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SCADA System for Islanded DC Microgrids

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Abstract— **This paper develops a supervisory control and data acquisition (SCADA) system to monitor an islanded DC microgrid including wind turbine, photovoltaics, and battery units. The SCADA system is based on KingView 6.55, and establishes data communication between the host and the slave computers through intelligent modules and different communication techniques. The developed SCADA system can monitor real-time parameters such as voltages, currents, or powers, and can store the important parameters into the database. Users can get historical data realistically and effectively through SQL access. When some values in the system exceed or fall below the predetermine limits, the SCADA system can pop up the alarm screen, give an alert and send a text message or call an specified person via an SMS module. The host not only can monitor the operation status of the system, but also give orders to control the action of the slaves. This way, it implements the combination of required monitoring and control functions. The SCADA system includes an energy management system (EMS), monitoring of state of charge (SOC) of the battery management system (BMS), and black start operation. The system is in operation in a DC microgrid system in Tianjin, China.**

Keywords—*battery management system (BMS); SCADA; DC microgrids; energy management system (EMS)*

I. INTRODUCTION

With the raise of the energy crisis and environmental pollution, microgrids with distributed generation systems as main power sources have been paid more attention in many countries [1]. Microgrids are one of the key technologies to realize large-scale deployment of distributed generation systems and the smart grid [2]. Microgrids can be operated either in grid-connected or islanded modes [3], [4].

As an indispensable part of the microgrid, the supervisory control and data acquisition (SCADA) system is needed to ensure its reliable and stable operation. The structure and function of the monitoring system are very different because the power supply and network structure of the microgrid can change a lot from one to another application.

In previous works [5], [6], a microgrid monitoring system based on LabView is presented. They analyzed the needs of wind/photovoltaic/battery hybrid system and design its energy management system. However, they did not introduce the problem of historical data storage and query.

In [7], the authors use Qt to design a PC interface of the monitoring system, and the slaves were based on a microcontroller unit with ARM cortex. The monitoring system analyzed the problems of three-phase load power balance, grid-connected and islanded operations.

In [8], the communication between the host computer and the slaves was realized by using CAN bus. However, in this work, neither energy management nor threshold alarm was implemented. In [9], the hierarchical architecture of an intelligent substation was presented. The paper proposed a microgrid monitoring and energy management system based on three logical layers: equipment, management, and optimization layers; based on that a man-machine interaction platform was developed.

In this paper, the SCADA system for an islanded DC microgrid is presented, including distributed generation systems, such as a small wind turbine (WT), photovoltaic systems (PV), and a battery set (BS). The load is an electrical vehicle (EV) connected to a wireless charging system. The communication system use master-slave topology with the following functionalities. The host computer monitors the operating status of the microgrid all the time according to the received data. The energy management algorithm is implemented by the fact that the host computer gives orders to start or stop the power electronics converters connected to the distributed generators (WT, PV, and BS) or load (EV). Further, a small uninterruptible power supply (UPS) takes the power from the battery to provide power to the intelligent module and monitoring machine.

II. ARCHITECTURE OF THE DC MICROGRID

As shown in Fig. 1, PV, WT, and BS are supplying the entire islanded DC microgrid. The peak power of the PV array is 6 kWp and the one of the WT is 0.8 kWp. BS unit presents an output voltage of 200V@100Ah, an capacity of 20 kWh, with charging current of 1C (100A) and discharging current of 0.5 C (50A).

Normally, PV and WT are operating by using maximum power point tracking (MPPT) algorithms. The PV power is boosted by a DC/DC converter connected to the 360V DC bus. The WT is connected to an AC/DC converter, and then also boosted by a DC/DC converter connected as well to the 360V DC bus. The BS has to role to maintain the DC bus voltage constant. The nominal voltage of the outlet is 100V, which is also connected to the 360V DC bus after its DC/DC converter.
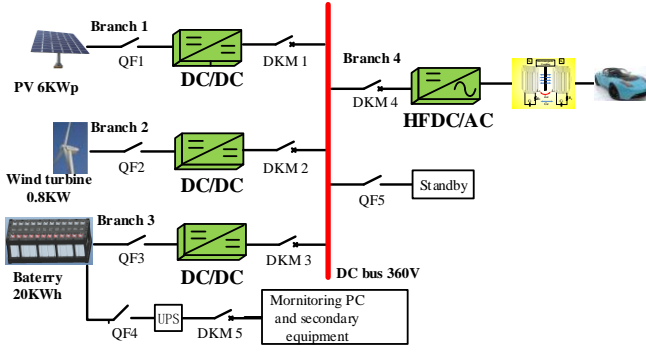
Fig. 1. Power stage of the dc microgrid including circuit breakers.

Finally, a high frequency (HF) DC/AC converter is connected between the DC bus and the wireless charging transmitter. The EV as a load of the whole DC microgrid system is charged through wireless power transmission.

In Fig. 1 also can be seen that the UPS takes power from the battery and supplies secondary equipment: about 300W split in 80W for the SCADA system and 220W for the quiescent power of DC/DC converters. The DC microgrid includes also a number of DC circuit breakers. QF1, QF2, QF3, QF4, and QF5 are manual switchers (not automatic breakers) for emergency operation. DKM1, DKM2, DKM3, DKM4, and DKM5 are automatic circuit breakers that can be commanded through RS-485 communications, so they can be controlled remotely by the SCADA system. Also, each DC/DC converter can communicate with the host computer and receive start/stop actions from the SCADA.

III. SYSTEM HARDWARE AND SOFTWARE STRUCTURE AND COMMUNICATIONS

A. Introduction to System Software Structure

The software development for the host computer in the microgrid SCADA system is the KingView 6.55, developed by the company Beijing Asian Control. The configuration software is a proper host computer monitoring software. It contains many features, such as a strong interface display, rich functional modules, powerful database functions, programmable command language, and so on. The configuration software can be divided into development and operating environments. Users in the development environment can build a man-machine interaction platform, implement control programs, and establish user data files. In the operating environment, the target application is loaded into the computer memory and put into real time operation. The configuration software supports that the user can modify the configuration directly without need for creating the operating environment, and the configuration modified take effect directly.

The configuration software can be installed in the operating system of Windows 2000(sp4)/Windows XP(sp2)/Windows 7 of a personal computer, which requires at least 128MB memory and RS-232C communication mode. The whole software system is based on the idea of modular design, communication between host computer and slave computers, and man-machine interaction platform. The structural diagram of the system is shown in Fig. 2.

B. Introduction to System Hardware Structure

The microgrid monitoring system uses touch screen machine, which is similar to bank queuing machine. The system uses from one to many communication connections form. One of them is based on that a variety of intelligent modules is connected to the RS-485 bus, and then connected thought an RS-232/485 converter to the host computer.

Another one is consists on that many intelligent modules are connected to the same switch, and then connected to the host computer through a cable. Also, remote monitoring is using GPRS service platform. The hardware connection diagram is shown in Fig. 3.

C. System Communication Mode

The communications of all intelligent modules in this system is divided into two kinds of communication modes. One is the Modbus RTU communication protocol and the other is the Modbus TCP/IP communication protocol.

The two communication modes are different in the data frame and settings in the configuration software, but they all use master-slave command mode. It means that the host computer sends a read/write command to the slave, and then the slave makes the relevant response according to the command, feedback data content, or sets the register.
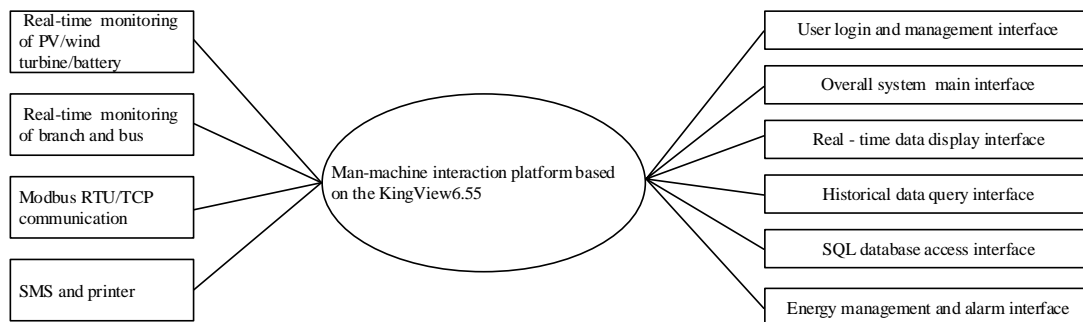

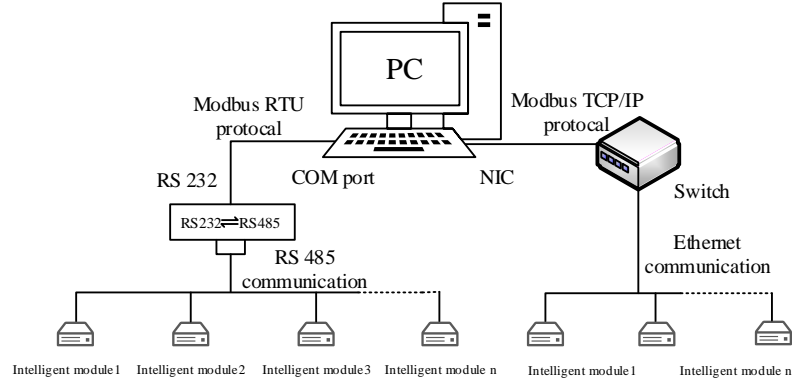Fig. 2. Block diagram of monitoring system software.

Fig. 3. Block diagram of the monitoring system hardware.

1) Modbus TCP/IP Communication Protocol

Modbus TCP/IP communication protocol uses the Ethernet standard in the physical layer and data link layer, and the Modbus protocol standard is used in the application layer. Modbus TCP/IP protocol is embedded into the Modbus frame by encapsulating, which makes that Modbus packets can be transmited by TCP/IP. Modbus TCP/IP does not change the contents of the Modbus protocol. It just changes the data transmission mode to meet the real-time requirements of industrial monitoring, and to improve the communication rate.

Modbus TCP/IP still uses the call/answer mode and master-slave communication, but it can improve the reliability of Ethernet communication. When the software is connected to an intelligent module based on Modbus TCP/IP protocol, the address format should be: *IP address: unit number*. General device port number is 502 in Modbus TCP/IP communication protocol.

2) Modbus RTU Communication Protocol

Modbus RTU communication protocol is a common industrial communication standard, which is widely used in the field of industrial automatic control.

TABLE I. FORMAT OF THE DATA FRAME.

Start	Device address	Function code	Date address	Date number	Check	Stop
T1-T2-T3	MAC-ID	FUN-ID	DATA-ADDR	DATA-NUM	CRC	T1-T2-T3

The format of the data frame in the host query mode is shown in Table I, including the following fields:

- MAC-ID: Slave device address or intelligent module query address. E.g. module #1 is defined as 01, module #2 is defined as 02, and so on.
- FUN-ID: Function code is the second byte of the message frame. The host computer tells the slave computer what to do by the function code. The function code is in the range of 1 to 255. For example, 03H stands for read slave station register data, 06H stands for write slave station register.

- DATA-ADDR: Starting address of the queried data, generally from low to high address to be queried. Note that queried address requirements must be continuous.
- DATA-NUM: Number of the queried data. The number of stored data from the start address to the end address.
- CRC: Cyclic redundancy check code. Calculating the CRC value in sender and receiver. It can be determined whether the communication is correct after comparing them.
- T1-T2-T3: Preparation time before sending. When sending or receiving data.

When the master configuration is communicating with slave intelligent modules based on Modbus RTU communication protocol, the address mode should be:

address: [Delay]: [Delay2]
Address 1-255 Device address
Delay 0-60000 Delay time after sending each command frame (ms)
Delay2 0-100000 Delay time before sending each command frame (ms)

When the external device addressing is completed, the communication parameters of serial port must be the same as the intelligent module. The general serial port basic parameters are set as shown in Table II.

TABLE II. DEVICE SERIAL PORT PARAMETER SETTING

Baud rate:	9600bps	*Data bit:*	8 bit
Parity:	No	*Stop bit:*	1 bit
Communication mode:	RS 232 bus transmission		
Communication timeout:	3000ms		

IV. MAN-MACHINE INTERACTION PLATFORM AND ENERGY MANAGEMENT

A. User Management and Login Interface

The user name and user password can be set, the priority access level, and safe operation area of each user can be selected. The platform configuration also supports modifying user name and password. The script is as follows:

```
if(MenuIndex==0)
{
LogOn();
}
if(MenuIndex==1)
{
LogOn();
ChangePassword();
LogOff();
}
if(MenuIndex==2)
{
LogOff();
ShowPicture("Login interface");
}
```

B. Real Time Data Display and Historical Data Query

In normal system operation, some important parameters from slave computers need to be displayed on the interface. So that users can know parameters and operation status of each component. Fig. 6 shows the voltage, currents, and the power flowing from each element. In this way, monitoring system can get real time values of some important parameters. According to the uploaded voltage and current parameters, you can visualize the analog voltage and current waveform. The monitoring system can get real-time battery temperature, outlet voltage, outlet current, and state of charge (SOC) value by communicating with the BMS. Fig. 4 can display charge/discharge status of the battery and its operation status. So that it can always monitor the battery operation, setting the alarms according to the settled temperature, voltage and current conditions. Further, the energy management algorithm of the entire monitoring system can be obtained according to the SOC value.

Fig. 5 shows the voltage, current, active power and power generation of the 360V DC bus. Operators can intuitively understand the bus voltage, current and other important parameters from the display. At the same time, the waveform of the bus current simulation can also be drawn through the current value uploaded from the slave computers.
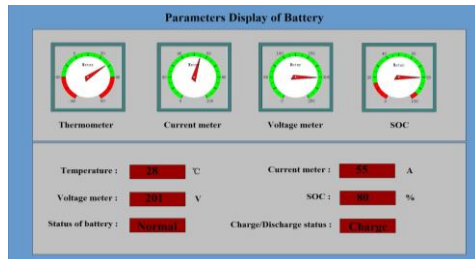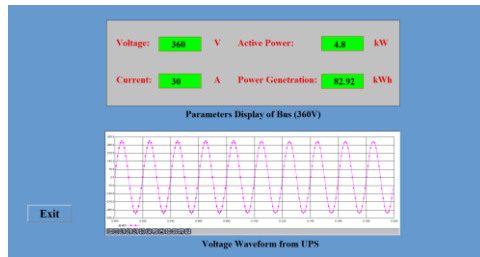

Fig. 4. Battery system parameters.

Fig. 5. Parameter display interface of bus and UPS.

There are some ways to query historical data by the operating system. For instance, reports, historical trend curves, historical data in web publishing, and historical curves in the browser. This paper uses the history report function to query historical data. Before querying IO variable historical data, IO variable in "Record and Secure Zone" must set tab settings. Setting the change sensitivity of the data to zero in the system recorded daily power generation of wind turbine and photovoltaic generation. In the "power generation statistics" interface, it is possible to set the start time, end time, variable selection, and time interval. Daily power generation statistics can be achieved with the following script.

```
if(\\This station\$Hour==0 &&\\ This station \$Minute==0 &&\\
This station \$Second==0)
   \\ This station \k1=\\ This station \ Power generation of PV;
   if(\\This station \$ Hour ==23 &&\\ This station \$ Minute ==59
&&\\ This station \$ Second ==59)
   {
   \\ This station \k2=\\ This station \ Power generation of PV;
   \\ This station \ Daily power generation of PV =\\ This station \k2-
\\ This station \k1;
   }
```

C. Alarm events and sending SMS

When the value of some variables in the monitoring system exceeds or falls below a determined limit, the system automatically generates the corresponding alarm information, indicating that the value of the variable is outside the nominal value, and reminding the operator.

Alarm and event interface record the fault of the system when some variables are abnormal, and recovering after repairing. So that it can provide a strong guarantee for system maintenance. For example, if a short circuit fault happened somewhere in branch 1 (see Fig. 1), it may produce high current flowing, which may cause serious faults to the equipment. Nevertheless, an alarm can prompt the operator to pay attention and avoid some unnecessary losses. Software configuration can use the function "PlaySound ("aa", 1)" to play the named "aa" alarm sound in order to effectively informing the operator.

In the monitoring system, alarm information can be classified into different groups, so that it can facilitate the visualization, recording and distinguishing alarm variables and faulty parts. At the same time, the system will automatically record the alarm information to facilitate users to view the historical alarm. The IO variable alarm group name and alarm limits can be set in a change tab.

Considering that the operator do not hear the system alarm when it occurs, the monitoring system includes an short message service (SMS) module. It means that the monitoring system will send alarm information to the designated operator. The information content is a string that was previously entered into the system and different alarm

conditions corresponding to different strings. The SMS module is a SIMCOM SIM900A, which is a GSM/GPRS module that can be programmed based on AT commands. The module is also connected with the host computer through the standard Modbus RTU communication protocol. If the alarm conditions are true after the connection is successful, monitoring system will send an SMS command to the SMS module. The command is as follows:

```
if(\\This station \New alarm==1)
{
\\ This station \ Designated number="18222219869";
\\ This station \Content="Voltage is abnormal in PV branch";
\\ This station \Send=1;
}
```

D. Black Start Operation and Energy Management System

1) Black Start Procedure

After the wind turbine (WT), photovoltaic (PV) system, battery (BS), load, and control equipment are completely installed, it is necessary to supply power to the device in order to debug the whole system. However, the power supply sequence is very important. If an improper operation is done, it may damage the equipment or even cause a security incident. A black start procedure was designed for this system as follows:

1. In the first operation, users can manually close switches in the WT, PV, BS, and UPS branches. That is to close QF1, QF2, QF3, and QF4.
2. Closing all the circuit breaker with communication function. Since BS is connected to the low side of the DC/DC converter, the voltage between the high and the low sides is the same. So that the proposed sequence is as follows:
    (1) Closing DKM5 to supply power to the equipment of the secondary side and monitoring PC.
    (2) Closing DKM3 to supply power to BS branch.
    (3) Closing DKM1, DKM2, and DKM4 to supply power to PV, WT, and load branches.
3. System internal control steps:
    (1) Giving an order to the DC/DC converter connected to the BS branch to supply the DC bus 360V.
    (2) Starting the DC/DC converter connected to the PV branch and the WT branch.
    (3) Starting the HF DC/DC converter load.
When the DC bus voltage is between 380V and 420V, the monitoring system will enter into the energy management system algorithm.

2) Energy Management System Algorithm

Most of the applications of grid-connected systems, for instance in which WT and PV are continuously injecting power into the grid, do not require extra power supplies. Thus, when the power generated by the microgrid is not enough but the load needs electricity, it can be supplied by the main grid. However, in an islanded microgrid, due to lack of the main grid support, it is necessary to build an effective energy management algorithm that can solve this problem.

The monitoring system is designed to start/stop DC/DC converters of PV, WT, BS, load, and UPS branches regarding the SOC of the BMS. According to the actual operation, SOC is divided into three modes as 0.95, 0.7 and 0.2 for energy management system. Specifically the energy management system algorithm is as follows.

1. SOC = 0.95, there are two cases in order to prevent the battery overcharge.
    (1) If the load is consuming power and SOC continues rising to 0.98, the monitoring system will alarm and give a command to stop the DC/DC converter of the WT and PV branches automatically.
    (2) If the load is not consuming power, the monitoring system will give a command to stop the DC/DC converter of the WT and PV branches automatically.
2. When the DC/DC converter in WT and PV branches are all stopped, SOC will gradually decrease due to the load and UPS consumption. So that when SOC = 0.7, the system will give a command to start the DC/DC converters of the WT and PV branches automatically.
3. In normal weather conditions, the system will transition between step 1 and 2. However, for instance in continuous rainy no-windy days, the power generated by PV and WT is very small. Even though implementing step 2, SOC will still continuous decreasing. In order to protect the BS from over-discharging situation, there are two cases when reaching SOC=0.2.
    (1) If the EV load is consuming power, the monitoring system will give a command to stop the HF DC/AC inverter load branch automatically.
    (2) If the EV load is not consuming power, SOC will still decrease since the UPS side is still consuming power. When SOC=0.15, the monitoring system will alarm and give a command to send short messages to the specified number and disconnect the circuit breaker DKM1, DKM2, DKM3, and DKM4 of the PV, WT, BS, and load branches. When SOC=0.14, disconnect the circuit breaker DKM5 from UPS branch. The whole system will stop operating.
4. When SOC=0.14, the entire system stop operating. Because the system has already informed operator by SMS, the operator only needs a timely reclosing to recharge the BS and to repeat the black start procedure.

The energy management algorithm and the system configuration software are as follows:

```
if(soc==0.95&&\\ This station \HF DC/AC!=1)
{
\\ This station \ DC/DC of wind turbine =0;
\\ This station \ DC/DC of PV =0;
}
if(soc==0.98&&\\ This station \HF DC/AC==1)
{
PlaySound( "aa", 1 );
\\ This station \ DC/DC of wind turbine =0;
\\ This station \ DC/DC of PV =0;
}
if(soc==0.7)
{
```

```
\\ This station \ DC/DC of wind turbine =1;
\\ This station \ DC/DC of PV =1;
}
if(soc==0.2&&\\ This station \HF DC/AC==1)
{
\\ This station \HF DC/AC=0;
}
if(soc==0.15)
{
PlaySound( "aa",1 );
\\ This station \ DC/DC of PV =0;
\\ This station \ DC/DC of wind turbine =0;
\\ This station \ DC/DC of battery =0;
\\ This station \HF DC/AC=0;
\\ This station \DKM1=0;
\\ This station \ DKM2=0;
\\ This station \ DKM3=0;
\\ This station \ DKM4=0;
}
if(soc<0.15) {
\\ This station \ DKM5=0;
}
```

Some experimental platform and historical data pictures are as follow. Fig. 6 shows the platform including the Photovoltaic array, wind turbine and a small house containing some equipment. Fig. 7 shows the photovoltaic outlet power curve in one day.
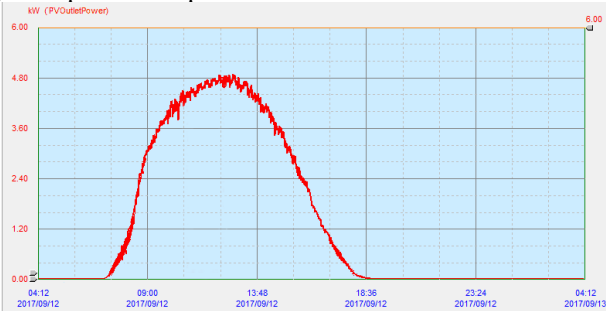

Fig. 6. Experimental platform.

Fig. 7. Photovoltaic outlet power curve.

V. CONCLUSION

The paper presented a SCADA system for an islanded dc microgrid based on wind, photovoltaics, and battery systems. An intelligent module, the configuration development environment, and communication systems (CAN bus and RS-485) are used to realize the monitoring and control between the host and slave computers. The developed SCADA system endows the DC microgrid the following features:

- Black start operation
- Energy management system
- Circuit breaker control through RS-485
- Battery management through CAN bus.

The system has been applied in a demonstration project in Tianjin, China. The DC microgrid has shown to be stable, highly efficient and reliable. The SCADA system has been validated and right now fully operational in the DC microgrid system.

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