INTELLIGENT ENERGY MANAGEMENT SYSTEM: VERIFICATION OF AN ALGORITHM FOR REDUCING ENERGY CONSUMPTION IN VARIABLE REFRIGERANT FLOW

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Abstract: A control system for reducing energy consumption in variable refrigerant flow (VRF) has been developed and the effectiveness of the system has been verified by applying it to actual operations in several facilities. The algorithm for this system enables VRFs to maintain the coefficient of performance at a higher level than that achieved by conventional operation by monitoring and controlling the operational mode of VRFs. The energy saving achieved by this system was verified to be up to 30% in one facility, and up to 20% in the other facility, both in the summer and in the winter.

Key Words: Intelligent BEMS, Saving Energy, Variable Refrigerant Flow

1 INTRODUCTION

According to the statistics by Energy Conservation Center Japan as illustrated in Figure 1, air-conditioning dominates 28% of the energy consumption volume (primary energy conversion) in sectors consisting mainly of office buildings. The majority of small or medium-sized buildings built after 1990 in Japan are equipped with variable refrigerant flows (VRFs) as air-conditioning systems.

Energy management of buildings with VRFs is not sufficient, because the residence of a superintendent is not required for almost of such small or medium-sized buildings. In addition, the effect of energy-saving measures in facilities with VRFs, such as sprinkling water over outdoor units during cooling, has not been verified very well.

As a measure for saving energy that is effective for small or medium-sized buildings, an energy-saving algorithm for VRFs and its verification on the basis of field operations at the library space of Kanto Gakuin University and the office space of Hokkaido Electric Power Co., Inc., is described in this paper.

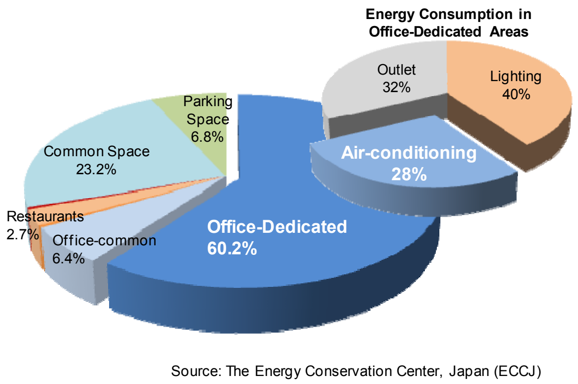

Figure 1 Energy consumption in office buildings

2 CHARACTERISTICS OF VARIABLE REFREGERANT FLOW

The analysis on the partial load characteristics of VRFs indicates that COP of VRFs drops sharply when the partial load rate drops below 0.5. The analysis on the operational characteristics of VRFs indicates that VRFs are operated with less than half the rated power consumption most of the time, i.e., VRFs tend to be operated at the low COP most of the time.

2.1 Partial load characteristics

The partial load characteristics of a VRF with 16 kW cooling capacity installed in a work palce at the Institute of Technology of Shimizu Corporation is illustrated in Figure 2.
During the examination period, the power consumption of outdoor units, the suction air temperature of outdoor fans, the discharge air temperature of outdoor fans, the room temperature and the other factors were measured every minute. The coefficient of performance (COP) was calculated from the results. The horizontal axis of Figure 2 indicates the partial load rate when considering the cooling capacity of 16 kW of VRF as 1, and the vertical axis indicates the COP.
When the partial load rate is 0.9, the COP is 3.1, while the COP drops sharply when the partial load rate drops below 0.5.

2.2 Operational characteristics

The power consumption of VRFs in a library of university, where four VRF systems are installed in a large room, is illustrated in Figure 3.
The effective power of outdoor units per minute was measured for the power consumption. Figure 3 indicates the total operation time (vertical axis, minutes) running with every 1 kW of power consumption (horizontal axis). Each VRF was operated with less than half the rated power consumption most of the time as indicated in Figure 3.

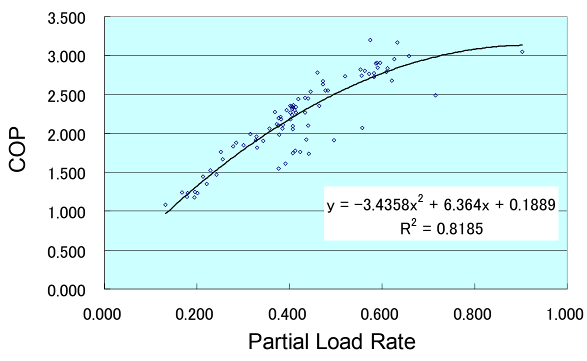

Figure 2 Partial load characteristics of VRF

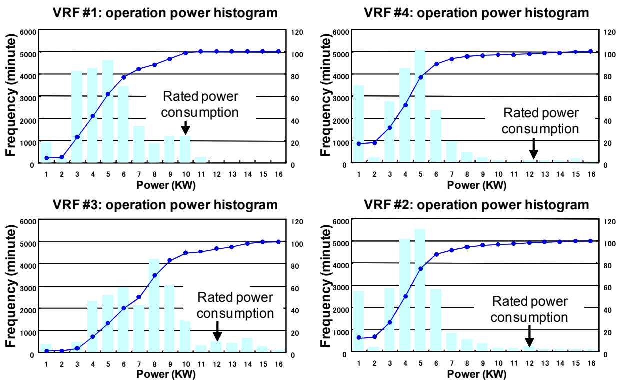

Figure 3 Operational characteristics of VRF

3 ENERGY-SAVING CONTROL ALGORITHM

The energy-saving control algorithm enables VRFs to maintain the coefficient of performance at a higher level than that achieved by conventional operation by monitoring and controlling the operational mode of VRFs is introduced in this section.

3.1 Outline of energy-saving control algorithm

The outline of energy-saving control algorithm is illustrated in Figure 4. VRFs keeps the operation at higher rate of partial load by this algorithm which monitors the operational status of the VRFs from the outside and makes a judgement of its operational status.

3.2 Judgement of operation status of VRFs

The rated power ratio, obtained by dividing the measured power consumption, i.e., effective value per minute, of the primary side of the outdoor unit by the rated power consumption is used for the evaluation of the operation status of the VRFs. Compared to the previous values of the rated power ratio, the operation status is judged as being one of seven stages: "start-up," "high load," "medium load," "low load," "ON/OFF, "stop," and "restart."

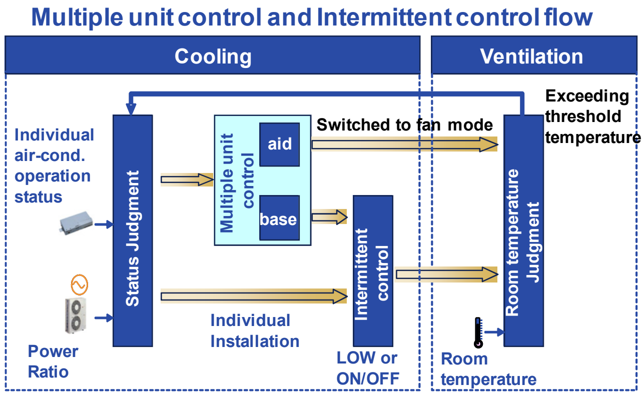

Figure 4 Outline of energy-saving control algorithm

3.3 Control of VRFs

According to the data pre-entered in the management PC, "Intermittent air-conditioning" is selected when one VRF is installed in one space, and "Multiple unit control" when more than two VRFs are installed.
When “Multiple unit control” is selected, each VRF is designated to be either "base" or "aid”. The rated power ratios of the VRFs are constantly monitored by control program, and when the operational condition changes from "stop" to "start-up," control starts. Until the room temperature becomes stable, both "base" and "aid" VRFs are operated, and after the threshold time, the operation mode of "aid" is changed from cooler mode to fan mode and the cooling load processed by "aid" shifts to "base”. However, the room temperature covered by "aid" is constantly monitored, and when exceeding the allowable temperature, the operation mode is switched from fan mode to cooler mode. Moreover, even "base" is switched to fan mode when it is determined to be "low load" or "ON/OFF."
For intermittent air-conditioning, the VRF is controlled as "base."
The air-conditioning evaluation system on a Web site was used so that users can evaluate the validity of the allowable temperature and the algorithm itself, the responses is monitored at any time during the experimentation.

3.4 System Configuration

The system configuration of this control system for saving energy consumption of VRFs is illustrated in Figure 5. This system can be realized by connecting a general-purpose PC and the centralized controller of VRFs via a network.

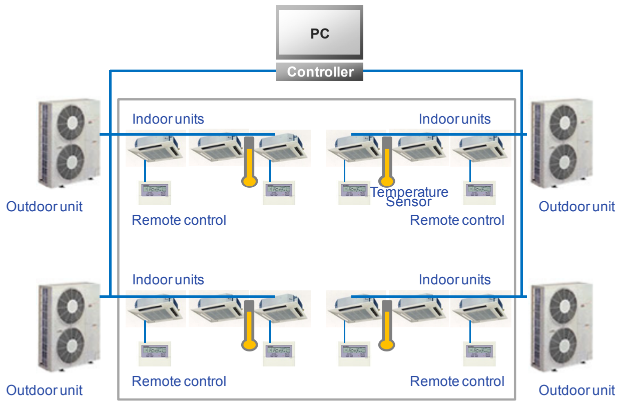

Figure 5 System Configuration

4 VERIFICATION OF ENERGY-SAVING CONTROL ALGORITHM

The results of verification of this energy-saving control algorithm in two facilities, a library space of a university and an office space, are described in this section.

4.1 Library space of Kanto Gakuin University

4.1.1 Outline of field for verification

The verification took place in an open-stack room on the third floor of a library building of Kanto Gakuin University (a three-storied reinforced concrete building). The layout of this room is illustrated in Figure 6. This is a large room with a floor area of 544 m^2 without partitions, which is divided into a storeroom and a browsing space. Each space has two VRF systems, four systems in total.
A power sensor was set up for each outdoor unit, and the effective power and room temperature on the top of tables were measured for verification. For multiple unit control mode, the VRFs in the browsing area were designated as "base," and those in the storeroom were controlled as "aid".

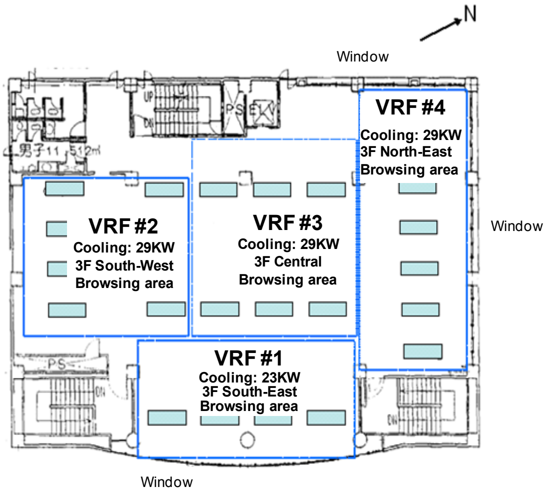

Figure 6 Verification field (University Library)

4.1.2 Results of verification in summer

Verification was carried out from mid-July to the end of September 2006, by alternatively repeating two patterns of operation, i.e., without any control and with multiple unit control. The set temperature was 26°C and the allowable temperature was 28°C, respectively, for the four systems throughout the tested period.
The rated power ratios, power consumption/rated power consumption for VRFs, are illustrated in Figure 7 along with the data taken on the days without multiple unit control. The power consumption of the four systems without control is high at start-up, however, the rated power ratios of all four systems drop to 30 to 40% after 11:00 due to the so-called wait-and-see operation. On the other hand, when multiple unit control is activated, the four systems work together at start-up, but later, while the VRFs in the browsing area are operating as base, the VRFs in the storeroom repeat on and off properly, and the rated power ratios are high on the whole.
The distribution of the power consumption, i.e., the sum of products of power consumption when the VRFs are in operation in the floor area by day, is illustrated in the lower part of

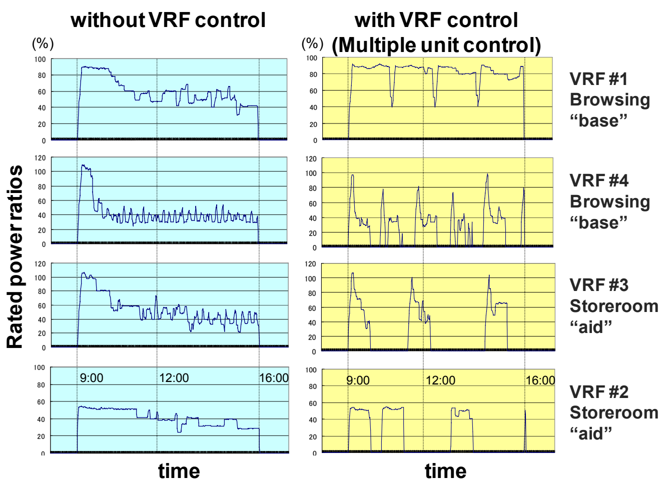

Figure 7 Rated power ratios with/without VRFs control

Table 1 Verification result of temperature in summer (University Library)

Average Room Temperature without VRF control

Date	Browsing Room South-East	Browsing Room North-East	Store Room South-West	Store Room Central	Daily Average
2006/08/08	28.4	28.8	26.8	27.3	27.8
2006/08/09	28.2	28.8	26.8	27.3	27.7
2006/08/22	28.0	28.6	26.5	27.1	27.5
2006/08/23	28.1	28.5	26.4	27.1	27.5
2006/08/25	27.7	28.3	26.4	26.9	27.3
2006/08/28	28.0	28.8	26.7	26.9	27.6
2006/08/30	27.6	28.1	26.2	26.7	27.2
Average	28.0	28.6	26.5	27.0	27.5

Average Room Temperature with VRF control

Date	Browsing Room South-East	Browsing Room North-East	Store Room South-West	Store Room Central	Daily Average
2006/09/05	26.9	28.6	27.4	27.7	27.6
2006/09/06	25.9	28.5	27.5	27.7	27.4
2006/09/07	27.0	28.5	27.1	27.5	27.5
2006/09/08	26.3	28.4	27.2	27.6	27.4
2006/09/19	26.3	28.5	27.3	27.3	27.3
2006/09/20	26.8	28.7	27.6	27.6	27.7
2006/09/21	26.5	28.4	27.8	27.5	27.5
2006/09/22	26.0	28.5	27.6	27.3	27.4
2006/09/28	26.6	28.2	27.3	27.2	27.3
Average	26.5	28.5	27.4	27.5	27.5

Figure 8 along with the daily average ambient temperature. The squares represent the days without control and the triangles represent the days with multiple unit control. There is a clear difference in energy consumption between with and without control. The solid lines in the as 0.6 and 0.8, so that it is concluded that the power consumption per square meter can be predicted from the daily average ambient temperature.
On the other hand, one might be worried about the deterioration of the room temperature distribution caused by switching the cooler mode to fan mode under multiple unit control.
The daily average room temperatures under no VRF control and under multiple unit control are descrided in Table 1. The space-time average room temperatures were the same, both 27.5°C.

4.1.3 Results of verification in winter

Verification was carried out from early December 2006 to the end of January 2007, using the same pattern of operation as used in summer. The set temperature and the allowable temperature were 20°C and 20.5°C, respectively, for the four VRF systems throughout the period. The distribution of the power consumption per square meter during heating along with the daily average ambient temperatures is illustrated in the upper part of Figure 8. As found in cooling, we can see a difference in energy consumption between with and without VRF control, and a strong correlation between the daily average ambient temperature and the power consumption per square meter.
The space-time average room temperatures were a little bit lower under multiple unit control. This was because the compressor was off until the room temperature reached below the allowable temperature.

4.1.4 Evaluation of energy-saving effect

When totaling the assumed power consumption by day obtained by multiplying the power consumption per square meter, which is calculated by substituting the daily average ambient temperatures from June 1 to October 31 (in 2006, only on working days), for the regression equation indicated in Figure 8 by the floor area of 5000 m^2 and an operation time of 8 hours during the verification period, the sum is 79,080 kWh when operated without control, and 56,309 kWh under multiple unit control, resulting in an assumed energy-saving rate of 28.8%.
On the other hand, when calculating the same for working days from December 1 to March 31 for heating, the power consumption is 61,810 kWh when operated with no control, and 22,608 kWh under multiple unit control, resulting in an assumed energy-saving rate of 63.4%. However, the room temperature could not be maintained at an even rate during the experiment. If the effect of multiple unit control is the same as that in summer, the rate can be expected to be at least 30%.

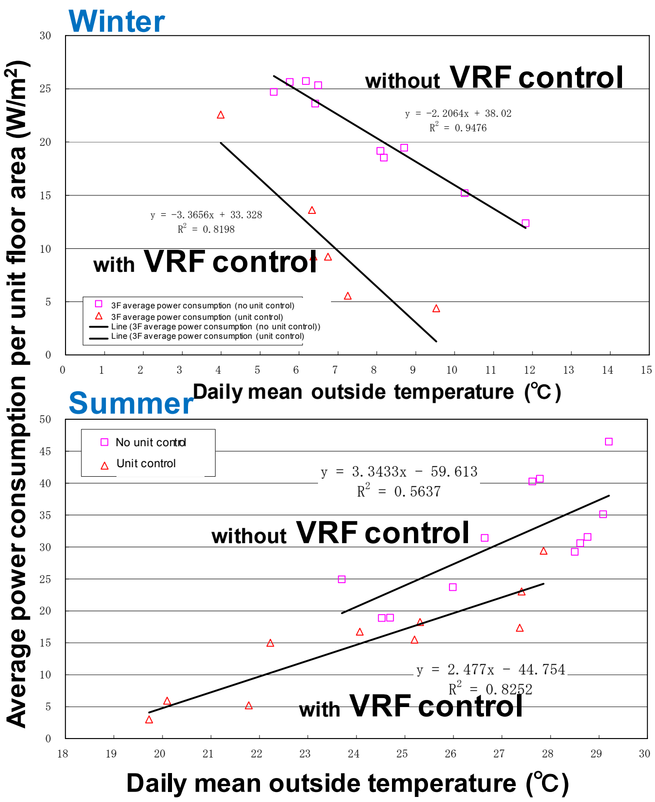

Figure 8 Verification results in summer and winter (University Library)

4.2 Office space of Hokkaido Electric Power Co., Inc

4.2.1 Outline of field for verification

The VRFs at the Sapporo North branch office comprise four systems. Three systems cover the first to third floors, and one system covers a part of the office and a small room on the second floor. All four systems have the same air conditioning capacities: 50 kW for cooling. Verification took place from January to March 2008 for winter, and from July to September 2008 for summer.

4.2.2 Results of verification in summer

The results of verification during summer period are illustrated in the lower part of Figure 9. The distribution of the power consumption, i.e., the sum of products of power consumption when the VRFs are in operation in the floor area by day, along with the daily average ambient temperature is illustrated in Figure 9.
When controlled by the algorithm giving priority to cooling, as this forced the indoor units originally used for the fan operation to switch to the cooling operation, energy consumption increased compared with no control mode. However, when using the algorithm giving priority to fan operation, the energy-saving rate was approximately 20% at a daily average ambient temperature of 21°C. The allowable temperature was set to 23°C.

4.2.3 Results of verification in winter

The results of verification during the heating period are illustrated in the upper part of Figure 9. In the chart, the pink squares represent the results under no control, and the red triangles represent those under control.
When the average ambient temperature was -6°C, the energy-saving rate was approximately 24%. The control temperature was left to users' discretion and the allowable temperature was set to 27°C.

4.2.4 Evaluation of energy-saving effect

Using the power consumption per square meter calculated by substituting the daily average ambient temperatures for the heating period (from November 2007 to March 2008) and for the cooling period (from July to September 2008) for the linear regression equation obtained in Figure 9 (Heating, Cooling, priority on fan), and assuming the floor area was 5000 m^2 and the air-conditioning time was 10 hours, the assumed power consumption for each period was calculated.
For heating, power consumption under no control was 81,643 kWh, and 65,010 kWh under control, which makes the energy-saving rate throughout the period approximately 20%. For cooling, it was 64,411 kWh under no control, and 53,053

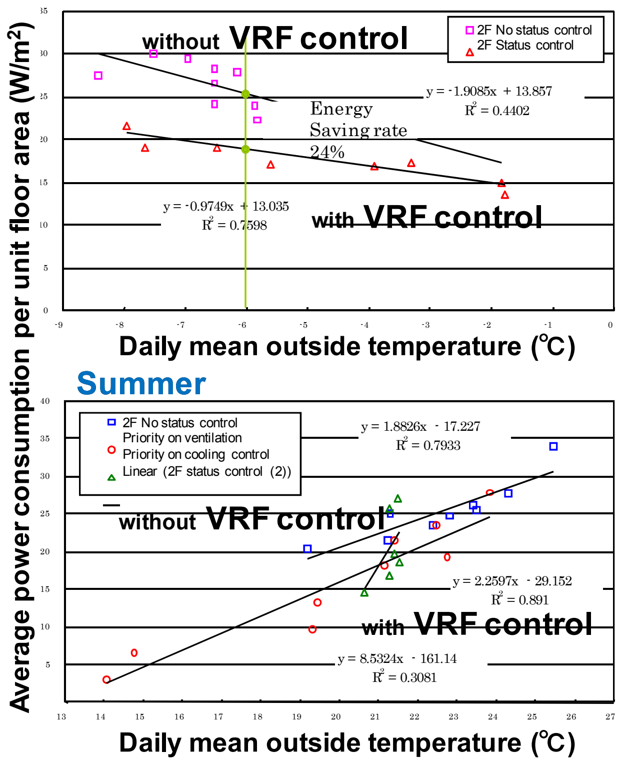

Figure 9 Verification results in summer and winter (Office space)

kWh under control, and the energy-saving rate was approximately 18%.

5 CONCLUSION

The effect of energy-saving algorithm for VRFs has been verified by applying its control system to the operation of actual facilities, and has been analized to be significant.
The analysis on the partial load characteristics and the operational characteristics of VRFs indicates that VRFs tend to be operated at the low COP most of the time.
The energy-saving control algorithm enables VRFs to maintain the coefficient of performance at a higher level than that achieved by conventional operation by monitoring and controlling the operational mode of VRFs is developed and applied for the library space and office space.
The result of verification of this algorithm indicates significant difference in energy consumption between no VRFs control and VRFs control, both in the summer and winter seasons.
By calculating the power consumption in summer and winter using the linear regression equation obtained from field verification, the energy-saving effect by multiple unit control at Kanto Gakuin University Library is analized to be approximately 30% for both summer and winter. At the Sapporo North branch office of the Hokkaido Electric Power Company, it is analized to be approximately 20% for both summer and winter.

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