

Dynamic Characteristic of a Fuel Cell Micro-Grid Using an Engine Generator to Base Load Operation*

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Abstract

The dynamic of a micro-grid consisting of an engine generator and sixteen fuel cells was clarified by the transfer function model using actual data from power generators. The micro-grid was composed of a 3kW engine generator and 1kW fuel cells, and the dynamic characteristics of the grid were analyzed using the energy demand model in February of a cold region. Consequently, the settling time (Time taken to converge on $\pm 5\%$ of the limit of an output target) of a micro-grid is 15 seconds from 10 seconds. The control parameter of a fuel cell system is significantly influenced by the settling time and overshooting of a micro-grid. Since any excess and deficiency in electric power can respectively be covered if two or more fuel cells are connected with a grid, the instant electric power demand load peak can be distributed. Compared with the number of fuel cells required when installing independently, the number of installations can be reduced for a micro-grid system.

Key words: Fuel Cell, Power Plant, Control Device, Dynamic Programming, Optimum Design, Energy Network

1. Introduction

As for a micro-grid technology⁽¹⁻³⁾, small units of energy equipment, such as engine generators and fuel cells, are connected to an energy network and the reduction of carbon dioxide gas emissions, peak cut and power backup in an emergency, etc. can be relied upon with the cooperative operation of such equipment. The varieties include an "interconnection type with power networks, such as commercial power" and an "independent network system" within the micro-grid component. This paper describes both the interconnection grid and independence grid types. With the interconnection grid type, electricity sales to utilities can be carried out via a commercial system. If the power can be stabilized and supplied to the commercial system, this type contributes to reducing the peak of an electric power plant. As regards the independence grid type, even if the power generator fails, the shortfall can be covered by other equipment. Therefore, although the interconnection grid type is used for the emergency power source of a wide area, the independence grid type is used for an emergency power source in a local area. When the supply-and-demand balance of the power is not well-matched, a reduction in the power quality within the micro-grid becomes problematic. The voltage and frequency become unstable when the power supply in the grid is unable to respond to the speed of demand and such instabilities are described as a "Dropping of the power quality" in this paper. In the interconnection grid type, the grid voltage and frequency are controlled to be synchronized with commercial power. Therefore, when the interconnection grid type is used, power quality can be maintained comparatively

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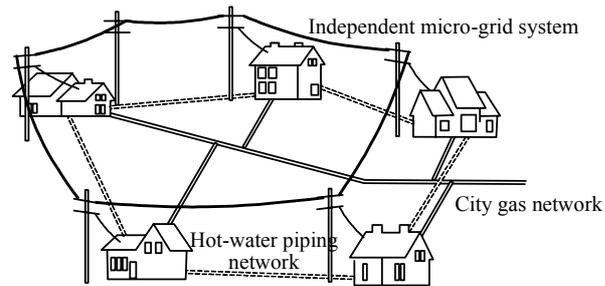


Fig. 1 Fuel cell energy network system

easily⁽⁴⁾. As for the independence grid type, a power generator connected to the grid is used as a basis, with which other power generators synchronize their voltage and frequency. Therefore, when the power quality of the basic power generator drops, there is the potential for the power quality of the overall grid to do likewise. Although the introduction of a battery can be considered as a possible measure, the cost of equipment is expensive and another issue arises. If the power demand within the independence grid type is subject to rapid fluctuation, two or more power generators will be operated so that this fluctuation may be followed. In this case, there is thought to be a significant influence on power quality and depending on the response characteristic of each power generator, the power quality of the grid changes significantly. Therefore, in this paper, the details of the dynamic characteristics of a fuel cell micro-grid at the time of installing an engine generator (EG) are investigated as a base load operation. Compared with a fuel cell, the EG equipment cost is low, and there are many introduction experiences. Generally, if a significant load fluctuation is added to EG, several seconds to tens of seconds will be required to stabilize the power⁽⁵⁾. Moreover, in order to maintain a high generation efficiency by EG, it is necessary to narrow the operation point (number of revolutions and load) as much as possible. In this study, EG is operated so that it may correspond to a fixed base load. Moreover, circumstances whereby a fuel cell is distributed and placed in two or more houses, and the micro-grid when these are made to operate in cooperation are examined. In this case, the fuel cells correspond to any fluctuation of the load. It is thought that the power output of the small-scale reformer now developed is stabilized for a short time compared with EG⁽⁶⁾. The dynamic characteristics of a micro-grid when installing a base load engine generator with a power generation capacity of 3kW in one house, and installing a fuel cell system with 1kW in 16 houses are investigated as an analysis case.

2. Micro-Grid Model

2.1 Power quality of a micro-grid

The independence micro-grid assumed in this paper is shown in Fig. 1 and the EG specification assumes a gas engine generator, while a proton exchange membrane (proton exchange membrane) is assumed for the fuel cell. Energy networks include the hot water piping network to implement the waste heat recovery of the distributed energy equipment, and the heat supply on each building. Moreover, there is a city gas network which supplies city gas to the reformer for fuel cells and the gas engine generator, consisting of power grids that supply power to each building. The power transported using the grid shown in Fig. 1 is based on the power output of a single power generator (basis power generator). Refer to the power output of the basis power generator for the voltage and frequency in the other power generator. On the other hand, the power of the interconnection grid type is controllable to synchronize with the voltage and frequency of the interconnection system. Therefore, the power quality of the interconnection grid type is stabilized by controlling the synchronization with the interconnection system, even in the event of rapid load fluctuation.

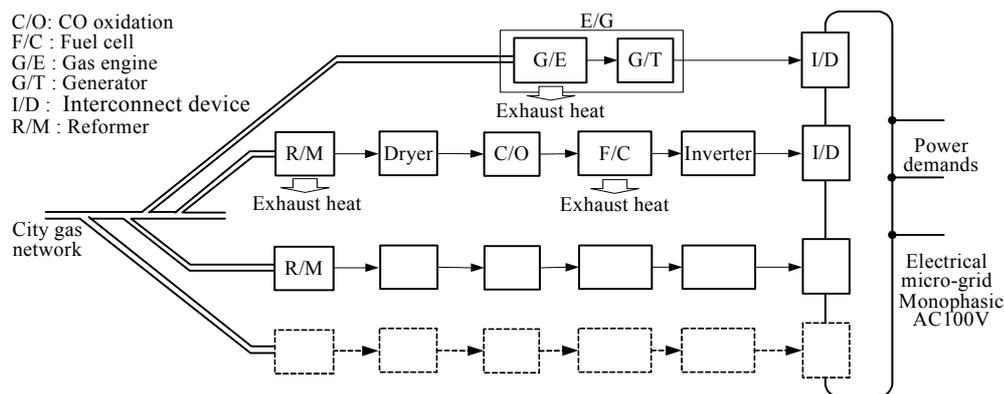


Fig. 2 Fuel cell micro-grid with a gas engine cogeneration

On the other hand, in the independence grid type shown in Fig. 1, if rapid load fluctuation is added to the grid, it will be thought that long time will be required to stabilize the power.

2.2 System Scheme

It is important because the power quality of the basis power generator is a standard of the voltage and frequency of the overall grid in the independence grid type. In Fig. 2, EG is set as the base power generator. Other than this, two or more fuel cell systems are connected to the grid, and an independence micro-grid is formed. In EG, a synchronous generator is connected to the engine axis of the rotation, and heat is obtained from a water jacket and an exhaust gas heat exchanger. If rapid load fluctuation is added to this engine, the power quality to generate will be influenced. So, there is a case involving conversion with "alternating current → direct-current → alternating current" with an electric circuit and an inverter, and supply to the demand side. However, this method results in additional equipment cost. In this paper, the power of a synchronous generator is directly supplied to the grid through an interconnection device and electricity production at the time of load fluctuation is adjusted by controlling the amount of fuel supply to the engine.

On the other hand, commonly, a reformer operates when city gas is burned during no-load status, to maintain the temperature of the reformer. As regards the load fluctuation of the reformer, the city gas supply to the burner for heat sources is controlled and adjusted so that reformer efficiency may be maintained. Here, the rate of "the calorific power of hydrogen in reformed gas" to "the calorific power of the supplied city gas" defines the reformer efficiency.

2.3 Control method of a system

In order to investigate the response characteristic of the power load in the system shown in Fig. 2, each response characteristic of the engine generator, fuel cell, reformer, inverter, and interconnection device is expressed by the primary or secondary delay system. Therefore, the response characteristic of all the equipment described above is decided by the method described in the following Section.

3. Response Characteristic of the System Configuration Equipment

3.1 Power generation characteristic of an engine generator

A model of the power generation characteristic of the engine generator installed into the independence micro-grid assumed in this paper is shown in Fig. 3⁽⁵⁾. This model is a response characteristic when controlling the production of electricity by adjusting the amount of fuel supply to the engine, and outputting the power to the grid via an interconnection device. The stability of the power requires about 20 seconds. However,

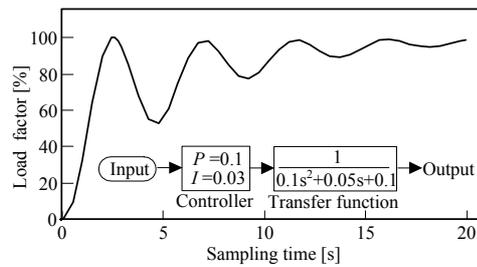


Fig. 3 Load response characteristics of step input for an engine generator⁽⁵⁾

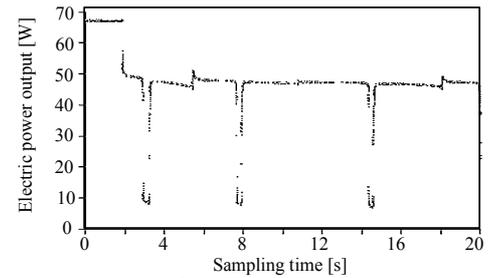


Fig. 4 Result of a solid polymer membrane type (PEM) fuel cell transient response test⁽⁶⁾. Percentage of load is 70%.

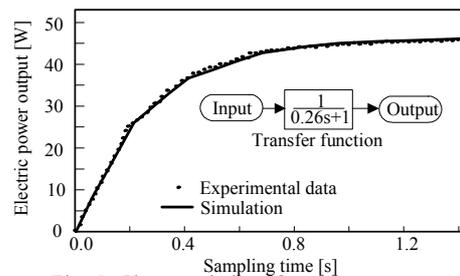


Fig. 5 Characteristics of transient response for a PEM fuel cell⁽⁶⁾

when the control parameters of the PI (proportion and integration) controller are adjusted, the settling time when converging on $\pm 5\%$ of range of a power output target is about 15 seconds. The settling time described in this paper is defined in time when converging on $\pm 5\%$ of a target value of power generation. The parameters of the PI control in this case and a transfer function are shown in Fig. 3.

3.2 Power generation characteristic of a fuel cell

Figure 4 shows the examination result of a response characteristic when inputting the step load of 70% of a load factor into a trial production PEM fuel cell⁽⁶⁾. This PEM fuel cell is the 100W type experimentally made in the research institution in China at low cost. The response characteristic shown in Fig. 5 is obtained from the result of Fig. 4, which may require the transfer function of a primary delay system from the characteristic in Fig. 5. The equation of the transfer function is shown in Fig. 5. In precise terms, it is thought that this transfer function is dependent on the load factor. Based on the testing result, because this difference was small, it is not taken into consideration. However, in Fig. 5, the settling time is not reached within the scale range of a horizontal axis. Fig. 6 (b) shows the system response result of a power output when the step load shown in Fig. 6 (a) is exposed to the fuel cell⁽⁶⁾. The settling time of the fuel cell at the time of 1kW maximum output is about 3 seconds⁽⁶⁾.

3.3 Output characteristics of a city gas reformer

Figure 7 shows the model which inputs the step-shaped load factor of 100% to 80%, and 100 to 50% into a city gas reformer^(6,7), while Figure 8 shows the system response result of the input of Fig. 7. This response characteristic is shown with the transfer function of a primary delay system shown in Fig. 8. It is thought as well as the fuel cell described in Section 3.2 that a transfer function has a precise influence on a load factor. In this paper, because there is no significant difference at the target range, the result of Fig. 8 is used.

3.4 Inverter and interconnection device⁽⁸⁾

The inverter of the voltage control type installed into the system is cheap. In an inverter, it is assumed that 120ms is taken although a power input is converted into the specified voltage and frequency. Here, the specified value is 95% or more of the targeted value. The

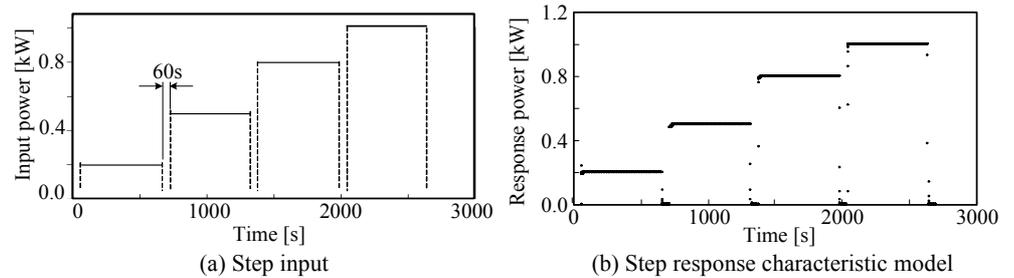


Fig. 6 Step response model for a PEM fuel cell⁽⁶⁾

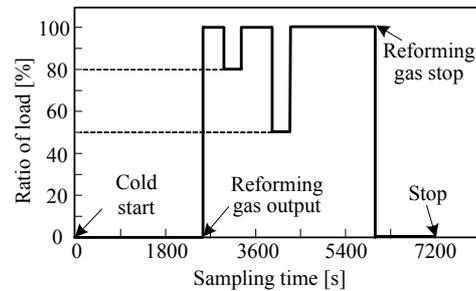


Fig. 7 Characteristics of a city gas reformer operation^{(6),(7)}

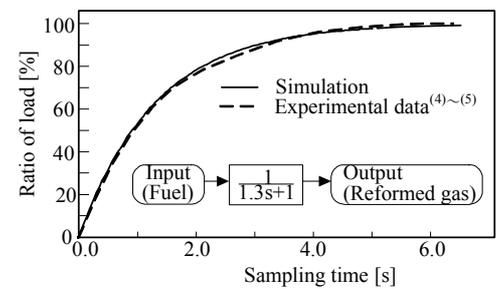
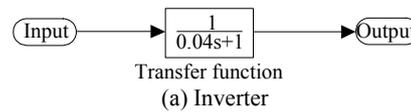
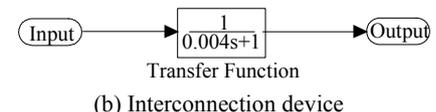


Fig. 8 Characteristics of transient response of a reformer



(a) Inverter



(b) Interconnection device

Fig. 9 Transfer function of an inverter and interconnection device

transfer function of a primary delay system of this inverter is the value shown in Fig. 9 (a). When switching the power (100V with single-phase) by the interconnection device, around 10 microseconds is required. It is also necessary to synchronize the frequency of the power between systems using control. The interconnection device assumed in this paper sets the switching time to 12ms. Consequently, the transfer function of the interconnection device by a primary delay system is the value shown in Fig. 9 (b).

4. Analysis Method

4.1 Control parameter of a fuel cell

The response characteristic at the time of inputting the loads of "0.2, 0.6, 1.0 kW" into a fuel cell system at steps is shown in Figs. 10 (a) to 10 (c)^(6,7) and the response characteristic of a fuel cell varies according to the set up control parameters used. The parameters of PI control are changed and analyzed in Fig. 10. As shown in Fig. 10 (c), in the 1kW of loads, the rise and settling times are not based on control parameters. As for the rise time, with a load of 0.2kW, P= 12.0 and I= 1.0 are short. However, as for settling time, P= 1.0 and I= 1.0 are short. With a load of 0.6kW, the rise time of "P= 12.0, I= 1.0" is short as compared with "P= 1.0, I= 1.0." Moreover, the settling time is almost the same and, as for overshooting, "P= 12.0, I= 1.0" are larger and "P=5.0, I= 1.0" are not suitable for control, because of the considerable steady state error during low loading. Therefore, in the analysis case of the following Section, the control parameters of a fuel cell are analyzed as "P=1.0, I= 1.0", and "P=12.0, I= 1.0."

4.2 Block Diagram and Analysis Method of a System

The basic system block diagram of a fuel cell micro-grid when operating an engine generator corresponding to a base load is shown in Fig. 11. Here, an engine generator is installed in House A and a fuel cell installed in Houses B and C. *u* in this figure shows the

power load and v_2 to v_4 show the power output in the block (Actions 1 to 3) which branches with the magnitude of u . Moreover, h_0 and h_1 show the power generation capacity of an engine generator and the fuel cell in House B, respectively. In this system, when the value of u exceeds the capacity h_0 of the engine generator corresponding to a base load, the fuel cell (capacity of h_1) in Home B is operated first. When the production of electricity is less than the value of u at this time, the fuel cell installed in House C is also operated. In this way, the number of operations of a fuel cell is controlled based on the magnitude of the load added to the system and the power generated by the equipment installed in Houses A to C can be supplied to arbitrary houses through the grid. Firstly, the load pattern of the power is given to the system in analysis. Next, Action1 to Action3 are selected from the power generation capacity (h_0 and h_1) of the equipment installed in each house, and the magnitude of load (u) by IF conditional branches. In Action1 to Action3, as shown in Figs. 12 (a) to (c), the electricity production of each power generator is output. The dynamic characteristics of each power generator are shown with PI control devices (Controller0 to Controller2) shown in Fig. 11, load limitation devices (Limiter0 to Limiter2), and transfer functions. This paper shows the dynamic characteristics of an engine generator with the transfer function described in Section 3.1. A fuel cell and reformer are shown with the transfer function described in Sections 3.2 and 3.3, respectively. By adding the electricity production of each power generator, the dynamic characteristics of the power supplied by the micro-grid can be known. The dynamic characteristics of a micro-grid are also analyzed using MATLAB (Ver. 7.0) and Simulink (Ver. 6.0) of Math Work. However, in the analysis case of the following Section, the solver to be used is the positive Runge-Kutta method and based on the sampling time of analysis, the error rate becomes less than 0.01%.

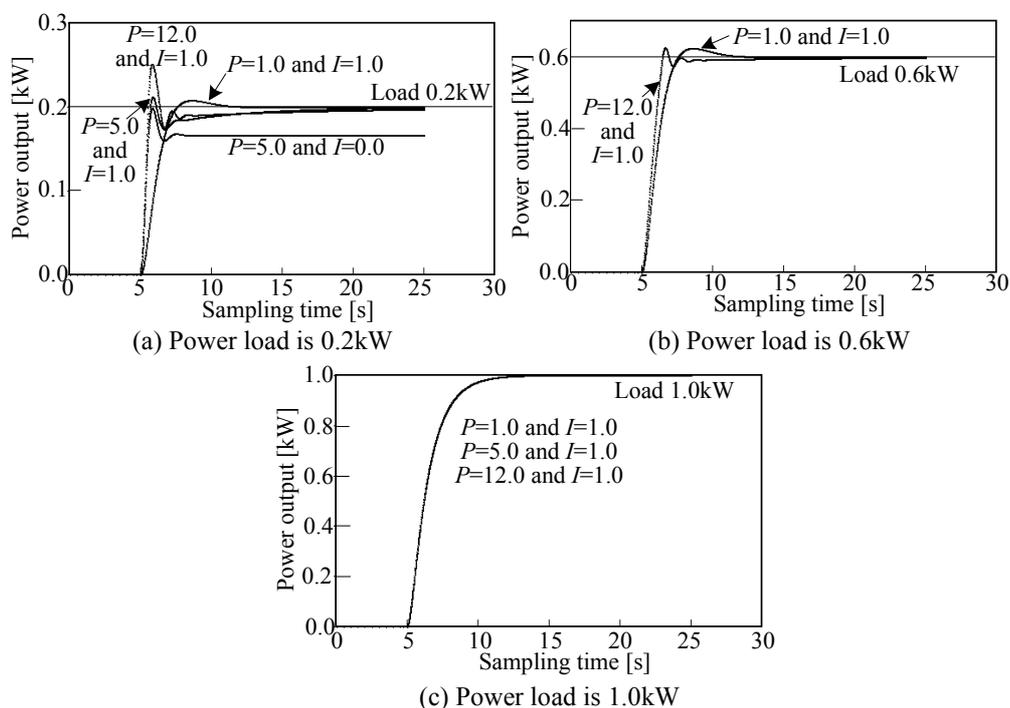


Fig. 10 Characteristics of electric power output of the system ⁽⁶⁾, ⁽⁷⁾

5. Case study

5.1 System Configuration

An engine generator with a power generation capacity of 3kW is installed in one house, while a fuel cell system with a power generation capacity of 1kW is installed in 16 houses.

The capacity of an engine generator and a fuel cell refers to the case of the engineering development in and outside the country, while the number of fuel cells installed was decided based on the demand pattern of power such as may be described below. In this case analysis, the time average value of the power demand of the House in Sapporo in February is used as load (Fig. 17) and the minimum load of this power demand pattern is decided as the value of the basis load (which in this case is 3kW). The number of fuel cells installed was decided as a value capable of responding to the maximum load during each sampling time of the power demand pattern and the system block diagram in this case analysis is changed from the block diagram shown in Fig. 11 so that it is capable of responding to 17 houses. The fuel cell systems installed in 16 houses are labeled Nos. 1 to 16, respectively and all shall have equivalent capacity and dynamic characteristics. Moreover, the transmission loss of the grid is not taken into consideration. Based on this, the position of houses does not influence the electrical power transmission of the grid, and the dynamic characteristics of the power.

The area enclosed with a chain line in Fig. 11 is a control block of a single fuel cell system and the grid investigated with this analysis case extends the area enclosed with this chain line to 16 sets. Because the engine generator corresponds to a base load, it is operated continuously and when the power demand exceeds the base load, it corresponds to the numeric operation control of 16 fuel cells.

The analysis results of "the response characteristic at the time of inputting a step-shaped load" and "the response characteristic at the time of inputting the power demand pattern of the individual house in Sapporo" in the micro-grid described in the top are shown below.

5.2 Step response characteristic

Figures 13 (b) to 13 (f) are the system response result when giving a step-shaped load (Fig. 13 (a)) to the grid. However, the parameters of the PI control device of all the fuel cell systems are P= 1.0 and I= 1.0. Figure 13 (b) shows the system response result of the grid, Fig. 13 (c) shows the system response result of the engine generator, and Figs. 13 (d) to 13 (f) show the system response result of the fuel cells Nos. 1,8, and 12, respectively. When the system response result (Fig. 13 (c)) of an engine generator is compared with the system response result (Fig. 13 (d) to 13 (f)) of a fuel cell, the fuel cell has few output changes and its settling time is shorter. The number of operations of a fuel cell also increases in tandem with the load added to the grid. Therefore, a fuel cell is operated following the load increase

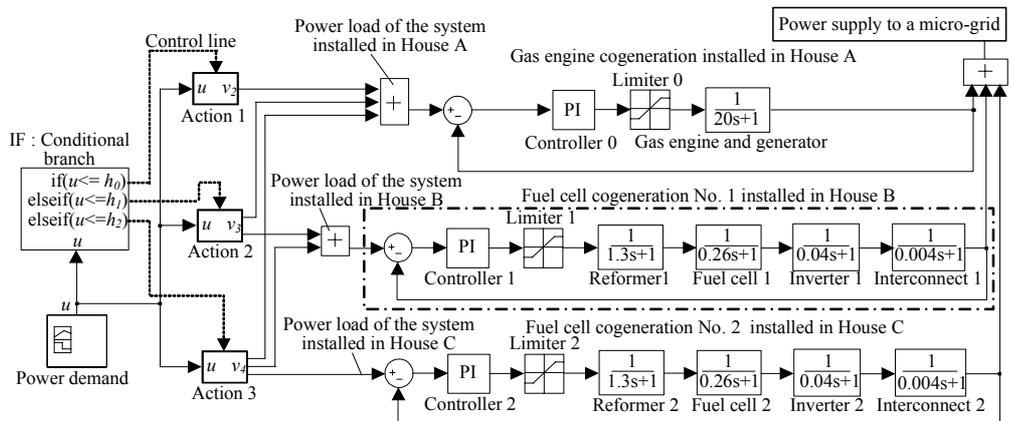


Fig. 11 Control block diagram of independent micro-grid system for three houses

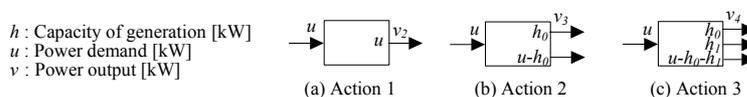


Fig. 12 Subprogram

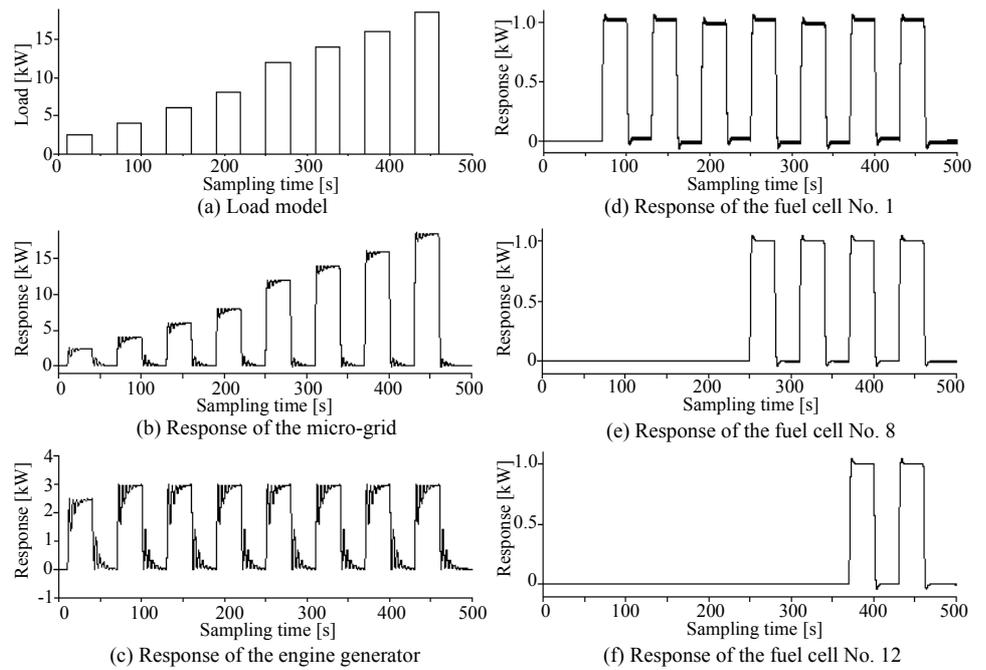


Fig. 13 Step response characteristics of the system. Control parameter of the fuel cell system is $P=1.0$ and $I=1.0$.

in the grid in the order of Nos. 1, 8, and 12 (Figs. 13 (d), (e), (f)).

The relation between the control parameter of the fuel cell system and the dynamic characteristics of the micro-grid was investigated. The system response result of the grid when setting control parameters as $P=12.0$ and $I=1.0$ is shown in Fig. 14. When Figs. 13 (b) and 14 are compared, it turns out that the latter extent of overshooting is larger. On the other hand, Fig. 15 shows the relation of the power load and settling time at the time of the control parameters " $P=1.0, I=1.0$ " and " $P=12.0, I=1.0$ " of the fuel cell system. The definition of settling time is the time to be converged at less than $\pm 5\%$ of load by the power supply of the grid. Based on the result of Fig. 15, the settling time of 15kW or less is barely dependent on the loads on the control parameters. When the load exceeds 16kW, the control parameters " $P=1.0, I=1.0$ " of the fuel cell system are about 5 seconds shorter. Moreover, although the settling time of the grid differs in terms of the magnitude of the load, it is 10 to 15 seconds ($P=1.0$ and $I=1.0$). Fig. 16 shows the difference of the power demand amount

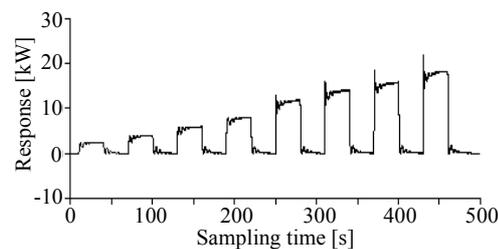


Fig. 14 Response of the micro-grid. Control parameter of the fuel cell system is $P=12.0$ and $I=1.0$.

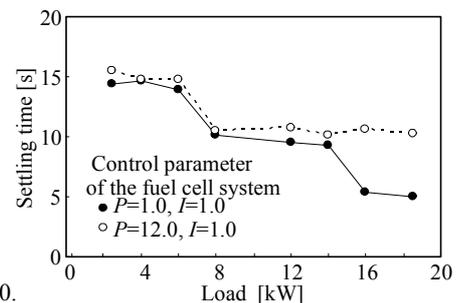


Fig. 15 Relation between load added to a micro-grid and settling time

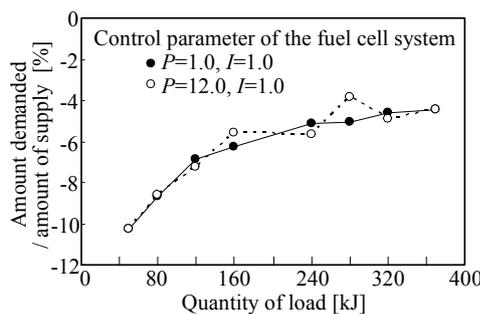


Fig. 16 Difference of amount demanded and the amount of supply

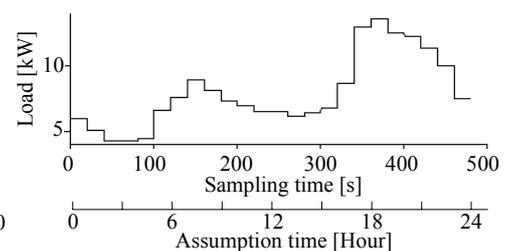


Fig. 17 Power demand model for 17 houses in February of Sapporo ⁽¹⁶⁾

of the grid, and the power supply. The differences of in power supply and demand are the main reasons behind the delayed response of the power generator. Figure 16 shows that the control parameters of the fuel cell hardly affect the difference between the power supply and demand in the grid. Therefore, although the control parameters of the fuel cell system significantly influence the settling time and overshooting, they hardly affect the difference of power supply and demand.

5.3 When the power demand pattern of a house is applied

Figure 17 shows the average power demand pattern of each hour in February, showing the representative days for about 17 houses in Sapporo⁽⁹⁾. In Sapporo, air-conditioners are not used for the summer season, but space heating in winter is carried out using kerosene equipment. Therefore, the power demand pattern is hardly influenced by outside air temperature. On the horizontal axis in Fig. 17, the sampling time of analysis and the assumption time are written together. The results of having analyzed the response characteristic of the grid using this power demand pattern are Fig. 18 (a) and Fig. 19 (a). In the analysis of Fig. 18 and Fig. 19, the control parameters of the PI control device of the fuel cell system is set to "P=1.0, I=1.0" and "P=12.0, I=1.0", respectively. As for overshooting of these results, "P=12.0, I=1.0" are larger. The reason with much fluctuation immediately after a start up (past 0:00) is based on the starting characteristic of the engine generator, as shown in Fig. 18 (b) and Fig. 19 (b). Next, the system response result of fuel cell No.1, No.3, No.5, and No.9 is shown in (c) to (f) in Figs. 18 and 19. Overshooting when taking load fluctuation on the fuel cell and the engine generator compared with Fig.

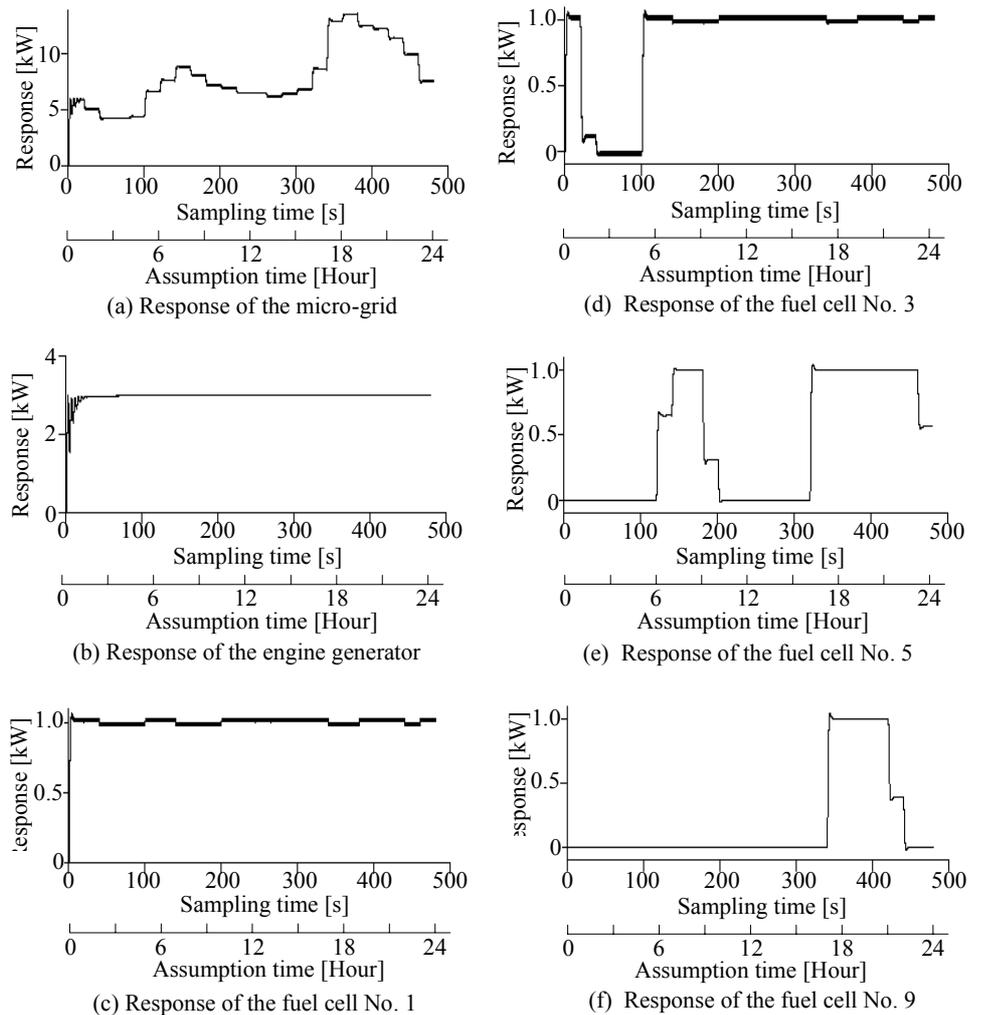


Fig. 18 Response results analyzed using an electricity demand pattern of a house in February of Sapporo. Control parameter of the fuel cell system is $P=1.0$ and $I=1.0$.

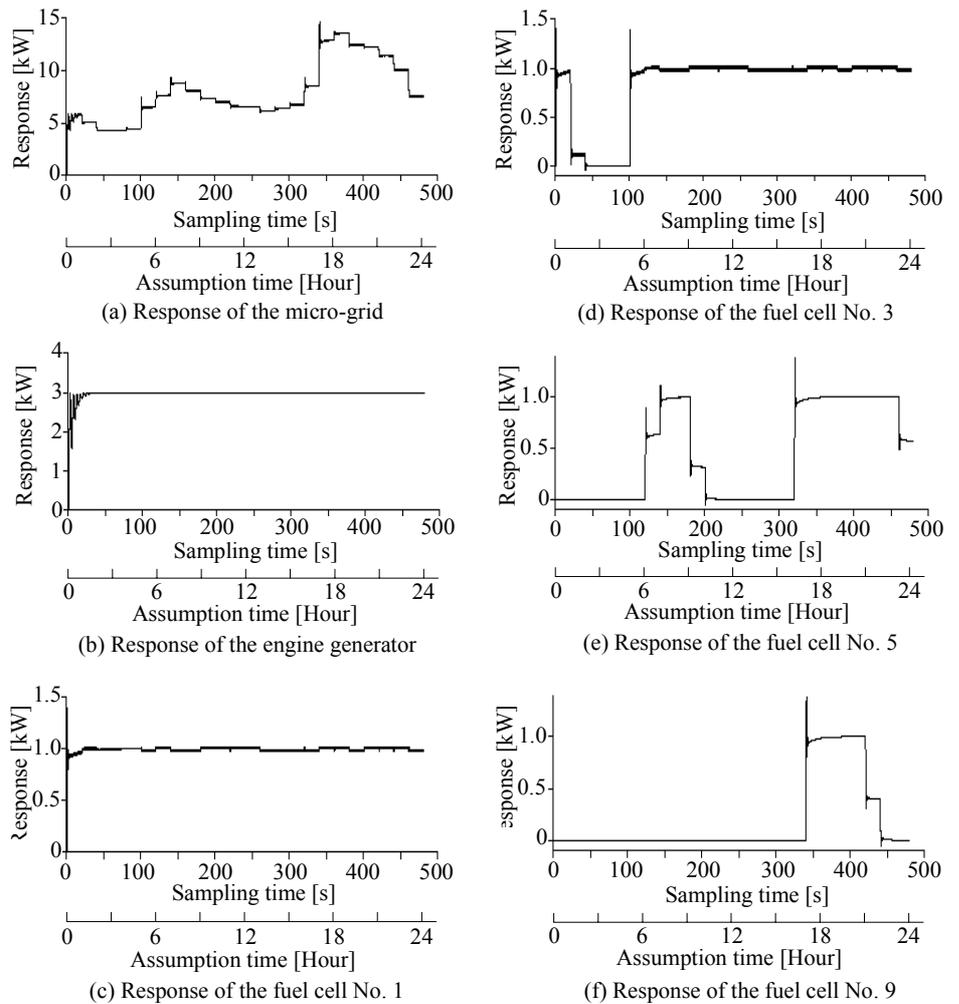


Fig. 19 Response results analyzed using an electricity demand pattern of a house in February of Sapporo. Control parameter of the fuel cell system is $P=12.0$ and $I=1.0$.

19 and Fig. 18 is large. The sufficiency rate of the amount of power supply relative to the demand amount in the grid for every sampling time is investigated. The result at the time of the control parameters "P= 1.0, I= 1.0" of the fuel cell system is Fig. 20, and the result at the time of "P= 12.0, I= 1.0" is Fig. 21. The difference of the sufficiency rate of power supply and demand is significant at the assumption time in Figs. 20 and 21 at 5:00 and 17:00 respectively. As Fig. 17 showed, the load fluctuation range during such period is larger than at others. Compared with Fig. 20, two or more positive differences (100% or more of the supply-and-demand difference) have occurred in the result of Fig. 21. At the analysis result of the sufficiency rate of the power supply-and-demand in the overall representative day, it is 99.74% in Fig. 20 and 99.63% in Fig. 21. Within the range of the PI control parameter set up with this case study, the influence on the sufficiency rate of power supply-and-demand is the measure shown in both figures. Within the range of these control parameters, the sufficiency rate is not significantly improvable. Although changing the control parameters does not enable the supply-and-demand difference of the power to be improved for every sampling time, we think the time constant of each piece of equipment must be improved.

However, it would be dramatically unusual for all the households to turn a large capacity load on and off all at once in actual fact.

5.4 Installed Number of Fuel Cells

As Section 5.1 described, the micro-grid assumed in this paper consists of one engine

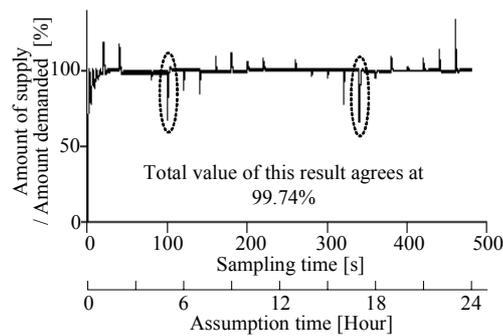


Fig. 20 Difference of amount demanded and the amount of supply. Control parameter of the fuel cell system is $P=1.0$ and $I=1.0$.

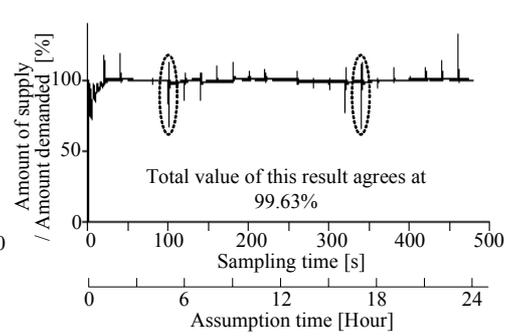


Fig. 21 Difference of amount demanded and the amount of supply. Control parameter of the fuel cell system is $P=12.0$ and $I=1.0$.

generator and 16 fuel cells. To install a fuel cell in a house independently (when not installing a network), it is necessary to set the power generation capacity of a fuel cell as the load peak of the instantaneous power in each house. In the fuel cell micro-grid in this paper, because the shortage and overage of the power are mutually able to cover each other, the capacity of the fuel cell installed in each house can be set up as smaller than the load peak. In the example using the power demand model of Fig. 17, only Nos. 1 to 12 of the 16 sets of fuel cells need be operational, while Nos. 13 to 16 need not be. In this way, it is thought that the equipment cost of the fuel cell will become advantageous, so that the number of houses increases. Moreover, it is necessary to change the starting sequence of the fuel cells within a fixed period, and make the operating ratio equal.

6. Conclusions

An engine generator with a power generation capacity of 3kW is installed in one house, and made to correspond to a base load. Moreover, a fuel cell system with a power generation capacity of 1kW is installed in 16 houses. The dynamic characteristics of the power grid at this time were investigated by numerical analysis and the following conclusions were consequently obtained:

- (1) Although the settling time (time to converge on $\pm 5\%$ of the power output target) of a micro-grid differs in terms of the magnitude of load, it is 10 to 15 seconds. However, the settling time also differs based on the control parameters of a fuel cell.
- (2) The control parameters of a fuel cell are also influenced by overshooting significantly besides the settling time of the micro-grid. The supply-and-demand difference of the power for every sampling time cannot be improved by simply changing the control parameters alone. In this case, the time constant of each power generator must be improved.
- (3) To install a fuel cell independently, it is necessary to exceed the instant power load peak for the capacity of the fuel cell. On the other hand, if two or more fuel cells are connected to a grid, the shortage and overage of the power can respectively cover each other. In other words, the instant power load peak can be distributed and supplied, meaning the number of fuel cells installed can be reduced compared with an independent method.

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