Installation Planning of Small-scale Fuel Cell Cogeneration Considering Transient Response Characteristics

(Load Response Characteristics of Electric Power Output)*

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Abstract

The transient response characteristics of the power supply of a small-scale fuel-cell co-generation system, constituted from a reformer, a fuel cell stack, an inverter, an interconnection device system with a changeover switch, and auxiliary heat sources were investigated. Furthermore, the relation among the settling time, time constant of the reformer and the fuel cell, and the setting values of the parameter in PI control was analyzed. By changing the PI control parameters according to the reforming load, the setting time is shortened. Moreover, the operating cost of the system was estimated, with reference to the power demand and heat demand pattern of individual houses in Sapporo and Tokyo. Consequently, the annual balance of payments achieved by installing a heat pump system with COP=3.0 into the fuel cell system shows a favorable balance in Tokyo, and a passive balance of about zero in Sapporo respectively.

Keywords: Fuel Cell, Transient Response, Energy Saving, Power Plant

1. Introduction

The introduction of proton exchange membrane fuel cells with a city gas reformer of about 1-kW power output to individual houses with significant fluctuations in power and heat demand is considered. The system, which consists of a fuel cell, a reformer, an inverter and system interconnection change equipment, etc. is investigated based on whether a stable energy supply is maintainable. In order to check the stability of the energy, it is necessary to clarify the transient response characteristic of the system. An examination of the transient response characteristic of a fuel cell will obtain a sufficient response characteristic that is stabilized according to the load characteristic of home electric appliances. However, details of the transient response characteristic when together with a reformer, etc. are not known. A reforming catalyst, conversion catalyst and oxidation catalyst that remove carbon monoxide are installed in the reformer and highly efficient operation is realized by controlling each catalyst to within the appropriate temperature range. The transient response characteristic of reformed gas output is slow compared with a fuel cell (1-3). Moreover, it is necessary to take the transient response characteristic of power and heat into consideration with cogeneration in mind. The details of the transient response characteristic of the fuel cell system include a reformer, a fuel cell, an inverter and system interconnection change equipment, etc. Moreover, there are no
detailed reports recorded on the transient response characteristic concerning the heat supply of the system composed from exhaust heat from the fuel cell, a back-up heat source and a heat storage tank, etc. In this paper, the transient response characteristic concerning the power output of small-scale fuel cell cogeneration for houses is analyzed, and the operational stability conditions of the system are investigated. In addition, the running cost, taking the transient response characteristic of the system, is investigated using the power and heat demand pattern of individual houses in Sapporo and Tokyo.

2. Fuel Cell System for Houses

2.1 System Scheme

A model of a fuel cell cogeneration system is shown in Fig. 1 (a) and Fig. 1 (b). As a back-up heat source, a boiler is used in Type A and a heat pump in Type B. In Types A and B, city gas is supplied to a reformer at flow rate $Q_{m,t}$. The steam reforming reaction of the reformer generates reformed gas with a high hydrogen concentration. A conversion reaction section and carbon monoxide oxidation reaction section are both installed in the reformer, and there is an optimum temperature range in each reaction. Consequently, city gas at flow rate $Q_{cb,t}$ is supplied to a combustor through city gas System 2. The heat generated with the combustor is used as a heat source of the catalysts with an endothermic reaction. Reformed gas is generated and supplied to the fuel cell, and this power is output to an AC-DC converter and inverter. After converting the generated power into a fixed alternating current frequency of 100 V with the inverter, power $E_{fr,t}$ is supplied to the system interconnection device. Other than the power of the fuel cell, the demand side is supplied using commercial power. The power is supplied to the demand side through system interconnection equipment from two lines, fuel cell power and commercial power. The power of the fuel cell can be sold to a commercial power system via the system interconnection device. $E_{fr,t}$ of Types A and B, electricity consumption $E_{pp1,t}$ of the heat transfer medium pump, and electricity consumption $E_{pp2,t}$ of the blower described above are supplied from power $E_{fr,t}$ of the interconnection device outlet. Even if the exhaust heat from the fuel cell is removed to tap water in Type A, when the quantity of heat is less than the demand, city gas $Q_{bo,t}$ is consumed and tap water is reheated using the boiler. In Type B, the evaporator of the heat pump and the exhaust heat from the fuel cell or the heat medium of the underground heat exchanger is heated and tapped water is heated using the condenser of the heat pump. However, in this paper, the evaporator of the heat pump is 278 K to 313 K, and the tap water of the condenser outlet is 323 K to 340 K. The heat pump for a cold region (Sapporo) is a geo-thermal heat source, while that for Tokyo is an air heat source. The operational power $E_{pp,t}$ of the heat pump is supplied from $E_{fr,t}$. Although a geo-thermal heat pump has electricity consumption of $E_{pp2,t}$ for a heat transfer medium circulating pump, this power is also supplied from $E_{fr,t}$. When the exhaust heat from the fuel cell of both types exceeds the heat demand, surplus heat is released from the radiator.

2.2 Transient response characteristic of equipment

In order to investigate the power transient response characteristic of the system in Fig. 1, the response characteristics of the fuel cell, reformer, inverter, and interconnection device is expressed by a primary delay system. The time constant of each piece of equipment is decided as follows:

(a) Fuel cell

Figure 2 shows the examination result of the transient response characteristic concerning the step input of the test fuel cell stack. However, the load factor is 70%. The transient response characteristic of Fig. 3 is obtained from this result, while Figure 4 shows the result of the primary delay system transfer function obtained from this response characteristic. To be exact, the transfer function influences the load factor. However, in the examination results, since this difference is slight, the load factor is not taken into consideration.

(b) City gas reformer
Figure 5 shows the response characteristic model of the step input to a city gas reformer.
This model shows the result when adding the step input of a load factor of 100% to 80%, and 100% to 50% respectively. Figure 6 shows the result of the transient response characteristic, while Figure 7 expresses this characteristic with the transfer function of the primary delay system. The transfer function influences the load factor exactly as (a) described above.

(c) Inverter
The inverter is of the voltage control type. A total of 120 ms is required to convert the power into 95% or more of the voltage and frequency required (6). Figure 8 expresses the transfer function of the inverter with the primary delay system.

(d) Interconnection device
The time needed to switch 100-V single phase power by an interconnection device is about 10 ms (7). However, since the frequency of system output and commercial power is synchronized, the operating time of the interconnection device assumed in this paper is 12 ms (6) and the primary delay transfer function of the interconnection device is shown in Fig. 9.

2.3 Energy balance equation
The power balance of Type A is expressed with Eq. (1), while that of Type B is expressed with Eq. (2).

\[ E_{s,t} = E_{f,s,t} + E_{cm,t} = \Delta E_{\text{need},t} + \Delta E_{\text{bwd},t} + \Delta E_{\text{bf},t} + \Delta E_{\text{pp},t} \]

\[ E_{s,t} = \Delta E_{\text{need},t} + \Delta E_{\text{bwd},t} + \Delta E_{\text{bf},t} + \Delta E_{\text{pp},t} \]

The left-hand side of Eq. (1) \( E_{s,t} \) expresses the power output of the system interconnection device outlet. This value is obtained by adding the power output \( E_{f,s,t} \) in the inverter outlet and the output of commercial power \( E_{cm,t} \). Moreover, the 1st term \( \Delta E_{\text{need},t} \) of the right-hand side of Eq. (1) expresses power demand, and the 2nd \( \Delta E_{\text{bwd},t} \) and 3rd terms \( \Delta E_{\text{bf},t} \) express the electricity consumption of the blowers. Furthermore, the final term \( \Delta E_{\text{pp},t} \) of the right-hand side expresses the power consumption of the heat medium circulating pump. On the other hand, as for the power balance equation of Type B, power \( E_{cm,t} \) and \( E_{pp2,t} \) of the electricity consumption of the heat pump and the heat transfer medium circulating pump of the underground heat exchanger is added to the right-hand side.

The heat balance of Type A is shown in Eq. (3). The 1st term \( H_{f,t} \) of the left-hand side expresses the exhaust heat from the fuel cell, and the 2nd term \( H_{bo,t} \) expresses the heat output of the boiler. In addition, the 1st term \( \Delta H_{\text{need},t} \) of the right-hand side expresses the heat demand, and the 2nd term \( \Delta H_{\text{rad},t} \) expresses the heat released from the radiator.

\[ H_{f,t} + H_{bo,t} = \Delta H_{\text{need},t} + \Delta H_{\text{rad},t} \]

3. Transient Response Characteristic of the System

3.1 Control block diagram and power control
The control block of both system types is shown in Fig. 10 (a) and Fig. 10 (b). The power demand at sampling time \( t \) is expressed with \( \Delta E_{\text{need},t} \), and the power of the inverter outlet of the fuel cell system is expressed with \( E_{f,s,t} \). In the operating mode, where power is not sold, the amount of fuel cell power generated is controlled by a controller, and \( E_{f,s,t} \) is output so as to eliminate the difference between \( \Delta E_{\text{need},t} \) and \( E_{f,s,t-1} \). On the other hand, in the operating mode with electricity sales to utility companies, the fuel cell is always operated at maximum output. The power representing the difference between the maximum output of the fuel cell and \( \Delta E_{\text{need},t} \) is sold. The system controller of this paper has proportional plus integral control (it expresses PI control in the following). Given the potential for a large overshoot, derivative control is not added.
Subsystems 1 and 2 in Fig. 10 (a), and Subsystems 5 and 6 in Fig. 10 (b) are operation block diagrams when heat demand exceeds exhaust heat from the fuel cell. In Subsystems 1 and 5, when exhaust heat from the fuel cell exceeds heat demand, the heat surplus released

(a) Type A

(b) Type B

Fig. 10 System block diagram

Fig. 11 Characteristics of load response by PI parameters
from the system is calculated. In Subsystem 2, the boiler power output when heat demand runs short of exhaust heat from the fuel cell is calculated. In Subsystem 6, when exhaust heat from the fuel cell runs short compared to heat demand, the quantity of heat output from the heat pump is calculated. Moreover, Subsystems 3 and 4 of Type B are those that calculate electricity sales to utility companies and the purchase of power, respectively. In this paper, the transient response characteristic of the power supply of a system is investigated.

3.2 Analysis method

The transient response characteristic of the power of a fuel cell system shown in Figs. 10 (a) and (b) is analyzed using MATLAB (Ver.7.0) and Simulink of Math Work (Ver. 6.0). The sampling time is decided so that there is an error of less than 0.1% as a solver using the positive Runge-Kutta method. The sampling period of the PI control of Sections 4 and 5 was set to 0.05 seconds or less so that the analysis did not diverge.

3.3 Transient response characteristic concerning the power

The transient response characteristic concerning the power output of each system of Figs. 10 (a) and (b) is investigated. In Types A and B, the control block from the controller to the system interconnection device is the same, and the following examinations are common to both system types. In analysis, the heat demand is set as zero and the following (1) and (2) are examined, excluding the influence of heat load.

(1) Response characteristic of power output by the control parameters

Figures 11 (a) to (c) show the analytical results of the transient response characteristic when inputting the step load in Fig. 11 (d) into a system. Each parameter of PI control is changed in the analysis. As shown in Fig. 11 (d), in this analysis, there is 20 seconds of standby time of power load zero. In the following, after maintaining a load input for 20 seconds, load zero is maintained every 20 seconds. This load pattern is then input from 0.2 kW to 1 kW. Although the rise time in Fig. 11 (a) is the fastest, the settling time in Fig. 11 (b) is the slowest and moreover, the steady state error of these results is less than 1%.

(2) Difference in the time constant of the reformer and the fuel cell

Table 1 shows the results of the time constant of the reformer, and the transient response characteristics (rise time, settling time, overshoot, steady state error) of the system. The PI control parameter was set at $P = 1.0$ and $I = 1.0$, based on the results of Fig. 11. When a reformer with a time constant ($g_{rm}$) of 1.3 seconds, as shown in Table 1, is installed in a general residence, the system settling time is less than about 3 seconds. However, the case of a 1-kW load is excluded. Moreover, the rise time for $g_{rm} = 0.6$ seconds is shorter than the results of the other time constants when a low-load region is removed. However, the settling time exceeds the results of the other time constants when a high-load region is removed. Accordingly, although the time constant of the reformer influences the transient response characteristic of a system, it differs according to the magnitude of the load. On the other hand, when a small time constant is set such as $g_{rm} = 0.3$, the result of Fig. 12 is shown by replacing the integral control parameter $I = 1.0$ with 2.0. The settling time of the system in this case improves within 1.2 seconds in all load regions. However, if a considerable time constant is set, such as $g_{rm} = 2.0$, and the PI control parameter is changed, an increase in overshoot and in steady-state error will occur. The following can be considered from the above results.

a. If the time constant of the reformer diminishes, the PI control parameters are set appropriately and the settling time can be greatly shortened.

b. The settling time can be shortened by changing the PI control parameter according to the load of the reformer.

Table 2 shows the analysis result of the transient response characteristic of the system when changing the time constant of the fuel cell. If the time constant of the reformer is changed, the system settling time will be significantly influenced. Compared with this, even if the time constant of the fuel cell changes considerably, there is minimal influence on system settling time, whereas in the case of $g_f = 0.52$, system overshoot becomes
significant. Therefore, the power settling time of the system can be made favorable by improving the transient response characteristic of the reformer rather than the fuel cell.

Fig. 12 Characteristics of load response $g_{\text{r}}=0.3$, $P=1.0$, $I=2.0$.

Fig. 13 Driving pattern of type B system

Fig. 14 Characteristics of system load response of type B system

Fig. 15 Individual house energy needs in Sapporo

Fig. 16 Individual house energy needs in Tokyo

Fig. 17 System driving cost
3.4 Transient response characteristic when installing a heat pump

The Type B system with heat load is operated with the operating pattern of Areas 1 to Area 3, as shown in Fig. 13. Area 1 shows the operating pattern of the power supply and the exhaust heat supply of the fuel cell, while Area 2 shows the addition of a heat pump driven by fuel cell power to Area 1. Moreover, Area 3 supplies power from the fuel cell, and the heat pump is driven by commercial power. Figure 14 shows the result of analyzing the transient response characteristics regarding the operating point of $\alpha$ to $\delta$ in Fig. 13. As a result of applying a trial-and-error method, the transient response characteristics at the time of $P= 12.0$ and $I= 1.0$ are favorable. Each of power loads $\alpha$ to $\delta$ in Fig. 14 (b) corresponds to $\alpha$ to $\delta$, as shown in Fig. 13. Although a boiler is operated under power load following the operation of Type A, the boiler does not affect the transient response characteristic of the power. However, since power $E_{m,t}$ for the drive of the heat pump is supplied from the fuel cell for Type B, the heat load affects the transient response characteristic of the power. Therefore, the optimum PI control parameters of Types A and B differ.

4. Analysis of Operation Cost

4.1 Operation cost calculation method

The amount of city gas consumed by a reformer ($Q_{c,t}$ and $Q_{h,t}$) and the amount of city gas consumed by a boiler ($Q_{bo,t}$) are added, this value is multiplied by the city gas unit cost, and the city gas cost of Type A is obtained. In this paper, the gas unit cost is calculated at 175 yen/m$^3$ for city gas assuming Japanese standard 13A (methane 68.9%, ethane 5.6%, propane 3.4%, butane 1.3%). Furthermore, the power rates are calculated from consumption $E_{c,t}$ of the commercial power, and the operation cost of the Type A system is obtained by adding the upper value. The purchase price of the commercial power is 26 yen/kWh. The operation cost of Type B is calculated except for $Q_{bo,t}$ using the calculation method described above. For each system type of Fig. 1 (a) and (b), the characteristics with/without electricity sales to utility companies are investigated.

(1) In operation without electricity sales to utility companies, it is ordered from a controller so that the difference between the power output of the system and the power demand may be reduced. Therefore, the system immediately follows a fluctuating power load. The system response characteristics in this case greatly depend on the response characteristics of the reformer or the fuel cell.

(2) Concerning operation with electricity sales to utility companies, maximum-output (in this paper, 1 kW) operation of the fuel cell is always conducted, and surplus power is sold. The unit cost of electricity sales to utility companies is the same as the purchase unit cost of the power, and it is 26 yen/kWh in this paper. In the operating method with electricity sales to utility companies, the load of the fuel cell is constant. Compared with (1), the influence of the transient response characteristic of the reformer and the fuel cell is considered to be comparatively small.

4.2 Analysis condition

The transient response characteristics of each piece of equipment described in Section 2.2 are installed in Types A and B, and the operation cost of the overall system with the transient response characteristics is considered, where the power and exhaust heat are assumed to be linear, and the ratio of power output to exhaust heat power is set at 1 to 5. The values of Table 3 are used for equipment efficiency irrespective of the operation condition, while the maximum output of the fuel cell is 1 kW. The PI control parameters used for analysis for Type A are $P= 1.0$ and $I= 1.0$, and for Type B, they are $P= 12.0$ and $I= 1.0$. Figures 15 and 16 show the energy demand pattern of a representative day in summer (August), mid-term, and winter (February) of an average individual house in a cold region (Sapporo) and in Tokyo, and these are used in this analysis. Although the breakdown of the power and heat demand is shown in Table 4, references are given for the amount of each load component.

4.3 Analysis result of the operation cost

Figures 17 (a) and (b) show breakdowns of the analysis results of the operation cost of both types, respectively. Moreover, Figs. 18 (a) and (b) show the results of the balance of
the price obtained by electricity sales to utility companies, fuel consumption of the system and the purchase of power (this result is described as the cost balance in the following).

(1) Analysis results of Type A

Electricity sales to utility companies ($\alpha$ in Fig. 17 (a)) and the fuel cost of the fuel cells ($\beta$) in Sapporo and Tokyo on a representative day in August are almost the same. Since the power menu according to the time zone is not taken into consideration, the result of Fig. 17 is decided by the sum of energy consumption rather than the load fluctuation pattern. The total power consumption in Tokyo and Sapporo on a representative day in August is 40.5 MJ and 39.7 MJ, respectively, and there is little difference. Therefore, the value of $\alpha$ and $\beta$ in Fig. 16 is almost identical. The result of $\alpha$ and $\beta$ on a representative day in May and February in Sapporo and Tokyo serves as the same value in each city. Although the result of $\beta$ in Tokyo in summer is considerable, it is because of the power supply to the cooling load. Since the heat demand is considerable on a representative day in February in Sapporo, the fuel cost of the boiler is high ($\chi$). The result of $\beta$ in Sapporo exceeds that of Tokyo throughout the year, while the same applies to the figure for the fuel cell operating.
ratio in Sapporo. Although the operating power of the boiler is significant on a representative day in February in Sapporo, it is hardly operated during the other months, whether in Sapporo or in Tokyo. Therefore, the heat supply of the fuel cell system installed in Tokyo can satisfy heat demand by the utilization of exhaust heat from the fuel cell, and the introduction of a heat storage tank.

Except for a representative day in August, there is higher power demand in the other months in Sapporo than the quantity demanded in Tokyo. Consequently, there are greater electricity sales to utility companies on a representative day in May and February in Tokyo than in Sapporo. As shown in Fig. 18 (a), the cost balance in Sapporo is a passive balance throughout the year, but for the cost balance in Tokyo, there is little passive balance except for a representative day in August.

(2) Analysis results of Type B

The price of electricity sales to utility companies on a representative day in August in Sapporo and Tokyo reveals almost the same result (Fig. 17 (b) \( \alpha \)). However, on a representative day in May and February, Tokyo will have a larger value. Although heat is supplied using the heat pump of COP=3.0 in Type B, the value of \( \alpha \) on a representative day of every month becomes larger than \( \beta \). As shown in Fig. 18 (b), the cost balance of Type B serves as a favorable balance compared with the result of Type A in many cases. The cost balance in Tokyo is favorable every month. In winter in Sapporo, since the purchase of power is taken by the operation of a heat pump, the cost balance becomes passive ((4) in Fig. 17 (b)). The annual cost balance when installing a heat pump of COP=3.0 as a back-up heat source of the fuel cell has a favorable balance in Tokyo, and a passive balance of about zero in Sapporo.

5. Conclusions

The transient response characteristics concerning the power supply of a proton exchange membrane fuel cell system, comprising a reformer, an inverter, a system interconnection change device, and a back-up heat source were investigated. As a result, the following results were obtained.

(1) If the time constant of the reformer is diminished and the PI control parameters are set appropriately, the system settling time can be greatly shortened.

(2) The settling time can be shortened by changing the PI control parameters according to the load fluctuation added to the reformer.

Furthermore, the power and heat demand pattern in an average individual house in Sapporo and Tokyo were installed, and the operation cost considering the transient response characteristics of the system was investigated. Consequently, when a heat pump of COP=3.0 was installed in the back-up heat source, the annual cost balance in Tokyo was favorable, but a passive balance of about zero was obtained in Sapporo.

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Nomenclature

\[ E : \text{power} \quad \text{kW} \]
\[ \Delta E : \text{power consumption} \quad \text{kW} \]
\[ G : \text{proportional gain} \]
\[ g : \text{time constant} \quad \text{s} \]
\[ H : \text{heat} \quad \text{kW} \]
\[ \Delta H : \text{heat consumption} \quad \text{kW} \]
\[ i : \text{parameter of the integral term in proportional-plus-integral control} \]
\[ p : \text{parameter of the proportion term in proportional-plus-integral control} \]
\[ Q : \text{mass flow rate} \quad \text{g/s} \]
\[ T : \text{temperature} \quad \text{K} \]
\[ t : \text{sampling time} \quad \text{s} \]
\[ u_i : \text{input} \quad (i = 1, 2, \ldots, 5) \]

**Subscript**

- **bo**: boiler
- **bwd**: blower for dryers
- **bwf**: blower for fuel cell
- **cb**: heater in the reformer
- **cm**: commercial power
- **f**: fuel cell
- **fs**: inverter outlet
- **mt**: electric motor of heat pump
- **need**: energy need
- **pp1**: heat-medium circulating pump for exhaust heat from the fuel cell
- **pp2**: heat-medium circulating pump for geo-thermal heat pump
- **ra**: radiator
- **rm**: reformer
- **s**: system-interconnection device outlet

**References**