Field Demonstration of Building Energy Management Systems

Tianmeng Shen[1], Daichi Kawashima[2], Ryogo Kubo[3], Masaru Ihara[4], Toshiro Togoshi[5], Hiroaki Nishi[6]

Graduate School of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa 223-8522, Japan

shin@west.sd.keio.ac.jp[1]; daichi@west.sd.keio.ac.jp[2]; kubo@elec.keio.ac.jp[3]; ihara@west.sd.keio.ac.jp[4]; togoshi@west.sd.keio.ac.jp[5]; west@sd.keio.ac.jp[6]

Abstract- **Many different approaches are currently utilized in the field of integrated network control systems, known as smart grids. We implemented an energy management system with the aim of developing a future standard for this area. It is difficult to connect heterogeneous systems that contain different standards, even if standardized technologies are available. A concept for an integrated network control system is proposed and demonstrated to overcome this problem. We considered distributed and shared operations in a large system containing various subsystems. This concept maintains interoperability between heterogeneous systems. The concept was demonstrated at the Fukue Port Terminal building in Goto City, Nagasaki Prefecture. A field demonstration of the building energy management system was conducted in the building. This system uses a variety of devices that are produced by seven different companies. An air-conditioning control system to reduce carbon dioxide emissions and achieve electric-load leveling with a battery was implemented and experimented with an application of the proposed system. The battery was emulated by real-time system simulation. Our results demonstrate the effects of a common platform and its advantages.**

Keywords- BEMS; Electric-Load Levelling; Heterogeneous System; Protocol

I. INTRODUCTION

Smart grid technologies have been actively studied for the aim of environmental load and cost reductions [1]. Some of the research in this area has included large projects in the electricity, information and communication technology (ICT), and motor vehicle industries, with each of these having conducted substantive experiments. In the case of Japan, since the Great East Japan Earthquake occurred in March 2011, a limited power supply has been a serious problem because of the shutdown of the atomic power plant. Therefore, power variation control, demand response, and autonomous distributed control of energy are highly sought after.

The concept of a smart grid is defined as the application of an energy management system (EMS) using ICT. Smart grid technology encompasses multiple areas such as electric power engineering, information engineering, and communication engineering. The issues of interoperability with these systems are discussed in IEEE P2030 [2], with contributions from experts for each area. In the ITU-T, a focus group on smart grids was established in 2010 to clarify the role of ICT in this paradigm. In addition, some alternative standardization organizations in the area of ICT are interested in smart grids and their applications.

From the perspective of communication engineering, Hauser et al. [3] clarified the communication requirements for large power systems. Gungor et al. [4] performed field tests on a smart grid using IEEE 802.15.4-compliant wireless sensor networks. The application of smart grids to machine-to-machine communications has also been researched [5, 6]. From the perspective of information engineering, Kim et al. [7] proposed a decentralized and data-centric information infrastructure for a next generation power grid. In addition, Lu et al. [8] presented an ontology-based data integration approach to resolve the semantic heterogeneity problem in smart grids. Our own group has also developed home EMS (HEMS) [9] and cluster EMS (CEMS) [10] applications using ICT. However, there has thus far been insufficient discussion on scalable and integrated management of smart grids covering the multiple areas and various existing standards.

As one of those substantive experiments, the Fukue Standardization and Implementation of Energy Management Sensor Network (FUSION) project is currently underway in the Goto Islands, Nagasaki Prefecture, Japan. Japan contains many islands that are isolated from energy resources. Hence, the utilization of a smart grid in these islands has been studied. The FUSION project uses 100 electric vehicles (EVs) on the island for studying everything to grid (X2G) technologies, the energy management system (EMS), and their standardization. This project is supported by the Ministry of Internal Affairs and Communications (MIC) and it is linked to the EV&Intelligent Transport System (ITS) project that is supported by the Ministry of Economy, Trade, and Industry (METI).

In this paper, as part of the FUSION project, an integrated network control system is proposed that utilizes information from a diverse range of devices. The constructed system utilizes a variety of devices that are produced by 7 different companies. To achieve the integrated network control system, an XML-based communication platform is proposed that allows for data acquisition and control in a heterogeneous smart grid. In addition, to show the availability of the system, some applications are proposed that utilize the constructed system. These applications are data visualization on the web and air-conditioner control, utilizing battery emulation with the aim of electric-load leveling.

II. INTEGRATED NETWORK CONTROL SYSTEM

In this section, the concept of the integrated network control system is defined and the XML-based interface for the communication of data introduced. First, the issues related to currently available systems, such as a smart grid, and their requirements are discussed.

A. Heterogeneity in a Smart Grid

Smart grids include many and varied subsystems, such as EMSs, (e.g., HEMS, building EMS (BEMS), and CEMS), EVs, and distributed renewable energy sources. Currently, each subsystem is designed on the basis of different existing standard technologies such that it is difficult to ensure interoperability between subsystems. If available protocols are restricted by new standards, interoperability is ensured at the cost of flexibility. However, in such a heterogeneous smart grid, a better solution would be to develop a common communication platform that can operate flexibly and manage any existing lower-layer protocols.

B. Standard Technologies Supporting Smart Grids

A smart grid encompasses multiple areas, such as power systems, information and communication systems, intelligent transport systems, EVs and information appliances. In other words, the heterogeneity of a smart grid arises from the various standard technologies or protocols employed. In each area, there already exists independent medium-level, control-level, and system-level standards, as shown in Fig. 1. For example, we can utilize an 802.11g-compliant wireless transceiver as a medium-level standard and 802.1x-compliant authentication as a system-level standard for information and communication systems.

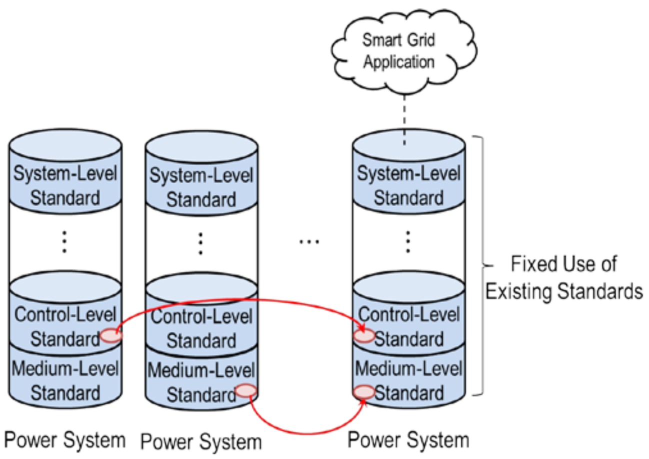

Fig. 1 Standard technologies surrounding a smart grid

The selection of standard technologies for each layer is fundamental to the system architecture. For smart grid applications, however, it would be unrealistic to expect available protocols to be standardized across all interfaces, since there are many kinds of data and infrastructures in a smart grid. In addition, subsystems in the smart grid are often installed on the basis of existing standard technologies in each area. Therefore, in order to construct a complete system, we need to select and combine appropriate standard technologies according to the communication requirements and data semantics.

C. Protocol Convergence

From the viewpoint of application-level system control, all infrastructures and standard technologies related to a smart grid are considered as resources for operating and managing the system, as shown in Fig. 2. The standard technologies surrounding the smart grid include medium control, quality of service control, security, etc. Wireless, wired, and power line communication technologies are already available for various infrastructures, e.g., in control area networks, sensor networks, and information appliance networks. Owing to smart grids being comprised of a combination of various subsystems, appropriate standard technologies have to be flexibly selected according to the flowing data type or its requirements.

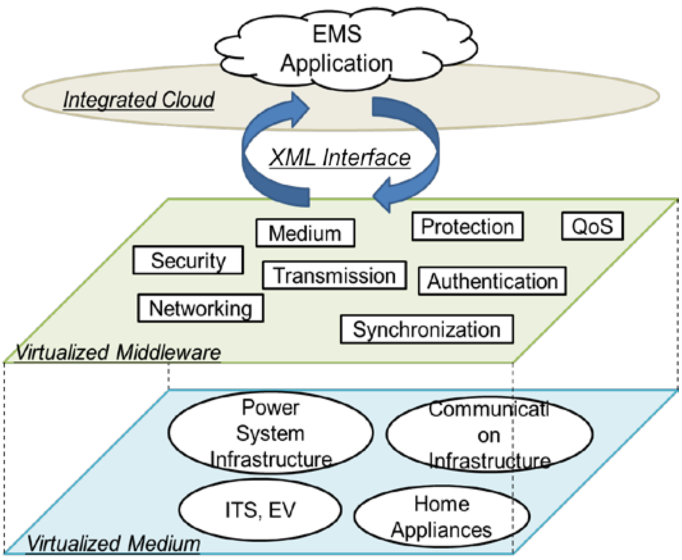

Fig. 2 Protocol convergence related to the smart grid

In practice, all infrastructures are connected by information/communication networks, and the standard technologies are available as resources beyond the range of each particular area. Therefore, a scalable and integrated communication platform is required to effectively operate and manage the resources. In addition, the platform should be flexible, cost-effective, and compatible with cloud services because future smart grid applications are expected to work in collaboration with other IP-based services, such as triple-play services and medical services.

D. System Concept

A simplified view of an integrated network control system is shown in Fig. 3. In this research, the interface between the resources and the platform, and the interface between the applications and the platform are designed so that they meet the above conditions. By using a formatted application-level message, a resource management server on the platform collects information on the infrastructure, sensors, and control, as well as other information regarding the configuration or specification of each component of a subsystem. This new scheme enables the flexible assignment of appropriate lower-layer protocols and standard technologies that fulfill each requirement.

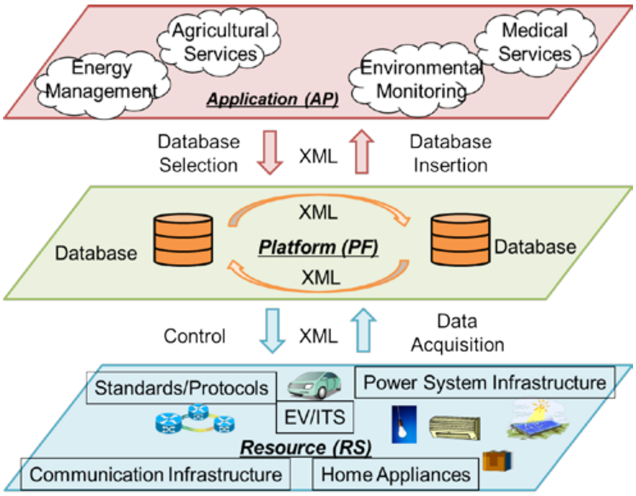

Fig. 3 Simplified view of the proposed system

E. Design of the Interfaces between Domains

This system is effective in collecting information from a diverse range of sensors, managing such information, then using it to control the electric devices. The system is comprised of an application (AP) domain, platform (PF) domain, and resource (RS) domain. In the AP domain, the user can manage and adapt the system using a wide variety of algorithms. In the PF domain, XML-based data exchange and acquisition are in operation. In addition, an I/O interface to the AP and RS domains is provided. All of the subsystems are included in the RS domain. The available subsystems are considered as wired/wireless communication infrastructure, electricity infrastructure (such as a photovoltaic generator and battery), environmental sensors, home information appliances, EVs, and so on.

The interfaces between the domains are defined as follows.

1) AP-PF Interface: The AP-PF interface is defined to realize database selection and insertion. For example, the applications access resource management servers on a platform using XML-based messages, and then obtain the sensor data from the resource management servers. In addition, the control data calculated by the applications are sent to the resource management servers by using XML-based messages.

2) RS-PF Interface: The RS-PF interface is defined to realize data acquisition and control. For example, the protocol converters collect the sensor data from the installed sensing devices, and then send them to the resource management servers on a platform using XML-based messages. In addition, the control data stored in the resource management servers are sent to the installed control devices by using XML-based messages.

3) PF-PF Interface: The PF-PF interface is defined to exchange data stored between databases. For example, the distributed resource management servers on a platform share EV battery information by using XML-based messages, and then provide navigation services to the drivers. In addition, database sharing makes it possible to provide virtualized cloud services.

With this concept, because the system can obtain a common platform and XML-based interface, new applications and new services are easily developed.

In this paper, an integrated network control system is conducted with a BEMS, and its applications utilizing a developed common platform are introduced. In the following section, the message description of the XML-based common platform is described.

III. THE COMMON PLATFORM

Message exchange between domain interfaces is conducted by XML. In this section, the common platform of the system is explained. First, the message description of the XML-based interface and message exchange method are described. Then, guidelines for defining each class of information are provided by taking a smart grid as an example.

A. Message Description

To exchange data through the RS-PF, AP-PF, and PF-PF interfaces, it is necessary to define the format of the XML-based message. Figure 4 provides examples of XML-based messages. The message through the RS-PF interface is shown in Fig. 4(a), and the message through the AP-PF interface is shown in Fig. 4(b).


```
<?xml version="1.0"?>
<inms>
  <head>
    <version> 1.0 </version>
    <id name="device"> 12345abc </id>
    <timestamp timezone="JST"> 2011-02-24 23:13:56 </timestamp>
  </head>
  <body>
    <group name="A01">
      <timestamp timezone="JST"> 2011-02-24 21:45:43 </timestamp>
      <in name="temperature" type="room" id="ABC" action="write"> Data </in>
      <in name="humidity" type="room" id="DEF" action="write"> Data </in>
    </group>
  </body>
</inms>
```


(a) **RS** → **PF**


```
<?xml version="1.0"?>
<inms>
  <head>
    <version> 1.0 </version>
    <id name="device"> 56789def </id>
    <timestamp timezone="JST"> 2011-03-14 03:42:53 </timestamp>
  </head>
  <body>
    <group name="A01">
      <timestamp timezone="JST"> 2011-03-14 03:41:45 </timestamp>
      <out name="temperature" type="room" id="ABC" action="read"> Data </out>
      <out name="humidity" type="room" id="DEF" action="read"> Data </out>
    </group>
  </body>
</inms>
```


(b) **PF** → **AP**

Fig. 4 Sample messages

The message starts with the definition of the version of XML. The message description is compliant with XML 1.0, released by W3C. For example, when the software in the AP domain requests data from the sensor in the RS domain, message exchange between interfaces will be performed in two stages. First, sensor data in the RS domain is written into the database in the PF domain via the XML-based interface. Second, on demand from the software in the AP domain, the sensor data are sent to the software from the database. Finally, the software in the AP domain accesses the sensor data in the RS domain via the database in the PF domain.

The message is comprised of a header element and a body element. Both the header and body elements are described between a start tag, <inms>, and end tag, </inms>.

- The Header Element

The header element is described between a start tag, <header>, and end tag, </header>. In the header element, descriptions of the format version, device ID, and time stamp is a mandatory requirement. The format version, device ID, and time stamp indicate the version of the message format, the ID of the message aggregator (e.g., the XML converter), and the aggregation time, respectively. The format version is described between a start tag, <version>, and end tag, </version>, with the current version being 1.0. The device ID is described between a start tag, <id name="device">, and end tag </id>. The time stamp is described between a start tag, <timestamp name="timezone">, and end tag, </timestamp>.

- The Body Element

The body element is described between a start tag, <body>, and end tag, </body>. The body element includes at least one group element, with the entire user data described between a start tag, <group name="group name">, and end tag, </group>. A nested structure of the group elements is allowed. In the group element, a description of the time stamp is mandatory, in the same way as in the header element.

Though the primary data, such as sensor data and control command, are described in the group elements, the data input into the PF domain are described between the start tag <in> and the end tag </in>, and the data output from the PF domain are described between the start tag <out> and the end tag </out>. The data name, class, terminal ID, and motion mode are assigned as the attribution. The data name is defined by the user as necessary.

B. *Message Exchange and Action Attribution*

As the action attribution of the <in> tag and <out> tag, the motion mode is defined with writing, read, ack, and transfer. For example, as shown in Fig. 5(a), when storing the data output from the RS domain or AP domain into the PF domain, the message with writing as the action attribution is sent to the PF domain. Similarly, as shown in Fig. 5(b), when the data are read from the PF domain to the AP domain, the message with read as the action attribution is sent to the PF domain and the PF domain returns the message with the ack as the action attribution to the AP domain. Illustrated in Fig. 5(c), when the data are transferred to the RS domain from the AP domain, the message with transfer as the action attribution is sent to the PF domain, and upon the PF domain storing the data, the PF domain transfers the message with write as the action message and it is sent to the RS domain.

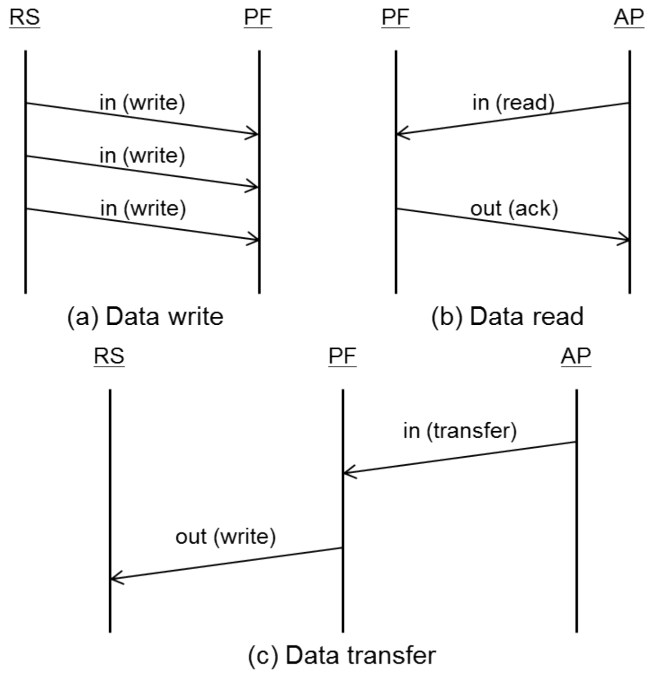

Fig. 5 The action attribution

IV. CONSTRUCTION OF AN EMS IN A PORT TERMINAL BUILDING

To substantiate the proposed system concept, the partial function of the common platform was implemented as the EMS. The Fukue-EMS (F-EMS) constructed at the Fukue Port Terminal building on Goto Island, Nagasaki Prefecture, provided a test bed environment for the proposed system. The Fukue Port Terminal building is a two-story facility with a floor area of 2330 m^2 and a volume of 341,345.5 m^3. The building includes a waiting lounge, tenant spaces, restaurants, and the port office. A photovoltaic power generator and a quick battery charger for the EV are located in a parking lot near the building.

The aims of this project were directed by the MIC as follows. Seven companies were included in this project.

- Formulate a system concept to enable the maintenance of interoperability between various systems.
- Construct an EMS as a test bed to substantiate the operation of the system.
- Achieve a minimum of a 10% reduction in carbon dioxide emissions through the application of the constructed system and its protocols to the control of air-conditioners, in accordance with MIC requirements.
- Develop a new application that utilizes the proposed system and highlights its availability.

A. System Composition

As a test bed environment, the system included the port terminal building, peripheral facilities, an EV, a quick battery charger for the EV, and a photovoltaic power generator. The constructed F-EMS manages the information generated by these facilities. The F-EMS consists of a resource management server, environmental sensors, electric power measurement instruments, EV, photovoltaic power generator, and the quick battery charger for the EV. These resources can be considered as subsystems. Fig. 6 shows the whole system. Each subsystem supports different standard technologies, applications, and services as defaults. With this, a common platform could not be achieved. Therefore, we described all communications between them using the proposed XML format. The structure of the subsystems is shown in Fig. 4. Every subsystem was constructed by a different company. The participating companies that provided the subsystems are shown in Table I.

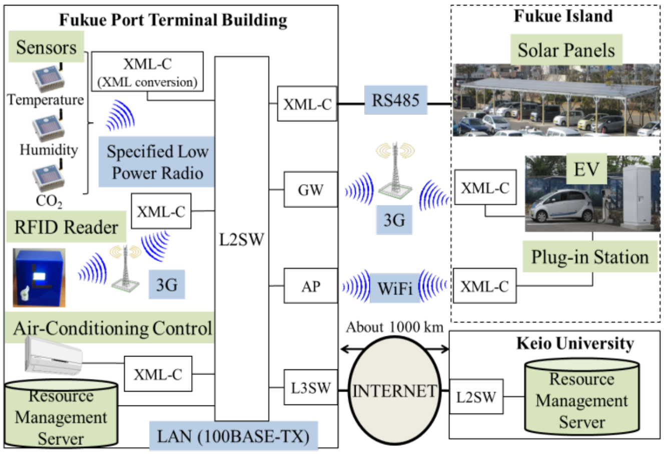

Fig. 6 Constructed system

TABLE I PARTICIPATING COMPANIES OF THE SYSTEM

Subsystem	Participating Company
Photovoltaic power generator	Mitsubishi Heavy Industries, Ltd.
Terminal environment	Seiko Instruments Inc.
Indoor environment of EV	Seiko Instruments Inc.
Drive history of EV	Hitachi Information & Communication Engineering, Ltd. KDDI Corporation
Quick battery charger for EV	KYUKI Corporation
Consumed electric power of outlet	Panasonic Electric Works Co., Ltd.
Consumed electric power of air-conditioner	Yakey Co., Ltd

The air-conditioner control system was used as the main control target in this system. A wireless environment measurement system was installed to monitor the target. This consisted of sensors located at 25 points in the building to monitor temperature, humidity, air flow, illumination, motion, and carbon dioxide concentration. Electric power measurement sensors monitored the real-time electric power consumption at over 230 points. The system measures the received electric power, electric power generated by the photovoltaic power generator, power consumed by the air-conditioner, outlets, electric power engine, while the lights are independently measured. The driving history and indoor environment of the EV are also measured and stored in the central database. The sampling interval was 5 s, and two million data entries can be inserted into the database. Each subsystem is explained in the following sections.

B. Environmental Measurement System

Wireless environmental sensors were installed to measure the internal conditions of the building. The wireless sensor system consists of sensor nodes, bases, and a router. Some sensor nodes are operated using their own photovoltaic panel. The size of these nodes is 8 cm × 8 cm × 2 cm. Each sensor node sends data measurements to the base and router. The base module of the wireless sensor node communicates with a network connection device via RS232C. The device translates transportation data into the proposed XML format. The data are then sent to the resource management server. The environmental sensors were distributed throughout the building, restaurants, tenant spaces, offices, and waiting lounge. The external environment of the building was also measured. The system measures humidity, temperature, and other environmental factors so that it can precisely determine the indoor conditions using a predicted mean vote (PMV). Thus, the wireless sensor network can be used to control the air-conditioning based on environment conditions, such as discussed in [11].

C. Electric Power Measurement System

The electric power measurement system measures the power consumption of the receiving point, air-conditioner, electric power engine, lighting devices, outlets, photovoltaic power generator, quick EV battery charger, and EV battery. A total of 230 points were used in the electric power measurement system.

Power consumption by the air-conditioner was measured by units installed in the air-conditioner compressor. Power consumption of the receiving point was measured using a pulse sensor.

The photovoltaic power generator was placed in the building's car park. This generator consists of panels, a power conditioner, an actinometer, and a temperature meter. The power generator was connected to the secondary side of the receiving point. Data from the generator are measured via the power conditioner using a measurement unit. The measurement sampling interval was 10 s.

Power consumption by the outlets, electrical power engines, and lights were measured by a network distribution board in compatible measurement units.

Data from the EV quick battery charger were measured using a dedicated controller module. The module sends data to the resource management server. The data are collected every time the quick charger is used.

All of the measured data were then translated into the proposed XML format and sent to the resource management server.

D. Measurement of Driving History and Internal EV Conditions

The network-connected device sends data in XML format, based on GPS positioning data measured by a GPS receiver, and sends it to the resource management server through a public network.

Internal EV conditions are also measured using environmental sensors. The internal condition measurement system utilizes the same wireless sensors as the environmental measurement system. It measures temperature, humidity, carbon dioxide concentration, illumination, and wind velocity. The sampling interval of the measurement was 60 s, and the data were sent through the public network. These data were utilized to predict EV battery usage and mileage.

This system has several heterogeneous subsystems. It operates as a test bed environment for the proposed XML format, confirming the availability of the proposed common platform, which forms the basis of the proposed concept of the system. Measuring power consumption allows the property demands of the building to be determined. Utilizing information for real-time power usage and environmental data allows applications to manage load control for the building by showing their availability through the integrated resource management system, thus ensuring the interoperability of the system. The following section describes how this is achieved using a unified format. The chosen format is based on the proposed concept of the system.

V. APPLICATION TO AIR-CONDITIONER CONTROL

Utilizing the constructed system and handling data with the common platform facilitates the development of various applications. The proposed air-conditioner controller is described in this chapter as an application of the established system. The air-conditioner controller controls an air-conditioner installed in the terminal building to reduce carbon dioxide emission. It provides a demonstration of an application developed with the common platform. We selected reduction in carbon dioxide emission to evaluate the system because the application controls two types of air-conditioner, i.e., an all-in-one air-conditioner using electric power and an air-conditioner using oil.

A. Installation of the Air-Conditioner Control System

Using the common platform and proposed XML-based interface makes it easier to construct an air-conditioner control system compared with conventional systems. This is because the application design simply uses the proposed format for the new system to implement a new application, with no concern for the differences in devices, as shown in Fig. 3. Various air-conditioner control systems that integrate with network systems have been proposed [12]. These conventional methods only propose an environment based on the experimental environment, so expansion and implementation of the system into actual operation in a real environment are out of their scope. Therefore, previous systems must be viewed as intrinsic systems. The air-conditioner control system proposed in this research is superior to conventional methods because we can expand the implementation to an existing integrated network system, containing subsystems from several different companies.

The constructed air-conditioner controller operates as follows. First, the control schedule of the air-conditioner is designed by a resource management server. This controller can be designed by issuing a standardized XML message to send commands to the air-conditioner, or by directly inserting or updating a table entry in the central PostgreSQL database. The server then sends a control command to the air-conditioner controlling device. The air-conditioner controlling device switches its relay in accordance with the command given by the air-conditioner control.

B. Control Method of the Air-Conditioners

As the control algorithm, we employed the method developed in the research described in [9–11]. To reduce the carbon dioxide emissions by the air-conditioner, the air-conditioner was turned ON/OFF by the static algorithm and dynamic algorithm. In the case of the static algorithm, the air-conditioner is turned ON/OFF based on a prepared schedule. On the other hand, in the case of the dynamic algorithm, the air-conditioner is turned ON/OFF based on measured data, such as environmental information.

C. Experiment Results

Changes in the power consumption of the all-in-one air-conditioner located in the Goto City Tourism Association office on January 17 are shown in Fig. 7. The blue and red lines indicate energy consumption per minute and the control commands, respectively. When the control command was ON, the control device forcibly turned off the air-conditioner. Energy consumption was 0 Wh when the control command was ON. The air-conditioner began peak temporal energy consumption after several minutes and this behavior was repeated throughout the experiment. A similar trend to this was observed for the amount of oil consumed, controlled by the oil-based air-conditioner.

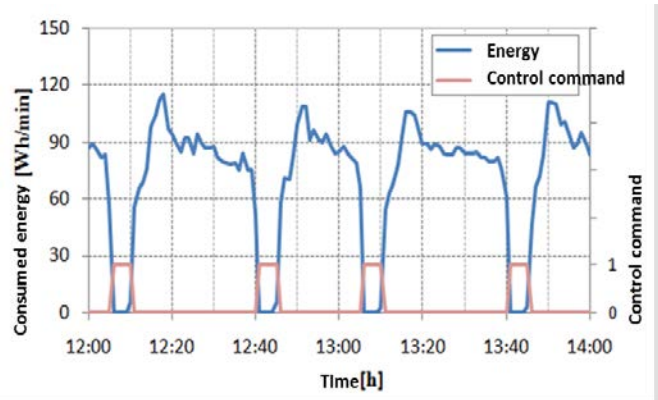

Fig. 7 Power consumption by the air-conditioner

Changes in temperature at the Goto City Tourism Association office on January 17, 2011 are shown in Fig. 8. The temperature started to drop about 3 min after control commenced. Thus, the control system influenced the environment. This falling temperature may have been caused by a low external temperature.

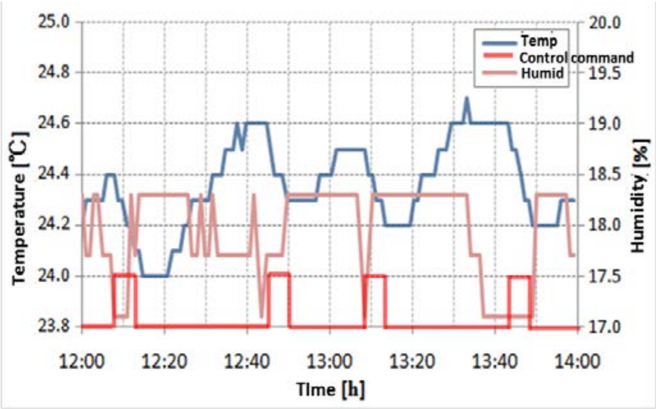

Fig. 8 Office temperature and humidity with control

D. *Evaluation of the Air-conditioner Controller*

The reduction in carbon dioxide emissions with the application was evaluated. A questionnaire survey was conducted with terminal building users to evaluate the environmental conditions.

The reduction in carbon dioxide emissions was calculated by multiplying the reduction in energy resources consumed by the carbon dioxide coefficient. The reduction was converted according to the energy resource used by the target air-conditioner, i.e., the electrical power or oil. The carbon dioxide coefficient was calculated for electricity or oil. Each questionnaire was conducted on the days of the experiment and days without control. The sample comprised of 23 users who worked the building. Thermal comfort was evaluated with five levels. 0 indicated that the participants experienced the best level of comfort. 1 and 2 indicated that they felt discomfort because of heat. –1 and –2 indicated that they felt discomfort because of cold. The questionnaire allowed us to determine how the participants felt about the environment when the air-conditioner control was active.

E. *Evaluation Results*

Table II shows the actual reduction in carbon dioxide emissions experienced compared to when the conditions were not controlled. Total carbon dioxide emissions were calculated based on the energy consumption of the controlled air-conditioner. The reduction in carbon dioxide emissions increased with an increase in the configured cut rate. There was a difference observed between January 17 and 19 in the amount of the cut emissions, even though the configured cut rate was the same. Carbon dioxide emissions may be more efficiently reduced if the parameter settings are better adjusted.

TABLE II EVALUATION RESULTS

Date of January	13	17	19	21
Total CO_2 emission [kg]	287.31	310.87	281.75	271.53
Cut CO_2 emission [kg]	9.11	20.99	26.4	36.44
Achieved cut rate [%]	3.17	6.75	9.37	13.42
PMV	−0.48	−0.44	−0.43	−0.29
Outside temperature [°C]	3.4	3.7	4.9	5.8

Results of the questionnaire are shown in Table III. Most participants felt comfortable or a slight discomfort due to cold. Though the experiment took place on January 17 and 19, i.e., when the air-conditioner control was active, the answers were almost the same as those gathered for January 18 and 20 when the air-conditioner control was inactive. Thus, the comfort level reported by users had no connection, or a very weak connection, to the air-conditioner control.

TABLE III RESULTS OF THE QUESTIONNAIRE

Date	**Comfort level**				
	-2	-1	0	1	2
	Participants				
January 17, 2011	2	7	12	0	0
January 18, 2011	3	6	12	1	0
January 19, 2011	1	6	12	2	0
January 20, 2011	2	6	12	1	0

The capability of the air-conditioner controller to operate on a common platform and its effects are demonstrated. The application reduced the total carbon dioxide emissions by about 10% on this site. According to the questionnaire, it was also found that the comfort level experienced by users showed no significant relationship to the control of the air-conditioner.

In the following section, to show the availability of the project, the experimental combination of air-conditioner control and battery use is achieved by expanding this application to the building, utilizing real-time simulation for leveling the load.

VI. APPLICATION TO ELECTRIC-LOAD LEVELING

In this section, to more effectively utilize the air-conditioner control system described in Section V, a combination of battery use and air-conditioner control for electric-load leveling is proposed. Though the battery is used for electric-load leveling, the battery is not actually installed in the building. Since we conducted the experiment by emulating the battery through real-time simulation, the system latency and response in the real environment are reflected in the results of the experiment. In the experiment, the power consumption of the air-conditioners is chosen as the electric-load. Though the power consumption of the receiving point is chosen as the electric-load generally, since to reflect the air-conditioner control into the result, we chose the power consumption of the air-conditioners.

A. *Electric-Load Leveling with a Battery and Air-Conditioner Control*

In Japan, the demands for large power consumers, such as factories and buildings, to save energy are growing because of the limited power supply caused by the Great East Japan Earthquake. More particularly, there have been inevitable requests for cuts and shifts in peak demand. Electric-load leveling can realize these requests by installing a battery.

Electric-load leveling has been researched in relation to vehicle-to-grid (V2G) technologies [13–15]. These studies indicate that EVs have great potential for solving the present problems faced by the power grid.

The concept of electric-load leveling with a battery and air-conditioner control is shown in Fig. 9. The battery charges the power when the electric-load is lower than the leveling set point, and discharges the power when the electric-load is higher than the leveling set point. In addition, the conduct of the air-conditioner control depends upon the state of the battery, with a lowering of the charging/discharging power of the battery sought. As a result, we endeavored to achieve a more effective electric-load leveling. The peak shift with the battery and peak cut with the air-conditioner control are endeavored to be combined.

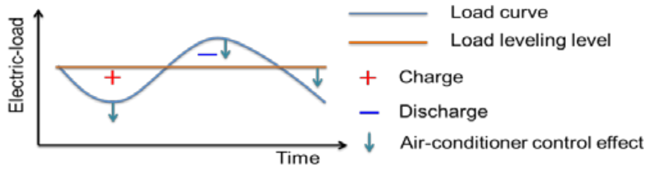

Fig. 9 The concept behind the application

B. *Real-Time System Simulation with Battery Emulation*

In the F-EMS project, a simulation model of the electrical power system of the Fukue Port Terminal building had already been developed and evaluated in [16] using Matlab/Simulink. The research also developed a simulation model for a general commercial battery. What discussed in [16] is the utilization of an EV's battery as V2G technology in the Fukue Port Terminal building for load leveling. Since the model developed in [16] used the SimPowerSystems library of Matlab/Simulink, terms such as loss of power transmission and loss of battery charge/discharge are calculated using the model. Therefore, the model is approximately equivalent to the real environment.

In this paper, a real-time system simulation to emulate the use of a battery is constructed using the models developed in [16]. In addition, the constructed system is connected to the actually operating F-EMS in order to experiment with electric-load leveling for air-conditioner control and battery use.

The real-time system simulation is shown in Fig. 10. As mentioned in Section IV, the real experimental system was implemented at the Fukue terminal in Nagasaki Prefecture while the emulating battery controller and demand control center were implemented at Keio University in Kanagawa Prefecture. The distance between these two locations is about 1,000 km. As described in Sections II and III, the real-time system simulation acts as the application of the F-EMS, utilizing the established common platform. Therefore, the real-time system simulation belongs to an AP domain. Since the exchange of data occurs via the proposed XML-based interface described in Section III, the real-time system simulation can directly and easily connect to the PF domain.

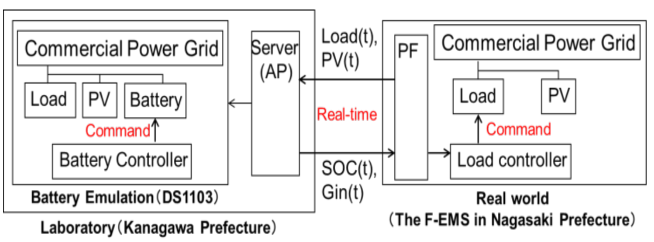

Fig. 10 Real-time simulation system

To use the virtual battery in real-time, a DS1103 control board (produced by dSPACE Inc.) was utilized for rapid control prototyping. On this device, the simulation model can be performed sequentially in the order of milliseconds. In addition, this particular type of control board has serial ports for data I/O with the real environment. The battery model and the model of the electrical power system of the Fukue Port Terminal building were implemented on this device board. It provided feedback of the measured power consumption of the load (labeled Load in Fig. 10) from the building to the device in real-time. Then, the device calculated the power consumption of the battery (labeled Gin in Fig. 10). The device provided feedback on the power consumption data to the common platform in order to use the calculated power consumption to control the air-conditioners. In this way, we realized a real-time system simulation for attaining a remote virtual battery in the real building. We also confirmed that the communication and calculation delay is about 5 ms in total, and that this delay can be negligible in this simulation.

C. *Method of Controlling the Air-Conditioners*

As the control constraint, the integral values of the power consumption for every 30 min were controlled so that their amounts were equivalent in each time period. In Japan, to evaluate electric-load leveling, this amount should adhere to the Electricity Enterprises Law. We separated each 30 min period into 2 phases, and the air-conditioner controller calculated the increase in power consumption over the first 15 min. Then, the controller balanced out this increase by controlling the air-conditioners over the following 15 minutes. The control method is summarized in Fig. 11. For example, if the increase in power consumption, d_Gin, was 900 W, the integral power consumption of 15 min (Area X) became 150 Wh. Therefore, for the following 15 min, the air-conditioners were controlled to balance out 150 Wh (Area Y). The control target was chosen based on the dynamic algorithm described in Section V. The index used in this experiment was PMV. The PMV is an index for evaluating environmental amenity. The air-conditioner controller calculates the PMV of each room from the measured environmental data, and controls the air-conditioners according to the PMV through consideration of the demand for electric power and the virtual battery. The air-conditioner of the most comfortable room is chosen to control the OFF setting. The choice of control target process continued until the sum of the power consumption of the control target reached 150 Wh. For the battery control, the fuzzy logic described in [16] was utilized.

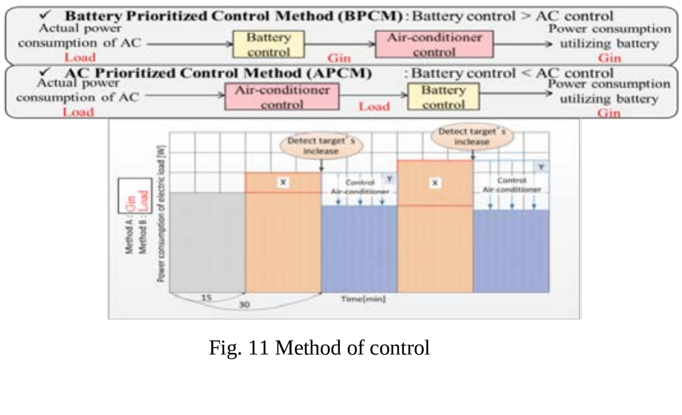

Fig. 11 Method of control

In the present experiment, in order to compare results, we conducted the following two patterns of control method:

- Control Method A : Battery Prioritized

The summation of power consumption utilizing the virtual battery (Gin) is considered as the detecting target. In this control method, the battery control is used prior to the air-conditioner control for total demand leveling.

- Control Method B : AC Prioritized

The actual power consumption of the air-conditioners (Load) is considered as the increasing factor. In this control method, the air-conditioner control occurs prior to the battery control.

D. Results of the Experiment

The experiment was conducted in the Fukue Port Terminal building during December 2011. In this experiment, to lucidly confirm the effect of the air-conditioner control, the power consumption of the air-conditioners was chosen as the target for electric-load leveling. The summary of the experiment is shown in the Table IV. The result of the experiment on December 12, 2011 is shown in Fig. 12. From the Fig. 12, we can see that the peak shift and peak cut are achieved.

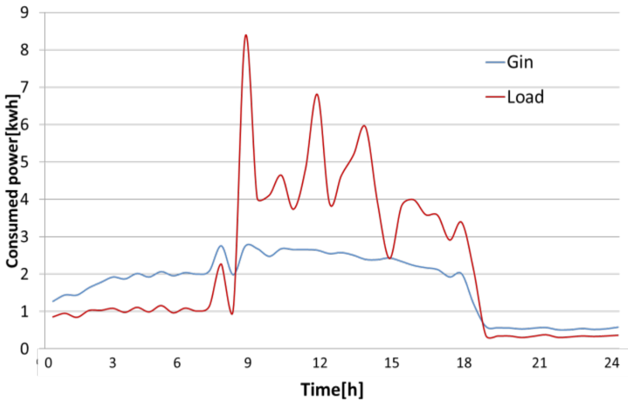

Fig. 12 The result of the experiment conducted on 2011/12/12

TABLE IV EXPERIMENT SUMMARY

Control Method	Air-Conditioner Control	Month/Day of the Experiment
A	With	12/5, 12/9, 12/12, 12/14, 12/16, 12/19
	Without	12/8, 12/10, 12/11, 12/13, 12/15, 12/17, 12/18
B	With	12/21, 12/22, 12/24
	Without	12/20, 12/23, 12/27, 12/28, 12/29, 12/30, 12/31

The experiment was evaluated by managing the system over a long time period. During the experimental period, there were days where there was air-conditioner control, and there were days where there was no control. Therefore, comparisons of the control method and system were conducted for a long-term operation. The evaluation terms in Table V denote the battery's average state of charge (SOC_ave), the average power consumption utilizing the virtual battery (Gin_ave), the Gin's coefficient of variance (Gin_CV), the average of the actual power consumption of the air-conditioners (Load_ave), the average temperature of the day (T), and the average PMV of each room air-conditioner that was installed. The results are shown in Tables V to VIII. The values in Table VII to VIII are the average over all experiment days, grouped as either with or without air-conditioner control.

TABLE V RESULTS OF THE EXPERIMENT WITH CONTROL METHOD A

Day	SOC_ave.	Gin_ave [kW]	Gin CV	Load_ave [kW]	PMV	T [°C]
5	78.9	0.69	93.29	0.94	0.21	12
8	81.0	0.76	48.92	0.74	0.13	11
9	72.7	1.94	53.91	4.81	-0.13	7
10	63.0	1.66	53.92	2.35	-0.27	8
11	60.1	1.86	26.47	3.71	-0.28	9
12	53.8	1.84	44.41	2.84	-0.17	11
13	50.8	1.64	45.41	1.98	-0.06	12
14	53.3	1.19	53.97	1.42	0.09	12
15	54.9	1.93	38.06	2.92	0.00	10
16	42.5	2.38	31.75	5.68	-0.22	6
17	24.1	2.82	13.16	5.73	-0.26	6
18	19.1	3.26	7.87	4.78	-0.27	9

TABLE VI RESULTS OF THE EXPERIMENT WITH CONTROL METHOD B

Day	SOC ave.	Gin_ave [kW]	Gin CV	Load_ave [kW]	PMV	T [°C]
19	39.7	4.77	20.78	4.19	-0.23	8
20	52.5	3.02	26.73	4.71	-0.25	7
21	62.1	3.10	57.03	3.77	-0.18	9
22	67.5	2.76	50.77	4.36	-0.29	8
23	64.0	3.18	56.32	5.26	-0.40	6
24	63.3	3.75	54.98	6.69	-0.46	6
28	80.2	3.82	63.05	5.76	-0.43	7
29	83.0	3.02	50.54	4.87	-0.30	10
30	86.9	1.88	46.48	2.34	-0.29	9
31	77.4	2.96	45.03	6.06	-0.27	9

TABLE VII RESULTS OF THE EVALUATION VALUE GROUPED BY WITH AND WITHOUT AIR-CONDITIONER CONTROL (CONTROL METHOD A)

AC control	SOC_ave	Gin_ave [kW]	Gin_CV	Load_ave [kW]	PMV	T [°C]
With	60.3	1.6	55.5	3.1	-0.04	9.6
Without	50.4	2.0	33.4	3.2	-0.14	9.3

TABLE VIII RESULTS OF THE EVALUATION VALUE GROUPED BY WITH AND WITHOUT AIR-CONDITIONER CONTROL (CONTROL METHOD B)

AC control	SOC_ave	Gin_ave [kW]	Gin_CV	Load_ave [kW]	PMV	T [°C]
With	58.1	3.6	45.9	4.8	-0.29	7.8
Without	74.0	3.0	48.0	4.8	-0.32	8.0

From Load_ave, it can be said that with air-conditioner control, both control methods can achieve a cut in the load. From Gin, different tendencies are observed between the two control methods. For example, from the Gin and Gin_Cv observed with Control Method A, it can be said that the electric-load level was reduced when the air-conditioning was controlled compared to when it was not. However, the fluctuation in the load was larger in the former compared to the latter situation. This means that though air-conditioner control can reduce the power consumption, it affects the fluctuation in the electric-load suppression by the battery. Under Control Method B, from Gin and Gin_CV, it can be said that though the leveling of the electric-load was less effective with control than without, the load fluctuation is improved. This means that though the air-conditioner control affects the electric-load leveling by the battery, it assists the fluctuations in electric-load suppression. Therefore, from these results, the advantage of the use of an air-conditioner controller for electric-load leveling is dependent upon the way the air-conditioner control and battery control are combined. If the battery control occurs prior to the air-conditioner control, the fluctuation in the electric-load is improved compared to when there is no control of the air-conditioner. If the air-conditioner control occurs prior to the battery control, the power consumption is improved compared to when there is no control of the air-conditioner.

In the future, we can calculate on not only the air-conditioners but also the other electric devices will be control targets. Therefore, this application will be utilized for the electric-load leveling of power consumption of the receiving point. In this paper, the model case of the application is demonstrated.

VII. CONCLUSION

A common platform was constructed based on a proposed concept system using XML format. It maintained interoperability between heterogeneous systems. The EMS constructed at the Fukue Port Terminal building in Goto City, Nagasaki Prefecture provided a test bed environment for the proposed system and common platform. The EMS included heterogeneous subsystems comprised of various devices produced by seven different companies. Though the system included various heterogeneous subsystems, it was constructed in a short timeframe using the proposed XML format and operated as a single integrated system. Operation of the EMS and management of the data that it measured confirmed that the system maintained interoperability between heterogeneous systems via a common platform.

An air-conditioner controller was developed and successfully demonstrated as an application of the common platform. The experimental results showed that the system reduced carbon dioxide emissions by 10%.

Finally, electric-load leveling experiments were conducted using real-time system simulations of a battery. The system was constructed by developing the application based on the previously described system concept. The experimental results showed that installation of the battery and air-conditioner control was effective for electric-load leveling.

ACKNOWLEDGMENT

This study was partially supported by the Ministry of Internal Affairs and Communications (MIC), the Ministry of the Environment (MOE), and the Special Coordination Funds for Promoting Science and Technology.

REFERENCES

[1] F. Li *et al*., "Smart Transmission Grid: Vision and Framework," *IEEE Trans. Smart Grid*, vol. 1, no. 2, Sep. 2010, pp. 168–177.

[2] IEEE Std P2030-Dt.0, "Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads," Mar. 2011.

[3] C.H. Hauser *et al*., "Security, Trust, and QoS in Next-Generation Control and Communication for Large Power Systems," *Int. J. Critical Infrastructures*, vol. 4, no. 1/2, Jan. 2008, pp. 3-16.

[4] V.C. Gungor *et al*., "Opportunities and Challenges of Wireless Sensor Networks in Smart Grid," *IEEE Trans. Ind. Election*., vol. 57, no. 10, Oct. 2010, pp. 3557–3564.

[5] D. Niyato *et al*., "Machine-to-Machine Communications for Home Energy Management System in Smart Grid," *IEEE Commun. Mag.*, vol. 49, no. 4, Apr. 2011, pp. 53–59.

[6] Z.M. Fadlullah *et al*., "Toward Intelligent Machine-to-Machine Communications in Smart Grid," *IEEE Commun. Mag.*, vol. 48, no. 11, Nov. 2010, pp. 58–65.

[7] Y.-J. Kim *et al*., "A Secure Decentralized Data-Centric Information Infrastructure for Smart Grid," *IEEE Commun. Mag.*, vol. 48, no. 11, Nov. 2010, pp. 58–65.

[8] B. Lu *et al*., "Research on Heterogeneous Data Integration for Smart Grid," *Proc. IEEE ICCSIT'10*, Jul. 2010, pp. 52–56.

[9] Y. Suhara *et al*., "Distributed Demand Side Management System for Home Energy Management," *Proc. IEEE IECON'10*, Nov. 2010, pp. 2430–2435.

[10] Y. Kamiyoshi *et al*., "Construction of Energy Measuring System in a University for Cluster Energy Management System," *Proc. IEEE IECON'10*, Nov. 2010, pp. 2423–2429.

[11] T. Nakabe *et al*., "Environmental-Amenity Aware Controller for Demand Side Management," *Proc. IEEE INDIN'10*, Jul. 2010, pp. 798–803.

[12] K. Katabira *et al*., "Real-Time Monitoring of People Flows and Indoor Temperature Distribution for Advanced Air-conditioning Control," Proceedings of the 11th International IEEE Conference on Intelligent Transportation System, Oct. 2008, pp. 664–668.

[13] S. Huang *et al*., "The Potential of Domestic Electric Vehicles to Contribute to Power System Operation through Vehicle to Grid Technology," *Universities Power Engineering Conference (UPEC), 2009 proceedings of the 44th international*, Sep. 2009, pp. 1–5.

[14] P. Kadurek *et al*., "Electric Vehicles and their Impact to the Electric Grid in Isolated Systems," *Power Engineering,*

Energy and Electrical Drives, 2009. POWERENG '09. International Conference on, March. 2009, pp. 49–54.

[15] P. Mitra *et al.*, “Wide Area Control for Improving Stability of a Power System with Plug-in Electric Vehicles,” *Generation, Transmission & Distribution, IET*, Oct. 2010, pp. 1151–1163.

[16] M. Ihara *et al.*, “A Simulation Study of Electric Power Leveling Using V2G Infrastructure,” *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, Nov. 2011, pp. 3224–3229.

Tianmeng Shen received the B.E. degree in system design engineering from Keio University, Japan, in 2011. He is currently working toward the M.E. degree in science for open and environmental systems at Keio University, Japan.

Daichi. Kawashima received the B.E. degree in system design engineering from Keio University, Japan, in 2011. He is currently working toward the M.E. degree in science for open and environmental systems at Keio University, Japan.

Ryogo Kubo received the B.E. degree in system design engineering and the M.E. and Ph.D. degrees in integrated design engineering from Keio University, Japan, in 2005, 2007, and 2009, respectively. In 2007, he joined the NTT Access Network Service Systems Laboratories, NTT Corporation, Japan. Since 2010, he has been with the Department of Electronics and Electrical Engineering, Keio University, Japan, where he is currently a Research Associate.

Masaru Ihara received the B.E. degree in system design engineering from Keio University, Japan, in 2011. He is currently working toward the M.E. degree in science for open and environmental systems at Keio University, Japan.

Toshiro Togoshi received the B.E. degree in system design engineering from Tokyo Metropolitan Technical College, Japan, in 1969. In 2969, he joined NEC Corporation, Japan. Since 2010, he has been with the Green Society ICT Life Infrastructure Research Center, Keio University, Japan, where he is currently a Researcher.

Hiroaki Nishi received the B.E., M.E., and Ph.D. degrees in system design engineering and the M.E. and Ph.D. degrees from Keio University, Japan, in 1994, 1996, and 1999, respectively. He was Researcher with Real World Computing Partnership, and the Central Research Laboratory, Hitachi Ltd., Japan. Since 2002, he has been with the Department of System Design Engineering, Keio University, Japan, where he is currently an Associate Professor.