HYDROENERGETIC SYSTEMS

BY

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ABSTRACT -- It is presented an overview of the methods used for energy and power supply reliability studies. In particular it is focused the equivalent reservoir modeling and the dependence of power availability of hydro systems to the operation of the reservoirs.

INTRODUCTION

A hydroenergetic system for generation of electric energy is composed of a thermal system (conventional thermal and/or nuclear plants) and a hydro system, linked to the load centers through the transmission lines.

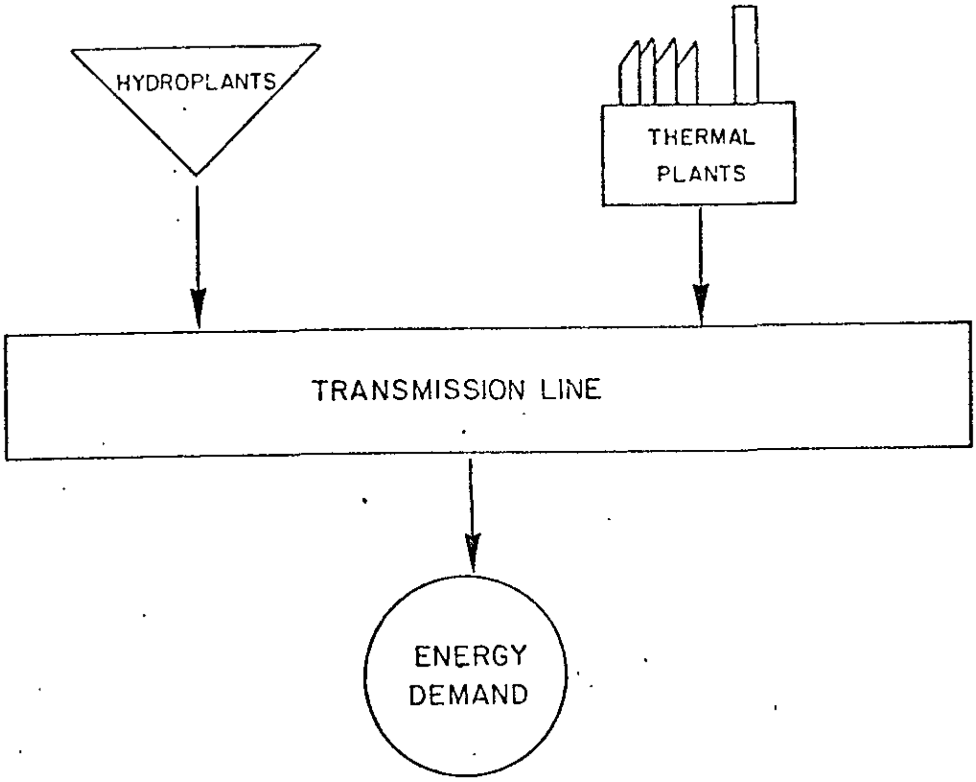

Figure 1 : Schematic Representation of a Hydroenergetic System

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The Brazilian hydrothermal system is predominantly hydro : 95% of the generation output in 1981 (of the order of 140 Twh) was produced by hydroplants and 85% of the installed capacity (of the order of 30 GW) was hydro. Although the thermal system is comparatively small, it plays a critical role regarding operation cost and reliability of the hydrothermal system as a whole.

Thermal plants burn expensive fuel to heat the water into vapor, which is used to move the turbines. On the other hand, the direct operating cost of the hydroplants can be neglected, since in this case the "fuel" is plain water, which the river supplies free of charge. However streamflow input to the plants is a stochastic process and if at the begining of a "dry sequence" one does not have enough stock of water in the reservoir system, it is quite possible that before the end of this sequence the stock will be null. In this case the energy demand will not be met, even if one turns all the thermal units on.

Engineers in charge of the system operation planning have to decide periodically, say at each month or week, whether they produce a higher energy output from the thermal plants, with imediate cost, or produce this output depleting the water stock. In the first case the water kept in the reservoirs may be used in the future in the event of a "dry sequence". This eventually means that the energy demand will be met and else, the most expensive thermal units will not be turned on. On the other hand, if it comes a "wet sequence", rather than a dry one, some of the reservoirs will eventually spill and the amount of money used to pay the fuel could simply be saved.

Since it is impossible to have perfect forecasts of the future inflow sequences, the operation problem is essentially stochastic. For systems provided with reservoir with large regulating capacity, the time horizon of the operation planning may be of several years. In the brazilian case, it is tipically used a five years horizon (sixty monthly stages). The mass conservation of water inputs to and output from the cascaded reservoirs, and the water flow and power constraints of each hydroplant, impose a multitude of restrictions and links between the problem variables. It can be said that the operation planning problem is :

(i) stochastic;
(ii) multiple periods;
(iii) multiple reservoirs.

There are several papers in the literature that tackle the problem by relaxing one or two of these features. Yeh (1982) gives a comprehensive state-of-the-art survey of these techniques. Pereira and Pinto (1983) have recently developed a new approach to the problem, based on decomposition techniques for optimization, that deal simultaneously with the three features.

Since the operating cost for a time interval depends on the difference between the energy demand and the total hydro production, a reasonable way of approaching the problem is by lumping all the real reservoirs into a single ideal reservoir, the so called "equivalent reservoir". Treating the problem as stochastic, multiple period and single reservoir, one can develop a strategy that gives for each time interval and state of the system (more precise difinitions will follow) the partitioning between hydro and thermal production.

Once a strategy for operating the equivalent reservoir is available, one can perform simulation studies to assess the energy reliability, effect of delays in the construction of new plants, shortage of fuel, etc..

The equivalent reservoir representation is reasonable if all the hydroplants are subjected to the same hydrological conditions. In this situation one can expect that the reservoir storages will evolute in a similar way, that is, if one of the reservoirs is spilling water it is likely that all of them will be also in the same condition and it is said that the equivalent reservoir is spilling energy. The same kind of reasoning can be made with regard to the emptying of the reservoirs.

Another condition the system must fulfill to make the equivalent reservoir a reasonable model is the perfect integration of the electric network. In other words, it is assumed that there are no constraints to route the power produced by any plant to the consumption centers.

There are situations when clearly the equivalent reservoir model is not appropriated. For example, the South and Southeast of Brazil have quite different hydrological conditions and their electrical networks are linked through a transmission line with limited capacity. Since the amount of energy to be exchanged between the two subsystems is in this case as much important as the bulk thermal production, one approach to the problem is to adopt two equivalent reservoirs, explicitly taking into consideration the transmission line. This approach leads to the problem of how to operate reservoirs in paralell, which can also be generalized to more than two subsystems. Again, once a strategy for operating the reservoirs in paralell is available, one can perform simulation studies to assess, for example, the worth of the transmission line, measured by the difference in the reliability of energy supply for the entire system when there is and there is not the line.

Since the availability of peak offer is a function of the available head, the power supply reliability studies are better done if one adopts a multi-reservoir model which represents in detail all the plants and reservoirs, as well as the relationships among the variables. This type of model splits the total hydro production, defined by the single equivalent or n-paralell equivalent models, among the hydroplants. At each month this can be accomplished by assuming that the reservoir inflows are known, which makes the problem deterministic, single period (only the present time interval is considered) and keeps the multiple reservoirs feature of the original formulation.

The multiple reservoir model can be used in simulation studies to assess not only the power reliability but also the power interchange between the utilities and expected fuel consumption. These simulation studies are developed for different hydrologic scenarios, usually represented by synthetic traces produced by stochastic streamflow models. The simulation model itself may be just the recurrent application of the single period optimization model or more simply a plain simulation tool that put together the rule curves and the filling and emptying priorities of the reservoirs, which are derived from operation experience and/or empirical methods.

ENERGY RELIABILITY STUDIES

The Single Equivalent Reservoir Model

The representation of a hydro system as one energy-storage reservoir was first suggested by Gilbreath and Brudenell (1959). Early studies of power development in Brazil [Canambra, 1966] and the Columbia power system operation [Arvaniditis and Rosing, 1970] were also based on this concept.

The value of storage in a hydro power system depends on the total developed head downstream of a site. Therefore the total storage capacity of this system must be expressed in terms of the energy content of this storage rather than the storage water volume. Since the water head in each plant is a function of its reservoir level, the total energy produced by the system will depend on the operation rules. A simplified operation strategy is thus assumed in this model in order to transform all stored volumes into energy. A similar procedure is used to evaluate the energy content of the water inflows to the plants. Further details are described by Terry et al (1980).

The optimal operating policy is calculated with a dynamic programming recursion. The monthly control is a function of two states variables:

- Stored energy in the equivalent reservoir
- Hydrological trend, represented by the energy inflow in the previous month. The stochastic model supplies the distribution of inflow in month k conditioned by the inflow in month k-1.

In the beginning of month k ($k = 1,2,\ldots, h$, where h is the length of the period), the following values are known (see figure 2):

- Stored energy EA_k
- Energy inflow during month k-1, EAF_{k-1}
- Energy load L_k.

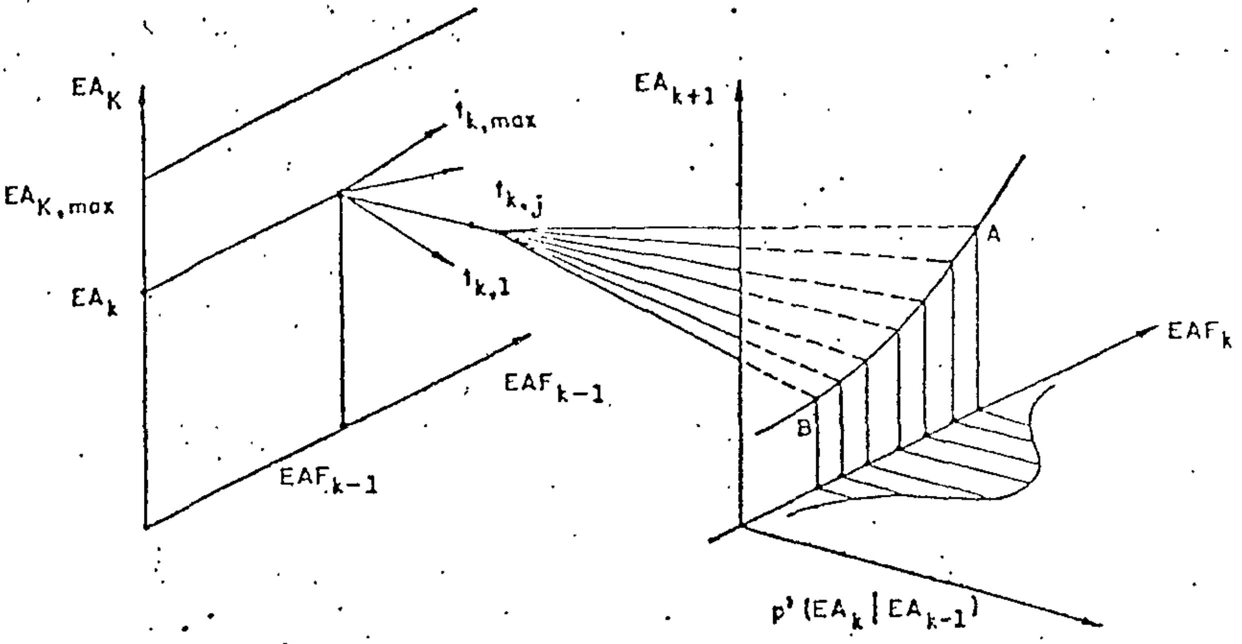


Figure 2 : State Transition From Stage K to Stage K+1

The control variable is the thermal generation. After choosing the j^{th} thermal option $t_{k,j}$, the system will try to meet the load with the hydro units, that is:

$$H_k = L_k - t_{k,j}$$

The final state of the reservoir, EA_{k+1}, is then a function of EAF_k, the energy inflow during month k:

$$EA_{k+1} = EA_k + t_{k,j} - L_k + EAF_k \tag{1}$$

The probability distribution of EAF_k is conditioned by EAF_{k-1}, which is also known; curve AB in figure 2 shows the possible states in the beginning of month k+1, represented by $\{EA_{k+1}, EAF_k\}$.

The expected future cost associated with decision $t_{k,j}$ and state $\{EA_k, EAF_{k-1}\}$ is

$$f_k(EA_k, EAF_{k-1}, t_{k,j}) = C(t_{k,j}) + \{f^*_{k+1}(EA_{k+1}, EAF_k) \cdot \frac{1}{1+\alpha} + \tag{2}$$

$$+ d(EA_k, EAF_k, t_{k,j})\}$$

where:

$C(t_{k,j})$ is the cost of thermal decision $t_{k,j}$

$\{EA_{k+1}, EAF_k\}$ is the state reached from state EA_k, inflow EAF_k and decision $t_{k,j}$

$d(EA_k, EAF_k, t_{k,j})$ is the cost of a deficit resulting from state EA_k, inflow EAF_k and decision $t_{k,j}$

$E(.)$ is the expected value

α is the monthly discount rate

$f^*_{k+1}(EA_{k+1}, EAF_k)$ is the expected future operating cost from state $\{EA_{k+1}, EAF_k\}$ under optimal policy.

Bellman's optimality principle states that

$$f^*_k (EA_k, EAF_{k-1}) = \min_{t_{k,j}} f_k(EA_k, EAF_{k-1}, t_{k,j}) \tag{3}$$

The above recursion is then used to find the optimal policy for all periods.

The choice of the boundary condition f^*_h is discussed by Terry et al (1980).

All variables are discretized in the model : EA_k is discretized in equidistant intervals and EAF_{k-1} in equiprobable intervals. Interpolation among neighboring states is used to evaluate f_{k+1} when $\{EA_{k+1}, EAF_k\}$ falls between points of the grid.

The process can be summarized as follows:

scan every month k of the period (backwards)

 scan the grid for EAF_{k-1}

  scan the grid for EA_k

   scan all thermal decision $t_{k,j}$

    scan the conditional pdf of EAF_k

     compute $f^*_k = \text{Min}_{t_{k,j}} f_k(EA_k, EAF_{k-1}, t_{k,j})$

The equivalent reservoir model may be used in a simulation mode. For any sequence of energy inflow, hystorical or synthetized by some stochastic model, the simulation will represent the evolution of the stock of energy in the reservoir under the strategy defined by the optimization mode and several relevant descriptors of the system may be evaluated, such as:

$$\text{Probability of} \begin{cases} \text{deficit} > \alpha L_k \\ \text{spillage} > \alpha L_k \end{cases}$$

where α - a specified proportion

L_k - the monthly load

$$\text{Expected value of} \begin{cases} \text{number of deficit events} \\ \text{number of spillage events} \\ \text{cost of generation (any thermal plant)} \\ \text{cost of deficit} \\ \text{spilled energy} \\ \text{thermal generation (any thermal plant)} \end{cases}$$

The same results may also be obtained without simulation through a Markov chain analytical approach (Pereira, et al, 1979).

The cost of deficit, $d(EA_k, EAF_k, t_{k,j})$ depends upon how one appraises the impact of deficit in the economy and in the lives of citizens. No deep investigation has ever been carried out in Brazil in this matter, reason why standard figures for the cost of deficit, existing for some countries, are not available. However, the sensitivity of the operation strategy and of the system's descriptions to variations on the unit cost may be evaluated, as described by Franco et al (1982).

The unit cost of deficit has been assumed in the brazilian operation planning as a parameter to be calibrated according with the procedure outlined in figure 3, where the system's reliability is measured by the probability of deficit.

An alternative approach has been suggested by Araripe (1983) who included in the objective function just the thermal production costs. The probability of deficit has been taken into consideration by restricting, whenever possible, the decisions in such a way that the target risk of deficit is not violated. For one particular stage and state of the system, what realy matters is

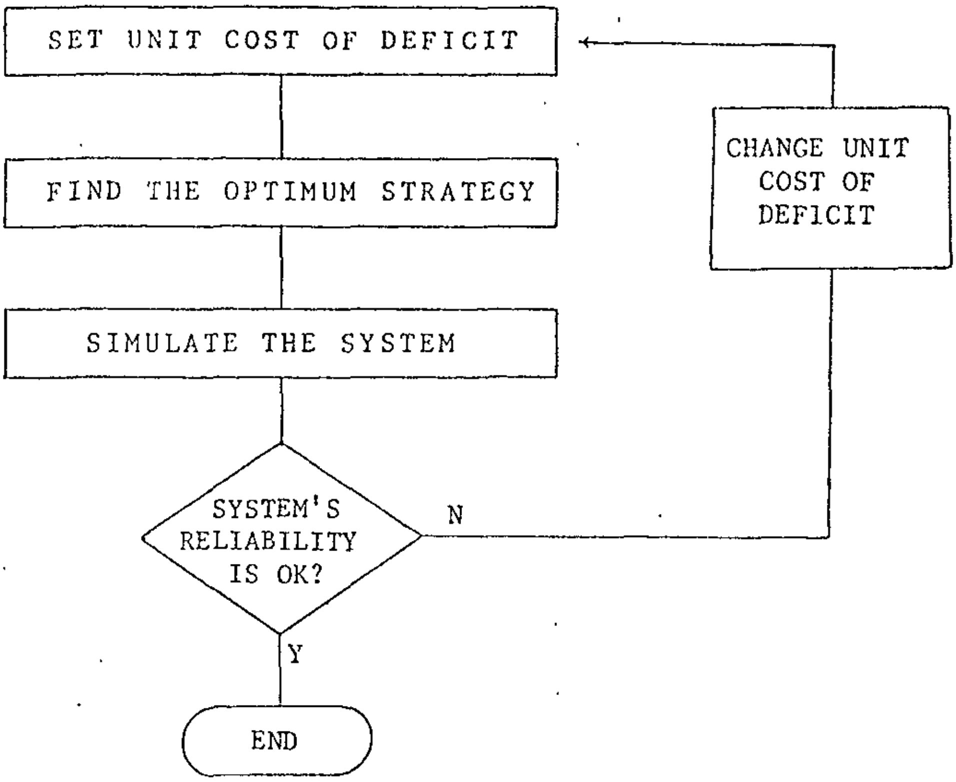
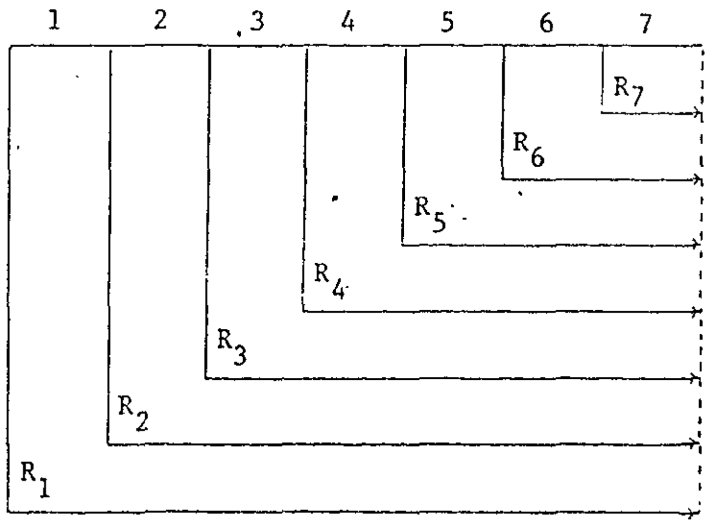


Figure 3 : Calibrating The Unit Cost of Deficit

the probability of deficit from that point in time to the end of the planning horizon, never mind if deficits have or have not occurred in the past. Based on this reasoning the reliability constraint is in fact a nested set of constraints, as shown in figure 4.



R_k = Probability of deficit in the interval from K to the end of the planning horizon

Figure 4 : Nested Reliability Constraints

This particular formulation is well suited to the dynamic programming recursion, since for a particular stage k, state (EA_k, EAF_{k-1}) and decision $t_{k,j}$, R_k depends on the values of R_{k+1} for all possible states in stage $(k+1)$, which has already been calculated in the previous step of the backwards algorithm. In other words, calculation of R_k is quite similar to calculation of $f_k(.)$ in equation 2. Any decision $t_{k,j}$ that leads to a R_k value higher than a previously defined acceptable value for stage k is rejected, unless there is not any other thermal unit to be turned on.

The n-equivalent Reservoir Model

A simple extension of the equivalent model to the n-reservoir case would imply the handling of 2^n state variables. Even for $n = 2$ this would be computationaly unfeseable.

Campelo and Coutinho (1979) have approached the problem by using a successive - approximation procedure as follows:

a) Find the optimal operating policy for each sub-system independently.

b) Simulate the simultaneous operation of all systems; generation is scheduled aiming to equalize the expected future marginal costs; power flow constraints are taken into account; both historical and synthetic energy sequences can be used.

c) Evaluate the average flow of energy for each pair of systems for each month of the simulation.

d) Subtract from the load for each system for each month the net average flow calculated in (c).

e) If convergence criteria is not met go to (a).

This method is not exact only because the future marginal costs are calculated without due consideration to the interchange of energy between the sub-systems.

Silva (1981) has neglected the energy inflow to the equivalent reservoir in the previous month as a state variable , keeping just the stored energy.. In this way a two-systems case can be solved by a dynamic programming approach. Silva recognized that with this approach the available information at stage k would not be properly used. In fact if the energy inflow to the reservoir was a markovian stochastic process the previous month inflow would be the only information needed to define the conditional probability distribution of present month inflow . Since the markovian assumption on a monthly basis can hardly ever be accepted, Silva has calculated the future expected cost, for each stage for state , through the help of streamflow synthetic sequences, produced by any stochastic model , not necessarily of a markovian type.

Costa, Pereira and Kelman (1983) have studied the relationship between stored energy and previous month inflow energy for a fixed expected future cost. They found out that this relationship is often represented by a straight line, which means that a new state variable, a linear combination of the two former state variables, can be used, with substancial reduction of computational requirements. This approach can be extended to the two sub-systems problem, since only one state variable would be used for each one of them.

Araripe (1983) has adopted an iterative approach to the two sub-systems problem analogous to the one proposed by Campelo and Coutinho (1979). However, the joint simulation is made taking into account the probability of deficit in each sub-system rather then the expected future marginal costs.

It can be seen that the n-equivalent reservoir model is a topic still under study. Engineers in Canada and Norway, countries with power production of predominantly hydro origin, are also working on this issue. For example Egeland et al (1982) describe the power pool model adopted in Norway which is quite similar to the one proposed by Campelo and Coutinho (1979). Turgeon (1980) optimizes each reservoir in conjunction with the aggregate representation of the remaining system. This technique, which has been applied to the canadian system, requires no iterations. It is very relevant because of the reduction of the n-subsystems problem to the two subsystems problem.

POWER RELIABILITY STUDIES

Classical LOLP (Loss of Load Probability) evaluation methods were originally developed for systems with a high proportion of thermal units. Since the available power in such plants depends only on forced outages, LOLP is usually represented as a function of peak load distribution and the forced outage rate of each unit.

The available power of a hydro plant is a function of its water head, i.e. the difference between its forebay and tailwater elevations. The tailwater elevation is a function of the plant outflow and of the storage of the reservoir immediately downstream. Available power in a hydroelectric system is therefore a multivariate random variable which depends on both past inflows and operation policy.

Figure 5 gives an idea of the importance of this effect even when outages are not considered : it shows the evolution of the total available power over 2000 months of simulation of the Brazilian system planned for 1987. It can be seen that the loss of available power reaches 5000 MW (12.5% of total installed capacity in 1987). This is not the worst example because Itaipu, which accounts for 12600 MW (30%) of this total capacity suffers no loss of head due to either reservoir depletion (it is operated as a run-of-the-river plant) or to tailwater elevation. For other systems, the total reduction can go up to 20%.

The effect of reservoir operation can be taking into account by using a mixed simulation/analytical approach which represents operation of the reservoirs in detail and at the same time avoids the use of very large samples typical in Monte Carlo studies.

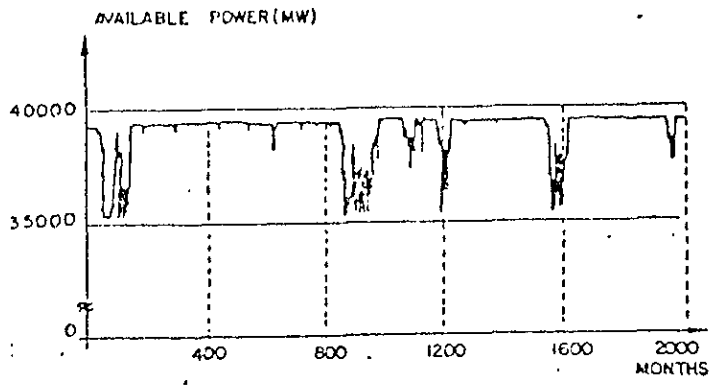


Figure 5 : Evolution of the Available Power in the South/Southeast System

This approach can be divided in two steps, as reported by Cunha et al (1982)

a) Simulation of system operation to obtain samples of the joint distribution of available power.

b) Application of classical LOLP evaluation methods to each sample.

LOLP is estimated as $\frac{1}{N} \sum_{i=1}^{N} LOLP_i$, where N is the number os samples and $LOLP_i$ is the LOLP of each sample.

The simulation model represents in detail all the hydro plants in the system. Monthly operation is close to the "real" operation policy. For a given sequence of inflows, the simulation step produces the "trajectory" of the system, that is, the volume and outflow of each reservoir for each month and, therefore, the available power of each plant for each month.

The number of sample points is equal to the number of different inflow sequences in the simulation step. Inflows can be obtained either from historical records or generated streamflow sequences. Once the sample available power has been obtained for each reservoir for a given month of one streamflow sequence, LOLP evaluation is straightforward : LOLP is once again a function of load distribution and forced outages. Note that peak load uncertainty can be included in this step.

The mixed simulation/analytical approach has some definite advantages : Monte Carlo methods are used to evaluate the joint distribution of a random variable that is a very complex function of past history of operation and inflow; analytical methods take into account the outage distribution of the equipment. The LOLP estimation converges very fast with the sample size, that is, samples around 40 give the same result as samples of 1000.

This sample size is very small compared to "pure" Monte Carlo approaches which generally require thousands of simulations. This can be explained because the second "analytical" step enhances the "effective" sample size : for each inflow sample, a Monte Carlo method would require hundreds of additional simulations to take into account the equipment outage rates.

The LOLP values found through this methodology are very sensitive to changes in the stochastic model used to produce synthetic streamflow sequences. Pereira et al (1983) report an investment difference of up to US$ 1 billion in peaking capacity for the year of 1987 when one shifts from the use of a seasonal - auto-regressive-monthly stochastic model to an annual-auto-regressive-disagreggated-into-monthly-values stochastic model.

COMPARING ENERGY AND POWER SUPPLY RELIABILITIES

Franco et al (1982) have studied jointly the risk of load shedding due to the lack of water in the reservoirs and due to lack of power. They found, as expected, that the years on which greater energy curtailments are expected, more frequent load sheddings due to lack of power are incurred. This is predictable due to the dependence of peak capacity hydraulically available to the energy stored in the reservoirs. They also found that the expected energy not supplied due to lack of water is roughly one order of magnitude higher than the expected energy not supplied due to load shedding because of lack of power. However, as noticed by the authors "... the lack of energy and lack of power affect load supply differently. In the first case, the expected energy shortage-predictable well in advance - will give rise to a curtailment plan that dictates, possibly for months, load sheddings conveniently chosen over the daily load curve. In the second case, a lack of power capacity will result in a forced reduction of the reserve causing high probability of frequent and unpredictable load sheddings, mostly during the peak period".

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