Multi-objective control method of battery Energy storage system for distribution system

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ABSTRACT

The voltage deviation in a low-voltage distribution system is one of many problems caused when a large number of PV systems is introduced. In this study, we constructed various models of power distribution systems in consideration of the district divisions of the supply area and evaluated the amount of expansion in the PV introduction limit by controlling the battery system. The effectiveness of the proposed control method is verified by a power flow calculation. In addition, the stand-alone operation using a battery energy storage system was verified.

INTRODUCTION

Since the Great East Japan Earthquake, the introduction of renewable energy such as photovoltaic (PV) is promoted by national policy. A battery energy storage system (BES) is expected to be one solution to protect against voltage deviations in distribution networks caused by the installation of a large number of PV systems. However, its cost is quite expensive for wide-spread use in distribution networks. We examined the effective arrangement, the capacity of the battery systems, and their operation in distribution networks using a voltage estimation method based on a power flow calculation. Active- and reactive-power control methods were verified in many distribution models in Tokyo Electric Power Company (TEPCO) in consideration of various district divisions, and we proposed a multi-objective control method for a battery system.

DISRTRIBUTION SYSTEM MODELS

A 6.6-kV middle-voltage (MV) distribution system has power distribution channels from the substations to the customer site. The configurations extend radially outward around the substations because a line was extended whenever new electric demand occurred. Therefore, standard power distribution models do not exist in general. In accordance with the investigation [1] of 223 real distribution power lines, we classified four of the district divisions as "industrial," "downtown," "residential," and "rural" areas on the basis of the supply object. In this study, we constructed two types of models for each district division: an "average" model that has a mean line length and a "severe" model that has a long line length. Therefore, we constructed eight models each having two line lengths with four district divisions.

As the survey result for the power factor of the low-voltage (LV) power lines was approximately 100% [1], the LV load was simulated only as active power and was equally assigned to the LV lines (main lines, branch lines). The number of installed PV systems was calculated using the past survey ratio (for a light load, PV/load = 1.8553; for a heavy load, PV/load = 0.00568). For each model, the voltage was calculated as a parameter for the amount of installed PV, and the PV introduction limit was assumed to be the case in which a voltage deviation had occurred for each model.

Table 1. Features of each distribution model

District	Model	Distance		Heavy-load	Load ratio	Pole trans	SVR
		Main	Branch	Light-load	High :Low		
Industrial area	Average	3.8km	0.2 km	2220kW	1:0.07	8	0
	Severe	18.4km	5.5km	833kW	1:0.95	62	3
Residential area	Average	3.0km	4.3km	2113kW	1:1.37	70	0
	Severe	6.1km	3.7km	1132kW	1:0.80	54	1
Downtown	Average	1.2km	0.5km	1677kW	1:0	0	0
	Severe	2.8km	1.9km	631kW	1:3.44	75	0
Rural area	Average	7.6km	1.8km	1547kW	1:0.51	30	1
	Severe	6.2km	2.2km	823kW	1:0.09	7	0

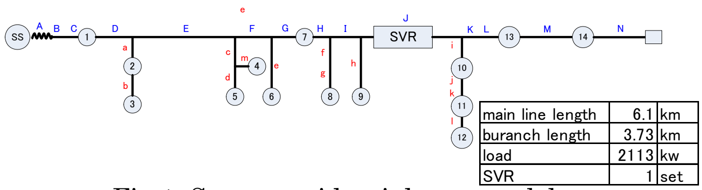


Fig.1. Severe residential area model

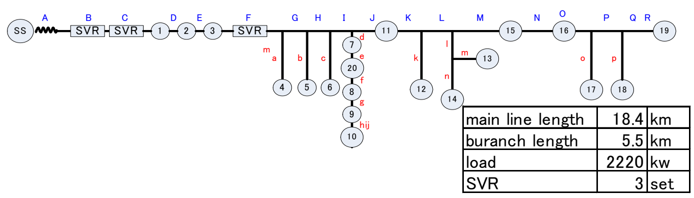


Fig.2. Severe industrial area model

PV INTRODUCTION LIMIT QUANTITY

To determine the PV introduction limit for each model, the MV and LV at each observation point are obtained from the power flow calculation under the abovementioned load conditions. When all LV customers install up to 100% of the PV system, voltage deviations were confirmed in three models (industrial severe model, residential severe model, and rural severe model).

Table 2. PV limit for each distribution model

District	Model	Distance		H-load	SVR	Acceptable PV limit
		Main	Branch	L-load		
Industrial area	Average	3.8km	0.2km	2220kW	0	100<
	Severe	18.4km	5.5km	833kW	3	20
Residential area	Average	3.0km	4.3km	2113kW	0	100<
	Severe	6.1km	3.7km	1132kW	1	90
Downtown	Average	1.2km	0.5km	1677kW	0	-
	Severe	2.8km	1.9km	631kW	0	100<
Rural area	Average	7.6km	1.8km	1547kW	1	100<
	Severe	6.2km	2.2km	823kW	0	80

REACTIVE POWER CONTROL

Fig.3 shows one of the calculation results for the voltage distribution (the severe residential model shown in Fig.1). In this model, an SVR is placed between nodes 12 and 13, and the voltage greatly fluctuates owing to the non-linear SVR movement. For PV = 100% (all LV customers install a PV system), a voltage deviation from the regulation level (>107 V) occurs at nodes 14–19 because of the reverse current of the PV systems.

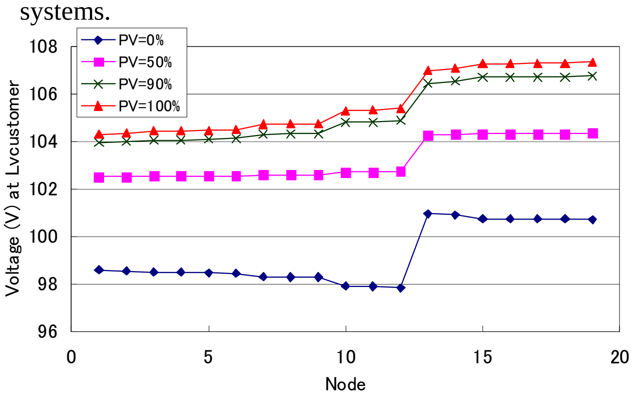


Fig.3. Voltage distribution in consideration of the PV introduction rate (severe residential area model)

To overcome the voltage deviation, we estimated the effect of the reactive power control of a battery system placed in the MV distribution lines. In traditional compensation position determining methods, the compensator is placed around the point where a voltage deviation or some problem has occurred. Therefore, the method overlooks its economic efficiency and the voltage improvement effect in the entire distribution system after compensation.

Thus, we examined the "constant voltage control method" as a reactive power control method. This method decreases the voltage deviation by adjusting each parameter of the BES in real-time on the basis of the measuring voltage and passing current. The voltage control scheme is explained as follows.

$V_{tgt}(t)$ is the target voltage at measuring point, $Z(t) = R(t) + jX(t)$ is the line impedance between the substation and measuring point, and $I(t)$ is the current at the measuring point. The voltage difference between the target voltage and the measuring point (V_{mp}) is expressed in equation (1).

$$\Delta V(t) = \left|V_{tgt}(t) - V_{mp}(t)\right| \tag{1}$$

When $\Delta V(t)$ surpasses the dead band ε, the BES outputs the reactive power adequately in consideration of the difference between a detection level and the target levels. Thus, the distribution voltage is adjusted to suppress voltage fluctuations.

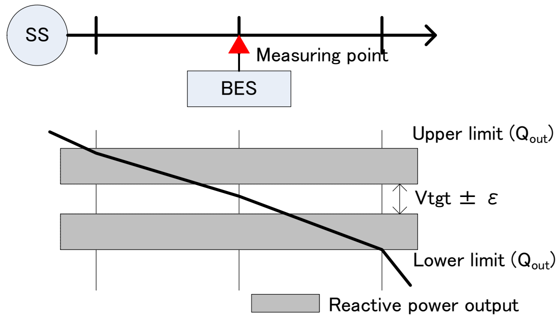


Fig.4. Constant voltage control scheme

Fig.5 shows the effect of reactive power control using the constant voltage control method as a parameter of the capacity of battery system set at three points in the distribution network. In this case, it was confirmed to improve the voltage, and the voltage problem was solved with greater than 50-kVA reactive power control.

Similarly, to confirm the most suitable capacity and placement, we studied the effect of dividing the BES capacity into 1–3 parts (each part has the same BES capacity and the each total capacity was same).

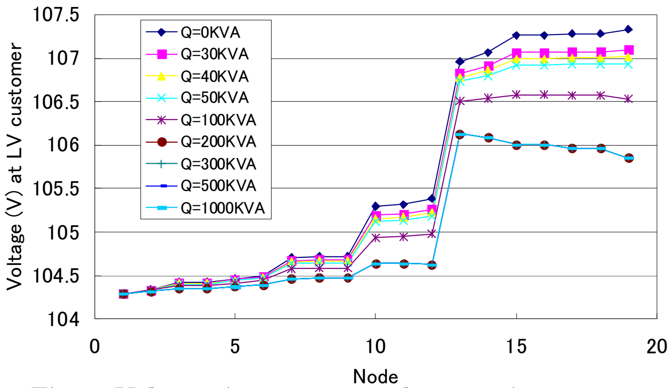


Fig.5. Voltage improvement by reactive power control (severe residential area model)

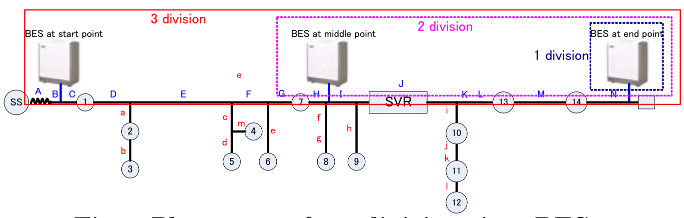


Fig.6. Placement of 1-3 divisions in a BES

Fig.7 shows the voltage improvement associated with the battery positions and capacities. For division of BES capacity into three parts (start, middle, and end nodes), one division (end node) achieved the most effective results because the voltage improvement from the reactive power was caused by multiplication of the line impedance and the magnitude of the reactive power.

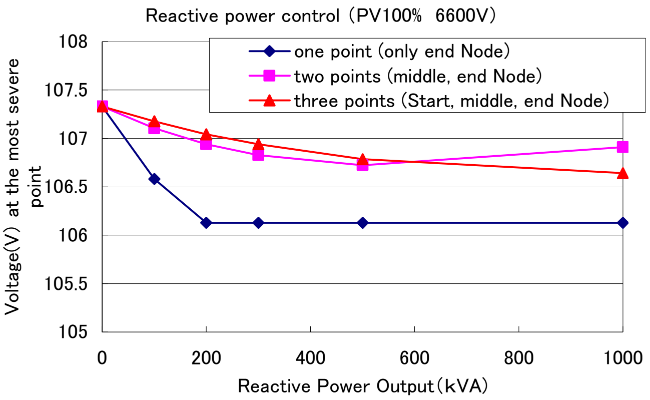


Fig.7. Relationships for the setting position and the capacity of the battery systems

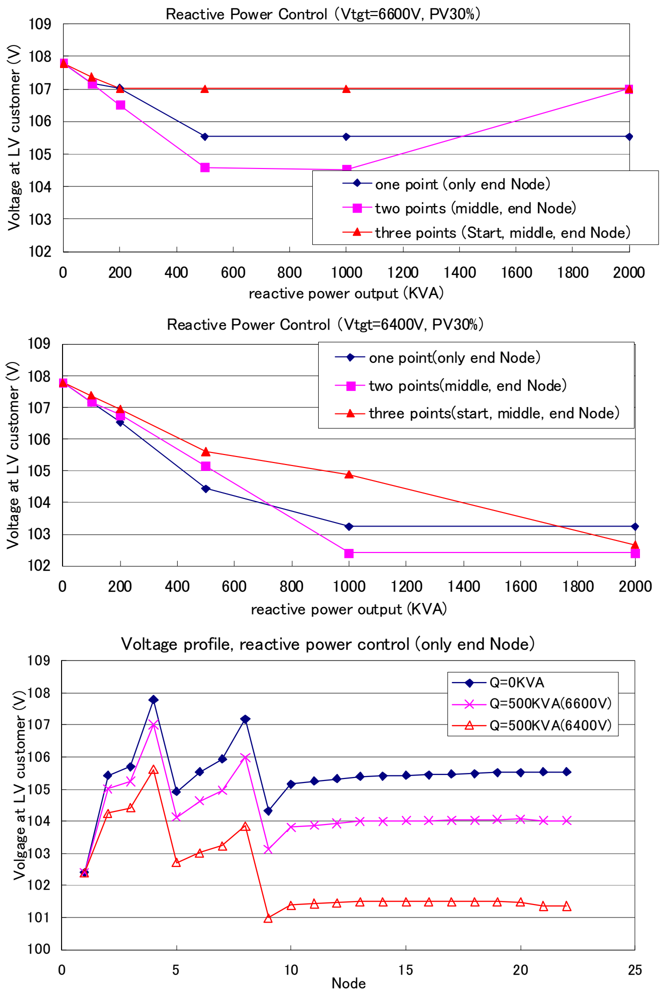


Fig.8. Voltage suppression effect

For the residential severe model, 6,600-V constant voltage control with 50-kVA reactive power output achieved the appropriate voltage range.

On the other hand, it is necessary to change the target voltage if the distribution line is too long, as in the industrial severe model. Fig.8 shows the calculation results of the industrial severe model. The target voltage controlled by the BES (V_{tgt}) is constant at 6,600V.

The voltage improvement effect was saturated over the 500-kVA BES output of the reactive power. For V_{tgn} = 6400 V, the voltage over the entire distribution line was controlled with 500-kVA reactive power output and could achieve the legal voltage range.

ACTIVE POWER CONTROL

Optimized control of the BES output to restrain the voltage deviation is divided into two methods: reactive power control and active power control. Active power control directly cancels the PV output. Fig.9 shows the calculation results for the industrial severe model. Active power control in the MV lines was conducted to cancel the PV output. The voltage improvement effect was saturated for BES output greater than 200 kW. However, overcompensation occurred when the active power output exceeded 300 kW because of the non-linear SVR tap change. Fig.10 shows the voltage improvement related to the battery positions and capacities.

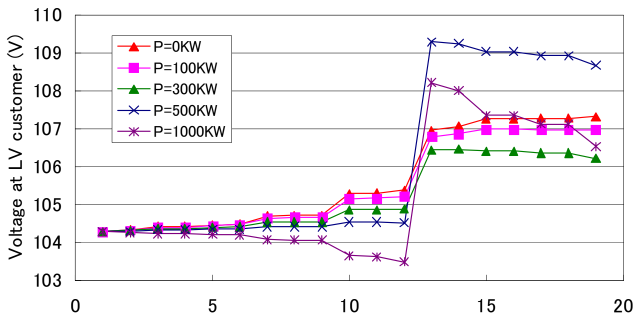


Fig.9. Voltage improvement by active power control (severe residential area model)

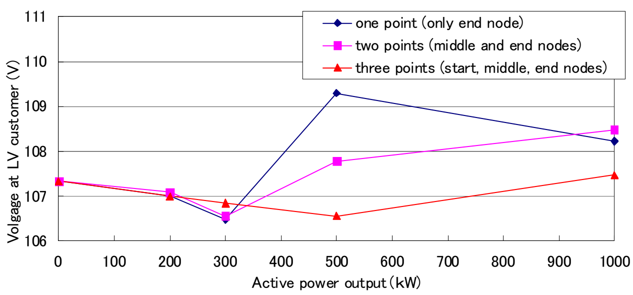


Fig.10. Effect of active power control at the end point in the MV lines (severe residential area model)

The three divisions (start, middle, and end nodes) of the

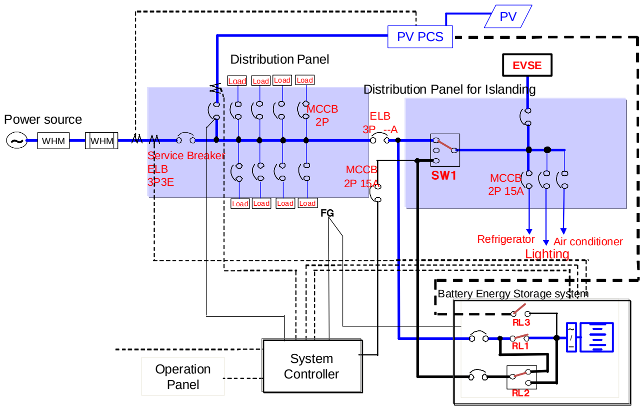
BES was the most effective result because PV systems were installed over the LV distribution lines, and area compensation was more effective than pin-point compensation for active power control. Table.3 summarizes the voltage improvement effect per battery output at 1 kW/1 kVA.

Table 3. Voltage improvement

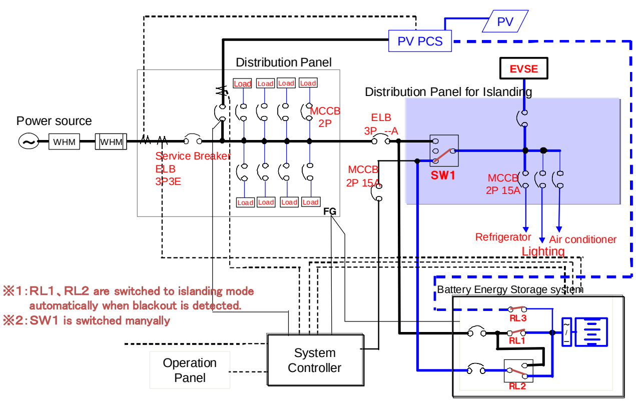
area	Residential severe		Industrial severe	
BES output	Reactive power	Active power	Reactive power	Active power
V/kW V/kVA	0.001 - 0.008	0.0015 - 0.0017	0.001 - 0.007	0.003 - 0.004

ISLANDING OPERATION

In order to further determine the value of using a battery system, this study also focuses on stand-alone operation in a smart house, which can avoid inconvenience when a blackout occurs. Through various studies, we proposed an effective method of stand-alone operation and load control using battery and PV system. Fig.11 shows the circuit of the distribution panel that switches into islanding operation when a blackout has occurred in a house.



a) Distribution circuit at the grid interconnection



b) Distribution circuit during islanding operation

Fig.11. Switching into the islanding mode during a blackout

The battery has 2-kW (1 kW for each phase) output for three single-phase lines of 100/200 V during islanding operation. The battery was connected in parallel with the PV, and the PV output used first priority for small load consumption. We selected the important apparatuses (Top 4: lighting, TV, PC, and refrigerator), air-conditioners, and a heater during islanding operation.

The inspected results of islanding operation are presented in table 4. Top 4 and the seasonal household appliances (air-conditioner or heater) could be available in a situation with limited output and capacity. Furthermore, the household appliances could be effectively available by using an HEMS. Because the EVSE charge requires 2.4 kW, the BES (maximum of 2 kW) could not charge it during islanding operation. However, the HEMS could restrict to its charge amount of 1.2 kW, and the EVSE could be charged in this situation (see Fig.12).

Table 4. Islanding results

Load equipment	Islanding operation			
	Load(A)	THD_V(%)	THD_I(%)	islanding
Top4(Lightings, TV, PC, refrigerator)	0.94	1.63	0.94	○
Top4＋Air-conditioning(cool 22degrees C)	3.29	2.42	23.07	○
Top4＋Air-conditioning(heating 26degrees C)	13.9	3.49	16.85	○
Top4＋Air-conditioning(defumidification)	6.07	2.33	21.84	○
Top4＋Heater(330W)	5.84	1.12	7.96	○
Top4＋Heater(660W)	8.87	0.96	4.73	○
Top4＋Heater(990W)	12.01	0.79	3.65	△

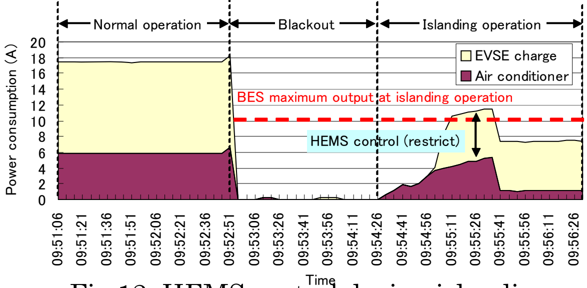


Fig.12. HEMS control during islanding operation

CONCLUSION

In this paper, we described voltage control methods for a battery system and validated it using a power flow calculation of the real distribution models in TEPCO. Active and reactive power control for the BES were confirmed to be effective, but each physical phenomenon of the effect is different. The use of a suitable control technique would allow for the introduction of more PVs. Furthermore, it would become the spread of BES promotion by utilizing a battery system with multiple purposes such as islanding operation.

REFERENCES

[1] Technical committee of the problem of power factor in a distribution network, 2011, "The problem of power factor in a distribution network", *Electric Technology Research Association.* vol. 66-1, 10-17