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Optimal operation of DC smart house system by controllable loads based on smart grid topology

Kenichi Tanaka [a], Akihiro Yoza [a,*], Kazuki Ogimi [a], Atsushi Yona [a], Tomonobu Senjyu [a], Toshihisa Funabashi [b], Chul-Hwan Kim [c]

[a] University of the Ryukyus, 1 Senbaru Nishihara-cho Nakagami, Okinawa 903 0213, Japan
[b] Meidensha Corporation, 36-2 Nihonbashi-Hakozakicho Chuo-ku, Tokyo 103 8513, Japan
[c] Sungkyunkwan University and NPT Center, Suwon City 440 746, South Korea

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ABSTRACT

From the perspective of global warming mitigation and depletion of energy resources, renewable energy such as wind generation (WG) and photovoltaic generation (PV) are getting attention in distribution systems. Additionally, all-electric apartment houses or residence such as DC smart houses are increasing. However, due to the fluctuating power from renewable energy sources and loads, supply-demand balancing of power system becomes problematic. Smart grid is a solution to this problem. This paper presents a methodology for optimal operation of a smart grid to minimize the interconnection point power flow fluctuation. To achieve the proposed optimal operation, we use distributed controllable loads such as battery and heat pump. By minimizing the interconnection point power flow fluctuation, it is possible to reduce the electric power consumption and the cost of electricity. This system consists of photovoltaic generator, heat pump, battery, solar collector, and load. To verify the effectiveness of the proposed system, results are used in simulation presented.

1. Introduction

Due to global warming and exhaustion of fossil fuels, we are required to reduce CO_2 emissions and energy consumption. However, CO_2 emissions and energy consumption are increasing rapidly due to the proliferation of all-electric houses. As countermeasures against these problems, in residential sector, installation of photovoltaic (PV) system and solar collector (SC) system are proposed. On the other hand, many of the dispersed generators such as PV can be connected to Direct Current (DC) sources and DC systems are expected to be of high efficiencies and lower cost due to the absence of inverter and rectifier circuits. It is possible to operate PV and SC systems in residential house with high efficiency. Therefore, these equipments can help to reduce the use of fossil fuel and the emission of CO. As these research, suppress of power fluctuation by renewable energy are proposed [1–6]. However, installation of renewable energy causes frequency fluctuation and distribution voltage fluctuation because output power from renewable source fluctuates due to weather condition. In addition, electricity cost is determined by maximum electric power consumption for the year. Hence it is possible to reduce electricity cost by achieving load following control using power storage facility. It is necessary to smooth power flow from distribution system to achieve above technical problems and reduce electricity cost. Because of the above factors, smart grid concept is developed which cooperatively balances supply-demand between power supply side and power demand side [7,8]. By applying the smart grid concept, we can expect high efficiency power supply, energy conservation and low-carbon society. For the research of smart grid, a method to obtain the optimal operation of thermal unit, battery and controllable loads by deciding the thermal unit commitment is already proposed [9]. The thermal units can operate in high efficiency by operating the controllable loads in coordinated manner and can achieve to reduce the total cost of thermal units. However, the reference [9] mainly focus on supply side in power system, so it is important to considering demand side. As a countermeasure at demand side, for maintaining supply-demand balance, controllable loads can be used. The study of supply-demand balancing by power consumption control of controllable load at each demand side in small power system is already reported in Ref. [10].

This paper presents an optimal operation method of DC smart-house group with the controllable loads in the residential houses as

* Corresponding author. Tel.: +81 98 895 8686; fax: +81 98 895 8708.
E-mail addresses: b985542@tec.u-ryukyu.ac.jp (A. Yoza), funabashi-t@mb.meidensha.co.jp (T. Funabashi), chkimskku@yahoo.com (C.-H. Kim).

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a smart grid. The DC smart house consists of a solar collector (SC), a PV generator, a heat pump (HP), and a battery. HP and battery are used as controllable loads in this paper. The proposed method has been developed in order to achieve the interconnection point power flow within the acceptable range and the reduction of max-min interconnection point power flow error as low as possible to smooth the supply power from distribution system. Power consumption of controllable load is determined to optimize the max-min interconnection point power flow error based on the information collected from power system through communication system. By applying the proposed method, we can reduce the interconnection point power flow fluctuation, and it is possible to reduce electricity cost due to the reduction of the contract fee for the electric power company. Also, by using battery as the power storage facility, which can operate rapidly for charge and/or discharge, the rapid output fluctuations of DC load and PV generator are compensated. Ultimately, it is important to assume an independently operation from power system such as isolated island [11–13]. Effectiveness of the proposed control system is validated by simulation results using MATLAB.®

2. Power system model

In this section, configuration of the proposed smart grid is described. Smart grid and DC smart house are described in section 2.1, and PV system and SC system are described in section 2.2 and 2.3, respectively.

2.1. Smart grid system

The smart grid model is shown in Fig. 1. The smart grid has six smart houses, and connected to power system and control system through transmission line and communications infrastructures. The control system sends required control signals to smart-house group which response to system conditions. Each smart house determines the operation of controllable loads. The interconnection point power flow is the power flow from the power system to the smart grid in Fig. 1. DC smart-house model is shown in Fig. 2, which consists of a DC load, a PV generator, a SC, a HP and a battery. HP and battery are used as controllable loads. Battery capacity is 30 kWh and inverter capacity is 4 kW. HP is used for hot-water supply. The standard is a 370 l type with 1.5 kW heater, to heat the water till 55 °C (summer) and 85 °C (winter) using midnight power in general. In this paper, we assume a summer day as the simulation case.

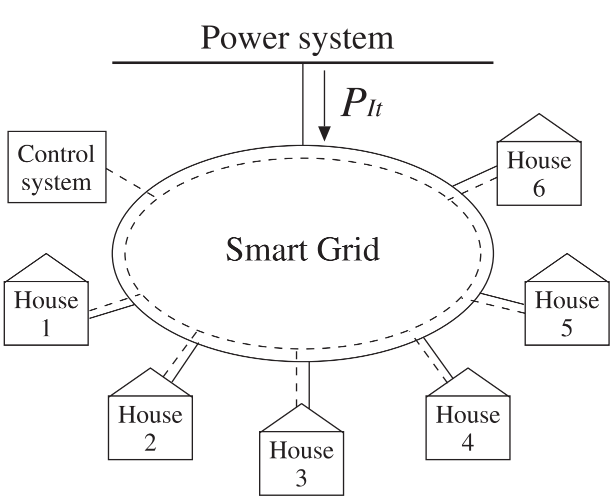

Fig. 1. Smart grid model.

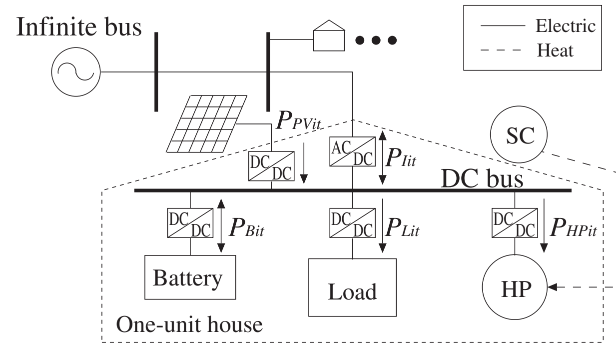

Fig. 2. DC smart-house model.

2.2. Photovoltaic system

The amount of PV generation P_s can be calculated by

$$P_s = \eta S \alpha I_a (1 - 0.005(t_O - 25)) \quad [kWh] \tag{1}$$

where, η is the conversion efficiency of PV array (%), S is the array area (m^2), I_a is the solar radiation (kW/m^2), t_O is the outside air temperature (°C).

In this paper, it is assumed that sum of total insolation are falling on the PV array, and the angle of incidence is not considered.

2.3. Solar collector system

The proposed solar collector system has HP as the auxiliary heating source. The hot-water temperature in storage tank is adjusted by diluting with water, and hot-water is supplied to the house. In case of hot-water temperature in storage tank lower than 60 °C at 19:00, hot-water in storage tank is heated to 60 °C by HP.

The SC system can be described by (2)–(8) [14]. Fig. 3 shows the numerical model of SC system. The temperature alteration and dynamic characteristic of water temperature can be written as

$$\frac{dT_h}{dt} = \frac{Q_h}{1,000 A_w} \tag{2}$$

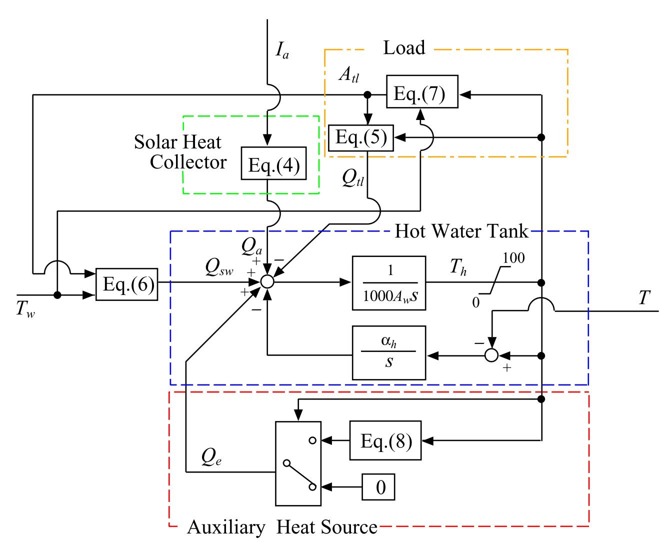

Fig. 3. Model of solar collector system.

$$\frac{dQ_h}{dt} = -\alpha_h(T_h - T) \quad (3)$$

where T_h is the hot-water temperature in storage tank, Q_h is the heat quantity of hot-water in storage tank, β is the unit conversion parameter ($\beta = 1000$ g/l), A_w is the tank capacity, α_h is the coefficient of heat transfer, T is the air temperature.

Calories obtained from solar radiation can be calculated by

$$Q_a = \eta_h I_a S_c \quad [\mathrm{J}] \quad (4)$$

where η_h is the heat transfer coefficient, S_c is the solar collector area.

In this paper, it is assumed that sum of total insolation will be falling on the solar collector and array, and it does not consider the incidence angle of insolation a solar collector array.

Using the calories from hot-water of storage tank Q_{tl} and obtained the calories by water supply Q_{sw} can be calculated by

$$Q_{tl} = 1000 A_{tl} T_h \quad [\mathrm{J}] \quad (5)$$

$$Q_{sw} = 1000 A_{sw} T_w \quad [\mathrm{J}] \quad (6)$$

$$A_{tl} = A_{sw} = \frac{T_l - T_w}{T_h - T_w} A_l \quad [\mathrm{l}] \quad (7)$$

$$Q_e = 1000 A_w (T_e - T_h) \quad [\mathrm{J}] \quad (8)$$

where, T_l is the temperature of hot-water supply, T_w is the temperature of municipal water, A_l is the supplied hot-water of house, and using the hot-water from storage tank A_{tl} is equal to the supplied water A_{sw}.

If there is no solar radiation and the water temperature is still below the desired temperature T_e, the HP provide calorie Q_e. The parameters of heat collector and electrical heater system are shown in Table 1.

3. Optimization method

In this section, optimal operation of smart grid is determined to minimize the interconnection point power flow fluctuations. The objective function and constraints are described in section 3.1, and tabu search is described in section 3.2.

3.1. Set-up of objective function

From Fig. 1, P_{It}, P_{Lt}, P_{Bt}, P_{PVt} and P_{HPt} represent the interconnection point power flow, power consumption except controllable loads, power consumption of battery, PV output power, and power consumption of HP, respectively, where:

$$P_{It} + P_{Bt} + P_{PVt} - P_{HPt} = P_{Lt} \quad (9)$$

The supply-demand balancing can maintain the equilibrium state to satisfy the above equation. In this paper, the objective function minimizes the interconnection point power flow fluctuation. Due to reduce the interconnection point power flow fluctuation, it is possible to suppress the harmful effects to power system, and it is possible to reduce electricity cost. The objective function and constraints are described by the following equations:

Objective function:

$$min\ F = \sum_{t \in T} \{B_{Icen} - P_{It}\}^2 \quad (10)$$

Constraints:

$$P_{Imin} < P_{It} < P_{Imax} \quad (11)$$

$$|P_{B_{it}}| < P_{Bmax} \quad (12)$$

$$C_{Bmin} < C_{B_{it}} < C_{Bmax}. \quad (13)$$

Where

T: All time section

I: Smart house i group

B_{Icen}: Interconnection point power flow reference

P_{It}: Interconnection point power flow from power system to smart grid

P_{Imin}: Interconnection point power flow bandwidth minimum value

P_{Imax}: Interconnection point power flow bandwidth maximum value

$P_{B_{it}}$: Charge/discharge power of battery

P_{Bmax}: Charge/discharge power maximum value of battery

$C_{B_{it}}$: Remaining energy capacity of battery

C_{Bmin}:Battery capacity minimum value

C_{Bmax}: Battery capacity maximum value

Where, we have power flexibility by defining bandwidth for interconnection point power flow in equation (11). We set power flexibility to ±10% from power reference B_{Icen} given by power system in this paper. Equations (12) and (13) show battery inverter and capacity constraints, and $P_{Bmax} = 4$ kW, $C_{Bmin} = 20\%$ and $C_{Bmax} = 80\%$, respectively. Furthermore, the proposed configuration of electric price as shown in Fig. 4 assumes the smart grid system in the future. If interconnection point power flow within the bandwidth (Region A), electric purchase cost is 10 Yen/kWh, and if interconnection point power flow departs from the bandwidth (Regions B and C), electric purchase cost are 20 Yen/kWh and 30 Yen/kWh, respectively. Moreover, electric selling cost to power system is 10 Yen/kWh. The bandwidth is given by power system to smart grid as power reference. Therefore, it is important that the customer follows the power reference and interconnection point power flow within the bandwidth.

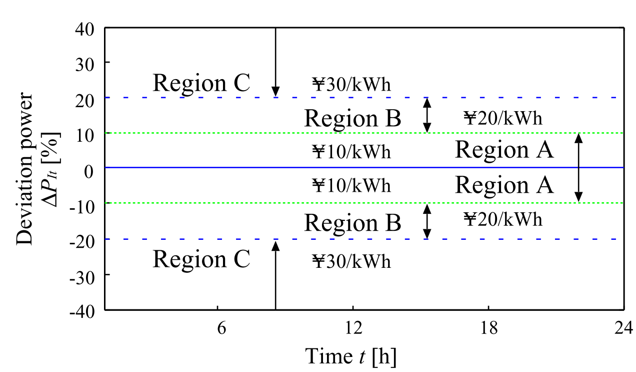

Fig. 4. Electric price.

Table 1
Parameters of heat collector and electrical heater system.

Solar Heater Collector		
Heat collection efficiency	η_h	60%
Heat collection area of one panel	A_c	1.655 m^2
Number of panels	A_c	3 panels
Electrical Heater		
Boiler efficiency	η_b	80%
Capacity of water storage tank	A_w	370 l
Heat transfer coefficient	α_h	0.0060209

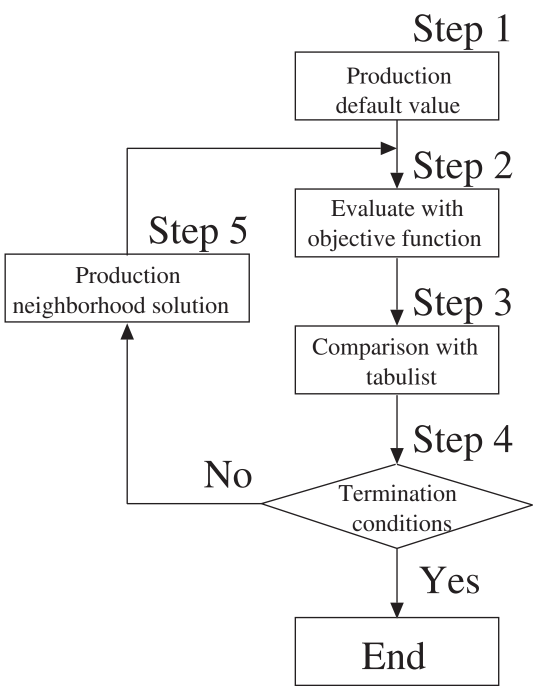

Fig. 5. Tabu search flow chart.

3.2. Tabu search

TS with local search methodology, which always moves neighborhood solution, are used for optimal technique in order to address the problems for determine charge/discharge power of battery and HP operation time for each smart house. In this paper, it is possible to determine heating time of HP by assuming power consumption, except controllable loads and heat load which could be forecasted. Therefore, charge/discharge power of battery and HP operation time for each smart house are calculated by using tabu search under the objective function and constraints. Of course, the proposed method can be calculated according to other optimization methods such as dynamic programming and GA. However, the searching area is not wide scale so we adopt tabu search. The details of the optimization is described as follows.

1. It is possible to forecast loads except controllable load for electrical and heat in each smart house: PV power output and amount of SC heat collection are calculated based on insolation forecasting data.
2. When hot-water temperature in storage tank is lower than 60 °C at 19:00, hot-water is heated to 60 °C by HP. HP heats the required heat by a fixed power consumption.
3. Based on the objective function and constraints, we determine charge/discharge power of battery and HP operation time for each smart house by using tabu search.

TS algorithm is an extended local search algorithm. By introducing a memory system called tabu list to record the latest moves, TS algorithm can escape from the current local optimum. TS algorithm has advantages like high search efficiency of local search algorithm and global search ability of intelligent algorithm.

The flow chart of tabu search is shown in Fig. 5, and the searching procedure of TS algorithm can be described as follows.

Step 1 The initial search origin is determined. The tabu list is formatted.

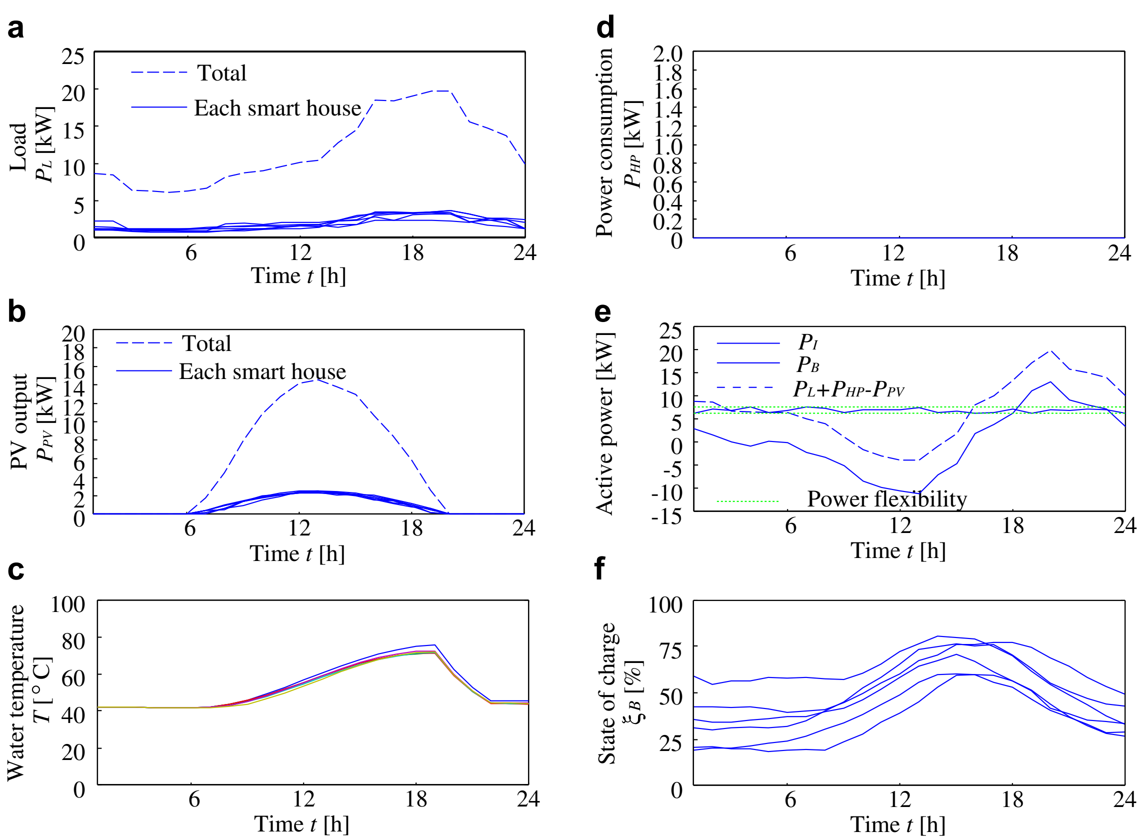

Fig. 6. Simulation results in sunny weather condition. (a) Power consumption except controllable loads. (b) PV output power. (c) Water temperature of HP. (d) Power consumption of HP. (e) Supplying power from infinite bus. (f) Remaining energy capacity of battery.

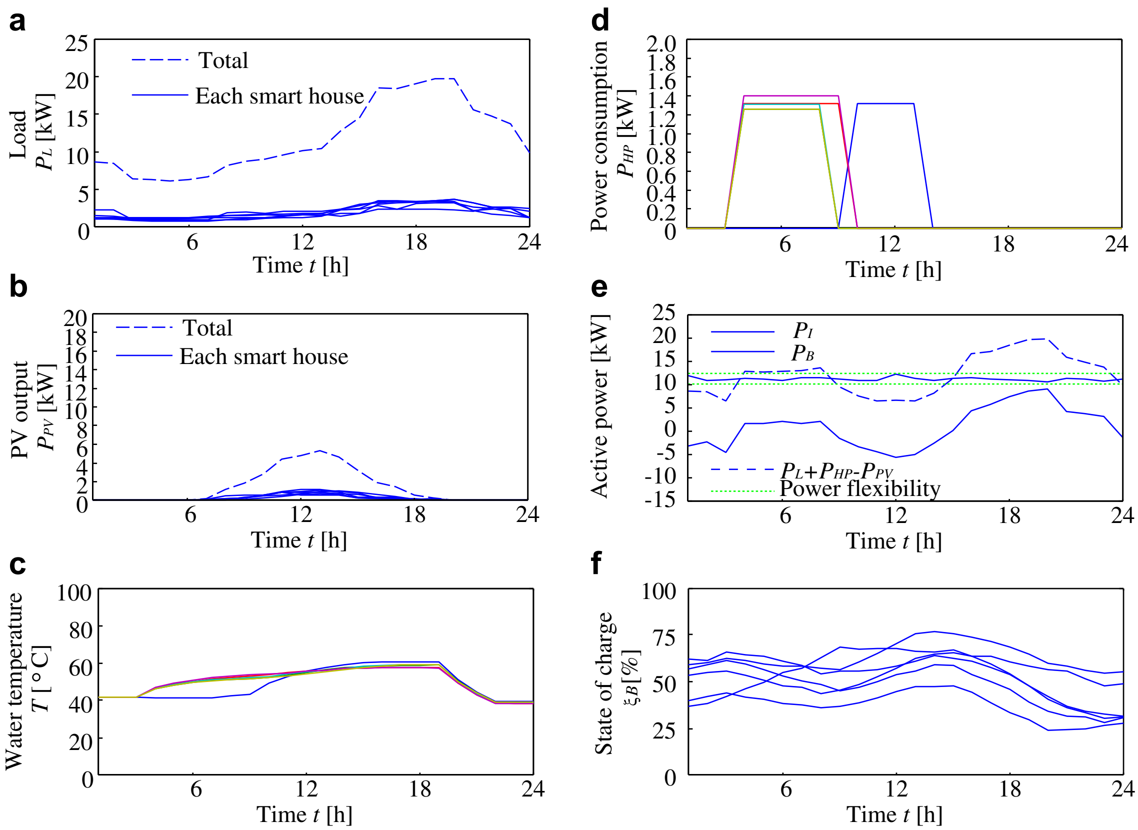

Fig. 7. Simulation results in cloudy weather condition. (a) Power consumption except controllable loads. (b) PV output power. (c) Water temperature of HP. (d) Power consumption of HP. (e) Supplying power from infinite bus. (f) Remaining energy capacity of battery.

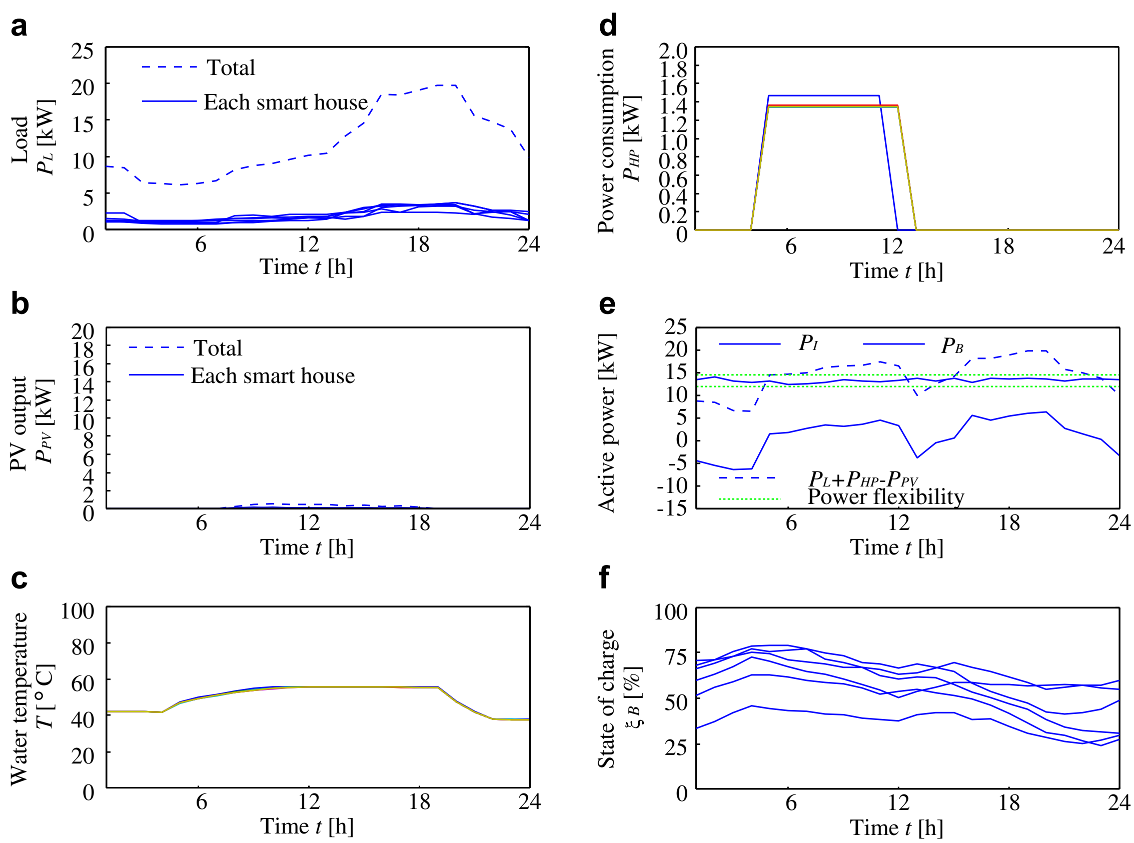

Fig. 8. Simulation results in rainy weather condition. (a) Power consumption except controllable loads. (b) PV output power. (c) Water temperature of HP. (d) Power consumption of HP. (e) Supplying power from infinite bus. (f) Remaining energy capacity of battery.

Table 2
Operation cost [Japanese Yen].

	Sunny	Cloudy	Rainy
without controllable load	1610	2899	3420
with controllable load	1601	2679	3167
with fault and without controllable load	1610	2899	3420
with fault and controllable load	1583	2739	3185

Step 2 The neighborhood solutions around the origin are evaluated.
Step 3 For the neighborhood solutions evaluation, the best neighborhood solution is not recorded in the tabu list which is selected as the next origin. If the evaluated solution is better than the recorded best solution, the best solution is updated. The earliest data in the tabu list are cleared, and new evaluated solutions are recorded as latest data.
Step 4 The neighborhood solutions around the origin are evaluated, and the best neighborhood solution, which is not recorded in the tabu list, is selected as the next origin. If the evaluated solution is better than the recorded best solution, the best solution is updated. If the conditions of termination are satisfied, the search process is terminated. Otherwise, go to Step 5.
Step 5 For the best solution in Step 3, the neighborhood solutions are generated.

In this paper, it is possible to determine heating time of HP by assuming power consumption except controllable loads and heat load which could be forecasted. Therefore, charge/discharge power of battery and heating time of HP are calculated by tabu search. The following algorithmic implementation parameters are used for simulation.

global_iteration_max	1000
tabu_length	30
local_iteration_max	48

4. Simulation results and discussion

In this section, we present the simulation results and a discussion to verify the effectiveness of the proposed optimal method. Simulation conditions are described in section 4.1, and the discussion at simulation results are described in section 4.2 and 4.3.

4.1. Simulation condition

For smart grid model that has six smart houses as shown in Fig. 1, we assume that it is possible to forecast loads and PV power output of smart house, and simulate for weather conditions like sunny, cloudy and rainy. PV output power can be calculated from equation [1] using insolation of each weather condition. In addition, for heat loads of each smart house, we assume that three people used 100 L hot-water for 1 h in shower from 19:00 to 22:00. Therefore, a shower takes 3 h for 3 peoples in the simulation. Then hot-water temperature in storage tank is lower than 60 °C at 19:00, hot-water in storage tank is heated to 60 °C by HP based on Fig. 3.

4.2. Simulation results

Simulation results for sunny, cloudy and rainy weather conditions are shown in Figs. 6–8, respectively. Assuming power

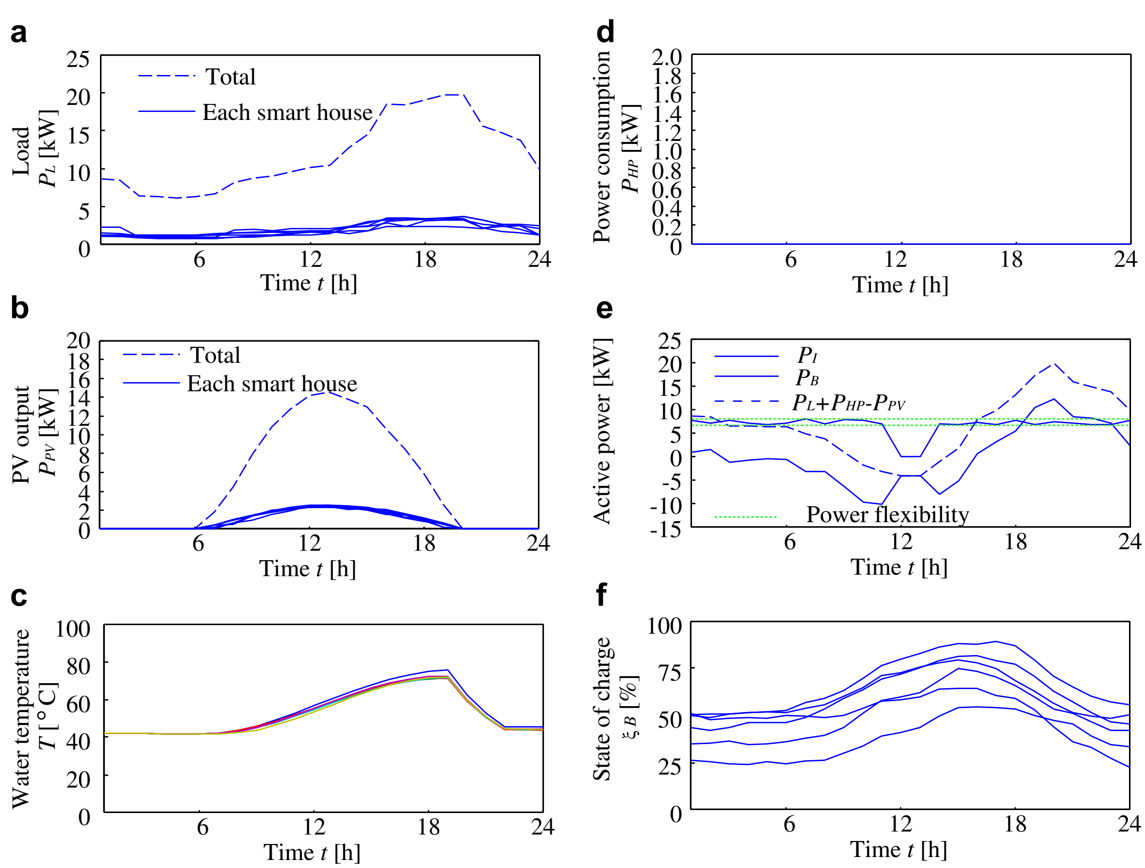

Fig. 9. Simulation results with fault in sunny weather condition. (a) Power consumption except controllable loads. (b) PV output power. (c) Water temperature of HP. (d) Power consumption of HP. (e) Supplying power from infinite bus. (f) Remaining energy capacity of battery.

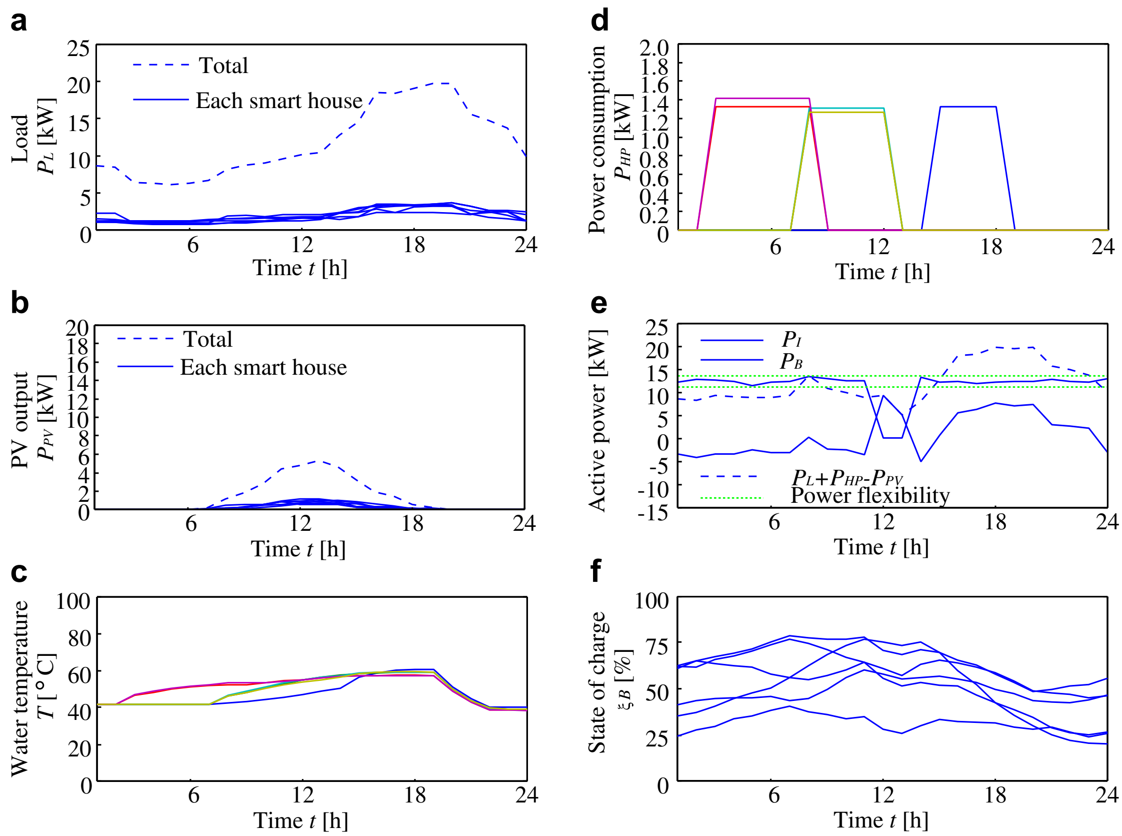

Fig. 10. Simulation results with fault in cloudy weather condition. (a) Power consumption except controllable loads. (b) PV output power. (c) Water temperature of HP. (d) Power consumption of HP. (e) Supplying power from infinite bus. (f) Remaining energy capacity of battery.

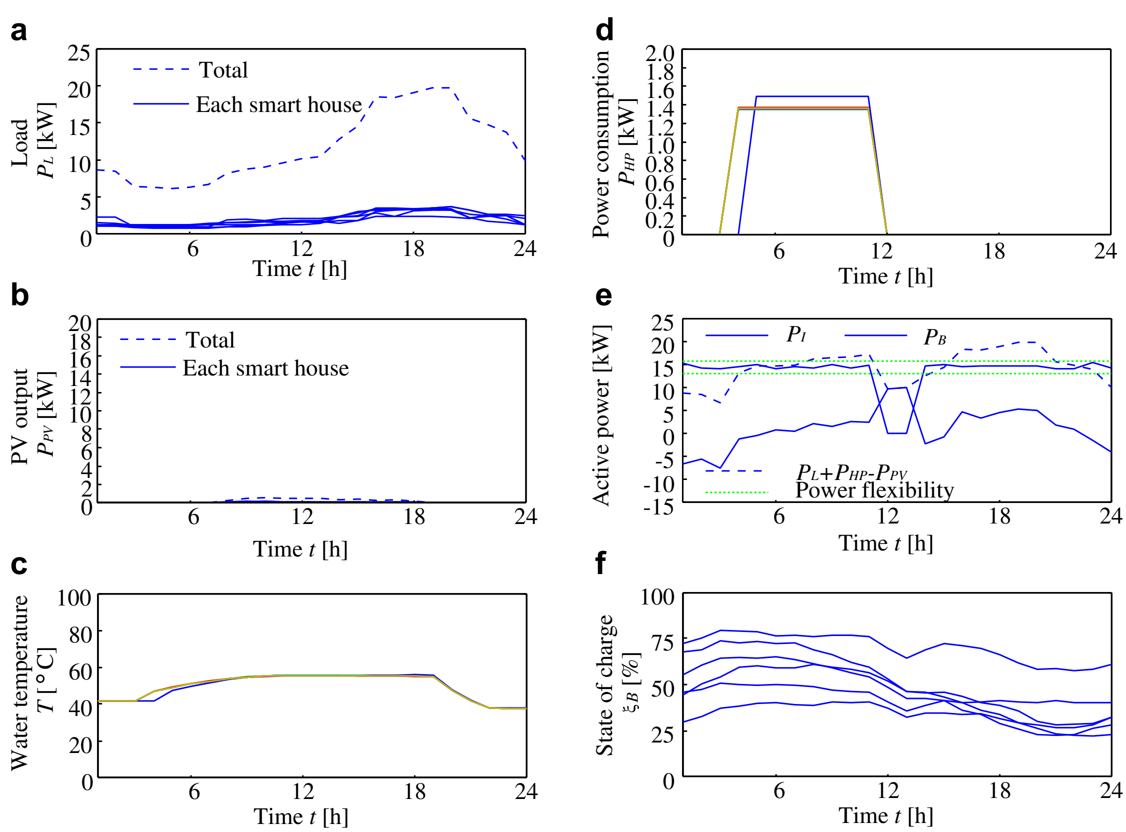

Fig. 11. Simulation results with fault in rainy weather condition. (a) Power consumption except controllable loads. (b) PV output power. (c) Water temperature of HP. (d) Power consumption of HP. (e) Supplying power from infinite bus. (f) Remaining energy capacity of battery.

consumption except controllable loads and PV output power in each weather conditions are shown in Figs. (a) and (b), respectively. These figures show power consumption except controllable loads and PV output power in smart grid and each smart house, respectively. For sunny weather, hot-water temperature in storage tank is higher than 60 °C at 19:00, hot-water in storage tank is not heated by HP (Fig. 6(d)). However, for cloudy and rainy weather conditions, hot-water temperature in storage tank is lower than 60 °C at 19:00, hot-water in storage tank is heated to 60 °C by HP. Water temperature of storage tank and power consumption of HP are shown in Figs. 7(c),(d) and 8(c),(d), respectively. Water temperature for each weather conditions are higher than 60 °C at 19:00 by operating HP, and operating time of HP is determined by the proposed optimal method. In addition, interconnection point power flow for each weather conditions are shown in Figs. 6(e), 7(e) and 8(e), respectively. From these figures, it is observed that the interconnection point power flow is within the bandwidth (Region A), and power consumption is smoothed by controlling the controllable loads. Furthermore, remaining energy capacity of the battery in each smart house are shown in Figs. 6(f), 7(f) and 8(f), respectively. From this figures, charge/discharge control of battery is achieved within the acceptable range of battery capacity. Operation costs with/without control are shown in Table 2. It is possible to reduce the cost with the proposed control because the interconnection point power flow is controlled within bandwidth by operating controllable loads. In the sunny weather condition, PV power output and SC heat generation are highly generated due to sufficient insolation. Therefore, it is not necessary to heat by HP and power consumption for each house is not increased anymore. So, the sunny weather condition is the lowest cost in the three cases.

4.3. Simulation results with fault

Simulation results with system fault for sunny, cloudy and rainy weather conditions are shown in Figs. 9–11, respectively. We assume disconnection of the supply power from infinite bus from 12:00 to 13:00. By assuming the simulation results with fault conditions, the smart grid system can be expected to operate as independent system without power system. Assuming power consumption except controllable loads and PV output power in each weather conditions are shown in Figs. (a) and (b), respectively. These figures show power consumption except controllable loads and PV output power in smart grid and each smart house, respectively. For sunny weather condition, hot-water temperature of storage tank is higher than 60 °C at 19:00, hot-water of storage tank is not heated by HP (Fig. 9(d)). For cloudy and rainy weather conditions, hot-water temperature of storage tank is lower than 60 °C at 19:00, and hot-water of storage tank is heated to 60 °C by HP. Water temperature of storage tank and power consumption of HP are shown in Figs. 10(c),(d) and 11(c),(d), respectively. Water temperature of each weather conditions are higher than 60 °C at 19:00 by operating HP, and operating time of HP is determined by the proposed optimal method. In addition, interconnection point power flow for each weather conditions are shown in Figs. 9(e), 10(e) and 11(e), respectively. From these figures, it is found that interconnection point power flow is within the bandwidth (Region A) except from 12:00 to 13:00, and power consumption is smoothed by the controlling controllable loads. Furthermore, remaining energy capacity of battery in each smart-house are shown in Figs. 9(f), 10(f) and 11(f), respectively. From this figures, it can be said that charge/discharge control of battery is achieved within the acceptable range of battery capacity. Operation costs with/without control are shown in Table 2. It is possible to reduce the cost compare with using controllable loads because the interconnection point power flow is controlled within bandwidth by operating controllable loads. In the sunny weather conditions, PV power output and SC heat generation are high due to sufficient solar radiation. Therefore, it is not necessary to heat by HP and power consumption for each house is not increased anymore. So, the sunny weather conditions are the lowest cost in the three cases.

5. Conclusion

This paper has determined an optimal operation for DC smart-house group, in smart grid, which consists of a battery and a HP as controllable loads, that may steadily increase in the demand side in the future. As an optimization method, we have used the tabu search which determines the operation method of controllable loads, to suppress interconnection point power flow fluctuation within the bandwidth, based on information obtained by the communications infrastructures. By smoothing interconnection point power flow, it is possible to reduce electricity cost due to the reduction of the contract fee of the electric power company. Power consumption in smart grid is smoothed by achieving the proposed method, so we can suppress the impact of PV against power system. Consequently, we can expect high quality power supply and reduce the cost by cooperative control in smart grid.

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