STORAGE PLANTS ENERGY OPTIMIZATION IN PROBABILISTIC PRODUCTION COST MODELS

Andrés Ramos

UNIVERSIDAD PONTIFICIA COMILLAS
Alberto Aguilera, 23
28015 Madrid, SPAIN

José Arrojo

CIDESPA
Bravo Murillo, 203
28020 Madrid, SPAIN

Abstract - This paper presents a new approach called *energy marginal analysis* to improve the current optimization algorithms of storage plants energy usage in probabilistic production cost models. The proposed algorithm determines the optimal reservoir utilization levels for multiple storage plants under given charging and discharging orders. This algorithm is applied when the optimal reservoir utilization of an storage plant is limiting the reservoir utilization of the following plants in the loading or offloading order.

The combinatorial nature of storage plants loading order problem is discussed and several criteria to obtain an initial loading order are examined. Counterexamples show that none of the initial loading orders proposed and analyzed gives the global economic optimum.

Keywords - *production costing, probabilistic model, pumped hydro, storage units, storage energy.*

1. INTRODUCTION

Probabilistic production cost models are widely used by many electric utilities in different functions of midterm operations planning (i.e., maintenance scheduling, hydrothermal coordination) and long term generation expansion planning (i.e., long range fuel contracts, new technologies evaluation). These models have attracted much attention since their appearance in 1967. Multiple-block treatment of thermal units, multiple hydro and storage units have been successively introduced into the models, see [2], [5], [18], [9], and [10]. Besides, recent analytical approximations to the load duration curve (method of cumulants [15] and [16], Esscher's large deviation approximation [17], discrete convolution [11], mixture of normals approximation [14], segmentation method [1], etc) have added new possibilities to the models. So they can now be integrated into automatic long term generation expansion planning tools where production costing is extensively required.

Storage units operation can only be modeled reasonably if the study period is as short as pumping/generation cycle, such as a day or a week in most cases. Otherwise, nonsensical results could be obtained. Chronological production cost models are also used very often to simulate storage units operation. However, they are not designed to obtain the optimal reservoir utilization levels but to check or simulate the feasibility of different energy storage policies.

In probabilistic production cost models storage units were firstly dispatched at fixed and priorly known energy, see [8]. The amount of energy to be pumped and generated by storage units was specified by the user. The model determined which thermal units would provide the specified charging energy and which units would be offloaded by the generating side of storage plants. Later, several methods have been developed and implemented to address the energy optimization problem of multiple storage units for a given loading order, see [3], [4], [12], and [13]. Their theoretical basis is explained in section 2. A new method has been recently proposed, see [6], to improve the computational efficiency of previous methods by exploiting the piecewise nature of the cost function. The issue is particularly important in systems with a large number of storage units and critical when used in generation expansion planning models.

Aforementioned methods assume that optimal reservoir utilization levels for storage plants are mutually independent. This is not longer true and additional order constraints should be included into the models for realistic dispatching of storage units. Precisely, the optimal reservoir utilization level of an storage plant can influence optimal levels of the following plants in the loading order, since none of these levels can exceed the deconvolution point of previous plants. This issue is presented in section 3.

To the authors knowledge, current methods do not take into account the possibility of improving the "optimal" solution when several storage units are charged or discharged till the same deconvolution point of the same marginal thermal unit. In that case, further improvement can be achieved doing an *energy marginal analysis*. Such case can occur because of the similarity in efficiency and capacity factors of storage units in a power system. This topic is analyzed in section 3 and a new method is proposed to obtain additional economic profit when this situation appears. The method proposed in this paper, *energy marginal analysis*, can be easily included in any of the current approaches as an improvement of the "optimal" reservoir utilization levels.

Despite these refinements a key point remains unsolved: storage plants loading order has to be given a priori. Therefore, criteria to attain the loading order that provides the global economic optimum are needed. They must guarantee optimality conditions and avoid oscillatory solutions. Several criteria for initial loading orders are studied in the paper and none leads to the global optimal loading order. That issue is discussed in section 4.

The complexity and importance of the combinatorial problem of storage plants loading order is shown in section 5. The problem of finding the optimal loading order remains still unsolved and is under investigation.

The problem of storage plants energy optimization is very complex and will be presented in an intuitive manner. Everywhere examples are shown.

2. CURRENT ALGORITHM

The most widely used method for storage plants energy optimization with a previously known loading order is based on the computation of the piecewise benefit-cost curve. This curve is composed of two independent stairs, as represented in figure 1. The descending stair is obtained by evaluating the benefit associated with the potential energy produced by an storage unit, when the same amount of thermal energy is substituted. The y axis represents the marginal value of substituted energy (marginal benefit of discharging) and the x axis represents the cumulative substituted energy. The ascending stair is obtained by evaluating the cost associated with the potential energy consumed by an storage unit. The y axis represents the marginal cost of pumped energy (marginal cost of charging) and the x axis the cumulative pumped energy. To represent together both stairs it is necessary to plot them from the same point of view. Because of the charged and discharged energy of an storage unit are related by its cycle efficiency it will be necessary to adjust one of both. As represented in figure 1, the ascending stair has been adjusted. It means that pumping variable cost is divided by cycle efficiency and pumped energy is multiplied by cycle efficiency.

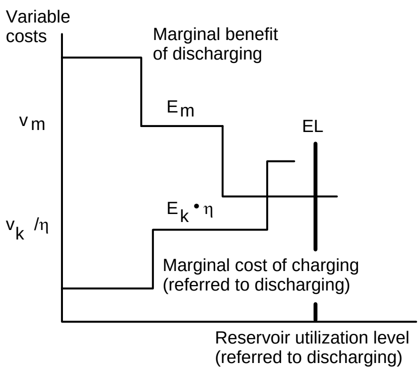

Figure 1. Piecewise benefit-cost curves.

Area between the two stairs represents total net benefit for a certain amount of energy pumped (and generated) by an storage plant. Their intersection provides optimal reservoir utilization level for that storage plant. No additional benefit can be obtained by pumping more energy. This energy level certainly has to be less than the storage plant reservoir limit (EL). Three different situations can appear in the intersection point computation:

- *charging*
- *discharging*
- *reservoir limit constraining*

The first situation is reached when no extra profit can be obtained from pumping more energy (as presented in figure 1). The second situation implies that it is not profitable to substitute additional energy from thermal plants. Finally, in the third situation there is not intersection point before the reservoir limit and, therefore, this is binding.

This method is exact when there is only one storage plant. However, if there are multiple storage plants the solution becomes rather cumbersome.

The natural extension of this method to deal with multiple storage units is to compute the piecewise benefit-cost curve and to evaluate independently the intersection point for each storage plant. A detailed description can be found in [7] and [12]. It should be noted that the computation of the piecewise benefit-cost curve for each storage unit depends on the chosen storage plants loading order and therefore the optimal solution too.

3. ORDER CONSTRAINTS AND ENERGY MARGINAL ANALYSIS

Current algorithm is based on the independence of the computation of optimal reservoir utilization levels for storage units. Then, exclusively loading order becomes important. Besides, two additional energy constraints for storage plants should be considered: convolution and deconvolution order constraints energy limits, imposed to avoid modifying the storage plants discharging and charging orders. These orders are based on the different utilization hours of storage plants, see [6]. That ranking is a necessary condition to keep unchanged the loading order. However, it is not a sufficient condition to guarantee that an storage plant pumping load is deconvolved before the pumping load of another storage plant previous to it in the loading order. Deconvolution points where charging process of each storage unit stops should also be ranked in reverse order that the units. Their exact deconvolution and convolution points should be computed.

To analyze the problem of storage plants energy optimization the following simple power system is used. The load duration curve (LDC) is trapezium shaped with a maximum demand of 1800 MW and a minimum of 800 MW (figure 2). The system is composed of only thermal units (table 1) and two storage plants (table 2). For simplicity, all thermal units are supposed to be perfectly reliable. The time period is 100 hours.

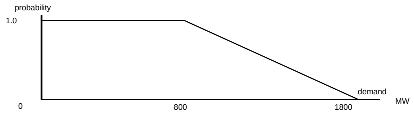

Figure 2. Load duration curve.

Thermal plant	Capacity (MW)	Variable costs ($/MWh)
THRM1	300	20
THRM2	300	40
THRM3	300	60
THRM4	200	80
THRM5	200	100
THRM6	200	120
THRM7	200	140
THRM8	200	160

Table 1. Thermal units characteristics.

Storage plant	Pump&Gen capacity (MW)	Cycle efficiency p.u.	Availab p.u.	Energy limit (MWh)
STOR1	200	0.75	0.9	∞
STOR2	200	0.9	0.75	∞

Table 2. Storage units characteristics.

The loading order STOR1-STOR2 is chosen. The dispatch of thermal plants under the LDC and storage units above the LDC is presented in figure 3. The piecewise benefit-cost curves for storage plants STOR1 and STOR2 are presented in figure 4a and 4b. Figures in y axis correspond to thermal variable costs and those over the segments of the piecewise benefit-cost curve to thermal energy charged or discharged. If the energy constraint imposed by the first unit is not considered the optimum will be greater but the units dispatch would be incorrect, as presented in figure 3. The deconvolution point of STOR2 exceeds the deconvolution point of STOR1 in both sides, pumping and generating.

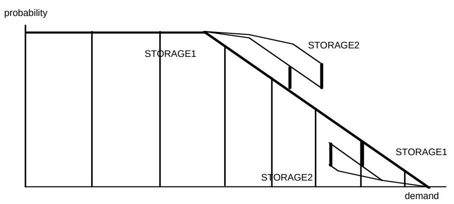

Figure 3. Thermal and storage plants dispatch.

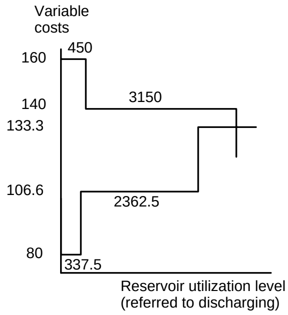

Figure 4a. Piecewise benefit-cost curve for STOR1.

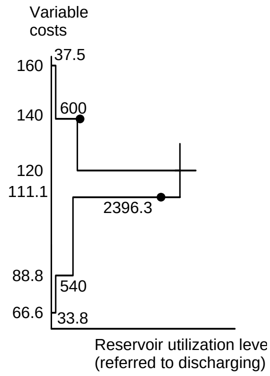

Figure 4b. Piecewise benefit-cost curve for STOR2. Black dots represent the limits imposed by STOR1 in their pumping and generating sides.

The condition to begin with the *energy marginal analysis* to improve the "optimal" solution obtained by current methodology is the following:

one or several storage plants (in priority positions of the loading or offloading order) at their optimal energy reservoir utilization levels are constraining the levels of one or several of the following storage plants (not reaching their optimal points) in the loading or offloading order.

Let us suppose that storage units are enforced to produce a little amount of energy. This will cause economic benefit if the cost of surpassing the intersection point for unit STOR1 is less than the profit obtained by pumping additional energy with unit STOR2. The condition to continue with the *energy marginal analysis* is the following:

the sum of net marginal benefits of all the storage plants at their current reservoir utilization levels should be positive.

In other cases the energy marginal analysis does not attain any additional benefit over the optimal solution obtained by current method for a given storage plants loading order.

An example showing the solution improvement by using the energy marginal analysis is presented in section 5.

4. INITIAL LOADING ORDER

In determining the initial loading order of storage plants several data are directly implied:

- cycle efficiency η
- pumping availability p^P
- pumping capacity C^P
- generating availability p^G
- generating capacity C^G
- reservoir energy limit (referred to discharging side) EL

Several criteria to build the initial loading and offloading orders are analyzed. None of these criteria gives the economic optimum. Counterexamples are shown. The same LDC and thermal plants of previous example are used.

i. Utilization hours depending on reservoir limit.

In the optimal solution, storage plants in loading and offloading orders are ranked by utilization hours. However, optimal energy pumped and generated is unknown a priori. If all the reservoirs were filled till or close to their energy limits, this order would be a good initial guess.

The computation of utilization hours for an storage plant will be:

$$H_P = \frac{EL/\eta}{p^P\, C^P}$$

used to compute the loading order and

$$H_G = \frac{EL}{p^G\, C^G}$$

used to compute the offloading order.

Let us suppose the following data for the two storage plants (example 1):

Storage plant	Pump&Gen capacity (MW)	Cycle efficiency p.u.	Availab p.u.	Energy limit (MWh)
STOR1	200	0.75	1	2900
STOR2	100	0.8	1	1500

The initial loading order according to utilization hours will be STOR2-STOR1. However, the economic benefit obtained by loading storage plants in reverse order is greater.

ii. Utilization hours depending on typical or historical data.

That estimation would be heuristic. Reservoir utilization hours are evaluated with data of historical or expected use and loading and offloading orders built.

This criterion would be of uncertain use if data are unavailable or the utility is changing the utilization policy of storage plants, because of an increase in nuclear power for example.

iii. Cycle efficiency.

Cycle efficiency is an important feature to elaborate the loading order, because it determines the forbidden range of thermal units variable costs, i. e., the minimum interval between thermal units variable costs causing profit in pumping/generating process. Better cycle efficiency smaller forbidden range. Therefore, storage plants will be charged in decreasing cycle efficiency order.

The same data of example 1 are taken excepting their energy limits, that now become infinite (example 2).

With this example the results for the establish order are correct. Later on the paper, in section 6, we will see a counterexample.

iv. Product of cycle efficiency and availability.

In previous examples, for simplicity, we have studied only units with no unavailability. Now the effect of unavailability in storage plants is analyzed.

It could be thought that two storage plants with the same product of cycle efficiency and availability would have the same opportunity to be in the loading order, but the following example shows the opposite.

The same data of the example presented in section 3 are taken.

The economic benefit with the STOR2-STOR1 loading order is greater than the reverse.

v. Special case.

There is an special case that invalidates all these criteria: when two storage plants are exactly equal.

It would be possible that the benefit obtained were the same if two storage plants were dispatched independently that if dispatched together as one equivalent unit. However, this counterexample shows that charging them together causes more benefit.

Let us suppose the following data for both storage plants (example 3):

Storage plant	Pump&Gen capacity (MW)	Cycle efficiency p.u.	Availab p.u.	Energy limit (MWh)
STOR1	200	0.8	1	∞
STOR2	200	0.8	1	∞

Storage plants clustering causes benefit although the two storage plants are not exactly equal and certainly it should be taken into account in production cost models. Cluster of two storage units means that both plants split each other. To determine when it is economically interesting to build a cluster of two or more storage units is an important question in storage plants energy optimization.

The selection of the initial orders become even more complicated when pumping and generating capacity of storage units are different, because conflicting cases can appear in both loading and offloading orders among different thermal and storage units.

5. LOADING ORDER PROBLEM

To study the combinatorial nature of storage plants loading order problem a more complex case study will be used. A hypothetical electric power system derived from EPRI northeast region is considered. The electric system is composed of 31 thermal units and 4 storage plants whose data are described in table 3 and 4 respectively.

	Nuclear	Coal	Oil	Gas
Number of units	3	5	8	15
Capacity (MW)	1400	900	850	300
Unavailability (p.u.)	0.132	0.050	0.040	0.080
O&M Var Cost ($/MWh)	1.7	1.1	1.4	3.2
Fuel Var Cost ($/MWh)	7.383	55	77	77

Table 3. Thermal units data.

	STOR1	STOR2	STOR3	STOR4
Capacity (MW)	200	200	200	200
Unavailability (p.u.)	0.06	0.06	0.06	0.06
Energy Limit (GWh)	500	500	500	500
Cycle efficiency (p.u.)	0.85	0.80	0.76	0.74

Table 4. Storage units data.

Load duration curve has a minimum and maximum demand of 1600 MW and 20000 MW respectively and its shape resembles the complimentary normal distribution function.

A complete dispatch of the thermal power plants with all the loading order combinations was done, representing the 24 combinations (4 !) of the 4 storage plants. The first combination corresponds to storage plants ordered by decreasing cycle efficiency and the following are obtained doing binary changes in the loading order. 1234 means a loading order STOR1-STOR2-STOR3-STOR4 respectively.

1234	1243	1324	1342	1423	1432
2134	2143	2314	2341	2413	2431
3124	3142	3214	3241	3412	3421
4123	4132	4213	4231	4312	4321

The net economic benefit for each storage units order combination is obtained for three different cases and represented in figure 5:

- "optimal" solution under current algorithm, that assumes independence among optimal storage plants reservoir utilizations (upper piecewise function)
- including order constraints, evaluating exactly the deconvolution and convolution points (lower piecewise function)
- doing an energy marginal analysis when profitable from previous solution (middle piecewise function)

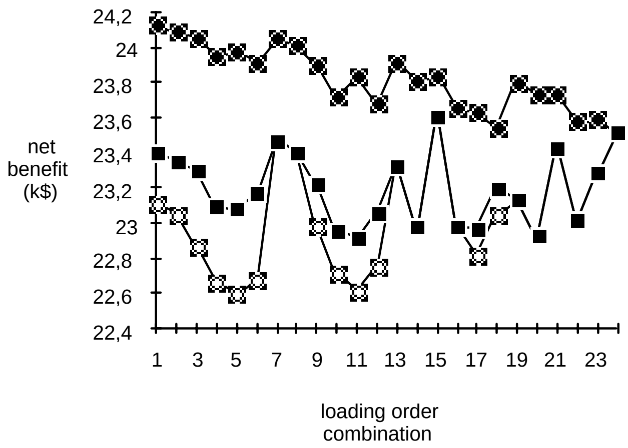

Figure 5. Net benefit versus storage plants loading order combination.
→ current algorithm ◊ order constraints imposed
o energy marginal analysis

Their shape is quite different and the global optimal loading order is obtained for the fifteenth combination STOR3-STOR2-STOR1-STOR4. Also from figure we see the relative impact on the net benefit that the changes in loading order positions represent and the importance that order constraints and energy marginal analysis can have in storage plants loading order problem. Variations caused by the three factors have the same order of magnitude.

In the first combination STOR1-STOR2-STOR3-STOR4, storage plants are ranked by decreasing cycle efficiency, showing a counterexample to this initial loading order criterion.

The three piecewise curves include many local optima, for example, the seventh combination STOR2-STOR1-STOR3-STOR4. These local maxima invalidate a possible binary interchange approach to reach the global optimal loading order. Enumerative, heuristic or more complex algorithms have to be analyzed to solve the optimal loading order problem.

6. CONCLUSIONS

Two key issues in storage plants energy optimization problem in probabilistic production cost models are addressed in this paper. Firstly, computation of optimal energy utilization levels of storage units given a preset loading order.

And secondly, the determination of loading order that gives the global optimal solution. Both issues are treated on the paper.

Deficiencies in the current algorithm have been detected, based on the supposed independence of the computation of optimal reservoir utilization levels for different storage units. A new method, *energy marginal analysis*, to improve the solution obtained by current methodology including the loading and offloading order constraints has been presented. This method is based on the possibility of improving the solution when certain loading or offloading order constraints are binding for several storage units.

The approach previously presented increases the knowledge about the storage plants energy optimization problem with a preset loading order in probabilistic production cost models giving a valuable skill to planning engineers.

Numerous and very simple cases are presented to study several criteria to obtain an initial loading order. None of them gives the global optimal solution.

An exploration of the combinatorial nature of the loading order problem is presented. Complete solution remains still under investigation.

The algorithm described in the paper has been implemented in a probabilistic production cost model based on the cumulants method on a IBM PC/XT (640 kB RAM) microcomputer.

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BIOGRAPHIES

Andrés Ramos was born in Guadramiro, Spain, in 1959. He received the degree of Ingeniero Industrial, majoring in Power Systems, from the Universidad Pontificia Comillas, Madrid, Spain, in 1982.

From 1982 to 1984 he was a junior research staff at the Energy Group of the Instituto Tecnológico para Postgraduados. From 1984 up to now he is a senior research staff at the Instituto de Investigación Tecnológica in Generation and Transmission Planning Group.

His major areas of interest cover applications of operations research in reliability and maintainability engineering of power plants, in optimization of operations and planning of electric power systems.

José Arrojo was born in Madrid, Spain, in 1965. He received the degree of Ingeniero Industrial, majoring in Power Systems, from the Universidad Pontificia Comillas, Madrid, Spain, in 1989.

From 1989 to date he is a junior staff in CIDESPA in Power Systems studies.

His area of interest is optimization of operations and planning of electric power systems.