Distributed Optimization-Based Power Trade Strategy for We-Energy in Energy Internet

Fei Teng
School of Information Science and Engineering
Northeastern University
Shenyang, China
brenda_teng@163.com

Qiuye Sun
School of Information Science and Engineering
Northeastern University
Shenyang, China
sunqiuye@mail.neu.edu.cn

Zhao Zhang
School of International Finance and Banking
University of Science and Technology Liaoning
Anshan, China
zhangzhao333@hotmail.com

Huaguang Zhang
School of Information Science and Engineering
Northeastern University
Shenyang, China
hgzhang@ieee.org

***Abstract*—A novel distributed power trade strategy is proposed to address the pricing problem for we-energy-based energy internet, considering the psychological fluctuation caused by the self-decision ability of the we-energy during the process of buying and selling power. A pricing model is presented based on the distributed optimization theory, by which the minimum generation cost of the energy internet can be achieved. Furthermore, to accurately analyze the process of bidding pricing with the disturbance resulted from the psychological fluctuation of each we-energy, the multi-agent system with an uncertainty function is utilized. One example is used to verify the effectiveness of the proposed framework.**

***Index Terms*—Energy Internet, we-energy, power trade strategy, pricing model, distributed optimization, bounded uncertainty.**

I. INTRODUCTION

More and more researchers have focused on the energy internet, with the demand of energy keeping growing. As the future energy system for low-carbon, environmental-friendly, secure, sustainable utilization of energy, the vision of energy internet, which is regarded as smart grid 2.0 [1], is firstly presented by Jeremy Rifkin [2]. In the proposed vision of future energy system, energy internet comprises plenty of distributed devices (e.g., distributed generations, distributed storage devices), which can effectively make use of large-scale renewable energy [3]. As a result, there exists a lot of distributed cooperative control and distributed optimization problems in the energy internet [4-6], among which is the pricing problem of power trade.

In the previous papers [7-9], the power management and trade of the energy internet are implemented by the traditional major energy supplier, namely, the traditional power system. However, because of the existence of the plenty of distributed devices, users in the energy internet can also have the ability of power generation and control their energy needs via the small distributed renewable energy resources. Then a novel energy entity, named we-energy, is developed in energy internet [10-12]. Different from traditional power systems, the existence of the we-energy, which is the combination of an energy producer and an energy consumer, blurs the boundary of power generation, power transmission, power distribution and power consumption. Due to the decision-making ability of power trade for each we-energy, there may exist resistance behaviors, caused by the psychological fluctuation of each we-energy, against the power trade strategy for energy internet. And the psychological fluctuation of each we-energy is influenced by the bidding price of the power trade and the balance between power supply and power demand, which is the decisive factor to the success of pricing strategy for we-energies. Then the existing power trade strategies are no longer applicable, in light of the psychological fluctuation of we-energies, which can influence the process of bidding pricing. Thus, how to effectively develop a power trade strategy for we-energy-based energy internet is a hot issue.

Due to the characteristics of less computations and communications, distributed optimization problems based on multi-agent systems arise in varieties of engineering applications, such as the optimal generation control in power systems [13], the frequency recovery in microgrids [14-15], the energy management and pricing strategy in smart grid [16] and so on. According to above analysis about the concept of the we-energy, a "we-energy" has the decision-making ability for the status of power production, power consumption and power trading. And it may execute or resist the expected pricing strategy from the energy internet, considering the impact of the we-energy's self-interested psychological characteristics. In fact, the we-energy can be seen as an economically motivated agent, of which the psychological fluctuation can be seen as a disturbance in the multi-agent system. Therefore, the distributed optimization based on the multi-agent system with

This work was supported by the National Natural Science Foundation of China (61573094) and the Doctoral Scientific Research Foundation of Liaoning Province (20170520192).

978-1-5386-1427-3/17/$31.00 ©2017 IEEE

disturbance can be a way to solve the pricing problem for we-energy-based energy internet, considering the self-interested psychological fluctuation caused by the self-decision ability of the we-energy during the process of power trade. And this is what we mainly focus on in this paper.

The remainder of this paper is organized as follows. In Section II, the characteristics and the cost model of we-energy are introduced. In Section III, the power trade strategy for we-energy-based energy internet based on distributed optimization is proposed. In Section IV, one simulation case is given to verify the effectiveness of the proposed method. Finally, Section V concludes this paper.

II. Characteristics and Cost Model of We-Energy

In this section, the characteristics of we-energy are introduced. Moreover, the cost optimization model of we-energy is constructed aiming at minimize the generation cost of the energy internet.

A. Characteristics of We-Energy

Traditional power systems composes of generation, transmission, transformation, distribution and consumption sections, each of which is in charge of producing, transporting, transforming, distributing or consuming eletricity individually. As previously stated in the introduction, a power prosumer is a hybrid entity of a producer and a consumer, namely, a power prosumer can become a power seller/buyer to neighbouring power prosumers or the main grid for/after its self-supply. And a power prosumer can be a microgrid, a building or even a factory, which is comprised of conventional power generation and/or distributed energy resources, loads and storage devices, as shown in Fig. 1.

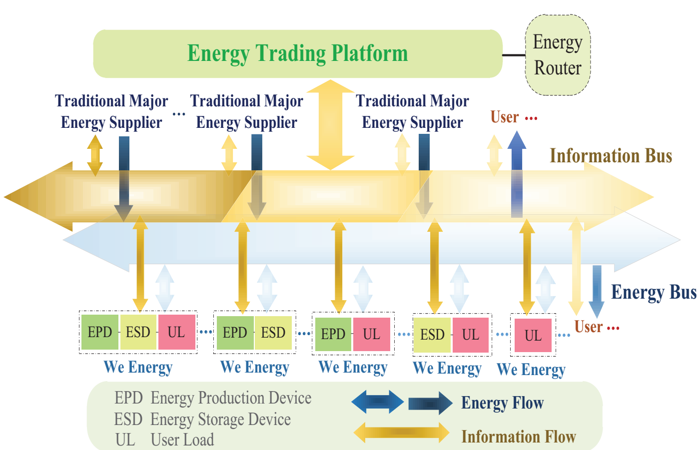


Fig. 1. Operation Mode of We-Energy in the Energy Internet.

The main features of the we-energy can be concluded as:

- Producer-Consumer Integration: by the leadership of the traditional major energy supplier, the traditional energy supply pattern is broken. In the past, the energy entities (e.g., the power generation and the user) can only participate as a power seller or power buyer. However, for we-energy-based energy internet, the power generation, the power transmission, the power consumption and the power storage can be implemented by one We-Energy itself. And each we-energy is an interactive energy entity, which can be a power generator, a power transmitter, a power consumer and an energy storage at the same time.
- Energy Supply Complementarity: the energy internet comprises plenty of We-Energies, by which the power generation, the power transmission, the power consumption and the power storage can be achieved. Due to the uniqueness of the power demand of each user, the mode of the power generation and the power consumption of each We-Energy is different. The regional diversity and complementarity of the the power generation and the power demand contribute to achieving the power balance among We-Energies. Meanwhile, the utility efficiency of renewable energy and the cost of power transmission can be reduced.
- Openness of Operating Mode: most of we-energies are grassroots-level energy entities. The development of we-energies makes the energy trading mode change into the peer-to-peer mode.
- Regionalization of Power Consumption: the regional self-sufficient power supply mode can be realized with the large-scale use of renewable energy resources and other clean energy resources, along with the increase of We-Energies, which can weaken the advantage of long-distance transmission capacity of fossil energy.

B. Bidding Price-Based Cost Function of We-Energy

For a we-energy in the energy internet, the generation cost function $C_i(P_i)$ can be commonly expressed as a quadratic function [14],

$$C_i(P_i) = a_i P_i^2 + b_i P_i + c_i, \tag{1}$$

where P_i denotes the power output of we-energy i, a_i, b_i, c_i are parameters which are non-negative for we-energy i.

Then denoting the marginal cost of we-energy i as the reference bidding price P_{ri}, we can obtain that

$$P_{ri} = \frac{dC_i(P_i)}{dP_i} = 2a_i P_i + b_i, \tag{2}$$

and the power output of we-energy i can be expressed as

$$P_i = \frac{P_{ri} - b_i}{2a_i}. \tag{3}$$

Then the generation cost function depending on the reference bidding price P_{ri}, namely function $C_{oi}(P_{ri})$, can be gotten,

$$C_{oi}(P_{ri}) = \frac{P_{ri}^2}{4a_i} + c_i - \frac{b_i^2}{4a_i}. \tag{4}$$

Obviously, it is convex.

Because of large-scale renewable energy resources in the energy internet, the generation cost function of we-energy may not be a simple quadratic function, but a general convex function of power output P_i (e.g., an exponential function [17]). For a conventional convex generation cost function $C_i(P_i)$, the reference bidding price P_{ri} can be expressed as the marginal cost of we-energy i as follows

$$P_{ri} = \frac{dC_i(P_i)}{dP_i}. \tag{5}$$

Then, we reconsider the generation cost function $C_i(P_i)$ as a new generation cost function $C_{oi}(P_{ri})$ with respect to the reference bidding price P_{ri},

$$C_{oi}(P_{ri}) \triangleq C_i(P_i) = C_i({C'}_i^{-1}(C'_i(P_i))) = C_i({C'}_i^{-1}(P_{ri})). \tag{6}$$

To judge whether the new bidding price-based generation cost function $C_{oi}(P_{ri})$ is a convex function in the general case, we propose Lemma 1.

Lemma 1: The generation cost function $C_{oi}(P_{ri})$ with respect to the reference bidding price P_{ri} is convex if the generation cost function $C_i(P_i)$ is a smooth convex function of the power output P_i and the following inequality holds

$$({C''}_i(P_i))^2 - {C'}_i(P_i){C'''}_i(P_i) \geq 0. \tag{7}$$

proof 1: For the generation cost function $C_i(P_i)$ is smoothly convex, the second derivative of the function $C_{oi}(P_{ri})$ can be obtained

$$\begin{aligned}\frac{\partial^2 C_{oi}(P_{ri})}{\partial P_{ri}^2} &= \frac{\partial\left[C'_i({C'}_i^{-1}(P_{ri}))\frac{1}{{C''}_i({C'}_i^{-1}(P_{ri}))}\right]}{\partial P_{ri}}\\ &= \frac{{C''}_i(P_i) - {C'}_i(P_i)\frac{{C'''}_i(P_i)}{{C''}_i(P_i)}}{({C''}_i(P_i))^2}\\ &= \frac{({C''}_i(P_i))^2 - {C'}_i(P_i){C'''}_i(P_i)}{({C''}_i(P_i))^3}.\end{aligned} \tag{8}$$

Due to $({C''}_i(P_i))^2 - {C'}_i(P_i){C'''}_i(P_i) \geq 0$, $C_i(P_i)$ is smoothly convex which results $({C''}_i(P_i))^3 > 0$. Then from (8), one can conclude that $\frac{\partial^2 C_{oi}(P_{ri})}{\partial P_{ri}^2} > 0$, which means that the generation cost function $C_{oi}(P_{ri})$ is convex. This ends the proof.

III. Power Trade Strategy for We-Energy in Energy Internet

Because there are plenty of autonomous We-Energies in the energy internet, a multi-agent system-based power trade strategy is proposed in this section.

A. Classification and Task Decomposition of Agents

Considering the functional responsibilities of the devices (as shown in Fig. 1) in the energy internet, four kinds of agents are presented, which are separately We-Energy Agent, Traditional Major Energy Supplier Agent, Load Agent and Energy Router Agent. And the definition and the specific task of the agents are described as follows:

- We-Energy Agent (WEA): corresponding to each We-Energy in energy internet. It is in charge of monitoring the real-time operating state of the distributed generation and distributed energy storage device. And the bidding price-based generation cost function is constructed by it according to its traditional generation cost function. It can also calculate the power generation allowance of each distributed generation, responding to the control signal of the Energy Router Agent (ERA). In light of the distributed cooperative control command of ERA, each WEA, cooperating with other WEAs or the Traditional Major Energy Supplier Agent (TMESA), tries to achieve a bidding price of power trade, to satisfy the balance between the power supply of the distributed generation and distributed energy storage device and the power demand of the users, considering the psychological fluctuation caused by its self-decision ability of the we-energy during the process of power trade. Meanwhile, the generation cost of the energy internet can be minimized.
- Traditional Major Energy Supplier Agent (TMESA): corresponding to the traditional major energy supplier, namely, the traditional power system. It can integrate energy demand information and the power flow with each WEA. According to distributed cooperative control command of ERA, a TMESA, as the external power supplement, can cooperate with the WEAs to satisfy balance between the power supply of the distributed generation and distributed energy storage device and the power demand of the users.
- Load Agent (LA): corresponding to each load in energy internet. It is in charge of monitoring the real-time operating state of each load and reporting the energy demand of users to ERA. It can also cut load in accordance of the control comment of ERA.
- Energy Router Agent (ERA): corresponding to the energy router in energy internet. The optimization objective function of power trade in energy internet is constructed by it. On the basis of the requirement of the power demand sent by LA, ERA makes the plans to satisfy the energy demand of the users. Then it can make specific distributed power trade strategy, which is sent to and executed by the cooperation of WEAs, to keep the balance between the power supply of the distributed generation and distributed energy storage device and the power demand of the users, and maintain the energy internet operating normally.

B. Distributed Optimization-Based Power Trade Strategy

To achieve a reasonable bidding price, a power strategy based on distributed optimization theory is proposed, as is shown in Fig. 2. During the process of obtaining a reasonable solution to the power trade for the we-energy-based energy internet, the specific approach is provided as follows:

Step 1 Construct the global optimization objective function of power trade for we-energy-based energy internet: the aim of developing the pricing strategy is to minimize the expected generation cost of we-energy-based energy internet of ensuring supply-demand balance and reach an agreement on the reference bidding price. As a we-energy can sell/buy power to/from the neighbouring we-energies or the main grid for/after its power self-supply, considering

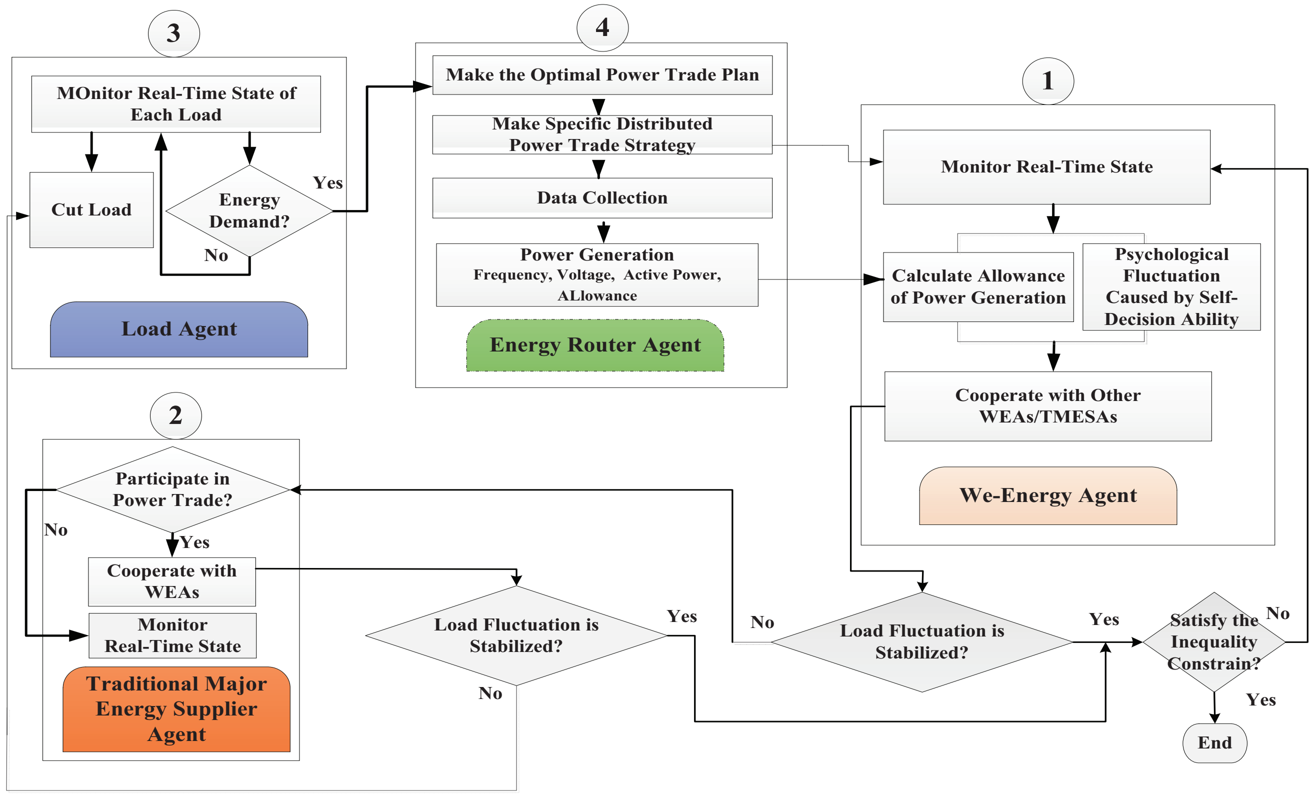


Fig. 2. Distributed Power Trade Strategy Based on Distributed Optimization.

the bidding-price-based generation cost of each we-energy, the global objective function can be gotten

$$
\begin{aligned}
\min \quad \tilde{f}(P_r) =& \sum_{i=1}^{N} C_{oi}(P_{ri}) + P_{rg}\Big[P_{load} \\
&+ P_{loss} - \sum_{i=1}^{N}\Big(\frac{P_{ri}-b_i}{2a_i}\Big)\Big] \\
=& \sum_{i=1}^{N}\Big[C_{oi}(P_{ri}) - \frac{P_{rg}P_{ri}}{2a_i} \\
&+ \frac{P_{rg}b_i}{2a_i} + P_{rg}(P_{load}^i + P_{loss}^i)\Big] \\
\triangleq& \sum_{i=1}^{N} f^i(P_{ri}),
\end{aligned} \tag{9}
$$

where N is the total number of we-energies, P_{load} is the total load demand of the energy internet, P_{loss} is total network loss of the energy internet, P_{rg} is the bidding price with the main grid of each we-energy.

Step 2 Make an assumption before designing the specific strategy.

Assumption 1: Each f_i is differentiable and $m-$strongly ($m > 0$) convex, and ∇f_i is Lipschitz over a convex set $\Psi \subset \mathbb{R}^d$, which means that $\forall x, y \in \Psi$ the following inequalities hold

$$
(x-y)^T(\nabla f_i(x) - \nabla f_i(y)) > m_i\|x-y\|^2, \quad x \neq y,
$$
$$
\|f_i(x) - f_i(y)\| \leq l_i\|x-y\|,
$$

where the maximum of Lipschitz parameters and the minimum of strongly convex parameters are denoted as $L_1 = \max\{l_1, l_2, \ldots, l_N\}$, $M = \min\{m_1, m_2, \ldots, m_N\}$.

Step 3 Make the specific distributed power trade strategy for each we-energy: considering the self-interested psychological fluctuation caused by its self-decision ability of each economically motivated we-energy, the pricing strategy based on the distributed optimization with disturbance is presented

$$
\begin{aligned}
\dot{v}^i =& \alpha\beta\sum_{j=1}^{N} a_{ij}\big[(P_{ri} - P_{rj} + g_i(P_{rj})d_i(t))\big], \\
&+ \alpha\beta g_i(P_{ri})d_i(t) \\
\dot{P_{ri}} =& -\alpha\nabla f^i(P_{ri}) \\
&- \beta\sum_{j=1}^{N} a_{ij}(P_{ri} - P_{rj} - g_i(P_{rj})d_i(t))) \\
&- v^i + \alpha\beta g_i(P_{ri})d_i(t),
\end{aligned} \tag{10}
$$

where $g_i(P_{rj})d_i(t)$ describes the disturbance of we-energy i caused by we-energy j, $g_i(P_{ri})d_i(t)$ describes the disturbance of we-energy i caused by itself, $g_i()$ is the self-decision function about the bidding price for we-energy i, $d_i(t)$ is the parameter of the psychological fluctuation, which is a bounded, namely $|d_i(t)| \leq k$, where k is a positive constant, α and β are the parameters of the distributed optimization algorithm.

Step 4 Calculate the power output of each we-energy (as equation 3 in Section 2), and judge whether the solution satisfies the inequality constrains which is decided by the capacity of the power generation for each we-energy.

IV. Simulation studies

In this section, the effectiveness of the obtained criteria will be shown.

Consider an energy internet consisting 6 we-energies (as shown in Fig. 3) and the following the global objective

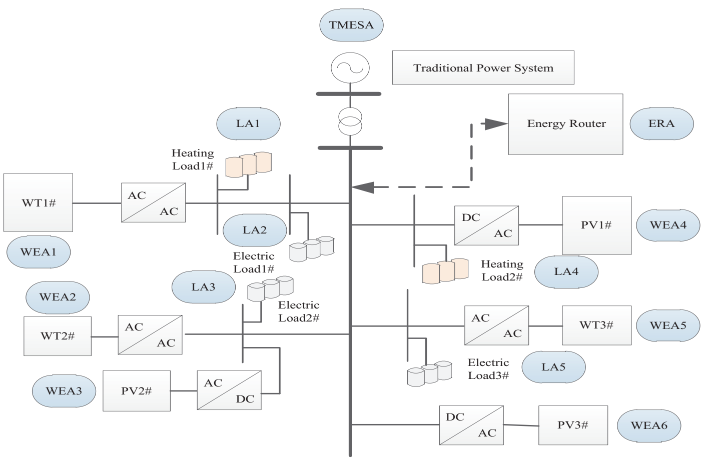


Fig. 3. Simulation Models of the Distributed Multi-Agent System-Based Energy Internet.

function of we-energy-based energy internet:

$$\min \quad \tilde{f}(P_r) = \sum_{i=1}^{6} \Bigg[C_{oi}(P_{ri}) - \frac{P_{rg}P_{ri}}{2a_i} + \frac{P_{rg}b_i}{2a_i} + P_{rg}(P_{load}^i + P_{loss}^i) \Bigg] \triangleq \sum_{i=1}^{6} f_i(P_{ri}) \tag{11}$$

where the bidding price-based generation cost for we-energies are

$$f_1(P_{ri}) = e^{0.3}P_{ri} - 3.3, \qquad f_2(P_{ri}) = e^{0.2}P_{ri} - 1,$$
$$f_3(P_{ri}) = 3.5P_{ri}^2 - 14P_{ri} + 4, \qquad f_4(P_{ri}) = 3e^{0.5}P_{ri} - 0.7,$$
$$f_5(P_{ri}) = 1.5P_{ri}^2 - 6P_{ri} + 2.5, \qquad f_6(P_{ri}) = 3e^{0.3}P_{ri} - 2.3,$$

Now, utilizing multi-agent system with disturbance (10) consisting of six agents to solve optimization problem (11). And the communication topology of the agents is depicted in

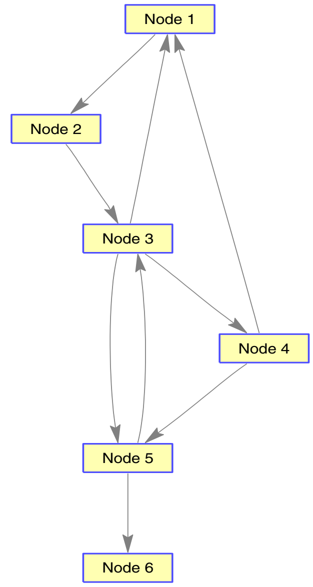


Fig. 4. Topology of Multi-Agent System.

Fig. 4, where a node represents a we-energy-based agent. The parameters in system (9) are chosen as $\alpha = \beta = 0.3$.

As mentioned above, for we-energy-based energy internet, uncertain resistance behaviors caused by the psychological fluctuation, which is resulted from its self-decision ability of the we-energy in the power trade, should be considered. The transient behavior of $P_{ri}(t)$ with disturbance, which is employed to describe the psychological fluctuation, is shown as Fig. 5. The initial value is chosen as $\mathbf{0}$. It can be seen that all the agents states $P_{ri}(t)$ converge to the optimal solution 0.395, which means that the solution of the bidding price is $0.395 yuan/KWh$. More specifically, the states of the agents

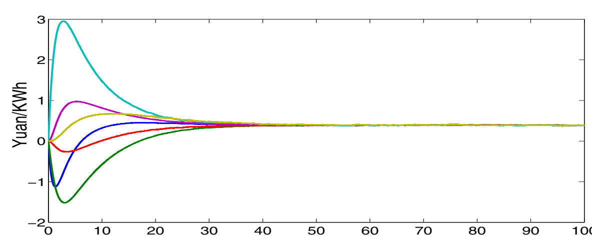


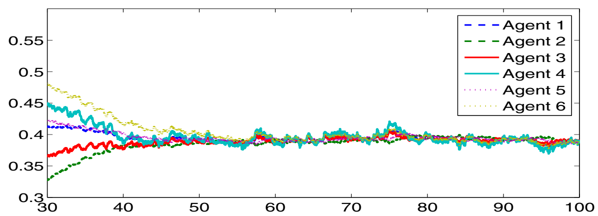
Fig. 5. Transient Behavior of $P_{ri}(t)$ of Agents with disturbance.

are oscillated by the disturbance between an interval which are shown in Fig. 6.

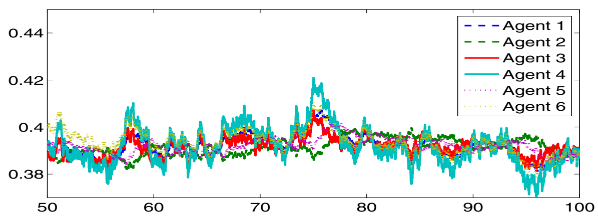
It is obvious that the simulation result illustrates that the transient behavior of agents are oscillating in $(0.37, 0.42)$, which is caused by the concerned disturbance in Fig. 7.

V. Conclusion

Considering the psychological fluctuation caused by the self-decision ability of the we-energy-based energy internet,



(a) The states of the agents oscillating in (0.3,0.5) after 30s



(b) The states of the agents oscillating in (0.37,0.42) after 50s

Fig. 6. States $P_{ri}(t)$ of Agents Oscillated by Disturbance.

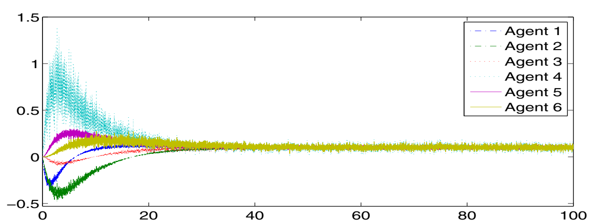


Fig. 7. Dynamic Curve of Disturbance $P_{ri}(t)d(t)$.

a novel power trade strategy has been proposed. And the uncertainty disturbance has been introduced to describe the psychological fluctuation of each we-energy. Moreover, a distributed optimization-based bidding pricing model has been presented, by which the minimum generation cost of the we-energy-based energy internet can be achieved and the power reference bidding price can be obtained.

References

[1] Q. Sun, F. Teng, and H. Zhang, "Energy internet and its key control issues," *Acta Automatica Sinica*, vol. 43, no. 2, pp. 176-194, 2017.

[2] J. Rifkin. "The third industrial revolution: how lateral power is transforming energy, the economy, and the world," *New York: Palgrave MacMillan*, 2011.

[3] A. Q. Huang, M. L. Crow, G. T. Heydt, et al, "The future renewable electric energy delivery and management (FREEDM) system: the energy internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133-148, 2011.

[4] Q. Sun, F. Teng, H. Zhang, and D. Ma, "Construction of dynamic coordinated optimization control system for energy internet," *Proceedings of the CSEE*, vol. 35, no. 14, pp. 3667-3677, 2015.

[5] H. Zhang, Y. Li, D. Gao, and J. Zhou, "Distributed optimal energy management for energy internet," *IEEE Trans. Ind. Informat.*, DOI: 10.1109/TII.2017.2714199, 2017.

[6] Q. Sun, B. Wang, B. Huang, and D. Ma, "The optimization control and implementation for the special energy internet," *Proceedings of the CSEE*, vol. 35, no. 18, pp. 4571-4580, 2015.

[7] J. Cao, K. Meng, J. Wang, Yang Mingbo, et al, "An energy internet and energy routers," *Science China: information sciences*, vol. 44, no. 6, pp. 714-727, 2014.

[8] R. Huang, L. Ye, and H. Liao, "Microelectronics technologies in renewable energy internet," *Science China: information sciences*, vol. 44, no. 6, pp. 728-742, 2014.

[9] M. Geidl, and G. Andersson, "Optimal power flow of multiple energy carriers," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 145-155, 2007.

[10] F. Teng, Q. Sun, and H. Zhang, "Coordinated optimization control strategy for we-energy in energy internet," *Chinese Control and Decision Conference*, DOI: 10.1109/CCDC.2016.7531889, 2016.

[11] Q, Sun, and Y. Chen, "Multi-energy flow calculation method for we-energy based energy internet," *IEEE International Conference on Energy Internet*, DOI: 10.1109/ICEI.2017.13, 2017.

[12] J. Hu, Q. Sun, and F. Teng, "A game-theoretic pricing model for energy internet in day-ahead trading market considering distributed generations uncertainty", *IEEE Symposium Series on Computational Intelligence*, DOI: 10.1109/SSCI.2016.7849839, 2017.

[13] W. Zhang, W. Liu, X. Wang, L. Liu, and F. Ferrese, "Online optimal generation control based on constrained distributed gradient algorithm," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 35-45, May 2014.

[14] Z. Wang, W. Wu, and B. Zhang, "A fully distributed power dispatch method for fast frequency recovery and minimal generation cost in autonomous microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 19-31, Nov. 2015.

[15] Q. Sun, R. Han, H. Zhang, J. Zhou, and J. M. Guerrero, "A multi-agent-based consensus algorithm for distributed coordinated control of distributed generators in the energy internet," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3006-3019, Apr. 2015.

[16] V. Loia, A. Vaccaro, "Decentralized economic dispatch in smart grids by self-organizing dynamic agents," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 4, pp. 397-408, June 2014.

[17] H. Xing, Y. Mou, M. Fu, and Z. Lin, "Distributed bisection method for economic power dispatch in smart grid," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3024-3035, 2015.