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Performance Evaluation of Microgrid Management System by using a Hareware-In-Loop-Simulation Method

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Abstract. This paper presents a real time digital simulator based test system as a new method for testing microgrid management system (MMS). This system is composed of a real time digital simulator and a developed communication emulator. Real time digital simulator runs a simulation case for microgrid model and distributed generation source model. Communication module emulates communication functions of micro-sources in microgrid by transmitting the simulated signals to MMS. The MMS controls operation of micro-sources to control the power flow at the point of common coupling (PCC) and the voltage and frequency of microgrid. A prototype MMS was tested for stand-alone and grid-connected operation to verify the validation of the developed hardware-in-the-loop simulation (HILS) system.

Key words

Microgrid, HILS (Hardware-In-the-Loop Simulation), MMS (Microgrid Management System), RTDS (Real Time Digital Simulator)

1. Introduction

Even though the penetration of distributed generators (DGs) into the electric power system is constrained by the lack of economical benefits, it is expected that the DG penetration will be accelerated for another reasons, such as: environmental friendliness, the diverse needs of the end user for higher power quality, the restructuring of the electric power industry, and restrictions on the extension of power transmission and distribution facilities. The increase in DGs penetration depth and the presence of multiple DGs in electrical proximity to one another have brought about the concept of the microgrid [1-2], which is a cluster of interconnected DGs, loads and intermediate energy storage systems.
There have been some relevant studies on control, simulation and tests of microgrid and its control systems [3]. A pilot plant or test field for microgrid has been developed for a system validation [4]-[9]. Field tests were designed and performed for frequency and voltage control algorithm, and for the utility inter-connection device [4]-[5]. Test-beds for microgrid with multi-energy generators were built in laboratory to investigate optimal structures, unbalance problems and control strategies of microgrid systems [6]. A number of pilot plants have been commissioned internationally to demonstrate and validate for microgrid [7]-[9]. And also, there have been some trial to adapt a real-time simulation technique for verifying control system of power electronic system such as a power conditioning system and a flexible AC transmission system device [10]-[11].
So far, to verify a function of microgrid components, a test-bed or pilot plant has been used. As a new method, a conceptual idea and simple result of hardware in-the-loop simulation (HILS) system was introduced to test a microgrid management system (MMS) [12]. This paper presents a detailed concept, structure and specification of HILS system for testing MMS. To verify the validation of the developed HILS system, a prototype MMS was tested for stand-alone and grid-connected operation. In this paper, the cooperative control strategy of microgrid components is presented and evaluated performance of management functions by a hardware test using pilot plant.

2. Microgrid

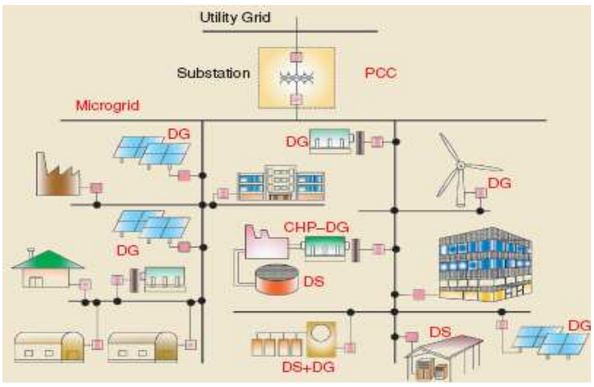

Fig. 1. Typical configuration of a microgrid.

Figure 1 shows a microgrid schematic diagram. The microgrid encompasses a portion of an electric power distribution system that is located downstream of the distribution substation, and it includes a variety of distributed energy resource (DER) units and different types of end users of electricity and/or heat. DER units include both distributed generation (DG) and distributed storage (DS) units with different capacities and characteristics. The electrical connection point of the microgrid to the utility system, at the low-voltage bus of the substation transformer, constitutes the microgrid point of common coupling (PCC). The microgrid serves a variety of customers, e.g., residential buildings, commercial entities, and industrial parks [13].

3. Proposed HILS Test System

A. Concept and Configuration

Proposed HILS system is a test system for management and communication functions of MMS in real-time. This system is made up of a specifically designed communication emulator and a RTDS.

The microgrid has a hierarchical control structure as shown in figure 2. It has two control layers: MMS and local controller (LC). The MMS is a centralized controller that deals with management functions such as disconnection and re-synchronization of the microgrid and the load shedding process. In addition to this function, the MMS is responsible for the supervisory control of micro sources and the energy storage system. Using collected local information, the MMS generates power output set points and provides them to the LCs. A LC is a local controller that is located at each micro source and controls the power output according to the command from the MMS. This LC may be a power conversion system (PCS) for a renewable energy source (RES) or a governor for a synchronous generator type source.

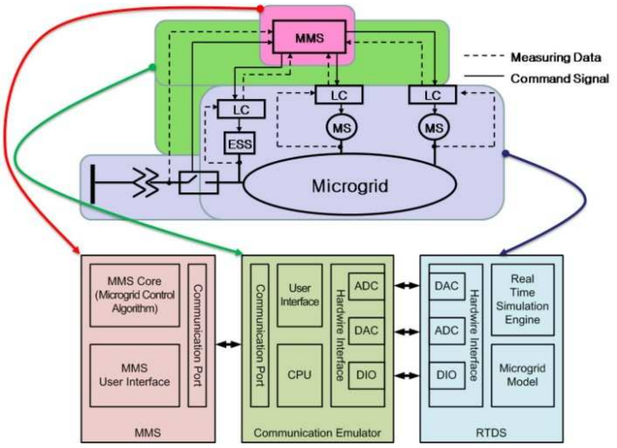

Fig. 2. The hierarchical control structure of microgrid and a schematic diagram of the proposed HILS test system

Figure 2 shows a schematic diagram of the proposed HILS system for testing MMS in real-time. The HILS system is made up of three major parts, which are a MMS under test, a communication emulator for interfacing between MMS and RTDS and a RTDS for real-time simulation of a microgrid.

In figure 2, MMS is a device under test. A major object of this HILS system is a microgrid management function test of MMS. RTDS simulates a microgrid model including microsources, loads, distribution line in real-time. Communication emulator transfers system status and monitoring data of real-time simulated microgrid in RTDS and control command of MMS by communication methods. It is an important role in this system. MMS controls microgrid components by communication methods. For that reason, the interface between MMS and microgrid components is only communication ports. For testing management function of MMS, a real-time device for microgrid simulation must have communication methods. In our case, there is no real-time simulator with available communication methods. RTDS, a real-time power system simulator, has only hardwired interface method. Therefore, communication emulator provides an interface method between MMS and RTDS. As using a developed communication emulator, this system can test communication functions of MMS such as communication protocols.

B. RTDS Hardware and Software

Fig. 3. A RTDS System of HILS system for testing MMS

Figure 3 shows a RTDS system of HILS system for testing MMS. The RTDS Simulator is a fully digital electromagnetic transient power system simulator used to conduct: closed-loop testing of physical devices such as protection equipment and control equipment to perform analytical system studies; and to educate operators, engineers, or students. RTDS consists of hardware and software. Hardware's parallel processing architecture is designed specifically for power system simulation and software is the user's link to the simulator hardware. The main elements of the software are the graphical user interface, RSCAD, and the libraries of power and control system component models [14].

1) Building up the test system in RTDS Hardware

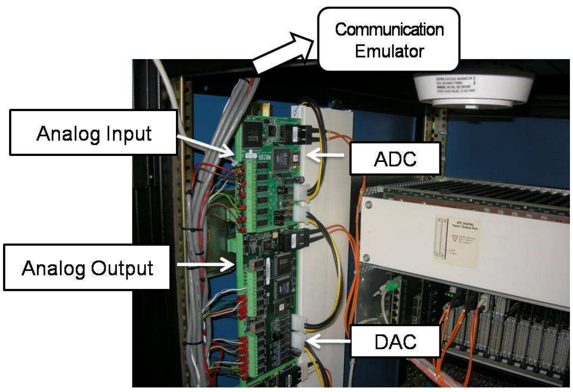

Fig. 4. An analog input and output interface between RTDS and communication emulator

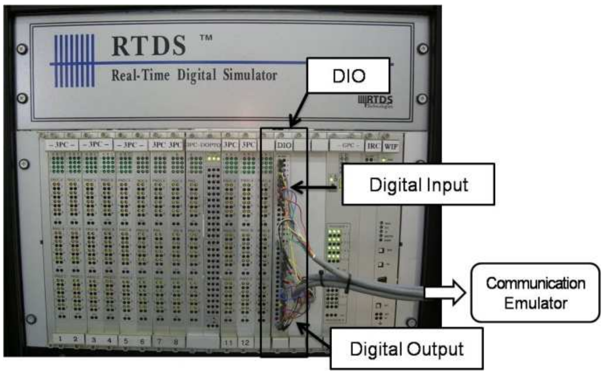

Fig. 5. A digital input and output interface between RTDS and communication emulator

For the real-time simulation of microgrid, RTDS hardware consists of some triple processor card (3PC) for microgrid component simulation, a gigabit processor card (GPC) for network solution and some hardwired interface card for external equipment.

Hardwired interface cards are three types, which are analog output card, analog input card and digital input and output card. For analog output interface, two 16 bits digital to analog converter (DAC) cards are used. Analog output data of RTDS, a microgrid monitoring data for MMS, transmit to communication emulator. For analog input interface, two 16 bit analog to digital converter (ADC) cards are used. Analog input data for RTDS comes from communication emulator to control the power output of microsources by MMS. Figure 4 shows an analog input and output connection between RTDS and communication emulator. For digital input and output interface, one 32bit digital input and output (DIO) card is used. Digital input and output data of RTDS, status and operation command of microgrid components, communicates with communication emulator. Figure 5 shows a digital input and output connection between RTDS and communication emulator.

2) Building up the test system in RTDS software

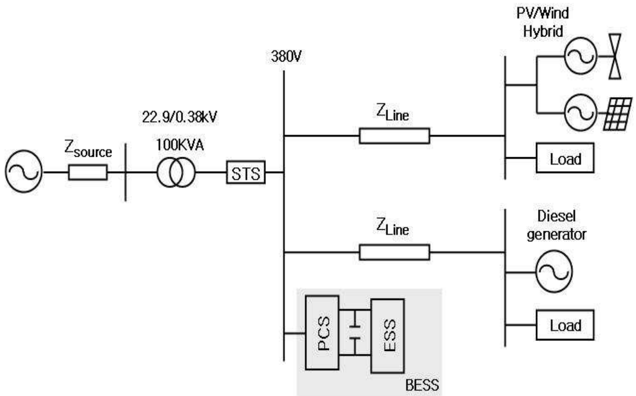

Fig. 6. Configuration of studied microgrid system for HILS test system

Figure 6 shows a configuration of studied microgrid in this paper. A PV/wind hybrid and diesel generation system has been connected to 380V low voltage lines, which connects to a 22.9kV distribution feeder through a pole transformer. A BESS is connected to a 380V busbar, which is near the PCC. The 380V line is connected to microsources and two loads through the overhead line. The major parameters of the test system are as Table I.

Table I. - Major Parameters of Implemented microgrid For HILS Test

Item	Description & Parameters
Test System Configuration	- No. of Sources: 3 (Hybrid, Diesel generator, BESS) - No. of Loads: 2
Generation Capacity of Microsources	- Hybrid 20kW - Diesel generator 20kW - BESS system 10kW
Total Load	- 30kW+j18kVar - Constant impedance model (R/X)
Transformer	- 3phase 22.9/0.38kV 100kVA - Leakage impedance %Z = 6%
Line impedance	- R= 0.1878Ω/km, X=0.0968Ω/km

C. Communication Emulator

Communication emulator is an interface device between RTDS and MMS. It consists of communication ports for MMS, hardwire ports for RTDS and main processor for data handling. It interchanges microgrid simulation results of RTDS with control commands of MMS.

This module is a TMS320VC33 based platform. For MMS communication, it implements a user-defined-protocol and a modbus protocol for MMS communication. For RTDS interface, it realizes analog to digital conversion, digital to analog conversion and digital input and output functions. Major specifications of communication emulator are listed in Table II.

Table II. - Specifications of developed Communication Emulator

Item	Specification
CPU	TMS320VC33-150
Analog Input	16 Channel, ±10V, 12bit Resolution 500kS/s, 1kHz-40dB bandwidth
Digital Input	16 Channel, TTL
Analog Output	12 Channel, ±10V, 12bit Resolution 1kHz-40dB bandwidth
Digital Output	12 Channel, TTL
Communication	RS-232 1Port, RS-485 1Port
User Interface	Status LED 8EA, Character LCD
Size	300mm x 210mm x 80mm

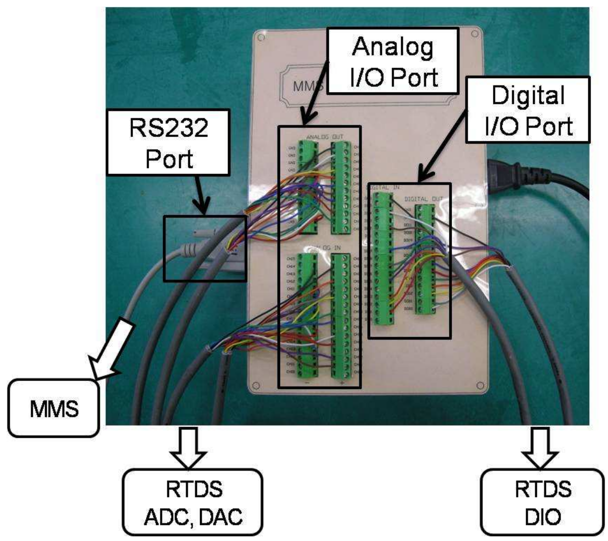

Fig. 7. Developed communication emulator

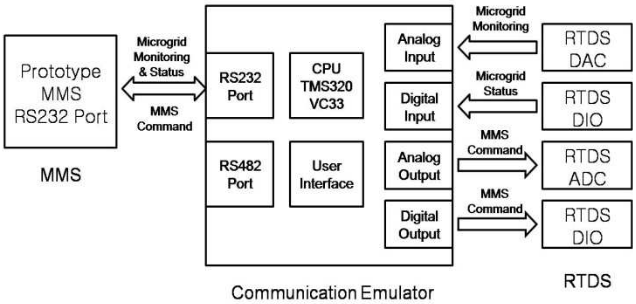

Fig. 8. Configuration and interface of communication emulator

Figure 7 is a real feature of developed communication emulator. Figure 8 shows a block diagram of communication emulator and signal interface with other devices.

Communication emulator is designed for implantation of communication functions in real microgrid. It reads real-time simulation data from RTDS by hardwired analog and digital input ports and transforms these data into a proper protocol for MMS communication. It forwards these transformed data to MMS and MMS uses these data to monitor and control microgrid. And then, control algorithms in MMS generate control commands of microgrid components. MMS transmits these control commands to communication emulator by assigned protocol form. Communication emulator changes these data to analog and digital signal form. RTDS uses these analog and digital signals to simulate a microgrid model in real-time.

D. Prototype MMS

Developed prototype MMS is a PC-based equipment and designed for management of small scale microgrid pilot plant which consists of RES source, diesel generator and BESS as shown in figure 6 and Table I. It controls microgrid components by RS232 and RS485 serial communication methods. Figure 9 shows developed prototype MMS.

Developed prototype MMS consists of MMI module and management function algorithm module. The MMI module gives operating status information of microgrid and trend view. Management function algorithm is implemented by C++ language. MMS is connected with communication emulator by RS-232 serial communication port as it connected with LCs in real microgrid system.

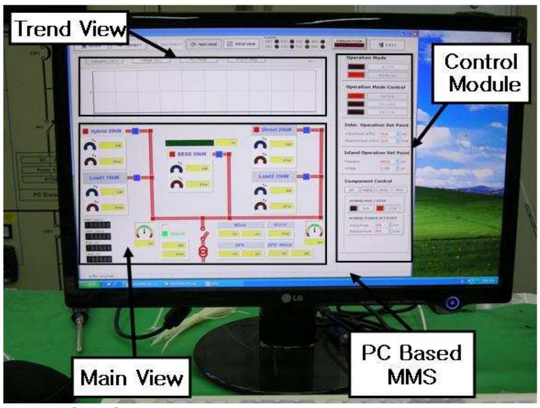

Fig. 9. Developed prototype MMS

Table III shows some major specifications of developed prototype MMS. Table IV is a list of input signals to monitor microgrid pilot plant and Table V shows a list of output command signal to control microgrid pilot plant.

Table III. - Specifications of Prototype MMS

Item	Specification
Stand-alone Mode Functions	Voltage and Frequency Control of Microgrid Resynchronization
Grid-connected Mode Functions	Real and Reactive Power Flow Control at PCC Power Factor Control at PCC
Component Size	PCC 1 point, 3 DGs, 2 Loads, 3 Buses
Communication	RS-232 3Port
Protocol	User-defined-protocol for LCs Modbus protocol for digital meters
Monitoring Data Update Rate	Microgrid Status Date : Every 0.1sec
Command Data Update Rate	Operation and Reference Command : Every 1 sec

Table IV. - Input Signal List of Prototype MMS

No.	Name	Description	Type
1	POUT_Hybrid	Real Power Output of Hybrid System	Analog
2	POUT_DS	Real Power Output of Diesel Generator	Analog
3	POUT_BESS	Real Power Output of BESS	Analog
4	QOUT_Hybrid	Reactive Power Output of Hybrid System	Analog
5	QOUT_DS	Reactive Power Output of Diesel Generator	Analog
6	QOUT_BESS	Reactive Power Output of BESS	Analog
7	POUT_PCC	Real Power Input from Grid at PCC	Analog
8	QOUT_PCC	Reactive Power Input from Grid at PCC	Analog
9	P_Load1	Real Power Consumption of Load 1	Analog
10	P_Load2	Real Power Consumption of Load 2	Analog
11	Q_Load1	Reactive Power Consumption of Load 1	Analog
12	Q_Load2	Reactive Power Consumption of Load 2	Analog
13	VTL_PCC	Bus Voltage at PCC	Analog
14	VTL_Bus1	Bus Voltage at Bus1	Analog
15	VTL_Bus2	Bus Voltage at Bus2	Analog
16	Status_SSW	Switch Status at PCC (On:1/Off:0)	Digital
17	Status_CB1	Switch Status at CB1 (On:1/Off:0)	Digital
18	Status_CB2	Switch Status at CB2 (On:1/Off:0)	Digital
19	Status_CB3	Switch Status at CB3 (On:1/Off:0)	Digital
20	Status_CB4	Switch Status at CB4 (On:1/Off:0)	Digital
21	Status_CB5	Switch Status at CB5 (On:1/Off:0)	Digital
22	Status_CB6	Switch Status at CB6 (On:1/Off:0)	Digital
23	Status_CB7	Switch Status at CB7 (On:1/Off:0)	Digital

Table V. - Output Signal List of Prototype MMS

No.	Name	Description	Type
1	RUN_BESS	Operation Command for BESS	Digital
2	RUN_Hybrid	Operation Command for Hybrid System	Digital
3	RUN_DS	Operation Command for Diesel Generator	Digital
4	Trip_SSW	Trip Command for Switch at PCC	Digital
5	Trip_CB1	Trip Command for CB1	Digital
6	Trip_CB2	Trip Command for CB2	Digital
7	PREF_Hybrid	Real Power Command for Hybrid System	Analog
8	PREF_DS	Real Power Command for Diesel Generator	Analog
9	PREF_BESS	Real Power Command for BESS	Analog
10	QREF_Hybrid	Reactive Power Command for Hybrid System	Analog
11	QREF_DS	Reactive Power Command for Diesel Generator	Analog
12	QREF_BESS	Reactive Power Command for BESS	Analog
13	PREF_PCC	Real Power Flow Command at PCC	Analog
14	PFREF_PCC	Power Factor Command at PCC	Analog
15	VREF_PCC	Voltage Command at PCC	Analog

4. Test Results

There are two test results for validation of the proposed HILS system: Grid-connected mode and Stand-alone mode.

A. *Constant power control in grid-connected mode*

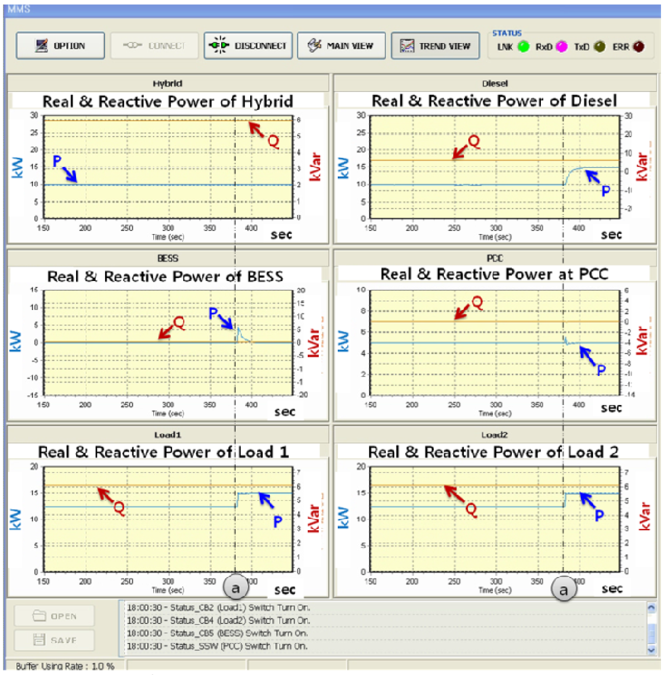

Fig. 10. Feature of MMS in grid-connected operation.

As mentioned in prototype MMS, in this operating mode, the BESS controls the power flow at PCC in primary, and then the secondary regulation control action of MMS is executed to make the power output of BESS be zero. Figure 10 shows the feature of tested MMS in grid-connected mode.

The initial condition is characterized by each load of 12.5kW+j6kVar, the generation of PV/Wind hybrid 10kW+j6kVar, and diesel generator 10kW+j6kVar. The graph of "Real & Reactive Power at PCC" in figure 10 shows that 5kW of active power comes from upstream grid. The area before □ point in figure 10 shows initial condition simulation results.

Total load increases from 25kW+j12kVar to 30kW+j12kVar at ⓐ point. By certain load changing, the power output of BESS increases from zero to near 5kW very quickly and it is returned to zero due to secondary regulation control, which is performed in the MMS. The power output of micro-sources is changed from an initial constant value to a new set point calculated by MMS. The area after ⓐ point in figure 10 shows simulation results after sudden load change.

B. *Frequency and voltage control in stand-alone mode*

In this operating mode, as mentioned in prototype MMS, the BESS controls the frequency and voltage in primary and then the secondary regulation control action of MMS is executed to make the power output of BESS be zero. Figure 11 shows the feature of tested MMS in stand-alone mode.

The initial condition is characterized by a total load of 30kW+j12kVar and the generation of PV/Wind hybrid 10kW+j6kVar, and diesel generator 15kW+j6kVar. Imported power from upstream grid is 5kW. The area before ⓐ point in figure 11 shows initial condition simulation results.

The two consecutive events are applied. The first one is ⓑ point in figure 11. At this point, the microgrid is disconnected from upstream grid due to fault. And the last one is ⓒ point. At ⓒ point, total load decreases from 30kW+j12kVar to 25kW+j12kVar.

At ⓑ point, the control mode of BESS is changed from constant power flow control to frequency and voltage control as soon as the disconnection from upstream grid is detected. During disturbance, the power output of BESS changes from zero to a certain value to control the frequency and the voltage as soon as the disturbance occurs, and it is returned to zero due to secondary regulation control of MMS.

The area from ⓐ point to ⓑ point in figure 11 shows simulation results after sudden load change in grid-connected mode. The area after ⓑ point in figure 11 shows simulation results in stand-alone mode. The area after ⓒ point shows simulation results after sudden load change in stand-alone mode.

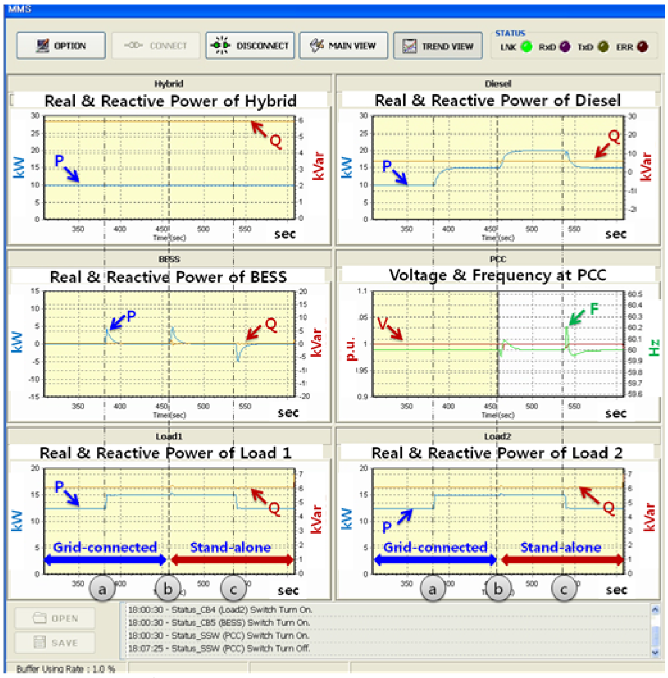

Fig. 11. Feature of MMS in stand-alone operation.

5. Conclusions

This paper proposed a HILS test system as a new method to test and develop major functions of MMS. The proposed HILS test system was composed of RTDS and a communication emulator. RTDS performed real-time simulation of pilot plant models and the communication emulator simulated communication functions of components of pilot plant.

A prototype MMS was designed for managing a 50kVA scale microgrid pilot plant that included a PV/wind hybrid source, a diesel generator and a BESS. Two main strategies of the MMS, grid-connected and stand-alone modes of operation, were tested to validate the proposed HILS system.

The test results showed that the proposed HILS system was useful and effective in developing and testing control algorithms and operation strategies of MMS. Also the developed communication emulator can be available for test and development of microgrid communication protocols.

Various devices and functions of microgrid system require extensive field tests before real applications into real power system. Constructing a field test site will need tremendous amount of time and cost. Parallel use of the propose HILS with field tests may reduce trials and errors considerably.

In spite of good performances, the HILS system has some limitations inherent in model based simulation. In addition, there exist some technical constraints such as real-time processing. To obtain reliable test results, therefore, users should consider more details including system bandwidth, detail level of models, hardware interface methods, simulation time steps, simulator calculation capability.

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