Real-time Grid Simulation Platform for System Analysis Using Virtual Power Source

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Abstract
A smart grid test bed with 6.6kV experimental distribution network which includes mega-photovoltaic generation systems, rechargeable batteries and so on has been conducted. In order to demonstrate the system performance of smart grid with this test bed, a new simulation platform has been developed. The simulation platform consists of BTB (Back-To-Back), real-time power system simulator and interface controller, and it performs the upper power grid which can reproduce various disturbances such as frequency deviation and instantaneous voltage drop. This paper describes the system configuration, verification test result and application example of this simulation platform.

Keywords—Smart grid, Power system simulator, BTB, System Interface Controller

I. INTRODUCTION
In order to realize smart grid, a large amount of renewable energy sources such as photovoltaic generation and wind power generation must be penetrated into power system, and some energy storage systems such as rechargeable battery will be introduced to the power system. Furthermore, it is necessary to clarify a lot of technical issues about power system such as maintaining power system frequency, securing power system stability, controlling the voltage of distribution system and restraining harmonics. To solve these issues, entire power system needs to be operated and controlled by application of information and communication technology. In order to do that, it is very important to evaluate the effect of a large amount of renewable energy penetrated into power system. For that evaluation, a test environment including various kinds of equipment such as photovoltaic generation system and rechargeable battery must be constructed.

This time, a new grid simulation platform which can simulate entire power system with renewable energy sources by using a BTB (Back-To-Back) as virtual power source has been developed. This platform can simulate various power system phenomena due to interaction between the upper power system and test beds such as power system frequency deviation due to the output fluctuation of photovoltaic generation. This platform consists of following equipment:

a. BTB with voltage source converter
b. A real-time power system simulator
c. An interface controller between BTB and real-time power system simulator

This paper is organized as follows. Section II and III introduce the components and purpose of this platform. In Section IV and V, the details of real-time communication control and connection method between test beds and the real-time power system simulator are introduced. Section VI demonstrates the validity of the virtual connection by comparing the test result of this platform with the result of RMS analysis. Section VII describes one of the demonstration test results for smart grid by use of this platform, which was carried out in order to verify a new supply and demand control optimized for power grid with a large amount of photovoltaic generation and rechargeable battery system.

II. SYSTEM CONFIGURATION
An in-company smart grid verification system-wise at three works in Japan has been performed toward its practical use. In the largest one located in Amagasaki, a smart grid demonstration system is constructed with 6.6kV experimental distribution network and many kinds of test beds including totally 4MW photovoltaic generation systems, rechargeable batteries, diesel generation simulator and so on [1]. As for test bed configuration currently used in many projects, the experimental distribution network including test beds is energized from the power grid supervised by electric power utilities. So such system is not enough to demonstrate the
system performance in smart grid because any disturbances such as frequency deviation and instantaneous voltage drop cannot be reproduced to the real power grid supervised by utilities. Therefore, a new grid simulation platform which can overcome this defect has been developed so far. The system configuration of this platform is shown in Fig. 1. The details of each component of this platform are described below.

A. BTB (Back-To-Back)

In this platform, a BTB is connected to the experimental distribution network. The BTB performs as large-capacity voltage amplifier. Since the BTB acts as the upper power source of the experimental network, no system influence is made on the power grid supervised by electric power utilities. The BTB consists of voltage source converters using IGBTs (Insulated Gate Bipolar Transistor). The rated voltage is 6.6kV and the rated capacity is ±1MVA (bidirectional). The voltage source converter on the experimental network side consists of three single-phase converters so that each phase voltage of experimental network side can be independently controlled and the BTB can output unbalanced voltage.

B. Real-Time Power System Simulator

The real-time power system simulator is the RMS value type of fully digital power system simulator which operates in real time with 10-millisecond time step. The real-time power system simulator was developed for constructing the upper power grid which was virtually connected with the experimental distribution network via BTB. The composition of upper power grid on the real-time power system simulator can be freely changed so that test beds in the experimental distribution network can be connected to upper power grid with a wide range from a 500 kV bulk power grid with many distribution network to a 22 kV small power grid on an isolated island. This point is a great difference from other existing test beds. Therefore, not only experimental distribution network but also bulk power grid with renewable energy can be demonstrated by this platform.

C. Interface Controller (BaSIC)

The interface controller called BaSIC (BTB and Simulator Interface Controller) was developed for realizing virtual connection between the upper power grid on the real-time power system simulator and the experimental distribution network with test beds [2]. The terminal units of BaSIC system are connected to BTB, real-time power system simulator and some test beds. Each terminal unit can measure the values of voltage and current at the connecting point of equipment. Although the terminal units are located at multiple points of the experimental distribution network, the measured data of all terminal units need to be time-synchronized. Therefore, wide-area and real-time measuring system by means of distributed synchronous Ethernet network where the communication control algorithm is packaged on FPGA (Field-Programmable Gate Array) is applied. By using generic Ethernet devices, the network system can be constructed very flexibly. A terminal unit which is connected to BTB is the master station and the other terminal units are the slave stations of the synchronous network. This synchronous network system can send or receive measured data sampling in 0.9375-degree of electrical angle, and can synchronize the master and all slave stations with maximum errors of ±0.2 microseconds. The BaSIC system realizes real-time operation whose bidirectional transmission delay is less than 30 degrees of electrical angle. The transmission delay is sufficiently shorter than the 10 millisecond time step of real-time power system simulator so that BaSIC system made the simulation platform with various test beds realized inexpensively.

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Fig. 1. System configuration of this simulation platform.
III. PURPOSE OF THE PLATFORM

This platform can connect some test beds in the distribution network to upper power grid on the real-time power system simulator. RMS value type of real-time power simulator is applied to this platform so that this platform can simulate some phenomena of second order such as frequency deviation. Actual equipment and control system can be connected so that their technical performance can be examined on this platform. For example, an actual EDC (Economic load Dispatch Control) system for power system with large amount of wind power generation and some rechargeable batteries can be verified and demonstrated. In addition the BTB can generate arbitrary waveform of AC voltage by open-loop control. This is a different function of this platform from the closed-loop control between test beds and real-time power system simulator. By use of this function, for example, the fault ride through capability of actual power conditioning system can be verified by use of this platform.

IV. ETHERNET-BASED REAL-TIME COMMUNICATION CONTROL

A. Background of development

As described above, all the terminal units of BaSIC system are synchronized via its private LAN (Local Area Network). As a general method for realizing the real-time communication, IEEE 1588 PTP (Precision Time Protocol), which can realize the time synchronization in error by less than 1 microsecond, can be captured. However, PTP requires the special packet for time synchronization besides packets with measured data. Therefore, any measured data cannot be transmitted in the period when the special packet for time synchronization is processed. BaSIC system is necessary to process the measured data of all terminal units and the output voltage reference of BTB which with 0.9375-degree resolution in real time. For this reason, the real-time communication method which does not require any special packets for synchronization, in other words, the time synchronization control method with only data packets is applied [3]. Additionally, in order to improve the reliability of BaSIC system, BaSIC system has two types of master stations. BaSIC-PCI in Fig. 1 is the master station for simulator calculation. Its hardware is based on the standard of generic PC architecture and it is specialized for arithmetic capacity. BaSIC-ADB in Fig. 1 is the other master station for time synchronization. The hardware is based on Japanese standard for digital protective relays and protective equipment so that the packet can be processed as UDP broadcast normally.

B. Characteristics

The characteristics of real-time communication control in BaSIC system are described below;

1) Real-time communication control can realize time synchronization with only data packet so that any special packets for synchronization are unnecessary.

2) Fig. 2 shows simplified diagram of synchronization. Packet reception time is measured by detecting the rising edge of Data Valid signal of GMII (Gigabit Media Independent Interface), which is an interfacing protocol between OSI layer 1 and 2. Therefore, time measurement can be completed in OSI layer 2 so that jitter in synchronization control can be reduced compared to PTP which requires OSI layer 4 for time measurement.

3) Fig. 3 shows the mesh topology of communication between master and slave stations in BaSIC system. Master station for time synchronization makes UDP/IP broadcast communication by poling control with 0.9375-degree interval. Only one slave station in the mesh topology is allowed to respond in one broadcast communication so that any collisions of packets from multiple devices can be avoided. The UDP/IP broadcast communication repeats 16 times in 15-degree electrical angle so that the mesh topology of master and slave communication can be constructed in 15-degree electrical angle.

4) Fig. 4 shows packet configuration. Data for time synchronization is included in the payload of packet so that the packet can be processed as UDP broadcast data normally.

C. Operational results

BaSIC system has been under operation since March 2011. The operational results are described below;

1) Real-time bi-directional communication network system which orients to process bus has been constructed. It has been achieved that the desired value of packet loss is less than 2.5E-8% per terminal, which means that packet loss is less than once a day.

2) It has been achieved that sampling synchronization error stays within ±0.2 microseconds. This is ±0.46% of 43.4 microseconds which corresponds to electrical angle of 0.9375 degrees at 60 Hz. Fig. 5 shows the sampling synchronization error of all terminal units by probability density function. The function and arrangement of each terminal unit is shown in Fig. 1.

Fig. 2. Simplified diagram of synchronization control.
V. METHOD FOR VIRTUAL CONNECTION AND CLOSED-LOOP CONTROL

This simulation platform constructs a virtual connection via BTB between upper power grid on real-time power system simulator and some test beds at the experimental distribution network, and can simulate various power system phenomena due to interaction between the upper power grid and test beds by closed-loop control. The method for realizing the virtual connection is described below. In order to realize the virtual connection, measured instantaneous voltage and current values at the experimental distribution network must be converted to RMS values, and the voltage and frequency output of real-time power system simulator must be converted to instantaneous values. This is because real-time power system simulator is RMS value type of power system simulator.

First, as shown by dashed line in Fig. 1, BaSIC system measures the instantaneous voltage and current at the connecting point of BTB or other test beds, and calculates active power \( P \) and reactive power \( Q \) from the measured instantaneous voltage \( v_a, v_b, v_c \) and instantaneous current \( i_a, i_b, i_c \) by following equations:

\[
P = v_a i_a + v_b i_b + v_c i_c
\]

\[
Q = \frac{1}{3} \left\{ (v_a - v_b)i_b + (v_b - v_c)i_c + (v_c - v_a)i_a \right\}
\]

Measured voltage and current values are filtered for removing harmonics and DC component before calculating active and reactive power. And then, the calculated active and reactive power values are transferred to real-time power system simulator. Real-time power system simulator constructs the upper power grid and generators or loads with transferred active and reactive power are set to some electrical buses in the upper power grid. In this way, optional test beds in experimental distribution network can be mapped to optional generator or load of upper power grid on the real-time power system simulator. Therefore the state change of test beds such as the output deviation of photovoltaic generation system can be reflected in the upper power grid on real-time power system simulator. On the other hand, as shown by dotted line in Fig. 1, real-time power system simulator outputs the RMS voltages in symmetrical component \( V_1, V_2 \) and \( V_0 \) and voltage phase in symmetrical component \( \phi_1, \phi_2 \) and \( \phi_0 \) and angular frequency \( \omega \) of the connection bus in the upper power grid to experimental distribution network. BaSIC system converts the output values to three-phase instantaneous voltage by following equations:

\[
v_a = V_1 \sin(\alpha + \phi_0) + V_2 \sin(\alpha + \phi_1) + V_0 \sin(\alpha + \phi_2)
\]

\[
v_b = V_1 \sin(\alpha + \phi_0) + V_2 \sin(\alpha + \phi_1) - \frac{2\pi}{3} + V_0 \sin(\alpha + \phi_2) + \frac{2\pi}{3}
\]

\[
v_c = V_1 \sin(\alpha + \phi_0) + V_2 \sin(\alpha + \phi_1) + \frac{2\pi}{3} + V_0 \sin(\alpha + \phi_2) - \frac{2\pi}{3}
\]

BaSIC system transfers these three-phase instantaneous voltages to BTB as the voltage reference, so the voltage and frequency output of real-time power system simulator is reflected in test beds at the experimental distribution network via BTB. This closed-loop control operates in real time with 10 milliseconds time step, and the state change of upper power grid on real-time power system simulator and test beds at the
Such virtual connection by exchanging voltage and current has a stability condition of closed loop which is determined by the impedance of upper power grid on real-time power system simulator and that of experimental distribution network [5]. When the percent impedance of upper power grid is \(Z_1\) and that of experimental distribution network which is calculated from the same base MVA as \(Z_1\) is \(Z_2\), the stability condition of closed loop is shown as follows:

\[
Z_1 < Z_2
\]  

(6)

However, this stability condition of closed loop can be satisfied in most cases because the base capacity of upper power grid is generally larger than that of experimental distribution network. Therefore, the percent impedance of upper power grid is smaller than that of experimental distribution network when the both percent impedances are calculated from the same base MVA.

Fig. 6 shows the time-relation between the input and output signals of the closed-loop control. The input signals are active and reactive power values \(P_n\) and \(Q_n\) calculated by each terminal unit. One data packet includes 16 instantaneous value data with 0.9375-degree resolution as shown in Fig. 4, and all input signals are time-synchronized with each other. On the other hand, the output signals of real-time power system simulator, which are RMS voltage \(v_{BTB}\) and angular frequency \(\omega_{BTB}\) for the output voltage reference of BTB, are not time-synchronized with the input signals. The output signals are calculated from the input signals before 10 milliseconds as 1 time step of real-time power system simulator. This time delay of output signals does not make a large impact on the simulation results of this platform. This simulation platform dedicates to emphasize phenomena of second order such as frequency deviation of power grid, where more precise time-synchronization between input and output signals of the closed-loop is not necessary.

VI. VERIFICATION TEST FOR CLOSED-LOOP CONTROL

The verification test for closed-loop control was carried out. Fig. 7 shows a simple power grid used for the verification test. In this test, the power grid was divided by two as shown in Fig. 8. One subsystem was experimental distribution network and the other was simulated on the real-time power system simulator. In this test, the entire experimental distribution network was mapped to a variable load which was connected to the connection bus in the power grid on the real-time power system simulator.

The validity of closed-loop control was examined by comparing the simulation results of this platform with the results of RMS analysis of the entire power grid. The capacity of generator #2 and load in the experimental distribution network was much smaller than that on RMS value analysis, so the capacity enlarging gain was set to 1000 for fitting the capacity of generator #2 and load on this platform to that on RMS analysis. On this test, the experimental distribution network was simulated by RTDS, which is a commercially available real-time simulator and BTB was simplified as a controllable voltage source. As one of the verification tests, power swing phenomenon between generator #1, generator #2 and infinite bus in case that 400 MW passive load was suddenly separated was simulated. Fig. 9 shows the active and reactive power output of generator #1 and generator #2 when the load was separated at 1.0 sec. Fig. 9 compares the result of RMS analysis and that of simulation on this platform, and they are very similar each other. Therefore, the results shows the closed-loop control of this platform operates properly and the
dynamic characteristics of the power grid can be simulated by this platform.

![RMS analysis results](image1)
![Verification test](image2)

Fig. 9. Comparison between the results of RMS analysis and verification test of this platform.

VII. APPLICATION FOR SMART GRID DEMONSTRATION EXPERIMENT

In order to verify a new supply and demand control system optimized for smart grid, some verification and demonstration tests were conducted by using this simulation platform. Fig. 10 shows one of the power grid model used for the verification test. A small power grid on an isolated island was modeled. A 200 kW diesel generation simulator (motor-generator system) and a 200 kW Li-ion battery are connected to the experimental distribution network and these test beds are mapped to generator and battery of the power grid on the real-time power system simulator. Diesel generation simulator is mapped to generator #1, and Li-ion battery is mapped to battery #1 (BAT1). The capacity of test beds is enlarged by setting the capacity enlarging gain. Photovoltaic generation is simulated on real-time power system simulator. This platform made it possible to carry out the verification with actual supply and demand control system and rechargeable battery on an isolated island power grid.

Fig. 11 shows one of the test results. The figure shows frequency deviation of power grid, the active power output fluctuation of photovoltaic generation and the active power outputs of some generators and rechargeable batteries during 60-minutes simulation. The black curve shows the measured active power output, the red curve shows the output reference from EDC (Economic load Dispatching Control) and the blue curve shows the total output reference from EDC and LFC (Load Frequency Control). The output of photovoltaic generation is greatly fluctuated. Supply and demand control system controls the outputs of generators and batteries to compensate the output fluctuation of photovoltaic generation and suppress the frequency deviation of power grid. Although generator #1 and battery #1 are mapped to real equipment at the experimental distribution network, the outputs of these generator and battery are controlled as same as the other generators and battery simulated by real-time power system simulator embedded with demand and supply control system, and the frequency deviation is suppressed within ± 0.2 Hz (within ± 0.1 Hz in most time).

VIII. CONCLUSION

A new simulation platform for system effect analysis of renewable energy penetration was developed. This platform consists of BTB, real-time power system simulator and interface controller (BaSIC). This platform can simulate various phenomena of second order such as frequency deviation. The phenomena include the interaction between test beds such as photovoltaic generation and rechargeable battery and upper power grids on real-time power system simulator by closed-loop control. This simulation platform will be used for further system evaluation of smart grid. For example, verification for new frequency control system which can apply for power grid with large amount of wind power generation, simulation study for wide-area-interconnected power grid with large amount of renewable energy and so on.

REFERENCES

Fig. 10. Power grid model for demonstration experiment.

Fig. 11. Results of demonstration experiment.