]. At the same time, the threshold of market participation is lowered. Individual users can directly participate in the shared transactions. An auction-based sharing mechanism between shared facility controllers and residential units in a large building was proposed in [13]. In [14], EV users were divided into buyers and sellers. The corresponding sharing and incentive mechanisms were designed. The pricing and subsidy mechanisms for encouraging resource sharing between resource owners and renters were designed in [15]. Constructing sharing mechanism by distinguishing users into buyers and sellers restricts the role of prosumers in trading process. This relatively raises the threshold for users to participate in sharing. The flexibility of transactions is reduced as well, which makes it difficult to fully utilize the resources.

Some of the studies set the roles of all prosumers in the sharing market as symmetric. In [16], a Stackelberg game model among microgrid operator (MGO) and prosumers was established. Electricity was traded among MGO and prosumers who had the same utility function. The P2P mode was also used in the energy sharing mechanism. A multi-stakeholder trading framework including the prosumer agent was proposed in [17]. The market clearing price was determined by the Energy Sharing Coordinator Agent (CA). A two-stage control model was further developed in [18]. In the above studies, the prices of energy sharing are decided entirely through agents, which raises the transaction cost. The influence of individual prosumers on prices is also ignored. In [19], an energy-sharing mechanism for prosumers was established based on a generic supply and demand function, which was proved to achieve a Pareto improvement. However, the energy-sharing mechanism in [19] can only converge to social welfare maximization when the number of prosumers is large [20], that is, it cannot achieve social optimum.

Based on the above analysis of existing research, this paper establishes an energy sharing mechanism of ADN based on prosumers considering household energy storage. The distributed market clearing is realized without a trading center for users with energy production capacity and energy storage equipment in ADN. The social welfare maximization is achieved based ADMM algorithm. We also analyzed the effect of increasing social welfare and promoting the use of renewable energy of the proposed mechanism. The main contributions of this paper are as follows:

1) The energy sharing mechanism proposed in this paper is a decentralized distributed trading mechanism, in which users in ADN participate in the market as prosumers without the supervision of a third party. The distributed clearing of the energy market is achieved automatically with low cost. Prosumers can share their excess electricity with each other and temporarily gain access to production capacity. After participating in energy sharing, social welfare increases and flexible resources are optimally allocated.

2) This paper takes into account the participation of prosumers who own household energy storage in the energy sharing market. The economic analysis of the utility of energy storage devices is analyzed and depicted with a charging and discharging utility model. The influence of the number of prosumers with energy storage on social welfare is also analyzed.

3) The centralized social welfare maximization problem is analyzed first. It is decomposed into sub-problems and tackled with ADMM algorithm. Different from existing research, which can only converge to social welfare maximization under certain conditions, the result of our distributed solution is the same as centralized solution, that is, the social optimal can be achieved.

4) The privacy of prosumers is well protected in the proposed trading mechanism. Prosumers in ADN only need to upload their private information of electricity use and production to their smart meters. The distributed solving process is completed locally.

The rest of this paper is organized as follows. A trading decision model of prosumer including a utility model for energy storage devices is established in Section II. A centralized transaction model aiming at maximizing social welfare is established first in Section III and the energy sharing mechanism is constructed based on ADMM algorithm. A two-prosumer example is analyzed in Section IV. A case with ten prosumers is studied in Section V. Conclusions are summarized in Section VI.

II. TRADING DECISION MODEL OF PROSUMERS

In the energy sharing mechanism designed in this paper, the energy sharing transactions only happen among prosumers. Normal users who only consume electricity do not participate in energy sharing. Therefore, in this paper, we only consider the set of prosumers $\mathcal{P} = \{1, 2, \ldots, N\}$. For each prosumer $i \in \mathcal{P}$, it has distributed generation devices. To simplify the problem, the generation capacity of prosumers with two or more distributed generation devices is aggregated into one generalized generation unit. The actual active power generated by the generalized generation unit is S_i. Besides, the actual demand of prosumer i is D_i. In ADN, due to the cost limitation of energy storage devices, only some of the users have household energy storage. For each prosumer $i \in \mathcal{P}$, the maximum capacity of its household energy storage is $SOC_{i,\max}$. Therefore, for prosumers without energy storage device, $SOC_{i,\max} = 0$.

A. UTILITY MODEL OF PROSUMERS

The subscripts t of the variables in the model are omitted because the trading decision model proposed in this paper is for a single time slot only.

1) Consumption/Production utility of prosumers

According to the principle of economics, electricity as a commodity has the characteristics of decreasing marginal utility and increasing marginal cost. As the price rises, the demand decreases, whereas as the production expands, its cost will show an increasing trend, as shown in Fig. 1.

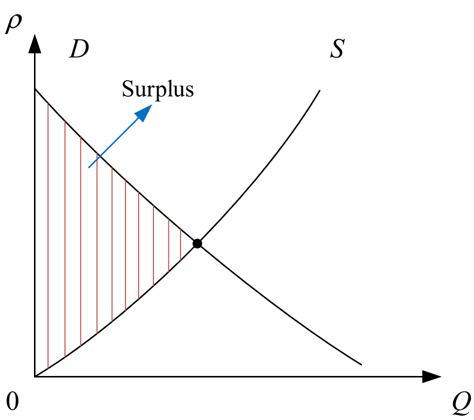

FIGURE 1. Marginal utility/cost curve.

Since the producer-consumer has both producer and consumer functions, the marginal utility function of electricity use and the marginal cost of generation function of the prosumer can be fitted with a primary function [19], [21], [22], which can be given as follows:

$$\begin{cases} U_i^{demand} = a_i - b_i D_i \\ U_i^{supply} = \alpha_i + \beta_i S_i \end{cases} \tag{1}$$

where U_i^{demand} is the marginal utility of electricity use for the prosumer i as a consumer. U_i^{supply} is the marginal generation cost of the prosumer i as a producer. a_i and b_i are the fitting coefficients of the marginal utility function of the prosumer i. α_i and β_i are the fitting coefficients of the marginal cost of generation function for the prosumer i. $a_i, b_i, \alpha_i, \beta_i > 0$.

Integrating equation (1) yields the cumulative utility of electricity use function and the cumulative cost of generation function for prosumer i.

$$\begin{cases} F_i^{demand} = \int_0^{D_i} U_i^{demand} dD_i = a_i D_i - 0.5 b_i D_i^2 \\ F_i^{supply} = \int_0^{S_i} U_i^{supply} dS_i = \alpha_i S_i + 0.5 \beta_i S_i^2 \end{cases} \tag{2}$$

where F_i^{demand} is the cumulative utility function of electricity use for the prosumer i. F_i^{supply} is the cumulative generation cost function of the prosumer i.

The surplus of a prosumer is its cumulative utility of electricity use minus its cumulative cost of generation, as shown in Fig. 1. In general, the prosumer's surplus is maximized at the intersection of the two curves. However, it may not be maximized in the actual scenario due to the constraints (Section II.A) for each consumer's demand and generation.

2) Charging/Discharging utility of household energy storage

Energy storage devices are generally used to store the surplus electricity produced by the prosumer. On the one hand, it can avoid the loss of electricity. On the other hand, it can be used in the later electricity consumption to increase the utility of its own electricity use. In the proposed power sharing framework (Section III.C), energy storage devices can not only be used for storing electricity by the owner, but also for sharing energy storage devices to obtain utility by giving away the right to use. In fact, the sharing of energy storage devices is also carried out by means of energy trading.

Similarly, from the perspective of Economics, electricity is abundant for the prosumer when the charge state of the household energy storage device is high, while it is scarce for the prosumer when the charge state is low. The marginal utility and marginal cost of charging and discharging energy storage devices can be given as follows:

$$\begin{cases} U_i^{charge} = c_{ch,i} - d_{ch,i} Q_{ch,i} \\ U_i^{discharge} = c_{dis,i} + d_{dis,i} Q_{dis,i} \end{cases} \tag{3}$$

where U_i^{charge} is the marginal charging utility of the household energy storage device for the prosumer i. $U_i^{discharge}$ is the marginal discharge cost of the prosumer i. $c_{ch,i}$ and $d_{ch,i}$ are the fitting coefficients of the marginal charging utility function of the prosumer i. $c_{dis,i}$ and $d_{dis,i}$ are the fitting coefficients of the marginal discharge cost function for the prosumer i. $Q_{ch,i}$ is the charging electricity of the energy storage device of the prosumer i. $Q_{dis,i}$ is the discharging electricity of the energy storage device of the prosumer i. $c_{ch,i}, d_{ch,i}, c_{dis,i}, d_{dis,i} > 0$.

Similarly, the integration of equation (3) yields:

$$\begin{cases} F_i^{charge} = \int_0^{Q_{ch,i}} U_i^{charge} dQ_{ch,i} = c_{ch,i}Q_{ch,i} - 0.5d_{ch,i}Q_{ch,i}^2 \\ F_i^{discharge} = \int_0^{Q_{dis,i}} U_i^{discharge} dQ_{dis,i} = c_{dis,i}Q_{dis,i} \\ \qquad +0.5d_{dis,i}Q_{dis,i}^2 \end{cases} \tag{4}$$

where F_i^{charge} is the cumulative charging utility function of the energy storage device of the prosumer i. $F_i^{discharge}$ is the cumulative discharging cost function of the energy storage device of the prosumer i.

B. CONSTRAINTS

1) Demand response potential constraint

In ADN, the flexible loads of customers can actively participate in the regulation of the system. Considering that only a portion of the prosumer's load can participate in demand response as a flexible load, the prosumer's demand for electricity is set within a certain range:

$$\underline{D}_i \le D_i \le \bar{D}_i \tag{5}$$

where, $\underline{D}_i$ and $\bar{D}_i$ are the lower and upper bounds of electricity demand for the prosumer i, respectively. The envelope formed by $\underline{D}_i$ and $\bar{D}_i$ corresponds to the demand response potential of the prosumer [23].

2) Power generation constraint

Most of the distributed power generation devices of prosumers are renewable energy generation devices represented by photovoltaic and wind power. The active power can be regulated below the maximum power generation by the action of inverter.

$$0 \le S_i \le \bar{S}_i \tag{6}$$

where $\bar{S}_i$ is the maximum value of the power generated by the prosumer i. In the actual scenario, $\bar{S}_i$ is the real-time predicted output of the corresponding generation unit.

3) Household energy storage constraints

Charging and discharging of household energy storage devices cannot be done simultaneously, which can be expressed by introducing state variables:

$$\begin{cases} 0 \le Q_{ch,i} \le u_i\bar{Q}_{ch,i} \\ 0 \le Q_{dis,i} \le (1-u_i)\bar{Q}_{dis,i} \end{cases} \tag{7}$$

where $\bar{Q}_{ch,i}$ and $\bar{Q}_{dis,i}$ are the upper limit of the charge/discharge power of the energy storage device of the prosumer i respectively. u_i is the charge/discharge state variable of the energy storage device. Energy storage device charges when $u_i = 1$ and discharges when $u_i = 0$.

In addition, the charging and discharging of energy storage devices has a timing characteristic. Energy storage capacity has an upper limit.

$$SOC_i(t+1) = SOC_i(t) + \eta_{ch}Q_{ch,i} - \frac{Q_{dis,i}}{\eta_{dis}} \tag{8}$$

$$SOC_i(t) \le SOC_{i,\max} \quad t \in T \tag{9}$$

where $SOC_i(t)$ is the state of charge of the energy storage device of the prosumer i at time slot t. T is the total time period, $t \in T$. η_{ch} and η_{dis} are the charging and discharging efficiency of the energy storage device, respectively.

4) Electricity balance constraint

For each prosumer, the sum of the electricity produced/discharged plus the shared electricity purchased is equal to the sum of the electricity it consumes/charges, which can be given as follows:

$$S_i + Q_{dis,i} + E_i = D_i + Q_{ch,i} \tag{10}$$

where E_i is the shared electricity purchased by the prosumer i. When prosumer i purchases electricity from other prosumers, $E_i > 0$. When prosumer i sells electricity to other prosumers, $E_i < 0$.

5) Line capacity constraint

Considering the short distance between nodes within the ADN, the line loss can be ignored. To simplify the calculation, the sharing electricity is limited to the interval range to prevent line congestion.

$$\underline{E}_i \le E_i \le \bar{E}_i \tag{11}$$

where $\underline{E}_i$ is the lower limit of sharing electricity of the prosumer i. $\bar{E}_i$ is the upper limit of sharing electricity of the prosumer i.

6) Sharing electricity balance constraints

In the sharing transactions among prosumers, the amount of electricity purchased is equal to the amount of electricity sold, which can be given as follows:

$$\sum_{i=1}^{N} E_i = 0 \tag{12}$$

C. TRADING DECISION MODEL

Based on the above prosumer utility model and the related constraints, the prosumer's individual transaction decision model can be given as follows:

$$\begin{cases} \max F_i^{demand} - F_i^{supply} + F_i^{charge} - F_i^{discharge} - \\ \gamma_i(Q_{ch,i} + Q_{dis,i}) - \lambda_e E_i \\ \text{s.t. } (5) - (12) \end{cases} \tag{13}$$

where γ_i is the charging and discharging loss of the energy storage device, which can be expressed by a linear function [24], [25]. λ_e is the sharing price.

III. ENERGY SHARING MECHANISM BASED ON ADMM ALGORITHM

In the previous section, a transaction decision model (Eq. (13)) is established for a single prosumer by analyzing the utility of the prosumers. However, there are two problems with this model:

1) Although the objective function of the model is to maximize the total benefit of the prosumer i in the process of energy sharing, the social welfare (i.e., the sum of the utilities of all prosumers) cannot be optimized. Without a suitable trading mechanism, individual prosumers will only pursue their own utility maximization. In this circumstance, the optimal allocation of resources cannot be achieved. From the perspective of game theory, the prosumers make decisions according to their own optimal responses according to equation (13), thus reaching an equilibrium. The existence of the coupling variable E_i leads to a generalized Nash equilibrium [26] (GNE) among prosumers. Reference [19], [20] has demonstrated that the generalized Nash equilibrium point can only converge to a perfectly competitive market when the number of prosumers is large enough, and the social welfare converge to the optimum.

2) Electricity prices in the sharing market still require a unified market clearing by the trading center. On the one hand, this will increase the total transaction cost. On the other hand, the clearing price cannot intuitively reflect the value recognition of individual prosumers.

Considering the above two problems, in this section, we will propose an energy sharing mechanism based on ADMM algorithm. The proposed mechanism is able to maximize social welfare. The sharing price can automatically achieve distributed clearing through the value recognition of individual prosumers.

A. CENTRALIZED SOCIAL WELFARE MAXIMIZATION ENERGY SHARING MODEL

First, a centralized energy sharing transaction model is established. We assume that there is a centralized institution with the right to dispatch all prosumers. Its goal is to maximize social welfare through optimal dispatch. The centralized social welfare maximization model is shown in equation (14). In Eq. (14), the cost of purchasing sharing electricity for each prosumer $\lambda_e E_i$ is omitted. This is because the transaction cost of shared power is balanced within the active distribution network when the constraint (12) is satisfied.

$$\begin{cases} \max \sum_{i=1}^{N} [a_i D_i - 0.5 b_i D_i^2 - \alpha_i S_i - 0.5\beta_i S_i^2 + \\ c_{ch,i} Q_{ch,i} - 0.5 d_{ch,i} Q_{ch,i}^2 - c_{dis,i} Q_{dis,i} - \\ 0.5 d_{dis,i} Q_{dis,i}^2 - \gamma_i (Q_{ch,i} + Q_{dis,i})] \\ \text{s.t. } (5) - (11) \forall i \in \mathcal{P} \\ \sum_{i=1}^{N} E_i = 0 : \lambda_e \end{cases} \quad (14)$$

In Eq. (14), the sharing price λ_e is the dual variable of the sharing electricity balance constraint. Although Eq. (14) can maximize social welfare, it is too dependent on the central institution and has high transaction costs. In addition, the personal privacy information of prosumers, such as a_i, b_i, α_i, β_i needs to be reported to the central institution. The privacy of individuals cannot be protected. Therefore, this paper proposes the following distributed solution method.

B. DISTRIBUTED SOLUTION BASED ON ADMM ALGORITHM

The ADMM algorithm can decompose the original problem into multiple subproblems for distributed iterative solution. In this paper, the original problem is equation (14). The problem is a convex optimization problem consisting of N prosumers. Define the decision variables of the prosumer i as x_i. The augmented Lagrangian function of Eq. (14) can be given as follows:

$$\begin{aligned} L(x_i, \lambda_e) = &-[a_i D_i - 0.5 b_i D_i^2 - \alpha_i S_i - 0.5\beta_i S_i^2 + c_{ch,i} Q_{ch,i} \\ &- 0.5 d_{ch,i} Q_{ch,i}^2 - c_{dis,i} Q_{dis,i} - 0.5 d_{dis,i} Q_{dis,i}^2 \\ &- \gamma_i (Q_{ch,i} + Q_{dis,i})] + \frac{\rho}{2} \left\| \sum_{i=1}^{N} E_i + \frac{\lambda_e}{\rho} \right\|_2^2 \end{aligned} \quad (15)$$

where ρ is the step length.

The solution process of ADMM algorithm is as follows.

Step1: Initialize step length ρ, convergence accuracy of primal residual e^{pri}, convergence accuracy of dual residual e^{dual}, initial value of sharing electricity E_i^0 for each prosumer and initial value of sharing price λ_e^0. $k = 1$.

Step2: Starting from the first consumer, the optimization problem is solved in turn according to the following equation while satisfying the corresponding constraints (Eqs. (5)-(11)). It is clear that the problem is a convex problem with linear constraints, which is easy to solve. Therefore, we solve the problem using Yalmip toolbox with Gurobi 9.1 commercial solver based on Matlab 2020b platform.

$$x_i^{k+1} = \arg\min L(x_i, \lambda_e^k) \quad i = 1, 2, \ldots, N \quad (16)$$

Step3: Update the Lagrangian multiplier according to equation (17).

$$\lambda_e^{k+1} = \lambda_e^{k+1} + \rho(\sum_{i=1}^{N} E_i) \quad (17)$$

Step4: Determine whether the algorithm has reached convergence. If both equation (18) and equation (19) hold, the algorithm converges and the iteration ends. Otherwise, let $k = k + 1$ and return to step 2 to continue the iteration.

$$\left\| \sum_{i=1}^{N} E_i^{k+1} \right\| < e^{pri} \quad (18)$$

$$\rho \left\| E_i^{k+1} - E_i^k \right\| < e^{dual} \quad (19)$$

where Eqs. (18) and (19) are the primal residual and dual residual expressions of Eq. (14), respectively.

C. ENERGY SHARING MECHANISM

Based on the above ADMM distributed solution process, an energy sharing mechanism for prosumers in ADN can be established. The specific trading mechanism flow is as follows.

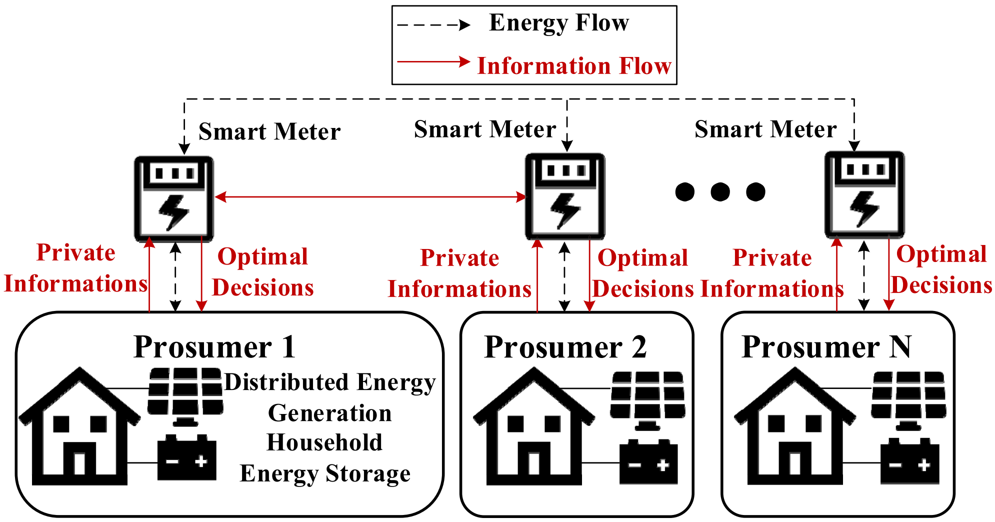

FIGURE 2. Framework of the proposed energy sharing mechanism.

TABLE 1. Parameters of prosumers.

Parameters	a_i	b_i	α_i	β_i	$c_{ch,i}$	$d_{ch,i}$	$c_{dis,i}$	$d_{dis,i}$
Prosumer 1	2	0.001	0.03	0.02	5	0.0005	0.02	0.003
Prosumer 2	0.008	0.009	0.006	0.001	0.0008	0.06	0.04	0.0001

1) Each prosumer enters its own private information into the smart meter. The privacy information includes $a_i, b_i, \alpha_i, \beta_i, c_{ch,i}, d_{ch,i}, c_{dis,i}, d_{dis,i}$ and other parameters related to individual utility and constraints. At the same time initialize its own sharing energy E_i^0. In addition, the sharing price is initialized ($\lambda_e^0 = 0$) in the smart meter of the last prosumer (prosumer N. The order of prosumers is determined by the operator of the grid).

2) The calculation starts from the prosumer 1. Equation (16) is solved based on the data and parameters in its smart meter. The corresponding constraints (Eq. (5)-Eq. (11)) need to be satisfied. The solution is broadcasted to all smart meters via a wireless signal. After that, the rest prosumers complete the above steps sequentially according to its own parameters and the received broadcast information until the prosumer N completes the calculation.

3) The smart meter of prosumer N determines whether the convergence accuracy is achieved according to the pre-set primal residual convergence accuracy e^{pri} and dual residual convergence accuracy e^{dual}. If not, the smart meter updates the sharing price based on the equation (17). Then the next iteration starts from the first prosumer. If the convergence accuracy is reached, the final sharing price is broadcasted to all participating prosumers.

4) Each smart meter feeds back the final sharing price and the decision information obtained from the last calculation to the prosumer, who performs production/consumption or charging/discharging operations. Finally, the distribution network operator dispatches electricity according to the transaction results.

The above process is based on the energy sharing transaction framework, as shown in Fig. 2.

IV. ILLUSTRATIVE EXAMPLE

A. CASE SETUP

In order to illustrate that the energy sharing mechanism proposed in this paper can realize the optimal allocation of resources and improve social welfare, we set up an illustrative example including two prosumers for analysis. The calculation results are used to analyze the intrinsic principles of the energy sharing mechanism.

The parameters of the two prosumers are shown in Table 1. The units of a_i, α_i, $c_{ch,i}$ and $c_{dis,i}$ are \$/kWh^2. The units of b_i, β_i, $d_{ch,i}$ and $d_{dis,i}$ are \$/kWh. The demand response potentials for prosumer 1 and prosumer 2 are [80kWh, 100kWh], [140kWh, 200kWh]. The maximum value of distributed generation output is set to 150kWh. The capacity of energy storage device is 100kWh and 90kWh respectively. the maximum values of charging and discharging electricity are 6kWh and 5kWh respectively. the charging and discharging losses of energy storage device are uniformly 0.0003 \$/kWh. For the convenience of the analysis, the Line capacity constraint is ignored in this case.

B. ANALYSIS OF RESULTS

1) Comparison between the centralized algorithm and the ADMM algorithm. Based on the above data, the centralized (Eq. (14)) and ADMM algorithms were used to solve the problem respectively. The obtained solution results are shown in Table 2. The convergence process of ADMM algorithm iterations is shown in Fig. 3.

TABLE 2. Calculation results.

Methods	$[E_1, E_2]$	λ_e	Social Welfare
Centralized	[15, -15]	/	40.0165
ADMM	[15, -15]	0.925	40.0165

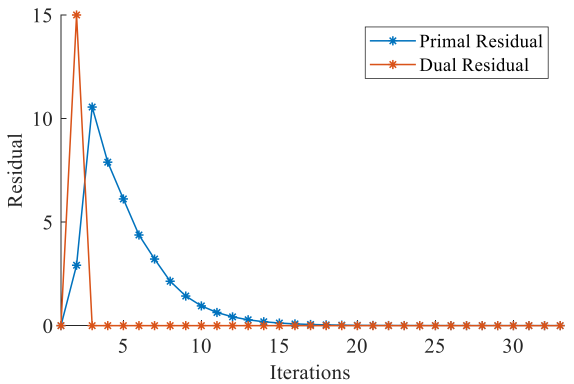

FIGURE 3. Iteration process of ADMM algorithm.

The unit of E_i is kWh. The unit of λ_e is \$/kWh. The unit of social welfare is \$.

From the above results, it can be seen that ADMM algorithm has good convergence performance for the established energy sharing model. Convergence is achieved in about 20 iterations. The main reason is that the model is a convex optimization problem. Moreover, the solution results of the centralized method and the distributed solution of the ADMM algorithm are identical. Therefore, the distributed solution by ADMM algorithm can also maximize the social welfare.

2) *Comparison between participating in energy sharing and not participating in energy sharing*. Add the following constraint to equation (14):

$$E_i = 0 \quad \forall i \in \mathcal{P} \tag{20}$$

After adding the constraint, the sharing electricity among prosumers is 0, which means they do not participate in energy sharing. The calculation results before and after adding the constraint are compared, and the results are shown in Table 3.

As shown in Table 3, after participating in energy sharing, the electricity demand of prosumer 1 increases and the production of electricity decreases. In contrast, the production of electricity by prosumer 2 increases. The shortage of electricity supply due to the reduction of electricity production of prosumer 1 is compensated by the electricity shared by prosumer 2. This result can be explained by the fact that prosumer 1 has a higher utility of electricity use but higher cost of electricity production compared with prosumer 2 (see Tables 1). Therefore, more electricity use of prosumer 1 and more electricity generation of prosumer 2 can lead to an overall increase in utility. This adjustment process is achieved through the sharing of electricity. In other words, prosumer 1 borrows prosumer 2's generation device with lower generation cost to supply itself with electricity.

TABLE 3. Calculation results.

Methods	$[E_1, E_2]$	$[D_1, D_2]$	$[S_1, S_2]$	Social Welfare
Not sharing	[0, 0]	[88.1, 140]	[94.1, 135]	13.7320
Sharing energy	[15, -15]	[100, 140]	[91, 150]	40.0165

The social welfare data in Table 3 also shows that the overall society welfare increases after participation in sharing.

The above results indicate that the proposed power sharing mechanism can achieve the optimal allocation of resources and increase social welfare.

V. 10-NODE SIMULATION STUDY

In order to further analyze the characteristics of the proposed energy sharing mechanism in simulation, a 10-node ADN of prosumers is constructed in this paper. The topology is shown in Fig. 4. The parameters of the prosumers are shown in Tables 4 and 5.

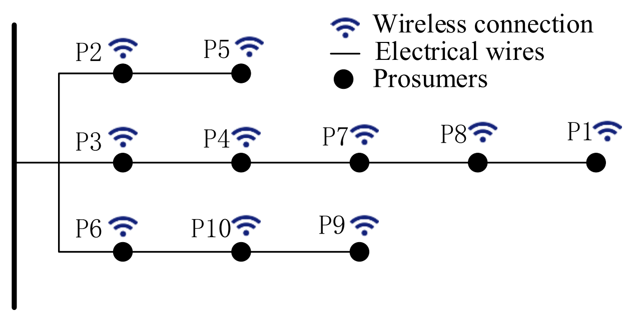

FIGURE 4. The prosumer network topology of a 10-node ADN.

In contrast to the illustrative example in the previous section, the analysis in this section requires further consideration of the security issues arising from the capacity constraint of the lines (Equation (11)), since the analysis in this section is simulated in a distribution network interconnected among the 10 prosumers through transmission lines. The energy sharing model and solving process are the same as the two-prosumer illustrative example in the previous section.

The step length $\rho = 0.01$. The algorithm reaches convergence after 261 iterations. The total time of solving is 2 min 52 s, which can meet the real-time dispatching requirements. The optimization results can be given as follows:

TABLE 4. Parameters of prosumers.

Parameters	a_i	b_i	α_i	β_i	$c_{ch,i}$	$d_{ch,i}$	$c_{dis,i}$	$d_{dis,i}$
Prosumer 1	2	0.001	0.03	0.02	5	0.0005	0.02	0.003
Prosumer 2	0.08	0.009	0.006	0.001	0.0008	0.06	0.04	0.0001
Prosumer 3	0.07	0.005	0.05	0.01	0.003	0.003	0.01	0.002
Prosumer 4	0.5	0.001	0.06	0.02	0.2	0.01	0.001	0.0008
Prosumer 5	0.02	0.002	0.002	0.005	0.02	0.08	0.02	0.004
Prosumer 6	1.5	0.003	0.001	0.01	0.007	0.0006	0.08	0.0006
Prosumer 7	0.06	0.007	0.007	0.002	0.02	0.001	0.1	0.0007
Prosumer 8	1.2	0.006	0.04	0.003	5	0.002	0.002	0.0003
Prosumer 9	0.05	0.009	0.006	0.001	0.7	0.0003	0.001	0.005
Prosumer 10	0.8	0.002	0.05	0.02	0.002	0.01	0.004	0.002

TABLE 5. Parameters of prosumers.

Parameters	$SOC(0)$	$[\underline{D}_i, \bar{D}_i]$	$\bar{S}_i$	$\bar{Q}_{ch,i}$	$\bar{Q}_{dis,i}$	$[\underline{E}_i, \bar{E}_i]$
Prosumer 1	2	[80, 100]	150	6	6	[80, 100]
Prosumer 2	0.08	[140, 200]	150	5	5	[-50, 50]
Prosumer 3	0.07	[120, 150]	150	4	4	[-19, 19]
Prosumer 4	0.5	[80, 90]	85	5	5	[-80, 80]
Prosumer 5	0.02	[150, 180]	175	6	6	[-20, 20]
Prosumer 6	1.5	[160, 200]	185	4	4	[-100, 100]
Prosumer 7	0.06	[190, 210]	196	5	5	[-20, 20]
Prosumer 8	1.2	[185, 190]	190	3	3	[-35, 35]
Prosumer 9	0.05	[192, 220]	210	5	5	[-30, 30]
Prosumer 10	0.8	[98, 130]	150	0.02	0.002	[-30, 30]

The sharing electricity results of each prosumer are shown in Fig. 5. The electricity used and the electricity generated by prosumers are shown in Fig.6 and Fig.7. Prosumers share electricity with each other and the amount of electricity shared differs from one another because the prosumers have different utility models. Besides, the social welfare result is −287.05 $.

We also optimized the centralized problem using the same network and parameters. The solving results are exactly the same, which verified the conclusion we get from illustrative example again.

Then, we consider the case where the prosumers do not participate in energy sharing. The final social welfare result is −$373.84 for the case. Compare with −287.05 $, the non-participation in sharing makes the social welfare lower. The results again verify the correctness of the conclusions in the previous section.

Fig. 8 shows the electricity charged and discharged of energy storage devices for each prosumer. From Fig. 5 and Fig. 8, it can be seen that the transfer and storage of electricity within the active distribution network is achieved through energy sharing and charging and discharging of energy storage devices between prosumers. In essence, it is the flow of electricity from the prosumer with low utility to the prosumer with high utility. From the perspective of the optimization model, the introduction of the energy sharing mechanism expands the decision space of the prosumers, so that the optimization result is inevitably no worse than the original result.

A. INFLUENCE OF HOUSEHOLD ENERGY STORAGE

In order to analyze the impact of the configuration of household energy storage devices on the final energy sharing results, we calculate the prosumer network with different energy storage configurations separately. The relationship between the number of prosumers with energy storage and social welfare is shown in Fig. 7.

As can be seen in Figure 7, the social welfare is on a phase upward trend as the number of prosumers with home energy storage increases. This reflects the increase in the flexibility of electricity use with the deployment of home energy storage devices. From the perspective of the optimization model, the presence of energy storage further expands the decision space

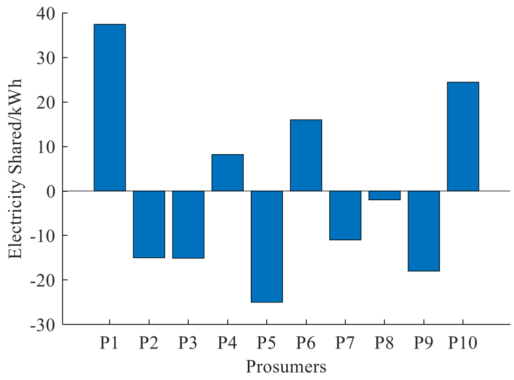

FIGURE 5. Electricity shared among prosumers.

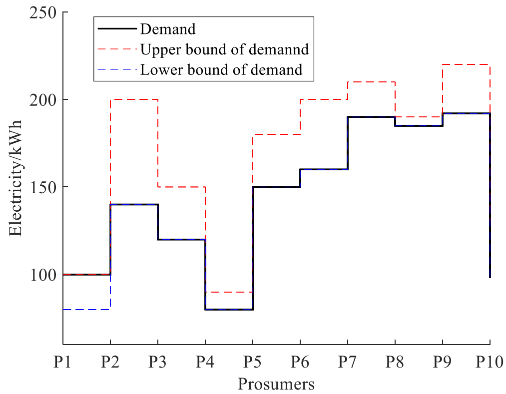

FIGURE 6. Demand of prosumers.

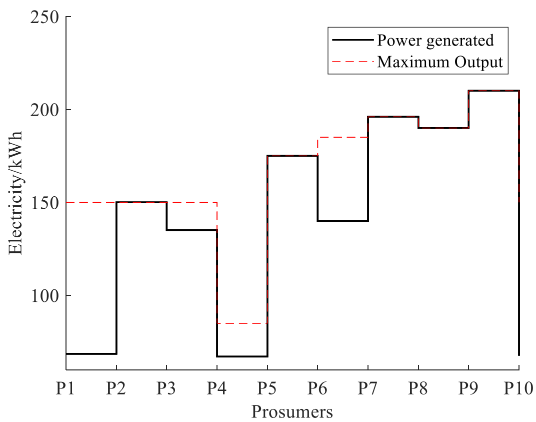

FIGURE 7. Power generated by prosumers.

of prosumers. The prosumers are able to find a more optimal solution.

B. COMPARISON OF RENEWABLE ENERGY ACCOMMODATION BEFORE AND AFTER ENERGY SHARING

Considering the current trend that most of the distributed generation units are renewable energy generation and the future renewable energy access will increase, this paper assumes that all the distributed generation units of producers and

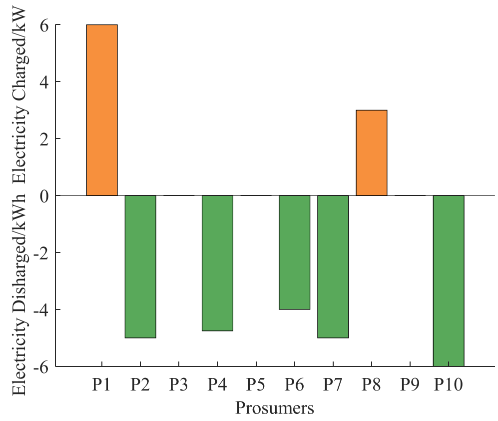

FIGURE 8. Electricity charged and discharged of energy storage devices of prosumers.

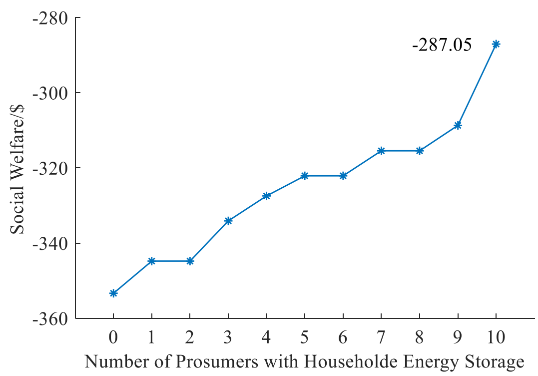

FIGURE 9. The relationship between social welfare and household energy storage configuration.

TABLE 6. Comparison of renewable energy accommodation.

	The degree of renewable energy accommodation
Not sharing	0.8485
Sharing energy	0.8527

consumers are renewable energy generation. The degree of renewable energy accommodation is defined as follows:

$$\xi = \sum_{i=1}^{N} S_i / \sum_{i=1}^{N} S_{\max} \tag{21}$$

We calculate the degree of renewable energy accommodation before and after participating in energy sharing. The results are shown in Table 6.

VI. CONCLUSION

In this paper, a distributed energy sharing trading mechanism of active distribution network for prosumers considering household energy storage is established. Firstly, the utility model of the prosumers is constructed. On the basis of the utility model, a centralized social welfare maximization problem is established. Then, the ADMM algorithm is used to decompose the centralized problem. The distributed energy sharing framework is designed based on the solution process. Finally, the effectiveness of the mechanism is analyzed by an illustrative example and a 10-node simulation case. The obtained conclusions are given as follows:

1) The participation of prosumers in energy sharing can lead to the optimal allocation of resources and the improvement of overall social welfare.

2) The solution results of the ADMM algorithm-based energy sharing mechanism are the same as the solution of the centralized social welfare maximization problem. The proposed mechanism can maximize social welfare.

3) The more prosumers with household energy storage devices, the greater the social welfare.

4) In the situation of large amount of distributed renewable energy access, the proposed energy sharing mechanism can improve the degree of renewable energy accommodation.

Practical application of the trading mechanism on a small scale and model validation with data in actual network is our next research direction.

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