Load Leveling Effects by Massively Introduced Residential Battery Storage Systems

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***Abstract*—Renewable energy is frequently promoted to improve sustainability and low carbonization of energy systems. However, high penetration of renewable energy by technologies such as photovoltaics (PV) decreases power generation from thermal power plants. As a result, supply and demand balancing capabilities can be reduced overall in power systems. Therefore, the capability of residential batteries in balancing supply and demand (particularly demand) is expected to contribute toward the preparation for massive introduction of renewable energy power generation. This work develops a residential battery optimum operation scheduling model using mixed integer linear programming for leveling a system load. Through the use of this model it can be determined whether many batteries can level the whole system load without sharing information on each battery state. It was found that the system load could be leveled effectively when batteries are charged by a lower power than by the rated power.**

Keywords—Battery; Load Leveling; Peak Load Shifting; Demand Response; Optimization

I. INTRODUCTION

It has recently been shown that renewable energy generation technologies such as photovoltaics (PV) and wind power generation improve sustainability and reduce carbonization of energy systems. According to an announcement by the Japanese government [1], PV will be introduced in Japan up to 64 GW by 2030. However, large-scale renewable energy deployment will make the balancing of supply and demand difficult because the output of renewable energy generation depends on weather conditions. Moreover, the number of thermal power plants in operation, which adjust supply and demand, will be reduced; consequently, supply and demand balancing capabilities will be decreased. Taking these factors into consideration, it is anticipated that the electric power system requires not only supply and demand balancing capabilities (on the supply side such as thermal power generation and pumped storage power generation) but also additional capabilities.

To tackle this issue, a distributed energy management system using information and communication technology is required for supply and demand balancing on the demand side [2]. The conventional electric power system is a centralized energy management system that provides electricity in one direction (from the power generator to each customer). By comparison, in the distributed energy management system, electricity and information (such as demand or power generation) flow in both directions. A battery is an energy management device that can be easily charged or discharged. Many energy management studies have been competed using batteries. For example, peak load shifting has been studied by using the price of electricity as a marker to control batteries [3], [4], whereas investigations involving the demand response by using electric vehicles have also been undertaken. The capability of EV to fill the valley of system load evaluated [5]. Reduction in fluctuation of renewable energy generation by using plug-in hybrid electric vehicle was studied [6].

Previous work has outlined the development of a basic optimum operation scheduling model [7] for domestic electric appliances to allow for the control of balancing supply and demand as a function of home energy management systems. In this present study, the model has been improved to allow for leveling daily fluctuations in a whole system load by using residential batteries installed in each household. With the use of this new battery optimum operation scheduling model, we evaluated the system load leveling effects by using residential batteries with several penetration rates of batteries and several partial load rates at charging.

II. STUDY OUTLINE

A. Aim

In this study, a future is assumed in which a large number of residential batteries are popular and in which many renewable energy generation technologies are introduced into a power system. If many residential batteries can be controlled for the whole power system, supply and demand balancing capabilities are improved overall. The purpose of this study is therefore to quantitatively evaluate the leveling effect of massively introduced residential batteries.

B. Procedure

In this study to evaluate the leveling effects mentioned above, a battery optimum operation scheduling model using a mixed integer linear programming (MILP) was developed. The model included the assumption that each household scheduled battery operation (for contribution to load leveling) by using only the information about predicted system load provided from a power system operator. We analyzed the load leveling effects accomplished without sharing information about battery

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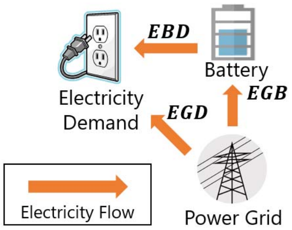

Figure 1. Energy flow in the optimum operation model.

operations between households. The electric flow calculated by the model is as shown in Figure 1. Considering the voltage rise problem in the power distribution system, a reverse power flow is not allowed in this model. Furthermore, charged electricity is not shared throughout the grid and is consumed only in each household. Temporal resolution of the scheduling model is 30 minutes and scheduling period of a battery operation is 24 hours. In this study two objective functions are set, namely: the system load range which is calculated as the difference between maximum and minimum value of system load, and the integrated value of step change in system load which is taken every 30 minutes. The formulation of the model is described in detail in Section III. Prediction values up to 24 hours ahead of the net load in a whole power system and the electricity demand in each household were used as the input data. By applying these input data to the model, the optimum charging/discharging schedules of the residential battery in each household were determined. Based on the optimized schedules up to 24 hours in advance, a simulation for 12 hours is performed. An optimization calculation is then conducted again from that point up to 24 hours in advance. In this study, this model was applied to allow calculation for up to 9 days by repeating the optimum scheduling and the simulation in an iterative way. In this calculation, it is assumed that there is no uncertainty in input data. Overall model calculations therefore evaluated the potential of massively introduced residential battery storage systems for power system load leveling.

In this study, the leveling effect of residential batteries was analyzed from two viewpoints as discussed below.

1) Analysis of the Penetration Rate of Batteries

The leveling effects of the batteries depend on the penetration level of the battery storage system. Firstly, these effects were analyzed with several penetration rates, assuming that the battery may be charged only at the rated power.

2) Analysis of Partial Load Rate at Charging

Second, the leveling effects with several partial load rates at charging were analyzed. Generally, batteries are charged with rated power. For leveling the system load efficiently, it is assumed that batteries may be charged with lower power. However, charging at too low a partial load rate causes frequent switching-loss. Therefore, in this work the amount of partial load charging sufficient to level the system load efficiently was analyzed.

C. Calculation conditions and input data

In this study, the calculation target period was nine days from Apr 28 to May 6 and analysis target period was five days from May 1 to 5. This analysis period is a holiday week in

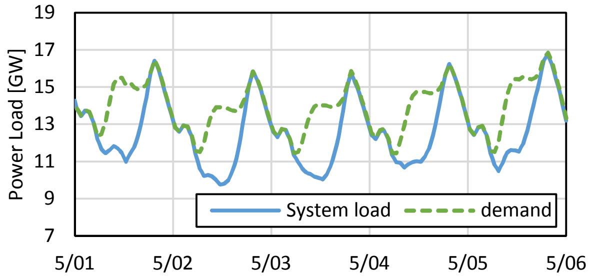

Figure 2. Electricity demand and System load used in model.

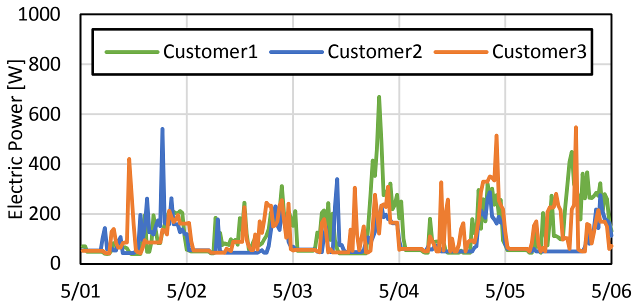

Figure 3. Electricity demand model data of each household used in model.

Japan when many families may be away from home. The system load during daytime is therefore not large. Moreover, the output of PV generation in this week is relatively large. As a result, the net system load becomes the smallest in the year. The target system is the Kansai power system (electricity distributed by Kansai Electric Power Company) which is located in the middle of the main island of Japan. In this region, there are approximately eight million households. The system load in this period is shown in Figure 2. The electricity demand data indicated by a dashed line in Figure 2 are actual data recorded in 2010. In this work, a future is assumed that has contributions of 6 GW of PV systems and 0.3 GW of wind power introduced into the power system. The system load indicated by a solid line is calculated by subtracting the power generation of PV and wind power from electricity demand data.

Together with this, model data [8] for the electricity demand consumed in each household are used. These electricity demand data are created by considering the structure of each household and associated floor area. Examples of model demand data in three households are shown in Figure 3. Customer 1 is taken as a four-person family consisting of a couple and two children; Customer 2 is taken as a three-person family consisting of a couple and a child; Customer 3 is taken as a two-person family consisting of a couple. It is assumed that battery storage systems are only introduced into detached houses, which account for approximately half of all households. 2525 types of model data are employed in this study. These data were taken into consideration of an actual household breakdown in Kansai region. The electricity consumption including the battery operation in each house was calculated. Finally, the sum of 2525 types of calculation results was multiplied by constant to correspond to the number of

TABLE I. BATTERY SPECIFICATION

Type	a	b	c	d
Rated Power [kW]	2	2	3	3
Storage Capacity [kWh]	6	8	10	12

introduced storage batteries in Kansai region, then the leveling effect in the whole power system was evaluated.

It is assumed that four types of battery storage systems with different rated power outputs and storage capacities are introduced, as shown in Table I. The battery type is randomly selected for each household.

In this calculation, the initial electricity charged in the battery is set to zero on Apr 28 which corresponds to three days before the start of the analysis period. To eliminate the influence of the initial value, the analysis period was taken as five days from May 1.

III. OPTIMUM OPERATION SCHEDULING MODEL

This work discusses the development of an optimum operation scheduling model of residential battery storage system for leveling power system load. This model uses the MILP solved by a solver: Gurobi Optimizer 6.5 [9]. In the following section, two objective functions and constraints in this model are described. Each decision variable corresponds to the energy flow in Figure 1. Subscript “*t*” denotes a time step and varies between 1 and 48 because time resolution was set to 30 minute intervals. Twenty-four hour schedules were calculated with one optimization calculation.

A. Minimize Daily System Load Variation Range

1) Objective Function1

Firstly, the difference between the maximum and minimum values of daily system load is set as the objective function as shown in Eq. (1). The aim of using this objective function is to cut the peak load and to fill the valley of the load.

$$\min: PDH - PDL \tag{1}$$

where PDH and PDL represent the maximum and minimum values of the power system load in 24 hours as measured in kilowatt. A conceptual diagram of these decision variables is shown in Figure 4.

2) Constraints of Objective Function 1

PDH and PDL in Eq. (1) are constrained by Eq. (2), and (3).

$$PDH \geq PNL_t \ (\forall t \in T) \tag{2}$$

$$PDL \leq PNL_t \ (\forall t \in T) \tag{3}$$

PNL_t denotes the power system load in the whole power system at time t in kilowatt. PNL_t is expressed in Eq. (4).

$$PNL_t = enl_t + k \cdot \frac{cpi_{ave}}{cpi} \cdot \frac{(EGB_t - EBD_t)}{rsl} \tag{4}$$

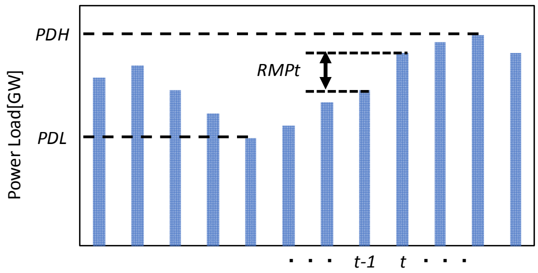

Figure 4. Conceptual diagram showing relationship between decision variables used for objective function and system load.

where EGB_t and EBD_t are the decision variables representing the charging electricity from the grid and discharging electricity to the demand at time t in kilowatt-hours. Constant rsl denotes the temporal resolution, which is set to be 0.5 h. Constants cpi_{ave} and cpi denote the average rated power of all batteries and the rated power of each battery respectively. Constant k denotes the number of batteries introduced in the power system. Constant enl_t denotes the net power load without operating batteries at time t. enl_t is applied to the net load as described in Section 2.

In this study, each house is unaffected by the operations of batteries of other households. Therefore, the second term on the right side of Eq. (4) means total charging or discharging electricity in the power system when applying the control in one’s own house to all other batteries.

3) Constraint of electricity demand

Electricity demand in each household is supplied by the power grid and/or each battery.

$$dme_t = EGD_t + EBD_t \tag{5}$$

In (5), the decision variable EGD_t represents the amount of electricity from the power grid to the demand at the time t in watt-hours. Constant dme_t is the electricity demand consumed by each household at time t in kilowatt-hour. The model demand data described in Section 2 applies to dme_t.

4) Constraint of battery

The specification of the battery, STE_i, which represents the stored electricity in the battery, is constrained by the rated capacity of each battery cpe as shown in Eq. (6).

$$STE_t \leq cpe \tag{6}$$

Charging efficiency was set to $eff = 0.9$. The step change of the stored electricity in the battery is constrained by Eq. (7).

$$STE_t = (1 - lst) \times STE_{t-1} + eff \cdot EGB_t - \frac{1}{eff} \cdot EBD_t \tag{7}$$

The charging and discharging electricity are constrained by Eq. (8) and (9).

$$EGB_t \leq ICH_t \cdot cpi \tag{8}$$

$$EGB_t \geq ICH_t \cdot btl \cdot cpi \quad (9)$$

Decision variable ICH_t is a binary variable which can only be 0 or 1 and represents whether the battery is charged or not at time t. The upper limit of the charging power is determined by cpi (rated active power). The lower limit is therefore determined by the multiplication of btl and cpi. Constant btl denotes partial load rate at charging. When $btl = 1$, the battery can be charged at the rated power. If btl is less than 1, the battery is charged at less than the rated power.

The discharging amount is constrained by the rated capacity as shown in Eq. (10) and (11).

$$EBD_t \leq IDC_t \cdot cpi \quad (10)$$

$$EBD_t \leq IDC_t \cdot dme \quad (11)$$

IDC is a binary variable like ICH. When the battery is discharged, IDC is equal to 1. If the battery is not discharged then IDC is equal to 0. Charging and discharging cannot be performed at the same time as constrained by Eq. (12).

$$ICH_t + IDC_t \leq 1 \quad (12)$$

5) Boundary Condition

Equation (13) describes the boundary condition regarding stored electricity in the battery.

$$STE_0 = STE_{24} \quad (13)$$

B. Minimize Integrated Value of Step Change in System Load

1) Objective Function 2

A further objective function is set as shown in Eq. (14). The aim is to reduce the integrated value of step change in the system load.

$$\min: \sum_{t-1}^{48} RMP_t \quad (14)$$

In this equation, RMP_t denotes step change of the system load from time t-1 to t in kilowatt.

2) Constraints of Objective Function 2

Constraints of *Objective Function 2* are defined as follows.

$$RMP_t \geq PNL_t - PNL_{t-1} \quad (15)$$

$$RMP_t \leq PNL_t - PNL_{t-1} \quad (16)$$

Constraints are set in Eq. (15) and (16) instead of Eq. (2) and (3). If the integrated value of the system variations from t-1 to t is positive then Eq. (15) dominates. For the opposite case Eq. (16) dominates.

Finally, Eq. (17) is set as an additional boundary condition.

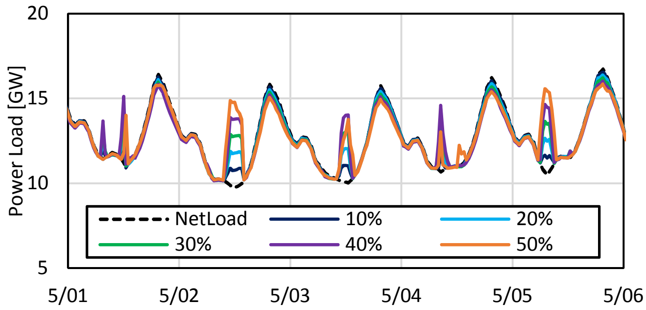

Figure 5. Power load calculated with *objective function 1* for penetration rates of the battery storage systems.

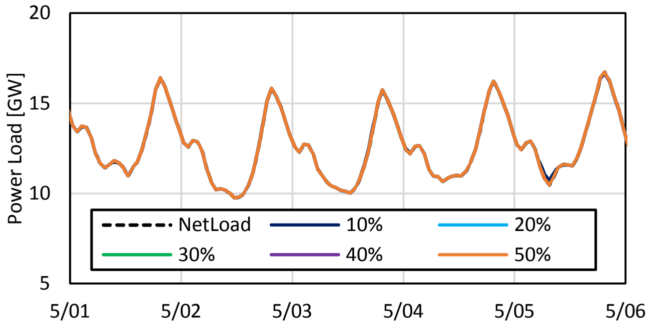

Figure 6. Power load calculated with *objective function 2* for penetration rates of the battery storage systems.

$$PNL_0 = PNL_{24} \quad (17)$$

IV. CALCULATION RESULTS

A. Analysis ofthe Penetration rate of the battery

Initial analysis investigated a change in power load by changing the penetration rate of the battery. In particular, a constant k, which denotes the number of batteries introduced in the whole area, was varied. The penetration rate of the battery was set to 10, 20, 30, 40, 50% of the detached houses. Furthermore, in this calculation the battery was charged with rated power only; btl was set to 1. The calculation results in the case of *Objective Function 1* and *2* as shown in Figures 5 and 6, respectively.

In Figure 5 batteries are charged at a time corresponding to low power load. However, as the penetration rate increases more charging occurs simultaneously. This results in a spike in high demand, which is not good for supply and demand balancing.

In Figure 6 it is seen that most results are similar to net load. That means it is preferable not to operate charging and discharging for reduction in fluctuation amount. This is because this model does not share operation schedules between households and because it was judged that a spike will be generated by overlap of the charging times.

In both objective functions, these results show that it is necessary to control the charging load more efficiently to disperse the charging load.

Total charging and discharging electricity for five days is shown in Table II. Consideration of *objective function1* shows

TABLE II. THE AMOUNT OF CHARGING AND DISCHARGING BY THE PENETRATION RATE OF THE BATTERY.

	btr [%]	10	20	30	40	50
Objective Function 1	Charging [GWh]	9.6	19.7	30.0	39.5	41.3
	Discharging [GWh]	7.0	14.3	22.1	29.0	25.0
Objective Function 2	Charging [GWh]	1.5	0	0	0	0
	Discharging [GWh]	1.2	0	0	0	0

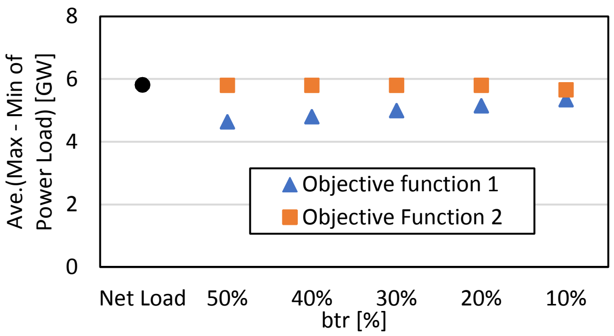

Figure 7. Average of fluctuation range compared with *objective function 1* and *2 for* penetration rates of the battery.

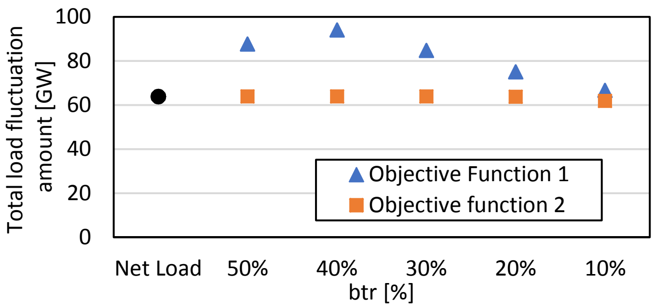

Figure 8. The total amount of fluctuation compared with *objective function 1* and *2 for* penetration rates of the battery.

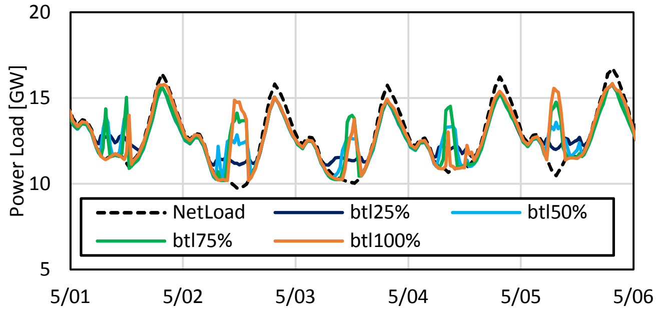

Figure 9. Power load calculated with *objective function 1* for partial load rates.

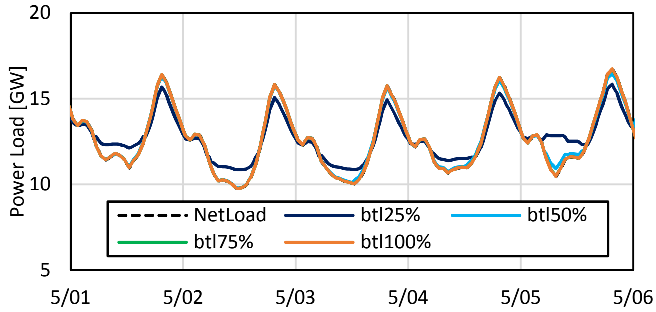

Figure 10. Power load calculated with *objective function 2* for partial load rates.

TABLE III. THE AMOUNT OF CHARGING AND DISCHARGING BY THE PARTIAL LOAD RATE AT CHARGING.

	btl [%]	25	50	75	100
Objective Function 1	Charging [GWh]	47.3	50.7	49.8	41.3
	Discharging [GWh]	36.3	39.2	39.5	25.0
Objective Function 2	Charging [GWh]	44.5	4.8	0.1	0
	Discharging [GWh]	33.4	3.4	0.1	0

that as the penetration rate increases, charging electricity also increases. However, penetration rates (*btr)* of 40 and 50 % result in very similar values of charging electricity. For *objective function2*, Table II indicates that the batteries are not operated.

To evaluate these results quantitatively and to compare the results of the two objective functions, two evaluation indices are introduced in this work.

The first index is the daily average of the difference between maximum and minimum values of the power load in a day, for five successive days. It is illustrated in Figure 7. In o*bjective function1*, as *btr* increases the average of the difference decreases. For *objective function 2*, all values are approximately the same because the batteries are not operated.

The second index is the integrated value of step change of the system load for five days. The results are shown in Figure 8. In *objective* function1, despite decreasing the average maximum variation range, the operation of batteries is counterproductive to the integrated value of step change of the system load for all penetration rates of the battery.

B. Analysis of the partial load rate at charging

In this section, the amount of fine control required to level power load efficiently is analyzed. Specifically, the constant *btl*, which determines the lower limit of charging power in our model, was varied. For example, when *btl* equals 0.5, partial load at charging is decreased to 50% of the rated power of the battery. The partial load rate was set to 25, 50, 75, 100% of the rated power. Furthermore, in this section the penetration rate of the battery is 50%. The calculation results for the cases of *Objective Function 1* and *2* are shown in Figures 9 and 10, respectively.

In Figure 9, as the partial load rate decreases, charging load is dispersed, and the peak of the power load decreases. When *btl* equals 25 %, the spike in high demand disappears and the power load at charging is almost uniform.

In Figure 10, *btl* is over 75% and most batteries are not operated. The power load is leveled efficiently only when *btl* equals 25%.

Total charging and discharging electricity for five days is shown in Table III. When *btl* is 25% the charging and discharging electricity of *Objective Function 1* is larger than that of *Objective Function 2*. In addition, Table III shows that the batteries are not operated efficiently when *btl* is larger than 25%.

As previously described, the average of the difference between the maximum and minimum values of the power load

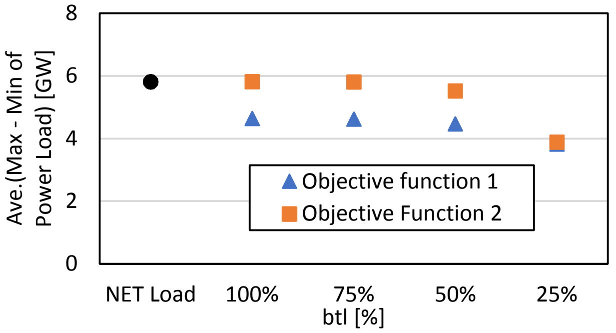

Figure 11. Average of fluctuation range compared with *objective function 1* and *2* for partial load rates.

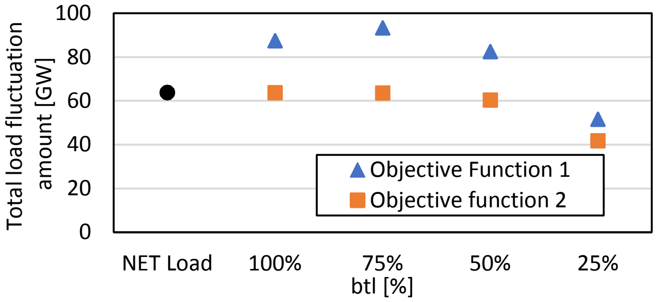

Figure 12. The total amount of fluctuation compared with *objective function 1* and *2 for* partial load rates.

for five days was calculated and shown in Figure 11. In *Objective Function 1*, the difference between the maximum and minimum values of all *btl* is smaller than of the net load. Moreover, the indexes of *btl* 50, 75, 100 % are almost the same. Despite the difference in the objective function, both indexes are approximately the same at *btl* 25 %.

The second index is shown in Figure 12. In *Objective Function 1*, unless *btl* is under 25 %, the total amount of fluctuation is larger than that of net load. Therefore, to operate the batteries for leveling the whole system, it is necessary for them to be charged at 25 % of the rated power. Comparison of *Objective Function 1* and *2*, especially when *btl* is 25 %, indicates that *Objective Function 2* is better than *Objective Function 1*. It is therefore possible to charge the battery at less than 25 % of the rated power, *Objective Function 2* which denotes the total fluctuation of system load per time is more suitable for objective function.

V. Conclusion and Future work

In this study, a battery optimum operation scheduling model to calculate contributions to the power system is described together with results from this model. The model included the assumption that residential batteries are introduced massively and the possibility of leveling the system load by using these residential batteries was examined. The leveling effects of batteries from two points of view were analyzed by comparing two objective functions.

Firstly, the penetration rate of batteries was analyzed. It was shown that it is hard to level the system load by simply using the difference between maximum and minimum values of system load or the integrated value of step change in system load as objective functions. These objective functions resulted in spiked charging load which is not desirable for supply and demand balancing or no battery operation.

Secondly considering previously determined results, an analysis of how fine charging control is necessary to distribute the charging load and level the system load was completed. An optimized calculation by the partial load rate was performed and this indicates a lower limit of charging power. In both objective functions, it is possible to level the system load efficiently when the lower limit of the input power is 25% of the rated power. In addition, when comparing two objective functions, minimization of the total amount of fluctuation every 30 minutes was more favorable as the objective function.

In conclusion, if controlling the charging load as partial load down to approximately 25% is achievable, it was shown that it is possible to level the system load without sharing the operating information of each customer's battery.

Future work could involve optimization calculations in different conditions such as different system loads. Incentives for customers should also be investigated in this regard.

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