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SMART APARTMENT WITH DEMAND-RESPONSE AND FIXED BATTERIES

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ABSTRACT

In Japan, each apartment's dweller generally make contract with the electric power company to receive low voltage electric power. However, in recent years, trader of bulk high voltages (aggregators) have been increasing. In this study, the introduction of demand-response along with the utilization of a fixed battery in the apartment is proposed in order to decrease the peak load and reduce the peak load cost of receiving high voltage. In this way, the trader of bulk high voltage can increase the profits whereas, apartment dwellers can decrease their electricity bills by demand-response. Accordingly, this study applies a multi-objective optimization method. The profit of the trader is maximized while the electricity charge for the apartment dwellers is decreased by Non-dominated Sorting Genetic Algorithms-II (NSGAII) which is utilized multi-objective optimization algorithm.

INTRODUCTION

The trader of bulk high voltages (aggregators) deal with electric power company in high voltage and then sell the power to apartment's dwellers. Receiving high voltage power has an advantage of low price per kWh. Thus, the difference between electricity charges from apartment and for electric power company become the profit for the trader of bulk high voltage. In this research, the trader of bulk high voltage applies the real-time pricing as a demand-response to level the load demand of apartment (Angarita and Usaola, 2007; Nguyen and Yoon, 2014; Zakariazadeh et al., 2014). Furthermore, the trader utilizes a fixed battery, electric vehicle (EV), and heat pump (HP) to perform peak-cut of load. On the other hand, the each apartment dwellers can reduce the electric charges significantly by adjusting one's power consumption for real-time price. However, there is a trade-off relationship between increasing profit for the trader and decreasing electricity charge for the apartment dwellers. In this paper, from the above relationship, NSGAII that is multi-objective optimization algorithm is applied (Deb, 2001; Ippolito et al., 2014). The real-time price and operation schedules of a fixed battery, EV, HP for a full day are optimized for considering the benefit between the trader and apartment dwellers. The demand-response characteristics of dwellers are simulated by sigmoid function (Tahara et al., 2015). MATLAB which is numerical computation tool is used for simulation.

SMART APARTMENT MODEL

Figure 1 illustrates the smart apartment model which includes 100 households (Yoza et al., 2011) . The photovoltaic system (PV) and a fixed battery have been introduced into the apartment model. The rated power of the photovoltaic system is 20 kW. The capacity of a fixed battery and rated inverter output are 2,000 kWh and 20 kW respectively. In addition, 10 HPs with a rated power consumption of 10 kW have been introduced into the apartment. It can be defined that a COP value of the heat pumps is 3.5. The proposed contract form among the smart apartments, a electric power company and the trader of bulk high voltage is shown in Figure 2. The trader of bulk high voltage deals with the electric power company for getting high voltage power, then sales the low voltage power to aprtment's dwellers. The receiving power contract in high voltage has an advantage of low price. Thus, the difference between electricity charges from dewlers and for electric power company become the profit of the trader of bulk high voltage. Moreover, in order to perform load power leveling, the bulk high voltage trader apply real-time pricing as a demand-response method and utilize the fixed battery, EVs and HP. Therefore, the trader of bulk high voltage can reduce the peak load cost by raceiving high voltage from electric power company. On the other hand, the each dweller can reduce the electricity charges significantly by adjusting one's power consumption for real-time price.

The hot water supply system from HP using solar

In this paper, the HP has three solar collection panels (SC) as a auxiliary heat source (Yoza et al., 2014). The space of a SC A_{SC} , the efficiency of SC η_{SC} are 1.6 m^2, 60 % correspndingly. The hot water supply system using SC can be modified by equations (1)$\sim$(7) (Yoza et al., 2013; Yoza and Funabashi, 2013). The characteristics of hot water temperature depends on the ambient temperature, the solar insolation and time. The characteristic is obtained as follows:

$$\frac{dT_h}{dt} = \frac{Q_h}{1,000A_w} \qquad (1)$$

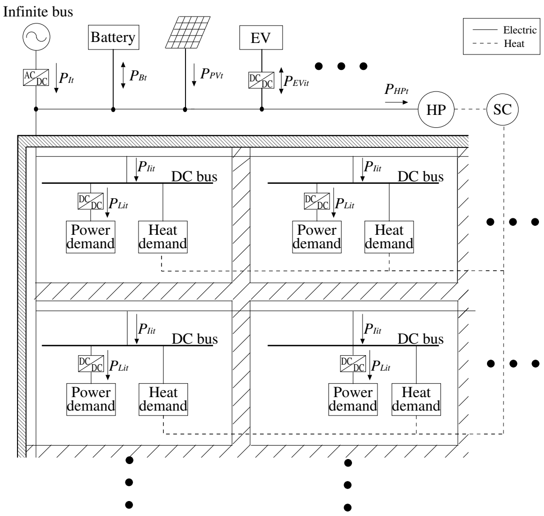


Figure 1 The smart apartment model

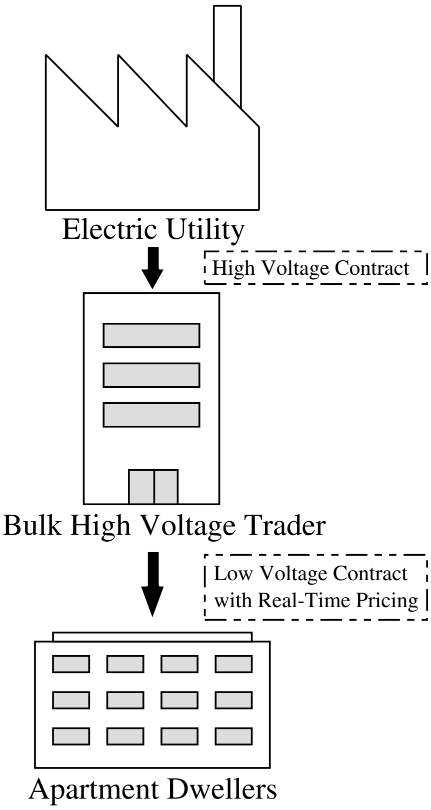


Figure 2 The proposed contract form

$$\frac{dQ_h}{dt} = -\alpha_h (T_h - T) \tag{2}$$

where, T_h [°C], Q_h [J], A_w [l], α_h, T [°C] are water temperature in storage tank, quantity of heat in tank, capacity of the storage tank, the specific heat of the water, the ambient temperature respectively. The amount of heat from solar insolation is obtained by

$$Q_a = \eta_{SC} I_a n A_{SC} \quad \text{[J]} \tag{3}$$

where, I_a[J], n and A_{SC} [m^2] are the solar insolation, the number of SC panels respectively. The heat loss by

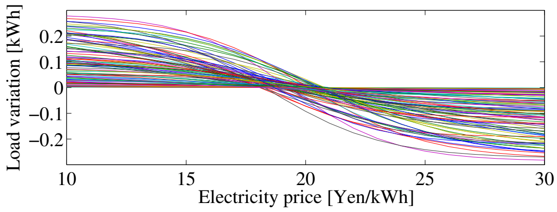


Figure 3 Function of power response.

supplying hot water Q_{tl} [cal], the added heat by city's water supply Q_{sw} [cal], the amount of hot water supply $A_{tl}[l]$, the amount of city's water supply $A_{sw}[l]$, the heat from SC Q_e [J] are calculated as follows:

$$Q_{tl} = 1,000 A_{tl} T_h \quad \text{[J]} \tag{4}$$

$$Q_{sw} = 1,000 A_{sw} T_w \quad \text{[J]} \tag{5}$$

$$A_{tl} = A_{sw} = \frac{T_l - T_w}{T_h - T_w} A_l \quad [l] \tag{6}$$

$$Q_e = 1,000 A_w (T_e - T_h) \quad \text{[J]} \tag{7}$$

where, T_l [°C], T_w [°C], A_l [l], T_e [°C] are temperature of hot water supply, temperature of city water supply, the amount of hot water supply, target temperature correspondingly.

Real-Time Pricing Model

In this study, the real-time prices are assumed as follows:

$$C_{Lt} = \frac{w}{1 + \exp\{d \times (P_{La} - P_{Lt} - k)\}} + l \tag{8}$$

where P_{La} and P_{Lt} are the mean value of load power in apartment for a full day [kW], the total load power in apartment [kW] correspondingly. Moreover, w, d, k, l are the parameters of the real-time pricing. Electric power company can adjust these parameters to lead load demand. In this study, these parameters are optimized in order to maximize the profit of trader and minimize the electricity charges for the consumers.

Demand Response Characteristic Model

Demand response characteristics of each dweller is illustrated in Figure 3. In this study, it is assumed that power demand response of each dweller are based on each characteristics in Figure 3.

Optimization Problem Formulation

In this paper, it is assumed that the electric power demand and hot water's consumption of apartment dwellers, output power from PV for a full day can be predicted. In this section, the multi-objective optimization problem is explained. The multi-objective optimization problem that is formulated in this study which has two objectives. The first objective is to minimize total electric charges of apartment dwellers. The second one is to maximize the profit of the trader of bulk high voltages. In this study, to formulate the problem as a two-objective minimizing optimization problem, the profit of trader is reversed. The multi-objective optimization problem is defined as follows:

•The objective functions

$$\min \quad M_{day} = \sum_{t \in T}^{T} \{P_{Lt}C_{Lt} + P_{EVrt}C_{EVrt} - P_{It}C_{It} - P_{Im}C_{Im}\} \qquad (9)$$

$$\min \quad C_M = \sum_{t \in T}^{T} \{P_{Lt}C_{Lt}\} \qquad (10)$$

•The constraint conditions

(i)The total amount of load power variation constraint

$$|\Delta U_L| < 0.05 \times U_L \qquad (11)$$

The total amount of load power variation before and after the demand response is limited.

(ii)The amount of load power variation for each dwellers constraint

$$|\Delta U_{ln}| < 0.1 \times U_{ln} \qquad (12)$$

The total amount of load power variation for each dwellers before and after demand response are limited.

(iii)The upper/lower bound of real-time price constraint

$$10 < C_L < 35 \ \ [\text{Yen/kWH}] \qquad (13)$$

The bound of real-time price is limited to 10∼35 Yen.

(iv)The profit of trader constraint

$$M_{day} < 0 \qquad (14)$$

The trader must get the profit.

(v)The parameters of the real-time pricing constraint

$$w > 0, \ \ d > 0 \qquad (15)$$

In order to reduce the peak of load, these parameters must be positive value.

(vi)The adverse power currents constraint

$$P_{lit} \geq 0 \qquad (16)$$

In this paper, it is assumed that dwellers can not sell the electric power.

(vii)The demand-response peak constraint

$$P_{Lm} \leq P_{Pm} \qquad (17)$$

The peak load after demand response must be smaller than predicted load.

(viii)State of charge(SOC) constraint for a full day

$$0.2 \times \xi_{Bm} \leq \xi_{Bt} \leq \xi_{Bm} \qquad (18)$$

The SOC of a fixed battery must be operated in 20 ∼ 100 [%].

(ix)SOC constraint at 24:00

$$\xi_{B(t=0)} \leq \xi_{B(t=24)} \qquad (19)$$

In order to verify accurately the effectes of demand-response, the SOC of a fixed battery is 50 % at $t = 0$, and must be 50 % or more at $t = 24$.

(x)Active power of fixed battery constraint

$$|P_{Bt}| \leq P_{Bm} \qquad (20)$$

The fixed battery is not able to charge or discharge beyond the rated power.

(xi)SOC of EV constraint for a full day

$$0.2 \times \xi_{EVm} \leq \xi_{EVt} \leq \xi_{EVm} \qquad (21)$$

The SOC for all EV batteries must be operated in 20 ∼ 100 [%].

(xii)SOC of EV constraint at 24:00

$$\xi_{EV(t=0)} \leq \xi_{EV(t=24)} \qquad (22)$$

In order to verify accurately the effectes of demand-response, the SOC of EV batteries are 50 % at $t = 0$, and must be 50 % or more at $t = 24$.

(xiii)Active power of EV constraint

$$|P_{EVt}| \leq P_{EVm} \qquad (23)$$

The EV batteries are not able to charge or discharge beyond the rated power.

(xv)Interconnection point power flow constraint

$$P_{Im} \leq P_{Lm} \qquad (24)$$

The maximum of interconnection point power flow must be smaller than maximum load.

where

- M_{day} : Profit of trader for a full day [Yen]
- P_{Lt} : Load power of all apartment dwellers [kW]
- C_{Lt} : Real-time price [Yen/kWh]
- P_{EVrt} : Consumption power of EV [kW]
- C_{EVrt} : Price of EV consumption [Yen/kWh]
- P_{It} : Interconnection power flow [kW]
- C_{It} : Price of purchasing power in high voltage contract [Yen/kWh]
- P_{Im} : Maximum of interconnection power flow [kW]
- C_{Im} : Basic fees on power receiving contract with electric utility [Yen/kW]
- C_M : Total electricity charges of dwellers for a full day [Yen]
- U_L : The amount of load power in the apartment for a full day [kWh]
- ΔU_L : Variation amount of load between before and after the demand-response [kWh]
- U_{ln} : Amount of power consumption in dweller n for a full day [kWh]
- ΔU_{ln} : Variation amount of power consumption between before and after the demand-response in dweller n [kWh]
- P_{lnt} : The load power in dweller n after demand-response [kW]
- P_{Lm} : Maximum load power of apartment after demand-response[kW]
- P_{Pm} : Predicted maximum load power of apartment [kW]
- ξ_{Bt} : SOC of a fixed battery [%]
- ξ_{Bm} : Maximum SOC of a fixed battery [%]
- P_{Bt} : Active power of a fixed battery [kW]
- P_{Bm} : Maximum active power of a fixed battery [kW]
- ξ_{EVt} : SOC of EV [%]
- ξ_{EVm} : Maximum SOC of EV [%] (100%)
- P_{EVt} : Active power of EV [kW]
- P_{EVm} : Maximum active power of EV [kW]

SIMULATION RESULTS

Simulation Conditions

In this study, it is assumed that the usage of EVs, the output power from the PV system, the consumption of hot water from storage tank, the consumption of electric power for a full day can be predicted. The consumption from EVs, the output power from the PV system, and the consumption of hot water from storage tank are illustrated in Figures 4, 5, 6. 10 EVs which are introduced into the apartment. In this research, apartment's dwellers can rent these EVs at 50 Yen/kWh. However, in order to perform the effectiveness of demand-response, the charges for EV consumption considered different from the electricity charges of dwellers. Figure 7 shows the predicted power demand of apartment. The amount of predicted power demand of each dweller is 10 kWh. Since there are 100 dwellers, the total amount of predicted power demand is 1,000 kWh. The electricity price with conventional electricity contract (low voltage) is 25 Yen/kWh. Therefore, if conventional electricity contract are agreed, the total of electricity charges would be 25,000 Yen. This must be noted to comparison to the proposed contract form. Otherwise, the time-besed power rate in high voltage is assumed as shown in Figure 8. In this study, the defined optimization problem is solved by NSGA2 which is multi-objective optimization algorithm.

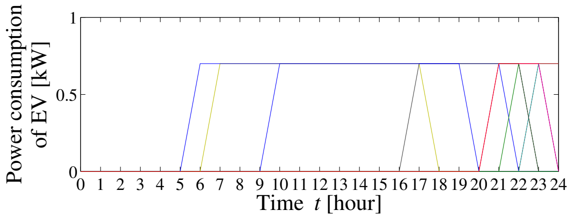


Figure 4 Consumption of EV.

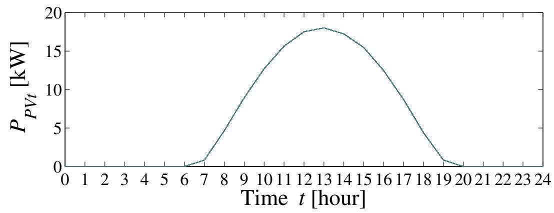


Figure 5 PV output power.

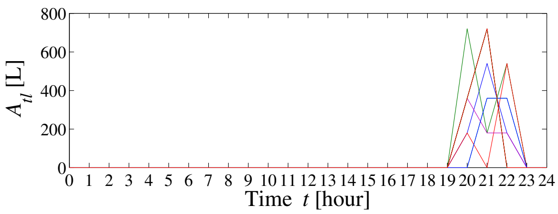


Figure 6 Consumption of hot water.

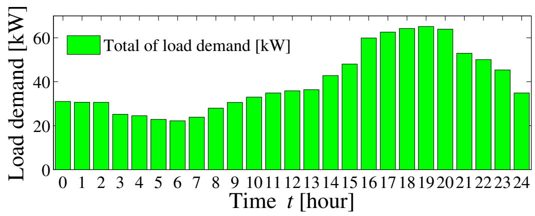


Figure 7 Predicted load demand.

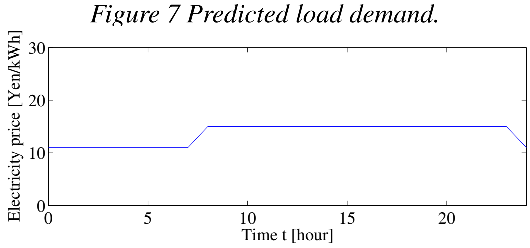


Figure 8 Electricity price for high voltage receiving.

Simulation results

Figure 9 illustrates the pareto solution that was calculated by NSGAII. As shown in Figure 9, the total elec-

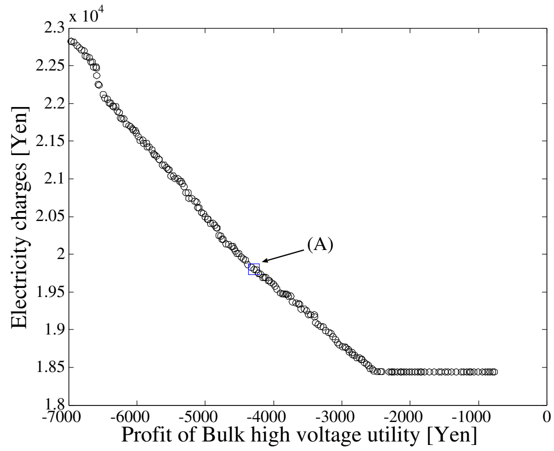


Figure 9 Pareto solution.

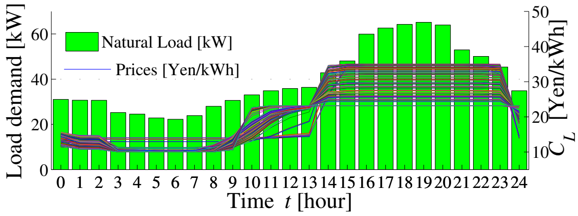
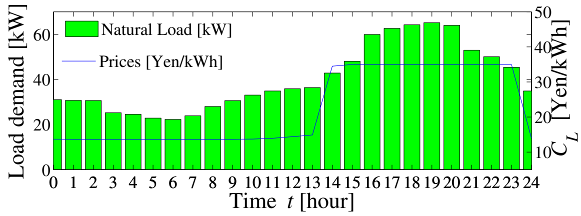
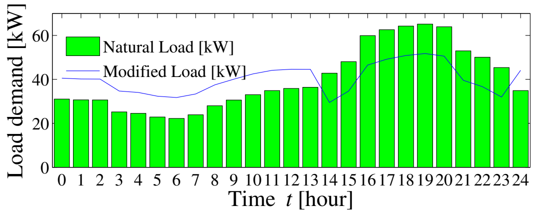


Figure 10 Predicted load and real-time prices.

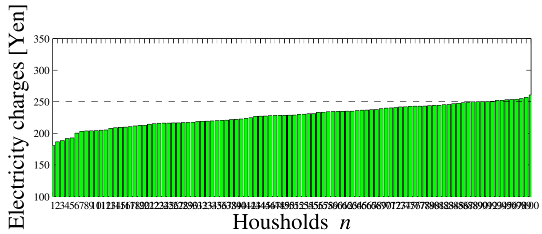
tricity charges with all solutions are less than 25,000 Yen. Furthermore, it is recognized that the trader of bulk high voltage can make profit with all solutions. The real-time prices with all solutions are shown Figure 10. In order to level the load demands at each time, the trader has to perform the peak-cut and bottom-up of the load by applying real-time pricing and utilizing a fixed battery. According to Figure 10, when load demand is high, the real-time prices are high. In this paper, the solution (A) is explained as an illustration. The simulation results with solution (A) is presented in Figure 11. Figure 11(a) shows the real-time price as a curve. The load demand before the demand-response are also illustrated as a bar graph in Figure 11(a). In Figure 11(a), when the load demand is high, the real-time price is high too. The load demand after the demand-response are presented as a curve in Figure 11(b). According to Figure 11(b), it is ascertainable fact that the load demand is leveled. In Figure 11(c), the electricity charges of each dweller after the demand-response is illustrated. It can be defined that all dwellers can reduce their own charges. Figures 11(d) and 11(e) show the load demands of two dewllers before and after the demand-response. The one got biggest benefit and the other got smallest benefit by demand-response. In Figure 11(d), if the real-time price is high, while the load demand is reduced. In contrast, Figure 11(e) have hardly any difference between before and after demand-response. Figures 11(f) and 11(g) show the power consumption from HPs, and the temperature of hot water in the storage tanks respectively. According to Figure 11(f), the most HPs are operating in daytime to consume output power



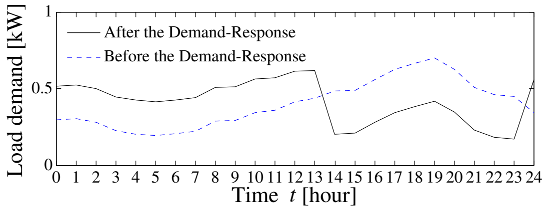
(a) Electricity prices for consumer.



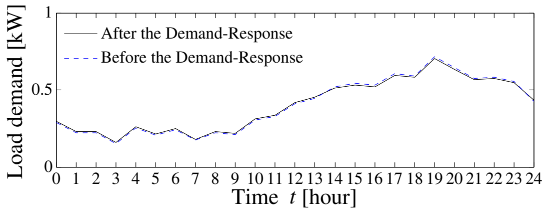
(b) Modified Load.



(c) Charges for consumers.



(d) Modified Load with biggest benefit.



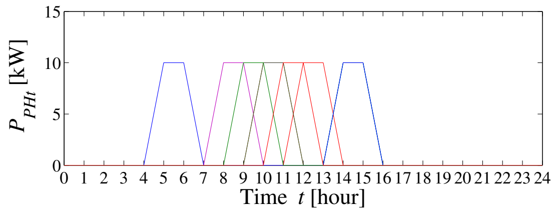
(e) Modified Load with smallest benefit.

Figure 11 Simulation results with (A).

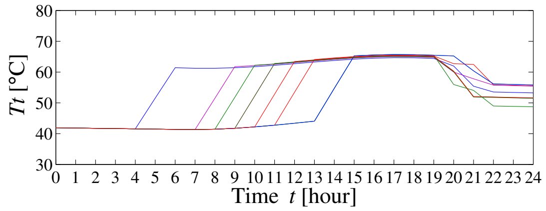
from PV system. Moreover, the temperature of hot water in the storage tanks is increasing with operation of HPs. Figures 11(h) and 11(i) show the state of charge (SOC) for a fixed battery, and the SOCs for EVs. In Figure 11(h), a fixed battery is charging during morning, and discharging during daytime. As shown in Figure 11(i), all EVs are charged to over 50% by 24:00 due to constraint condition. Figure 11(j) presents the interconnection power flow between the apartment and the power grid. The interconnection power flow is leveled to perform the peak-cut.

CONCLUSION

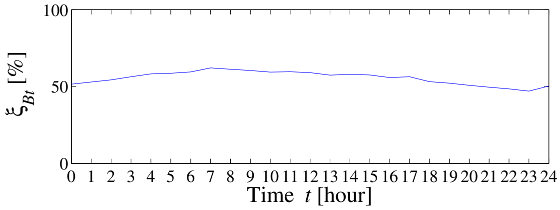
In this study, the demand-response along with the utilization of a fixed battery, HPs and EVs in the apartment have been proposed. The trader of bulk high volt-



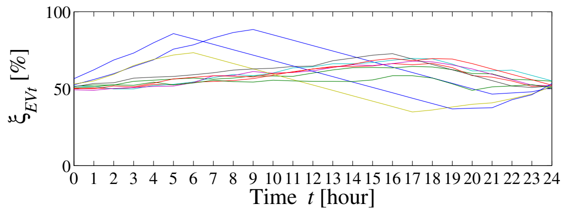
(f) HP output power.



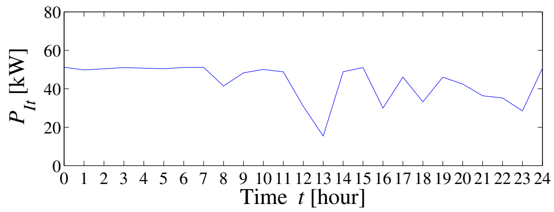
(g) Temperature of the water.



(h) SOC of fixed battery.



(i) SOC of EVs.



(j) Power flow.

Figure 11 Simulation results with (A) .

age can purchase power from electric power company at low price with high voltage. Moreover, the trader can make the profit by applying the real-time pricing for the apartment dwellers.

Otherwise, the apartment's dwellers could reduce own electric charges significantly by demand-response.

However, there is a trade-off relationship between the benefits of the trader and the apartment's dwellers. In this research, this relationship has been solved as a multi-objective optimization problem by using NSGAII. The real-time price and operation of a fixed battery, EVs, and HPs were optimized for minimizing electricity charges for apartment dwellers and maximizing the profit of the trader.

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