FUTURE CONSUMED POWER ESTIMATION OF TIME DEFERRABLE LOADS FOR FREQUENCY REGULATION

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ABSTRACT

In order to restrict the frequency fluctuation caused by the fluctuating or uncontrollable output of dispersed generators, load control is cost-effective and reasonable. An algorithm to control time deferrable loads with the minimum inconvenience of the users has been developed, which needs the estimation of a future consumed energy. In this paper, It has been investigated how to estimate the energy in such loads as electric water heaters and air conditioners.

INTRODUCTION

Connection of a large number of dispersed generators to distribution networks is not easy due to various technical considerations. One of the serious problems is the increase of the frequency fluctuations due to the imbalance between demand and supply, which is caused by the fluctuating or uncontrollable output of dispersed generators. In fact, the extensive penetration of wind energy has been limited by an electric power utility in an area in Japan. Therefore, it is necessary to develop some ways to manage for demand and supply balancing of the whole electric power system. Although distributed storage devices such as secondary batteries, supercapacitors, flywheels, and SMES [1] have all been considered for frequency control, mass installation of them is very expensive and not realistic at the present time.

In order to solve this problem, load control is cost-effective and reasonable. In Japan, air conditioners and electric water heaters have been popularized widely, and their potential for the load frequency control is enough. Some algorithms for the load control have been proposed [2,3] and it has been used in some islands successfully. However, for example, the electric power system on Rum Island, where the load control has been adopted [4], has large heating demands in a castle and its load configuration is unusual in comparison with the mainlands. Thus it is necessary to develop the load control methods for general electric power systems.

We have developed an algorithm to control such time deferrable loads with the minimum inconvenience of the users. The loads consume electric energy at high-frequency situation and stop it at low-frequency situation under the restriction that required energy must be input within prescribed time. We have demonstrated by numerical analyses that its frequency regulation ability is high enough [5]. In the algorithm, it is necessary to estimate a future consumed energy required during a period. Therefore, it is investigated in this paper how to estimate the energy in the time deferrable loads.

ELECTRIC WATER HEATER

Electric water heaters (EWHs) are set for residential hot-water supply. Typical EWH has a water volume of 370 litters and a heater of 4.4 kW, which heats the water at night up to about 85°C in winter and 55°C in summer. The conventional EWHs consume the electric power constantly during working periods within nightly 8 hours (from 23:00 to next 7:00), and the required heating time t_{req} depends on the remainder hot-water volume and the inlet water temperature. That is, at present, EWHs are anticipated to act not for keeping the demand and supply balance but for only improving the load factor in the whole electric power system. About three millions of EWHs have been penetrated and the total capacity is about 10 GW, which is about 1/20 of total capacity of whole generation in Japan [6].

Control Algorithm

In this section, the load-control algorithm for EWHs is introduced briefly. Each EWH consumes $p_{\min} \cong 0$ kW during off state and $p_{\max}$ (heater power) during on state. Future consumed energy $e_{\mathrm{req}}(0)$ which is required by prescribed heating-end time t_{limit} ($t_{\mathrm{limit}} \leq 8$ h) to heat the water up to prescribed temperature T_{last} is calculated as $e_{\mathrm{req}}(0) = p_{\max} \cdot t_{\mathrm{req}}$. The future average consumed power p_{tar} and the future average consumed ratio γ at each time t are defined as

$$p_{\mathrm{tar}}(t) = \frac{e_{\mathrm{req}}(t)}{t_{\mathrm{limit}} - t} = \frac{e_{\mathrm{req}}(0) - \int_0^t p(t)dt}{t_{\mathrm{limit}} - t} \qquad (1)$$

$$\gamma(t) = \frac{p_{\mathrm{tar}}(t) - p_{\min}}{p_{\max} - p_{\min}} \qquad (2)$$

where $p(t)$ indicates the consumed power at time t ($p(t) = p_{\min}$ or $p_{\max}$). The range of $\gamma(t)$ is $0 \leq \gamma(t) \leq 1$. $\gamma(t)$ decreases while $p(t) = p_{\max}$, and increases while $p(t) = p_{\min}$. If $\gamma(t)$ has decreased to zero, the EWH cannot be heated any more. If $\gamma(t)$ has increased to one, the EWH cannot stop to be heated any more till $t = t_{\mathrm{limit}}$. These restrictions satisfy user's demand on this EWH.

Each EWH measures frequency error Δf, and they decide to switch or not. Here, Δf_{h} and Δf_{l} are calculated as $\Delta f_{\mathrm{h}} = \Delta f_{\mathrm{th}} \cdot (1-\gamma(t))$ and $\Delta f_{\mathrm{l}} = -\Delta f_{\mathrm{th}} \cdot (1-\gamma(t))$, respectively, where Δf_{th} is the prescribed threshold of frequency error for load control. If $\Delta f > \Delta f_{\mathrm{h}}$, the EWH turns on and starts to be heated. If $\Delta f < \Delta f_{\mathrm{l}}$, the EWH turns off and stops to be heated. By these actions, the total consumed power $P_{\mathrm{EWH}} \equiv \Sigma p$ by whole EWHs in the electric power system is adjusted to reduce Δf.

In the case of such on-off controlled type of loads as EWHs, it is necessary for a system operator to adjust the number of on-state EWHs in the electric power system. Because the deviation of the total consumed power $P_{\rm EWH}$ must be avoided for effective load frequency control, nevertheless each consumed power p of each EWH is always one-sided ($p_{\rm min}$ or $p_{\rm max}$) [5].

Experiment

Apparatus. An EWH of 150-litters water storage with 2.1-kW heater has been prepared. In EWHs, hot water flows out from the upper part and cold water inlets from the lower part when the heated water is used, and they are not mixed easily. Its remaining water temperature is measured using thermistors which are set on the outer surface of the tank. In this EWH, 8 thermistors have been set with vertically distributed arrangement at regular intervals (#1~#8) in order to measure the temperature distribution (T_1~T_8) of stored water. Both inlet and outlet water temperature ($T_{\rm in}$, $T_{\rm out}$) and ambient temperature ($T_{\rm amb}$) are also measured. A flow meter is set in the water outlet side. The configuration of this apparatus is shown in Fig. 1.

Heat radiation. The stored water was heated once and kept for 3 days. By this test, the time constants t_{ci} of heat radiation at #i were measured: t_{c1} = 92.3 h, t_{c2} = 92.1 h, t_{c3} = 91.9 h, t_{c4} = 91.1 h, t_{c5} = 90.6 h, t_{c6} = 86.6 h, t_{c7} = 74.9 h, t_{c8} = 61.8 h. This result indicates that the lower-part water cools down earlier, and these time constants of this 150-litters EWH are smaller than that of typical 370-litters EWHs.

Stored energy estimation. The EWH was operated as follows: First, half of heated water was used, and after that whole water was heated intermittently. This operation imitates the situation that the consumed power of the EWH is controlled for the load frequency control. It is necessary to estimate the stored thermal energy $e_{\rm str}(t)$ in this situation in order to use the proposed load-control algorithm. Once this $e_{\rm str}(t)$ is known, future consumed energy $e_{\rm req}(t)$ in Eq. (1) is approximated easily as

$$e_{\rm req}(t) = \{cmL_{\rm tot}(T_{\rm last} - T_{\rm in}) - e_{\rm str}(t)\}/\eta \qquad (3)$$

where η is heating efficiency, and c, m and $L_{\rm tot}$ are the specific heat, the density and the volume of stored water, respectively. Typically $\eta \cong 0.9$ and the loss is caused by drainage due to thermal expansion, and so on. Heat radiation is not considered in Eq. (3).

Stored thermal energy is estimated from both the temperature distribution and power balance. By the temperature distribution, $e_{\rm str}(t)$ is estimated as

$$e_{\rm str}(t) = cm\sum_{i=1}^{n} L_i (T_i - T_{\rm in}) \qquad (4)$$

where n is the number of thermistor to measure the stored water temperature, L_i ($i \geq 2$) is partial water volume between thermistor #i and #(i+1), and $L_1 = L_{\rm tot} - \sum_{i=2}^{n} L_i$. On the other hand, by the power balance, $e_{\rm str}(t)$ is estimated as

$$e_{\rm str}(t) = e_{\rm str}(0) - cm(T_{out} - T_{\rm in})\int_0^t F dt + \eta\int_0^t p dt - cm\int_0^t \left\{ \sum_{i=1}^{8} L_i \frac{(T_i - T_{\rm amb})}{t_{ci}} \right\} dt \qquad (5)$$

where F is the flow rate of hot water outlet. In Eq. (5), the second, third and last terms in the right-hand side indicate the power output with hot water, the electric power input, and the heat radiation, respectively.

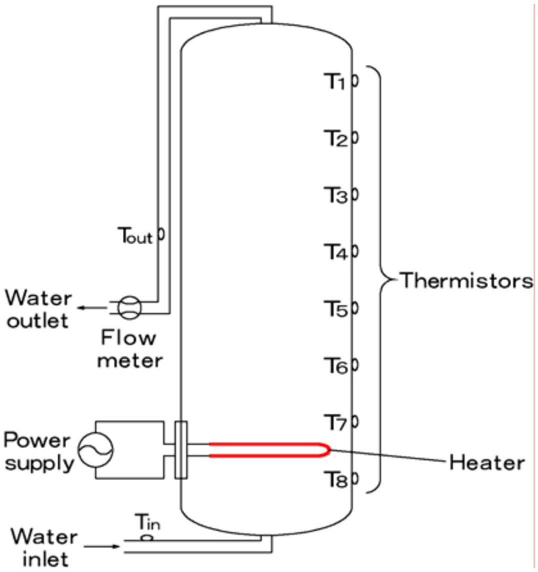


Fig. 1 Configuration of tested EWH and sensors

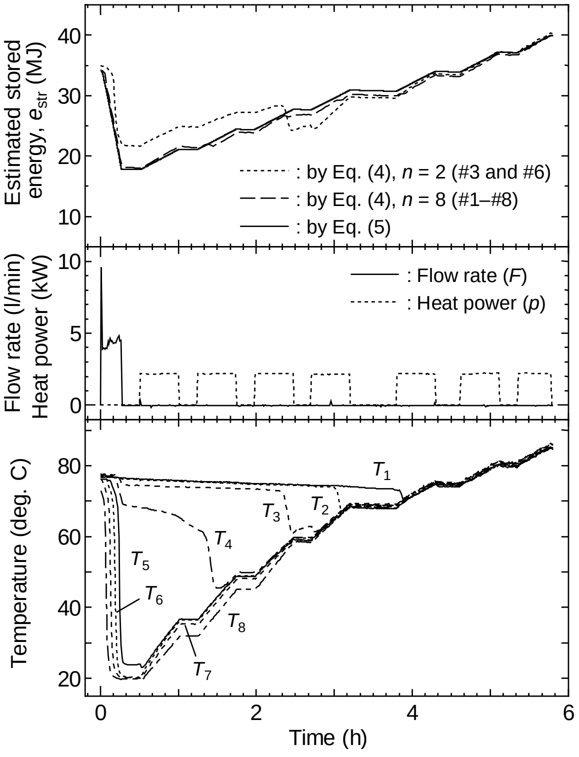


Fig. 2 Intermittent heating after half dissipation in EWH

Fig. 2 shows water temperature T_1~T_8, flow rate F, heat power p and estimated stored energy $e_{str}(t)$ during this operation. In the estimation by Eq. (5), η is set to 0.889 in order to adjust the final $e_{str}(t)$ to the values by Eq. (4). Since two curves of $e_{str}(t)$ which are estimated by different methods (by Eq. (4) with $n = 8$ and by Eq. (5)) are very similar in Fig. 2, it has been demonstrated that the stored energy can be estimated precisely from the temperature distribution when at least 8 thermistors have been utilized. Furthermore, since the error of $e_{str}(t)$ by Eq. (4) with $n = 2$ is also not so large, there is a possibility that $n < 8$ is enough for this estimation. In conclusion, the future consumed energy of EWHs can be estimated using some thermometers with high accuracy.

AIR CONDITIONER

Air conditioners are used to keep room temperature and humidity comfortable. In Japan, they have become widely used and the greatest factor of the highest electric demand in summer. It is said that cooling load increases 4.5 GW in the whole of Japan when air temperature rises 1°C at peak demand time in summer. Furthermore, a survey shows that about 80% of users are tolerable for 10 minutes' shut down of air conditioners [7]. Therefore, control of the air conditioners is a promising method for frequency regulation, as the power consumption for air conditioning has a very high ratio in the total demand and it is adjustable for a short time.

Control Algorithm

In this section, the load-control algorithm for inverter-driven air conditioners (IACs) is introduced briefly. The largest difference of IACs from EWHs in regard to load control is that IACs are able to adjust their consumed power p in succession and avoid the deviation of p for itself. Thus each IAC make $p(t)$ approached $p_{tar}(t)$ while the frequency error Δf is not so large ($\Delta f_l \leq \Delta f \leq \Delta f_h$). The flowchart to decide p of IACs is shown in Fig. 3. The parameters α and β in Fig. 3 should be set to $0 < \beta << \alpha < 1$. By this control, the total consumed power $P_{IAC} \equiv \Sigma p$ by whole IACs in the electric power system is adjusted to reduce Δf.

In the case of such continuously controlled type of loads as IACs, the order from the system operator is not necessary. Because the deviation of the total consumed power P_{IAC} doesn't occur, since each consumed power p of each IAC is controlled to be balanced automatically for itself [8].

Experiment

Apparatus. In order to know the characteristics of practical IACs, a test room was prepared. The room has a floor space of 50 m^2, a ceiling height of 2.7 m, windows on the northeast side, and it is located in our institute. The IAC system consists of a 2.35-kW inverter-driven compressor unit and two indoor heat exchanger units. IAC operates in air cooling mode, and three thermistors are utilized to measure the temperature of outdoor (T_{t1}), air-inlet of an indoor unit (T_{t2}) and a side of a remote controller (T_{t3}) during the experiment. The height of thermistors for T_{t2} and T_{t3} is 2.5 m and 1.55 m from the floor, respectively. No heavy load had been used in the room and the sunshine injection had been interrupted by blinds for the experiment.

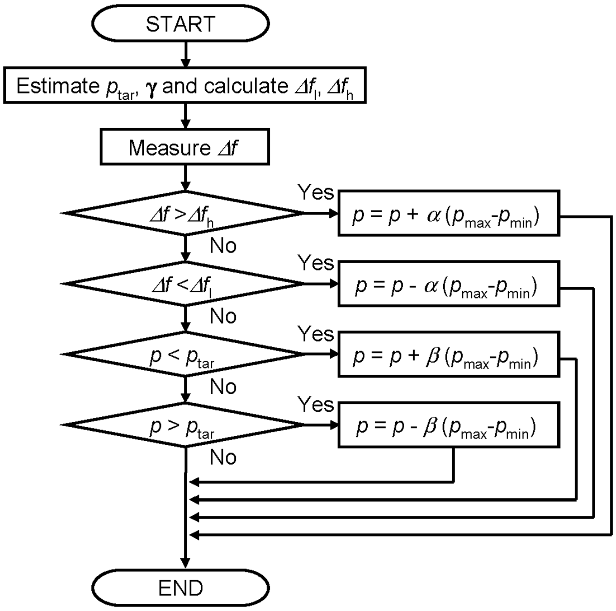


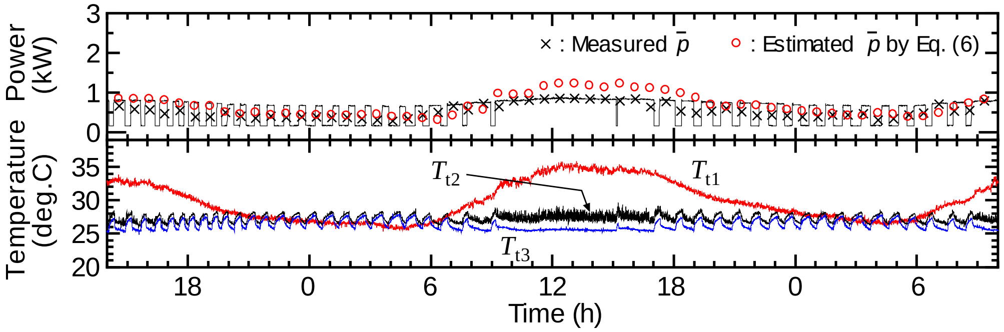
Fig. 3 Procedure to control loads with successive consumed power

Operation characteristics. Time variation of consumed power in the IAC and temperature are shown by curves in Fig. 4. From Fig. 4,

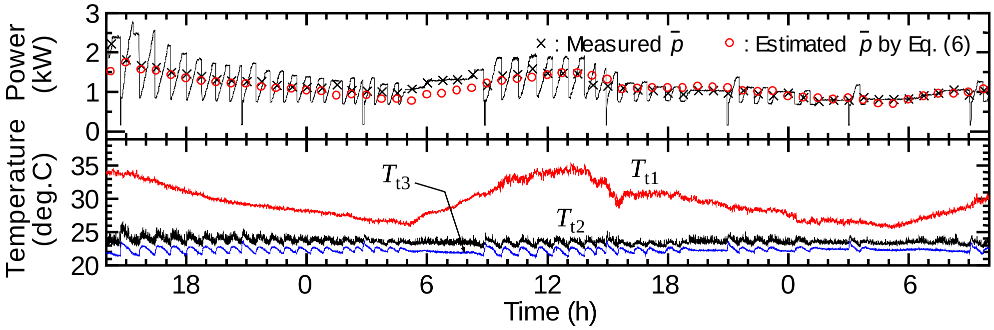
- IAC consumes 150 W at the blower mode and at least 700 W at the compress mode. Consumed power p had never been 150 W < p < 700 W. When the laying temperature T_{set} is high, the room temperature had been controlled by the on-off operation of the compressor.
- When the laying temperature T_{set} is low, p had repeated the sawtooth variation at intervals of about 45 minutes (to increase gradually and to drop suddenly to 700 W).
- When p was high, the room temperature difference T_{t2}-T_{t3} was high.

Future Consumed Power Estimation. It has been described that the detailed physical modelling based on energy balance is necessary for the precise estimation of required power in air conditioners [9]. For the physical modelling, many parameters are needed such as temperature evolution, the solar radiation, thermal capacity and thermal resistance of the walls, air, furniture, and so on. However, easily obtained parameters in air conditioners are, in general, only temperature evolution (T_{t1}, T_{t2}, T_{t3}) at the most. Thus it was tried to estimate the future consumed power from the previous records of temperature evolution empirically.

First, the averages of room temperature T_{room} (=T_{t2}), outdoor temperature T_{out} (=T_{t1}) and consumed power p were calculated over the 45 minutes interval. The data on July 23-29 was used for the calculation, and T_{set} = 26 on July 27-29, which is not shown in Fig. 4. After that, the coefficients in Eq. (6) were asked by least-squares method.



(a) July 23-25, T_{set} = 28°C



(b) July 25-27, T_{set} = 24°C

Fig. 4 Time variation of consumed power in IAC and temperature

$$\bar{p} = \xi\left(\bar{T}_{out} - \bar{T}_{room}\right) + \psi\left(T_{set} - \bar{T}_{room}\right) + \zeta \qquad (6)$$

where over bar signifies the average value. The coefficients were calculated as ξ = 89.0, ψ = -383.8, ζ =711.7. This result means that this IAC consumes 712 W even if T_{out} = T_{room} and T_{set} = T_{room} in order to remove the stored heat in the walls and furniture. The average of error $\left|\bar{p}_{eq6} - \bar{p}\right| / \bar{p}$ is 25%, where $\bar{p}_{eq6}$ is average consumed power calculated by Eq. (6). $\bar{p}$ and $\bar{p}_{eq6}$ are also shown in Fig. 4 with marks × and ○, respectively. The future consumed power p_{tar} can be roughly estimated by replacing the parameters of Eq. (6) as $p_{tar} = \xi (T_{t1}-T_{t2}) + \psi (T_{set}-T_{t2}) + \zeta$ in a steady state. Eq. (6) is not available in a transient state since it doesn't consider the thermal capacity. Although we had tried to consider it with the other method, the result was still not satisfying [8].

CONCLUSION

Future consumed power estimation of time deferrable loads for frequency regulation has been performed using practical equipment. Its accuracy has been enough in the case of the electric water heater using some thermometers. Empirical estimation using previous records of temperature evolution has resulted in 25% error in the case of the air conditioner.

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