

# MAS-based solution to energy management strategy of distributed generation system



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## ABSTRACT

This paper focuses on the energy management issue of a Distributed Generation System (DGS) for ensuring energy supply with high security. Firstly, considering that the DGS is composed of many types of Distributed Energy Resources (DERs) and a group of loads, a Multi-Agents System (MAS) based two hierarchical decentralized coordinated control scheme is constructed to deal with the complex energy management problem of the DGS, and JADE platform is applied to implement the MAS based energy management strategies. Then, the mode switching behaviors of each DER or load unit are described based on Petri Net (PN) models. And a Voltage Security Assessment (VSA) *L*-index is constructed. According to the *L*-index, four different operating modes of the DGS are determined and the coordinated control commands in the upper level agent are drafted. Based on PN models, according to the coordinated control commands, the switching control strategies are designed in the lower level respective unit agent to ensure secure energy supply against variable operating conditions. Moreover, the decentralized continuous controller in the lower level unit agent is also presented to dynamically regulate the output performance. Finally, the validity of proposed control scheme is demonstrated by means of simulation results.

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## Introduction

DGS, connected with utility grid and composed of different kinds of DER units, usually operates in different modes to meet various energy demands. The energy management of the DGS is a relatively complex issue, in which security and reliability of the energy supply, especially voltage security, have been recognized as essential concerns. With increasing penetration of distributed generation units, maintaining voltage security has become a more major concern for the DGS [1,2]. For this reason, when solving the problem of energy management for the DGS, more attentions should be paid to security and reliability so that effective control strategy could be implemented timely.

A DGS, which includes various DER units and different kinds of load demands, is a typical hybrid dynamic system. And DER units are divided into two categories: Distributed Generation (DG) units like wind turbines and Photovoltaic (PV) panels, and Distributed Storage (DS) units such as batteries and ultra capacitors. DER units as the sources of the DGS have multi-mode characteristics because they can operate in different modes subjected to their constraint conditions or the load demands of the system. If the operating

modes of the DER units are effectively controlled, the DGS can offer dispatchable power supply to meet load demand and maintain voltage profile [3,4]. Therefore, in this paper, in view of multi-mode characteristics of DER and load units, the coordinated control commands based on Voltage Security Assessment Index (VSAI) combined with switching control strategies are mainly researched so as to solve the energy management problem of DGS.

With development of multi-agent technology in recent years, MAS has attracted many power system researchers' attention so that it has been applied to the field of microgrids and hybrid energy systems for energy management and distributed control [3–16]. In [3,4], the MAS was applied to implement a hierarchical management and control for dealing with the energy management problem of the high penetrated distribution grid and the microgrid. A multi-agent solution to energy management was presented for a hybrid energy generation system in [5]. And in [6,7], the studies mainly focused on how to switch the operation modes of the storage units based on the MAS by using fuzzy-logic-rules or logic judgments for ensuring energy supply security and reliability. In [8], the MAS was proposed to implement DER scheduling in microgrids by means of the hierarchical control scheme. In [9,10], the MAS was proposed as a solution to distributed control and power management of microgrids respectively. In [11,12], the distributed control and management of the distributed

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generation system are researched based on MAS structure. A multi-agent solution to distribution system restoration was presented and implemented in FIPA-ACL with JADE (JAVA Agent Development Framework) in [13,14]. In [15], JADE, as an effective platform for developing MAS, was proposed. All the above researches imply that the MAS based control scheme can deal with complex energy management and hierarchical distributed control of microgrids or hybrid energy systems more effective, since it can provide the following advantages:

- (1) *Feasibility*: inside the MAS-based hierarchical scheme, different levels of agents not only can plan their respective decision-making asynchronously in parallel, but also achieve the goal of overall system in a cooperative manner.
- (2) *Flexibility*: different levels of agents not only can perceive and react fast to environmental changes, but also depend on each other to adjust the operational status in response to the changes.
- (3) *Reliability*: in case one-agent failure, other agents should maintain the proper system operation. The failure of one or several agents cannot make the overall system fail.
- (4) *Reduced computation and communication burden*: each agent can process dynamic information, basic computation, action-planning, and decision-making locally. It is only knowledge information to be exchanged between the agents. In this way, the MAS-based scheme not only can reduce the computation and communication burden, but also achieves fully operational performance of each unit.

For the reasons given above, in this paper, based on the voltage security assessment, the MAS based hierarchical decentralized coordinated control are researched to deal with the complex energy management problem of the DGS.

Firstly, corresponding to an example of DGS connected with a utility grid, the hierarchical control scheme based on MAS is established, composed of an upper level coordinated control agent in the view of whole system and several lower level unit agents. Moreover, the structures of different hierarchical agents and the interactions among agents are designed respectively. Secondly, in order to effectively describe the multi-mode behaviors of DER units, Petri-nets (PNs) are proposed for modeling DER units. As an effective tool of describing the discrete events, PN model has been applied in the field of distributed generation and hybrid energy system to draft energy management and distributed control strategies in different operating modes [16–18]. Thirdly, a VSA method is studied based on information fusion technique. Finally, as the most important work, the coordinated control commands are drafted according to the VSA *L*-index in the upper level agent, and according the coordinated control commands, switching control strategies of operating modes are designed in respective unit agent. Executing the following process: the DGS is defined as four operating modes according to the VSA *L*-index, so that range change of the VSA *L*-index will lead to the change of operating mode of the DGS; When the operating mode of the DGS changes, the upper level agent would send corresponding coordinated control commands to the lower unit agents, so that the lower unit agents implement mode switching according to its switching control strategies. Besides the switching controls designed, the generalized design method of local continuous controller in the unit agent is also presented to implement real-time dynamic regulation. In fact, the unit agents implement hybrid controls for its unit, since the switching control integrated with the continuous dynamic controller is essentially hybrid control.

The paper is organized as follows. The MAS based control scheme is constructed in section 'MAS based hierarchical control scheme'. In section 'PN based DER models', the DER and load unit

is modeled by using PN model. The VSAI is researched in section 'Voltage security assessment'. In section 'Coordinated control commands based on the VSA *L*-Index in the upper level agent', the coordinated control commands in the upper level agent is designed. The hybrid controls including the switching control and continuous controller in respective unit agents are designed in section 'Hybrid controls in the lower level unit agents', respectively. The simulation study is presented in section 'Simulation study'. In section 'Conclusion', concluding remarks are summarized.

## MAS based hierarchical control scheme

A typical DGS connected with utility grid through a static switch that is called as Point of Common Coupling (PCC), is shown in Fig. 1.

The DGS is composed of interconnecting DG units such as wind turbine, PV panel and Microturbine & Fuel Cell (MT & FC) units, and energy storage devices including battery for providing long-term energy supply and ultra capacitor or flywheels for the fast dynamic power regulation. The WT and MT & FC generation units are interfaced to the AC-bus via AC/AC inverters and separators. The PV and storage units are connected to a common DC voltage bus and interfaced to AC bus through dedicated converters. There are two types of load, one is critical load which should be supplied uninterrupted, and another one is non-critical load which could be shed when power supply is insufficient. Every DER, utility grid or load unit has its own associated agent that called as lower level unit agent to control operating mode and to regulate power output of respective unit. There is one upper level DGS Coordinated Control (DGSCC) agent in whole system view that is responsible for drafting coordinated control commands that are sent to every unit agent to implement operating mode switching. All agents are constructed as two hierarchical MAS to handle the energy management problem in a coordinated way to ensure the energy supply of the DGS more security.

### Structure design of MAS

#### DGSCC Agent (DGSCCA) – upper level coordinated control agent

The main goal is to draft coordinated control commands for coordinately switching operating mode of whole DGS connected with utility grid and ensuring energy supply more secure. The agent is designed as shown in Fig. 2. In this agent, the security of voltage is firstly assessed in the security assessment module based on measuring data and information of whole system. According to voltage security assessment indexes, the coordinated control commands are drafted in decision making module for switching the operating mode of DER or load units. And the switching control commands are sent to DER or load units through the action implementation module.

#### DER Agent (DERA) or Utility Grid Agent (UGA) or Load Control Agent (LCA)—lower level unit agent

The main intent is to implement hybrid controls including real-time dynamic control and the switching control strategies. That is to say, the operating modes of respective unit are switched according to the switching control strategies complying with the control commands from the DGSCCA and PN model. And the continuous performance is regulated by means of the real-time dynamic control. The hybrid controls for different types of units are very different issues, which are subjected to multi-mode characteristics and continuous dynamic characteristics of respective units. Therefore, the lower level unit control agent is designed as a hybrid agent in Fig. 3, which consists of a reactive layer and a deliberative layer. The reactive layer is defined to have properties of "perception and

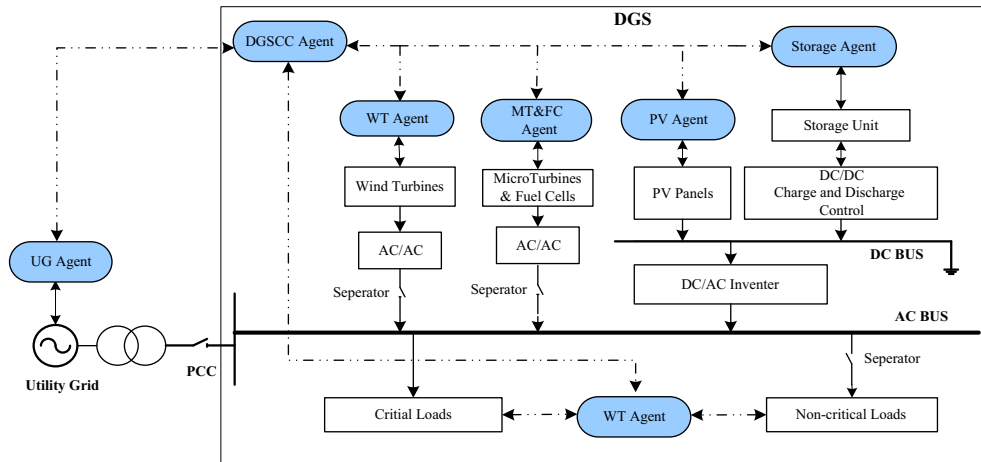


Fig. 1. The MAS based control scheme of the DGS.

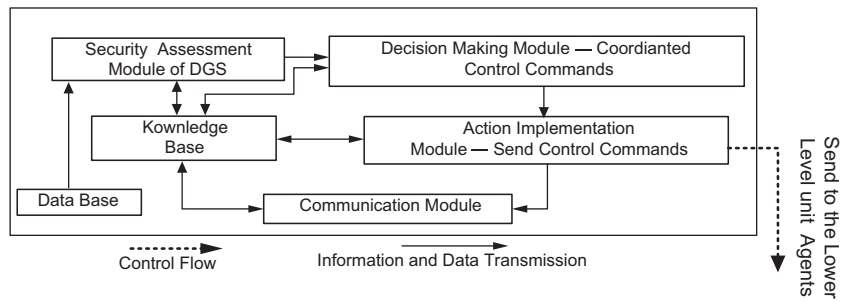


Fig. 2. The structure of DGSCCA.

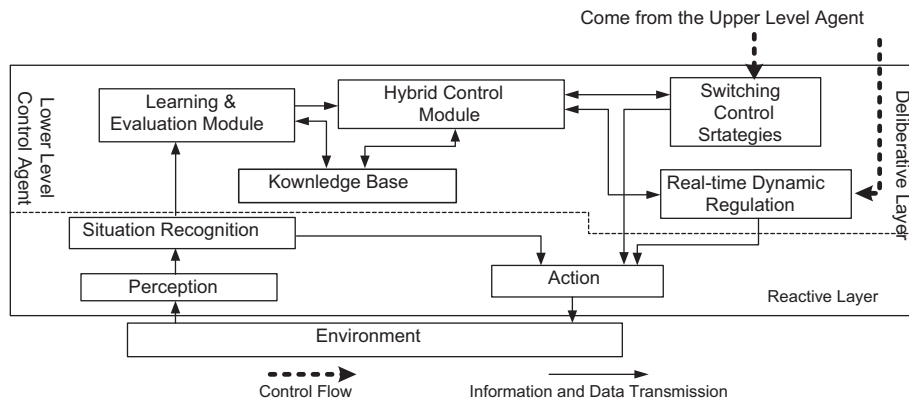


Fig. 3. The structure of lower level agent.

action”, and it is composed by a perception, a recognition, and action implementation modules. It has priority to respond quickly to the emergencies of environment. For instance, the reactive layer of renewable resource unit agent can perceive a sudden change of nature conditions by the perception and recognition modules, so as to determine whether it should switch operation mode immediately. The switching action is implemented by the action implementation module. The deliberative layer is defined as “belief, desire and intention”, composed by a knowledge data module, evaluation module, decision making module, mode switching module and continuous controller module. It has higher intelligence on controlling or planning the behavior of DER or load units by the hybrid controls. The hybrid controls are drafted based on

data information, knowledge data, state evaluation and communication information and are implemented by the action module.

In the designed hierarchical MAS, the interactions among agents include both direct and indirect interactions. From top to bottom, the coordinated control commands from the upper level agent to every lower level unit agent are implemented through direct interactions. Conversely, interaction behaviors from the lower level unit agents to the upper level agents are indirect interactions based on the environment and communication. In other words, the change of lower level unit agents modifies the status data of operation environment and communication information so as to lead to the revision of the coordinated control commands. The interactions between unit agents include direct and indirect

interactions, such as when the cooperation request of a unit agent is responded by another one agent, this interaction is direct, while when a unit agent modifies another unit agent's environment so as to trigger its reaction, this interaction is indirect.

#### The MAS framework based on JADE

In this paper, JADE (Java Agent DEvelopment) is employed as a multi-agent framework for handling the energy management problem of the DGS. JADE is an agent-based platform which acts as a middleware layer, providing a set of functions and classes to implement agent functionality, such as Agent Management Service (AMS), Directory Facilitator (DF), Messaging Transport Service (MTS), security and behaviors. These primary directory services are hosted on the main container, which has default agent such as AMS, DF and RMA (Remote Management Agent), provided and launched in the JADE platform. A JADE platform is made up of a collection of containers in which agents live, but only one main container. A platform encompasses all the containers within an agent system and can span multiple computers. The communication among agents in JADE is carried out according to FIPA-specified Agent Communication Language (ACL), whose messages is characterized by performative, conversation ID, content and intended receivers [13]. An agent in JADE platform has only one conversation ID that can be identified by other agent. There are 22 kinds of performatives for communication between agents, such as inform, request, cfp (call for proposal), propose and so on. The JADE interface of MAS is snapshot in Fig. 4.

Each of defined agents including DGSCCA, UGA, DERA and LA is coded by JAVA language in JADE platform, which is respectively regarded as single agent system. The first operating step of JADE is that each agent should be registered to get a unique ID and define their own behaviors according to their characteristics. Then MAS will automatically complete the task of energy management according to hybrid control. The coordination control of MAS and interactions among agents are described as follows: 1. the VSAI of the DGS is firstly calculated based on related data and information; 2. according to the index, DGSCCA accesses into the JADE platform and sends 'inform' message to UGA; 3. after UGA receives and returns message, the operation mode of the DGS is determined; 4. DGSCCA sends corresponding coordinated control commands to

WTA, PVA, BA, MF & FCA and LA; 5. they will return 'request', 'propose' or 'refuse' message to the DGSCCA according to their current operating modes. 6. the unit agents implement respective hybrid controls. In this way, the energy management of the DER units will be completed.

#### PN based DER models

In terms of power flow and energy control, DER units can be divided into two categories: dispatchable units and nondispatchable units. As nondispatchable units, the WT and PV unit can operate in different modes only depending on the natural conditions of wind speed or solar irradiance. But as dispatchable units, the storage and MT & FC unit can frequently switch its operating mode according the operation conditions to maintain the balance between power supply and demand. In order to effectively switch operating modes of the dispatchable units, the switching control strategies must be designed according to the multi-mode behaviors all DER units. PN is here proposed for modeling every DER unit. Based on PN model, the mode switching behaviors of DER units can be described by triggering enabled transition so that token is transformed into corresponding place, and switching control strategies of all the dispatchable DER units can be designed according to the principles of PN models.

#### PN based WT unit model

The WT can operate in different modes according to the wind speed, which lead to different output power of its power generation unit. The output power is described as follows:

$$P_W(v) = \begin{cases} 0 & (v < v_{in}) \\ P_R \cdot \frac{v - v_{in}}{v_R - v_{in}} & (v_{in} \leq v < v_R) \\ P_R & (v_R \leq v < v_{off}) \\ 0 & (v \geq v_{off}) \end{cases} \quad (1)$$

where  $P_R$  is the rated power of the wind turbine,  $v_{in}$  and  $v_{off}$  are the cut-in and cut-off wind speed respectively,  $v_R$  is the rated wind speed.

In view of its output characteristic, the WT unit is defined in three modes: stop mode, Maximum Point of Power Tracking (MPPT) mode and constant output mode, which is modeled by

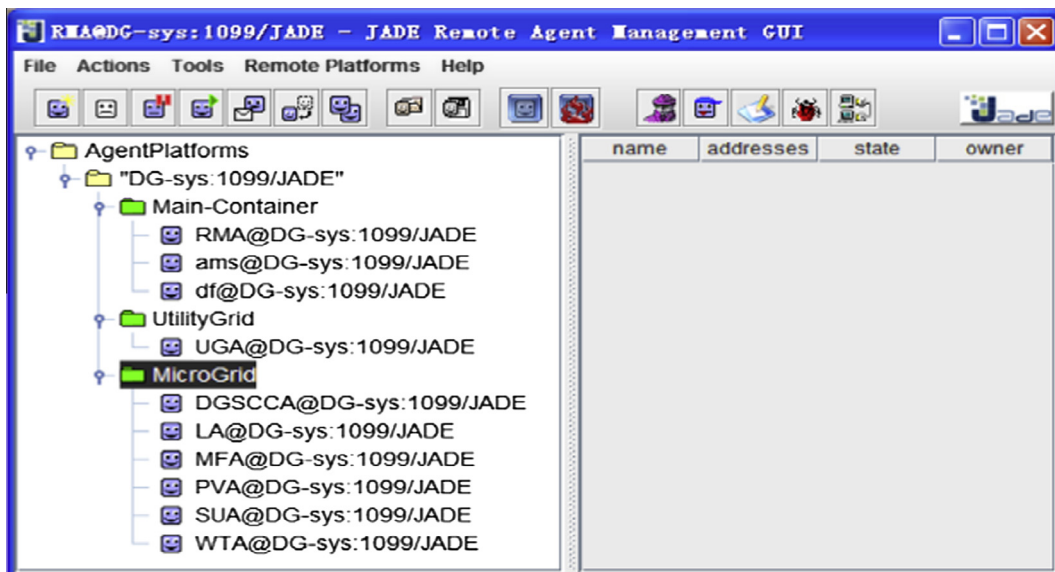


Fig. 4. The JADE interface of MAS.

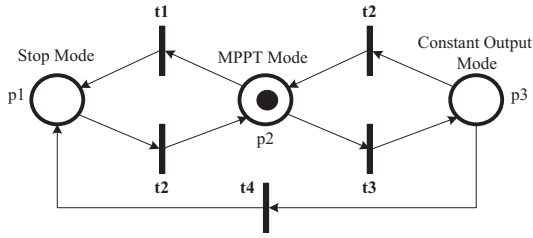


Fig. 5. PN based model of the WT unit.

**Table 1**  
Descriptions regarding places and transitions.

| Name | Description            |
|------|------------------------|
| p1   | Stop mode              |
| p2   | MPPT operating mode    |
| p3   | Constant output mode   |
| t1   | $v < v_{in}$           |
| t2   | $v_{in} \leq v < v_R$  |
| t3   | $v_R \leq v < v_{off}$ |
| t4   | $v \geq v_{off}$       |

PN as shown in Fig. 5. At any time, there is only one place with a token in the PN. And the token can be transformed into another place when corresponding transition is triggered. Descriptions of places and transition triggering conditions are given in Table 1.

#### PN based model of PV unit

Solar irradiation and ambient temperature are two main factors that affect output power of PV generation unit. In addition, the PV unit can use MPPT technique to continuously deliver the highest output power when there are variations in irradiation and temperature. The output power of PV unit is described as follows:

$$P_{PV} = \begin{cases} P_{PV\_MPPT} & (G_{ING} > C) \\ 0 & (G_{ING} \leq C) \end{cases} \quad (2)$$

where  $P_{PV}$  is the output power of the generation unit;  $P_{PV\_MPPT}$  is the maximum power in MPPT mode;  $G_{ING}$  is the incident irradiance; and  $C$  is a threshold value according to the performance of the PV cell.

There are two modes are considered to describe the PV unit by means of PN model. One is MPPT mode with  $P_{PV} = P_{PV\_MPPT}$ . The other one is limitation mode with  $P_{PV} = 0$ . The PN model of PV panel is shown in Fig. 6, and descriptions of places and transition triggering conditions are given in Table 2.

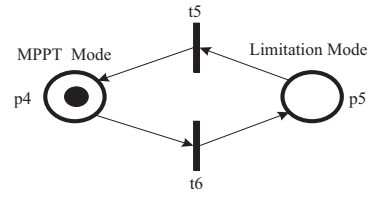


Fig. 6. PN based model of the PV unit.

**Table 2**  
Descriptions regarding places and transitions.

| Name | Description      |
|------|------------------|
| p4   | MPPT mode        |
| p5   | Limitation mode  |
| t5   | $G_{ING} > C$    |
| t6   | $G_{ING} \leq C$ |

#### PN based model of storage unit

Differed from nondispatchable WT and PV units, the dispatchable storage unit plays important roles in the system by means of charging and discharging. On one hand, when storage unit in saturated state, meanwhile, the utility grid and other DER units cannot provide sufficient energy supply to meet the load demand, the storage unit is requested to operate in discharging mode by the control commands. On the other hand, the storage unit is requested to operate in charging mode by the control commands and is regarded as a load if the energy supply from utility grid or other DER units exceeds the load demand. State of charge (SOC) indicates overcharging or undercharging of the storage unit, which is main factor of the storage unit that largely impacts the performance of the system. When  $SOC \leq SOC_{min}$ , where  $SOC_{min}$  is the minimum SOC, the storage unit will stop operating because of insufficient charges; when  $SOC_{min} < SOC < SOC_{max}$ , where  $SOC_{max}$  is the maximum value of SOC, the storage unit is in an operating mode (charging or discharging); when  $SOC \geq SOC_{max}$ , the storage unit will stop operating because of excessive charges. The maximum SOC and the minimum SOC are confined at 90% and 10% of its capacity, respectively.

According to the above characteristics, the operating modes of the storage unit will change based on the level of SOC and the power demand. Therefore, PN model of the storage unit is built as Fig. 7, and places and triggering condition are defined in Table 3.

#### PN based model of MT & FC unit

Though the MT & FC is dispatchable DER unit, but in view of operating cost, it has the lowest priority to other DER units for

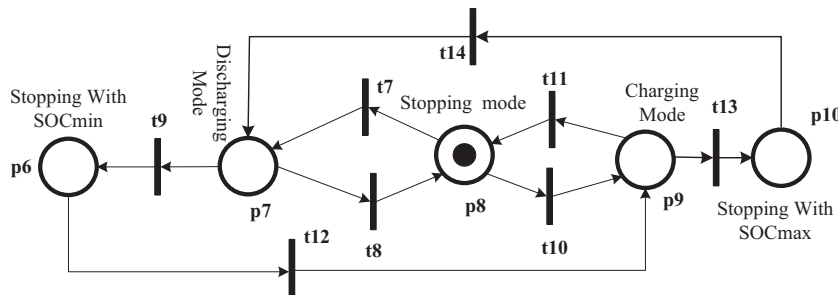


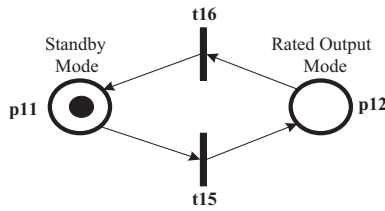
Fig. 7. PN based model of the storage unit.



**Table 3**

Descriptions regarding places and transitions.

| Name | Description   |
|------|---|
| p6   | Stopping mode because of $SOC = SOC_{min}$  |
| p7   | Discharging mode  |
| p8   | Stopping mode with $SOC_{min} < SOC < SOC_{max}$                                    |
| p9   | Charging mode   |
| P10  | Stopping mode because of $SOC = SOC_{max}$  |
| t7   | There is a control command to request discharging in order to increase power output |
| t8   | There is a control command to request stopping in order to decrease power output    |
| t9   | The storage unit discharges to minimum allowable value of $SOC$                     |
| t10  | There is a control command to request charging in order to decrease power output    |
| t11  | There is a control command to request stopping in order to increase power output    |
| t12  | There is a control command to request charging                                      |
| t13  | The storage unit charges to maximum allowable value of $SOC$                        |
| t14  | There is a control command to request discharging                                   |

**Fig. 8.** PN based model of the MT & FC unit.**Table 4**

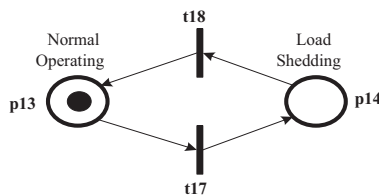
Descriptions regarding places and transitions.

| Name | Description   |
|------|---|
| p11  | Standby mode  |
| p12  | Rated output mode   |
| t15  | There is a control command to request increasing power output |
| t16  | There is a control command to request stopping                |

power regulation. On normal condition, the MT & FC unit operates in standby mode. But when the energy supply is insufficient, MT & FC unit has to be requested to switch to the rated output mode by the control commands to increase the power supply. PN model of the MT & FC unit is given in Fig. 8, and descriptions of places and transition triggering conditions are given in Table 4.

#### PN based model of load unit

Two kinds of loads are here considered: critical load and non-critical load. The system must ensure secure energy supply to the critical loads. While the non-critical loads can be regarded as dispatchable unit, and play a role of maintaining the power balance through load shedding when the energy supply is much less than the load demand. Therefore, two modes of load unit would be described by PN model in Fig. 9. And the related descriptions are given in Table 5.

**Fig. 9.** PN based model of the load unit.**Table 5**

Descriptions regarding places and transitions.

| Name | Description  |
|------|--|
| p13  | Normal operating mode                                |
| p14  | Load shedding mode                                   |
| t17  | There is a control command to request shedding load  |
| t18  | There is a control command to request restoring load |

#### Voltage security assessment

In this section, a more reliable indicator is developed to measure the voltage security degree of the DGS. Based on the index, four operating modes of the DGS can be defined, which will be discussed in the following section. The VSAI is briefly discussed in the following content.

##### VSA indexes of all main nodes at any instant

The voltage sequences on the  $i$ -th node form Wide Area Measurement System (WAMS) are represented as  $V_i = [V_i^1, V_i^2, \dots, V_i^m]^T$

- (1) The voltage moving average value of the  $i$ -th node at the  $j$ -th instant from  $N$  available measurements can be expressed as

$$V_i^{(j)} = \sum_{k=1}^j V_i^k / j \quad j \in 1, 2, \dots, N \quad (3)$$

The percentage of diversity between the measured voltage  $V_i^j$  and the moving average value  $V_i^{(j)}$  at the  $j$ -th instant is defined as

$$C_i^j = \frac{V_i^j - V_i^{(j)}}{V_i^{(j)}} \times 100, (j \in 1, 2, \dots, N) \quad (4)$$

- (2) By dividing the area under the percentage of diversity curve, the VSA index of the  $i$ -th node at the  $j$ -th instant is defined as

$$U_i^{(j)} = \sum_{k=1}^j (C_i^k + C_i^{k-1}) / 2j \quad j \in 1, 2, \dots, N \quad (5)$$

##### Integrated VSA L-index based on information fusion technique

In order to evaluate the voltage security of the whole system, an information fusion technique based on D-S evidence theory is discussed as follows:

According to VSA indexes of all main nodes at any instant, a basic probability function is constructed as

$$m_i^j(U) = U_i^{(j)} / [U_i^{(j)} + (1 - \gamma_i)] \quad (6)$$

where  $m_i^j(U)$  denotes basic probability assignment of the  $i$ -th node at the  $j$ -th instant;  $\gamma_i$  is the weight coefficient of voltage on the  $i$ -th load node, which is limited to rational numbers between 0 and 1.

According to the D-S evidence theory, the fusion criterion of two different basic probability functions is

$$m(c) = \begin{cases} 0 & c = \Phi \\ K^{-1} \sum_{A_i \cap B_j = c} m_1(A_i) m_2(B_j) & c \neq \Phi \end{cases} \quad (7)$$

$$K = 1 - \sum_{A_i \cap B_j = \Phi} m_1(A_i) m_2(B_j). \quad (8)$$

According to (7) and (8),  $m_i^j(U)$  for all  $j \in 1, 2, \dots, N$  are firstly fused, and fusion result is  $m_i(U)$ . Then,  $m_i(U)$  for all nodes are fused again and fusion result is  $m(U)$ , which is called as integrated VSA  $L$ -index. The VSA  $L$ -index is usually limited to rational numbers between 0 and 1.

### Coordinated control commands based on the VSA $L$ -index in the upper level agent

In this section, the researches are mainly focused on how to draw up the coordinated control commands based on the VSA index in the DGSCCA.

#### Operating modes of DGS based on the $L$ -index

In view of the security of the energy supply, four operation modes are defined according to the range of the VSA  $L$ -index, as follows:

- (1) the DGS is in DGS supplied mode when  $0 < L < 0.90$ ;
- (2) the DGS is in pre-utility mode when  $0.90 \leq L < 0.95$ ;
- (3) the DGS is in utility supplied mode when  $0.95 \leq L < 0.99$ ;
- (4) the DGS is in load shed mode when  $0.99 \leq L < 1.0$ .

The switching process of DGS operating mode is depicted in Fig. 10. And descriptions regarding places and transition triggering conditions are given in Table 6.

#### Control commands of DGSCCA for coordinately switching operating modes of unit agents

The operating modes of the nondispatchable DER units, like like WT and PV units, mainly depend on natural energy conditions, and are uncontrollable. Other dispatchable units including storage, MT/FC and load units, especially storage unit, can be switched between different operating modes to regulate their power supply and load demand in the face of different operating modes of DGS. For this reason, control commands are required to coordinately switch the operating modes of these dispatchable unit agents. The upper level DGSCCA is just responsible drawing up the coordinated

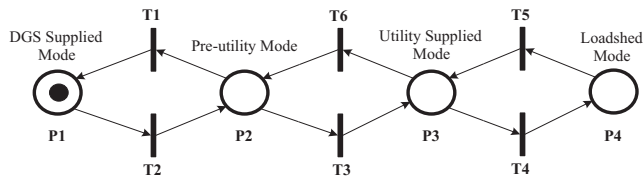


Fig. 10. Operation modes modeling of the DGS based on PN.

Table 6  
Descriptions regarding places and transitions.

| Name | Description   |
|------|---|
| P1   | DGS supplied mode   |
| P2   | Pre-utility mode  |
| P3   | Utility supplied mode   |
| P4   | Load shed mode  |
| T1   | $L$ index drops to $0 < L < 0.90$ from $0.90 \leq L < 0.95$       |
| T2   | $L$ index rises to $0.90 \leq L < 0.95$ from $0 < L < 0.90$       |
| T3   | $L$ index rises to $0.95 \leq L < 0.99$ from $0.90 \leq L < 0.95$ |
| T4   | $L$ index rises to $0.99 \leq L < 1.0$ from $0.95 \leq L < 0.99$  |
| T5   | $L$ index drops to $0.95 \leq L < 0.99$ from $0.99 \leq L < 1.0$  |
| T6   | $L$ index drops to $0.90 \leq L < 0.95$ from $0.95 \leq L < 0.99$ |

control commands and sending them into corresponding unit agent respectively. The coordinated control commands are designed as follows:

**Command 1:** According to current operating mode of the storage unit, request switching this unit to suitable subsequent mode so as to increase its power output.

**Command 2:** According to current operating mode of the storage unit, request switching this unit to suitable subsequent mode so as to decrease its power output.

**Command 3:** According to current operating mode of the storage unit, request switching this unit to stopping mode.

**Command 4:** According to current operating mode of the MT/FC unit, request switching this unit to suitable subsequent mode so as to increase its power output.

**Command 5:** According to current operating mode of the MT/FC unit, request switching this unit to suitable subsequent mode so as to decrease its power output.

**Command 6:** According to current operating mode of the load unit, request switching this unit to the shedding mode so as to decrease its power demand.

**Command 7:** According to current operating mode of the load unit, request switching this unit to the normal mode so as to increase its power demand.

Only when the operating mode of the DGS is switched, the corresponding control commands will be activated and sent into corresponding lower level unit agents respectively. More details will be discussed in the following subsection.

### Hybrid controls in the lower level unit agents

In this section, the researches are mainly focused on how to design the switching control strategies according to the coordinated control commands and the continuous controller in the lower level unit agents.

#### Switching control strategies of unit agents according to the coordinated control commands

1. When  $L$ -index always keep in one of the above four ranges, then the DGS always operates in corresponding mode, in this case, no control command is activated.
2. When  $L$ -index drops to  $0 < L < 0.90$  from  $0.90 \leq L < 0.95$ , T1 is triggered, and the DGS will be switched to P1 from P2.

At the moment,  $P_W + P_{PV} > \sum_i^m P_{loadi}$ , and Command 2 and Command 5 are activated and sent into the storage and MT/FC unit agents respectively, then two agents will make following judgments and switching controls at the same time:

- (a) if the MT/FC unit is in p12, then it will be switched to p11;
- (b) if the storage unit is in p6 or p8, then it will be switched to p9;
- (c) if the storage unit is in p7, then it will be firstly switch to p8, after a moment, will be switched to p9 again.

By the above switching controls, the DGS will ultimately satisfy

$$P_W + P_{PV} - P_{S-} = \sum_i^m P_{loadi} \quad (9)$$

where  $m$  is the number of load,  $P_W$  and  $P_{PV}$  represent the output power of the WT and PV units respectively;  $P_{S-}$  is the charge power of the storage unit;  $P_{loadi}$  is the power demand of the  $i$ -th load.

3. When  $L$ -index rises to  $0.90 \leq L < 0.95$  from  $0 < L < 0.90$ , then T2 is triggered, the system will be switched to **P2** from **P1**. According to the output powers of power generation units that are informed by every unit agent, the DGSCCA will do following judgments:

(a) if  $P_W + P_{PV} = \sum_i^m P_{loadi}$ , at the moment, the DGSCCA sends Command 3 and command 5 into the MT/FC and the storage unit agents respectively at the same time, then two unit agents will make following switching controls:

- ① if the storage unit is in p7 or p9, then it will be switched to p8;
- ② if the MT/FC unit is in p12, then it will be switched to p11.

(b) if  $P_W + P_{PV} < \sum_i^m P_{loadi}$ , at the moment, the DGSCCA firstly sends Command 1 into the storage unit agent, and subsequent switching controls in storage unit agent will occur:

- ① if the storage unit is in p8 or p10, then it will be switched to p7;
- ② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again.

After the storage unit agent finishes its switching control, it informs the DGSCCA. Then according to the current operating mode of the storage unit, the DGSCCA will send Command 4 or 5 into the MT/FC unit agent, then the MT/FC unit agent will make following switching controls:

- ③ when the storage unit has been switched to p7, and if the MT/FC unit is in p12, then it will be switched to p11;
- ④ when the storage unit cannot run in p7 because of insufficient charge, and if the MT/FC unit is in p11, then the DG will be switched to p12.

By the above switching controls, the DGS will ultimately satisfy

$$P_W + P_{PV} + P_{S+} = \sum_i^m P_{loadi} \quad (10)$$

where  $P_{S+}$  is discharge power of the storage unit

(c) if  $P_W + P_{PV} + P_{S+} < \sum_i^m P_{loadi}$ , at the moment, Command 1 and Command 4 are sent into MT/FC and storage unit agents respectively at the same time, then two unit agents will make following switching controls:

- ① if the storage unit is in p8 or p10, then it will be switched to p7;
- ② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again;
- ③ if the MT/FC unit is in p11, then it will be switched to p12.

By the above switching controls, the DGS will ultimately satisfy

$$P_W + P_{PV} + P_{S+} + P_{MT/FC} = \sum_i^m P_{loadi} \quad (11)$$

where  $P_{MT/FC}$  represents output power of the MT/FC unit.

4. When  $L$ -index rises to  $0.95 \leq L < 0.99$  from  $0.90 \leq L < 0.95$ , then T3 is triggered, the system will be switched to **P3** from **P2**. According to the output powers of power generation units, the DGSCCA will do following judgments:

(a) if  $P_{UG} + P_W + P_{PV} > \sum_i^m P_{loadi}$ , where  $P_{UG}$  represents the transmission power of tie line between utility grid and DGS, at the moment, The DGSCCA sends Command 2 and Command 5 into MT/FC and storage unit agents respectively at the same time, then two unit agents will make following switching controls:

- ① if the MT/FC unit is in p12, then it will be switched to p11;

② if the storage unit is in p6 or p8, then it will be switched to p9;

③ if the storage unit is in p7, then it will be firstly switch to p8, after a moment, will be switched to p9 again.

By the above switching controls, the DGS will ultimately satisfy

$$P_{UG} + P_W + P_{PV} - P_{S-} = \sum_i^m P_{loadi} \quad (12)$$

(b) if  $P_{UG} + P_W + P_{PV} = \sum_i^m P_{loadi}$ , at the moment, Command 3 and Command 5 are sent into the storage and MT/FC unit agents at the same time, subsequent switching controls will occur in the two unit agents:

① if the storage unit is in p7 or p9, then it will be switched to p8;

② if the MT/FC unit is in p12, then it will be switched to p11.

(c) if  $P_{UG} + P_W + P_{PV} < \sum_i^m P_{loadi}$ , at the moment, Command 1 is firstly sent into the storage unit agent, and subsequent switching control will occur

① if the storage unit is in p8 or p10, then it will be switched to p7;

② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again.

After the storage unit agent finishes its switching control, it informs the DGSCCA. Then according to the current operating mode of the storage unit, the DGSCCA will send Command 4 or 5 into the MT/FC unit agent, then the unit agent will make following switching controls:

③ when the storage unit has been switched to p7, and if the MT/FC unit is in p12, then it will be switched to p11;

④ when the storage unit cannot run in p7 because of insufficient charge, and if the MT/FC unit is in p11, then it will be switched to p12.

By the above switching controls, the DGS will ultimately satisfy

$$P_{UG} + P_W + P_{PV} + P_{S+} = \sum_i^m P_{loadi} \quad (13)$$

(d) if  $P_{UG} + P_W + P_{PV} + P_{S+} < \sum_i^m P_{loadi}$ , at the moment, Command 1 and Command 3 are sent into MT/FC and storage unit agents respectively at the same time, then two agents will make following switching controls

① if the storage unit is in p8 or p10, then it will be switched to p7;

② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again;

③ if the MT/FC unit is in p11, then it will be switched to p12.

By the above switching controls, the DGS will ultimately satisfy

$$P_{UG} + P_W + P_{PV} + P_{S+} + P_{MT/FC} = \sum_i^m P_{loadi} \quad (14)$$

5. When  $L$ -index rises to  $0.99 \leq L < 1.0$  from  $0.95 \leq L < 0.99$ , then T4 is triggered, the system will be switched to **P4** from **P3**. According to the output powers of power generation units, the DGSCCA will do following judgments:

At the moment, Command 1, Command 4 and Command 6 are sent into the MT/FC, storage and load unit agents respectively at the same time by the DGSCCA, then three agents will make following switching controls:

① if the storage unit is in p8 or p10, then it will be switched to p7;

② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again;



- ③ if the MT/FC unit is in p11, then it will be switched to p12;
- ④ if the load unit is in p13, then it will be switched to p14.

By the above switching controls, the DGS will ultimately satisfy

$$P_{UG} + P_W + P_{PV} + P_{S+} = \sum_i^{m-l} P_{loadi} \quad (15)$$

where  $l$  is the number of non-critical load which will be shed.

6. When  $L$ -index drops to  $0.95 \leq L < 0.99$  from  $0.99 \leq L < 1.0$ , then T5 is triggered, the system will be switched to **P3** from **P4**. According to the output powers of power generation units, the DGSCCA will do following judgments:

(a) if  $P_{UG} + P_W + P_{PV} + P_{S+} + P_{MT/FC} \geq \sum_i^m P_{loadi}$ , at the moment, Command 7 is sent into the load unit agent, subsequent switching will occur

- ① if the load unit is in p14, then it will be switched to p13.

(b) if  $P_{UG} + P_W + P_{PV} + P_{S+} \geq \sum_i^m P_{loadi}$ , at the moment, the DGCCA sends Command 5 and Command 7 into the load and MT/FC unit agents, subsequent switching will occur at the same time

- ① if the load unit is in p14, then it will be switched to p13;
- ② if the MT/FC unit is in p12, then it will be switched to p11.

(c) if  $P_{UG} + P_W + P_{PV} \geq \sum_i^m P_{loadi}$ , at the moment, Command 3, Command 5 and Command 7 are sent into MT/FC, storage and load unit agents respectively at the same time, then three agents will make following switching controls:

- ① if the load unit is in p14, then it will be switched to p13;
- ② if the MT/FC unit is in p12, then it will be switched to p11;
- ③ if the storage unit is in p7 or p9, then it will be switched to p8.

(d) if  $P_{UG} + P_W + P_{PV} - P_{S-} \geq \sum_i^m P_{loadi}$ , at the moment, DGSCCA sends Command 2, Command 5 and Command 7 into the MT/FC, load and storage unit agents respectively at the same time, then three agents will make following switching controls:

- ① if the load unit is in p14, then it will be switched to p13;
- ② if the MT/FC unit is in p12, then it will be switched to p11;
- ③ if the storage unit is in p6 or p8, then it will be switched to p9;
- ④ if the storage unit is in p7, then it will be firstly switch to p8, after a moment, will be switched to p9 again.

7. When  $L$ -index drops to  $0.90 \leq L < 0.95$  from  $0.95 \leq L < 0.99$ , then T6 is triggered, the system will be switched to **P2** from **P3**. According to the output powers of power generation units, the DGSCCA will do following judgments

(a) if  $P_W + P_{PV} + P_{S+} + P_{MT/FC} \geq \sum_i^m P_{loadi}$ , at the moment, Command 1 and Command 4 are sent into the MT/FC and storage unit agents respectively at the same time, then the two unit agents will make following switching controls:

- ① if the storage unit is in p8 or p10, then it will be switched to p7;
- ② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again;
- ③ if the MT/FC unit is in p11, then it will be switched to p12.

(b) if  $P_W + P_{PV} + P_{S+} \geq \sum_i^m P_{loadi}$ , at the moment, Command 1 and Command 4 are sent into the MT/FC and storage unit agents, then two unit agents will make following switching controls

- ① if the storage unit is in p8 or p10, then it will be switched to p7;
- ② if the storage unit is in p9, then it will be firstly switched to p8, after a moment, will be switched to p7 again;
- ③ if the MT/FC unit is in p12, then it will be switched to p11.

(c) if  $P_W + P_{PV} = \sum_i^m P_{loadi}$ , at the moment, the DGSCCA sends Command 3 and Command 5, then the storage and MT/FC unit agents will make following switching controls at the same time

- ① if the MT/FC unit is in p12, then it will be switched to p11;
- ② if the storage unit is in p7 or p9, then it will be switched to p8.

#### Continuous controllers of unit agents

The continuous controller of every unit agent is designed by using unit local states and implemented in a distributed way, and is mainly responsible for adjusting dynamic performance of its unit.

The continuous controller structure of the unit agent is shown in Fig. 11. More detailed  $P$ - $Q$  control scheme is given in Fig. 12. Each DER inverter has an outer power loop based on droop control. The real active/reactive powers are calculated by using the output voltage and current variables. Then errors between the active/reactive power references and the real powers act as the inputs of the droop controllers.

In the low-voltage DGS, the line impedance may be approximately resistance, so that the droop control can be designed as

$$f - f_0 = k_q(Q - Q^*) \quad (16)$$

$$E - E_0 = k_p(P - P^*) \quad (17)$$

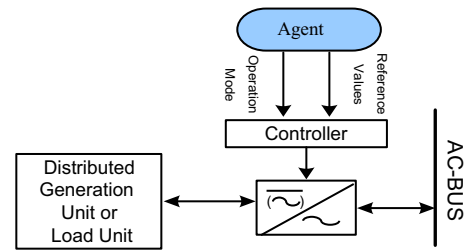


Fig. 11. Continuous controller structure of unit agent.

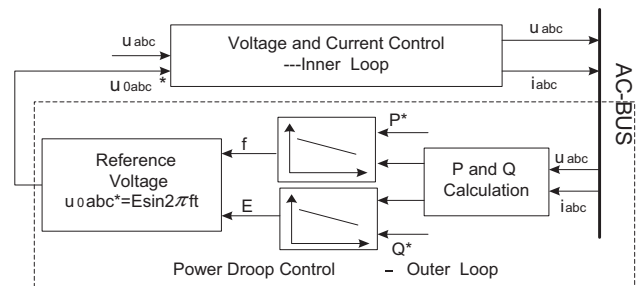


Fig. 12.  $P$ - $Q$  control scheme of the continuous controller.

where  $f$  and  $E$  are the frequency and the amplitude of the output voltage, respectively, and  $k_p$  and  $k_q$  define the corresponding slope coefficients.  $P^*$  and  $Q^*$  are active/reactive power references. The voltage reference is obtained through the droop control, which acts as the reference input of inner loop voltage/current control. Considering the uncertainty and multi-mode characteristics, the  $H_\infty$  robust control method based on multiply Lyapunovs is here proposed to design the inner loop controller. The method had been introduced in detail in the author's previous contributions [18,19].

### Simulation study

Simulation studies are performed on the DGS as shown in Fig. 1. The rate output power of each DER units is shown in Table 7.

Versus the load curve during 24 h in a day as shown in Fig. 13, the VSA  $L$ -index also varies between 0 and 1 so that the DGS is transformed into different operating modes as shown in Fig. 14. By the coordinated control commands and the switching control strategies based on the two hierarchical MAS, the power assignments among DER units are determined as shown in Fig. 15.

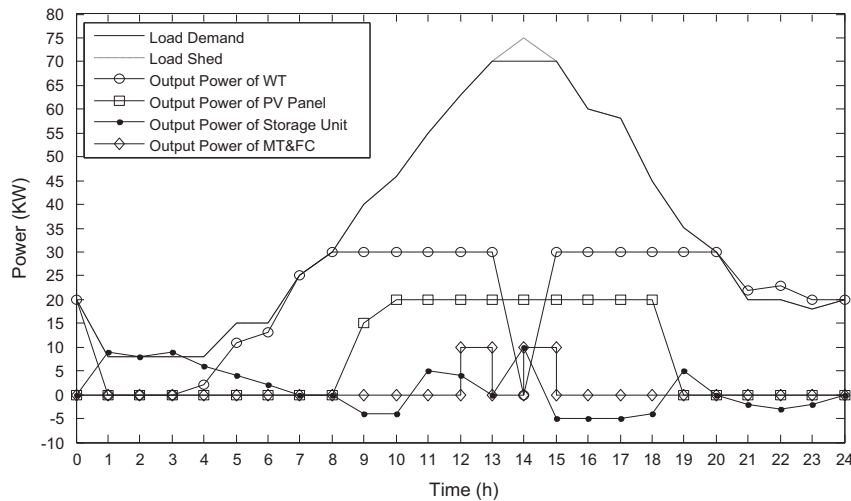
**Table 7**  
Rate output powers of DER units.

| DER unit    | WT    | PV    | Storage unit | MT & FC |
|-------------|-------|-------|--------------|---------|
| Rated power | 30 kW | 20 kW | 10 kW        | 10 kW   |

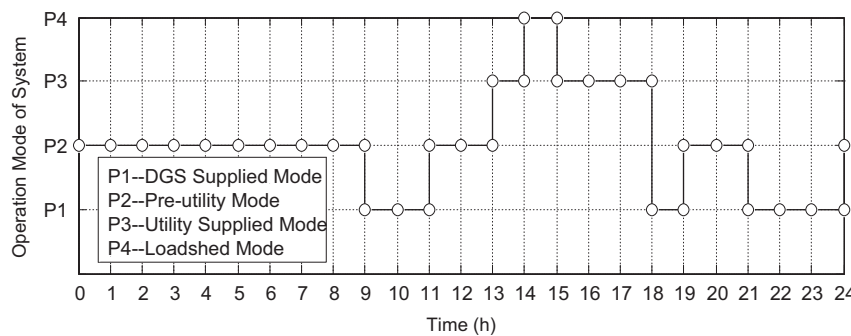
Fig. 15(a)–(e) display the switching process of operating mode in the WT, PV, storage, MT & FC and load unit agents, respectively.

The value of the VSA  $L$ -index can be accurately and expediently updated and computed based on real-time voltage measurements. During 1:00 h to 9:00 h, the  $L$ -index is between 0.90 and 0.95, so the system is operating in pre-utility mode. At 1:00 h, because of lesser wind speed and no solar irradiance, both MT and PV units operate in stopping mode, so the storage unit is request discharging to meet the load demand. At 4:00 h, the WT unit is switched to MPPT operating mode. And the load demand is supported by both the WT and storage units until 7:00 h when the storage unit discharges to the minimum allowable value of SOC so that it had to be switched to stopping mode. With the improvement of solar irradiation and temperature condition, PV unit can provide power output from 8:00 h to 19:00 h, that is, the PV unit works in MPPT mode during this period of time. From 9:00 h to 11:00 h, the value of  $L$ -index decreases to under 0.90, the system returns to DGS supplied mode. Thanks to the increasing output power of PV unit, the storage unit begins to charge at 9:00 h.

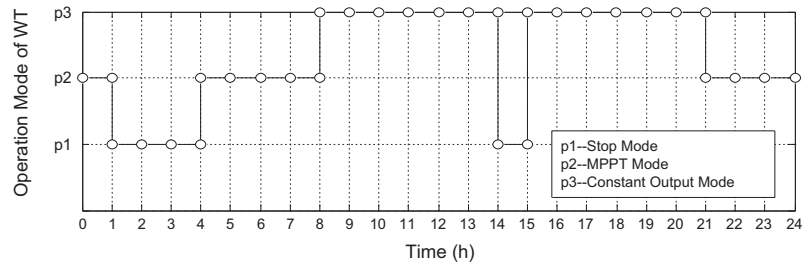
With the load demand increasing, the  $L$ -index of system exceeds 0.90 and the DGS is switched into pre-utility mode again at 11:00 h. As well, the storage unit is requested discharging to increase output power because the output powers of both WT and PV units cannot meet the increasing load demand. At 12:00 h, MT & FC unit is requested transferring to rated output mode from standby mode in order to meet growing load demand. At 13:00 h, utility grid is requested connecting into the DGS so as to maintain the balance between supply and demand. At the same



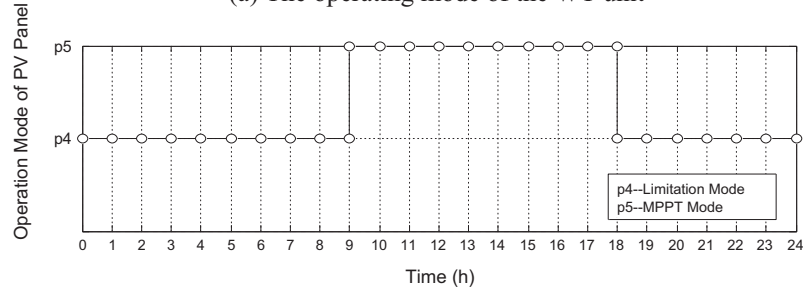
**Fig. 13.** The power assignments of DER units versus the load demand.



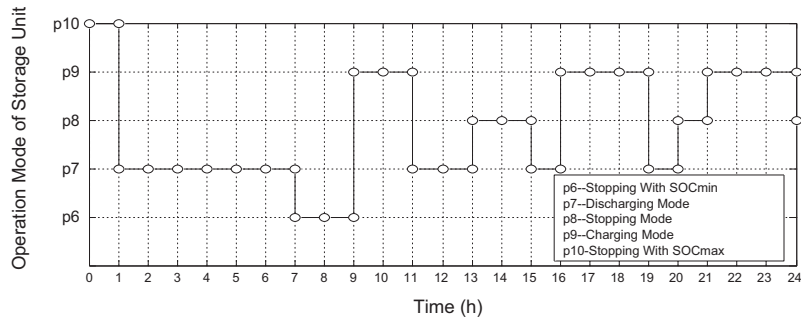
**Fig. 14.** The operating mode of the DGS.



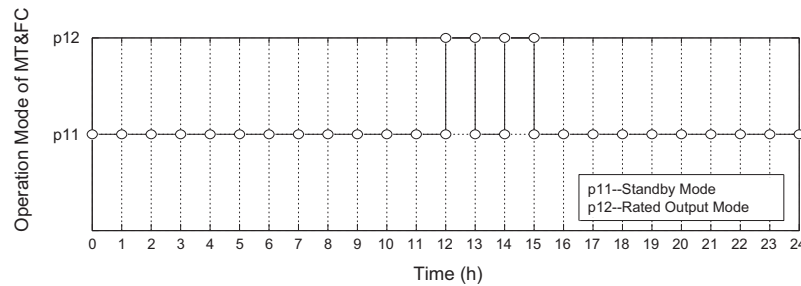
(a) The operating mode of the WT unit



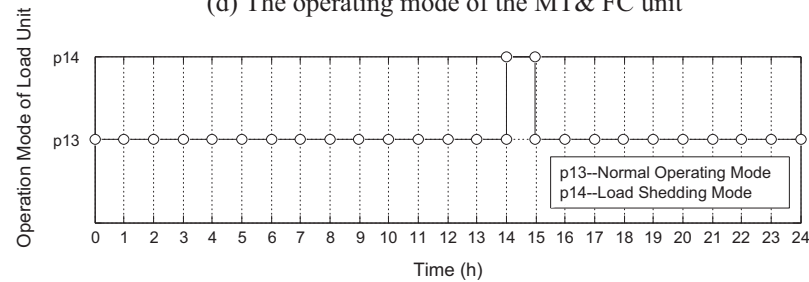
(b) The operating mode of the PV unit



(c) The operating mode of the storage unit



(d) The operating mode of the MT&amp; FC unit



(e) The operating mode of load unit

**Fig. 15.** The modes switching of DER units.

time, the storage unit and MT & FC unit switch to stopping mode because the load demand is mainly supplied by the utility grid.

At 14:00 h, WT unit stop operating because of lesser wind speed so that the value of  $L$ -index is exceed 0.99 abruptly and the output

power of whole system cannot meet the load demand in spite of increasing supplement of the storage unit and the MT & FC unit. So, some non-critical load unit is requested shedding from the system so that the load unit is switched to load shed mode. From

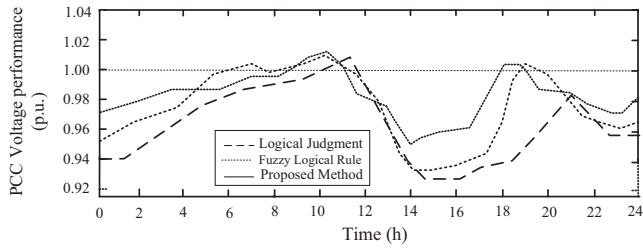


Fig. 16. The PCC voltage performance.

15:00 h, the value of  $L$ -index of system begins to decline with the decrease of load demand. Meanwhile, the WT unit returns to constant output mode because wind speed rises, so that the system returns to utility supplied mode. From 18:00 h to 19:00 h and

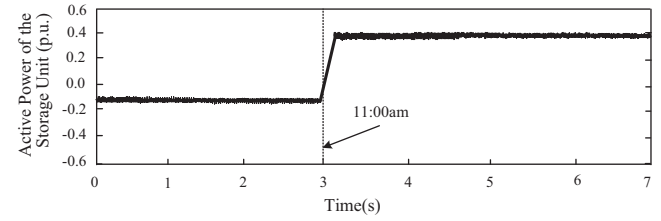


Fig. 17. The power stabilization performance.

21:00 h to 24:00 h, the DGS disconnects from the utility grid and operates in DGS supplied mode. The storage unit discharges because the output power of WT unit cannot meet load demand during 19:00 h to 20:00 h. And from 21:00 to 24:00, the storage unit charges because the output power of WT unit is sufficient.

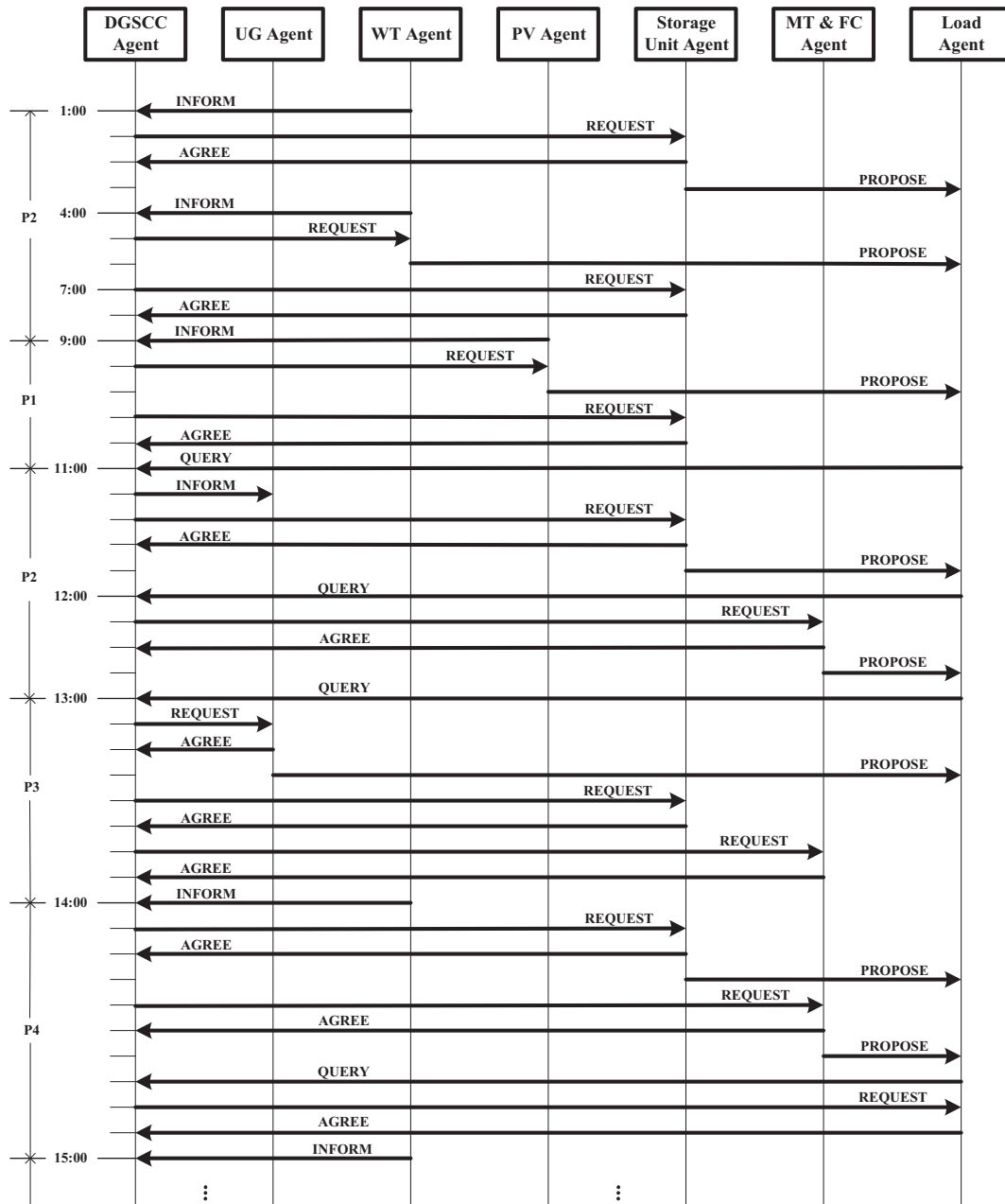


Fig. 18. The interactions between agents.

Next, we use three kinds of MAS based energy management schemes: the proposed scheme in this paper, compared scheme 1 similar to [5], compared scheme 2 similar to [6] to test the security performance of the voltage. The PCC voltages under the three kinds of schemes are shown in Fig. 16. From the above results, it can be seen that by the means of the proposed energy management method, the PCC voltages are controlled between 0.95 p.u. and 1.01 p.u., and the fluctuation value is limited in the satisfactory range of  $\pm 5\%$  rated value. While because the logical judgment and the fuzzy-logic rule lack adaptability in the compared scheme 1 and scheme 2, the PCC voltages even drop to below 0.95 p.u. during 14.00 h and 16.00 h. Compared with scheme 1 and 2, the proposed energy management method can make the DGS security performance better.

The above simulation results imply that by means of the proposed schemes, the proposed mode switching controls can ensure energy supply with higher security in response to the load demand changes.

Taking the battery unit as an example, the performance regarding the continuous controller tested. Because, at the 11:00 h instant, the operation mode of the battery unit is switched from the charging mode to discharging mode according to the switching control strategy as shown in Fig. 15(c), therefore, in order to testify the stabilization performance before and after the mode switching, the simulation is shown before 3 s and after 4 s of 11:00 h. Fig. 17 shows that the unit continuous controller is able to regulate the output power and stabilize it down quickly in the face of the mode change. Because that the unit continuous controller is designed by using local states and implemented in a distributed way rather than in a centralized one, so it is able to react fast enough to deal with the disturbance.

In addition, the interactions among two hierarchical agents regarding the switching control are implemented based on JADE platform. The corresponding messages exchanged between agents during 1:00 to 15:00 is shown in Fig. 18.

When the  $L$ -index changes from one range to another range, DGS will switch its operation mode and send “INFORM” message to DGSCCA. In addition, unit agents will also send “INFORM” message to DGCCA when they are switched from one mode to another mode. Then, DGSCCA receives their messages and send corresponding “REQUEST” commands to storage unit agent, MT & FC unit agent and load unit agent to switch operation modes so as to increase or decrease power supply or load demand. And the corresponding agents will return corresponding message to DGSCCA according to their current operating modes. As shown in Fig. 16, the interactions between agents are expressed by corresponding performative, which accomplishes the complex energy management task in MAS. These messages can be traced by sniffer agent in JADE platform, and all of information exchanging between agents are completed in a very short time.

## Conclusion

The DGS, although small in size, has complex energy management requirements. This paper has proposed MAS based

decentralized coordinated control scheme as the solution of the energy management. It is worthwhile to mention that, according to the coordinated control commands, the switching control strategies can switch the operating modes of DER or load units in an intelligent manner following load changes, so that the DGS can offer continuous energy supply with high security and reliability. The better system performance has been demonstrated by means of simulation results.

## Acknowledgments

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