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Agent-based Coordinated Operation Strategy for Active Distribution Network with Distributed Energy Resources

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***Abstract*—With the development of distributed energy resources (DERs) and the increasing flexibility in active distribution networks (ADNs), the economic operation of ADN coordinating both generation and demand sides is required to be studied. In this paper, considering the electricity price response of DER, a coordinated operation strategy for ADN is presented based on a bi-level agent framework. DER agent makes their own response based on the technical operability and economic consideration, while ADN agent will finally coordinate each participant by using the interactive benefit prioritization (IBP) principle. The simulation results indicate that the proposed strategy cannot only reduce the power imbalance, but also improve the economic operation of ADN. Moreover, consumption of renewable energy is ameliorated as well.**

***Index Terms*—active distribution network, multi-agent, distributed energy resources, interactive benefit prioritization, price response**

I. INTRODUCTION

Recently, the decarbonisation, decentralisation and digitisation are driving the transition to a bidirectional power system with increasing level of distributed energy resources (DERs) [1]. To improve the operability and flexibility of the new system, the concept for planning, construction, and operation of the active distribution networks (ADNs) were proposed [2]. It provides the feasibility to manage and coordinate the various types of DERs including distributed generator (DG), energy storage (ES) and flexible load (FL) etc. [3], [4]. Besides, the participation of electricity consumers as active and controllable load could provide the flexibility for generation and demand balance [5]. Thus, the potentials of energy facilities can be utilized in the distribution networks and the overall energy efficiency can be improved [6]. So far, several demonstration projects have been developed worldwide, e.g. ADINE in Europe, RDSI in the United States, YSCP in Japan and 863 Program in China etc. to explore the feasibility and operability of ADN [7].

The optimal operation of ADN is incentivised by distribution network operators (DNOs) and researchers. It was regarded as an optimal power flow problem considering the DERs in most works [8]. Thus, the conventional centralized optimal approach (COA) was implied to realize the optimal dispatching of DERs in ADN with different global optimal objective. For instance, considering the battery ES and wind-based embedded DG in ADN, an active-reactive coordinated optimal power flow model was presented in [9] to maximize operational profits. Dynamic optimal power flow was introduced to deal with temporal characteristic of ES and directly/storage-based flexible load in [10]. Based on that, a dispatching management framework was proposed including DG in ADN context. In [11], the day-ahead bidding strategy and real-time optimal operation of ES were integrated. By solving the two stages optimization model, the effective charging/discharging (C&D) plan can be obtained considering the DG and load uncertainty. Since the surplus DG outputs will cause overvoltage, a robust optimal dispatch model was proposed to determine the critical photovoltaic unit in ADN for providing ancillary services by using a second-order cone programming [12]. However, the above works based on COA always optimize the operation of ADN with the expense or disregard of DER's benefit and willingness. That is partly due to the unsolvable of high order strong nonlinear and nonconvex model, while they are formulated in optimal operational problem [13]. Moreover, with the improvement of market mechanism in ADN, the maximal interests are dedicated to the collaborative management and independent decisions of participants. In this context, COA shows more deficiencies to characterize and collaborates the interests of various market participants [14], [15].

Thus, the agent technology was introduced to build ADN model for realizing the communication and interaction among DERs in a decentralized way [16]. The concept and practical application of agent enables the analysis of interactions of DERs and the dynamic simulation of multi-entity and multi-factor [17] in ADN. A basic agent technology based dispatching scheme for distribution system with DG was proposed in [18]. The model-free control procedure of multi-agent was illustrated by adopting control net protocol. Considering the dynamically and efficiently management of DGs and loads for power balance, a non-hierarchical agent framework was proposed for energy dispatching [19]. The communication ontology was presented in detail and each element in the distribution system, e.g. substation, bus, and feeder etc., were represented by the relevant agent, but the participation of ES and FL was not involved. In [20], agent-based operation architecture was presented for the economic operation of local

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DERs and overall ADN. The regional agent is responsible for communication between ADN agent and several DERs within a certain area, while the electricity price response of ES and FL was ignored. Similarly, a tri-level decentralized agent system framework was proposed to improve dynamic stability, self-healing, and security etc. of ADN [21]. The mode switching of different hierarchical agents according to the system condition was presented for hybrid operation control. Moreover, considering the power balance coordination between each area in ADN, a hierarchical agent-based scheduling strategy was proposed in [22]. The Petri Net model was used to describe behaviour of DERs, without regard for FL, integrated with bi-level agent-based energy management strategy of ADN [23]. Since the market mechanism rise its significance, the optimal bidding for market participant of ADN was implemented by a tetra-level agent system in [24]. An extra top-level agent was presented to maximize the profit of the overall system based on the commonly used tri-level framework. For realising the market mechanism of ADN, the market operator agent was introduced to determine the market clear price and bidding process [25]. Since ADN agent took in charge of power management, the market clearing problem and coordinated dispatching problem were combined with the proposed coordinated scheduling model. The participation of FL was further exploited in [26]. However, the communication efficiency of the agent system was not discussed at all.

Generally, there are two issues for the agent framework of above works. The first one is the supervisory agent between DER agent and ADN agent. The main concern is to share the burden and clarify the respective duty [17]. It is more effective in large-scale system rather than ADN, which contain a small number of DERs in aggregated way. The other one is the decoupling of market and power management in ADN [27]. Indeed, the distinct responsibility will reduce system complexity, but the utilization of the agent cannot be improved. Besides, the communication consumptive of both that is unavoidable. Thus, combining with the price response of DERs, a bi-level agent system is presented in this paper. Based on that, a coordinated operation strategy is proposed to promote the participation of each DER in ADN and improve power imbalance of ADN. In the proposed strategy, DER agent responsible for controlling the output/demand of the relevant component and response to the interactive information from ADN agent. ADN agent needs to balance the power supply of ADN and coordinate each DER agent by using price incentive. The main contributions of this paper are as follows:

- An agent-based model of ADN is built, where the technical characteristics and economical interactions of DERs, including DG, ES and FL, are established.
- The deep participation mechanism for price response of DERs, i.e. DG, ES and FL are integrated into the optimal operation of ADN.
- The market mechanism of ADN and economic operation of DERs are combined based on the interactive benefit models.
- Agent-based operation strategy for each DER in ADN is proposed based on the interactive benefit prioritization (IBP) principle, to maximize the renewable energy consumption and minimize power imbalance of ADN.

The rest of the paper is organized as follows: Section II describes the modelling of each agent. Section III presents the agent-based coordinated operation strategy. Section IV conducts the case studies in test system, and conclusions are drawn in Section V.

II. Modelling of the Agents

In this paper, DER agents are supposed as an aggregated form of the same kind of DER units at relevant bus. For instance, FL agent is consisted of multiple FLs with a small capacity within a neighbourhood, so that it is scale enough for price response. ES agent is aggregated by a group of kilowatt/watt-level ES units in a certain area and DG agent is the same. Although there is no connection between each DER agent in presented agent system, as shown in Fig. 1, the interaction among DER agents can still be achieved through ADN agent in an indirect way. Besides, it needs to be noted that, there is only information transfer between agent in this paper. Power transmission is realized through network.

Thus, in this section, the power model for different kind of DER agent is established firstly. And then, the function of ADN agent is also presented. The interactive benefits model of DER agent and coordinated operation strategy will be expounded in the next section.

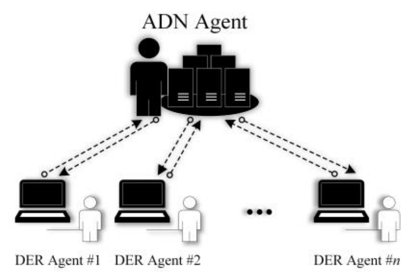


Fig. 1. Structure diagram of bi-level multi-agent system

A. Model of DG agent

In this paper, we only discuss two most common types of DG: wind turbine (WT) and photovoltaic (PV). The probability distribution function with natural condition parameters and sequential Monte Carlo simulation is applied to describe the output of DG. The DG agent needs to use the historical data to predict the output of aggregated DG units. The predicted output and real-time output will be sent to ADN agent. The power prediction model of WT and PV unit is given in detail as follows.

1) Wind turbine

Output of WT unit varies with wind speed with quantified relationship defined in (1). Wind speed is generally modelled by the Weibull distribution. It is a straightforward and widely used probabilistic model to simulate wind speed distribution. The shape and scale parameters of the Weibull distribution are determined based on the historic data of wind speed at the installation location. Thus, the output of WT unit can be obtained in the time series simulation by using [9]:

$$P_{i,t}^{\mathrm{WT}}=\begin{cases} P_{i,N}^{\mathrm{WT}} & v_{i,N}<v_{i,t}\le v_i^{\text{cut-out}} \\ \dfrac{v_{i,t}-v_i^{\text{cut-in}}}{v_{i,\mathrm{N}}-v_i^{\text{cut-out}}}\times P_{i,N}^{\mathrm{WT}} & v_i^{\text{cut-in}}<v_{i,t}\le v_{i,N} \\ 0 & v_{i,t}\le v_i^{\text{cut-in}}\ or\ v_{i,t}>v_i^{\text{cut-out}} \end{cases} \quad (1)$$

where $P_{i,t}^{\mathrm{WT}}$ is the active power of the i^{th} WT unit at time period t; $P_{i,N}^{\mathrm{WT}}$ is the rated power of the i^{th} WT unit; $v_{i,t}$ is the wind speed of the i^{th} WT unit at time period t; $v_i^{\text{cut-in}}$ is the designed cut in wind speed of the i^{th} WT unit; $v_i^{\text{cut-out}}$ is the designed cut out wind speed of the i^{th} WT unit; $v_{i,N}$ is the rated wind speed of the i^{th} WT unit.

2) Photovoltaic

The output of PV unit is greatly determined by the intensity of solar radiation. Usually, the ultraviolet (UV) light intensity is approximated by using beta distribution. According to the historical illumination intensity data of the installed location, the shape parameters of the distribution function can be obtained, so that the actual illumination intensity can be predicted. Theoretically, the output of PV unit can be calculated using the following formula [28]:

$$P_{i,t}^{\mathrm{PV}}=\frac{\left[1+k_i\times\left(T_{i,t}-T_i^{\tau}\right)\right]\times r_{i,t}}{r_i^{\mathrm{STC}}}\times P_i^{\mathrm{PV,STC}} \quad (2)$$

where $P_{i,t}^{\mathrm{PV}}$ is the active power of the i^{th} PV unit at time period t; $P_i^{\mathrm{PV,STC}}$ is the output of the i^{th} PV unit under standard test condition; r_i^{STC} is the UV light intensity corresponding to $P_i^{\mathrm{PV,STC}}$ of the i^{th} PV unit; $r_{i,t}$ is the UV light intensity of the i^{th} PV unit at time period t; k_i is the power temperature coefficient of the i^{th} PV unit; $T_{i,t}$ is the sum of the battery temperature of the i^{th} PV unit at time period t, T_i^{τ} is the reference temperature of the i^{th} PV unit.

B. Model of ES agent

The state of charge (SOC) of ES unit is the current capacity of the battery determined by its C&D power and initial SOC [29]. The SOC can be calculated as follows:

$$SOC_{i,t+1}=SOC_{i,t}+\frac{\left(\eta_i^{\mathrm{cha}}\times u_{i,t}^{\mathrm{cha}}-\eta_i^{\mathrm{dis}}\times u_{i,t}^{\mathrm{dis}}\right)\times P_{i,t}^{\mathrm{ES}}}{E_{i,\mathrm{N}}^{\mathrm{ES}}}\times\Delta t \quad (3)$$

subject to:

$$\begin{cases} SOC_i^{\min}\le SOC_{i,t}\le SOC_i^{\max} \\ u_{i,t}^{\mathrm{cha}}+u_{i,t}^{\mathrm{dis}}\le 1 \\ u_{i,t}^{\mathrm{cha}},u_{i,t}^{\mathrm{dis}}=\{0,1\} \\ \sum_{t=1}^{\Delta T}\left(u_{i,t}^{\mathrm{cha}}+u_{i,t}^{\mathrm{dis}}\right)\le N_{i,\max}^{\mathrm{cha}}+N_{i,\max}^{\mathrm{dis}} \\ 0\le P_{i,t}^{\mathrm{ES}}\le P_{i,\max}^{\mathrm{ES}} \\ 0\le N_i^{\mathrm{cha}}\le N_{i,\max}^{\mathrm{cha}} \\ 0\le N_i^{\mathrm{dis}}\le N_{i,\max}^{\mathrm{dis}} \end{cases} \quad (4)$$

where $SOC_{i,t}$ is the SOC of the i^{th} ES unit at time period t; $P_{i,t}^{\mathrm{ES}}$ is the C&D power of the i^{th} ES unit at time period t; N_i^{cha} and N_i^{dis} are the actual charging and discharging times of the i^{th} ES unit within control cycle ΔT; η_i^{cha} and η_i^{dis} are respectively the C&D efficiencies of the i^{th} ES unit; $E_{i,\mathrm{N}}^{\mathrm{ES}}$ is the rated capacity of i^{th} ES unit; Δt is the unit control time period; $u_{i,t}^{\mathrm{cha}}$ and $u_{i,t}^{\mathrm{dis}}$ are the binary variable indicating the C&D behaviour of ES unit, that $u_{i,t}^{\mathrm{cha}}$=1 represent i^{th} ES unit charging at time period t, otherwise $u_{i,t}^{\mathrm{cha}}$=0, and $u_{i,t}^{\mathrm{dis}}$=1 represent i^{th} ES unit discharging at time period t, otherwise $u_{i,t}^{\mathrm{dis}}$=0; $SOC_i^{\min}$ and $SOC_i^{\max}$ are the minimum and maximum SOC of the i^{th} ES unit; $P_{i,\max}^{\mathrm{ES}}$ is the maximum C&D power of the i^{th} ES unit; $N_{i,\max}^{\mathrm{cha}}$ and $N_{i,\min}^{\mathrm{dis}}$ are the maximum C&D times of the i^{th} ES unit within ΔT.

Commonly, ES unit will absorb the redundant power from the ADN and compensate the power shortage. As with the economic incentive when market mechanism is introduced, ES unit would discharge at high electricity prices and charge at low electricity prices to maximize its own profit [30]. An example of the C&D plan of ES unit without price incentive is shown in Fig. 2 (let ΔT=24h, Δt=1h).

Firstly, the minimum discharging price $c_{\min}^{\mathrm{dis}}$ and the maximum charging price $c_{\max}^{\mathrm{cha}}$ (the two horizontal dotted line in Fig. 2) are determined by the maximum allowable C&D times of ES unit (let $N_{\max}^{\mathrm{cha}}$=6, $N_{\min}^{\mathrm{dis}}$=5) and the scheduled electricity price profile (the blue dashed line in Fig. 2). Concretely, due to constrains of the maximum allowable C&D times, ES unit will discharge at the highest top five ($N_{\min}^{\mathrm{dis}}$) electricity prices corresponding to the time periods of 11-16 and charge at the lowest top six ($N_{\max}^{\mathrm{cha}}$) electricity prices corresponding to the time periods of 1-4 and 22-23. In order to simplify the above analysis process, the sixth ($N_{\min}^{\mathrm{dis}}$+1) highest electricity price within ΔT is defined as the minimum discharging price $c_{\min}^{\mathrm{dis}}$ and the seventh ($N_{\max}^{\mathrm{cha}}$+1) lowest electricity price within ΔT is defined as the maximum charging price $c_{\max}^{\mathrm{cha}}$. Thus, ES unit will discharge during the time periods where the electricity price is higher than $c_{\min}^{\mathrm{dis}}$, and charge during the time periods where the electricity price is lower than $c_{\max}^{\mathrm{cha}}$.

The C&D plan of ES unit within a control cycle can be easily determined according to $c_{\min}^{\mathrm{dis}}$ and $c_{\max}^{\mathrm{cha}}$. Specifically, during the time periods of 1-4 and 22-23, ES unit will charge from system since electricity price is lower than $c_{\min}^{\mathrm{dis}}$ (the green thick line in Fig. 2). During the time periods of 5-11, 17-21 and 24, ES unit keeps inaction because electricity price is between $c_{\min}^{\mathrm{dis}}$ and $c_{\max}^{\mathrm{cha}}$ (the black thick line in Fig. 2). During the time periods of 11-16, thanks to electricity price is higher than $c_{\max}^{\mathrm{cha}}$, ES unit will discharge to system (the red thick line in Fig. 2). Furthermore, combining the C&D plan of aggregated ES units, ES agent will send it to ADN agent.

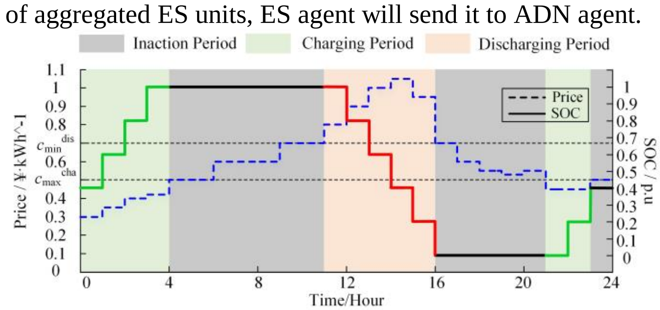


Fig. 2. C&D plan of ES Agent without price incentive

C. Model of FL agent

There are various FL units that can be controlled in ADN, some examples include electric vehicles, air-conditions and thermostatic loads etc. The electricity price response sensitivity of FL unit can be characterized by the demand elasticity coefficient ε [31], the demand response (DR) function is formulated as:

$$P_{i,t}^{\mathrm{FL}} = P_{i,t}^{\mathrm{FL,sch}} \times \left(\frac{c_t^{\mathrm{ADN,DR}}}{c_t^{\mathrm{ADN,sch}}} \right)^{-\varepsilon}$$
$$P_{i,t}^{\mathrm{FL}}, P_{i,t}^{\mathrm{FL,sch}} \in \left[P_{i,t}^{\mathrm{FL,min}},\ P_{i,t}^{\mathrm{FL,max}} \right] \tag{5}$$

where $P_{i,t}^{\mathrm{FL,sch}}$ and $P_{i,t}^{\mathrm{FL}}$ are the power demand before and after DR of the i^{th} FL unit at time period t, respectively; $c_t^{\mathrm{ADN,sch}}$ and $c_t^{\mathrm{ADN,DR}}$ are electricity price before and after DR at time period t, respectively; $P_{i,t}^{\mathrm{FL,min}}$, $P_{i,t}^{\mathrm{FL,max}}$ are the minimum and maximum power demand of the i^{th} FL unit at time period t.

Thus, the function of FL agent is gathering the scheduled power demand plan of neighbouring FL units and send to ADN agent.

D. Model of ADN agent

ADN agent is responsible for the effective operation of ADN based on its objection:

$$\min \Delta Q_t^{\mathrm{ADN}} = \sum \left(-\sum_{j}^{N_{\mathrm{PV}}} P_{j,t}^{\mathrm{PV}}, -\sum_{k}^{N_{\mathrm{WT}}} P_{k,t}^{\mathrm{WT}}, \sum_{l}^{N_{\mathrm{ES}}} P_{l,t}^{\mathrm{ES}}, \sum_{m}^{N_{\mathrm{FL}}} P_{m,t}^{\mathrm{FL}}, P_t^{\mathrm{L}} \right) \tag{6}$$

where $\Delta Q_t^{\mathrm{ADN}}$ is power imbalance of ADN at time period t, that $\Delta Q_t^{\mathrm{ADN}}>0$ means the power generation from DG is insufficient to meet load, while $\Delta Q_t^{\mathrm{ADN}}<0$ indicates the power generated from DG is redundant; N_{PV}, N_{WT}, N_{ES} and N_{FL} are the numbers of PV agent, WT agent, ES agent and FL agent; $P_{j,t}^{\mathrm{PV}}$, $P_{k,t}^{\mathrm{WT}}$ $P_{l,t}^{\mathrm{ES}}$, and $P_{m,t}^{\mathrm{FL}}$ are the actual output/demand of aggregated PV agent, WT agent, ES agent and FL agent at time period t; P_t^{L} is the total demand of conventional load at time period t.

At each unit control time period Δt, ADN agent needs to gather the scheduled plans and interactive information from all DER agents. When power imbalance happens, ADN agent will distribute the guidance price to each DER agent. For the sake of suppressing electricity use or stimulating power generation, the guidance price needs to be increased based on external power grid, the grater the imbalance power, the greater the increase. Conversely, in order to incite electricity use or restrain power generation, the guidance price would decrease accordingly. Therefore, the guidance price is formulated by the function of c_t^{PG} and $\Delta Q_t^{\mathrm{ADN}}$ [32],

$$c_t^{\mathrm{ADN},k} = \left(1 + \gamma \cdot guid_k(\Delta Q_t^{\mathrm{ADN}})\right) \cdot c_t^{\mathrm{PG}} \quad k \in \{\mathrm{DG, ES, FL}\} \tag{7}$$

where γ is the maximum allowable regulation of the guidance price; $guid_k(\cdot)\in[-1, 1]$ is the pricing function for DER agent and sign function [33] is adopted as the pricing function in this paper.

After DER agent response to ADN agent with the interactive plan for their own benefit, ADN agent will coordinate all DER agents to decide the operation plan to minimize the power imbalance. DER agents will then be instructed by ADN agent to implement the final plan.

III. Agent-based Coordinated Operation Strategy

For the proposed bi-level agent system, the objective of the bottom-level agent is to attain the maximum economic operation of the DERs. However, ADN agent is pursuing the minimum power imbalance. Indeed, the contradictive objection between the DER agents and ADN agent is inevitable. That leads to a multi-objective optimisation model. Here, this model is not solved as a centralized/decentralized optimal problem like existing work. Considering the characteristic of agent technology, in this paper, a simple coordinated strategy by using the IBP principle is presented to solve it and provide operation plan for ADN. It converts the solving of the operation problem into a coordination process. Therefore, it is easy operation and without convergence concern of iteration. The IBP principle means ADN agent response DER agents in order of benefit priority. Specifically, the most profitable DER agent is firstly responded. Iteration continues for ADN agent to select the suitable DER agent based on interactive benefit ranking, until the power balance is achieved, or all the available DER agents are instructed. In this section, the interactive benefit of each DER agent is summarized as follows.

A. The interactive benefit of external power grid

In conventional distribution network, power imbalance between generation and load is dealt by external power grid. However, power imbalance in ADN will be firstly diminished by the DERs. Then the remaining imbalance power will be consumed by external power grid. Since we are from the DNO's point of view, who hope to minimal the purchasing power of ADN, the interactive benefit of external power grid is defined as benchmark:

$$bf_t^{\mathrm{PG}} = 0 \tag{8}$$

From this, the corresponding interactive benefits of DER agents are calculated based on (8), respectively.

B. The interactive benefit of DG agent

Since DG, i.e. WT and PV, use free nature energy, the generation cost is assumed to be zero. Moreover, the capacity of DG is limited by the energy sources, such as wind speed and light intensity. That means the DG output could only be decreased but not increased. Thus, the interactive benefit of DG agent at time period t is defined as:

$$bf_t^{\mathrm{DG}} = \begin{cases} -\infty & \Delta Q_t^{\mathrm{ADN}} > 0 \\ P_t^{\mathrm{DG,AR}} \left(c_t^{\mathrm{ADN,sch}} - c_t^{\mathrm{ADN,DG}} \right) \Delta t & \Delta Q_t^{\mathrm{ADN}} < 0 \end{cases} \tag{9}$$

$$P_t^{\mathrm{DG,AR}} = \begin{cases} -P_t^{DG} & \Delta Q_t^{\mathrm{ADN}} < -P_t^{DG} \\ \Delta Q_t^{\mathrm{ADN}} & -P_t^{DG} \le \Delta Q_t^{\mathrm{ADN}} < 0 \\ 0 & \Delta Q_t^{\mathrm{ADN}} > 0 \end{cases} \tag{10}$$

where P_t^{DG} is the total output of DG agent at time period t; $P_t^{\mathrm{DG,AR}}$ is the actual response power of DG agent at time period t; $c_t^{\mathrm{ADN,DG}}$ is the guidance price for DG agent from ADN agent at time period t.

C. The interactive benefit of ES agent

From Section II B, it is known that a C&D plan of ES unit follows the electricity price. In this paper, when power imbalance occurs, ES agent will adjust C&D plan for its benefit according to the guiding price provided by ADN agent as follows,

When $\Delta Q_t^{\mathrm{ADN}}>0$, the guidance price $c_t^{\mathrm{ADN,ES}}$ for ES agent will be increased by ADN agent during the time period t.

Once the guidance price is higher than $c_{\min}^{\mathrm{dis}}$, ES agent will shift to discharging mode and provide power supply under the new electricity price. This action will also change the minimum discharging price $c_{\min}^{\mathrm{dis}}$ accordingly. Thus, the interactive benefit of ES Agent at time period t is defined as:

$$bf_t^{\mathrm{ES}}=\begin{cases}P_t^{\mathrm{ES,AR}}\left(c_t^{\mathrm{ADN,ES}}-c_{\min}^{\mathrm{dis}}\right)\Delta t & \Delta Q_t^{\mathrm{ADN}}>0\\ P_t^{\mathrm{ES,AR}}\left(c_{\max}^{\mathrm{cha}}-c_t^{\mathrm{ADN,ES}}\right)\Delta t & \Delta Q_t^{\mathrm{ADN}}<0\end{cases} \tag{11}$$

$$P_t^{\mathrm{ES,AR}}=\begin{cases}P_{t,\max}^{\mathrm{ES,dis}} & P_{t,\max}^{\mathrm{ES,dis}}<\Delta Q_t^{\mathrm{ADN}}\\ \Delta Q_t^{\mathrm{ADN}} & -P_{t,\max}^{\mathrm{ES,cha}}\le\Delta Q_t^{\mathrm{ADN}}\le P_{t,\max}^{\mathrm{ES,dis}}\\ P_{t,\max}^{\mathrm{ES,cha}} & \Delta Q_t^{\mathrm{ADN}}<-P_{t,\max}^{\mathrm{ES,cha}}\end{cases} \tag{12}$$

where $P_t^{\mathrm{ES,AR}}$ is the actual response power of ES agent at time period t; $c_t^{\mathrm{ADN,ES}}$ is the guidance price for ES agent from ADN agent at time period t; $P_{t,\max}^{\mathrm{ES,dis}}$ and $P_{t,\max}^{\mathrm{ES,cha}}$ are the maximum C&D power of ES agent at time period t.

Fig. 3 gives an example. In the morning load peak with insufficient DG output, ADN agent identifies a power shortage ($\Delta Q_t^{\mathrm{ADN}}>0$) and inform ES agent with the guidance price $c_t^{\mathrm{ADN,ES}}=0.85$ ¥/kWh. It is higher than the minimum discharging price $c_{\min}^{\mathrm{dis}}=0.7$ ¥/kWh and ES agent does not reach the limit of maximum discharge times. So, ES agent changes the scheduled C&D plan to pursue profit, i.e. the discharge plan for the 12 a.m. in the schedule is shifted to 9 a.m. Moreover, the price increase changes the sixth highest electricity price within ΔT from 0.70 ¥/kWh to 0.8 ¥/kWh, so the minimum discharging price $c_{\min}^{\mathrm{dis}}$ is also changed to 0.8 ¥/kWh. The rest of the time period still operate as scheduled. The same procedure for power redundant ($\Delta Q_t^{\mathrm{ADN}}<0$)

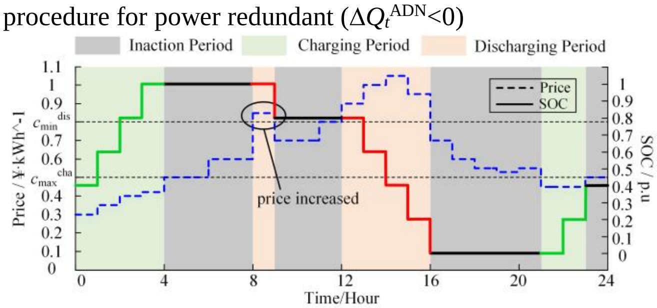


Fig. 3. C&D plan of ES agent with price incentive

D. The interactive benefit of FL agent

FL agent responds to the fluctuation of the guidance price constantly during the interaction process. Fig. 4 illustrates the DR and associated margin revenue of power demand. The interactive benefit of FL agent at time period t is defined as:

$$bf_t^{\mathrm{FL}}=\int_{P_t^{\mathrm{FL,sch}}}^{P_t^{\mathrm{FL,AR}}}\left(c_t^{\mathrm{ADN,sch}}\times\left(\frac{P_t^{\mathrm{FL,DR}}}{P_t^{\mathrm{FL,sch}}}\right)^{-1/\varepsilon}-c_t^{\mathrm{ADN,FL}}\right)\times dP_t^{\mathrm{FL,DR}} \tag{13}$$

$$P_t^{\mathrm{FL,AR}}=\begin{cases}\max(P_t^{\mathrm{FL,min}},P_t^{\mathrm{FL,sch}}-\Delta Q_t^{\mathrm{ADN}}) & \Delta Q_t^{\mathrm{ADN}}>0\\ \min(P_t^{\mathrm{FL,max}},P_t^{\mathrm{FL,sch}}-\Delta Q_t^{\mathrm{ADN}}) & \Delta Q_t^{\mathrm{ADN}}<0\end{cases} \tag{14}$$

where $P_t^{\mathrm{FL,AR}}$ is the actual response power of FL agent at time period t; $c_t^{\mathrm{ADN,FL}}$ is the guidance price for FL agent from ADN agent at time period t; $P_t^{\mathrm{FL,sch}}$ is the total demand of FL agent at time period t; $P_t^{\mathrm{FL,DR}}$ is the DR variable of FL agent at time period t; $P_t^{\mathrm{FL,min}}$ and $P_t^{\mathrm{FL,max}}$ is the minimum and maximum demand of FL agent at time period t.

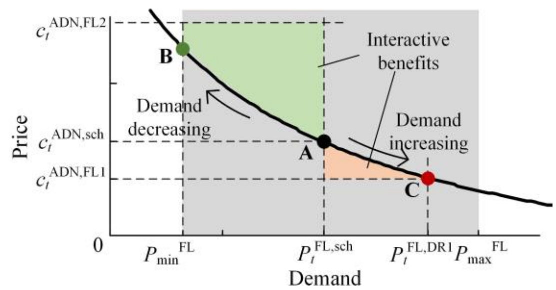


Fig. 4. Interactive benefit of FL agent based on DR

As show in Fig. 4, point A is the scheduled operating point of FL. $P_t^{\mathrm{FL,sch}}$ and $c_t^{\mathrm{ADN,sch}}$ are the scheduled power demand of FL and the scheduled electricity price. When there is no power imbalance or FL agent rejects to participant the interactive process, it will operate as scheduled. Otherwise, it will adjust demand depends on imbalanced power and the guidance price from ADN agent. The arrow indicates the DR process of FL agent in the case of redundancy or insufficient generation.

For instance, when there is redundancy power ($\Delta Q_t^{\mathrm{ADN}}<0$), ADN agent will send FL agent with the guidance price $c_t^{\mathrm{ADN,FL1}}$, which is lower than the scheduled price. Thus, FL agent responses change of electricity price along with DR curve and increases its actual power demand to $P_t^{\mathrm{FL,DR1}}$. The operating point of FL agent in DR is moved from point A to point C. Therefore, the orange area in Fig. 4 represents the interactive benefits of FL agent by taking the advantage of price reduction. The response process from point A to point B for $\Delta Q_t^{\mathrm{ADN}}>0$ is similar.

In addition, DR capability of FL agent is limited. When the power demand corresponding to the given guidance price is beyond this range, FL agent will operation according to the boundary power demand. As a result, the interactive benefit area will be transformed from a curved triangular to a curved trapezoid, shown as green area in Fig. 4.

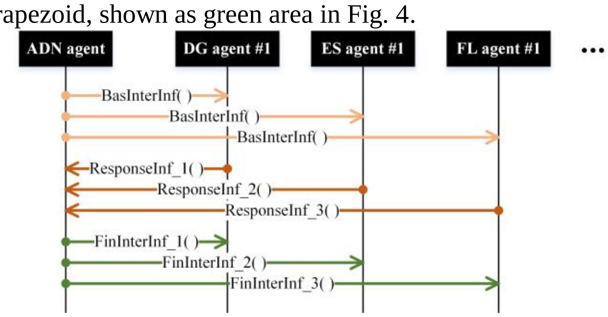


Fig. 5. Communication mechanism of agent system

E. The coordination process based on agent system

The communication mechanism of presented agent system is shown in Fig. 5 [19]. As discussed previously, when power imbalance happens in ADN, each DER agent will be broadcasted by ADN agent with the imbalance power and the guidance price information (i.e. BasInterInf()), and then they generate feasible operation strategy considering their own technical constrains and corresponding interactive benefit. Afterwards, they will send the actual response power and interactive benefit back to ADN agent (i.e. ResponseInf_1(), ResponseInf_2() and ResponseInf_3()). At the end, ADN agent needs to coordinate the information by using the IBP principle, where each DER agent will get a priority order to decide their acceptance sequence by ADN agent and informing each DER agent with their final output/demand (i.e. FinInterInf_1(), FinInterInf_2() and FinInterInf_3()).

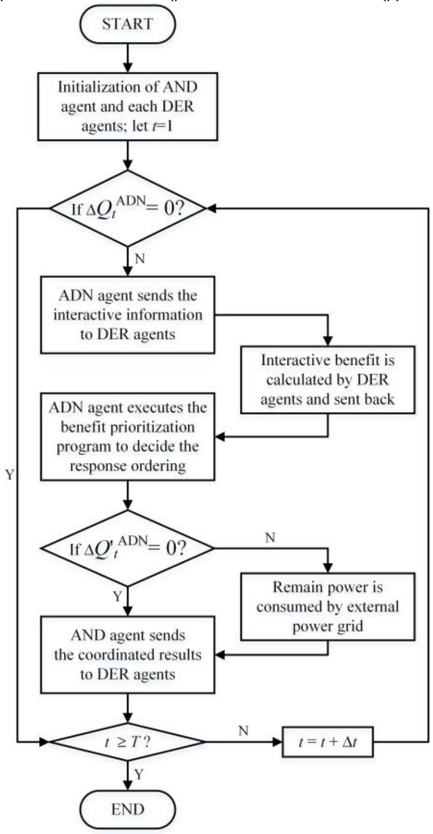


Fig. 6. Flowchart of agent-based coordinated operation strategy

The flowchart of coordination process within T is shown in Fig. 6. The power redundancy, i.e. $\Delta Q_t^{ADN}<0$, is taken as an example to explain the process of proposed coordinated operation strategy.

Step 1: ADN agent determines the guidance price to DER agents based on the imbalance power and the external electricity price. The information including the guidance price and volume of imbalanced power is delivered to each DER agent.

Step 2: On the receipt of the imbalance power and the favourable guidance price that ADN agent works out, DER agents calculate the actual response power, i.e. $P_t^{DG,AR}$, $P_t^{ES,AR}$ and $P_t^{FL,AR}$, and interactive benefit, i.e. bf_t^{DG}, bf_t^{ES} and bf_t^{FL}, by using (8)-(14). That information is sent back to ADN agent.

Step 3: ADN agent prioritizes each DER agent based on the IBP principle. If power imbalance finally is eliminated, ADN will achieve the self-balancing mechanism that improves the safe and reliable operation of ADN and reduce balancing burden on wider energy system. However, if power imbalance is still not eliminated, the redundancy power needs to be consumed by the external power grid. Even so, power imbalance could be relieved to some extent.

IV. Case Study

A. *Case description*

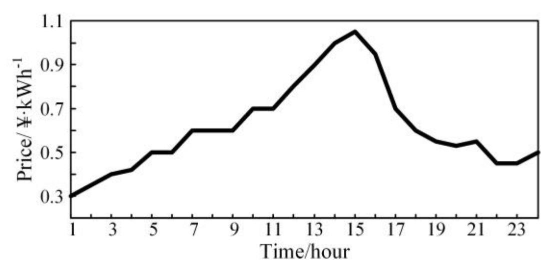


Fig. 7. Time-of-use electricity price profile

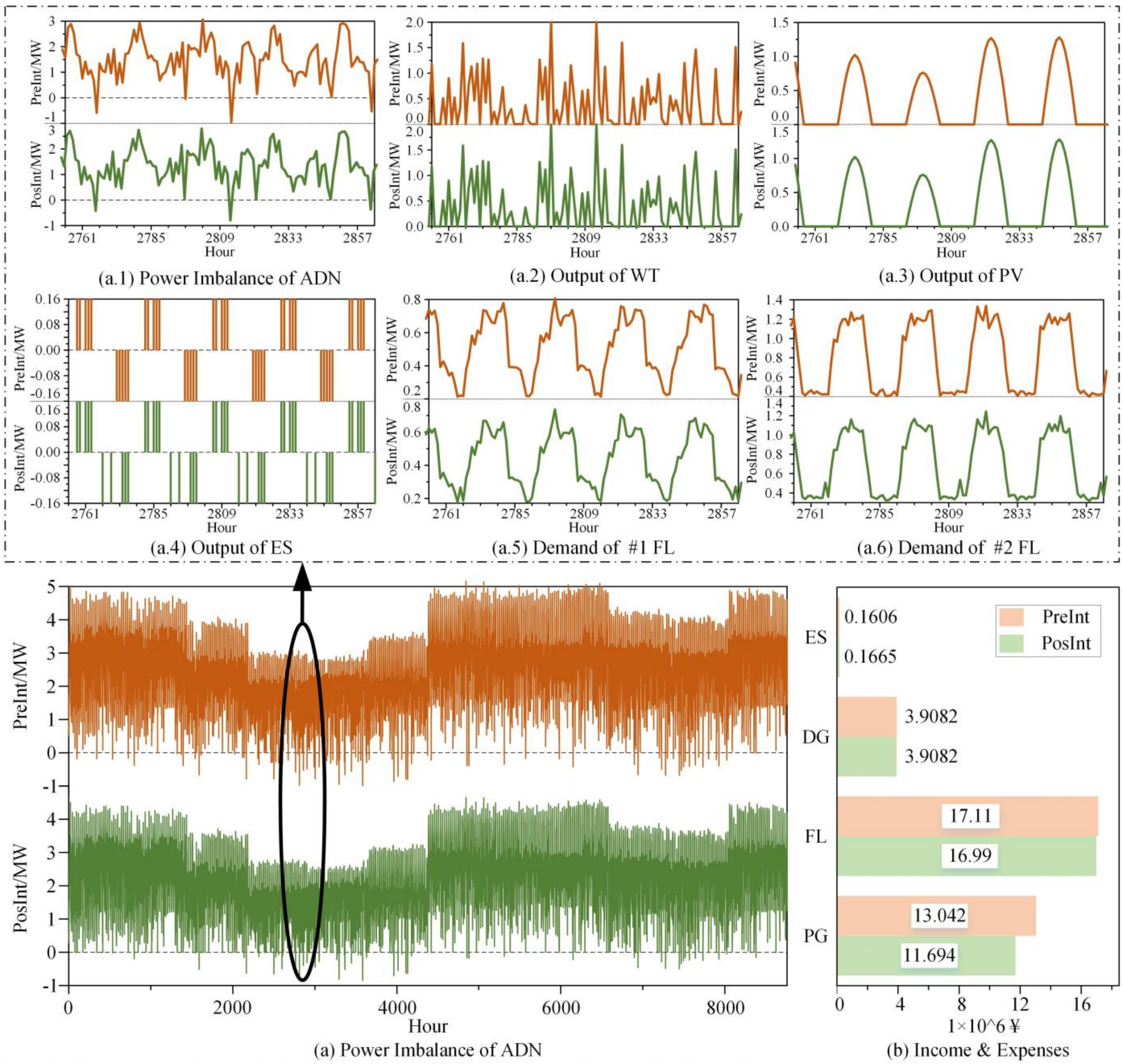
In this section, the proposed operation strategy for ADN is applied to the IEEE 33-bus system [34]. The time-of-use electricity price profile in Fig. 7 is applied in this study as c_t^{PG}. For demonstrating the proposed strategy, we assume ε=1 and γ=0.1. Bus 6, 14, and 27 is integrated with aggregated ESs (total capacity is 0.8MW), PVs (total capacity is 1.5MW) and WTs (total capacity is 2MW) respectively. Let Δt=1h, ΔT=24h, the simulation time-scale is one year (i.e. T=8760h). The annual load prediction is achieved by using the morphological factor method [7], specified parameters and the distribution of FL units is given in Table. I. Thus, by using the sequential monte-calo method, simulation results are shown as Fig. 8.

TABLE. I LOAD TYPE AND FORECASTING PARAMETERS

LOAD TYPE	BUS	LOAD PARAMETERS	
Conventional Load	2, 3, 4, 12, 13, 14, 15, 16, 19, 20, 21, 23, 24, 26,28, 29, 31	Daily factor	{0.4, 0.4, 0.3, 0.3, 0.3, 0.6, 0.6, 0.6, 0.75, 0.85, 0.85, 0.9, 0.9, 0.9, 0.85, 0.85, 0.85, 1.25, 1.25, 1.25, 1.1, 1.1, 0.65, 0.55}
		Monthly factor	{1.1, 1.1, 1, 0.8, 0.8, 0.8, 1.3, 1.3, 1.2, 0.8, 0.8, 1.1}
#1 Flexible Load	5, 6, 7, 8, 9, 10, 11, 27, 30	Daily factor	{0.65, 0.65, 0.55, 0.4, 0.4, 0.4, 0.65, 0.75, 0.95, 0.95, 1 1 1.3, 1.3, 1.2, 1.2, 1.2, 1.3, 1.3, 1.3, 1.2, 0.7, 0.7, 0.7}
		Monthly factor	{1.2, 1.2, 1, 0.6, 0.75, 1, 1.35, 1.35, 1.35, 1.1, 1.1, 1.2}
#2 Flexible Load	17, 18, 22, 25, 32, 33	Daily factor	{0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.8, 1.2, 1.2, 1.4, 1.4, 1.35, 1.4, 1.4, 1.35, 1.35, 1.4, 1.4, 1.2, 0.8, 0.5, 0.5, 0.5, 0.5}
		Monthly factor	{1, 1, 0.95, 0.95, 0.95, 0.95, 1.2, 1.2, 1.25, 1.25, 1.05, 1.05}

B. Discussion

In Fig. 8 (a) and subfigures (a.1-a.6), the orange curves represent the normal operation without any intelligent coordination, while the green curves represent the results by using the proposed strategy. Fig. 8 (a) shows power imbalance in ADN. Positive imbalance means power shortage ($\Delta Q_t^{ADN}>0$), while negative imbalance means power redundant ($\Delta Q_t^{ADN}<0$). The improvement in power imbalance through agent-based coordinated operation strategy can be observed in two aspects: the reduced value in positive power imbalance, and the reduced number of negative power imbalance. Firstly, in negative power imbalance, the interaction between agents offers the ability to internally consume the surplus renewable energy in ADN, reduce the occurrence of power surplus events by 9.9% per annum, and relieve the renewable energy consumption burden on the external power grid. Secondly, for the situation of power shortage with positive power imbalance, since the total capacity of installed DG and ES cannot supply the full loads in ADN, power shortage happens in most of the time during renewable energy shortfall. However, we are appreciatively to see the overall power imbalance level is decreased by 10.73% through the proposed strategy. It is foreseeable to address that with the increasing penetration rate of DERs. Power imbalance in ADN could be eliminated by the proposed agent-based coordinated operation strategy.



Notes: **PreInt** represents the state before interactive and **PosInt** represents the state after interactive.

Fig. 8. Results of ADN operation using proposed strategy for one-year time scale

Then, we conduct a detailed analysis by zooming in the results between the 2753rd and 2863rd time period, which is shown in Fig. 8 (a.1)-(a.6). The effectiveness of the proposed strategy could be seen clearly in Fig. 8 (a.1), that both power surplus and shortage are minimised using agent-based technology in ADN. Particularly at the 2822nd and 2848th time period, power imbalance is completely eliminated by the coordination of ES agent and FL agent. It is worth noting that the power output of DG agents has no change by using the proposed strategy in Fig. 8 (a.2) and (a.3). This is due to the calculated interactive benefit of DG agent bf_t^{DG} is always negative, and thus has lower priority than the external power grid (bf_t^{PG}=0). As a result, ADN agent will seek assistance from external power grid to support the imbalanced power rather than DG agents. This is to prevent the renewable generation curtailment and ensure the effective renewable energy consumption.

In Fig. 8 (a.4), ES agent alters its C&D plan to participate in the power balance. For example, ES agent advances the scheduled discharging plan from the 2797th time period to 2791st time period to facilitate surplus power demand, while advances the scheduled discharging plan from the 2773rd time period to the 2770th time period to boost energy during power shortage. In Fig. 8 (a.5) and (a.6), both FL agents are encouraged to response power imbalance by the instructions from their respective agents. For example, #1 FL agent increase power demand at 2813rd time period from 0.2248 MW to 0.2698 MW when surplus power is detected but decreases power demand at the 2812nd time period from 0.3192 MW to 0.2579 MW when power shortage is identified.

Furthermore, interaction of ES and FL agent has been achieved by responding to the guidance price from ADN agent, as demonstrated at the 2935th and 2992nd time periods for example, where the results are given in Table. II.

TABLE. II RESULTS OF THE 2935th, 2940th ADN 2992nd TIME PERIOD (MW)

t	STATE	POWER IMBALANCE	OUTPUT OF ES	OUTPUT OF #1 FL	OUTPUT OF #2 FL
2935	PreInt	0.1473	0	0.2845	0.4455
	PosInt	0	-0.16	0.2894	0.4533
2940	PreInt	1.8272	-0.16	0.7186	1.1646
	PosInt	1.778	0	0.6388	1.0352
2992	PreInt	-0.4248	-0.16	0.8539	1.127
	PosInt	-0.1913	-0.16	0.9546	1.2598

At the 2992nd time period, the original power imbalance of ADN is 0.4248MW causing by the excessive power generation from DG agent and discharging plan from ES agent. Therefore, ADN agent sent out the guidance price of 0.85 ¥/kWh to both ES agent and FL agents. As the C&D times of ES agent have reached the limit, and the guidance price is no larger than $c_{\min}^{dis}$=0.85 ¥/kWh, ES agent will refuse to alter discharging plan. In the meantime, FL agents check their demand capacity limit and respond to the guidance price $c_t^{ADN,FL}$=0.85 ¥/kWh through DR. As shown in details, #1 FL agent increase demand from 0.8539 MW to 0.9546 MW, while #2 FL agent increases demand from 1.127 MW to 1.2598 MW, which managed to reduce to the ADN power imbalance to 0.1913 MW. At this time period, FL agent responds to the guidance price and increases its demand to consume surplus power. However, ES agent does not participate in this coordination due to the technical limitation and economic consideration.

The other one is at the 2935th time period, when the original power shortage appears to be 0.1473MW. At this time period, both ES agent and FL agent participate in the coordination process: ES agent firstly responds to the guidance price and advances the scheduled discharging plan from 2940th time period. Since the discharging power of ES agent is fixed at 0.16 MW, 0.0127 MW surplus power is introduced in ADN. As a result, FL agents respond to consume the surplus power by increasing #1 FL from 0.2845 MW to 0.2894 MW, and #2 FL from 0.4455 MW to 0.4533 MW. At the end, power imbalance in ADN is completed eliminated.

Furthermore, the bar chart in Fig. 8 (b) summarises the income/expenditure of DER agents in ADN and external power grid for one-year time scale. In FL sector, the expenditure of electricity custom reduces from 17.11 to 16.99 million RMB. This is due to the price incentive strategy that ADN agent sent to FL agents. In ES sector, the income of ES agent increases by 0.0059 million RMB, due to the optimised C&D plan based on the coordination process. However, income of DG agents does not change due to the negative interactive benefit, which prevents the ADN from curtailing the renewable energy generation. Income of the external power grid decreases significantly by 1.348 million RMB. However, the improvement in power self-balancing could greatly enhance the system security and save the investment cost of ancillary equipment of the external power grid. Therefore, the proposed agent-based coordinated operation strategy is proved to be useful to generate either economic or security benefits for all the DERs. In addition, there is an extra 1.1475 million RMB revenue after the implementation of the proposed strategy, which can be regarded as the income of DNOs.

V. CONCLUSION

In this paper, an agent-based coordinated operation strategy for ADN was proposed. By considering the coordination process, the price response of DERs is firstly integrated into the agent-based operating model.

As the results of case study, the proposed operation strategy can effectively reduce the power imbalance, increase the profit margins for ES agent and FL agent, and encourage renewable energy consumption. Conclusions could be drawn:

- The overall power imbalance level could be effectively improved by optimizing the C&D plan of ES agent, and utilizing the DR of FL agent from agent-based coordinated operation strategy;
- Since the interactive benefit of DG agents is always negative, the output from DG will not be curtailed by ADN agent, thus to guarantee the maximum renewable penetration rates;
- The price response of ES agent will sometimes lead to the non-participation of agent-based strategy due to the insufficient profit incentives. Even that, price response of FL agents is always willing to offer support through DR;

- The presented coordination process demonstrates the potential ability of totally eliminate power imbalance in future ADN with high penetration of DG and achieve an intelligent and self-balancing distribution network;
- Economic analysis shows the effectiveness of the proposed strategy, not only benefiting DERs, but also increasing the profits of ADN operation.

In future work, the development of DERs including electric vehicles will bring opportunities and challenges to the operation of ADN. The agent-based coordinated operation strategy will expand to include variety of DERs for optimization and coordination. Global operation strategies between different ADNs are also needed to be studied.

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