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장기전원계획에 있어서 수력운전을 고려한 운전비용 계산모형

Production Costing Model Including Hydroelectric Plants in Long-range Generation Expansion Planning

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Abstract

This paper describes a new algorithm to evaluate the production cost for a generation system including energy—limited hydroelectric plants. The algorithm is based upon the analytical production costing model developed under the assumption of Gaussian probabilistic distribution of random load fluctuations and plant outages[1]. Hydro operation and pumped storage operation have been dealt with in the previous papers using the concept of peak—shaving operation[2),3)]. In this paper, the hydro problem is solved by using a new version of the gradient projection method that treats the upper / lower bounds of variables saparately and uses a specified initial active constraint set. Accuracy and validity of the algorithm are demonstrated by comparing the result with that of the peak—shaving model.

1. Introduction

Production costing occupies one of the most important parts in optimal long-range generation planning studies. During the past decade, this problem has received considerable attention, and the motivation for more efficient and more sophisticated techniques of evaluating utility production cost has been increased. Also it has undergone significant changes during the past decade.

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At present, the essential point that must be considered is randomness of load fluctuations and plant outages. Conventional methods are based on the load duration curve[4)~7),9)]. A number of methods have been used successfully to represent the equivalent load duration curve (ELDC). All of them, however, have disadvantages of one kind or another. The most prominent disadvantage of all is that they are costly in terms of computer execution time. In the beginning of the 80's, the cumulant method of representing the ELDC was suggested,[5)] which was more accurate and faster than the existing methods.

Recently, a new analytical approach was developed by assuming Gaussian probability distribution for random load fluctuations and plant outages[1)]. The approach was based upon the load curve rather than the load duration curve. This new analytical method provided an accurate solution for the generation planning with much less computational effort than conventional approaches. At first, the study considered thermal plants only. The next papers included energy-limited hydro plant operations and pumped storage operations by applying the concept of peak-shaving [2),3)]. Peak-shaving gives a near-optimal solution to the use of available hydro resources, but it cannot reflect the effect of variances of hydro plant outages on other plant outputs. In addition, it is difficult to compute marginal investment costs.

Therefore, in this paper, we solved the hydro plant operations as the optimization problem itself. In this method, hydro plants can be operated in any loading order. We used a new version of the gradient projection method. First, it treats the upper / lower bounds of variables saparately, which gives a great reduction in computing time and truncation errors. Second, an initial active constraint set can be specified, so it has special merit in solving the hydro operation problem. Additional advantage of the gradient projection method is that marginal cost informations can be derived from sensitivity analysis.

2. Analytical Production Costing Model[1)]

2.1 Representation of Random Load Fluctuation

The load at a particular time of the day of a week in a given season fluctuates randomly and it is reasonable to assume that the load behaves with the Gaussian distribution since it is forecasted using a large number of previous historical data.

$$f(L_\Delta) = (1/\sqrt{2\pi}\sigma_\Delta^L)\ \exp[-0.5(L_\Delta - \bar{L}_\Delta)^2/\sigma_\Delta^{L^2}] \quad (1)$$

f : probability density function

Δ = i, s,t : year i, season s, time-band t

2.2 Expected Annual Energy Demand

Given the statistical values of future loads on a basis of one equivalent load curve, the expected annual energy demand for year i, $\bar{D}_i$, can be accounted as

$$\bar{D}_i = \sum_{s=1}^{S} n_s \sum_{t=1}^{T} \tau_t \bar{L}_\Delta \quad [\text{MWH}] \quad (2)$$

where

τ_t : length of time-band t

T : number of time-bands in a load cycle

n_s : number of load cycles in season s

S : number of seasons in a year

2.3 Available Generation Capacities

Given the installed capacity of plant type j in year i, the available generation capacity y_Δ^j for type j represented by the Gaussian distribution with its mean $\bar{y}_\Delta^j$ and variance $\sigma_\Delta^{j^2}$ can be obtained by incorporating the random plant outages, maintenance requirements, energy resource distribution factors, and aging factors, and are derived as :

$$\bar{y}_\Delta^j = p^j(1 - v_{i,s}^j)\beta_\Delta^j \gamma_i^j x_i^j \quad [\text{MW}] \quad (3)$$

$$\sigma_\Delta^{j^2} = p^j(1 - p^j)(1 - v_{i,s}^j)\beta_\Delta^j a^j \gamma_i^j x_i^j \quad [\text{MW}^2] \quad (4)$$

p^j : availability of units in plant type j

$v_{i,s}^j$: maintenance rate of plant type j in season s of year i

β_Δ^j : energy resource distribution factor of plant type j in time-band t, season s, year i

a^j : unit capacity of plant type j [MW]

γ_i^j : aging factor for units of type j in year i

x_i^j : total capacity of plant type j in year i[MW]

The aging factor γ_i^j is to reflect the unit retirements or ratings reduced with ages. The energy resource distrbution factor β_Δ^j is introduced in order to represent the reduction in available generation capacity due to the limited energy resources. β_Δ^j is fixed to one for non-hydro plants, but is determined optimally for hydro plants to minimize the total fuel cost since the hydro energy resource is limited. This factor, however, can also be used for other non-hydro plants whenever there is a shortage in fuel supply due to some political or economical reason.

2.4 Expected Plant Outputs and Annual Energy Generation

The conventional loading-order concept is employed for econmic operation. Let $j=1,\cdots,J$ be the indices of plant types already ordered in the order of increasing operation costs. In this study, however, hydro plants are ordered next to nuclear plants though hydro operation costs are less than those of nuclear plants.

Let ${}^{j}y_\Delta$ be the total available generation capacity from plant type 1 to j, i. e.,

$$ {}^{j}y_\Delta = \sum_{k=1}^{j} y_\Delta^k \qquad [MW] \qquad (5) $$

Then, the total power output from plant type 1 up to j, ${}^{j}P_\Delta$, does not exceed the load, and can be expressed as

$$ {}^{j}P_\Delta = \min(L_\Delta,\ {}^{j}y_\Delta) \qquad [MW] \qquad (6) $$

The expectation of the above equation is derived as

$$ {}^{j}\bar{P}_\Delta = \bar{L}_\Delta - {}^{j}\bar{Z}_\Delta\{0.5+\mathrm{erf}({}^{j}\bar{Z}_\Delta/{}^{j}\sigma_\Delta)\} - ({}^{j}\sigma_\Delta/\sqrt{2\pi})\exp(-0.5\,{}^{j}\bar{Z}_\Delta^2/{}^{j}\sigma_\Delta^2) \qquad [MW] \qquad (7) $$

where

$$ {}^{j}\bar{Z}_\Delta = \bar{L}_\Delta - {}^{j}\bar{y}_\Delta \qquad [MW] \qquad (8) $$

$$ {}^{j}\sigma_\Delta^2 = \sigma_L^{2} + \sum_{k=1}^{j}\sigma_\Delta^{k^2} \qquad [MW^2] \qquad (9) $$

erf(.) : error function

Here ${}^{j}\bar{Z}_\Delta$ represents the expected value of the difference between the load and the total available generation capacity from type 1 to type j.

Thus the expected power output of each plant type, $\bar{P}_\Delta^j$, can be simply computed as

$$ \bar{P}_\Delta^j = \begin{cases} {}^{j}\bar{P}_\Delta - {}^{j-1}\bar{P}_\Delta & [MW],\ j=2,\cdots,J \\ {}^{1}\bar{P}_\Delta & [MW],\ j=1 \end{cases} \qquad (10) $$

The expected annual energy generated by plant type j, $\bar{E}_i^j$, and the expected total energy in year i, $\bar{E}_i$, are

$$ \bar{E}_i^j = \sum_{s=1}^{S} n_s \sum_{t=1}^{T} \tau_t \bar{P}_\Delta^j \qquad [MWH] \qquad (11) $$

$$ \bar{E}_i = \sum_{j=1}^{J} \bar{E}_i^j \qquad [MWH] \qquad (12) $$

2.5 Reliability Measures

The expected unserved power $\bar{N}_\Delta$ is the excess of the expected load compared to the expected total power output from all j types, i. e.,

$$ \bar{N}_\Delta = \bar{L}_\Delta - {}^{J}\bar{P}_\Delta \qquad [MW] \qquad (13) $$

Associated with this unserved power, the loss-of-load probability is derived as

$$ LOLP_\Delta = 0.5 + \mathrm{erf}({}^{J}\bar{Z}_\Delta/{}^{J}\sigma_\Delta) \qquad [p.u.] \qquad (14) $$

where ${}^{J}\bar{Z}_\Delta$ and ${}^{J}\sigma_\Delta$ are defined in (8) and (9).

Consequently, the expected annnual unserved energy and the annual LOLP are integrated over a year as

$$ R_i = \sum_{s=1}^{S} n_s \sum_{t=1}^{T} \tau_t \bar{N}_\Delta \qquad [MWH] \qquad (15) $$

$$ LOLP_i = \left(\sum_{s=1}^{S} n_s \sum_{t=1}^{T} \tau_t \cdot LOLP_\Delta\right)/8760 \qquad [p.u.] \qquad (16) $$

2.6 Expected Annual Operation Cost

The annual operation cost consists of two terms: the fuel cost F_i and the non-fuel maintenance cost M_i.

$$ G_i(x_i^j, \beta_\Delta^j) = F_i + M_i = \sum_{j=1}^{J} [\, f_i^j \bar{E}_i^j + m_i^j x_i^j \,] \qquad (17) $$

f_i^j : unit fuel price [W / MWH]

m_i^j : unit non fuel maintenance cost [W / MW]

The fuel cost, F_i, is dependent upon the energy resource distribution factor β_Δ^j. It means that fuel cost is determined according to how hydro energy resources are utilized.

3. Hydro Plant Operation

3.1 Fuel Cost Minimization Problem

Given the total installed cpacity x_i^j and the hydro energy limit, the fuel cost is determined by the operation of hydro plants(β_Δ^{jh}).

In this paper, it is assumed that the hydro energy limit is given for each season. The hydro problem is to minimize the fuel cost $F_{i,s}$ with respect to β_Δ^{jh}. It can be formulated as :

$$\min F_{i,s}(\beta_\Delta^{jh}) = \min\left[\sum_{j=1}^{J} f_i^j n_s \sum_{t=1}^{T} \tau_t \bar{P}_\Delta^j\right] \quad (18)$$

$$\text{s. t.} \begin{cases} g(\beta_\Delta^{jh}) = n_s \sum_{t=1}^{T} \tau_t P_\Delta^{jh} \leq W_{i,s}^{jh} & (19) \\ 0 \leq \beta_\Delta^{jh} \leq 1 & (20) \end{cases}$$

$$\text{for } jh \in JH$$

where

$W_{i,s}^{jh}$: available hydro energy limit of plant type j in year i, season s [MWH]

JH : index set of hydro type

Eq. (19) represents the seasonal hydro energy limit. How to share the annual hydro energy among seasons is being studied, and will be reported later.

The above minimization problem can be replaced with the concept of peak-shaving. however, peak-shaving operation gives a near optimal solution. Besides, it is difficult to derive marginal investment costs. By modifying the original load curve, probabilistic variances of the load and plant outages are lost, which gives a wrong result.

Therefore, in the paper, the hydro problem is solved as the minimization problem iteslf. This enables us to find the optimal solution, and to obtain sensitivity information which can be used in generation expansion planning.

3.2 New Version of the Gradient Projection Method

The gradient projection method is improved to be efficiently used for problems of the next form.

$$\min f(x) \quad (21)$$

$$\text{s. t.} \begin{cases} Ax \leq b & (22) \\ \underline{x} \leq x \leq \bar{x} & (23) \end{cases}$$

The newly added characteristics are as follows :

First, the conjugate gradient method is applied to the intersection of the active constraints. The conjugate gradient method has been frequently used in unconstrained cases because it has excellent convergence.

Second, the upper / lower bounds of variables are treated separately from ordinary constraints. This gives great reduction in computing time, truncation errors, and in memory storage. The larger is the proportion of bound constraints, the greater becomes the merit of this characteristic.

Third, an initial active constraint set can be specified. This shortens the optimum searching sequence by a good initial guess. This is especially effective on the kind of problem (18)-(20). Because we can guess that β_Δ^{jh} has the value of 1 at the peak load, an initial active set and a feasible point can easily be obtained by putting the corresponding upper bound into the active set with the other β_Δ^{jh} near zero. Besides, in the case of nonliear constraints as eq. (19), the optimal active set can be used in the next iterative procedure.

3.3 Flowchart of the Fuel Cost Minimization Procedure

Since eq.(19) constitutes a group of nonlinear inequality constraints, an iterative procedure is necessary. Optimal active constraint set of each procedure is utilized as an initial active set to the next one.

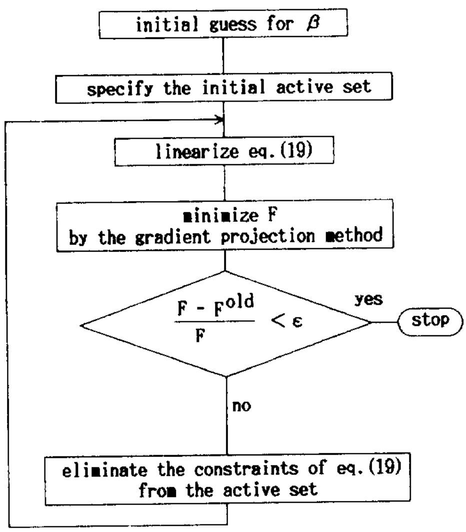

Fig. 1. Fuel cost minimization procedure.

4. Computational Example

4.1 System Data

Data for the load cycles and the generation system are chosen from EPRI Synthetic Utility Systems[8].

Table 1. Thermal plant data.

Plant Type	Unit Capacity [MW]	Total Capacity [MW]	Availability
1. Nuclear	1, 200	7, 200	0. 850
2. Nuclear	800	800	0. 850
3. Coal	800	800	0. 760
4. Coal	600	1, 800	0. 790
5. Coal	400	2, 000	0. 870
6. Coal	200	6, 600	0. 920
7. Oil	800	800	0. 760
8. Oil	600	1, 800	0. 790
9. Oil	400	800	0. 870
10. Oil	200	4, 600	0. 926
11. Combustion Turbine	50	4, 800	0. 760

Table 2. Hydro plant data.

Type	Unit Capacity [MW]	Total Capacity [MW]	Availability	Avaliable Energy [MWH]
1	300	900	0. 990	560, 000
2	200	600	0. 990	360, 000
3	200	400	0. 985	250, 000

Table 3. Optimal values of β_d^{jh} and comparison with peak-shaving.

HYDRO TYPE / TIME	MINIMIZATION ALGORITHM 1	2	3	PEAK-SHAVING 1	2	3
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	0.4814	0.0902	0.4571	0.6619	0.1288	0.4773
3	0.0516	0.0000	0.1845	0.0000	0.0521	0.4773
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0091
5	0.1871	0.0000	0.2767	0.0581	0.1288	0.4773
6	1.0000	0.8899	1.0000	1.0000	0.6703	0.4773
7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
⋮		⋮			⋮	
24	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
GENERATED ENERGY [GWH]	560.00	360.00	250.00	560.00	360.00	250.00
TOTAL ENERGY [GWH]	15015. 22			15015. 22		
TOTAL COST [$1000]	249772. 59			249778. 54		

4.2 Result and Comparison with Peak-Shaving

Table 3 compares the resultant values of the β 's computed by the minimization algorithm with the result of the peak-shaving algorithm. They are almost same but slightly different at the peak-shaving level. The difference is shown in Fig. 2 & 3.

According to the peak-shaving operation as in Fig. 3, a change in the loading order among the hydro plants 1, 2, 3 gives a different values of the β 's. But, it is reasonable that the loading order among them have little effect on the values of the β 's. The minimization algorithm used in this paper gave the same result from two loading orders among the hydro plants.

The fuel cost of the algorithm is less than that of peak-shaving as shown in Table 3.

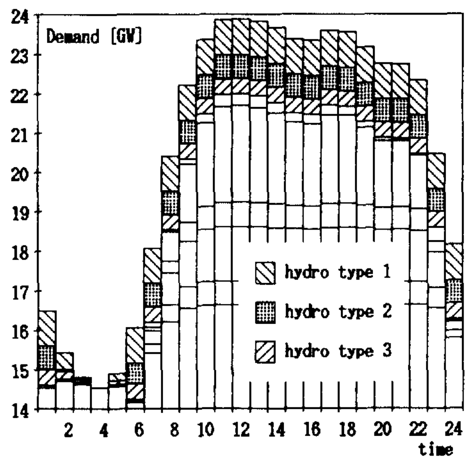

Fig. 2. Power generation by the hydro plants. Result of the minimization algorithm.

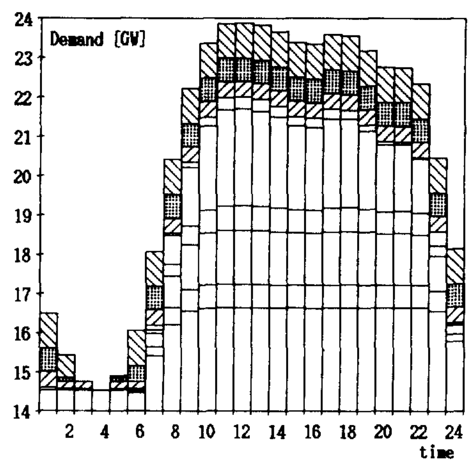

Fig. 3. Result of the peak-shaving algorithm.

5. Conclusion

This paper presents a new algorithm to evaluate the production cost for a generation system including energy-limited hydroelectric plants with the following conclusions :

1) It is more rigorous for the hydro plant operation to be solved as a minimization problem itself rather than as a peak-shaving operation. The fuel cost is really minimized to the value less than the cost obtained by peak-shaving.

2) The new version of the gradient projection method is very efficient for solving the hydro problem, and will be extensively used to the optimal long-range generation expansion planning.

3) Sensitivity analysis of the gradient projection method will give useful information for the marginal investment cost.

4) This model and the pumped storage operation model will be combined into a whole production costing model in the future.

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