Feasibility Study on Short Period Power Fluctuation Compensation Using Heat Pump Air Conditioning System

Shunsuke Kawachi†, Hiroto Hagiwara*, Jumpei Baba*, Kei Furukawa**, Eisuke Shimoda** and Shigeo Numata**

Abstract – In order to compensate power fluctuations caused by loads and renewable energy sources, the concept of controllable load has been proposed. In this paper, the use of heat pump air conditioning system as a controllable load is focused. To analyze the feasibility of using the heat pump for power fluctuation compensation, basic characteristics of heat pump concerning its power consumption and processed heat are measured by experiments and reported in this paper. The COP characteristics show that the efficiency of the heat pump is not affected so much by power consumption as long as it is operated above a certain level of power consumption. The Bode diagram of sinusoidal reference signal test shows that the heat pump can compensate power fluctuation which is in a certain region in the frequency domain without giving a large effect on processed heat.

Keywords: Controllable load, Heat pump, Microgrid, Smartgrid

1. Introduction

1.1 Background

Today, the global climate change is an issue of high importance that demands the reduction of greenhouse gas emission urgently. Furthermore, means to provide a stable supply of energy is sought in order to reinforce energy security. In such background, generation from renewable energy sources through photovoltaic cells(PVs) and wind turbines(WTs) in the power grid is increasing. However, the generation from these renewable energy sources is random and intermittent in nature. When these fluctuations become substantial, it will be difficult to maintain the balance between power supply and demand in the power grid.

The compensation of power fluctuation using energy storage systems(ESSs) is an effective solution to this problem. In previous research, the authors proposed a control method of distributed generation systems(DGs) to compensate power fluctuations in a microgrid and verified its effectiveness experimentally using real machines[1],[2]. It is, however, preferable to keep installed capacity of ESSs as small as possible since ESSs are generally expensive. Table I shows example of several ESSs’ costs per output power(kW) and costs per energy(kWh)[3].

Many studies have been done to develop ways to reduce the capacity of ESSs. In case of wind turbine, control of blade pitch angle can reduce the power fluctuation and thus can reduce the ESSs’ capacity[4]. Also, accurate forecasting of renewable energy source’s output power has possibilities to reduce ESSs.

1.2 Concept of controllable load

As another method of reducing the capacity of ESSs, the control of power that is used by electrical loads on the demand side is considered. In this paper, electrical loads whose power consumption can be controlled from grid controller are called "controllable loads".

There are several requirements for an electrical load to be treated as an ideal controllable load. They are:

(1) The power consumption of the load is large enough to compensate power fluctuation by control of its power consumption.

Table 1. Example of ESS’s Cost

<table>
<thead>
<tr>
<th>ESS</th>
<th>Cost per kW [1000$/kW]</th>
<th>Cost per kWh [1000$/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaS Battery</td>
<td>7.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Li-Ion Battery</td>
<td>6~15</td>
<td>1~14</td>
</tr>
<tr>
<td>NiMH Battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Speed Flywheel</td>
<td>0.5~1</td>
<td>120~240</td>
</tr>
<tr>
<td>EDLC*</td>
<td>2</td>
<td>50~</td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>1.5~2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*EDLC: Electric Double-Layer Capacitor

Figures show that most ESSs’ costs are still quite high.
(2) The response speed of the load’s power consumption to its reference signal is fast enough to compensate power fluctuation.

(3) The loss of convenience by control of power consumption is minor.

However, there isn’t any electrical load that satisfies these three requirements perfectly. Thus, loads that satisfy these requirements partially are treated as controllable loads in practice.

1.3 Heat pump as controllable load

Among electrical loads, heat pumps, which are used for air conditioning and water heating and so on, are attractive options for control and is likely to satisfy the three requirements mentioned in previous section [5]. In order to evaluate heat pump’s conformity to requirement 1), number and types of air conditioning equipments used in Japan has been surveyed. Fig. 1 shows percentage of air conditioning equipments in commercial sector in Japan based on their heating capacity. The graphs indicate that there is large percentage of heat pumps used for air conditioning. Thus, a large scale regulating capacity for active power in the power grid can be expected by the control of heat pumps.

![Fig 1. Percentage of air conditioning equipments in commercial sector in Japan in 2006.](image)

Generally, heat capacity of the room or water is quite large. This indicates that temperature of the room is insensitive to the fluctuation of heat pump’s processed heat (the amount of heat produced by the heat pump per second) caused by load control. In other words, heat energy that is stored in room or water can be regarded as energy buffer which is large enough to substitute ESSs. Thus, regarding to requirement 3), control of heat pumps is less likely to affect the convenience of their users compared to other electrical loads such as lighting equipments.

Assuming that a heat pump for air conditioning is used as a controllable load, its ability of power fluctuation compensation is estimated as following. The air conditioning system in the estimation is assumed for a building with total floor space of 10,000[m²]. The height of the floor is assumed to be 2.4[m] and air conditioning load per area is assumed to be 100[W/m²]. It is assumed that the COP (Coefficient of performance) of the heat pump is 4.0 and 20% of the heat pump’s rated power consumption can be controlled.

The power capacity of the heat pump as a controllable load can be calculated as (1).

\[
10,000[\text{m}^2] \times 0.1[\text{kw/m}^2] \div 4.0 \times 0.20 = 50[\text{kw}] \quad (1)
\]

When temperature fluctuation within the range of 2°C is accepted, the energy capacity of the heat pump as a controllable load can be calculated as (2). In (2), 1.092[kg/m³] is the density of the air and 1.006[kJ/kg·K] is the air’s specific heat at constant pressure.

\[
10,000[\text{m}^2] \times 2.4[\text{m}] \times 1.092[\text{kg/m}^3] 
\times 1.006[\text{kJ/kg·K}] \times 2[{}^\circ\text{C}] \div 4.0 \approx 3.6[\text{kWh}] \quad (2)
\]

Thus, a heat pump air conditioning system for a building with floor space of 10,000[m²] can be treated as an ESS with 50[kW] power capacity and 3.6[kWh] energy capacity.

With regarding to requirement 2), there isn’t any reported study that tested response characteristics of heat pump’s power consumption using a real machine. Thus, using a particular machine that is available today, a heat pump’s response characteristics to power consumption reference signal is measured experimentally in this research and its result is reported in the paper. Furthermore, to analyze the effect of power consumption control of the heat pump on its efficiency, the COP characteristics at various power consumption is measured and reported.

2. Experimental Conditions

The heat pump air conditioning system used in the experiment is located at the Institute of Technology of Shimizu corporation. Same type of this heat pump unit is widely used in mid-scale buildings. Ratings of the heat pump are shown in Table 2. The air conditioning system consists of...
two heat pump units. The figures shown in Table 2 are data of single units.

**Table 2.** Ratings of the Heat Pump

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power Consumption</td>
<td>44.9kW (Cooling)</td>
</tr>
<tr>
<td></td>
<td>53.0kW (Heating)</td>
</tr>
<tr>
<td>Rated Heating Capacity</td>
<td>177.5kW</td>
</tr>
<tr>
<td>Rated Refrigeration Capacity</td>
<td>157.5kW</td>
</tr>
<tr>
<td>Power Supply</td>
<td>AC 3φ 200V</td>
</tr>
<tr>
<td>Compressor</td>
<td>37kW</td>
</tr>
</tbody>
</table>

Fig. 2 shows the schematic diagram of the whole air conditioning system. The heat produced by the heat pump is distributed to fan-coil units inside the building by circulating water.

The major power-consuming component in the heat pump is the compressor that compresses refrigerant. In this heat pump unit, a screw type compressor is used. This type of compressor consists of two rotors and refrigerant is compressed within the gap between these two rotors.

At the low pressure side of this compressor, there is a valve that controls the amount of refrigerant compressed by the compressor. When the aperture of this valve is changed, the load of the compressor changes. Since the compressor is driven by an induction motor, the power consumption of heat pump unit changes.

In normal operation, the valve is controlled by a built-in controller so that the temperature of the water coming out from the heat pump would be kept constant. In this experiment, however, the valve needs to be controlled from outside. Thus, the valve in the heat pump unit is controlled by giving signal to two external terminals. The two terminals correspond to “Load Up” and “Load Down” respectively.

To control the power consumption of the heat pump to desired value, a control board was prepared. The control board generates the “Load Up” or “Load Down” signal based on current power consumption of the heat pump and reference value of the heat pump’s power consumption. Schematic signal flow diagram is shown in Fig 3. The experiment is conducted under heating operation. Among the two heat pump units, only one of them is controlled.

The measurement item in the experiment is the heat pump’s power consumption, the reference value of the heat pump’s power consumption, the “Load Up” and “Load Down” signal, the flow of the circulating water, the temperature of circulating water at the inlet(inlet water
Feasibility Study on Short Period Power Fluctuation Compensation Using Heat Pump Air Conditioning System

temperature) and at the outlet( outlet water temperature) of the heat pump, and the air temperature of outside. The error ratio of the measurement system is within 2%.

3. Experimental Result -COP Characteristics-

In this section, the experimental result concerning the COP characteristics of the heat pump at various power consumption is reported. Fig. 4 shows three representative case of the relation between power consumption and the COP of the heat pump. The cases are numbered as case[i], [ii], and [iii]. The outside temperature and the inlet water temperature is different in each case. The temperatures in each case are shown in Table III. The measured results are expressed by points and they are approximated by a function shown in (3). This function is proposed based on the function of beta distribution. In (3), \( a_1 \sim a_5 \) are constants and \( p \) represents the power consumption of the heat pump.

Table 3. Outside air and inlet water temperature

<table>
<thead>
<tr>
<th>Case</th>
<th>Outside temperature</th>
<th>Inlet water temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>[i]</td>
<td>10.7 °C</td>
<td>35.9 °C</td>
</tr>
<tr>
<td>[ii]</td>
<td>8.7 °C</td>
<td>28.9 °C</td>
</tr>
<tr>
<td>[iii]</td>
<td>15.8 °C</td>
<td>31.5 °C</td>
</tr>
</tbody>
</table>

\[
\text{COP}(p) = a_i \left( \frac{p - a_5}{a_2} \right)^{a_1} \left( 1 - \frac{p - a_5}{a_2} \right)^{a_3} \tag{3}
\]

Fig. 4 shows that the COP-Power consumption characteristics differ substantially depending on the outside temperature and entrance water temperature. However, three cases share common characteristic that the peak value of the COP is measured at power consumption value which is smaller than the rated power consumption. In case[i], the COP shows its peak at around 38kW. These values are much smaller than the value of rated power consumption 53.0kW. Meanwhile, the value of COP maintains a large value while the heat pump is operated above 25kW. Thus, it can be assumed that the control of heat pump’s power consumption does not affect the efficiency of the heat pump on a large scale as long as it is operated above certain level of power consumption.

From Fig. 4, it is clear that there is a relation between the peak value of COP and the difference between entrance water temperature and outside temperature. The temperature difference is smallest and the peak COP is largest in case[iii], whereas the temperature difference is largest and the peak COP is smallest in case[i].

In Fig. 5, the measured value of COP is plotted corresponding to each power consumption and value of temperature difference. The surface in the graph is drawn using the function shown in (4). The five parameters from \( a_1 \) to \( a_5 \) are treated as variables relating to the value of temperature difference between entrance water temperature and outside temperature(\( \Delta T \)). The value of \( a_i \) is acquired from linear function(5). The function is obtained by approximating the value of \( a_i \) in each temperature condition.

\[
\text{COP}(p, \Delta T) = a_i(\Delta T) \left( \frac{p - a_5(\Delta T)}{a_2(\Delta T)} \right)^{a_1(\Delta T)} \times \left( 1 - \frac{p - a_5(\Delta T)}{a_2(\Delta T)} \right)^{a_3(\Delta T)} \tag{4}
\]

\[
a_i = a \Delta T + \beta_i \tag{5}
\]

In Fig. 5, the measured value expressed by red points shows close agreement with the approximated green curving surface. Thus, COP characteristics can be
approximated by (3) and (5). However, theoretical explanation why COP characteristic can be represented by this function is still not clear and is currently studied.

4. Experimental Result -Response Characteristics-

To analyze the following capability of heat pump’s power consumption to its reference signal, sinusoidal reference signal test is conducted. In this test, the sinusoidal power consumption reference signal is given to the heat pump with various amplitude, period, and bias. The parameters of reference signal are shown in Fig. 6. For amplitude and bias (they are expressed as $[\text{bias}] \pm [\text{amplitude}]$), three cases were conducted and they are $30 \pm 15$ kW, $35 \pm 5$ kW, and $25 \pm 5$ kW.

![Fig. 6. Parameters of sinusoidal reference signal.](image)

Fig. 6. Parameters of sinusoidal reference signal.

Fig. 7 shows an example of the result in sinusoidal reference signal test. In this case, the bias and amplitude of the reference signal is $30 \pm 15$ kW and period of the signal is 200 seconds. The graph shows that the power consumption is not able to follow its reference signal completely, but still its error is small. Meanwhile, the value of processed heat is fluctuating with 40–50 seconds delay from the fluctuation of power consumption.

![Fig. 7. Result of sinusoidal reference signal test.](image)

Fig. 7. Result of sinusoidal reference signal test.

For more detailed analysis, the measured data is processed by discrete Fourier transform and amplitude and phase of the frequency component corresponding to the period of sinusoidal reference signal is calculated. The ratio of the measured power consumption’s amplitude to the reference signal’s amplitude is plotted as Bode diagram in Fig. 8. The horizontal axis of the graph represents the period of the sinusoidal reference signal. In Fig. 8, the phase difference between the reference signal and measured power consumption is also plotted.

![Fig. 8. Bode diagram of heat pump’s power consumption.](image)

Fig. 8. Bode diagram of heat pump’s power consumption.

The curves in the amplitude graph approximate the measured value by (6) and the curves in the phase graph approximate the measured value by (7). These equations are acquired from the characteristic of first-order delay element. $\gamma$ represents the amplitude ratio, $\Delta P$ represents the phase difference, $T$ represents the period of reference signal, and $b_1$, $c_1$, and $d_1$ are constants.

$$\gamma = -10 \log \left( 1 + \frac{b_1}{T} \right)$$  \hspace{1cm} (6)

$$\Delta P = \tan^{-1} \left( \frac{T}{C_1} \right) + d_1 T$$  \hspace{1cm} (7)

When the amplitude ratio or the phase difference is close to 0, it means that the power consumption is following its reference signal. Thus, Fig. 8 shows that when the bias and amplitude of the reference signal is $35 \pm 5$ kW, the response characteristic of the heat pump’s power consumption to sinusoidal reference signal is faster than other two cases.

Fig. 9 shows a Bode diagram for processed heat that is drawn by plotting the amplitude ratio of measured value of
processed heat to reference value of processed heat. As the reference value of processed heat, values obtained by multiplying the COP and power consumption is used. Value of the COP is calculated from the COP characteristic explained in section 3. The curves approximate the measured value by (6), but points below -12dB are neglected because the power consumption’s amplitude of the fluctuation is too small to calculate precisely. The Bode diagram of power consumption’s amplitude ratio is also shown in Fig. 9 again for comparison.

Fig. 9. Bode diagram of heat pump’s processed heat.

By comparing the Bode diagram of power consumption and that of processed heat, the shortest and the longest period of the fluctuation that the heat pump can compensate can be determined. In this analysis, the power consumption of the heat pump is regarded as following its reference signal when the amplitude ratio of power consumption is above -3dB. Meanwhile, the fluctuation of processed heat is regarded as not giving a large effect on the user when the amplitude ratio of processed heat is below -3dB. When amplitude ratio is -3dB, the amplitude of measured value is 0.7 times smaller than the amplitude of reference signal. Thus, the longest period of the fluctuation that the heat pump can compensate is determined by the processed heat characteristic and the shortest period is determined by the power consumption response characteristic.

Table 4 shows the maximum and minimum value of the fluctuation’s period in three cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum Period [sec]</th>
<th>Minimum Period [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30±15kW</td>
<td>241</td>
<td>109</td>
</tr>
<tr>
<td>25±5kW</td>
<td>225</td>
<td>60</td>
</tr>
<tr>
<td>35±5kW</td>
<td>267</td>
<td>30</td>
</tr>
</tbody>
</table>

When the bias and amplitude of the sinusoidal reference signal is 30±15kW, the heat pump can compensate power fluctuation whose period is from 241second to 109sec. The range of the fluctuation period is widest when the bias and amplitude is 35±5kW and its value is from 267sec to 30sec. Thus, it is effective to keep the range of heat pump’s power consumption between 30kW and 40kW when compensating power fluctuation. This range corresponds to range of 55% to 85% of the heat pump’s rated power consumption.

5 Conclusion

In this paper, basic characteristics of heat pump air conditioner are measured by experiment and its results are shown to analyze the feasibility of using the heat pump for power fluctuation compensation.

The COP characteristic shows that when the power consumption of the heat pump is above 50% of the rated power consumption, the value of COP is not affected so much even if its power consumption is changed. Thus, the control of heat pump’s power consumption will not affect heat pump’s efficiency when it is used in this region.

The Bode diagram of the heat pump’s power consumption and processed heat is plotted based on the result of sinusoidal reference signal test. The diagram shows that when heat pump is operated in the range of 55% to 85% of its rated power consumption, it can compensate power fluctuation whose period is from 267sec to 30sec.

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References


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