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An MAS based energy management system for a stand-alone microgrid at high altitude

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HIGHLIGHTS

- An energy management system based on MAS is developed for a stand-alone microgrid.
- Practical operation conditions and considerations for microgrid at high altitude are presented.
- A virtual bidding strategy is proposed to quickly establish operation schedule and capacity reserve.
- Model predictive control is used in real-time power dispatches to compensate the power control error of the DGs.
- The MAS and the proposed methods are implemented and verified in a RTDS–PXI joint real-time simulation platform.

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ABSTRACT

A multi-agent system based energy management system (EMS) is proposed in this paper for implementing a PV-small hydro hybrid microgrid (MG) at high altitude. Based on local information, the distributed generation (DG) sources in the MG are controlled via the EMS to achieve efficient and stable system operation. Virtual bidding is used to quickly establish the scheduling of system operation and capacity reserve. In addition, real-time power dispatches are carried out through model predictive control to balance load demand and power generation in the MG. The dynamic model and the energy management strategy of the MG have been simulated on a RTDS–PXI joint real-time simulation platform. The simulation results show that the proposed energy management and control strategy can optimally dispatch the DG sources in the MG to achieve economic and secure operations of the whole system.

1. Introduction

Microgrid (MG) has been extensively studied as an effective platform for integrating and managing distributed generation (DG) sources and for implementing demand side management (DSM). On the one hand, grid-connected MGs can help enhance system reliability, reduce pollutant emissions, and improve system efficiency [1]. On the other hand, stand-alone MGs have been considered as an attractive way to provide electricity for remote areas by eliminating the need of construction of new power lines and by better utilizing the local renewable energy resources [2–5].

Current research on energy management systems for MGs is mainly focused on centralized control schemes. Under a centralized framework, a microgrid central controller (MGCC) can be designed to carry out economic power dispatch for DGs and energy storage systems (ESS) at multiple time scales [6–11]. However, as the time scale increases, the design of a centralized controller struggles with challenges from larger prediction errors in renewable generation and more complexity in solving optimization problems. When the system size and the number of components are getting larger, it also becomes more challenging to realize real-time management. Moreover, reliability is another concern for centralized schemes since a single fault at the MGCC can cause the whole system stop working [11]. Even though heuristic algorithms and expert systems can be used to design a practical central management system of a microgrid, such design is lack of flexibility and scalability [12–16].

To avoid the drawbacks of centralized control scheme, multi-agent system (MAS) has been proposed for MG energy management. MAS, a distributed control approach based on local information and actions, is suitable for real-time control and has the following features [17–19]:

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Nomenclature

A	state matrix of prediction model
B	output matrix of prediction model
BESS	Battery energy storage system
$C_{bid,t}$	virtual price ($)
$C'_{bid,t}$	clearing price ($)
$C_{dyn,v,t}$	dynamic compensation price of PV plant ($)
$C_{dyn,d,t}$	dynamic compensation price of diesel power plant ($)
$C_{dyn,h,t}$	dynamic compensation price of small hydro plant ($)
$C_{mar,d}$	marginal cost of diesel power plant ($)
$C_{mar,v}$	marginal cost of PV power plant ($)
DG	distributed generation/generator
DGP	diesel generation plant
EMS	energy management system
ESS	energy storage system
H_s	standard water level (m)
H_t	water level (m)
k_i	frequency control coefficient (kW/Hz)
k_{h1}	fixed compensation of small hydro ($)
k_{h2}	variable compensation of small hydro ($/kW)
MAS	multi-agent system
MPC	model predictive control
P	power generation (kW)
$P'_{bid,t}$	clearing power generation (kW)
P_{eh}	power expectation of SHGP (kW)
P_{el}	peak load index (kW)
P_{ev}	PV power expectation (kW)
$P_{j,sch}$	dispatch power by virtual bidding (kW)
$P_{j,t}$	real-time output power (kW)
$P_{D,t}$	dispatch power for DGP (kW)
$P_{H,t}$	dispatch power for SHGP (kW)
$P_{L,t}$	load demand (kW)
$P_{V,t}$	dispatch power for PVGP (kW)
$P_{V,max}$	power limit of PV system (kW)
PCE	power control error (kW)
PVGP	photovoltaic generation plant
R	reserve power for system (kW)
$R_{V,t}$	reserve power for PV system (kW)
SHGP	small-hydro generation plant
SOC	state of charge for ESS
δ_L	power prediction error of load
δ_V	power prediction error of PV generation
Δf	system frequency variation (Hz)
ΔP_{ij}	adjustable power interval j for DG i (kW)
Δu_i	control variable of MPC
$\Delta U(t)$	vector form of control variables
Δx_i	state variable of MPC
$\Delta X(t)$	vector form of state variables
θ_f	set of DG based on frequency control
θ_c	set of DG based on constant power control

(1) *Flexibility:* The MAS structure can integrate various plug-and-play DG sources and adaptively adjust the control of MG according to actual conditions and targets.
(2) *Scalability:* It is convenient to extend the functions of an MAS based on the needs of customers; and
(3) *Fault-tolerance:* The localized control of individual DGs is robust to disturbances and faults in the MG.

The studies of MAS-based MG EMS have been carried out on the system framework, dispatch algorithms and coordination strategies of DGs. Detailed reviews on MAS for power engineering applications were given in [20,21]. In [22], it proposed an MAS system for voltage support by dispatching DGs on a distribution feeder, while the different characteristics of DGs were not considered. The agent-based models for trading DGs in the day-ahead electricity markets were presented in [23,24]. DC voltage control of microgrid was implemented in [25] through an MAS based state-flow diagram, but no specific energy management method was discussed. In [26,27], the MAS based bidding process was introduced in brief. An MAS based strategy was developed to switch an ESS system among 4 statuses [28]. While there are no detailed models and decision making rules discussed for specific DGs/agents. A multi-agent control system for buildings was presented in [29], where the agents run based on a proposed comfort index. Another control system of building was presented in [30] with the focus on energy consumption management. MAS based demand side management methods were used to balance power with assistance of DGs such as electrolyzer, fell cell and desalination [31] or energy storage systems considering the charging/discharging characteristics [32]. A framework of agent-based modeling and energy management method based on improved genetic algorithm was presented in [33] for grid-connected microgrid. In [34,35], different MAS-based price bidding mechanisms for power dispatch with different targets were proposed. In [34], the target was to maximize economic revenue, while the objective in [35] was to maximize the utilization of renewable sources. The authors of [36] proposed an MAS-based algorithm to balance the generation and demand by adjusting the generation of DGs in real time. However, the algorithm only targeted the dispatch of DGs according to their capabilities and did not consider the differences in their dynamic responses. In addition, all the above studies were only tested by non-real-time software simulations and need to be verified on hardware platforms that can better emulate practical conditions and meet industrial requirements and standards.

In this paper, a new MAS-based EMS is proposed for a PV-small hydro hybrid (PVSHH) microgrid. In the proposed EMS, the optimal dispatch of DGs is achieved by means of virtual bidding (VBD). Based on the VBD, the system operation schedule and capacity reserve are determined. The DGs are controlled to follow the schedules according to their individual control strategies and local information. In addition, the real-time power control error is compensated by the DGs with capacity reserve using a model predictive control (MPC) method. The proposed EMS is tested on a RTDS–PXI real-time simulation platform. The MAS is implemented based on a NI–PXI physical platform to realize local control strategies and agent functions such as dynamic price adjustment. The dynamic model of the hybrid microgrid is developed based on a real time digital simulator (RTDS). The communication between the NI–PXI and the RTDS is based on IEC 61850. The simulation results show that the proposed EMS meets all the strict practical requirements and can be used to implement a real PV-small hydro hybrid microgrid.

The remainder of the paper is organized as follows: Section 2 introduces the PVSHH microgrid project in brief and the design principles of its EMS. The proposed EMS is discussed in Section 3, followed by the study of the VBD and the dynamic power dispatch. Section 4 describes the structure of the MAS and its implementation on the RTDS–PXI real-time simulation platform. Both the snapshot and long-term simulation results are given in Section 5. Section 6 concludes the paper.

2. PV-small hydro hybrid microgrid project

The EMS proposed in this paper is for a PVSHH microgrid project that has been approved by the government of China. The stand-alone MG to be developed is in a remote area at an altitude above 4000 m. In the plateau environment, the low temperature and the shortage of oxygen cause incomplete combustion of fuels, which results in low system efficiency and high pollutant emissions. However, the solar energy resource in the area is abundant and highly stable, which makes it suitable for the development of photovoltaic (PV) power generation.

The original MG was composed of a small-hydro generation plant (SHGP) with four 1.6 MW small-hydro generators and a diesel generation plant (DGP) with four 2.5 MW diesel generators. The SHGP has a 6.4 million m^3 reservoir and is responsible for primary frequency regulation. In the wet season, i.e. spring and summer, the reservoir is close to full. However, the water in the reservoir is normally not enough to meet the electric power and water demand in the dry season.

The DGP works in load peak hours to assist the SHGP for secure system operation. Due to the high altitude, each diesel generator only generates a maximum of 1.0 MW under such environment. The emissions can cause significant adverse impacts on the vulnerable local ecological system. In addition, the transportation cost of fuels to the remote, plateau area is very expensive. The high cost and the high emission rate limit the operation time of the diesel generators.

As the load demand increases in the area, the SHGP can no longer meet the needs. Without increasing the generation of the diesel generators, renewable energy sources (RESs) are considered to serve the increasing demand. To utilize the abundant solar resources (with a sunshine duration over 2000 h in a year) in the area, a photovoltaic generation plant (PVGP) is planned to be developed and integrated with the existing system to form a new PVSHH microgrid as shown in Fig. 1. The PVSHH microgrid will be able to enhance system stability, improve efficiency, reduce emissions, and to meet the electric power and water demands of the area.

In phase I of the project, a 5 MWp photovoltaic (PV) system and a 5 MW h battery energy storage system (BESS) have been installed. Because of its high initial and maintenance cost, the BESS has a relatively limited capacity. The BESS is mainly used to smooth the power fluctuation and transfer the extra energy of the PV system.

To achieve a secure and efficient operation, the EMS of the PVSHH microgrid is designed based on the following considerations:

(1) The PVGP has the highest priority in generation. With the help of BESS, the extra energy of PV system if any will be stored in the daytime and used to support the peak load in the evening. This increases the utilization of the PV system and reduces the operation time of DGP. Only when the BESS is fully charged, the PV generation will be curtailed to balance the load demand and to avoid overvoltage.
(2) The operation of the SHGP has a high priority to meet the residential water demand, especially in the dry season. For most of the time, the SHGP undertakes the base load, and its total generation has to be above the lower output threshold. The SHGP is responsible for the system frequency regulation.
(3) The usage of the diesel generators should be minimized. The DGP is only used as a peaker to meet peak demands.

Since the PVSHH microgrid project was approved, extensive studies have been carried out on the design and implementation of the hybrid microgrid. We have been actively involved in the microgrid project and are in charge of the design and implementation of the EMS. Based on the design principles, the team proposes a MAS-based EMS and verifies it on a real-time simulation platform. The detailed discussion on the development of a MAS-based EMS for the PVSHH microgrid is given in the following section.

3. Energy management method based on MAS

The proposed MAS-based EMS carries out multi-time-scale energy management based on a virtual bidding (VBD) strategy and a dynamic power dispatch algorithm. The VBD determines the system operation schedule and capacity reserve based on a public bidding platform while the dynamic dispatch algorithm works in real time to compensate the power control error of the DGs. The high-altitude environment leads to a specific control target and parameters in the proposed system, such as the virtual price adjustment for different DGs, which reflects different operational considerations as discussed in Section 2. Nevertheless, the proposed method can be readily extended for other applications.

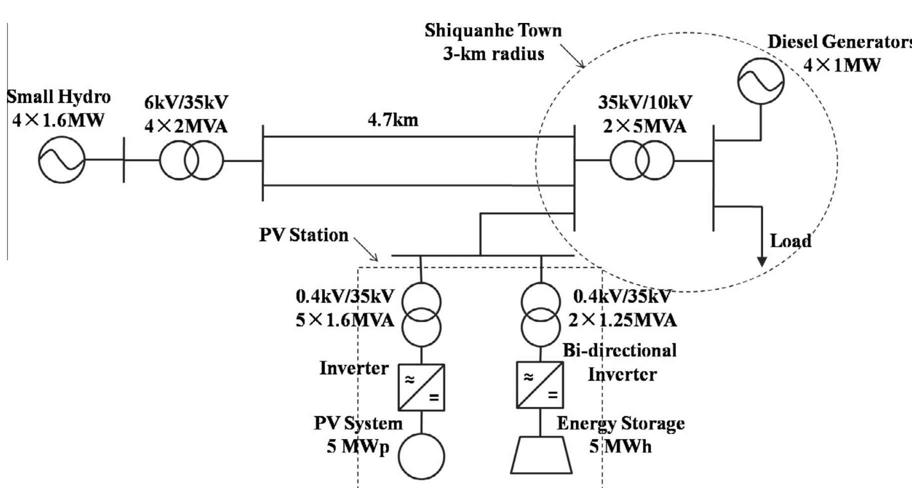

Fig. 1. Configuration diagram of the proposed PVSHH microgrid system.

3.1. Virtual bidding

For grid-connected MGs, the electricity price from utility is normally set as the reference for DGs to bid. However, this method is not suitable for standalone MGs not only because a standalone MG is isolated from the main power grid but also it fails to recognize the diversity in different DG techniques. Therefore, a VBD strategy is proposed to schedule the operation of the DGs in the hybrid microgrid with consideration of operational conditions and DG features, especially the resources utilization and allocation, instead of economic benefit only. It aims to improve system operation stability by meeting the base load via SHGP and the peak load using other resources, maximize the utilization of PV system with the help of BESS, and to reduce the operation time of the DGP in accordance with the system operational priorities/requirements discussed in Section 2.

As shown in (1), the virtual bidding price of a DG is composed of a marginal cost and a dynamic compensation cost. The marginal cost is determined by the actual generation cost while the dynamic compensation cost is updated in real time according to the generation limits, resources allocation and environment impacts.

$$C_{bid,t}(P) = C_{mar}(P) + C_{dyn,t}(\cdot) \tag{1}$$

In the PVSHH microgrid, the VBD centre first calculates the clearing price ($C'_{bid,t}$) and the corresponding power dispatch scheme ($P'_{bid,t}$) for the DGs based on their marginal costs and the load level of the system. The clearing price is the reference of dynamic compensation for the DGs and is similar to electricity price for grid-connected MGs.

To better utilize the PV generation, a parameter named PV power expectation (P_{ev}) is defined. The actual PV generation is expected to be between P_{ev} and the maximum PV generation. If the PV's clearing power generation ($P'_{bid,t}$) is smaller than P_{ev}, $C_{dyn,v,t}$ is set as a negative number to stimulate more PV generation; in contrast, if $P'_{bid,t}$ is greater than or equal to P_{ev}, $C_{dyn,v,t}$ is set as zero, as shown in (2). P_{ev} is a constant obtained in the system sizing optimization with operational considerations. The extra PV generation (i.e., the PV generation minus P_{ev}) is first stored in the BESS, and then used to support the peak load in the evening. The stored energy in the BESS has a fixed virtual price which is a little cheaper than that of the DGP aiming to reduce the operation time of the DGP.

$$C_{dyn,v,t}(\cdot) = \begin{cases} C'_{bid,t} - C_{mar,v}(P_{eV}) & P'_{bid,t} < P_{eV} \\ 0 & P'_{bid,t} \geqslant P_{eV} \end{cases} \tag{2}$$

The participation of the DGP is limited by another parameter named peak load index (P_{el}) which is a sign of peak load. If load demand ($P_{L,t}$) is greater than P_{el}, e.g. during the peak load period, the corresponding $C_{dyn,d,t}$ is negative to increase the generation from the diesel generators; otherwise, $C_{dyn,d,t}$ is greater than or equal to zero to limit the generation, as shown in (3). The P_{el} is different when the water level and load level vary in wet and dry seasons.

$$C_{dyn,d,t}(\cdot) = \begin{cases} C'_{bid,t} - C_{mar,d}(P_{L,t} - P_{el}) & P_{L,t} > P_{el} \\ 0 & P_{L,t} \leqslant P_{el} \end{cases} \tag{3}$$

The power expectation of the SHGP (P_{eh}) is determined by the residential water demand. If the power generation of the SHGP is smaller than or equal to P_{eh}, the corresponding $C_{dyn,h,t}$ is negative to increase the generation from the SHGP; otherwise, the $C_{dyn,h,t}$ is positive to limit the generation and save the water resource, as given in (4).

$$C_{dyn,h,t}(\cdot) = \begin{cases} -k_{h1} & P_{H,t} \leqslant P_{eh} \\ -k_{h2}(H_t - H_s) & P_{H,t} > P_{eh} \end{cases} \tag{4}$$

The flowchart of VBD is shown in Fig. 2. At the beginning, the schedule agent sends the information of load, the system clearing price $C'_{bid,t}$ and the corresponding power dispatch scheme ($P'_{bid,t}$) to the local agents, which are the "participation information" in Fig. 2 to help local agent with the made decision. Based on the information received from the schedule agent and the local information, each local agent will send back its virtual bidding price and power range to the schedule agent. The local agents can easily change their generation intentions by changing the corresponding dynamic compensation prices. If the local agents agree with the schedule, this round of VBD ends. While any local agents disagree, they would quit this round of VBD. The other agents continue to bid for the portion left by the uncommitted agents in operation/reserves schedule until all the remaining agents agree. Based on the real-time information exchange and feedback, the schedule agent and the local agents determine the schedule of operation and capacity reserve all together.

In practice, for the microgrid under study, the local agents agree with the operation/reserves schedule of SA, because the local agents send the power range and corresponding price to the SA after participating in the VBD. The schedule is carried out within the power ranges, i.e. each DG should have the capacity to complete the scheduling.

The generation priority of the DG sources is ranked based on their virtual prices, i.e. a DG with a lower virtual price has a higher generation priority. The dispatch scheme will be obtained as [$P_{H,t}$, $P_{D,t}$, $P_{V,t}$], i.e., the dispatch power for the SHGP, DGP and the PVGP. $P_{V,t}$ is the overall dispatch power of the PVGP that includes both the output of the PV system and the BESS in the PVGP. Due to the forecast error of PV generation, the potential minimum power ($P_{V,\max} - \delta_V P_{V,\max}$) may be smaller than $P_{V,t}$. This means the actual generation of PV system may be lower than the dispatch requirement which would cause a power shortage. Although the BESS may support, an appropriate reserve should be dispatched to guarantee the system's secure operation as given in (5). Meanwhile, the error from the load prediction can also cause the shortage of the power supply. Thus, the reserve should be large enough to compensate the power shortage caused by the prediction error of load and PV generation, as given in (6).

$$R_{V,t} = P_{V,t} - (P_{V,\max} - \delta_V P_{V,\max}) \tag{5}$$

$$R = \begin{cases} R_{V,t} + \delta_L P_{L,t} & R_{V,t} > 0 \\ \delta_L P_{L,t} & R_{V,t} \leqslant 0 \end{cases} \tag{6}$$

Only SHGP and DGP will then continue to bid for the reserve demand based on the dispatch scheme. The power reserve is vital to guarantee the stable operation of the microgrid and also is the base of the dynamic power dispatch. The unit commitment plan for the small-hydro generators and the diesel generators are obtained according to the corresponding dispatch power and the reserve demand.

The schedule of operation and reserve is shown in Fig. 3. The DGs take part in the system operation based on their virtual prices and power ranges. Because the virtual price is non-linear and segmented, it is difficult to calculate the balance point of the DG generation and load demand. The power ranges of the DGs will be divided into segments which are the increased generation (ΔP_{Hi}, ΔP_{Vi} and ΔP_{Di}) by raising a unit price. By priced low to high, the load demand is met with power segments (ΔP). If the load demand is totally met at the ith segment (C_{badi}), the dispatch power for SHGP is the sum of increased generations from 1st segment to ith segment ($\Delta P_{H1} + \Delta P_{H2} + \ldots + \Delta P_{Hi}$), PVGP and DGP are the same.

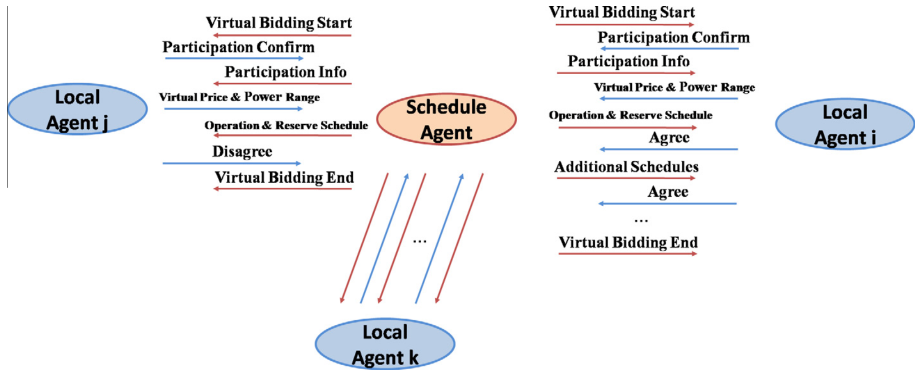

Fig. 2. Flowchart of virtual bidding.

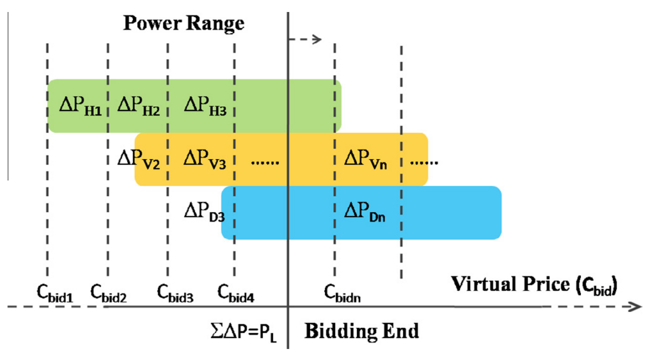

Fig. 3. Visualization of operation scheduling.

3.2. Dynamic power dispatch

The VBD formulates the system operation schedule and capacity reserve for DGs. However, due to the complexity of the actual situation, the DGs may not be able to exactly follow the schedules. For example, a large drop of the solar irradiance can cause the generation of the PV system is far lower than the schedule. In addition, in the MAS-based EMS, the DGs are controlled based on local information. Therefore, an operation agent (OA) is needed to compensate actual deviations in real time. Based on the error signals fed back from the local agents, the OA will carry out dynamic power dispatch to keep the system secure and stable.

In the proposed MG, the SHGP, i.e. the small-hydro generators, are responsible for frequency regulation and their output changes are proportional to the system frequency deviation. The other DG sources are operated as constant power sources. Hence, the power control error (PCE) can be calculated as:

$$PCE = \sum_{i\in\theta_f} k_i \Delta f + \sum_{j\in\theta_c} (P_{j,sch} - P_{j,t}) \tag{7}$$

Based on the model predictive control (MPC) method and the dynamic characteristics of the DGs, a dynamic dispatch algorithm is developed to distribute the PCE signal using the capacity reserve for DGs to balance the load demand and power generation, and to adjust the system dispatch plan in real time. Based on the capacity reserve and the dynamic characteristics of the DGs, the dynamic power dispatch is also an optimal process. The objective of the algorithm is to minimize the adjustment of the DGs' outputs.

$$\min \quad \sum |\Delta u_i(t)| \tag{8}$$

$$s.t. \quad \Delta X(t) = A\Delta X(t-1) + B\Delta U(t) \tag{9}$$

$$\sum \Delta x_i(t) = PCE \tag{10}$$

$$\Delta X_{\min} \leqslant \Delta X(t) \leqslant \Delta X_{\max} \tag{11}$$

$$X_{\min} \leqslant X(t) \leqslant X_{\max} \tag{12}$$

$$\Delta U_{\min} \leqslant \Delta U(t) \leqslant \Delta U_{\max} \tag{13}$$

$$U_{\min} \leqslant U(t) \leqslant U_{\max} \tag{14}$$

The control variables are the adjustment of the DG dispatch power and the quantity of load shedding. For a standalone MG, load shedding is a necessary measure for secure operations. The state variables are the changes in the DG outputs. The dynamic equations given in (9), which includes the frequency regulation characteristics, dynamic responses of the constant power sources, are used to predict the DG outputs. A first-order model that is derived based on the step response of the reference power is used as the prediction model for DGs [37]. Dynamic power dispatch takes advantage of fast DGs to compensate transient load/RES changes and use slow DG for slower dispatch and regulation needs. The constraints in (10) guarantee the power balance in the next step. The inequality constraints in (11)–(14) define the limits of the state and the control variables.

When a local emergency happens, the DGs will first adjust their outputs based on their local control strategies via the local agents. Meanwhile, the DGs for frequency regulation will adjust their outputs to respond the frequency deviation signals. The OA updates the operation schedule to compensate the PCE either in a regular manner or in emergent conditions. The VBD is for determining long-term operation schedules. Fig. 4 shows the whole time scales of the proposed EMS of the MG.

4. Implementation of microgrid EMS

The proposed EMS is for a practical PVSHH microgrid that is still under construction. To test the effectiveness of the proposed EMS for the future implementation, the EMS is simulated on a

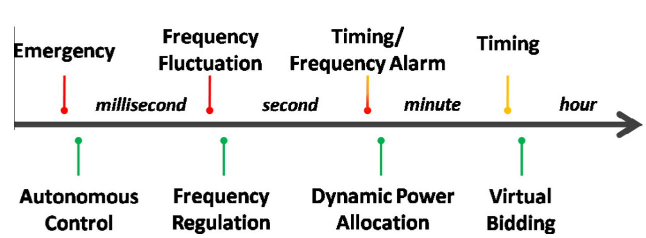

Fig. 4. Dynamic response process of the proposed EMS in different time-scale.

RTDS–PXI real-time simulation platform. In return, the simulation results can be used to improve the management algorithm.

The RTDS–PXI simulates the real-time operation of the studied MG. The MAS-based framework is realized on a NI–PXI platform. The communication system is designed based on IEC61850, which is also used in the actual MG. By implementing the practical standards and requirements in the simulation system, the RTDS–PXI platform recreates the practical operational conditions as realistic as possible and verifies the effectiveness of the proposed EMS.

4.1. RTDS–PXI real-time simulation platform

The real-time RTDS–PXI simulation system is composed of PXIe-1062Q, RTDS and its communication and data acquisition accessories as shown in Fig. 5. The communication protocol of the whole system is IEC 61850.

The PXI system is the platform for implementing the MAS to carry out functions such as VBD, dynamic power dispatch and local control. The following features of the adopted PXIe-1062Q system make it suitable for the task (i.e. the implementation of MAS): fast calculation speed for real-time control by utilizing a low-jitter internal 100 MHz reference clock and a large bandwidth up to 3 GB/s; scalable internal CPU, communication and acquisition cards; capable of parallel computing; and visualized code programming.

RTDS is used to model the MG by simulating the dynamic (including frequency and voltage) responses and the real-time control of the system. RTDS is a flexible real-time platform for time-domain simulations. It has an extendable computing rock and supports hardware-in-the-loop (HIL) simulation/emulation.

The PXI, RTDS, DGs and the other devices are interfaced through an IEC61850-based communication system. IEC61850 is a well-accepted standard for communication in power systems, which enhances the interoperability among the different DGs in the MG.

4.2. Structure and implementation of MAS

The structure of the MAS-based EMS for the PVSHH microgrid is shown in Fig. 6, which includes seven types of agents:

(1) *Schedule agent (SA):* The SA periodically calls for bidding based on the VBD mechanism. The SA makes and releases the operation schedule and reserve according to the bids and the power range of the DGs. As shown in Fig.6, the IEC61850 based *Communication Module* is an essential module for all the agents. In addition, the SA has a *Virtual Bidding Centre* to call for a VBD and gives the operation scheme and a *Reserved Power Check* module to make the reserve plan.

(2) *Operation agent (OA):* Based on the MPC method, the OA regularly adjusts the power dispatches according to the DGs' dynamic characteristics. Under extreme conditions, the OA launches urgently to secure the system frequency. Therefore, the OA has to monitor the change of frequency and the power flow through a *System State Monitor* and make the power dispatch in the *Dynamic Power Dispatch* module.

(3) *Dispatchable DG agent (DDA):* Based on local information and individual control strategy of DGP, the agent participates in the VBD and executes the generation schedules. In Fig. 6, the *VBD Participant* module is used to adjust the virtual price to cooperate with the *Virtual Bidding Centre* to participate in the VBD. According to the operation scheme and reserve demand, the unit commitment plan and power dispatch are executed under the local control strategy in the *Local Control* module.

(4) *Frequency regulation agent (FRA):* Based on local information and individual control strategy of SHPG, the FRA is responsible for system frequency regulation, participates in the VBD, and executes the generation schedules. Except the functions of *VBD Participant* and *Local Control*, there is a *Frequency Regulation* module for the frequency measurement and regulation.

(5) *Intermittent DG agent (IDA):* The agent predicts the generation of the PV system. Based on the prediction, local information and local control strategy, the IDA controls the PVGP to take part in the VBD and follows the generation schedules. Compared with the DDA, the IDA needs an additional *Generation Forecast* module to support decision-making of the *Local Control* and *VBD Participant* as shown in Fig. 6.

(6) *Energy storage agent (ESA):* The agent controls the BESS of the PVGP to smooth the output of the PV system and reinforces the system during the peak time in the evening if the stored energy of the BESS is sufficient. Corresponding to these functions, there are *Smooth Fluctuation* of PV generation, *Coordinated Control* with the PV system, and *Peak Shaving* modules in the ESA.

(7) *Demand management agent (DMA):* The agent carries out load forecast and sheds loads for secure operation as needed under the dispatch of OA. In Fig. 6, the DMA has *Load Forecast* module to support decision-making of the agents and *Load Curtailing* module to execute the order of OA in emergency.

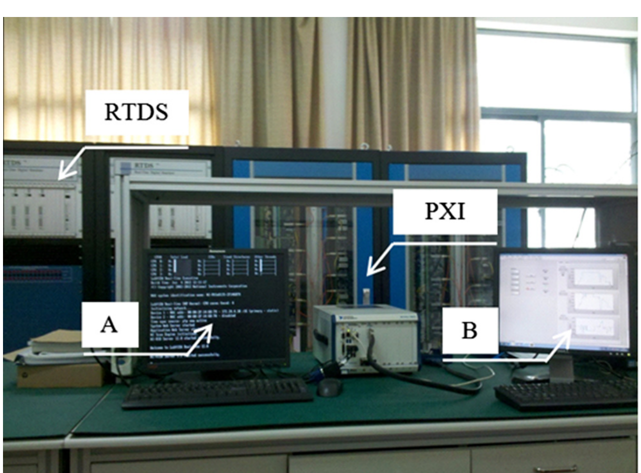

Fig. 5. Photo of the RTDS–PXI real-time simulation platform (A: real-time monitoring of PXI; B: real-time simulation results of MG).

In the studied PVSHH microgrid, the SHGP is controlled by the FRA, the diesel generators are controlled by the DDA, the PV system is controlled by the IDA, the BESS is controlled by the ESA, and the controllable loads are controlled by the DMA. The control and implementation of the proposed MAS-based EMS on the real-time simulation platform is shown in Fig. 7. The power network and the devices of MG, including the small-hydro generators, the diesel generators, the PV system and the BESS, are modeled and simulated in the RTDS. All the agents are implemented on the PXI. The commutation between the RTDS and the PXI is based on IEC61850. The simulation platform supports real-time simulation, real-time decision-making, and real-time commutation.

5. Real-time digital simulation of the microgrid operation

In the PVSHH microgrid system, the SHGP (consisting of four small-hydro generators) is rated at 6.4 MW and has to maintain a minimum of 0.5 MW generation to satisfy the residential water

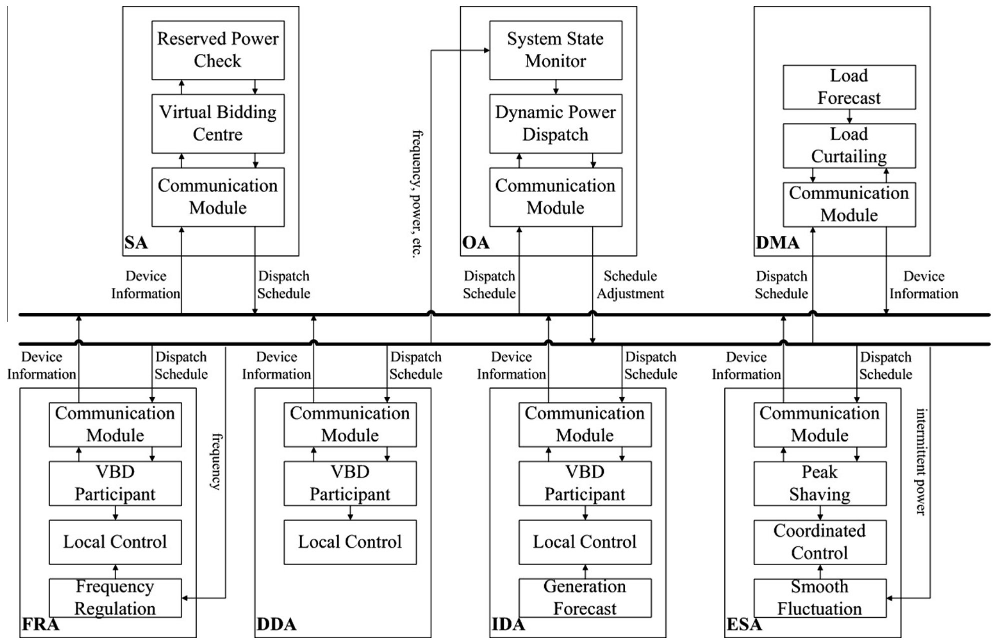

Fig. 6. Classification and functions of the agents.

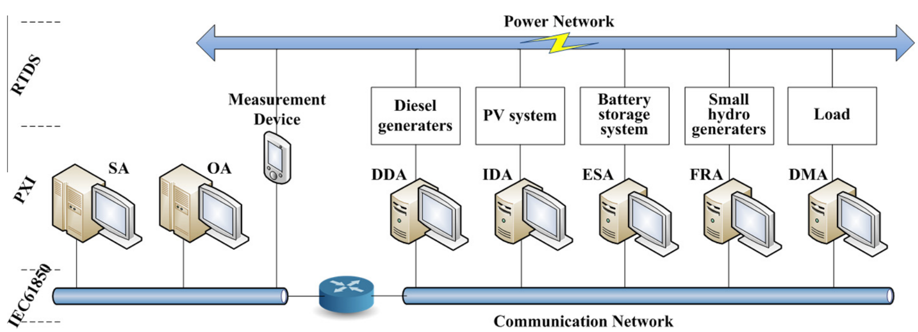

Fig. 7. Implementation of the real-time PXI-RTDS simulation platform.

demand. In addition, the SHGP serves as the 'master' unit to regulate the voltage and frequency of the MG actively. The 5.0 MWp PV system is aided with a 5.0 MW h/1.6 MW BESS. As indicated in Section 2, though the four diesel generators in the DGP have a total capacity of 10 MW, they are de-rated to 4 MW due to the high elevation of the plateau. The minimum generation of the DGP is 0.5 MW.

5.1. Snapshot simulation of emergency case

The power fluctuation of the standalone PVSHH microgrid is mainly caused by the load variation and the intermittency of the PV generation. Snapshot simulation studies have been carried out for seven possible emergency cases given in Table 1. To deal with the emergency cases, the schedule of operation is adapted based on the dynamic simulation results. The revised operation schedules are given in Table 2.

Normally the BESS will first supply the lack of generation if the stored energy is sufficient when the PV generation drops. To test the performance of the dynamic power dispatch, it is assumed that the BESS is lack of energy to give any support in these cases. Initially, the load is predicted to be 3300 kW. After the VBD, the outputs of the SHGP, the DGP and the PVGP are scheduled as 1000 kW, 800 kW and 1500 kW, respectively.

In Case 1 of Tables 1 and 2, by means of the dynamic power dispatch, all of the DG sources in the MG are involved to balance the demand increase. The generation of PVGP shows the largest change because of the fastest dynamic response of its power electronic

Table 1
Emergency cases (kW).

	Max power of PV	Load demand	Description
Prediction	2000	3300	
Case1	2134	3624	Load increases slightly, PV is adequate
Case2	2134	4888	Load increases significantly, PV is adequate
Case3	2134	2915	Load decreases slightly, PV is adequate
Case4	2134	1745	Load decreases significantly, PV is adequate
Case5	1377	3624	Load increases slightly, PV is inadequate
Case6	1377	4888	Load increases significantly, PV is inadequate
Case7	500	4888	Load increases significantly, PV is little

Table 2
Adjustment of operation schedule under emergency.

	Operation Schedule (kW)				Frequency deviation (Hz)	Computing time (ms)
	SH	DE	PV	Load cut-off		
Initial value	1000.0	800.0	1500.0	0	0	
Case1	1049.1	824.5	1745.4	0	−0.0245	1
Case2	1685.4	1000	2134.0	0	−0.3427	2
Case3	941.7	770.8	1208.3	0	0.0292	2
Case4	764.4	682.2	321.9	0	0.1178	2
Case5	1279.4	939.7	1377.0	0	−0.1397	2
Case6	2373.6	1000.0	1377.0	0	−0.6868	2
Case7	2999.8	1000.0	500.0	188.0	−1.0012	1

inverters. In Case 2, though the load demand is much bigger than the initial value and the upper limits of the PV system and the diesel generator plant are reached, the power balance is still met.

In Cases 3 and 4, the generation outputs of the DGP and the SHGP drop to their lower threshold values when the demand decreases. However, the generation would be still higher than the load demand if the PV system generates at its maximum potential. To achieve a stable and balanced operation, the generation of PVGP will be curtailed. Actually the extra PV generation will first be stored in BESS if possible under the coordinated control strategy of the local agent.

In Cases 5, 6 and 7, the generation outputs of the SHGP and the DGP are dispatched to balance the load demand when the PV generation is inadequate. In the extreme situation of Case 7 when the demand is higher than all the available generation power, load shedding is the last option to maintain the secure operation of the MG. But in reality this happens rarely. Because the load increase and the PV generation decrease occur at the same time which causes a large power shortage. And the BESS cannot give any support as assumed. All of this causes the lack of reserve power.

The time to do the dynamic power dispatch is only 1–2 ms, which is fast enough for real-time control.

5.2. Continuous simulation of system real-time operation

The SA calls for a virtual bidding every 15 min to make a schedule of operation for the next period. Fig. 8 shows the simulated operation records of the MG in 24 h, which are obtained from the monitoring system developed on the PXI platform. The monitoring system communicates with the RTDS every 200 ms and shows the data every 10s for a total of 8640 points in 24 h.

By means of the VBD, the schedule of operation is carried out to efficiently utilize the resources based on the DGs' characteristics. For example, when the solar irradiance is high during the period of 11:00–18:00, the PVGP generates as much power as possible. The DGP is responsible for supplying peak power, and the more economic and environmentally friendly SHGP supplies the daily base load as shown in Fig. 8. In addition, the BESS in the PVGP can assist the diesel generators during on-peak hours to further reduce the operation hours of the DGP.

The real-time PV generation and load profiles are shown in Fig. 9(a) and (b). The OA dynamically dispatches the power generation every 10 s to balance the area power demand. As shown in Fig. 9(c)–(e), the PVGP, the SHGP and the DGP all participate into meet the load demand. It is observed from the figures that the SHGP is the main part of the power generation when the PV generation is low. Once a large drop of PV generation happens at 16:00, the SHGP acts quickly to compensate the power shortage. It is because that on the one hand the SHGP instead of the DGP is designed as the main power source for frequency regulation, and

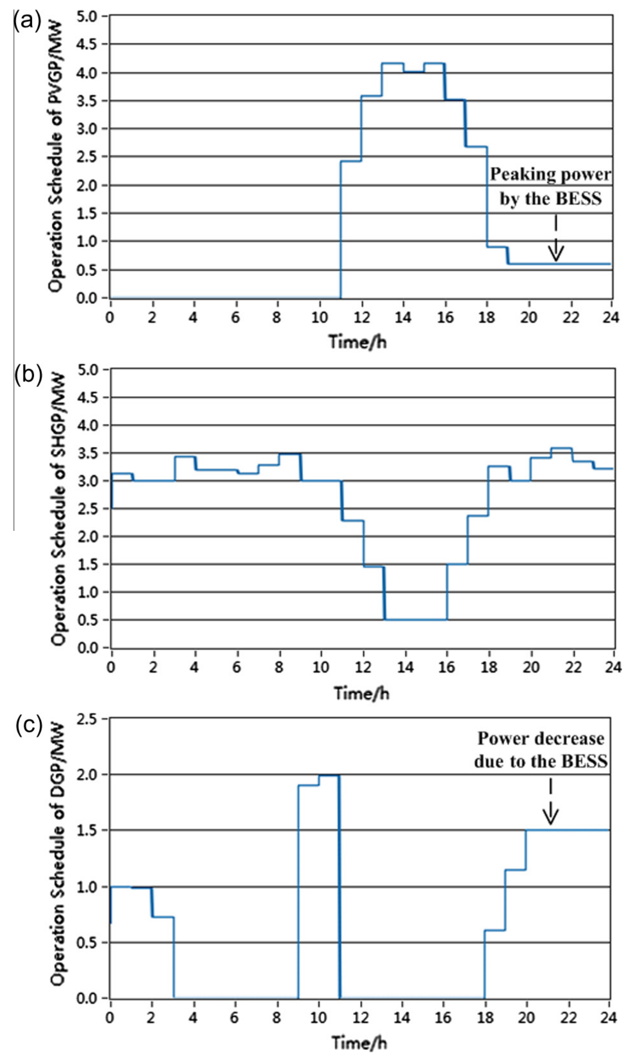

Fig. 8. Operation schedule after the VBD: (a) operation schedule of the PVGP, (b) operation schedule of the SHGP, and (c) operation schedule of the DGP.

on the other hand the dynamic response of the SHGP is faster than the diesel generators.

By coordinating the SA, the OA and the local agents, the proposed EMS adjusts the operation schedule at different time-scales. Fig. 10 shows the operation schedule of the SHGP. As shown in the figure, the generation of the SHGP basically follows the operation plan of the OA, which means the dynamic power dispatch can eliminate the power control error effectively. However, in the interval between 19:00 and 22:00, there is a large difference between the operation plan and the actual SHGP generation,

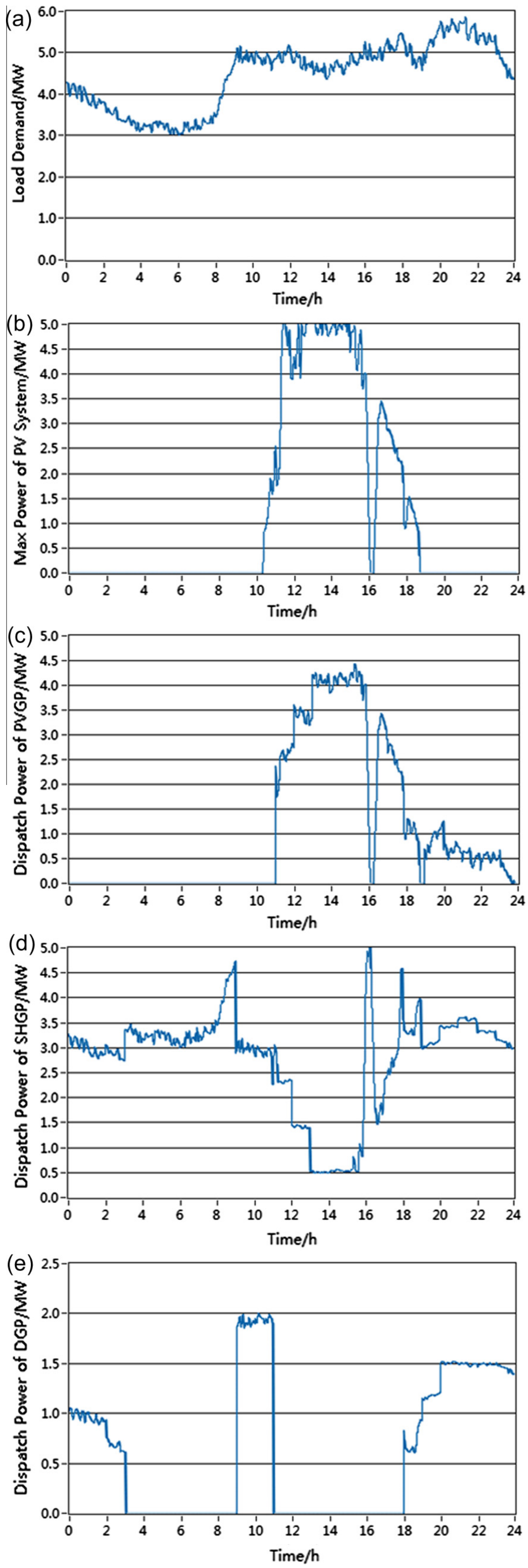

Fig. 9. Operation schedule after the dynamic power dispatch: (a) real-time load demand profile, (b) the maximum power that the PV can generate, (c) operation schedule of the PVGP, (d) operation schedule of the SHGP, and (e) operation schedule of the DGP.

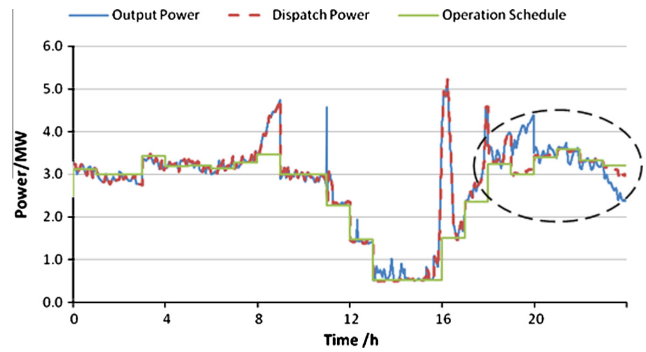

Fig. 10. Comparison between operation schedule, dynamic dispatch and actual output of the small-hydro generation plant.

shown in Fig. 10. It is because the OA assigns the BESS with more responsibility to dynamically follow the power demand by taking advantage of its large range for power adjustment and fast dynamic speed. However, the BESS refuses to execute the command because its local agent believes that the BESS is unable to afford such large assignment for a long period due to its limited storage capacity. Therefore, it shows a significant power shortage

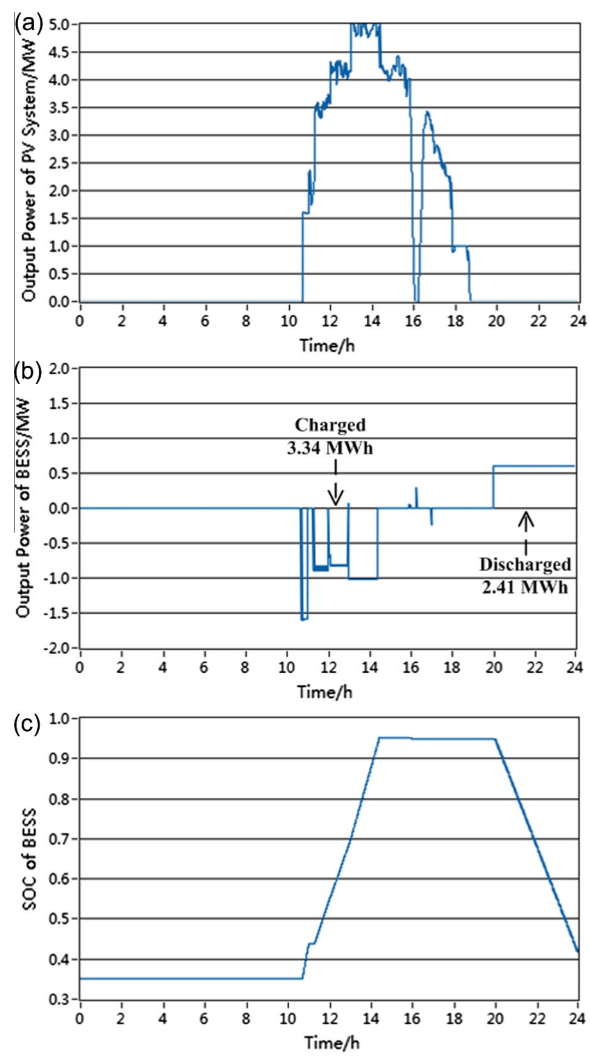

Fig. 11. Real-time operation of the PV plant: (a) power generation of the PV system; (b) power generation of the BESS and (c) the SOC of the BESS.

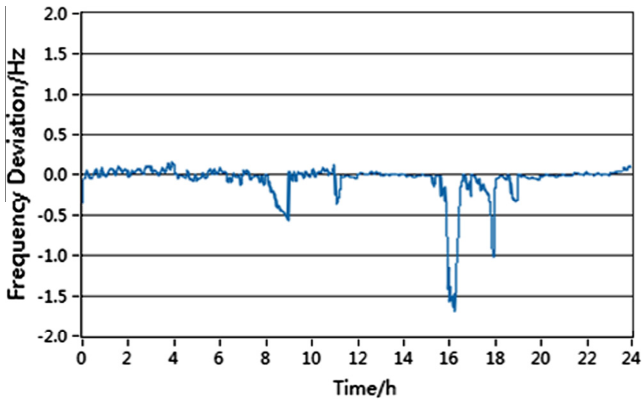

Fig. 12. System frequency deviation.

in Fig. 11(a). As the primary frequency regulation DG, the SHGP then has to compensate the power shortage to stabilize the system frequency.

In the MAS-based microgrid, the DGs are operated by their own local agents based on their individual control strategies and local information and are also coordinated by the OA. As shown in Fig. 11, at 16:00, the BESS is temporarily used to compensate the power shortage caused by the large and rapid drop of the PV generation. Meanwhile, the shortage is reported to the OA, which will assign some other DGs instead of the BESS to compensate the shortage in long term.

With the help of the OA, the BESS assists the PV system in operation. The BESS can also improve the utilization of the PV. After the dispatch of the SA and the OA, the PV utilization has reached 80.15%. It is further increased to 90.64% via the cooperation with the BESS. The BESS is charged with 3.34 MW h in the day time when PV generation is high, and discharges 2.41 MW h during on-peak hours. Considering the conversion efficiency of 0.8, there is a net of 0.33 MW h stored in the BESS during the whole day, shown in Fig. 11.

The fluctuation of the system frequency is shown in Fig. 12, in which the Y-coordinate represents the deviation of the system frequency from the rated frequency. In the figure, the frequency deviation is maintained within $-1.5{\sim}0.2$ Hz by adjusting the power generation, which meets the secure requirement. Moreover, even for the large drop of the PV generation at 16:00 as shown in the figure, the system handles it very well.

6. Conclusions

The paper proposes a MAS-based EMS for a practical PVSHH MG project. Individual agents have been designed based on their tasks and the characteristics of the systems/devices that they are designed for. Through the coordination of different agents (i.e., the SA, the OA, and local agents) at different time scales for different targets, the proposed MAS-based EMS has been developed using a PXI platform. By integrating the VBD and the dynamic power dispatch, the proposed EMS realizes an optimal and secure operation of the MG. The proposed MAS-based EMS has been successfully verified on a RTDS–PXI real-time simulation platform under different scenarios. The method will be implemented for the practical PVSHH MG project that is currently undergoing and will be continuously improved based on the real operational data and experiences that will be collected and learned.

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