A PROPOSAL OF AVERAGE-CONSENSUS-BASED LOAD CONTROL REDUCING UNFAIRNESS IN USE OF CUSTOMERS' LOADS

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ABSTRACT

This paper proposes an application of multi agent system to drawing coordinated behaviour from many controllable customers' appliances in order to support primary control and secondary control by modulating the consumption power of customers' appliances. The mechanism of the support is that a load controller installed in each customer's building modulates the consumption power when the frequency deviation measured locally by the controller exists within an assigned range, so that a similar effect of proportional control on frequency is created in overall power system. A problem caused by the load control system is unfairness in use of customers' appliances if the assigned ranges of frequency deviation are fixed to specified customers' appliances. In order to solve the problem, an application of average consensus algorithm (ACA), which is a method for multi agent system, to the load control system is proposed.

INTRODUCTION

Primary control and secondary control which are mainly provided by thermal generation units are last resorts to eliminate imbalance between generation and demand and to maintain system frequency at a nominal value. However, it will be difficult for those control systems to work fully because spinning reserve is short due to replacement of the thermal generation units with intermittent renewable energy sources such as photovoltaic generation and wind power generation. Therefore, it is necessary for power system operators to procure the other resources regulating balance between generation and demand. One of the resources is demand response [1].

This paper proposes an application of multi agent system to drawing coordinated behaviour from many controllable customers' appliances such as heat pumped air conditioners and electric vehicles in order to support primary control and secondary control by modulating the consumption power of customers' appliances. The mechanism of the support is as follows: A load controller installed in each customer's building modulates the consumption power when the frequency deviation measured locally by the controller exists within an assigned range, so that a similar effect of proportional control on frequency is created in overall power system. A problem caused by the load control system is that unfairness exists in use of customers' appliances if the assigned ranges of frequency deviation are fixed to specified customers' appliances. In order to solve the problem, an application of average consensus algorithm (ACA), which is one of the control methods for multi agent system [2], to the load control system is proposed.

AUTONOMOOUS DECENTRALIZED LOAD CONTROL AND ITS PROBLEM

Balancing Mechanism

In order to describe the autonomous decentralized load control (ADLC) studied by the authors, firstly, mechanism to maintain balance between generation and demand is explained briefly. The following equations are valid under the assumptions that all generators connected to transmission network are synchronously operated in an isolated power system, and voltage and power flows on the network are within their normal ranges.

$$\mathrm{M}\frac{d\Delta f}{dt} = \Delta P_m - \Delta P_e \quad (1)$$
$$\Delta P_m = -K_{Gov}\Delta f - K_I \int \Delta f dt \quad (2)$$
$$\Delta P_e = D\Delta f + \Delta L - \Delta P_{RES} \quad (3)$$

where M is system inertia constant, Δf is frequency deviation, and ΔP_m and ΔP_e are fractions of total mechanical and electrical power of all the generators, respectively. K_{Gov} is a governor control gain of the equivalent generator expressing all the generators, K_I is integral control gain of secondary control (LFC), D is a coefficient of frequency characteristics of total load, ΔL is a fraction of frequency-independent load and ΔP_{RES} is a fraction of total power output of renewable energy sources. In normal state, random changes of ΔL and ΔP_{RES} cause imbalance between ΔP_m and ΔP_e, so that Δf fluctuates and activates primary control and secondary control so as to eliminate the imbalance and the frequency deviation.

In order for primary control and secondary control to function completely, enough spinning reserve is necessary [3]. When the spinning reserve is short, those control cannot work fully, so that some measures to compensate for the lack of the control function are required. One of the measures is direct load control.

Concept of ADLC

When a direct load control system is designed to assist primary control and secondary control, we should carefully consider how the load control affects the convenience of customers' appliances for use. Since customers would dislike long and steady stop or unnecessary use of their appliances forced by the load control, a proportional control system of which the output signal changes temporarily in response to an input signal would be suitable for the load control compared with an integral control system of which the output changes with a bias. Therefore, the load control studied by the authors is based on proportional control and uses the part of the frequency-independent load ΔL as controllable load shown in the following equation.

$$\Delta L_c = K_{LC}\Delta f \tag{4}$$

where ΔL_c is total load under direct load control and K_{LC} is proportional control gain of the load control.

There are two approaches to form the load-frequency characteristics of Eq. (4) from a lot of customers' appliances. One of the approaches is to design the individual appliances to have the characteristics. If such appliances are produced and widely used, then the coefficient D in Eq. (3) increases, that is the frequency-dependent load $D\Delta f$ assists further primary control.

The other approach, which is studied by the authors, is to form approximately the characteristics of Eq. (4) by switching a lot of customers appliances on or off according to the magnitude of system frequency deviation Δf . In other words, as shown in Fig. 1(a), the consumption power of each customer's load is modulated autonomously by a load controller, which is called Customer Agent (CA) in this paper, with local measurement of the frequency deviation. When the measured frequency deviation exists within assigned ranges, the CA is activated and the customer's load changes according to the following equations.

$$\Delta L_{c\_n} = \begin{cases} \Delta L_n^+ \left(\Delta f \geq \Delta f_{th\_i}^+\right) \\ 0 \left(\Delta f_{th\_i}^+ > \Delta f > \Delta f_{th\_i}^-\right) \\ -\Delta L_n^- \left(\Delta f \leq \Delta f_{th\_i}^-\right) \end{cases} \tag{5}$$

where ΔL_{c_n} is modulated consumption power of customer #n, ΔL_n^+ and ΔL_n^- are increments of consumption power of customer #n when its load is increased or decreased respectively and $\Delta f_{th\_i}^+$ and $\Delta f_{th\_i}^-$ are thresholds of frequency deviation for customer group #i to be activated.

If all customers participating in the load control system are clustered into m groups, and a pair of intervals of frequency deviation $[-\infty, \Delta f_{th\_i}^{i}]$ and $[\Delta f_{th\_i}^+, \infty]$ (j=1, 2, …, m, $0 > \Delta f_{th\_i}^- > \Delta f_{th\_i+1}^-$, $0 < \Delta f_{th\_i}^+ < \Delta f_{th\_i+1}^+$) is assigned to one of the customer groups, then it is expected that load-frequency characteristics like a flight of stairs in Fig. 1(b) are formed from the m customer groups. The characteristics will converge the dotted line with a slope K_{LC} as the number of the groups increases. In the stairs, magnitude of one step corresponds to the sum of the modulated consumption power of the customers belonging to the customer group #i as shown in the following equation.

$$\Delta L_{CG\_i} = \sum_{n \in \Omega_i} \Delta L_{c\_n} \tag{6}$$

where Ω_i denotes a set of the customers belonging to customer group #i.

Unfairness in Use of Customers' Loads

An important problem with implementing the abovementioned ADLC is that a bias in use of customer's appliances arises. In the ADLC system, the activation ranges defined by Eq. (5) are assigned to the appliances in the individual customer groups. The appliances which are assigned the range partitioned by smaller thresholds of frequency deviation $\Delta f_{th\_i}^-$ and $\Delta f_{th\_i}^+$, modulate frequently their consumption power in response to small frequency deviation compared with the appliances assigned the ranges partitioned by the larger thresholds. This means that the former are used for a long time in comparison with the latter as shown in Fig. 2. According to [4], smaller customers usually prefer purchasing electricity at a constant price to buying it at a variable price on a wholesale market. Similarly, if the customers participating in the ADLC system prefer a constant price for the ancillary service of primary control and secondary control to a variable price depending on the contribution to the control, then such bias in use of customers' appliances will result in unfairness among the customers.

ADLC REDUCING THE UNFAIRNESS

An Approach to Relieving the Unfairness

The abovementioned unfairness comes from the fixed assignment of activation ranges of frequency deviation.

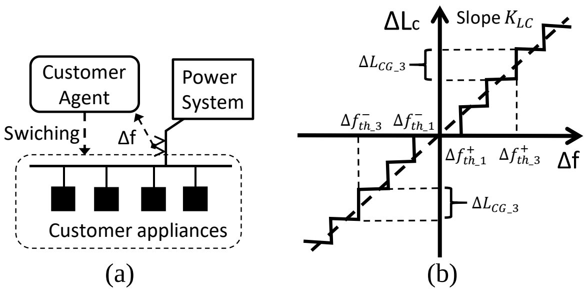


Fig. 1 A concept of ADLC

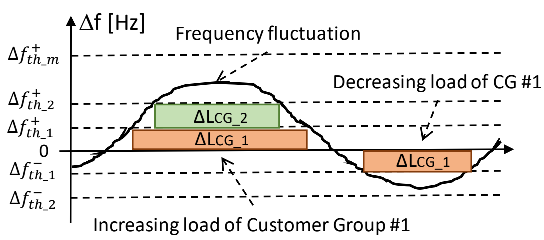


Fig. 2 Unfairness in use of customers' loads

One of the measures to relieve the unfairness is to make the assignment of activation range flexible. In order to perform it, first we should define an index representing the contribution of customer to the ADLC to evaluate the unfairness quantitatively. In our study, such index is defined as average energy used for modulation of consumption power of customers' appliances during some period with respect to customer group #i by the following equation.

$$AE_i = \int_{t_k}^{t_k+T_c} \frac{|\Delta L_{CG\_i}|}{t} dt \quad (7)$$

where t_k is time when the evaluation of energy used for the ADLC begins at in the kth evaluation turn and T_c is time interval for the evaluation.

If the number of the customers belonging to a customer group is the same among all customer groups, and magnitudes of the modulated consumption power ΔL_n^+ and ΔL_n^- in Eq. (5) are the same among all customers, in addition, AE_i is equal to AE_j, then a customer in the group #i and a customer in the group #j make the same contribution to the ADLC.

Next, we explain how to perform the flexible assignment of activation range by using the index AE_i. It is expected that the index AE_i decreases as the threshold of frequency deviation Δf_{th_i} increases as shown in Fig. 3. Here, we assume that $\Delta f_{th\_i}^+$ is equal to $|\Delta f_{th\_i}^-|$ in Eq. (5), and Δf_{th_i} denotes those thresholds, that is $\Delta f_{th\_i} = \Delta f_{th\_i}^+ = |\Delta f_{th\_i}^-|$. The relation between AE_i and Δf_{th_i} comes from the hypothesis that the consumption power of the customers assigned smaller Δf_{th_i} tends to be modulated for a long time compared with the customers assigned larger Δf_{th_i}. If the relation can be expressed as an approximated function, the replacement of the activation ranges for customer group #i is carried out in the following procedure.

P1) Compute average AdL with respect to the index values AE_i of all customer groups.

P2) Compute a value $\Delta \hat{f}_{th\_i}^{new}$ corresponding to $\mathrm{AE} = \mathrm{AdL} - (AE_i - AdL)$ by using the approximated function in Fig. 3, and find out a new threshold $\Delta f_{th\_i}^{new}$ which is close to $\Delta \hat{f}_{th\_j}^{new}$.

P3) The new activation range defined by the new threshold $\Delta f_{th\_i}^{new}$ is assigned to the customer group #i.

The cyclic replacement of activation range will result in equalization of AE_i among all customer groups from a long term viewpoint, that is the unfairness in use of customers' appliances for the ADLC will be relieved.

An Application of Average Consensus Algorithm

The abovementioned procedure to replace the activation range of a customer group with a new activation range is developed on the assumption that the index AE_i and the threshold Δf_{th_i} of all customer groups can be collected at one place. However, in our study, the replacement of activation range is carried out in the decentralized manner by each customer group. In the ADLC to be mentioned subsequently, which is called Consensus Load Control (CLC) in this paper, it is assumed that there exists an agent for an individual customer group, which is called Customer Group Agent (CGA). As shown in Fig. 4(a), CGA #i sends a threshold Δf_{th_i} defining an activation range for load modulation to all CAs belonging to the customer group #i. Then it collects the data of modulated load ΔL_{c_n} of all the customers from CAs. In addition, CGA #i computes the index AE_i by using the data of modulated load ΔL_{c_n} collected from the customers, and exchanges the data AE_i and Δf_{th_i} with only the adjacent CGAs, for instance, CGA #j and CGA #k as shown in Fig. 4(b), which are connected directly to CGA #i through communication links.

Since each CGA can obtain the information about AE and Δf_{th} of the adjacent CGAs, CGA #i can replace autonomously the activation range with a new one by applying average consensus algorithm ACA in the following procedure.

P1') Estimate the average AdL by using the following equation expressing ACA.

$$\begin{cases} AdL_i(k) = AdL_i(k-1) + r_i \sum_{j \in N_i} a_{ij} \left(AdL_i(k-1) - AdL_j(k-1) \right) \\ AdL_i(0) = AE_i, \text{and } AdL_j(0) = AE_j \end{cases} \quad (8)$$

where $AdL_i(k)$ is estimation of AdL by CGA #i at the k th data exchange with the adjacent CGAs, a_{ij} is i-j element of graph laplacian expressing topology of communication links among CGAs, r_i is a certain positive real number and

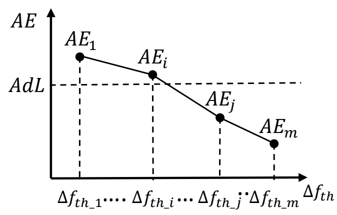


Fig. 3 Relation between AE_i and Δf_{th_i}

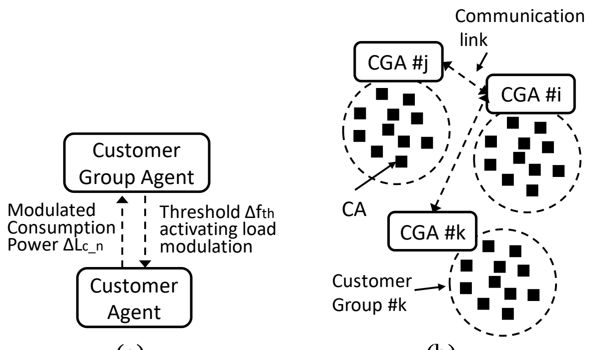


Fig. 4 Customer group agent

N_i is the number of the adjacent CGAs of CGA #i.

When the number of data exchange k reaches a specified number n_{ACA} , the estimation process stops.

P2') Estimate a following linear function representing approximately the relation between AE and Δf_{th}.

$$AE = \beta_0 + \beta_1 \Delta f_{th} \tag{9}$$

Since CGA #i has its own data, AE_i and Δf_{th_i} and can obtain the data of the adjacent CGA #j, AE_j and Δf_{th_j}, the coefficient β_0 and β_1 can be computed by using those data and regression analysis.

P3') By using Eq. (9), compute a value $\Delta \hat{f}_{th\_i}^{new}$ corresponding to $AE = AdL_i(n_{ACA}) - \left(AE_i - AdL_i(n_{ACA})\right)$ with the following equation.

$$\Delta \hat{f}_{th\_i}^{new} = \Delta f_{th\_i} + \left(\frac{2}{\beta_1}\right)\left(AdL_i(n_{ACA}) - AE_i\right) \tag{10}$$

Then, find out a new threshold $\Delta f_{th\_i}^{new}$ which is close to $\Delta \hat{f}_{th\_j}^{new}$.

P4') CGA #i replaces the activation range with the new range defined by $\Delta f_{th\_i}^{new}$.

SIMULATION STUDY

A Model for Frequency Control

For simulation study, a simplified model in Fig. 5 is used which represents the mechanism of LFC neglecting inertia dynamics because the dynamics of CLC is slow in comparison with it. The parameters of the model are as follows: D is 2 % MW/Hz, the inverse of regulation 1/R is 10 %MW/Hz, the frequency bias factor K_B is 12 %MW/Hz and the integration time constant T_I is 50 sec. It is assumed that the magnitude of the load change ΔL which LFC responds to is 5 % of a power system capacity, and ΔL changes like a sinusoidal curve with a time period of 30 min because it is easy to check the effectiveness of CLC.

Parameters for CLC

In order to illustrate clearly the activation range replacement, it is assumed that there exist four customer groups of which CGAs are connected with the adjacent ones as shown in Fig. 6, and the communication time delay is neglected. The magnitude of modulated load ΔL_{CG_i} of each customer group is set at 0.2 %. The thresholds of frequency deviation Δf_{th_i} in Eq. (5) which determine the frequency-load characteristics in Fig. 2 are assigned initially as follows: Δf_{th_1}=0.015 Hz, Δf_{th_2}=0.03 Hz, Δf_{th_3}=0.045 Hz and Δf_{th_4}=0.06 Hz. In simulation, ACA starts every 40 min and the average AdL_i is estimated with Eq. (8) by each CGA during 20 min, and then the activation range is updated autonomously based on the procedure described in the previous section.

Results of Simulation

The simulation of CLC was carried out. The duration is 180 min (10800 sec). Frequency deviation as shown in Fig. 7 is reduced by CLC in comparison with that of no CLC. However, the CLC causes repeatedly transient at the time when the load modulation occurs. This is because the load change is a step. We should improve the load modulation so as not to cause such transient.

Fig. 8 shows the modulated loads ΔL_{CG_i} and the indices AE_i of the customer groups. The activation range replacement is carried out every 40 min (2400 sec). For example, activation range of CGA #1 is replaced alternately with that of CGA #4, so that the situation where AE_1 is largest and AE_4 is smallest and the contrary situation appear alternately. The activation range replacement by CLC can equalize the energy used for load modulation $E_{ci} = \int_0^t \left|\Delta L_{CG\_i}\right| d\tau$ among the customer groups as shown in Fig. 9. Therefore, CLC is effective to reduce the unfairness in use of customers' appliances for compensation of the lack of primary and secondary control function.

Fig. 10 shows some parameters associated with the procedure of activation range replacement based on ACA described in the previous section. The average of the index AE_i , AdL can be estimated at the same value by all CGAs, and also the similar coefficient β_1 in Eq. (9) can be estimated by individual CGAs. Consequently, the individual CGAs compute the value $\Delta \hat{f}_{th\_j}^{new}$ suitable for finding the new thresholds $\Delta f_{th\_i}^{new}$ every 2400 sec by using Eq. (10). The changes in the activation ranges are shown in Fig. 10(c).

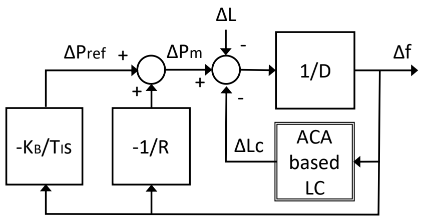


Fig. 5 A simplified model of LFC with CLC

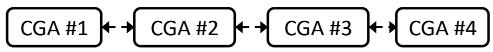


Fig. 6 A topology of communication links among CGAs

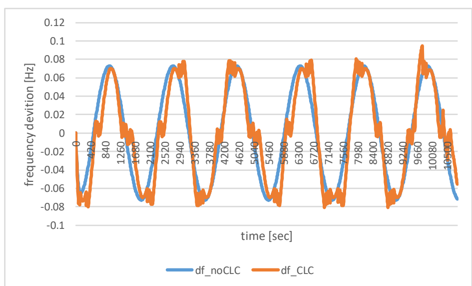
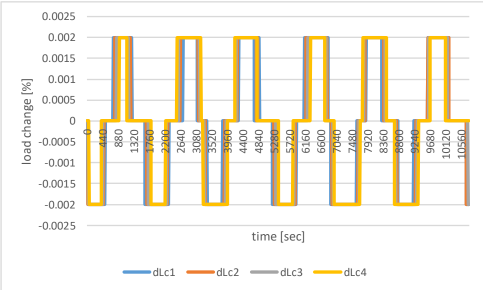
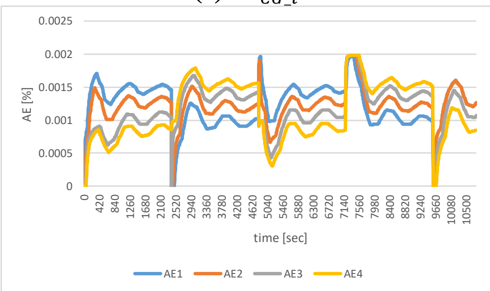


Fig. 7 Frequency deviations w/o and with CLC

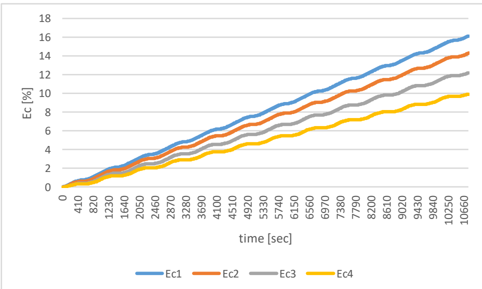


(a) ΔL_{CG_i}

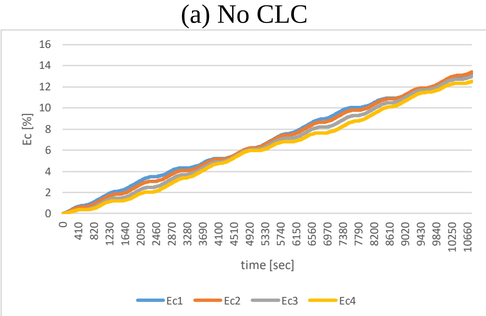


(b) AE_i

Fig. 8 Modulated loads ΔL_{CG_i} and index AE_i

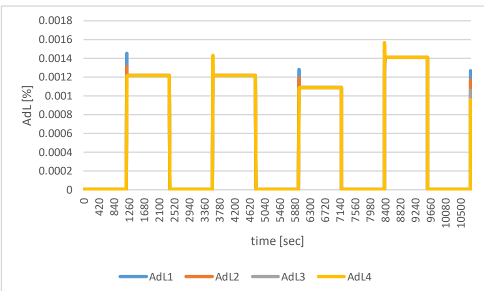


(a) No CLC

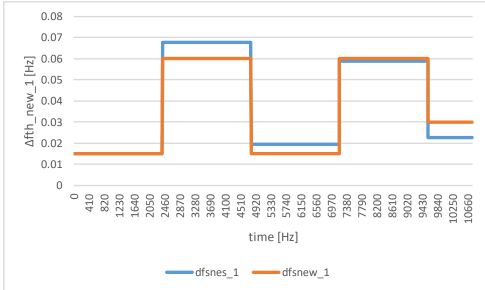


(b) CLC

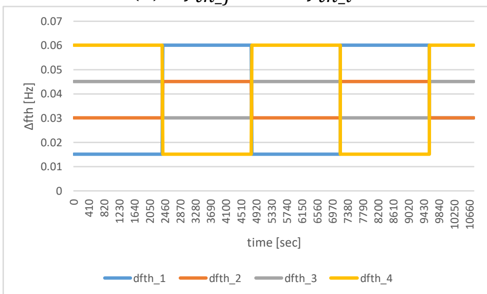
Fig. 9 Energy used for load modulation



(a) Estimation of AdL by CGA



(b) $\Delta\hat{f}_{th\_j}^{new}$ and $\Delta f_{th\_i}^{new}$



(c) Changes in activation ranges

Fig. 10 Parameters of activation range replacement

CONCLUSIONS

A novel method was proposed which can relieve the unfairness in use of customers' appliances for the load control assisting primary control and secondary control. The simulation result illustrates the potential of average consensus algorithm to make it possible that the activation range replacement is carried out in the decentralized manner so as to equalize the contribution of customer to ancillary service. The future works are to consider time delay of communication links and to analyse the effect of the number of customer groups and the variation of communication link topology on the performance of CLC.

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