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Probabilistic Operation of Electric Power Systems Considering Environmental Constraint (Part 16)*

—Consideration of the Effects of the Operation of An Energy Storage Facility—

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Abstract

To improve the power supply probability considering the enviromental pollution, the operation effectiveness of an energy storage facility is explained. The output power of two power stations is adjusted to satisfy the line capacities in the proposed method when the ordinary power dispatch introduces overflows in some power lines.

By simulating the results of a model system, relations between the improvement of the power supply probability and the capacity of the energy storage facility is shown. It is also argued that the optimum operation cannot simply be decided by the minimum expected value of the operating cost.

1. Introduction

We reported previously the optimum scheduling method for thermal power units when both power supply probability and environmental pollution are considered[1]. The operation is expected to become more optimum when the energy storage facility can be used for the pumping-up power unit[2]. In this paper, the effectiveness of the energy storage facility operation is described. The variations of the power supply probability and environmental pollution are shown which depend on some kind of capacity of the energy storage facility. The nitrogen oxide (NO_x) emission from each thermal unit is considered as a typical example of environmental pollution in this paper.

The power dispatch among thermal units is initially estimated considering the demand supply balance and environmental pollution. If some power-flows exceed the line capacity at this time, the power dispatch is adjusted to satisfy the capacity. The proposed method controls the output power of only two units to estimate the overflow of line capacity rapidly[3] even if it is not strictly economical.

The proposed method ignores the energy balance between input and output power from the storage facility, because this method considers the power supply in mainly a faulty state in order to improve the power supply probability.

A model power system is simulated by the proposed method. By using the

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simulation results, effectiveness of the energy storage facility is shown. A relation between the optimum schedule and the expected value of the operation cost is also checked.

2. Objective Function for Power Dispatch

When the transmission losses are ignored, eq. (1) is ordinarily used as the objective function for the economic load dispatch.

$$\phi=\sum_{m=1}^{M} f_m+\lambda\cdot\left(Ps-\sum_{m=1}^{M} g_m\right) \tag{1}$$

Where f_m and g_m are the fuel cost and the output power of the m-th thermal unit respectively. M is the number of the thermal units in the power system. Ps is the system load and λ is LaGrange's multiplier which is concerned with the power supply and demand balance. When eq. (1) is minimized, the economic load dispatch is obtained.

When the emission constraint must be also considered, eq. (1) is expanded to eq. (1)′.

$$\phi'=\sum_{m=1}^{M} f_m+\lambda\cdot\left(Ps-\sum_{m=1}^{M} g_m\right)+\mu\cdot\left(Y-\sum_{m=1}^{M} y_m\right) \tag*{(1)$'$}$$

Where y_m is the NO_x emission from the m-th thermal unit. Y is the constraint value of the NO_x emission in the whole system. μ is LaGrange's multiplier which is concerned with the NO_x emission. When eq. (1)′ is minimized, the emission constraint is economically satisfied.

3. A Method for Power Flow Control

When the DC method[4] is used, the power flow of each line becomes eq. (2).

$$[i]=[e][P] \tag{2}$$

Where, $[i]$ is a row vector whose element i_l is the power flow of the l-th line. $[e]$ is the sensitivity matrix. $[P]$ is a column vector whose element P_n is the real power on the n-th bus.

When $[P]$ is estimated by minimizing eq. (1), $[i]$ becomes economic power flow in eq. (2). If it exceeds the line capacity, the economic power flow must be adjusted to satisfy it so that the electric power can be transmitted.

The increase of power flow in the l-th line is Δi_l of eq. (3) because of eq. (2) when the m'-th unit increases the output power by Δg and the m''-th unit decreased the power by the same value.

$$\Delta i_l=(e_{lm'}-e_{lm''})\cdot\Delta g \tag{3}$$

Eq. (3) means that the m'-th unit and the m''-th unit can change their output power by Δg when the power flow must increase by Δi_l to satisfy the l-th line capacity. It is obviously possible that not only thermal power units but pumped-up power units change the output power to control flows. These are both simply called power units hereafter.

When the output power has to be adjusted strictly economically, modification of the output power must be estimated for every power unit. Because strict economy needs huge calculations[5], the proposed method adjusts the output power of two power units.

The unit pair to be used to adjust the power flow is chosen so that the absolute value of Δg becomes minimum in the proposed method. That is, the unit pair can consist of the units whose e_{lm} are the greatest and least independent of the value of Δi_l.

When only one line capacity is considered, the output power can be adjusted very easily by using eq. (3). But when many or all the line capacities must be considered, the procedure of power adjustment to control the flow becomes more complicated. In the proposed method, the unit pair to be used to adjust the power flow is decided by weighting e_{lm} with Δi_l. The unit pair is composed of the greatest unit and the least unit according to E by using eq. (4).

$$E = \sum_{l} \Delta i_l \cdot e_{lm} \tag{4}$$

When [P] of eq. (2) is estimated by minimizing eq. (1)′ to economically satisfy the emission constraints and some flows over the capacities, the unit pair to be used to adjust the power is chosen by eq. (4)′ to satisfy both the line capacities and emission constraints. If μ is negative, then it becomes less dependent on stricter emission constraints because of the Kuhn-Tucker conditions.

$$E' = \sum_{l} \Delta i_l \cdot e_{lm} - \mu \cdot \frac{dy_m}{dg_m} \tag{4$'$}$$

The capacity of all lines is not always satisfied by the adjustment of one unit pair, and the upper and lower output limits of the power unit must also be satisfied. The output power is then repeatedly adjusted to satisfy these constraints. To avoid an oscillatory or divergent repetition, the direction of the adjustment for each unit power output is fixed after the unit is initially selected by eq. (4) or eq. (4)′.

4. Simulations by a Model Power System

Table 1 shows the characteristic constants of each thermal unit of a model system[6]. Line data is snown in Table 2. Table 3 shows the load data of each bus of the model system. In the following simulations, each bus load varies depending on the rates of Table 3 and the system load, and the energy storage facility is assumed to be connected to the 8th bus.

The power supply probability was estimated by the proposed method, the results are shown in Fig. 1. 'ELD' in Fig. 1 means the simple results of eq. (1) being minimized. That is, the system load was simply and economically dispatched to each thermal unit, and neither power flow was controlled. 'None' means that the power system did not have any energy storage facility and the

Table 1. Characteristic constants of thermal units

No.	Bus	$f_m = a_m + b_m \cdot g_m + c_m \cdot g_m^2$			$y_m = d_m \cdot f_m$	Output limit		Error rate
		a_m	b_m	$c_m \times 1000$	d_m	$\underline{g_m}$	$\overline{g_m}$	
1	1	40	3.6	5.0	—	30	120	0.029
2	2	60	3.4	4.0	0.258	30	120	0.024
3	3	60	3.4	4.0	0.266	30	120	0.020
4	4	50	3.5	4.5	0.241	30	120	0.020
5	5	40	3.5	4.5	0.250	30	120	0.015

Note : No. 1 unit is not constrained for emissions because it is constructed in a remote area.

Table 2. Line data

Line	Node	X	Error rate	Line	Node	X	Error rate
1	1– 9	0.50	0.030	10	5– 6	0.36	0.024
2	1–11	0.16	0.010	11	5– 9	0.16	0.010
3	2– 3	0.50	0.030	12	7– 8	0.16	0.010
4	2– 7	0.28	0.020	13	7–10	0.24	0.016
5	2–10	0.16	0.010	14	8– 9	0.36	0.024
6	3– 4	0.24	0.016	15	8–10	0.24	0.016
7	4– 6	0.28	00.20	16	8–11	0.28	0.020
8	4– 8	0.28	0.020	17	10–11	0.36	0.024
9	4– 9	0.50	0.030				

Base : 100 MVA

Table 3. Load data

Bus	Load [MW]	Bus	Load [MW]
1	0	7	40
2	0	8	90
3	0	9	70
4	0	10	25
5	0	11	25
6	10		

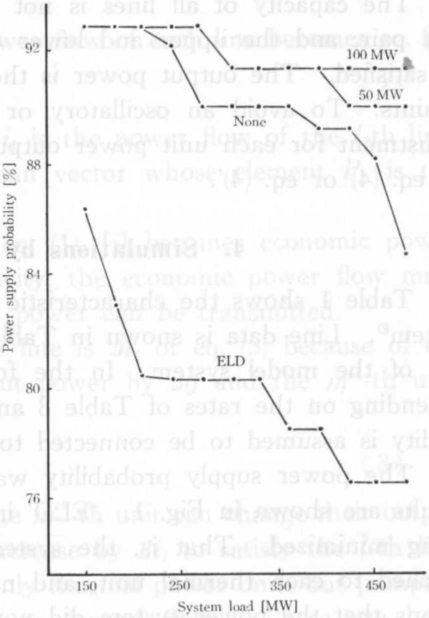

Fig. 1. The power supply probability.

power flows were controlled to satisfy the line capacities by using only thermal units by the proposed method. The curved lines of 50 MW and 100 MW are the results where the power system had an energy storage facility with a capacity of 50 MW or 100 MW, and the power flows were controlled by both the thermal units and the energy storage facility.

These results show that the power supply probability could be improved more than ordinary ELD by the proposed flow control method. Even when the energy storage facility was not operated, the improvement of it is about 10%. The power supply probability was more improved by greater energy storage facility when the system load was heavy.

The expected values of the operating cost and the NO_x emission were shown in Fig. 2 in the case of 420 MW. When the emission constraints were not considered by using eqs. (1) and (4), the results were the right-most points of each curved line in Fig. 2. From these points, each constraint of NO_x emission was satisfied by using eqs. (1)′ and (4)′. Fig. 2 shows the results of them. It can be recognized that the proposed method was able to satisfy each NO_x emission constraint without causing the highter cost of operation and the worse probability of the power supply.

However, an impression of Fig. 2 may be that a smaller energy storage facility is better because of less environmental pollution and lowere operating costs. The reason of result of fewer emissions and the lower cost of less capacity is a less reliable of power supply (see Fig. 1, system load was 420 MW). Fig. 3 shows the ratios of the expected value of the operating cost and NO_x emission

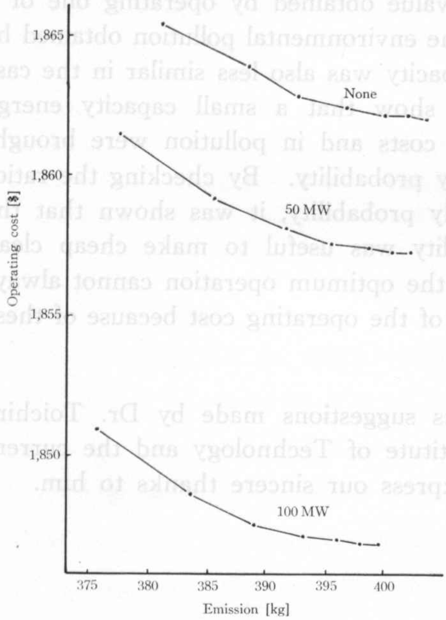

Fig. 2. The expected value of cost of emission constraints.

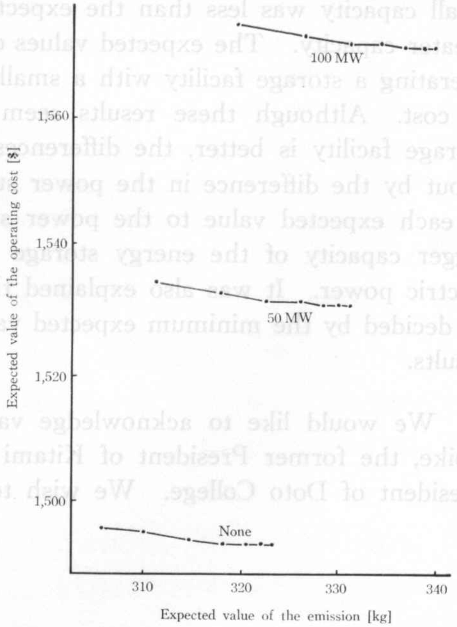

Fig. 3. The ratio to the power supply probability.

to the power supply probability. Each curved line means the cost and the emission per 100% probability.

It can also be shown by the results of Fig. 3 that greater capacity of the energy storage facility can bring about lowere operating costs and fewer NO_x emissions. Because the optimum operation has sometimes meant the operation whose expected value of the operating cost is the minimum, the results of Fig. 2 and Fig. 3 call our attention to the fact that the optimum operation does not always have the minimum expected value of the operating cost.

5. Conclusion

The effectiveness of the energy storage facility such as the pumping-up power unit was described to improve the system reliability and to satisfy the environmental constraints by using the previously reported method. The proposed method adjusted the output of two power units to satisfy the line capacities. The power units to control the power flows were selected by using the sensitivity matrix.

The proposed method was simulated by the model power system. It was shown that the proposed power flow control method could improve the power supply probability by about 10% at each load level. Bigger improvement was also shown when greater capacity facility for energy storage was operated. The proposed method was confirmed to satisfy the environmental constraints, impairing neither operating costs nor power supply probability. The expected values of the whole system cost obtained by operating an energy storage facility with a small capacity was less than the expected value obtained by operating one of a greater capacity. The expected values of the environmental pollution obtained by operating a storage facility with a small capacity was also less similar in the case of cost. Although these results seem to show that a small capacity energy storage facility is better, the differences of costs and in pollution were brought about by the difference in the power supply probability. By checking the ratios of each expected value to the power supply probability, it was shown that the bigger capacity of the energy storage facility was useful to make cheap clean electric power. It was also explained that the optimum operation cannot always be decided by the minimum expected value of the operating cost because of these results.

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