Coordinated Optimization Control Strategy for We-Energy in Energy Internet

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Abstract: A novel energy supply mode named "We-Energy" is first proposed for the Energy Internet in this paper. With the advanced features such as producer-consumer integration, energy supply complementarity, openness of operating mode and regionalization of energy consumption, We-Energy stimulates "grass-roots" energy entities to participate in energy productions and interactions, where more renewable and clean energy resources can be utilized. To construct a low-carbon and low-cost energy consumption structure, a multi-objective optimization model is presented. Furthermore, a distributed multi-agent system-based coordinated optimization control strategy is designed to achieve the optimal energy management of We-Energies. Finally, simulation results are given to illustrate the effectiveness of the proposed coordinated optimization control strategy.

Key Words: We-Energy, Energy Internet, Multi-Objective Optimization, Multi-Agent System, Coordinated Control

1 INTRODUCTION

With the development of society and economy, the demand for energy keeps growing. Due to the depletion of fossil energy and the aggravation of environmental pollution, there is a major concern about developing a sustainable energy system to realize low-carbon energy consumption, in which the fossil energy is mostly replaced by the renewable energy. Hence, the concept of "Energy Internet" is proposed to address the issue. The vision of energy internet is firstly proposed by Jeremy Rifkin in 2008 [1], and noted that energy internet would be an effective solution to utilize the renewable energy, as a core in the third industrial revolution. Then the related topics about energy internet have been widely studied: the structure of energy internet has been constructed in [2-4], the energy router has been developed in [5-7], the optimal dispatch approaches of the energy hub have been studied in [8] [9], the control of the solid-state transformer has been researched in [10-12], and the coordinated optimization control methods have been presented in [13] [14].

Previous researches on energy internet are completed in the case that the energy dispatch and trade are led by a traditional major energy supplier (e.g. the traditional power system). However, the traditional energy system has been developed into an open platform, on which energy resources are interconnected across regions and information can be widely spread and globally shared, with the popularization of energy internet. Because of the flattening structure of the forthcoming energy internet and the wide use of the information communication technology, the transmission mode of the energy and the information in the energy internet is changed to the peer-to-peer mode, instead of the peer-to-area mode in traditional energy system. Moreover， on account of the characteristics of openness, sharing, plug and play and peer-to-peer integration, the motivation of end users that work as major energy suppliers, are improved greatly, while the impact of the traditional major energy supplier is gradually weakened. And end users do not need supplying by a unified energy supplier. More energy options will be provided for multiple end users, according to their own energy demands. Therefore, the revolution of the energy consumption will inevitably create a great mount of new energy suppliers and energy supply modes.

Based on the discussions mentioned above and inspired by the internet mode which integrates the information collection and publication, a novel energy supply mode for the Energy Internet named "We Energy" is presented in this paper, which consists of numerous energy suppliers integrating the energy production and consumption and operates with bi-directional power flow. Based on this new energy supply mode, some basic control problems in power systems should be restudied such as the coordinated optimization control strategy, the relay protection, the power flow, the energy management, etc. Due to the limited space, this paper mainly focuses on the coordinated optimization control strategy of the Energy Internet in We-Energy mode.

The rest of the paper is organized as follows. Section 2 presents the definition and the characteristics of We-Energy. In section 3, the multi-objective optimization model is proposed. In section 4, the coordinated optimization control strategy of We-Energy is proposed, based on the distributed multi-agent system. In section 5, several simulation cases are given to show the effectiveness of the proposed method. Section 6 concludes the paper.

2 DEFINITION AND CHARACTERISTICS OF WE-ENERGY

In general, the proposed "We-Energy" is a novel energy production-storage-consumption mode (sees Fig.1), in which the normative or non-normative energy, generated by personal energy suppliers, can be provided to the specific majority or a single user in the energy internet, through advanced information communication technology,

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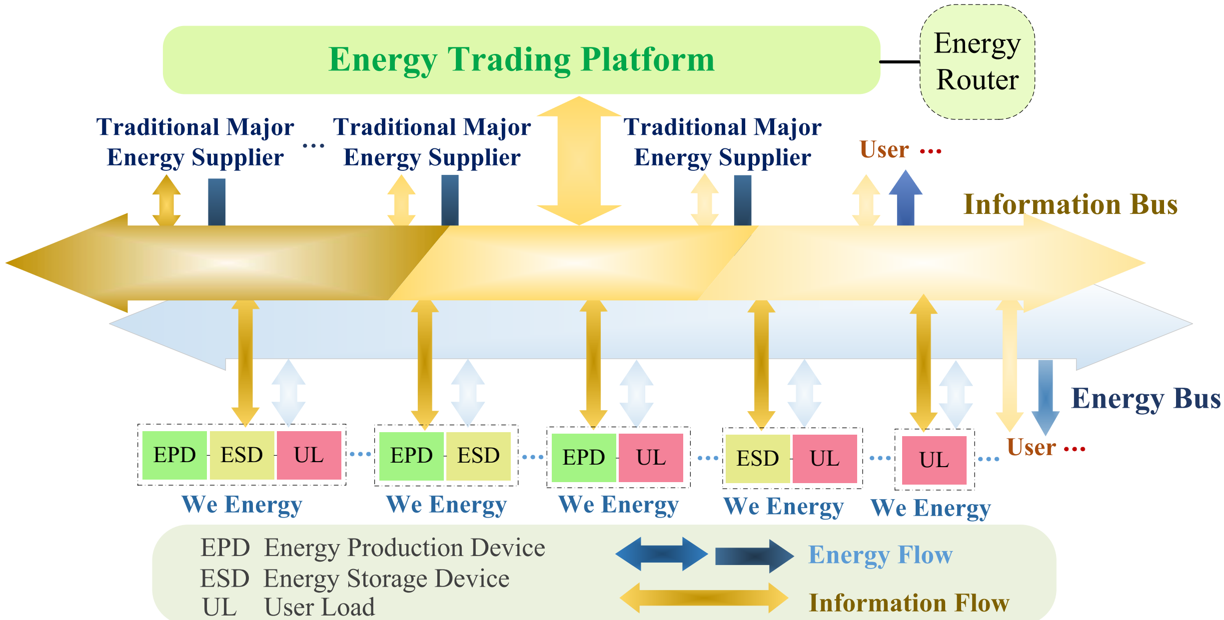

Fig 1. Operation mode of We-Energy in the Energy Internet.

power converter and automatic control technology. Specifically, We-Energy is an energy entity with the features of complementarity, openness and regionalization, which can work as both an energy producer and an energy consumer. Namely, a personal energy entity, enterprise, community, which is provided with energy production devices or energy storage devices (e.g. distributed generations, storage devices, Combined Cooling Heating and Power), can be defined as a We-Energy.

The main features of the proposed We-Energy are given as follows:

1. Producer-Consumer Integration: We-Energy breaks the energy supply pattern, led by the traditional major energy supplier. Common energy entities can participate in energy trades and transmissions, and the energy transmission are changed into bi-directional transmission. Therefore, in the times of the We-Energy, the energy production, transmission, storage and consumption can be done by each We-Energy in the energy internet. And then each energy entity is an interactive energy entity, no matter an energy producer, an energy transmitter, an energy storage, or an energy consumer;
2. Energy Supply Complementarity: various We-Energies are employed to achieve the energy production, energy transmission, energy storage and energy consumption. And the mode of the energy production and energy consumption of each We-Energy is different, while the energy demand of each user is unique. The regional diversity and complementarity of the energy production and the energy demand contribute to achieving the energy balance among We-Energies, reducing the cost of energy transmission, and improving the utility efficiency of renewable energy;
3. Openness of Operating Mode: We-Energies are the mass energy entities, most of them from the energy grassroots level. The participation of the amateurish energy entities makes the energy trading more peer-to-peer, more renewable and less utilitarian, promoting the development of the non-fossil energy;
4. Regionalization of Energy Consumption: by the increase of We-Energies, the regional self-sufficient energy supply can be realized, due to the broader renewable energy resources and other clean energy resources. Then the advantage of long-distance transmission of the traditional fossil energy is weakened greatly. As the energy production and the energy consumption of We-Energies are more convenient and flexible for the common users than that of the professional and large-scale traditional major energy suppliers, the development of the We-Energy can gradually change the structure of the traditional energy consumption and reduce the dependence on the fossil energy.

In conclusion, We-Energy is a comprehensive manifestation of energy producers, energy storages and energy consumers in the energy internet. By means of the "We-Energy", the user is not only a passive energy consumer, but also an active participant, even a potential energy producer in the energy interaction in the energy internet.

3 MULTI-OBJECTIVE OPTIMIZATION MODEL OF WE-ENERGY

In the We-Energy mode, the secondary energy resources contain both electricity and heat. Therefore, to address the optimization and energy dispatch problem of We-Energy, it is necessary to consider the effect of heat. In addition, many other factors make the optimal dispatch of We-Energy more difficult, such as the complexity of primary energy resources of We-Energies and diversity of the energy demand of the users. Accordingly, the multi-objective optimization model of We-Energy is investigated to achieve the optimal dispatch of We-Energies, to realize the optimal utilization of distributed renewable energy resources and construct a low-carbon structure of the energy consumption.

3.1 Objective Function

The aim of dispatching optimally We-Energies is to utilize more renewable energy and less fossil energy, while maximizes the environmental benefit and the economic benefit. The objective function is as follows:

$$f = \min\left(f_1, f_2\right), \tag{1}$$

where f_1 is the environmental benefit function of energy dispatch, f_2 is the economic benefit function of energy dispatch.

3.1.1 Environmental Benefit

To solve the energy crisis and environmental problems, the consumption of coal, natural gas and other fossil energy should be reduced. To maximize the environment benefit and minimize the carbon emission, the use of the renewable energy resources and clean energy resources should be maximized, which is expressed as

$$\begin{aligned} f_1 = \min \sum_{t=1}^{T}\sum_{j=1}^{N_G}\left(a_j P_{Gj,t}^2 + b_j P_{Gj,t} + c_j\right) \\ + \sum_{t=1}^{T}\sum_{j=1}^{N_G} Q_{Grj,t} + \sum_{t=1}^{T}\sum_{j=1}^{N_F} Q_{Fj,t} \end{aligned}, \tag{2}$$

where T is the number of dispatch intervals, N_G is total number of natural gas-fired CHP, a_j, b_j, c_j is the generation parameters for the jth natural gas-fired CHP, $P_{Gj,t}$ is the active power of the jth natural gas-fired CHP. $Q_{Grj,t}$ is the heat supply of the jth natural gas-fired CHP at time t . N_F is the amount of the traditional coal-fired boiler unit. $Q_{Fj,t}$ is the heat supply of the jth traditional coal-fired boiler unit at time t .

3.1.2 Economic Benefit

Energy internet is a hybrid energy supply system with We-Energies, whose primary energy resources contain natural gas, fossil energy and renewable energy, such as wind, solar, biomass and so on. The optimal sub-objective is to minimize the cost of energy supply and maximize the economic benefits under the condition that the energy demand of We-Energies and other loads can be satisfied. The sub-objective function can be denoted as

$$f_2 = \min\begin{pmatrix} F_{\cos t}^W + F_{res}^W + F_{\cos t}^S + F_{\cos t}^B \\ + F_{\cos t}^P + F_{\cos t}^G + F_{\cos t}^F \end{pmatrix}, \tag{3}$$

where $F_{\cos t}^W$ is the operating cost of wind turbine, $F_{\cos t}^S$ is the operating cost of the photovoltaic generator, $F_{\cos t}^B$ is the operating cost of the biomass generator. $F_{\cos t}^W$, $F_{\cos t}^S$ and $F_{\cos t}^B$ are all related to the capacity of active power and the feed-in tariff in electrical market. F_{res}^W is the compensation cost of standby capacity of wind turbines. $F_{\cos t}^P$ is the operating cost of the pumped storage unit. $F_{\cos t}^G$ is the operating cost of the natural gas-fired CHP.

3.2 Constraint Condition

Since heat is an energy transmission and consumption terminal in the energy internet, besides the conventional constraints in optimization problems of traditional power system, there are several conditions that should be considered such as the balance between the heat energy demand and heat energy supply, the maximum energy supply of heat producer and the capacity of heat transmission line.

4 COORDINATED OPTIMIZATION CONTROL BASED ON MULTI-AGENT CONSENSUS ALGORITHM

As there are numerous autonomous We-Energies in the energy internet, a multi-agent system based coordinated control strategy is presented in this paper.

4.1 Classification, Definition and Task Decomposition of Multi-Agent

According to the functional characteristics of the devices (see Fig.1) in the energy Internet， four kinds of multi-agents are defined, which are We-Energy Multi-Agent, Load Multi-Agent, Traditional Major Energy Suppliers Multi-Agent and Energy Router Multi-Agent. And the definition and task of the agents are described as following：

1. **We-Energy Agent (WEA)**: corresponding to a We-Energy in the energy internet, monitors the operating state of each energy production and energy storage device in real time; responds to the control signal of Energy Router Agent (ERA) and calculates the power generation/heating supply allowance of each energy supply device. According to the coordinated control instruction of ERA, a WEA cooperates with other WEAs or Traditional Major Energy Supplier Agents (TMESA), to adjust the power generation/heating supply state of each energy supply device to satisfy the energy demand of the users in the energy internet;
2. **Load Agent (LA)**: corresponding to a load in the energy internet, monitors the operating state of each load in real time; reports the energy demand of users to ERA; cuts load according to control instruction of ERA;
3. **Traditional Major Energy Supplier Agent (TMESA)**: corresponding to a traditional major energy supplier (e.g. traditional power system and heating network), integrates energy demand information with ERA. According to the coordinated control instruction, a TMESA cooperates with other TMESAs or WEAs to satisfy the energy demand of the users in the energy internet;
4. **Energy Router Agent (ERA)**: corresponding to the energy router. According to the energy demand, sent by LA, ERA makes plans to satisfy the energy demand of the users, keep the energy balance among WEAs and maintain the energy internet operating normally.

4.2 Energy Coordinated Control Strategy Based on Consensus Algorithm of Multi-agent

To schedule We-Energies and other energy suppliers effectively and efficiently in the energy internet, an energy coordinated control strategy based on the multi-agent consensus algorithm is designed, as is shown in Fig. 2.

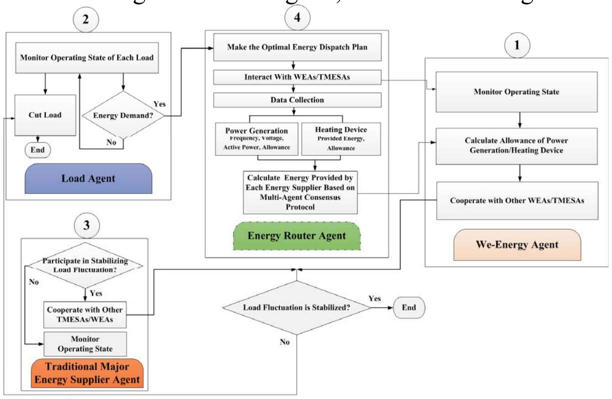

Fig. 2. Energy Coordinated Control Strategy Based on the Multi-Agent Consensus Algorithm.

In the process of stabilization of the load fluctuation in the energy Internet, the specific method of calculating electric/heat energy supplied by each energy supplier device (e.g. WEA, TMESA) is presented as following:

Step 1: Calculate the average of the electric/heating supply allowance of the power generation/heating device:

$$\begin{aligned} \dot{P}_{resi}(t) &= \sum_{j\in N_i} a_{ij}\left(P_{resj}(t)-P_{resi}(t)\right) \\ \dot{Q}_{resi}(t) &= \sum_{j\in M_i} a_{ij}\left(Q_{resj}(t)-Q_{resi}(t)\right) \end{aligned}, \tag{4}$$

where N is a number of WEAs and ESAs, corresponding to power generations, that participate in the coordinated control task. P_{resi} is the generating allowance of power generation i. M is a number of WEAs and ESAs, corresponding to heating device, that participate in the coordinated control task. Q_{resi} is the heating allowance of heating device i. a_{ij} is the connection weight of agent. If there is an information exchange between agent i and agent j, $a_{ij}=1$; otherwise, $a_{ij}=0$. P_{ave}, Q_{ave} are the average values of the electric/heating supply of the power generation/heating device respectively;

Step 2：Calculate the energy provided by each power generation/heating device：

$$\begin{aligned} P_{ui}/P_{need} &= P_{resi}/n\cdot P_{ave} \\ Q_{ui}/Q_{need} &= Q_{resi}/m\cdot Q_{ave} \end{aligned}, \tag{5}$$

where P_{ui} is the energy provided by power generation i. P_{need} is the energy demand of the electric load. Q_{ui} is the energy provided by heating device i. Q_{need} is the energy demand of the heating load.

Step 3：Use the multi-agent consensus algorithm to control the frequency and voltage of power generation, to ensure that the parameters are the same as distributed power system. The control objectives are：

$$\begin{aligned} &\lim_{t\to\infty}\left\|f_i(t)-f_{main}\right\|=0,\quad \forall i\in N \\ &\lim_{t\to\infty}\left\|V_i(t)-V_{main}\right\|=0,\quad \forall i\in N \end{aligned}, \tag{6}$$

where $f_i(t)$ is the frequency of power generation i. $V_i(t)$ is the voltage of power generation i. The frequency of the distributed power system $f_{main}=50Hz$ in China. The voltage of the distributed power system $V_{main}=220V$ in China. Specifically, the consensus protocol is designed as

$$\begin{aligned} \dot{f}_i(t) &= \sum_{j\in N_i} a_{ij}\left(f_j(t)-f_i(t)\right)+a_i\left(f_i(t)-f_{main}\right) \\ \dot{V}_i(t) &= \sum_{j\in N_i} a_{ij}\left(V_j(t)-V_i(t)\right)+a_i\left(V_i(t)-V_{main}\right) \end{aligned}, \tag{7}$$

5 SIMULATION

In order to verify the effectiveness of the proposed coordinated optimization control strategy for the We-Energy, the following simulation model is built according to the experimental system constructed by the State Key Laboratory.

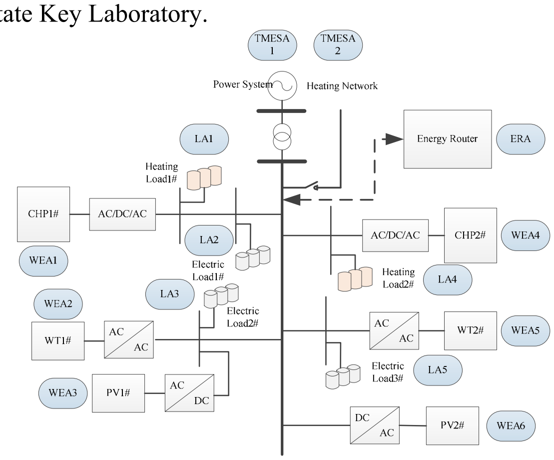

Fig. 3. Simulation Models of the Distributed Multi-Agent System-Based Energy Internet

We-Energies in the energy internet model contains two wind turbines, two photovoltaic generators, two natural gas-fired CHPs and relative electric/heating load. The sum of electric load in the energy internet is 60Kw, which is supplied by wind turbine 1# (providing 6Kw), wind turbine 2# (providing 25Kw), photovoltaic generator 1# (providing 12Kw), photovoltaic generator 2# (providing 10Kw), natural gas-fired CHP 1# (providing 4Kw) and natural gas-fired CHP 2# (providing 3Kw),respectively. The heat loads are provided by natural gas-fired CHP 1# and 2#. Assume that in the energy internet there is no power fluctuation of heating loads or energy exchange between heating energy entities. In normal operation mode, the state parameters of the devices are shown in Table 1.

Table 1 Parameters of the Energy Internet

Parameter	Value	Parameter	Value
Rated capacity of wind turbine 1# (Kw)	20	Rated capacity of natural gas-fired CHP 1# (Kw)	25
Rated capacity of wind turbine 1# (Kw)	40	Rated capacity of natural gas-fired CHP 2# (Kw)	25

Parameter	Value	Parameter	Value
Rated capacity of photovoltaic generator 1# (Kw)	30	Rated frequency of the energy Internet (Hz)	50
Rated capacity of photovoltaic generator 2# (Kw)	10	Rated voltage of the energy Internet (V)	220

In addition, the fixed electric load is 60Kw and the variable electric load is 50Kw in normal operation of energy Internet. Assume that when t=2s, variable electric load 2# (35Kw) is switched in the energy internet. Then the simulation results are shown in Fig. 4.

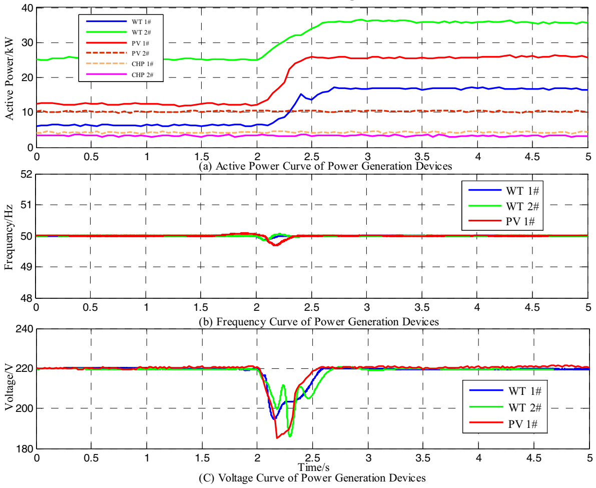

Fig. 4. We-Energy Response for Sudden Load Increase in Energy Internet: Energy Coordinated Control Based on Distributed Multi-Agent System

As is seen in Fig. 4, after switching the variable electric load into the energy internet, the ERA detected the energy demand signal, the available power generations are chose rapidly. Then the calculation results of the optimization were sent to WEAs (WEA2, WEA3 and WEA5). And the operating states of the wind turbine 1#, wind turbine 2# and photovoltaic generator 1# were adjusted. The simulation results illustrate that not only the objective that maximize the utilization of distributed renewable energy generation is realized, but also the load fluctuation in the energy internet is stabilized quickly, by using the energy coordinated control strategy proposed in this paper. Meanwhile, the frequency oscillation and voltage oscillation of each energy supply device is very small, which guarantees the stability of the energy internet and the high quality of the energy supply.

6 CONCLUSION

We-Energy, as a new energy generation-storage-consumption mode for the energy internet, has been first proposed in this paper. By means of We-Energy, the user has been not only a passive energy consumer, but also an active participant, even a potential energy producer in the energy internet. Moreover, to utilize the distributed renewable energies in the We-Energy mode reasonably, a multi-objective optimization model and a coordinated control method based on multi-agent consensus algorithm are proposed to solve the problem. Finally the simulation results have been shown to demonstrate the validity of the proposed approach.

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