Practical Operation Control and Planning of NAS Battery

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Abstract: - The role of the battery energy storage system (BESS) has become essential in modern power systems. Among various types of BESS, NAS (Sodium and Sulfur) battery is one of the most promising products. NAS battery system is a commercial product implemented widely in Japan. A practical strategy and planning of NAS battery operation is proposed in this paper. In Planning, a load forecast using past cases is introduction. In strategy, two important parameters are evaluated to get a satisfactory performance of the load following operation of NAS battery. The first one is the amount of reserve (margin) and the second one is the trigger of release. The amount of margin is defined as a percentage of “charged battery energy”. A predetermined threshold is used to control the battery energy use in this paper. By a series of computational simulations, it is verified that the load-following operation introduced by this strategy yields flexible and cost-benefit effectiveness.

Key-Words: - NAS Battery**,** Energy Storage System, BESS, Load Following Operation, Load Forecast

1 Introduction

The load leveling was an important strategy for electric power utilities to suppress new construction of generation plans. Pumped storage hydro plants have been utilized to improve the load-factor in Japan. The recent environmental requirements, however, do not allow building new hydro dams. NAS battery is one of the most promising BESS as an alternative for pumped storage hydro plants [1]-[2]. Deregulation of power industry made a motivation to improve a load factor in demand side. A flat and constant load has economical advantages to purchase cheaper electricity.

On the other hand, some industrial products require higher power qualities. For example, semiconductor manufactures, liquid crystal industries and food process companies, etc, have risks to suffer severe damages by small voltage perturbation. Under these circumstances, enhancements of power quality by BESS became an economical option in the demand side.

The expansion of renewable energy is one of obligations rather than targets in the world [3]-[4]-[5]. The image of ‘Green and Clean’ gives additional value to the wind and solar power. Good counter measures against fluctuation of unstable power outputs are indispensable.

Preparation against blackout is another quality issue. Future blackout might be caused by climate disasters and terrorism. BESS can be a good emergency power supply. Since BESS usually operates daily without noise and emission, smooth and secure startup would be ensured, if sufficient energy is stored.

Although a principal objective to install NAS battery was load leveling, recent installation is aimed to enhance the power quality. Fujitsu has installed NAS battery systems in their three factories. Honda has also installed a 12000 kW NAS system in Automobile R&D Center in Tochigi. This trend implies that the manufactures production line is very delicate and that the damage caused by small perturbations is severe. Since NAS battery contributes to the reduction of CO2-emission, those leading companies appeal the 'clean and green' image to the public. The advantage might be clearer when CO2-emission trade starts.

Fig.1 Appearance of NAS battery in Campus

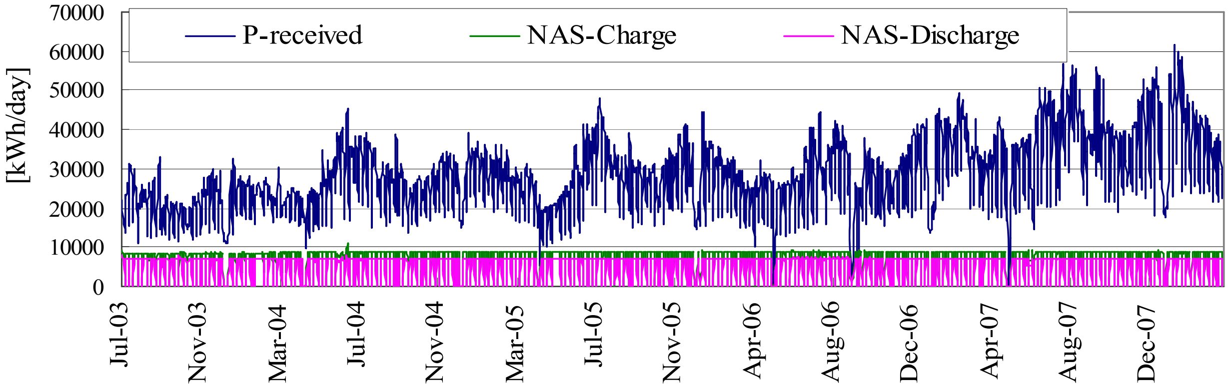

Fig.2 Operatinal record of NAS battery in Meisei Univ. (from 2003/7/23 to 2008/3/30)

Table.1 Specification of NAS battery in Meisei

Rated Output	1000kW
Rated Voltage	6.6kV (Three phase)
Units	4 Units (250kW × 4 units)
Energy Storage	AC7200kWh
Battery Module	5 module per unit 320 battery cells per module

Meisei University has installed a 1000kW NAS battery in campus in 2003. Appearance of NAS battery is shown in Fig.1. The capacity of one module is 50kW and one unit consists of five modules. Four units are installed in the campus, and so the total capacity of installations is 1000kW, 7200kWh. According to the operational record of NAS battery in Meisei University, the operation is very stable and total efficiency is 77.8% for 1692 days (from 2003/7/23 to 2008/3/30). The efficiency is better than traditional pumped storage hydro plants in Japan. The operational record is shown in Fig.2. It is almost one third of the life of this battery.

A wind power company (Japan Wind Development) has installed 30 MW NAS battery in their 50 MW wind-farm [6]-[7]. Since the location of wind-farm tends to be local sparse areas, power fluctuation should be suppressed. The wind-powers have started to be accepted in Japan, since they begin to flatten their power and to cooperate to keep quality of electricity.

In this paper, a practical operational strategy for BESS such as NAS battery is presented. The proposed control relates to load following operation. A key target is that charged energy has to be discharged without excessive discharge and without leaving surplus energy.

2 Operation Pattern of NAS battery

There are two types of operational patterns of NAS battery when load leveling is the first priority. The first one is a fixed pattern operation. The charge/discharge of NAS battery is fixed and scheduled in advance. Since all energy charged in the battery is scheduled to be discharged, efficiency is high and pre-determined.

Although this fixed pattern operation is stable, it is not flexible at all. The managers of demand side prefer more flexible operation of BESS, because it can help and assist their management of the load shape. Fig.3 shows the typical fixed pattern. Pattern a-1 is used usually and Pattern a-2 is used for summer season only.

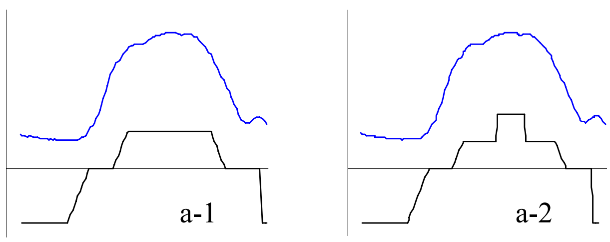

Fig.3 Typical fixed pattern operation of NAS battery

The second operational pattern of NAS battery is the load-following operation. The charge/discharge of NAS battery is controlled according to the load shape. Load following operation can correspond to an unexpected change of demand. However, there are risks producing shortage of energy and surplus of energy. Therefore, feedback control is essential to adjust its output (discharge). If the load following operation succeeded, receiving power from a utility or PPS will be flat.

Fig.4 (b-1) shows a successful case of the load following operation. (b-2) shows a failed case of the load following operations, where receiving power increases suddenly after battery energy has been used up. This surge of receiving power may cause higher tariff for demand charge. Therefore, it is important to avoid such unnecessary surges.

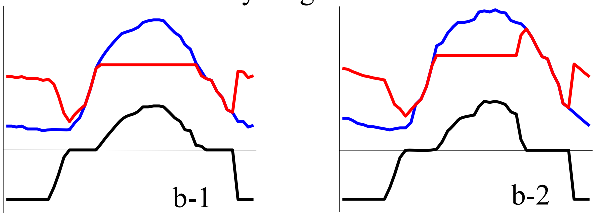

Fig.4 Load-following operation of NAS battery

3 Load Forecast in a Limited Area

In this chapter, a load forecast using past cases is introduced. This load forecast can be used for planning and load following operation control of NAS battery. The theme of load forecast is a traditional problem. Conventional approaches, however, concentrate on the forecast in a whole area of utilities. The forecasts in a limited area in a customer are relatively new problems. Daily load curve is required for forecasting instead of daily peak values.

3.1 Load Characterisitics in a University Campas

Many papers have been proposed to the area of load forecast in the supply(utility) side, because its accuracy affects to the economical operation control of a power plant. The needs for a load forecast in the demand side were not important. The deregulated environment, however, brought various chances and choices for energy management. Flat and constant loads or well-controlled loads have advantages to get more economical electricity price from suppliers. Understanding the load characteristics in demand side is essential to forecast and control the loads with BESSs.

Unlike to the wide area load in utilities, the limited area load in individual demand side is affected by local conditions. Since the load in university campus is strongly affected by campus schedules, seven categories were classified as shown in Table.2. Some categories were eliminated and merged with neighbors, so as to get sufficient population from a statistical view point of.

Table.2 Classification of Dates by School Scedule

	Weekday	Saturday	Holiday
Regular Class	C11	C12	
No Class Lectures	C21	C22	
Exam Period	C3		
Schooling Period	C4 (correspondence course)		
Special Events	C5		

3.2 Formulation of a Load Forecast

Precondition of load curve forecast is listed below;

- The target is one day-ahead (Tomorrow) forecast.
- The time-step is 0.5 hour.
- Weather forecast for tomorrow's average temperature is supposed to be available.
- Past case (load curves: 48 points/day) is available.

The formulation of load forecast using past case is shown in eq(1).

$$\tilde{P}_{i,j} = w_1 S_{1,j} + w_2 S_{2,j} + w_3 S_{7,j} + g \cdot w_4 S_{365,j}$$

$$S_{k,j} = P_{i-k,j} + \alpha \cdot \left(\tilde{T}_i - T_{i-k}\right) \cdot \frac{P_{i-k,j} - P_{i-k,\min}}{P_{i-k,peak} - P_{i-k,\min}} \qquad \text{......(1)}$$

where:

i :The target date for forecast. The value for date i is estimated value.

j :Time sequence number from 1 through 48. j=17 means time is 8:30 am. (j=1,2,3,,,48)

$\tilde{P}_{i,j}$:Forecasted load curve on date i at time j.

$\tilde{T}_i$:Forecasted mean temperature on date i.

T_{i-k}:Past recorded mean temperature on date i-k.

w_p:Weights for four past cases. p=1,2,3,4.

$S_{k,j}$:Past case curve after temperature compensation. k=1: yesterday, k=7: "the day one week ago", etc.

g :Annual growth rate of load.

α :Sensitivity of mean temperature against peak load. The value depends on season and category of date.

More detailed explanations of proposed formulation for load forecast are listed below;

- Four past case curves are used. These four days are "yesterday", "the day before yesterday", "the day one week ago" and "the day one year ago".
- Weighted summation of these four curves becomes the forecast curve.
- Each load curve is compensated / corrected by temperature using sensitivities obtained by previous chapter. The origin of expansion and reduction is bottom point of each curve.

- Past four cases are selected from same category. Suppose target is Monday, "yesterday" is Friday on last week.

The fourth curve such as "the day one year ago" is revised by an annual growth rate.

3.3 Temperature Sensitivity against Loads

Temperature sensitivity with regard to loads is using two types of temperatures and two types of loads. These parameters are the highest temperature, mean temperature, peak load [kW] and daily energy consumption [kWh]. From these four parameters, four types of temperature sensitivity against loads were obtained as shown in Fig.5, where season is summer and category is C11. The slope and R^2 of interpolated sensitivities are shown in Table.3. If the value of R^2 is close to one, it means correlation is strong.

Since the strongest and most stable correlations can be observed at "mean temperature against peak load", we decide to utilize this relation.

The temperature sensitivities are formulated by linear interpolation and its slopes are used in the process of load forecast. The temperature sensitivity in 2007 is not used in the process of load forecast for 2007.

Table.3 The values of slope and R^2 for Four Types of Sensitivity

year	Mean T-Peak D		Mean T-Enegy		Max T-Peak D		Max T-Energy	
	slope	R2	slope	R2	slope	R2	slope	R2
2004	121.0	0.93	1596	0.92	88.7	0.76	1049	0.61
2005	90.0	0.83	1188	0.73	63.1	0.78	813	0.66
2006	163.6	0.90	2061	0.91	94.8	0.84	1133	0.76
2007	159.1	0.74	1613	0.70	77.1	0.60	734	0.51

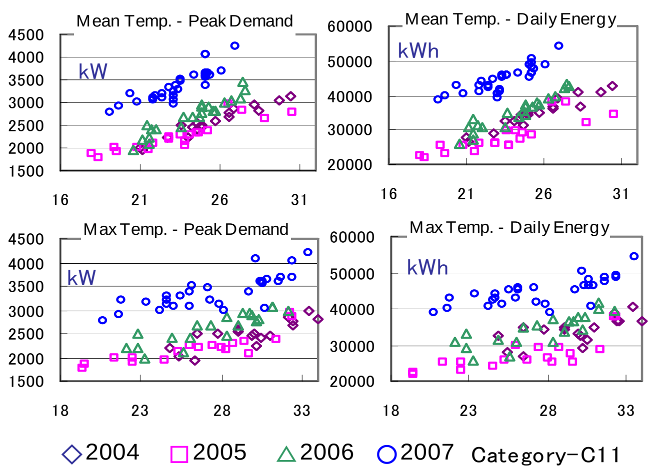

Fig.5 Temparature sensitivity against loads

3.4 Optimization of Weights

A kind of exhaustive search was applied to get optimal weights. All combination of weights is numerically examined and best combination is selected.

This approach is not elegant and not intelligent, but it is very simple and robust. Recent PC's computing ability and small data size made the simple approach possible.

Precondition for optimization of weights is below;

- The weights are constant, does not depend on seasons and categories.
- Total summation must be 1.00 ($\sum_{p=1}^{4} w_p = 1.0$).
- Minimum step size is 1.0 %.
- Past case (load curves: 48 points/day) is available.
- Other parameters such as α and g are determined in advance.

More detailed and step-by-step explanations for optimization of weights are listed below;

<u>Step-1:</u> Suppose a list like Table.4, where all possible combination of weights is shown (m=176851).

Table.4 Weights' Combination and their Evaluation

No.	Weights[%]				Date(Total=n)				Maximun Error
	w1	w2	w3	w4	1	2	**	n	for i=1,2,3,,,n
1	100	0	0	0	$\varepsilon_{1,1}$	$\varepsilon_{1,2}$	**	$\varepsilon_{1,n}$	$\varepsilon\varepsilon_1=\max(\varepsilon_{1,i})$
2	99	1	0	0	$\varepsilon_{2,1}$	$\varepsilon_{2,2}$	**	$\varepsilon_{2,n}$	$\varepsilon\varepsilon_2=\max(\varepsilon_{2,i})$
3	98	1	1	0	$\varepsilon_{3,1}$	$\varepsilon_{3,2}$	**	$\varepsilon_{3,n}$	$\varepsilon\varepsilon_3=\max(\varepsilon_{3,i})$
	:	:	:	:	:	:	:	:	:
m-1	0	0	1	99	$\varepsilon_{m-1,1}$	$\varepsilon_{m-1,2}$	**	$\varepsilon_{m-1,n}$	$\varepsilon\varepsilon_{m-1}=\max(\varepsilon_{m-1,i})$
m	0	0	0	100	$\varepsilon_{m,1}$	$\varepsilon_{m,2}$	**	$\varepsilon_{m,n}$	$\varepsilon\varepsilon_{m}=\max(\varepsilon_{m,i})$

<u>Step-2:</u> Prepare all recorded result load-curve data which have "the day one year ago" data. The number of n is 1216 (n=1216). Calculate the error of forecast using given weights and eq(2) for all available curves. Search the worst (maximum error) case in all forecasts. And memorize the value of maximum error for each set of weights.

$$\varepsilon_{k,i}^{ABS} = \sum_{j=1}^{48} \left| \widetilde{P}_{i,j}(\text{Weight No.} = k) - P_{i,j} \right| / 48$$

$$\varepsilon_{k,i}^{SQ} = \sum_{j=1}^{48} \left(\widetilde{P}_{i,j}(\text{Weight No.} = k) - P_{i,j} \right)^2 / 48$$

$$for \quad k = 1,2,3,,,m \ (\text{Weight No.}) \quad i = 1,2,3,,,n \ (\text{date No.}) \qquad \text{...... (2)}$$

<u>Step-3:</u> Optimal weight is defined as "Weights which minimize the maximum error evaluated in each forecast. Therefore the number of L that satisfies eq(4) will be "the best set No. of weights".

$$\varepsilon\varepsilon_k = \max\left(\varepsilon_{k,1}, \varepsilon_{k,2}, \varepsilon_{k,3},,, \varepsilon_{k,n}\right) \quad \ldots\ldots (3)$$

$$\varepsilon\varepsilon_L = \min\left(\varepsilon\varepsilon_1, \varepsilon\varepsilon_2, \varepsilon\varepsilon_3,,, \varepsilon\varepsilon_m\right) \quad \ldots\ldots (4)$$

Table.6 shows the "set of optimal weight" that was found by previous steps. The best "set of optimal weight" to two types of error functions in eq(2) is not identical, but they are close.

The numerical stability and validity around these "set of optimal weight" were examined. The fourth weight w4 is temporarily fixed to 10%. If w1 and w2 are determined, w3 will be dependent. The contours in Fig.6 show that the best set of weight is to be trusted.

Table.6 Optimal Weights to Two Objectives

	Value		Optimal Set of Weights			
	$\varepsilon\varepsilon_{k,i}^{ABS}$	$\varepsilon\varepsilon_{k,i}^{SQ}$	w_1	w_2	w_3	w_4
$\min\left(\varepsilon\varepsilon_{k,i}^{ABS}\right)$	87.8	12518	63	24	5	8
$\min\left(\varepsilon\varepsilon_{k,i}^{SQ}\right)$	88.0	12422	57	27	6	10

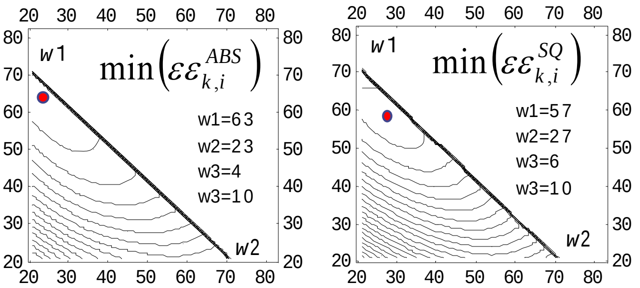

Fig.6 Numerical Stability around Optimal Weights

3.5 Tests of A-day Ahead Load Forecast

Numerical tests were evaluated for two summer sea-sons of category C11. C11 (Week-Day with lectures) is the most important category because peak load tend to emerge. The parameters are calculated using "past data". The weights are $w1$=0.60, $w2$=0.25, $w3$=0.05, $w4$=0.10. The other parameters are specified individually α=109.2 kW/^{o}C, g=1.12 for 2006 and α=124.9 kW/^{o}C, g=1.31 for 2007. The annual growth rate "g" for 2007 was evaluated by comparing the load data of April and May in 2006 and in 2007.

Typical forecast curves are shown in Fig.7 and Fig.8. The evaluations of errors are shown in Fig.9. The mean-error is less than 5% in most cases. The error rose suddenly when the campus was closed due to unexpected accident (epidemic; measles).

It can be observed that the large errors tend to emerge on Monday. The reason is obvious because there is not good past data nearby on Monday. This is one disadvantage of the proposed method.

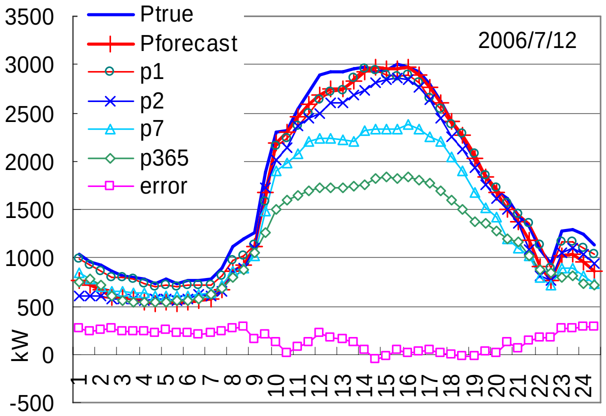

Fig.7 Example of Load Forecast (2006/7/12)

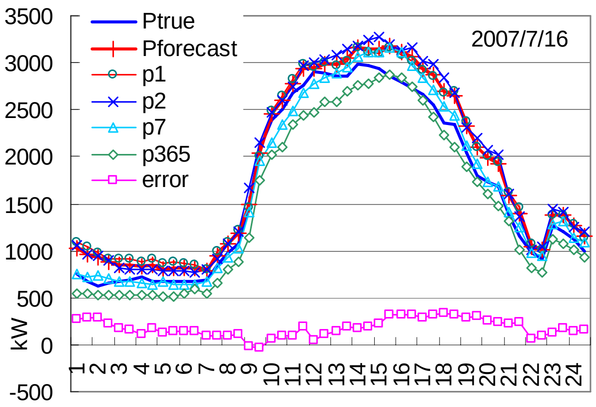

Fig.8 Example of Load Forecast (2007/7/16)

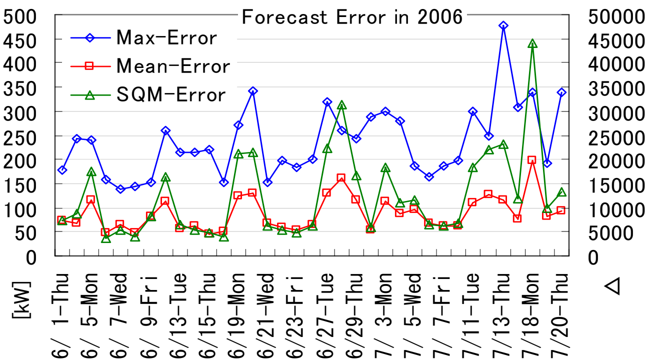

Fig.9 Error of Load Forecast in 2006
(Summer: category-C11)

4 Outline of Load Following Control

In this chapter, outline of a practical load following operation is presented. Situations and preconditions are listed below;

- Actual load curves are recorded for four years.

- Maximum and average temperatures in the vicinity of the region for past data are available.
- Before control starts, the load forecast curve for the next day is supposed to be calculated [8].
- The time-step is 0.5 hour (48 points/day).
- Control starts from 0:00 and continues 24 hours.
- Only load data that is successively measured can be used to decide the output of NAS battery.
- Only discharge of NAS battery is taken into consideration. Full energy (7200kWh) is supposed to be stored by 7:00.
- All energy stored in the battery should be used up by 22:00. At this time, the night discount tariff starts.
- The main objective is to suppress "the peak of receiving power", which determines the capacity tariff.

The strategy and other conditions are listed bellow;

- Control strategy is to specify P_0 as the target receiving power from utilities.
- If receiving power exceeds P_0, NAS battery starts to discharge the amount of excess.
- P_0 is calculated to cut the peak part of the load curve as shown in Fig.10(a). The colored area is equal to energy that can be discharged from the battery.
- Since the actual load differs from the forecasted curve, P_0 should be re-calculated. The interval of re-calculation is every one or two hours.
- The reforecast of load curve is done at the same time. A very simplified method, which is explained later, is used to this reforecast.
- The energy remaining in the battery is allocated to fit the re-forecasted curves. The rough sketch of procedure is shown in Fig.10(b).

(a

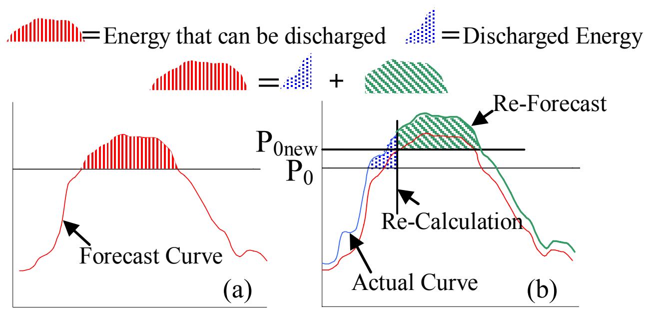

Fig.10 Calculation of the target receiving power P_0

The process of re-forecast at time= i is shown in eq(5) and rough sketch of the procedure is illustrated in Fig.11. Accumulated error is used to modify the further forecast.

$$P_{FN\,s} = P_{Fs} - dP - \frac{\Delta P - dp}{2^{s-h}} \qquad \cdots(5)$$

$$\left(for \;\; s = h, h+1,,,48\right)$$

where :

$$errsum = \sum_{k=h-4}^{h}\left(P_{F\,k} - P_{T\,k}\right), \qquad dp = \frac{errsum}{4}$$

$$\Delta P = P_{F\,h} - P_{T\,h}$$

h	:	Timing of re-calculation
$P_{FN\,s}$	:	New forecast of load (s=h,h+1,h+2,,,48)
$P_{F\,s}$	:	Previous forecast of load
$P_{T\,s}$	:	Actual (measured) load (s=1,2,3,,,,h)
dp	:	Mean error through time-h
ΔP	:	Forecast error at time-h

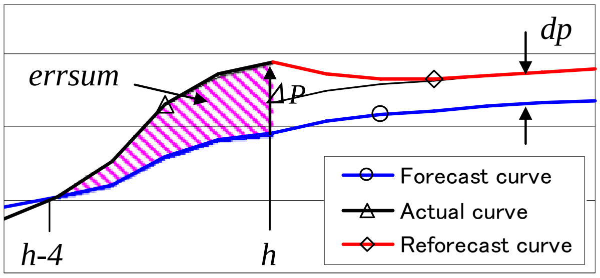

Fig.11 Process of Reforecast of load

5 Algorithm of Load Following Control

5.1 Risk of Shortage of Battery

The detailed process of load following control is described in a previous paper [9]. A simulation result is shown in Fig.12. Shortage of battery energy occurred in this case and the receiving power increases suddenly. This surge of receiving-power is hard to suppress. The improvement of load forecast is important. However, there is no countermeasure to suppress the excess after the battery energy is used up.

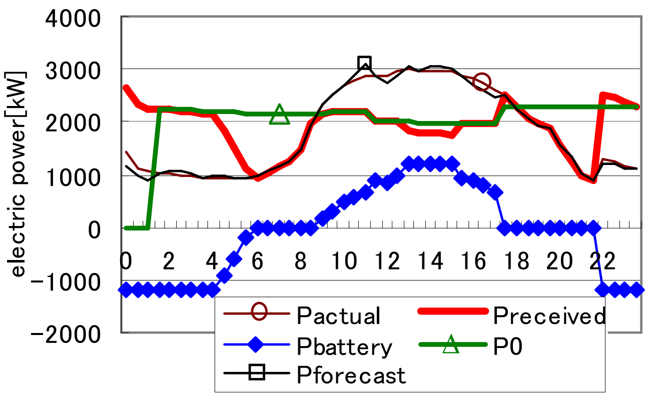

Fig.12 Surge of receiving power

Fig.13 shows the emergence timing of peak demand. Since the battery discharges with 120% of rated capacity from 13:00 through 16:00 as fixed must-run, the control should care the remaining time.

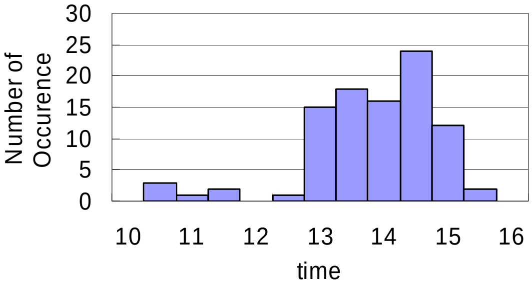

Fig.13 Emergence Timing of Peak Demand

5.2 Preparation of Best Margin

A simple way to prevent the sudden increase of receiving power is preparation of reserve. It means that a proper amount of battery energy will not be used until the risk of shortage has gone. A simple strategy to prepare reserve (margin) is listed below;

- A proper amount of charged battery energy is reserved as margin. This energy is not used until a trigger becomes on.
- If the risk of energy shortage has gone, the trigger becomes on. Then the reserved margin is released and is added to other energy to be used.

Two important parameters should be evaluated to get good performance. The first one is the amount of reserve (margin) and the second one is the trigger of release. The amount of margin is defined as a percentage of “charged battery energy”. Many strategies may be applied to the trigger. A predetermined threshold is used to control the battery energy use in this paper.

If residual of battery energy that can be used to peak-cut falls below a predetermined threshold, the trigger becomes on. An exhaustive search is done to obtain the best parameters. 3D contour lines, which indicate two parameters and improvements, are shown in Fig.14 and Fig.15. It indicates the best parameters are 25% for amount of margin, and 1000kWh for release threshold.

If much margin is prepared, receiving power in the evening will be suppressed. In the morning, however, receiving power might be up.

If the releasing timing of reserve is fast, the risk of energy shortage might occur again. If this timing is delayed, the reserve might be released after a severe peak.

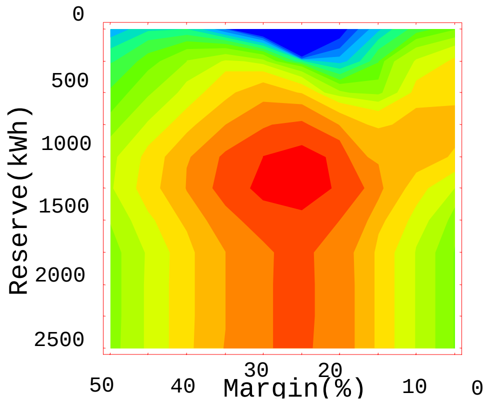

Fig.14 Two parameters and improvement of load following control (3D contour line plot)

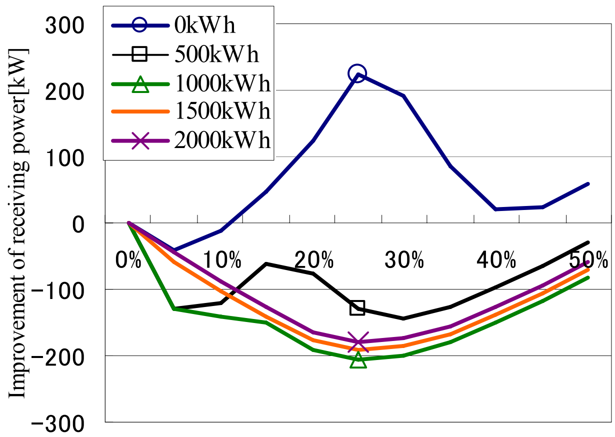

Fig.15 Two parameters and improvement of load following control (2D- plot)

The results, which are 25% reserve and release it when the residual falls below 1000kWh seems to be best. If the proper margin is prepared, the receiving power will be suppressed as shown in Fig.16 & Fig.17.

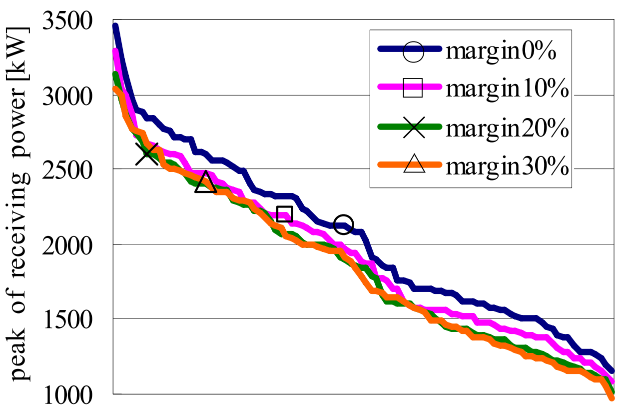

Fig.16. Improvement of peak receiving power by preparing proper margins

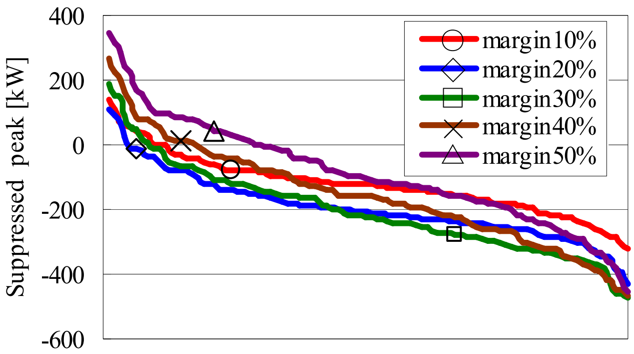

Fig.17. Suppressed peak receiving power by preparing proper margins

5.3 Flexible Charge of Battery

The battery should be charged during night when the tariff is discounted. If a customer has much night load, he has to charge the battery with care. Otherwise the peak load at night (include charging) might be exceed the peak record in daytime. In this section, the issue of night charging is considered.

Simulation was performed to identify the date when the night load will exceed some certain load levels. Fig.18 shows the results.

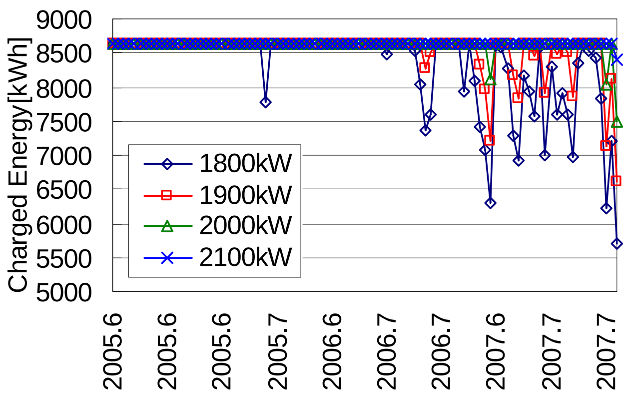

Fig.18. Possibility of peak over in night

Fig.18 shows that recent the night load in Meisei University is increasing and that risk of overload is also increasing. Since there are special contracts which allow overload at night-time, this issue is not critical in Meisei University. However, in general, night-time load should be also maintained and controlled like daytime.

A simple strategy for discharge is developed to prevent peak over in night-time. NAS battery is operated so that the demand at night should not exceed the recorded daytime peak. It is also requested that full energy must be charged to the NAS battery during night-time. After this improvement, full energy can be charged without exceeding the peak.

6 Conclusion

The practical load following operation is investigated in this paper. Two important parameters for reserve (margin) are obtained numerically. The first is the amount of reserve (margin) and the second is the trigger of release. The proposed strategy has succeeded to improve the performance of load following control. The operation at night-time is also improved. A simple strategy has succeeded to prevent peak load at night. This strategy ensures that the NAS battery can be fully charged before the discharging.

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APPENDIX

NAS battery is a battery storage energy system (BESS) that can charge electricity energy of a large capacity, and can discharge as a battery. Nihon Gaisi and TEPCO developed NAS battery. Although principal objective to install NAS battery was load reveling, recent installation is delicate load such as semiconductors needs high quality to electric power. The total capacity has already reached 181 MW 116 sites in 2007. This trend implies that the manufactures production line is very delicate and that the damage caused by poor quality of electric power is severe.

The merit of introduction of NAS battery is not limited to power quality. In addition, since installation of NAS batteries reduces CO2-emmition, companies appeal a "green and clean" image. A wind power company has installed 34MW NAS battery system in their 50MW wind-farm in Rokkasho, Japan. The exterior of NAS battery system in Rokkasho is shown in Fig.19. NAS has some advantages, a large capacity, compact, clean and various functions, comparing with other new types of battery systems. In Table.7, comparison of the NAS battery with other batteries is shown.

Fig.19 NAS battery systems in wind-farm

Table.7 Major Features of NAS and Comparison with other Batteries

	Unit	NAS	Redox Flow	Lead	ZincBr
Voltage	*V*	2.08	1.4	2	1.8
Ideal energy	*Wh/kg*	780	100	110	430
density	*Wh/l*	1000	120	220	600
Efficiency	*%-DC*	85	80	85	80
Temperature	*Cdeg*	280-350	40-80	5-50	20-50
Auxiliaries	-	Heater	Pump	Water	Pump
Self Discharge	-	no	yes	yes	yes

Ideal energy density, efficiency, and self-discharge is more dominant than other batteries. However, it is necessary to keep a temperature of 300C degrees. Therefore, heaters are mandatory in NAS battery systems. The heater also consumes the electric power; however, when NAS battery is operating (discharging), it is not necessary to use the heaters, because batteries are kept warm by discharging. NAS battery is composed of modules, which also consists of 320 cells. This module is the minimum unit of NAS battery, and output is 50kW. NAS battery cost is the same level to pumped storage hydro power plants in Japan. It is roughly 200-250 thousand yen/kW.

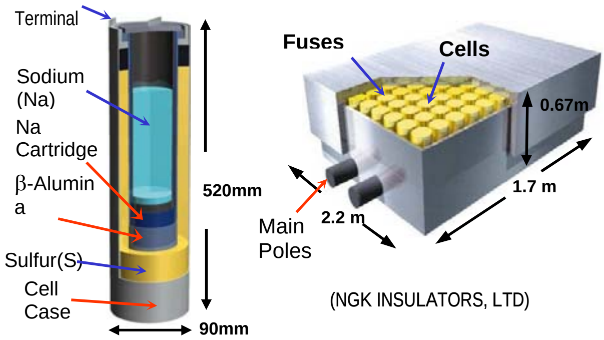

Fig.20 Details of Unit Cell and Module

Biography

Yusuke Hida graduated from Electrical Engineering Department of Meisei University, Tokyo Japan, in 2008. He is now a graduate student at the Graduate School of Environment and Energy Engineering in Waseda University, Japan. His reserach interests are environment and power system.

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Kouji Tanaka received the B.S degree in electrical engineering from Waseda University in 1981. He joined Tokyo Electric Power, Inc (TEPCO). in 1981. He has contributed to the development of NAS battery. He is a general manager of Corporate Marketing and Sales Department in TEPCO. Mr. Tanaka is a member of IEEJ.