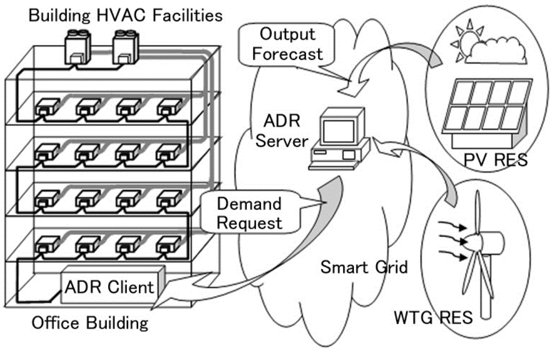
New Fast Demand Control of Building HVAC Facilities for Smart Grid



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Real-time, fast demand control is thought to be promising technology to compensate for highly variable renewable energy sources for the smart grid of the future. Recent HVAC(Heating Ventilation and Air-Conditioning) facilities for buildings (hereinafter air-conditioning systems) use sophisticated refrigerant flow control devices and Mitsubishi Heavy Industries, Ltd. (MHI) would like to propose quick-response (approx. 5 minutes), fast demand control (hereinafter new fast demand control) to replace existing on-off and coarse slow demand controls.It is, however, cumbersome due to the great complexity in controlling building HVAC systems. As a solution to this, we considered the use of a numerical formula model for statistical prediction to calculate the amount of electricity need five minutes in the future. Operational testing using a numerical formula model successfully proved the effectiveness of new, fast demand control.

1. Introduction

It is expected that the smart grid of the future will be closely interconnected with photovoltaic power generation systems or wind turbine generators, which use renewable energy sources. Such sources are also known for the fact that their output voltage fluctuates, depending upon momentary climate changes(1)-(3). Although it is possible to compensate for such fluctuations by using batteries with huge capacities, if future large-scale interconnection of renewable energy sources is assumed, it is easily conceivable that this will require an inordinate cost. In order to compensate for highly variable renewable energy sources without depending upon batteries alone, efficient fast demand control is one of the most effective solutions.[4-8]

In the smart grid field, office building air-conditioning systems are well known as an effective means to implement demand-side power control. Demand control of building air-conditioning systems has also been widely studied so far. In addition, there have been a number of research studies about demand control using a numerical formula model for statistical prediction (AR model).[9-12]

Contrary to this, research publications for quick (e.g., 5-minute intervals) prediction and control of the power consumed by building air-conditioning systems are scarce. The control mechanism of many predictive numerical formula models and control methods was based mainly on power on-off operation, consuming a long average time. Many researchers point out the necessity of quick-response demand control for future real-time power rate calculation and dynamic demand control.[13-19]

Office building HVAC systems[20] are prevalent in mid-sized buildings in Japan, as well as in countries in Asia, Europe and elsewhere. HVAC systems use a sophisticated refrigerant flow control device and it is considered possible to embody new, fast demand control by allowing this

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refrigerant flow control device to continuously change its operation.

This paper proposes a mechanism of new fast demand control for building HVAC systems. An AR model for the power consumed (every five minutes) by building HVAC systems will be developed from field test data, and prediction and control computation will be carried out through simulations executed by cloud computing. It is considered that the new fast demand control mechanism will be one of the mechanisms to balance supply and demand in real time in the smart grid of the future including interconnected renewable energy sources.

2. Demand control of buildings for the smart grid of the future

Figure 1 conceptualizes the new fast demand control of building air-conditioning systems for the smart grid. The figure contains only one building, but the control of many buildings may actually be possible. A gateway possessing an ADR (Automated Demand Response) client function communicates with DRAS (Demand Response Automation Server) to compensate for the momentary power fluctuations of renewable energy sources.

Our goal is to avoid exclusive dependence upon batteries for compensating for power fluctuations, that is, to develop equipment which quickly responds pursuant to new fast demand control.

A typical building HVAC system is composed of several outdoor and a large number of indoor units. In the cooling cycle of an air conditioner, outdoor units are equipment which allows refrigerant to condense, and indoor units are equipment which allows refrigerant to vaporize. Outdoor units are typically installed on the roof, and indoor units are buried in the ceiling of each room. Power for the system is supplied to the outdoor units. Using the power supplied, outdoor units compress refrigerant and distribute it to the indoor units. Typical building air-conditioning systems have a thermal inertia on the order of 3 minutes. Time-granularity control of 3 minutes or less is, therefore, meaningless. Further taking the resolution of the watt-hour meter's pulse count into account, this paper considers it appropriate to use control intervals of 5 minutes.

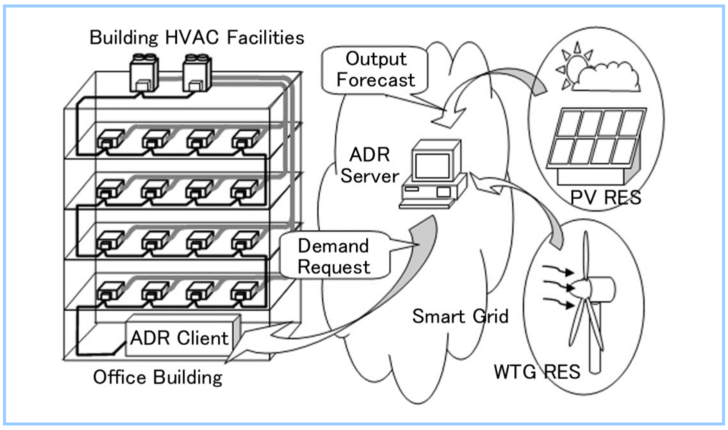


Figure 1 Structural diagram of building air-conditioning systems to realize new fast demand control

Figure 2 is a conceptual diagram of the refrigerant circuit in an HVAC system. The outdoor unit has a built-in inverter-driven compressor, heat exchanger, and controller. Each indoor unit has a built-in heat-exchanger, supply fan, electronic expansion valve (EEV), and controller. Indoor units regulate the electronic expansion valve to adjust refrigerant flow to the heat exchanger in conformity to the thermal load in the room.

Each indoor unit periodically transmits the required amount of flow to the outdoor unit. The outdoor unit periodically puts together these requirements to regulate the total amount of flow by altering the number of revolutions of the compressor. Thereafter, the outdoor unit distributes the corresponding amount of flow to each indoor unit. Each indoor unit regulates the opening position of the electronic expansion valve, using the value of the corresponding flow amount. The gateway responds to the demand from DRAS for demand control. Moreover, it communicates with each unit to assign an order of priority to the indoor unit, which regulates the opening position of expansion valve.

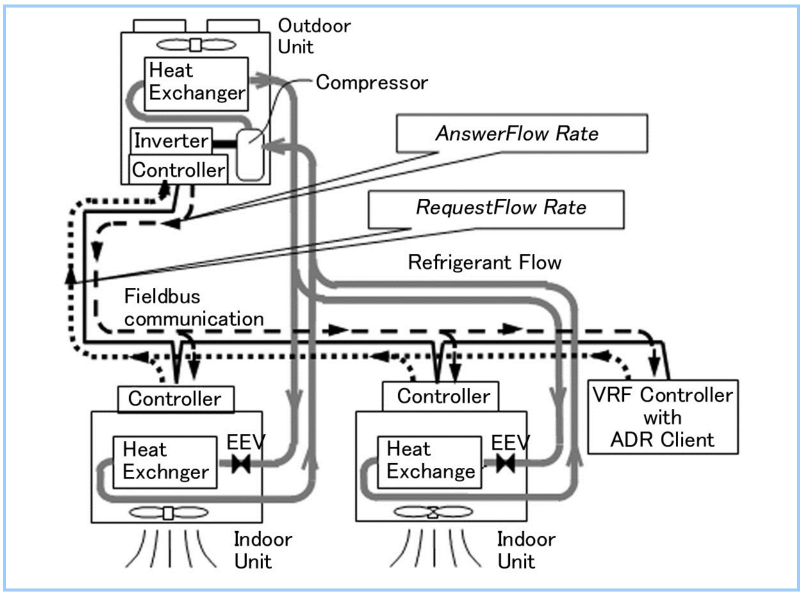


Figure 2 Structural diagram of HVAC facility refrigerant circuit control

3. Quick-response AR model

The AR model we propose uses 4 state variables. That is, momentary power consumption $P_{A5}(k)$, outdoor temperature $T_{O5}(k)$, temperature set from the weighted average of the nominal capacities of indoor units $T_{S5}(k)$ and total amount of 5-minute refrigerant flow $F_{R5}(k)$. The AR model system equation adopting these state variables is defined in Formula (1).

$$\begin{bmatrix} P_{A5}'(k) \\ * \\ * \\ * \end{bmatrix} = \sum_{l=1}^{L} \begin{bmatrix} A^{(l)}{}_{11} & A^{(l)}{}_{12} & A^{(l)}{}_{13} & A^{(l)}{}_{14} \\ A^{(l)}{}_{21} & A^{(l)}{}_{22} & A^{(l)}{}_{23} & A^{(l)}{}_{24} \\ A^{(l)}{}_{31} & A^{(l)}{}_{32} & A^{(l)}{}_{33} & A^{(l)}{}_{34} \\ A^{(l)}{}_{41} & A^{(l)}{}_{42} & A^{(l)}{}_{43} & A^{(l)}{}_{44} \end{bmatrix} \begin{bmatrix} P_{A5}(k-l) \\ T_{O5}(k-l) \\ T_{S5}(k-l) \\ F_{R5}(k-l) \end{bmatrix} + \begin{bmatrix} U_{PA5}(k) \\ U_{TO5}(k) \\ U_{TS5}(k) \\ U_{FR5}(k) \end{bmatrix} \qquad \text{Formula (1)}$$

Where k represents the integer value to be counted every five minutes; l, the integer value of expressed delay; L, AR model order; $A^{(l)}{}_{11}$, $A^{(l)}{}_{12}$, … , $A^{(l)}{}_{44}$, elements of the AR coefficient matrix; and $U_{PA5}(k)$, $U_{TO5}(k)$, $U_{TS5}(k)$, $U_{FR5}(k)$, prediction errors. $P_{A5}'(k)$ means the predicted value of 5 minutes-later power consumption.

First, a unique state variable $F_{R5}(k)$ which indicates the total amount of refrigerant flow is expressed in Formula (2).

$$F_{R5}(k) = \sum_{n=1}^{N} \sum_{m=1}^{M} F_{Rn}(t_m) \qquad \text{Formula (2)}$$

Where $n = 1, 2, \cdots, N$ is the number of indoor units, and $t_m = t_1, t_2, \ldots, t_M$ represents 5-minute measuring/sampling time. For example, if M=5, the measuring/sampling time t_m occurs every minute.

Next, 5-minute temperature $T_{S5}(k)$ set from a weighted average calculated using nominal indoor unit capacities was introduced. $T_{S5}(k)$ is given by the equation of Formula (3).

$$T_{S5}(k) = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} R_n(t_m) C_n T_{Sn}(t_m)}{\sum_{n=1}^{N} \sum_{m=1}^{M} R_n(t_m) C_n} \qquad \text{Formula (3)}$$

Where C_n is the nominal capacity of an indoor unit. $R_n(t_m)$ stands for a certain indoor unit n's state of operation/stop and is given as in Formula (4).

$$R_n(t_m) = \begin{cases} 1 & (n\text{th indoor unit is ON at } m\text{th sampling}) \\ 0 & (n\text{th indoor unit is OFF at } m\text{th sampling}) \end{cases} \qquad \text{Formula (4)}$$

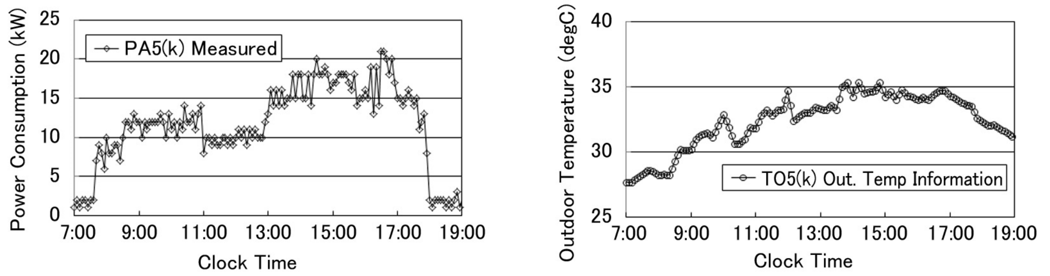
4. Operation test

Table 1 shows a description of the building used in the field tests for the measurement of data. The idea of fast demand control is particularly effective for larger buildings, but the building given here has a size large enough for our research to apply to the evaluation of its effectiveness.

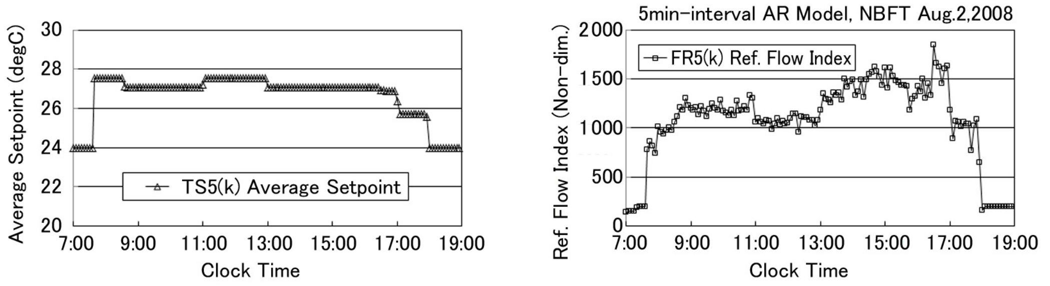
Table 1 Description of Field Test Building

Item	Specification
Kind of building	Typical office building
Gross floor area	5,000 m^2
Structure of building	Reinforced concrete
Number of indoor units existing within the building	30 units

Figure 3 shows measurement time-series data of five-minute intervals ($k = 1, 2, \cdots, 144$) from 07:00 to 19:00 on August 2, 2008. Instantaneous power consumption $P_{A5}(k)$ was measured by fitting a watt-hour meter in the outdoor unit and counting output pulses. The 5 minute-interval outdoor temperature measurements $T_{O5}(k)$ are data obtained from the Meteorological Agency. The set temperature of each indoor unit was observed and the set weighted-average temperature $T_{S5}(k)$ was measured. Meanwhile, the opening position of each indoor unit's electronic expansion valve was continuously measured and the total amount of refrigerant flow $F_{R5}(k)$ could also be obtained through measurement. The AR model coefficient matrix was later calculated by another computer. In the actual smart grid of the future, it is believed that data sampling, storage and memory will be handled using SaaS developed by cloud computing. With the AR model order $L = 2$, the AR coefficient matrix elopements $A^{(l)}{}_{11}$, $A^{(l)}{}_{12}$, … , $A^{(l)}{}_{44}$ were determined through computer calculation using the Yule-Walker Equation.



(a) 5 minute-interval time-series data of power consumption $P_{A5}(k)$ (b) 5 minute-interval time-series data of outdoor temperature $T_{O5}(k)$



(c) 5 minute-interval time-series data of average setpoint $T_{S5}(k)$ (d) 5 minute-interval time-series data of refrigeration flow index $F_{R5}(k)$

Figure 3 5 Minute-interval time-series measured data for period of 07:00 to 19:00

Figure 4 shows the 5 minute-interval power consumption predicted at the calculation for 07:00 to 19:00. In this figure, measurements are also indicated in an overlapped manner. Calculated values and measurements are almost identical as a whole. **Figure 5** magnifies Figure 4's much-power-consuming, just-past-noon time zone for comparison in detail. From Figure 5, it is found that calculated values less sharply change than measurements. In AR model predictive calculations, a prediction value can be obtained from the AR model coefficient-based linear combination of several past values. This is also referred to as a mutual smoothing effect, which prevents prediction values from changing sharply like measurements. Since the AR model predicts the next value from several values immediately before it, it is intrinsically difficult for the model to predict an extremely sharp change, if any.

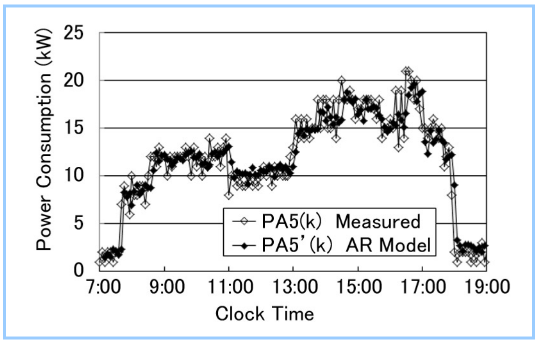


Figure 4 **5 minute-interval time-series data for period of 07:00 to 19:00 (calculated value-measurement comparison)**

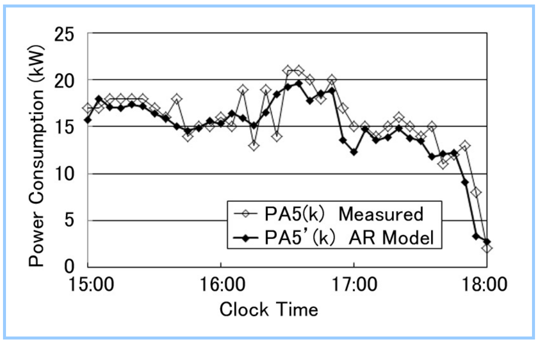


Figure 5 **5 minute-interval time-series data for period of 15:00 to 18:00 (magnified part of Figure 4)**

Figure 6 shows the result of a predictive calculation trial assuming fast demand control. On the assumption that smart grid demand was responded to between 16:00 and 16:55, 5-minute power consumption was calculated as the decrement in the total amount of refrigerant flow $T_{R5}(k)$. It is found that the effect of control was effectively and promptly reflected as soon as the control period started. Predictive calculation has yet to be quantitatively evaluated, so we intend to further improve the accuracy of refrigerant control and predictive calculation.

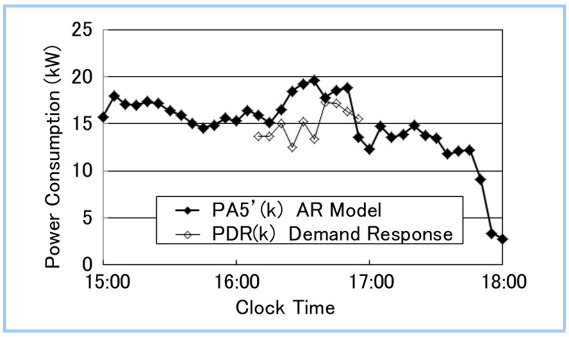


Figure 6 **Predicted value of power consumption controlled with assumed demand**

5. Examination

Table 2 compares an existing demand control of HVAC systems with our new, fast method. The existing demand control mainly switches the ON/OFF state of operation for control. The new demand control continuously regulates the amount of refrigerant flow. This allows momentary power consumption of systems as a whole to be quickly reflected and, as a result, our method prevents excessive and unnecessary halting of HVAC systems.

Power generation with renewable energy sources, involving large-scale interconnection, sometimes noticeably fluctuates during a period of 10 minutes or so. This is because of an abrupt, drastic change in sunshine for solar power generation and in wind speed for wind power generation. Conventional demand control technology is based on a time frame of 30 minutes and, therefore, remains unable to achieve timely, e.g., 10-minute, compensation for power control. Our new fast demand control technology enables the demand side's accurate and quick response and is also considered to help realize a real-time power rate system.

Table 2 **Comparison between Existing and Fine/Fast Demand Control**

	Existing demand control	New fast demand control
Prediction time granularity	1/2 to 1 hour	1 to 5 minutes
Time of response to ADR	Long	Short
Control accuracy	May possibly halt too often	Comfort-oriented fine control
Method of control	ON-OFF control	Continual feedback control
Power control mechanism	Thermostatic ON-OFF ratio	Adjustment of electronic expansion valve's opening position
Level required for control	Low	High
Embodiment	Control with integrated CPU	Control with cloud computing

6. Conclusion

This research obtained the following results:

(1) A new method of fast demand control for air-conditioning systems was proposed.

(2) An AR model of 5 minute-interval power consumption by air-conditioning systems in an entire building was derived from the field test data.

(3) On the assumption that demand is assumed and demand control is continuously implemented every 5 minutes, the calculation results verified effective and quick demand response.

The new fast demand control we are proposing will contribute to a real-time power rate system, virtual power plants, and other future smart grid initiatives interconnected with large-scale renewable energy sources.

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