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A multi-agent solution to energy management in hybrid renewable energy generation system

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ABSTRACT

This paper presents a multi-agent (MAS) solution to energy management in a distributed hybrid renewable energy generation system. An introduction and analysis of the system, including its constituents, characteristics and excitation mechanism are presented first. Then, validation of the MAS solution demonstrates its feasibility in meeting all the requirements of the system. Five kinds of agents are proposed to present the Energy Management System. Each agent is built as a three layered architecture. A macro MAS is also presented in detail with a framework containing its overall optimisation function based on JADE (Java Agent Development). Discussion about the agents' behaviours and a scenario case study on the MAS and its testing process are included in the paper. It indicates that the MAS is a suitable solution for the energy management of the distributed hybrid renewable energy generation system.

1. Introduction

Growing energy demand and shortages of energy supply, as well as energy use and environmental protection, are becoming critical considerations. In particular, meeting the energy demand in some remote regions (developing villages, islands and signal stations, etc.) is a challenging problem to be solved as it is not cost effective to extend the power grid to cover it. Developing the use of renewable energy (RE) in this case appears to be more and more promising because the energy source of RE is abundant in these regions. However, a single RE source alone often cannot meet the loads sufficiently and continuously, and its availability depends on weather and climatic changes [1]. In this respect, the hybrid system, formed by interconnecting small, modular generation (wind turbine, PV arrays, micro-turbine, full cell, etc.) and storage devices (battery bank, flywheel, etc.), has proved to be the best means of meeting the energy demand with high reliability, flexibility and cost effectiveness.

In a multi-source interconnected hybrid system, the system behaviour is becoming more unpredictable and more complex. Since the early 1980's, efforts have been spent to design a hybrid system, especially in selecting its constituents, capacity and optimal location and so on [2–8]. As a matter of real-life experience, because of inadequate system maintenance, excessive load growth and system degradation, the Xcalak hybrid system runs well in the first two years and is a complete failure by the seventh year [9]. It shows that optimisation, control and maintenance are the main factors to determine the system's life span and operational performance and they remain crucial concerns after the hybrid system is built. As a result, the energy management system (EMS) plays a significant role in the successful operation of the hybrid RE system by optimising and controlling the running process, such as balancing the supply and demand, using SCADA, fault alert and remote monitoring and control. This paper focuses on the development of the EMS for optimising the performance of the hybrid RE system based on the following rationale and observation:

1) In fact, the effect of the optimisation in the running process can be significant as it leads to 50% more energy produced [10].
2) Over sizing to a certain extent is the approach used to design a hybrid RE system to overcome the intermittent and uncontrollable characteristics of the RE sources.
3) Without optimisation and due care in scheduling the equipment and associated elements are always put to work on the maximum power point tracking even if there is excrescent energy supply.
4) A certain evaluation mechanism has to be introduced in the optimisation process to identify the equipment that needs regular maintenance, rather than waiting for the fault to happen.

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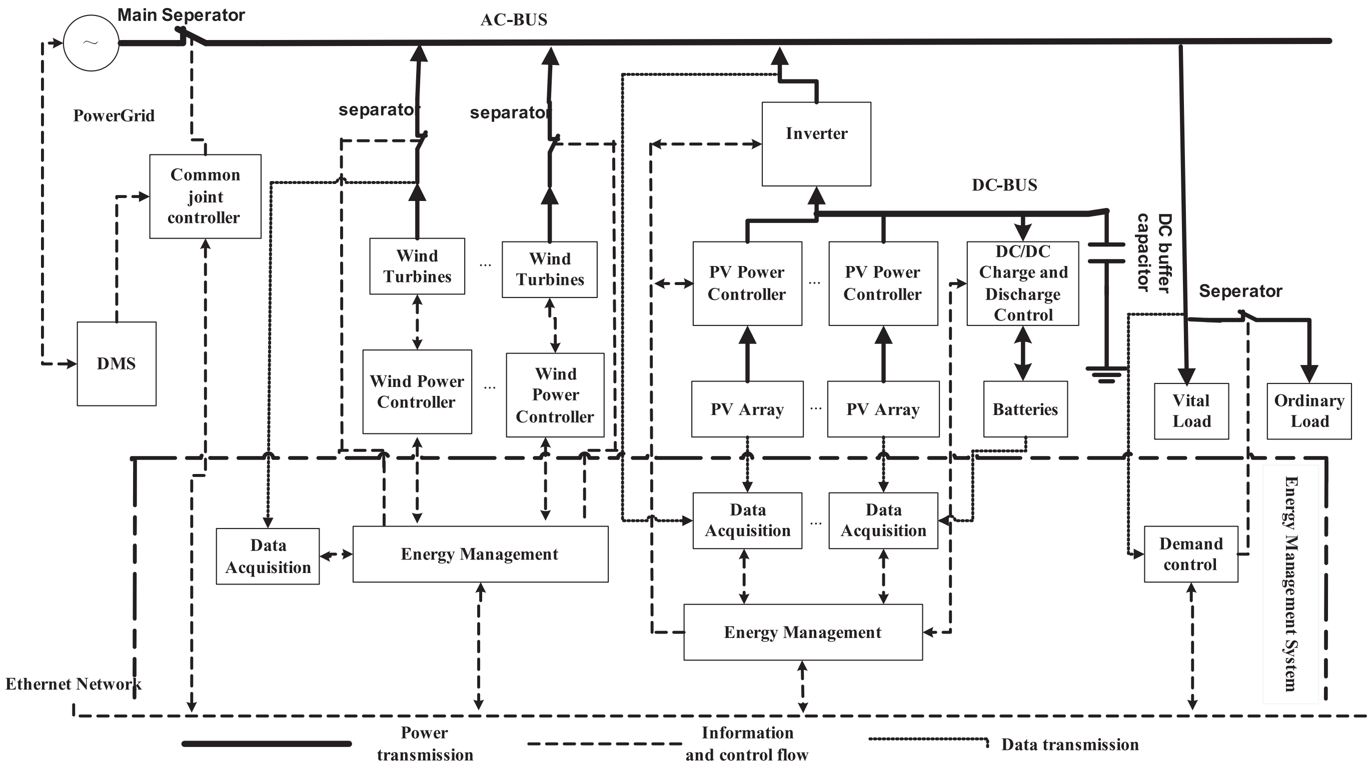


Fig. 1. A typical RE hybrid power system.

5) Minimising the cost for performance enhancement based on the balance of supply and demand is required.

Optimising the management and control of the hybrid system is a challenging task. Centralised control approaches, which involve the use of a genetic algorithm to minimise the total system cost [11], optimise the generation configuration and control [12], and minimise the use of generation [13], are the typical research interests. For other goals to minimise the operating costs, emission costs and level for the distributed generation system, different optimisation algorithms are applied, such as mesh adaptive direct search, sequential quadratic programming, genetic algorithms, and game theory [14]. Diaf presents a central method for the optimal number and type of units among a set of hybrid RE systems according to the loss of power supply probability and the levelised cost of energy [15]. These centralised control approaches can be used to determine the optimal control solution, but it requires the support of a powerful computing facility to handle huge amounts of data and a network with highly distributed communication capabilities and control strategy. In the paper, the distributed management units are regarded as one functioning with certain intelligence to complete the basic computation, planning action and decision-making. It not only reduces the computation and communication ability, but also fully respects the operational performance and requirements of the various parts. As that the hybrid RE system should work under different conditions to meet load changes, environment change, social changes, etc., it is assumed that an intelligent, self-adaptive, dynamic and open system is required. In the long run, a certain distributed control strategy is assumed to provide great convenience in configuring the connection of different REs. Multi-agent technology, as a new and promising paradigm, is widely used in power engineering applications, including diagnostics, condition monitoring, power system restoration, and market simulation [16,17]. Jignesh presented details of a multi-agent solution to distribution system restoration, which proposed a decentralised MAS implemented in FIPA-ACL

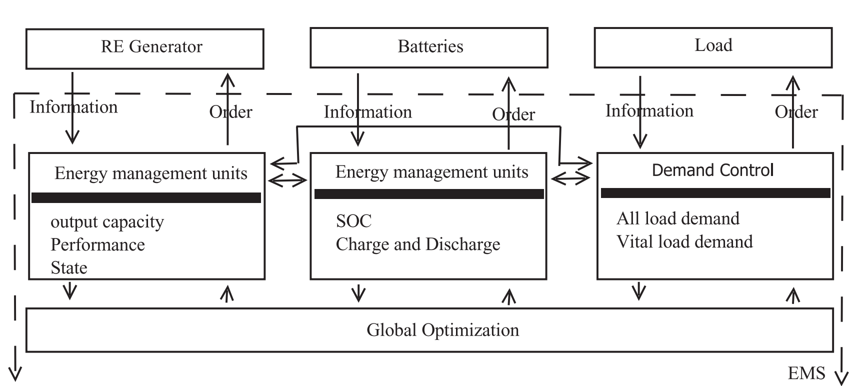


Fig. 2. The sketch map of EMS.

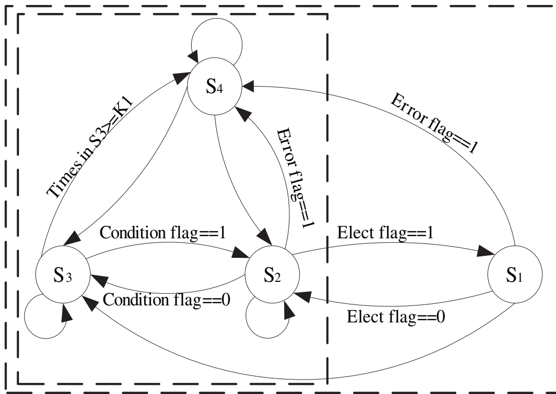


Fig. 3. The relationship and changing conditions between the states.

(Foundation for Intelligent Physical Agents (FIPA), Agent Communication Language (ACL)) with JADE (Java Agent Development Framework, JADE) and VTB (Virtual Test Bed) [18]. For the distributed renewable energy generated system, Dimeas presented an operation of a multi-agent system for the control of a Micro-grid and a classical distributed algorithm based on the symmetrical assignment problem [19]. However, the battery was represented as a production unit agent whilst the number of seller agents and buyer agents must be equal, which are the major disadvantages.

In this paper, an MAS is proposed to handle the energy management of the hybrid PV-wind generation system. It solves the reconfiguration and optimisation problems in respect of a change in the environmental conditions during the operational process and aims to adjust the burden of different RE units, prolongs the life span and postpones the degradation of the system via the following processes:

1) Optimal use of each component of the system is based on individual intelligence by which the embedded characteristic model and initial state are computed;
2) Find a way to compromise the system power performance and cost;
3) Reorganise the RE sources in response to environmental changes.

In general, the approach as proposed in the paper is to optimise and reorganise the hybrid RE system, which not only satisfies the overall interest, but should also show respect to the intention and decision made by each component. The general organisation of the paper is as follows. In Section 2, the typical energy management system in a hybrid RE generation system is presented. Requirements of the system, the mathematical model and states for each component in running process are analysed. In Section 3, the MAS technology is implemented to develop the RE generation system. The agent identification, role and relationship among the agents are presented with the further study in intelligent model building for individual agents and the framework for the design of MAS. Section 4 provides the framework building based on JADE. Section 5 demonstrates the feasibility of the MAS for energy management in the reorganisation and optimisation processes via a scenario analysis.

2. Distributed hybrid RE generated system

2.1. Energy management in hybrid RE generation system

A hybrid RE generated system is a power system that combines multiple sources of renewable energy in a distributed system. A typical wind/PV hybrid power system is depicted in Fig. 1. It is a modular system comprising wind turbine generators and PV generators as the primary sources of power with batteries as the energy storage device. The interconnection controller serves as the island or to connect the RE system to the power grid. The wind turbine generators are connected to the AC-bus via the separators. The PV generators and batteries are connected to the DC-bus, and interfaced to the AC-bus via DC/AC converters. The feeders also have two types of load, one is the vital load which should be supplied uninterrupted, and the other is the ordinary load. All the RE sources, batteries and loads are generally called entity nodes in this paper. The energy management unit and demand control unit form the whole Energy Management System (EMS). All the units in the EMS are virtual nodes. The purpose of the EMS is to make decisions to reconfigure and optimise the system according to the change in the environmental conditions for meeting the load demand, optimising the overall benefits and efficiency, and evaluating the system performance based on the best use of the multi-energy sources.

There are two excitation mechanisms that would lead to a process of optimisation and reorganisation. One is excited by the system itself, including the changing of load demand, weather and generation unit. The other is dispatched by the power grid. The two different excitation mechanisms correspond to different algorithms and functions for reorganisation and optimisation. This paper focuses on the former case. After the reorganisation is excited, the final decisions made by the EMS are based upon the load demand, the weather, the price and state of each source, and many other considerations related to the complex system, which are analysed as follows.

Firstly, the main power sources are RE. RE is highly dependent on the climate and environment, which leads to an intermittent and uncertain power supply. Each generator unit has its own output characteristic which is distinguishable from the others. Batteries should be correctly controlled to charge and discharge depending on the state of capacity and system demands. And the vital load must be guaranteed at any time and the non-vital load could be cut off when the supply is insufficient. So, the energy management unit for each entity should have a certain degree of intelligence to handle the change, make local decisions and evaluate its state.

Secondly, the system is a complex system. The system is not just a combination of individual components, rather, it is an entire system with the whole greater than the sum of its parts. Design of

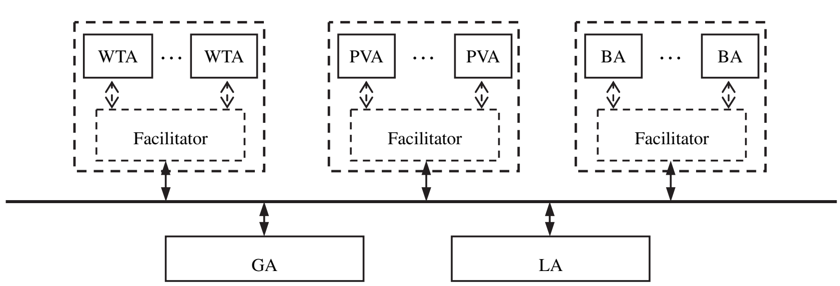


Fig. 4. The overview of MAS for the EMS.

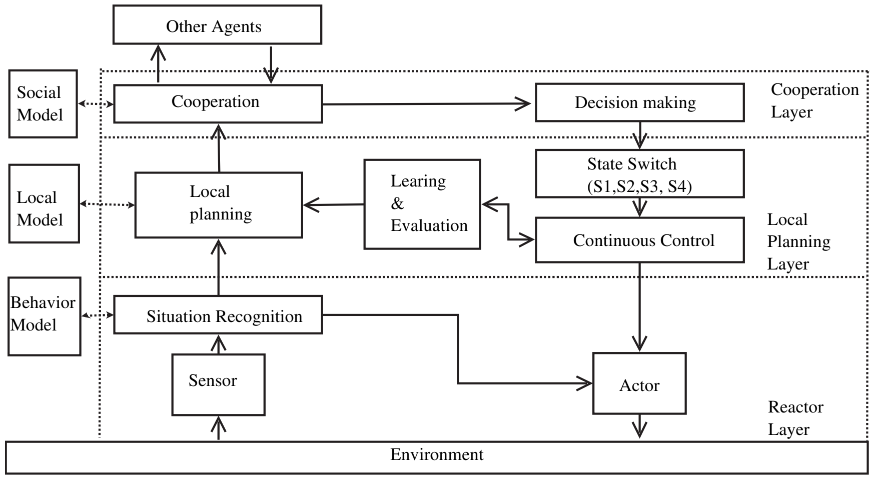


Fig. 5. The agent architecture.

Table 1
The details of each layer.

	In	Process	Out
React layer	Weather conditions (v, G_{ING}, k)/SOC	State assessment (S_2, S_3, S_4)	To upper layer: state, weather parameters.
	Reorganisation order	State compare ($S(t)$ and $S(t-1)$)	To actor: execute order/ask for quit, excite reorganisation.
Local planning layer	State related parameters	Compute output capability	To upper layer: state, output capability, performance value, cost
		Local decision-making	To lower layer: final decision
		State switch	
		Learning and evaluation	
		Continuous control	
Coordination layer	State, output capability,	Call for cooperation	To EMS: state, output capability, performance value, cost
	performance value, cost	Decision-making	To lower layer: global decision

the overview objective function is a challenging task. On one hand, there are many control parameters such as power, voltage and frequency that should be considered for the EMS. Other factors, such as cost, efficiency, power quality and their weightings would be merged into the function. On the other hand, the overall optimisation is achieved with respect to the local decision of each unit.

Thirdly, unpredictable growth of load demand has to be taken into account. The EMS needs to be adaptive so as to adjust itself when the RE sources are connected to or disconnected from the system. Handing a large amount of information exchange flow is the bottleneck with the growth of the system, because the EMS receives a large amount of information from the units, and provides various control commands for the optimal operation of the system.

Finally, the whole process includes making the discrete decision and continuous control sub-process. In other words, the discrete decision-making decides the state and strategies in the continuous control process, and vice versa the performance in the continuous control is one of the most important factors considered by the decision-making process.

In summary, the basic property of the EMS is characterised as heterogeneous, self-adaptive, distributed, autonomous, open and dynamic as shown in Fig. 2.

2.2. Basic characteristics

2.2.1. Wind turbine

One simplified and good model to simulate the power output of a wind turbine [20] is used in this paper and described as follows:

$$P_w(v) = \begin{cases} P_R \cdot \frac{v - v_{ci}}{v_R - v_{ci}} & (v_{ci} \le v \le v_R) \\ P_R & (v_R \le v \le v_{co}) \\ 0 & (v \le v_{ci} \text{ or } v \ge v_{co}) \end{cases} \tag{1}$$

where P_R is the rated power of the wind turbine; v_{ci} is the cut-in

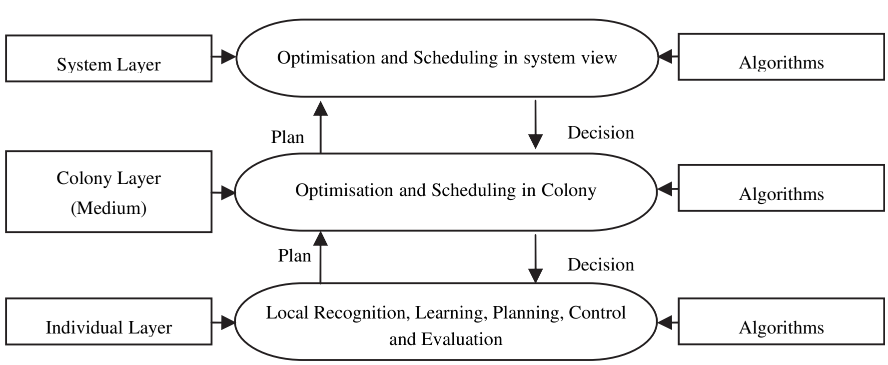


Fig. 6. The framework of MAS.

wind speed; v_R is the rated wind speed; and v_{co} is the cut-off wind speed.

2.2.2. PV array

The rated power output of the PV cell is computed at the standard condition (1000 w/m^2, 25 °C cell temperature). The real power output varied with many affects. Two main factors, solar irradiation and ambient temperature, are taken into account in this model [14]:

$$P_{PV} = \begin{cases} P_{stc}\frac{G_{ING}}{G_{STC}}(1 + k(T_c - T_r)) & (G_{ING} > C) \\ 0 & (G_{ING} \leq C) \end{cases} \tag{2}$$

where P_{PV} is the output power of the module at irradiance G_{ING}; P_{STC} is the module maximum power at the standard condition; G_{ING} is the incident irradiance; G_{STC} is the standard irradiance of 1000 w/m^2; k is the temperature coefficient of power; T_c is the cell temperature; T_r is the reference temperature 25 °C; and C is a threshold value constant according to the performance of the PV cell.

2.2.3. Battery bank

The battery bank plays two different roles in the system. When the renewable energy is insufficient to supply the load, the battery bank is discharged to meet the load demand as an energy supplier. When the supply from the renewable energy exceeds the load demand, the battery bank is charged and viewed as the load. Usually, there are two factors related to the performance of the system, state of charge (SOC) and the float charge current.

Firstly, the maximum SOC and the minimum SOC are confined at 100% and 20% of its Ah capacity, respectively. SOC is the index which would prevent the battery from overcharging and undercharging. So, the charged quantity of the battery is subjected to the following constraints as expression Eq. 3:

$$\mathrm{SOC_{min}} \leq \mathrm{SOC}(t) \leq \mathrm{SOC_{max}} \tag{3}$$

Secondly, the maximum allowable charge and discharge current must be less than 10% of the battery Ah capacity and are given by the following constraints as expression Eq. 4.[14].

$$\begin{aligned} P_{+} &\leq (0.1 \times V_{sys} \times U_{batt})/\Delta t \\ P_{-} &\leq (0.1 \times V_{sys} \times U_{batt})/\Delta t \end{aligned} \tag{4}$$

where P_{+} and P_{-} are the charge and discharge powers, respectively; V_{sys} is the system voltage at the DC-bus; Δt is the time step; and U_{batt} is the battery capacity in Ah. According to the P_{+} and P_{-}, the SOC can be obtained given by the following equation:

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) - P_{-} + P_{+} \tag{5}$$

2.3. State definition

To simplify and unify the behaviour of all components, four types of state are defined to describe the statues of the entity:

$$\mathrm{State} = \{S_1,\ S_2,\ S_3,\ S_4\} \tag{6}$$

where S_1 = running, S_2 = hot standby, S_3 = cold standby, $S_4 = I/M$. The state of hot standby shows that the entity has the ability to supply power but it is not selected provisionally by the EMS. The state of cold standby shows that the entity cannot supply power because of the limiting environment. I/M indicates that the entity is in inspection and maintenance mode. To the battery bank, the states have similar meaning to the wind turbine and PV array. The running state indicates that the battery bank is permitted to charge or discharge. The hot standby state is that the battery can be charged or has the ability to discharge. The state of cold standby means that the battery bank has no more capacity to charge or discharge. The relationship and changing conditions are shown in Fig. 3.

In the decision-making and continuous control processes, there are a few differences to be noted:

1) At the decision-making process,

$$\begin{array}{l} \text{if environment condition meets the requirement of running} \\ \text{then State} = S_2 \quad (\text{e.g. } V_{ci} < v < V_{co},\ G_{ING} > C) \\ \text{if environment condition do not meet the requirement of running} \\ \text{then State} = S_3 \quad (\text{e.g. } v < V_{ci} \text{ or } v > V_{co},\ G_{ING} < C) \\ \text{if some error or fault occure, or the state is cold standby lasted a long time} \\ \text{then State} = S_4 \quad (\text{e.g. Error Flag} = 1 \text{ or Times in } S_3 >= K_1) \end{array} \tag{7}$$

2) At the continuous control process, if the unit is in S_2 at the decision-making process and selected as the power supplier, the state of this unit turns into S_1. Otherwise, the unit is in the same state as the decision-making process.

$$\begin{array}{l} \text{if environment condition meets the requirement of running and the unit joins the task} \\ \text{then State} = S_1 \quad (\text{e.g. } V_{ci} < v < V_{co},\ G_{ING} > C) \\ \text{if environment condition meets the requirement of running and the unit does not join the task} \\ \text{then State} = S_2 \quad (\text{e.g. } V_{ci} < v < V_{co},\ G_{ING} > C) \\ \text{if environment condition do not meet the requirement of running} \\ \text{then State} = S_3 \quad (\text{e.g. } v < V_{ci} \text{ or } v > V_{co},\ G_{ING} < C) \\ \text{if some error or fault occure, or the state is cold standby lasted a long time} \\ \text{then State} = S_4 \quad (\text{e.g. Error Flag} = 1 \text{ or Times in} S_3 >= K_1) \end{array} \tag{8}$$

The purpose of defining the four kind states is to simplify the options for the system. The EMS continually makes judgments for each entity. If State$(t-1) = S_1$, and State$(t) = S_3$ or State$(t) = S_4$, then the energy management unit will excite a new configuration

Table 2
Description of behaviours associated with agents.

Agent/facilitator	Behaviour	Receive message			Send message				Description
		Performative	Conversation ID	Content	Performative	Conversation ID	Content	Receivers	
Load agent	LAReconfigureStar	–	–	–	Query-Ref	Reorganisation	Total demand, vital demand	Main facilitator	LA detects the changing of load demand, sends message with total demand and vital demand to main facilitator. A new reorganisation is start.
	LAReply	Accept proposal	Load control	Total demand, vital demand, Y1, Y2	–	–	–	–	LA receives the final answer about the supply and makes load control
Main facilitator	MaFReconfigurate	Query-Ref	Reorganisation	Total demand, vital demand	Request	Reorganisation	Order: start a new task	All facilitators	Saves the message and sends order to other facilitators
	MFDecision	Propose	ICReply	Agent members information array	Propose	Final decision	ID, work guide flag (0/1)	Facilitaors	Makes final decision using optimisation algorithm, and sends the results to the facilitators
	MFReply	–	–	–	Query-Ref	Reorganisation	Total demand, vital demand, Y1, Y2	LA	Main facilitator sends the final decision to LA
Facilitator	FAForward	Query-Ref	ICCompute	–	Request	ICCompute	Order: start a new task	Agent members	Saves the message and sends order to its member agents
	FAPropose	Propose	ICReply	–	Propose	ICReply	Agent members information array	Main facilitators	Receives and saves the message and sends to the main facilitator
	FADForward	Propose	Final decision	ID, work guide flag (0/1)	Propose	Final decision	ID, work guide flag (0/1)	Agent members	Saves the message and forwards to its member agents
Generator agent	GAICCalculate	Query-Ref	ICCompute	ID, work guide flag (0/1)	–	–	–	–	Using algorithms embedded in the layers, calculates the intention, capability, coefficient of performance etc.
	GAInform	–	–	–	Inform	ICCompute	ID, Intention, real capability, coefficient of state transition, unit price, performance coefficient	Facilitators	Saves the parameters and sends to its facilitators
	GAAct	Message of do or not							Receives the final decision and acts according the order

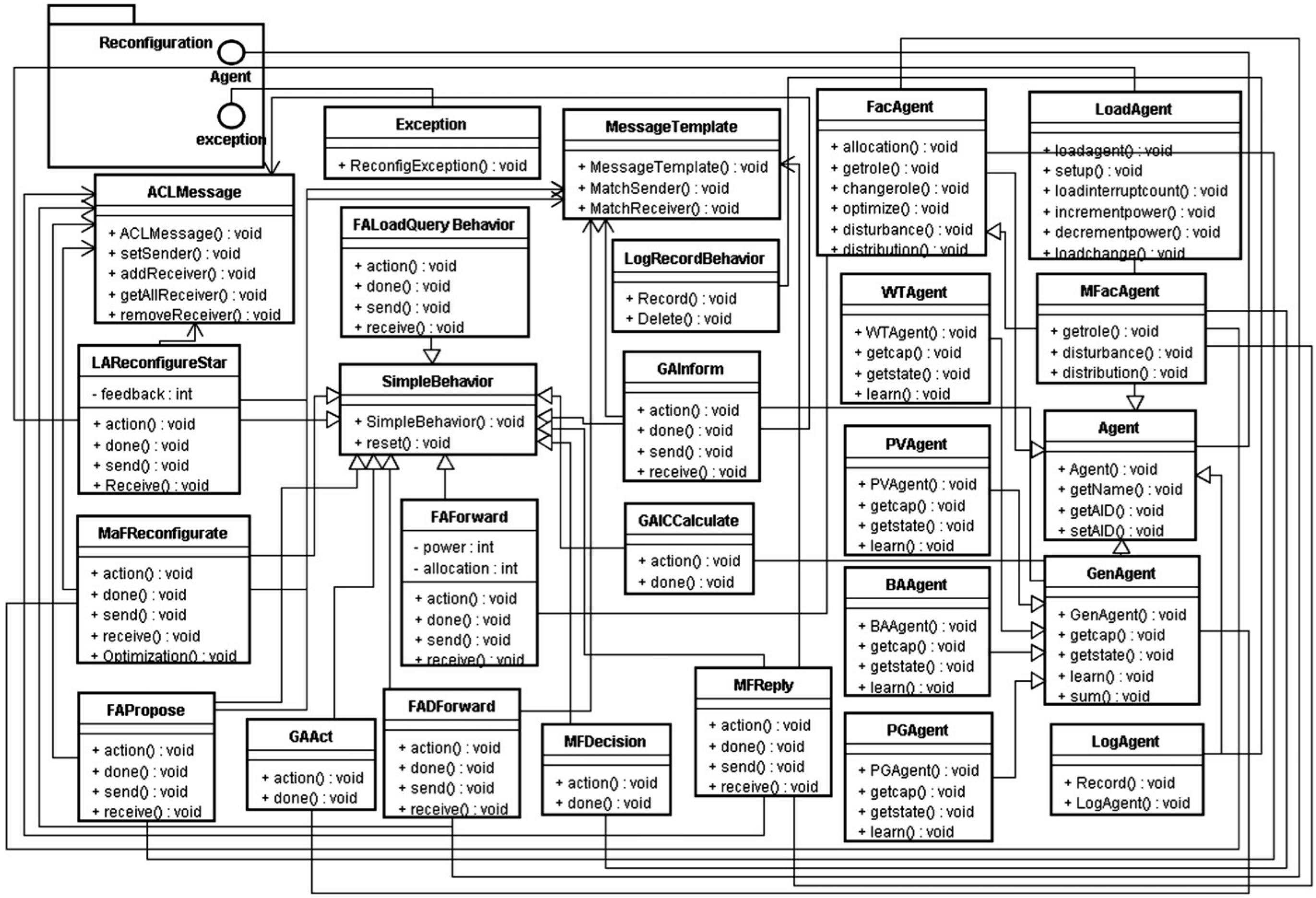


Fig. 7. The UML class diagram of the MAS.

and sends the requirement to the EMS. Or, if the unit receives the order to prepare a new configuration, the unit will judge its state according to Eq. (7) as the base of decision-making.

3. MAS implementation for EMS

As analysed above, it is necessary to build a model for the system from the bottom to top with modern distributed artificial intelligent (DAI) technology, which should meet the requirements (heterogeneity, self-adaptiveness, distribution, autonomous, dynamism and openness) as mentioned above. MAS technology is now attracting more and more attention from researchers due to its promise as a new paradigm of applications in distributed artificial intelligence. However, there is no strict definition about an agent until now. According to Wooldridge [21], an agent is a software (or hardware) entity that is situated in some environment and is able to autonomously react to changes in that environment. From [22], an agent is any entity (physical or virtual) that senses its environment and acts over it. While a multi-agent system is defined as a loosely coupled network of problem-solving agents that work together to find answers to problems that are beyond the individual capabilities or knowledge of each agent. Its conceptualisation, design, and implementation are widely applied in a complex system. In the system, various resources are typically distributed in different locations in a dynamical fashion, where system behaviours are often varied and system requirements always change. It is worthwhile to consider the comparability between the hybrid power system and MAS.

MAS is chosen as the approach to the EMS in this paper. According to the description and analysis of the EMS, five kinds of agents are defined in the system as follows.

(1) Wind turbine agents (WTAs): a kind of generator unit agent that is dedicated to represent the energy management unit for a wind turbine.
(2) Photovoltaic array agents (PVAs): a kind of generator unit agent that is dedicated to represent the energy management unit for PV arrays.
(3) Battery agents (BAs): a kind of energy storage unit agent that is dedicated to represent the energy management unit for batteries. Obviously, a battery has two statuses (charging and discharging corresponding to generator and load, respectively). For simplicity, a new concept of "reference state" is introduced as a reference direction in the electro-circuit. The power output is set as "+" during the discharging (generation) state and "−" during the charging state.
(4) Power grid agent (PGA): a power grid agent represents the grid. It should be mentioned that the grid can also play as the generation and load. In order to simplify the computation, the reference state is also used. The power output is set as "+" when grid sells power to the load and "−" when grid buys power from the WTA or PVA. However, it is not used in the following simulation.
(5) Load agent (LA): the whole loads in the system are represented by one load agent. It is simply designed as an expression, (overall load demand, vital load demand, Y1, Y2), where Y1 and

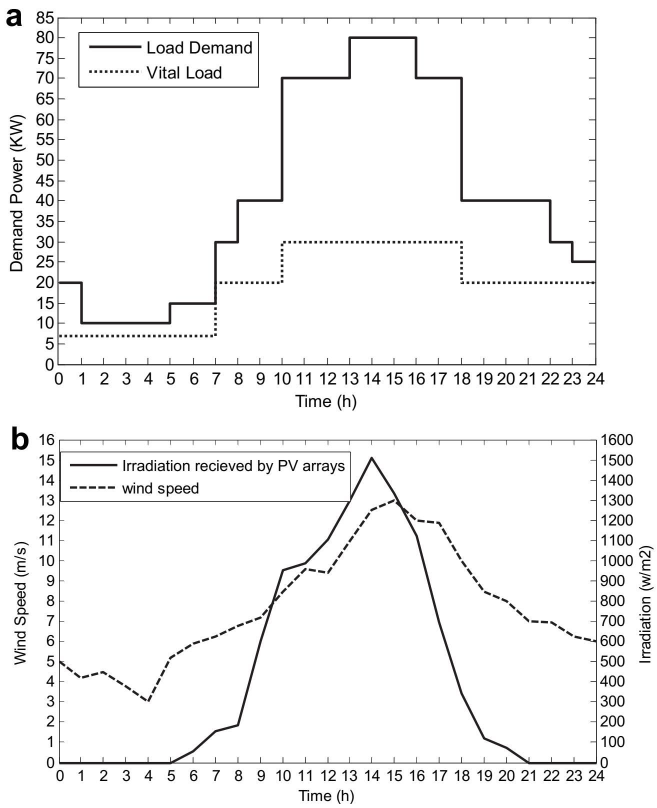


Fig. 8. Load demand, wind speed and sun irradiance versus the time for a typical day in summer.

Y2 show whether the load demand is fulfilled as presented by "0" and "1".

The total number of agents corresponds to the number of wind turbines, photovoltaic arrays and batteries. In general, the five kinds of agents could be simplified into two groups according to their role, generator agent and load agent. The MAS overview for the EMS is shown in Fig. 4. Facilitators are introduced into the WTAs, PVAs and BAs groups in the MAS to reduce the communication among the agents.

3.1. Model of EMS agents

Since high intelligence is assumed in each agent to make a local decision, a new architecture of agent model is presented as the system required. The agent architecture for WTA, PVA and BA is shown in Fig. 5. The whole process for this agent can be simplified into two parts, discrete decision-making and continuous control, which corresponds to reorganisation time and stable running time. The architecture describes a sense-recognise-planning-cooperation-decide-act cycle at the reorganisation time and control-evaluation cycle during the stable running time as shown in Fig. 5, where the evaluation mechanism is the most important bridge that connects both parts. In each loop of the cycle, the sensor detects the reorganisation order from the system or the change of the environment.

From Fig. 5, there are three layers in the agent. The information is transferred from the bottom to top and the control order flows from top to bottom. The behaviour bases are built corresponding to the three layers. Table 1 illustrates the detail of each layer. The agent constantly monitors the conditions to recognise its state. Once it detects its state turns into S_3 or S_4, the agent compares the last state and determines whether it should act immediately to ask for reorganisation or not. Otherwise, once it detects a reorganisation order from the EMS, it checks its state and sends to the upper layer. From the local planning layer, the cooperation layer would get its own parameters, including state, desire, expected output capacity and performance value. Then, the agent sends its own parameters to the related agents, asks for cooperation, and gets global decisions and information from the related agent. According to the global decision, the agent makes the final decision, switches its state and steps into a new continuous control cycle. During the continuous control timeline, a learning and evaluation mechanism will be acted, which is finally responsible for the performance value of local planning.

3.2. MAS for the EMS

3.2.1. Framework

The MAS is built as three layers with an individual agent layer, colony layer and system layer. The optimisation is carried out from bottom to top, and the decision-making is followed from top to bottom. The framework of the MAS is shown in Fig. 6.

3.2.2. Overall optimisation

As analysed in Section 2, the system is not just a combination of individual components, rather, it is an entire system with the whole greater than the sum of its parts. So, the optimisation and maximisation of the system's benefits must be taken into account with a system view. The energy management problem is formulated as the following objective function satisfying with the constraint:

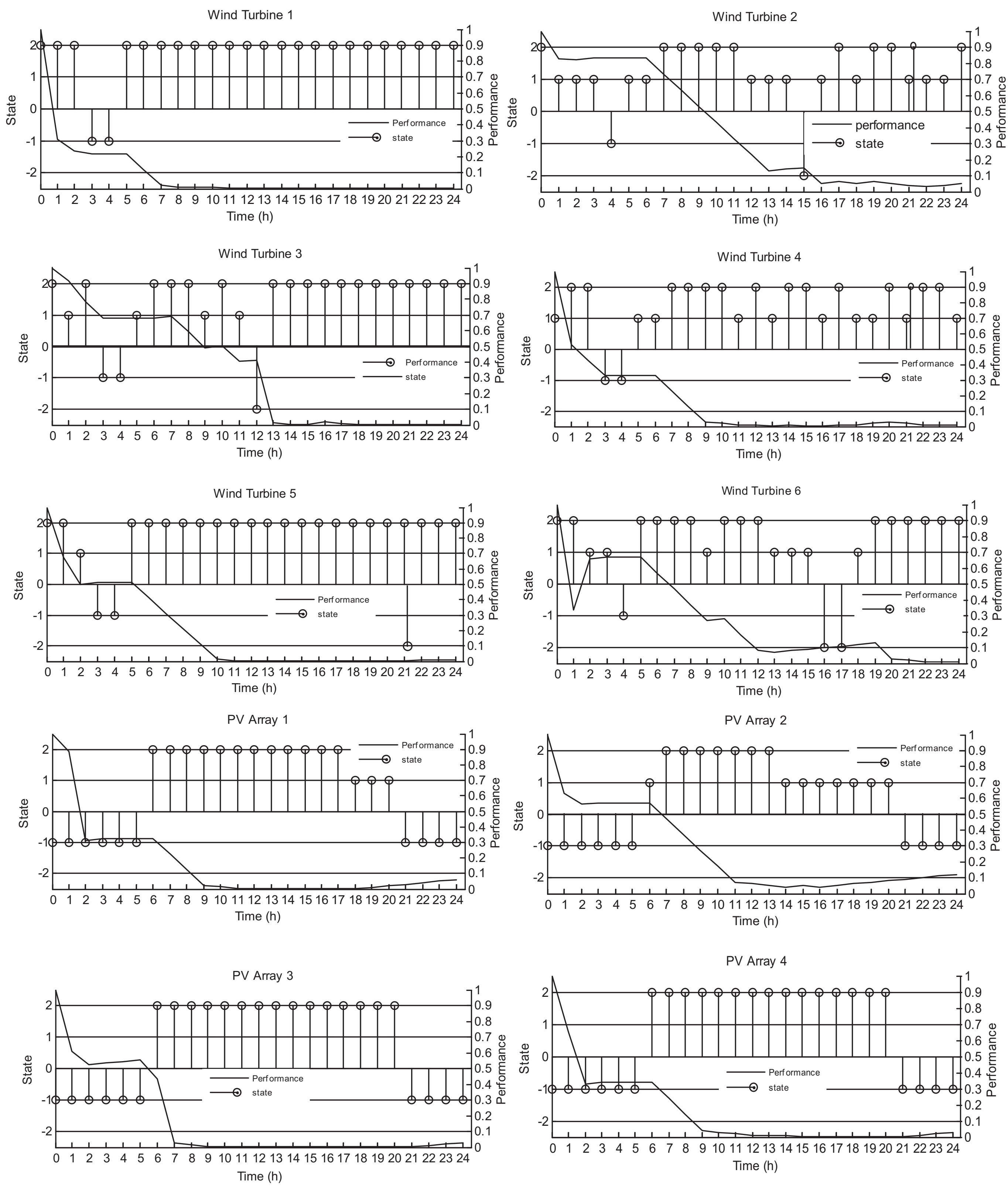
$$\min\ f = \sum_{i=1}^{4}\sum_{j=1}^{n}\alpha_{ij}\left(\beta_1 C_i + \beta_2 Perf_{ij}\right)P_{ij} \tag{9}$$

$$\text{s.t.}\ \sum_{i=1}^{4}\sum_{j=1}^{n}\alpha_{ij}P_{ij} = P_{load} \tag{10}$$

where α_{ij} is one of the most important parameters computed by the individual agent itself, which indicates whether the agent has the intention as the supplier at this condition. "$\alpha_{ij} = 0$" means that the generator will not attend at this time where State(t) = S_3 or State(t) = S_4. And "$\alpha_{ij} = 1$" means that the generator has the desire to attend at that time, where State(t) = S_2. β_1 and β_2 are the weights for the economic and quality index, respectively, which vary with the different aims of the system optimisation stage. C_i is the per-cost of each generator power output. $Perf_{ij}$ is the assessment value of power quality for each generator. P_{ij} is the capability of power output in the time step. i = 1, 2, 3, 4 stands for the type of energy source, including wind, PV, battery and grid power. The constraint

Table 3
Parameters of wind turbines and PV modules.

Parameters	PV1	PV2	PV3	PV4	Parameters	W1	W2	W3	W4	W5	W6
Optimum operating voltage (V)	30.2	33.2	31.6	37.7	Cut-in speed ((m/s)	4	3	4	4	4	3.5
Optimum operating current (A)	6.63	4.52	4.75	7.95	Rate wind speed (m/s)	12	11	10	11	10	10
Maximum power at STC (W)	200	150	150	300	Rotor diameter (m)	8	7	6	5	10	6
Total rate power (KW)	10	7.5	7.5	15	Rate power (kw)	15	10	7.5	5	15	7.5



(Note: 2=Running, 1=Hot Standby, -1=Cold Standby,-2=Inspect/Maintenance)

Fig. 9. The state of agents (wind turbines and PV arrays).

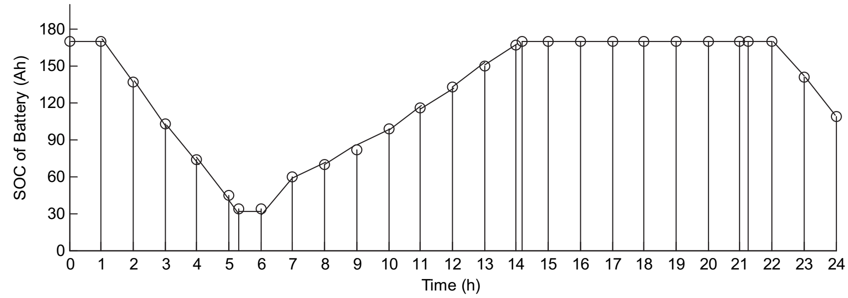


Fig. 10. The SOC of battery.

is shown in Eq. (9), which assures a balance between supply and demand.

For the overall objective function, three important differences distinguishable from the former model must be pointed out. The first one is that the time step is not fixed. When the excitation mechanism is excited, a new loop begins. Secondly, it is the introduction of α_{ij}, which insures that the intention and capability of each component are computed and decided by each component itself. That is to say, there is not only a system-level objective function that needs to be achieved, but also a decision made by each component should be respected. Thirdly, there is only one constraint, because the constraints of each component are also satisfied in their own models as described in Section 2 and achieved by the agent itself. So, the requirement of ability in computation and communication for the whole system is largely cut down.

3.2.3. *Main facilitator*

As mentioned above, the facilitator is introduced in the MAS to reduce the communication among the agents. During the optimisation process, the local behaviours and decisions can be adjusted adaptively based on the basic characteristics by the agents themselves. To the overall system, global optimisation is required, though the strategy is based on all agents. The problem is to find out which agent will be chosen as the final decision maker. At a certain time, the decision will be made by a facilitator. This facilitator is called the main facilitator at that time. That is to say, the main facilitator is the leader at that time, which makes the final decision according to the overall optimisation function. Every facilitator has the ability and chance to become the main facilitator, but there is only one main facilitator at any given time. The facilitators form small scale token ring networks. The token is moved during the facilitators according to the weather conditions and their performance. The main facilitator is the facilitator which holds the token. The whole process is:

1) The main facilitator receives the requirements from the exciter, and calls for a reorganisation to all the facilitators.
2) The facilitators forward the order to their agent members.
3) The agents receive the order and make their local planning and report to the facilitator then to the main facilitator.
4) The main facilitator makes the global decision and forwards it to the facilitator then to the agents.
5) The agents make the final decision and act accordingly.

4. Building platform of RE generated system based on JADE

JADE (Java Agent Development Framework) is the most widespread agent-oriented middleware based on peer-to-peer communication in use today. It supports features required by agents, the core logic of agents themselves, and a rich suite of graphical tools [23]. Communication among agents in JADE is implemented based on FIPA-specified Agent Communication Language (FIPA-ACL), which is the most important standardisation activity conducted in the filed of agent technology. FIPA-ACL messages are characterised by performative (there are 22 standard types), conversation ID, content and receivers.

The focus of this section is on the energy management using JADE as a multi-agent framework. Actually, the work done by an agent is carried out in the behaviours. The behaviours are also defined in Table 2. According to the discussion mentioned in Section 3, Table 2 shows the main behaviours with performative, conversation ID, content and intend receivers.

Fig. 7 shows the UML class diagram of the MAS for reform and optimisation of the system.

5. A case study of the simulation model

5.1. *Scenario*

The scenario simulation and experiment are carried out as shown in Fig. 8. In respect of the time for a typical day in summer Fig. 8(a) shows load demand and vital load demand, and Fig. 8(b) shows the wind speed and sun irradiance. The data of wind speed and sun irradiance come from the real measurement data of lab-building in the New Energy Research Center at South China University of Technology.

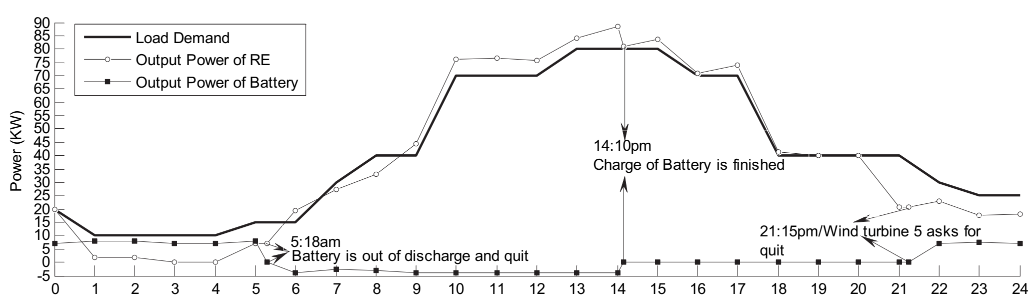


Fig. 11. The output power of RE and battery versus the load demand.

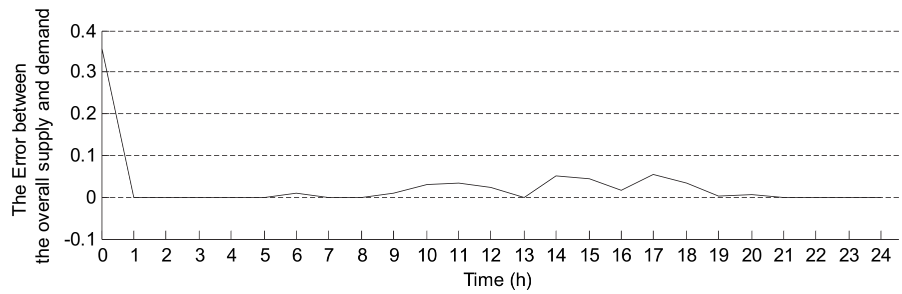


Fig. 12. The error between the overall supply and demand.

The hybrid RE power system includes six wind turbines, four PV arrays and a set of battery banks (170 Ah, 12 V). Their key parameters are shown in Table 3.

5.2. Simulation and results

When the main facilitator receives the requirement of reorganisation from the EMS, the agents do their local plan and send them to the facilitator. Then, the main facilitator makes a global decision according to Eqs. (9) and (10). In this paper, the overall optimisation is solved by turning the problem to integer programming. Let,

$$\begin{aligned} Z_i &= \alpha_i \left(\beta_1 \frac{C_i}{\sum C_i} + \beta_2 \frac{Perf_i}{\sum Perf_i} \right) P_i \\ W_i &= \alpha_i P_i \end{aligned} \tag{11}$$

where assumed $\beta_1 = 0.7$ and $\beta_2 = 0.3$; C_i and $Perf_i$ are normalised to $[0, 1]$ as shown in Eq. (10) to avoid the difference of their dimension.

If $\sum (P_w + P_{pv}) \geq P_{load}$, then the optimisation function is shown as expression Eq. (12):

$$\begin{aligned} \min\ f &= \sum_{i=1}^{10} Z_i Y_i \\ \text{s.t.} \quad & \sum_{i=1}^{10} W_i Y_i \geq P_{load} \end{aligned} \tag{12}$$

where, the energy sources do not include the battery and the left power denoted as the energy to charge the battery according to its local plan. After that, the excess energy would be discharged via the damping resistor.

If $\sum (P_w + P_{pv}) < P_{load}$, then the optimisation function is shown as expression Eq. (13).

$$\begin{aligned} \min\ f &= \sum_{i=1}^{11} Z_i Y_i \\ \text{s.t.} \quad & \sum_{i=1}^{11} W_i Y_i \geq P_{load} \end{aligned} \tag{13}$$

where the battery joins as the energy supplier. The output of the battery is computed as its maximum power. After the overall optimisation, the battery agent would determine the final output. If the energy supply is more than the overall load demand, the battery control unit would turn down its discharging current to cut down its output. If the energy supply is less than the overall load demand, the EMS would send an order to cut off the non-vital demand.

The final state of wind turbines, PV arrays and the battery are shown in Fig. 9 and Fig. 10. It is worthwhile to mention that, in the simulation, the initial parameters are assumed as described in the following context. The performance value and initial state of each entity are stochastic, and the initial SOC of the battery is 100%. Fig. 10 also shows the performance value of each agent, where the performance value is presented by the power quality of each energy source and normalised to [0, 1]. The more the minimum value is achieved, the better power quality is presented by the energy source. The algorithm to assess the power quality is proposed in detail in our former study [24,25].

From Fig. 9, the trends of the performance of each agent present an improvement in performance. And agent 1 has the best performance during this 24 h loop. There are several special points that are analysed as follows. Compared with agent 1, agent 6 exhibits lower performance than agent 1. Agent 6 is not selected during 12:00 to 16:00 and calls for *I/M* at 16:00, since it is in the cold standby state for a long time. At 15:00, agent 2 calls for *I/M* because it is always in the cold standby state for a long time. At 12:00, agent 3 calls for *I/M* because it receives the "error flag = 1" from the sensor. At 21:15, agent 5 asks to quit and calls for a new configuration. Agent 2 and agent 4 are selected to replace agent 5 based on acquaintance strategy.

Fig. 10 shows the SOC of the battery (in this paper, batteries are viewed as a whole). From 01:00 to 05:00, the battery is in discharging as one kind of energy source. At 5:18, the battery is out of charge and asks for disconnection. From 6:00 to 14:00, the battery is in the charging state as an ordinary load. At 14:10, the battery is full of charge and asks for disconnection. At 21:15, the battery sends its wish to be a candidate of energy source as shown in Fig. 10, since agent 6 asks for a new configuration. Obviously, it is not chosen and keeps in saturation.

Fig. 11 shows the output power of RE and the battery versus the load demand. The special point is pointed out in the figure. From 01:00 to 05:00, at 07:00 and 20:00, the energy is just supplied to the vital load, because the natural condition is limited and the battery is restricted by its maximum discharging current. With the improvement of the natural condition, the wind turbines and PV arrays can supply increasing energy from 06:00 to 20:00. The overall load demand is satisfied and the battery is charged according to its rules. Fig. 12 shows the error between the overall supply and demand. From Fig. 12, the supply is plentiful to satisfy the load demand, and the exceeding energy would be consumed by the damping resistor.

6. Conclusions

The distributed hybrid renewable energy generation system, although small in size, has complex energy management requirements. This paper presents a development of the proposed MAS for the reorganisation and optimisation of the energy management. In this paper, four parts of the system are presented. Firstly, the EMS in a typical RE generation system is introduced and analysed. Basic characteristics of the system components, wind turbines, PV arrays, battery and power grid, are analysed, respectively. To simplify the behaviours and situation recognition, four kinds of state are defined, which form the basis of the optimisation and reorganisation of the

EMS. Secondly, the MAS is envisaged as the feasible solution to satisfy all the requirements of the system. Five kinds of agents are envisaged to represent the EMS. "Reference state" is introduced to solve the problem and the battery and power grid can be considered as the generator and load of the hybrid system. With which, a three layered architecture of agents is presented, and the macro MAS is also proposed in detail with the framework together with the overall optimisation function included. Aiming at improving the performance of economic and power quality, the overall objective function is proposed and achieved. Especially, α_{ij} is introduced to the overall objective function. It lets the objective function not only satisfy the overall expectation, but also shows respect to the intention and decision made by each component. After all, the facilitator and main facilitator are envisaged in the macro-model of MAS to reduce the communication among the agents. The concept of the main facilitator is introduced as the executor to carry out the overall optimisation. Thirdly, a framework based on JADE is proposed in detail, including the discussion about agents, and their behaviours. Finally, a scenario case study is demonstrated and indicates that the MAS is a suitable solution for the energy management of the distributed hybrid renewable energy generation system.

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