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Design and Implementation of Energy Management System for Energy Hub in Smart Grid

Wei Pei, Wei Deng, Ziqi Shen, Zhenxing Zhao and Jiarui Wang
Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, 100190, China

Abstract: Part of distributed smart grid region can formed the energy hub through the energy management and coordination control with its distributed energy supply, energy consumption and energy storage units. The design and implementation of energy management system (EMS) for energy hub in smart grid are presented in this paper. The architecture, function module, subsystem interface and service mechanism of energy hub EMS are proposed in detail. The energy hub prototype and the EMS software are developed. Then the actual energy management tests of energy hub are performed based on EMS. The experimental results show that the design and implementation of EMS for energy hub are practicable and feasible, which demonstrates an effective solution for energy management and coordination control of energy hub in smart grid.

Key words: Smart grid, distributed generation, energy management system, energy hub, dynamic link library

INTRODUCTION

The Distributed Generation (DG) including renewable energy resources are the important complements to replacements of the fossil fuels for durability and environment friendliness (Nikkhajoei and Lasseter, 2009; Etemadi *et al*., 2012; Katiraei and Iravani, 2006; Lasseter, 2007; Katiraei, 2005). The new and improved technologies are applied to promote DG development in smart grid including (Afzal and Pothamsetty, 2012; Khamphanchai *et al*., 2011):

- Efficient use of resources
- Improved reliability and power quality
- Reduced investment risk
- Reduced environmental impact
- Peak shaving
- Safety operation and protection

Part of distributed smart grid region can formed the energy hub with efficient utilization of integrated energy resources and reliable power supply, through the energy management and coordination control with its distributed energy supply, energy consumption and energy storage units. Energy hub can operate both in the autonomous mode and the grid-connected mode. It integrates multiple DG to enhance the power system reliability, increase the utilization of renewable energy, promote investment savings, etc.

Energy hub was proposed to solve the optimal power flow problems for integrated energy systems (Schulze *et al*., 2008). It is expected to operate in both grid-connected and autonomous modes as a basic unit of smart grid and flexibly manage the energy exchange and information exchange to solve a variety of problems (such as mutual interference caused by multiple power source, poor power quality and low reliability) and eventually achieve the purpose of energy conservation and emission reduction. Currently, the research on energy hub mainly involve the conceptual discussion, intelligence control and operation analysis (Gao *et al*., 2012; Saputro *et al*., 2012; Lin and Chen, 2013; Yu *et al*., 2012; Markovic *et al*., 2013; Zhou *et al*., 2013; Gudi *et al*., 2012). However, Energy Management System (EMS) for energy hub and the actual experiments validation have not been studied in details.

In this Study, an EMS for energy hub is proposed and its design and implementation are performed in detail. The structure of this paper is shown as follows. Section II presents the architecture design. Section III presents the function module design. Section IV presents the subsystem interface and service mechanism. The actual system integration of energy hub EMS and the energy management tests are performed in section V. Conclusions are shown in section VI.

ARCHITECTURE DESIGN OF ENERGY MANAGEMENT SYSTEM

The architecture of energy hub is shown in Fig. 1. It is designed as three layers including management layer, coordination layer and field layer. These three layers are complementary. The filed layer can obtain the operation data from sensor and execute the instructions generated from upper layer. It can change the structure of physical network by switching the branch during operation. The

Correponding Author: Wei Deng, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, 100190, China

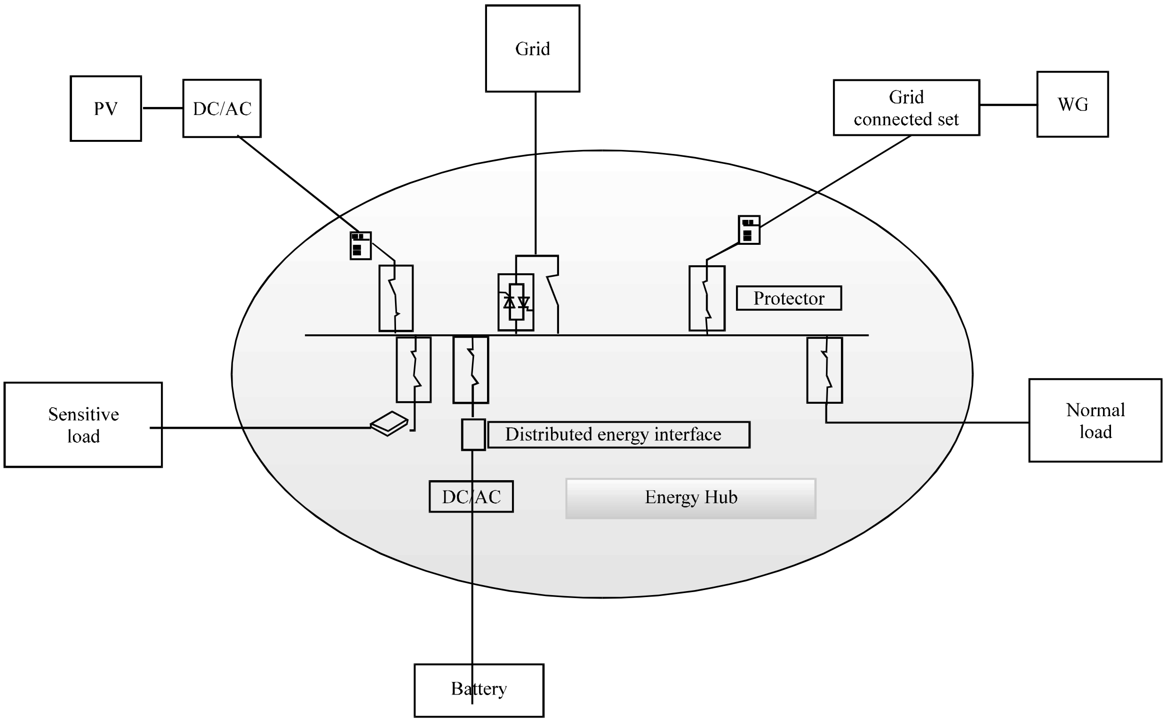


Fig. 1: Energy hub architecture

coordination layer is an interface layer between the management layer and the filed layer. The main function of the coordination layer is coordinate energy flow of energy hub. The management layer can determine the operate status of energy hub and generate control commands, which will be sent to the filed layer through the coordination layer.

EMS can be seen as the brain of energy hub. It is mainly used to provide the system operation control and coordination services by set the power and voltage value to each DG and energy storage units. According to different conditions, it automatically formulates and chooses the appropriate system mode to meet the operation requirements. It also can coordinate the inverters operation under different mode. In the event of incidents (sometimes caused by the operation mode change), it can orderly disconnect energy hub or perform the fault recovery functions. The global optimization, interaction with the Distribution Management System (DMS), monitoring and analysis of the operation data are also realized by EMS.

The designed structure of energy hub EMS is shown in Fig. 2. It adopts the hierarchical structure. Four layers are designed according to the complexity of energy hub and its operation requirements. This design can separate different functions and then put them into separate modules. It also can make all layers assigned to the different physical compute nodes or different processes to improve the system performance, with significant characteristics of high cohesion and low coupling.

The hierarchical structure of EMS is divided into four layers including presentation layer, logic layer, service layer and system layer. Each layer only has relationship with the adjacent layer. The lower layer provides the basic function for the higher layer:

- Presentation layer: to provide the user interface for EMS software. Its functions mainly include help users to maintain the EMS and accurately show the real-time information, historical information and alarm information
- Logic layer: to deal with the management tasks including the data processing and the alarm processing and then sent the data and related representations to the presentation layer
- Service layer: to deal with the application data. It mainly consists of the data processing, the data provider and the alarm events provider
- System layer: to deal with the collected data, sent command and save the real-time data and historical data. The real-time data are stored in the object-oriented database and the historical data are stored in the relational database

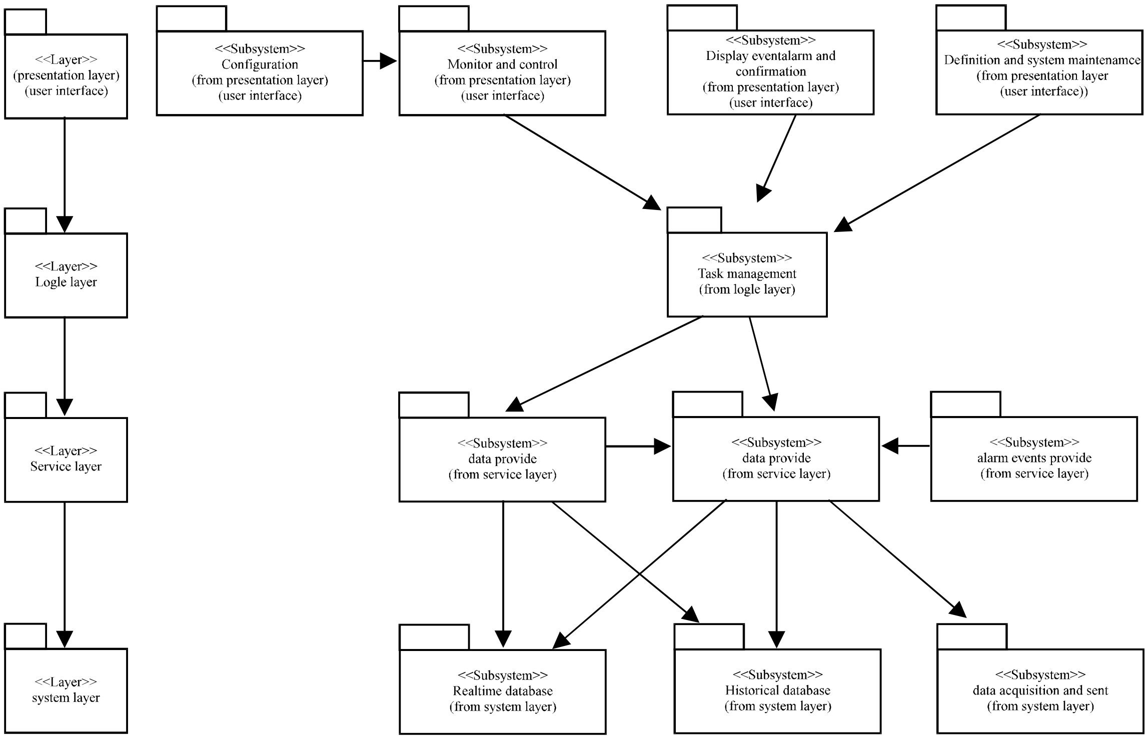


Fig. 2: System architecture of EMS

FUNCTION MODULE AND SUBSYSTEM DESIGN OF ENERGY MANAGEMENT SYSTEM

According to the common functions of EMS in power system and the special operation requirements of energy hub, EMS is divided into four modules including the Supervisory Control and Data Acquisition (SCADA), the Power Automatic Management Software (PAMS), the Real-Time Control Software (RTCS) and the auxiliary functions. A series of configuration library and the SCADA database are shared by PAMS and RTCS. All modules are specified as follows:

- SCADA: The main tasks of this module include the data acquisition, processing, storage and display. Then, the data will be sent to other modules. This module can be divided into the data front-end receiver, the real-time database, the historical database, the integration configuration software and the user advanced application
- PAMS: The control cycle of PAMS is slower than RTCS's. Under the condition of no fault, PAMS gets the latest operation data and then start the data analysis used to assess the current and future state of energy hub to make the corresponding control rules. It regularly obtains the historical data to develop power generation plans, evaluate the possibility of faults, record the safety operation and faults, etc. All of them are sent to RTCS. Overall, it is a strategy maker, whose main work is to prevent network fault and maintain the system economic and stable operation
- RTCS: It controls the energy hub according to the measured data and reaction rules that are dynamically modified by PAMS. After sending the instructions to DG or energy storage units, it will check the instructions revised by PAMS
- Auxiliary functions: Auxiliary functions mainly include the report generation and output, communication with DMS, Automatic Management (AM), Facilities Management (FM), Geographic Information System (GIS), the user information system and other functions

SCADA, PAMS, RTCS and auxiliary functions are mutually independent. On the view of physical devices, the whole EMS is installed in two hosts with single network structure. SCADA spans two hosts. PAMS and auxiliary functions are installed in the back-stage workstation and RTCS is installed in the front-end server. SCADA communicates with RTCS through the real-time database installed in the front-end server and their interface is the service module for real-time data. SCADA communicates with PAMS through the SCADA database installed in the back-stage workstation. In other words, the SCADA database is open for SCADA and PAMS. The SCADA data service module is their interface.

PAMS not only directly sends the dispatching order to each DG, energy storage units and load, but also triggers RTCS under a certain state (regular production, potential safety hazards, emergency, black-start, etc.) through modifying the corresponding control rules. RTCS communicates with PAMS through RTCS rules. There is no direct interface between them. New rules of PAMS are sent to RTCS by the real-time data service module.

Thus, SCADA, PAMS, RTCS and auxiliary functions are independent between each other. They access to the data through the corresponding interface. The interface, which consists of a serious of services and the function modules, can also be used by the corresponding processes and applications at the same time. The interface is realized by the Dynamic Link Library (DLL). In the future, some new functions of the software can be upgraded by only modifying the corresponding DLL modules.

Presentation layer of EMS has two functions including graphical configuration subsystem and advanced application subsystem. System layer and service layer have three subsystems including front-end subsystem, real-time data server subsystem and SCADA database subsystem. So there are totally five subsystems 11shown in Fig. 3.

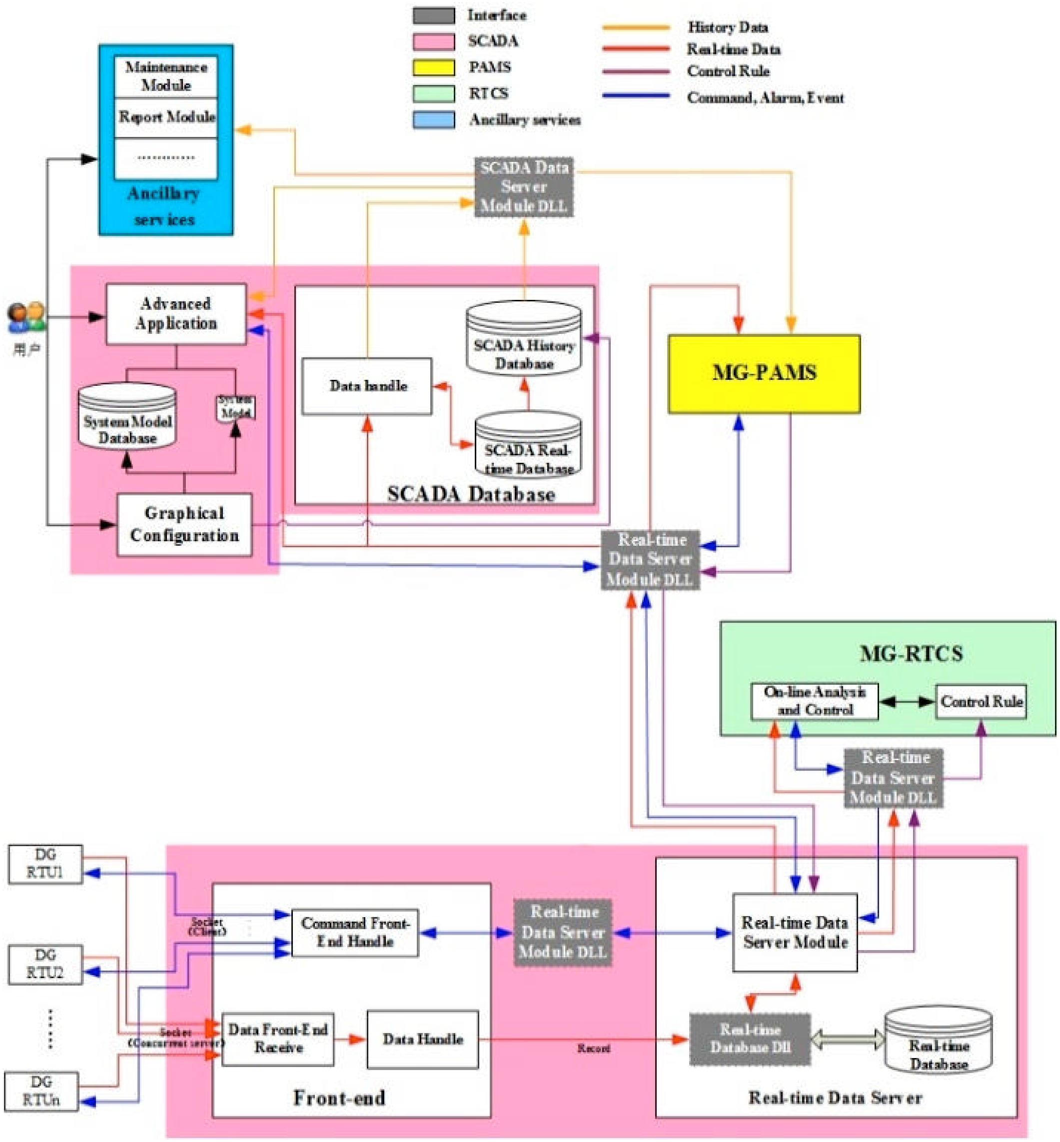


Fig. 3: Diagram of subsystem and data flow

The front-end subsystem and real-time data server subsystem are installed in the front-end server. The SCADA database subsystem, graphical configuration subsystem and advanced application subsystem are installed in the back-stage workstation.

Service layer is composed by the real-time data server module of the real-time data server subsystem and the real-time database DLL. Logic layer which is separated as an independent component, adopts the DLL technology to build the corresponding interfaces.

SUBSYSTEM INTERFACE AND SERVICE MECHANISM

Data is the core of EMS. The logic layer and service layer are the important bridge to connect EMS with each module. The real-time data server subsystem and SCADA database subsystem of service layer are the standard interface for the database. DLL of logic layer is the plug-in component. Other subsystems, PAMS and RTCS are linked to the database standard interface and transmit commands, events and warnings through the plug-in component. The data for EMS involve five aspects including the model data, real-time data, historical data, event/alarm data and command data. Based on the previously mentioned data, the service mechanisms are design as follow:

- Basic service: Use nomenclature function to show the models through corresponding interface; Use identification function to identify objects, classes and attributes; Use browse function to provide the ability to browse the namespace and find which data can be accessed; Use filter function to achieve top subscription based on the characteristic values filtering
- Request and response service: It is used to provide API service for public data access based on the hierarchical structure and realize the synchronized and no real-time access for the complex data structure
- High-speed data access service: It can provide API service for high-speed data access based on simple data structure. Under these circumstances, multiple instances are frequently accessed as a data set, whose memory space need to be efficiently mapped into the client. The data set defined in advance is usually released periodically. The high-speed data access service can be applied in the real-time data access, command execution, control values set and measurement point set, etc
- Publish and subscription service: It is used to provide the general API service for subscription/publish of the events and alarms. It contains the ability of subject subscription/releasing and also supports the exchange patterns to send events

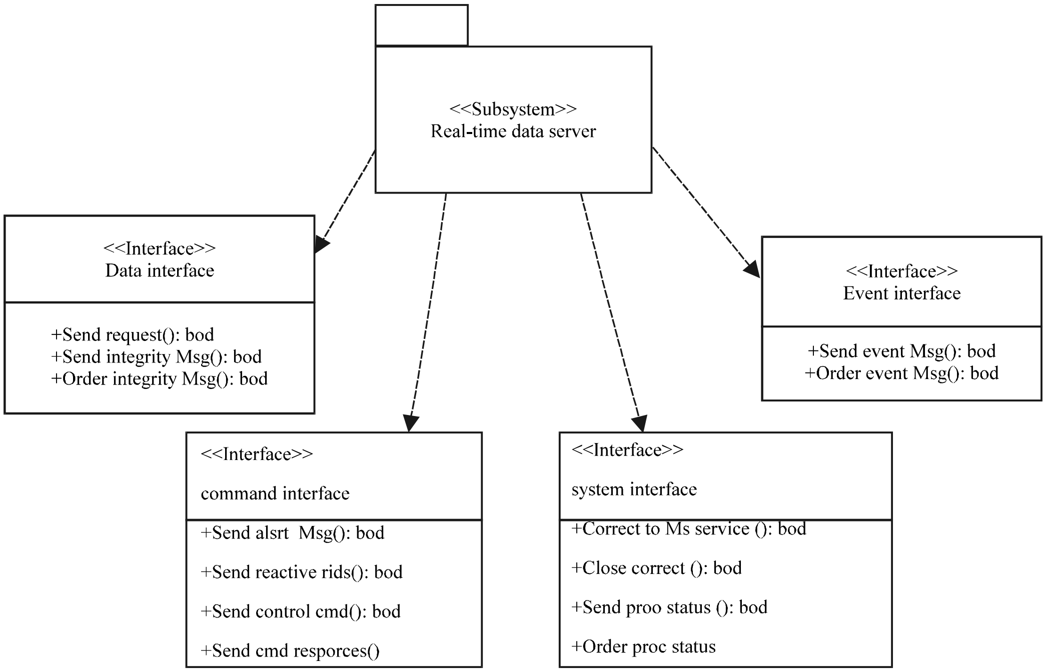


Fig. 4: MsgClient static structure diagram

Table 1: Function table of the real-time data server module DLL

MsgClient Class	Explanation
BOOL ConnectToMsgServer ( )	Establish the connection with MsgServer
BOOL CloseConnect ( )	Close the connection
BOOL SendRequest ( )	This API is called to send request to MsgServer for obtaining real-time data
BOOL SendAlertMsg ( )	This API is called by PAMS to send alarm analysis results to Msgserver (the alarm analysis results are forwarded to RTCS and SCADA by Msgserver)
BOOL SendReactiveRule ( )	This API is called by PAMS to send the recieved reaction rules to Msgserver (the reaction rules are forward to RTCS by Msgserver to update its rule bases)
BOOL SendControlCmd ( )	This API is called by RTCS; advanced application subsystem and PAMS do not directly send the instructions to DG
BOOL SendCmdResponses ( )	This API is called to give a reply to MsgServer showing that DG has received the control command and executed
BOOL SendEventMsg ( )	This API is called to inform MsgServer of the events and faults. These events and faults are forwarded by MsgServer to all related EMS modules which made a reservation for event messages
BOOL OrderEventMsg ( )	Reserve event notifications
BOOL SendIntegrityMsg ( )	Send notifications of complete data section; This API is called to inform MsgServer
BOOL OrderIntegrityMsg ( )	Reserve notifications of complete data section
BOOL SendProcStatus ( )	Send the state information about backstage process; This API is called by backstage process to inform MsgServer
BOOL OrderProcStatus ( )	Reserve state information about backstage process

DLL for logic layer includes the real-time data server module DLL and SCADA data server module DLL. The real-time data server module DLL is the most important interface of the whole EMS, which is responsible for linking the various modules to the real-time data server subsystem of service layer and making the modules to obtain the real-time data, events, command from real-time data server subsystem and then return the data to advanced application subsystem of presentation layer and PAMS, etc. At the same time, it also forwards orders and rules through the real-time data server subsystem.

Database access control use the streaming transmission, which is analogous with the Client/Server interaction access. Its basic principle is that the client submits the data application to the server based on defined rules and explains the refresh cycle of the requested data and then logins a stream towards the real-time database server. The server will periodically return the data to the client according to specified time interval. This method avoids the frequently acknowledgement between the server/client interaction to be sent by the server. The functions of the real-time data enhance the communication efficiency. Callback functions in the client side are used to deal with the data server module DLL-MsgClient are shown in Fig. 4 and Table 1. SCADA data server module DLL for logic layer is responsible for connecting the related backstage modules to EMS. It can enable various modules obtain the historical data, events and commands and return the data to graphical configuration subsystem, advanced application subsystem and PAMS in presentation layer which requested the data.

This DLL is different from the real-time data server module DLL. The data provider for the real-time data server module DLL is the server, which send data to the client periodically. However, the data provider for SCADA data server module DLL is the client including PAMS and advanced application subsystem, whose operation adhere to the rules of SQL. So it only needs to execute the SQL statements sent by the client and return the results saved in the corresponding variables.

Fig. 5: Prototype of energy hub

SYSTEM INTEGRATION

Prototype of energy hub is established, as shown in Fig. 5. Its several branches consist of the 20 kW photovoltaic power generation, the 50 KVA/150 kWh storage batteries, the 4 kW direct-drive small wind power generation, etc.

The EMS is developed to manage the energy hub. Its monitor interfaces are shown in Fig. 6. The hardware

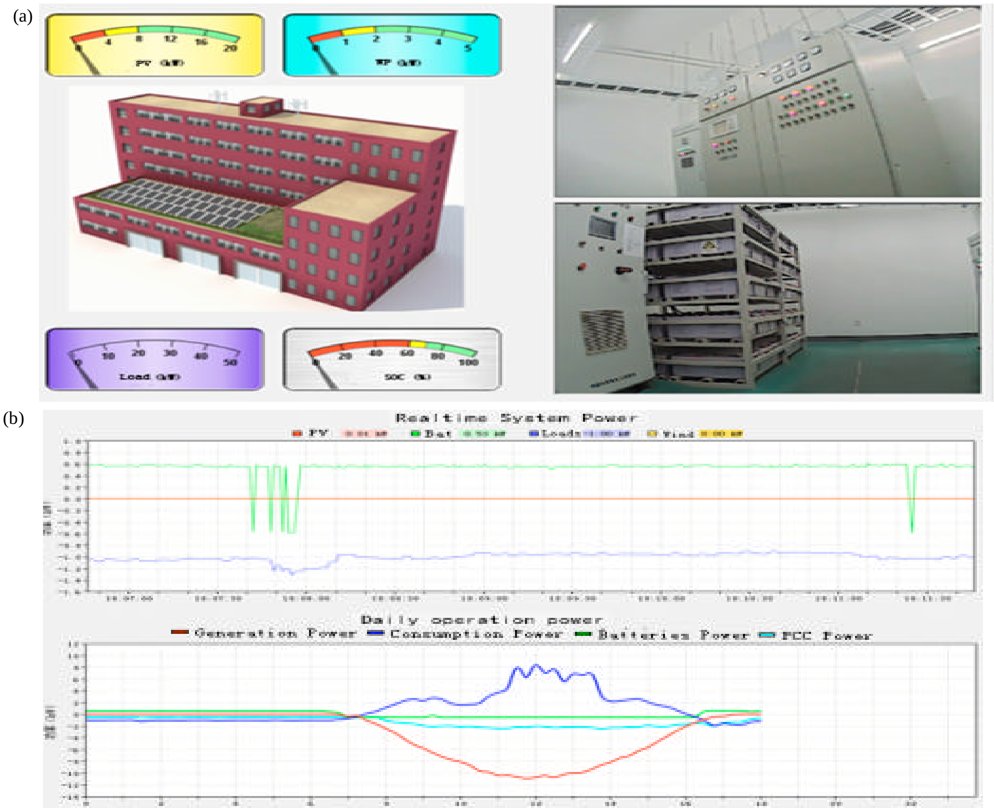
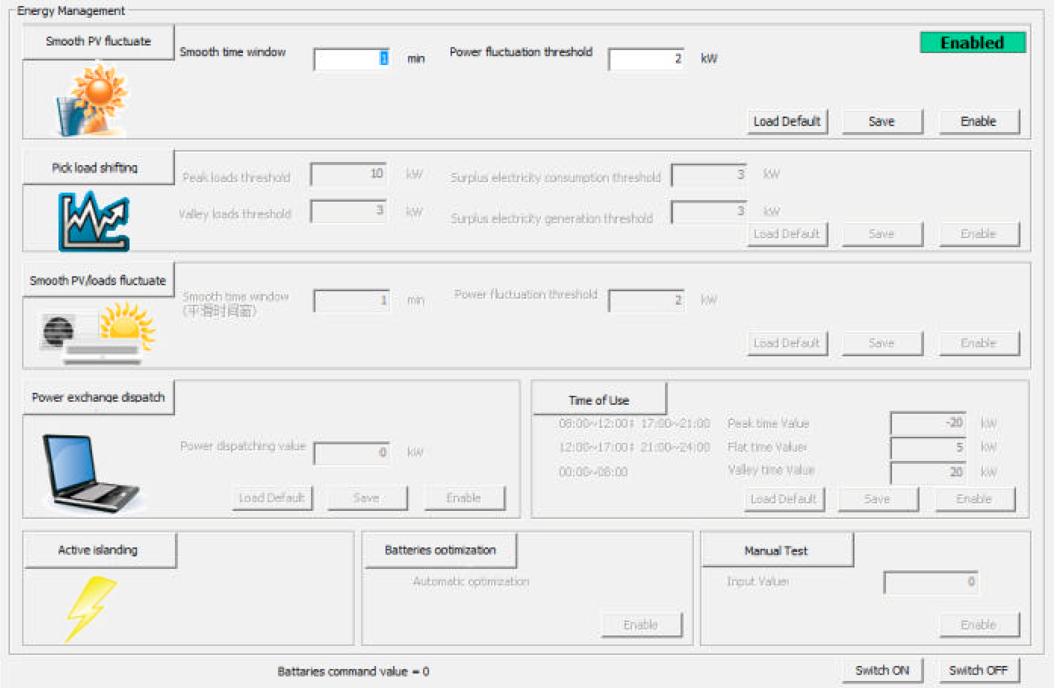


Fig. 6: EMS monitor interfaces



Smooth time window 1 min

Power fluctuation threshold 2 kW

Peak loads threshold 10 kW

Valley loads threshold 3 kW

Surplus electricity consumption threshold 3 kW

Surplus electricity generation threshold 3 kW

Smooth time window (平滑时间窗) 1 min

Power fluctuation threshold 2 kW

Power dispatching value 0 kW

08:00~12:00; 17:00~21:00 Peak time Value -20 kW

12:00~17:00; 21:00~24:00 Flat time Value 5 kW

00:00~08:00 Valley time Value 20 kW

Automatic optimization

Input Value 0

Battaries command value = 0

Fig. 7: EMS management interface

operation conditions can be directly monitored through the video based on EMS monitor interface. The main operation parameters such as PV power, wind power, load power and SOC of battery, are also shown in Fig. 6(a). The daily operation power and system status are shown in Fig. 6(b).

The management interface of EMS is shown in Fig. 7. The energy management strategies and optimized operation schemes base on different operation conditions can be formed through this interface. The parameters for each operation mode also can be modified in the management interface of EMS.

CONCLUSIONS

The EMS is the essential part for energy hub operation with widely concerned. It is primarily responsible for maintaining the stable operation. According to the optimized instructions, EMS can used to adjust the power flow and interface voltage and fast manage DG, energy storage units and load. The design and implementation of architecture, function module, subsystem interface and service mechanism of energy hub EMS are proposed in this paper. The energy hub prototype and EMS are developed and the corresponding experimental studies are carried out. The results show that EMS of energy hub is feasible. The energy hub can achieve the coordination optimization with grid, DG, energy storage units and load. It can provide effective techniques for safe and efficient operation of energy hub in smart grid.

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