Hydroelectric Power Plant Unit Efficiencies Evaluation and Unit Commitment

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Abstract – This work presents a methodology developed to obtain the unit commitment in hydroelectric plants. The methodology consists of three different stages, namely: definition of the system monitoring variable, unit efficiency evaluation, and unit commitment algorithm establishment. The efficiency of the proposed methodology was verified using a pilot project developed together with a hydroelectric plant having a capacity equal to 348 MW.

Index Terms- Efficiency Evaluation, Hydroelectric Power Plants, Quantitative Methods, Unit Commitment.

I. INTRODUCTION

The Brazilian national grid, usually referred to as SIN, can be considered particular in terms of size and other characteristics. It is composed by an hydrothermal system with strong predominance of hydroelectric power plants and the presence of multiple generation agents. In 2005, the capacity reached by SIN was approximately 91 GW from which 71 GW corresponded to hydroelectric power plants, 18 GW to thermal plants and 2 GW to nuclear power plants.

A hydrothermal system having characteristics and proportions of this kind needs to follow and assure the load behavior based on the hydroelectric generation and leaving almost constant along the day the thermal generation, unless system restrictions occur. Currently, the operation and dispatch planning is done by ONS (the Brazilian Independent System Operator). This operator requires a historical data sequence of river water discharges that allow annual, monthly and pre-operational planning.

In order to elaborate a daily schedule and planning, the operator sends a proposal to all the generation agents according to the load level (in an hourly basis). This is done based on the monthly and weekly planning guidelines and regarding aspects such as the load adjustments and affluences as well as electric and generation restrictions. In some cases, the operator demands from the generation agent a fixed number of units (greater than the necessary) to operate. The objective of this request is to reach pre-determined levels of reserves and/or support the system stability.

In the last decade, the Brazilian national grid has gone through a restructuring process which resulted in the deregulation and free access to the network. The new needs and changes imposed to the electrical sector urged the generation agents to have a greater interest for improving the efficiency of their generation units. This higher interest is directly related to the reduction of the operation and maintenance costs as well as to the increased energy commercialized.

Therefore, the optimized dispatch of the generation units becomes an important tool that necessarily has to go through the adoption of a performance criterion [4-5,9]. In thermal plants, a performance criterion normally used is the fuel cost minimization. However, in hydroelectric power plants the generation cost is more complex due mainly to the interaction among plants, this requires a specific form to treat the problem [7-8].

Although there has been an increase for searching a higher operative efficiency in generation units, most of the Brazilian hydroelectric power plants do not have water discharge local measurements, thus, only the water levels and the active power generated are measured. If needed, the efficiency values determined during the reduced model analysis are used. Another aspect to be discussed is the fact that the operative policies of the agents are based on the operators experiences which result in some operative restrictions imposed to the generating units. Sometimes such restrictions are due to the lack of specific tools for the dispatch of those units.

These factors impose difficulties to the optimized dispatch of the units inside a plant, thus resulting in a higher water consumption to fulfill the same energy demand.

In this work, a methodology to obtain an optimized dispatch of generation units in a hydroelectric plant, is presented. Such a methodology can be divided into three main stages, namely: the variables monitoring system definition, calculation of actual efficiencies, and the development of an optimal dispatch algorithm for the hydroelectric units.

The effectiveness of the proposed methodology was analyzed through a pilot project which included a hydroelectric plant with 3 generation units having a total installed capacity of 348 MW.

This work is organized as follows: Section II presents the formulation of the methodology and it is divided in three parts. Part II(A) presents the monitoring system proposed. Part II(B) presents the efficiency evaluation theory used for the generating units. Part II(C) presents the optimal dispatch problem formulation (unit commitment). Section III presents the tests and results obtained. Finally, Section IV presents the main conclusions of the work.

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II. PROPOSED METHODOLOGY

The proposed methodology is composed by three main stages, they are: definition of the monitoring system variables, efficiency evaluation and unit commitment.

A. Monitoring System

This first stage of the work presents the definition of the system that will allow the real time monitoring of the variables related to the proposed methodology.

The monitoring system variables are composed by a set of acquisition data instruments, a communication network, the supervisory system and an information database.

Figure 1 shows the sequence of the defined system aimed to monitor the problem variables.

![Proposed monitoring system](image)

The monitored variables are: active power, reactive power, water discharge, water head, gate opening and runner blade opening.

B. Efficiency Evaluation

The evaluation of the hydroelectric plant efficiency can be modeled in different ways, depending on both the available data and the desired accuracy imposed to the model. For long-term studies, with monthly discretization intervals, a constant value of \( \eta \) (equal to an average efficiency) is usually adopted.

Models regarding the operation of a hydroelectric plant having shorter discretization intervals, such as days, hours or real time, should consider the variations of \( \eta \) linked to the turbine operating conditions [10-11]. The term “Operating conditions” includes the net water head, water discharge (flow) and the power generated.

The power generated by the power plant can be obtained through (1), [1-2].

Figure 2 shows the performance curve of a Francis type turbine.

\[
p(t) = \eta \cdot \rho \cdot g \cdot h_l \cdot q(t) \tag{1}
\]

Where,

\( p(t) \) is the power generated (MW);

\( \rho \) is the specific weight of water (kg/m³);

\( g \) is the gravitational acceleration (m/s²);

\( \eta \) is the efficiency of the turbine/generator set (%);

\( h_l \) is the effective water head (m);

\( q(t) \) is the plant’s water discharge (m³/s).

Note in Figure 2 that there is a point in which the efficiency is at its maximum value. This is the point usually referred to as Project Point. Due to the reference values used to express percentages of power and effective head, the project point is the point in which power and effective head are both equal to 100%. In all other turbine operation conditions the efficiency will be less than that of the Project Point.

Figure 2 shows also that, as the effective head is increased, regarding the same opening of the turbine blades, the power generated will also be increased.

C. Unit Commitment Problem Formulation

The Unit Commitment can be formulated as an Economic Dispatch problem with the efficiency as the objective function to be maximized.

\[
\text{Max } F_T = \text{Max } \sum_{i=1}^{T} F(P_i) \tag{2}
\]

\[
s.t. \sum_{i=1}^{T} P_i - P_d = 0 \tag{3}
\]

\[
P_{\text{min}} < P_i < P_{\text{max}} \tag{4}
\]

\[
P_i \in N \quad i = 1, \ldots, T \tag{5}
\]

Where:

\( F_T \) is the objective function to be maximized. In the proposed problem, this function is represented by the plant efficiency in relation to the active power generated \( (P_i) \);

\( P_i \) is the active power generated by the \( i^{th} \) unit;

\( P_d \) is the total active power required by the power plant;

\( P_{\text{min}} \) and \( P_{\text{max}} \) are the minimum and maximum limits of generation, respectively;
The efficiency maximization of a unit, for the same active power generated, will cause a reduction in water discharge. In this way, when the unit is operating at its best efficiency, which is expected to occur during normal operation, it is said that the unit dispatch is being done in an optimized way. This point of operation is defined as the point of minimum fuel consumption for a maximum power generation.

The optimal solution for equations (2)-(4) can be obtained using Lagrangian techniques and Karush-Kuhn-Tucker (KKT) conditions. The Lagrange function for the proposed problem is presented next:

\[
L(P, \lambda, \mu) = F_T + \sum_{i=1}^{N} \lambda_i (P_i - P_d) + \sum_{i=1}^{N} \mu_i (P_i - P_{\text{max}}) + \sum_{i=1}^{N} \mu_i (P_{\text{min}} - P_i)
\]

The optimizing conditions, taking into account the proposed problem, for points \(x^o, \lambda^o, \mu^o\), are given by:

\[
\frac{\partial L}{\partial P_t} (x^o, \lambda^o, \mu^o) = 0 \quad \text{to} \quad t = 1, \ldots, N
\]

\[
(\lambda_i - \mu_i^o) (P_i - P_d) = 0
\]

\[
(P_i - P_{\text{max}}) (x^o) \leq 0
\]

\[
(P_{\text{min}} - P_i) (x^o) \leq 0
\]

\[
\lambda_i^o (P_i - P_{\text{max}}) (x^o) = 0
\]

\[
\mu_i^o (P_{\text{max}} - P_i) (x^o) = 0
\]

\[
\mu_i^o \geq 0
\]

Where \(N\) is the number of units and \(\lambda\) and \(\mu\) are the Lagrange multipliers for the equality and inequality conditions, respectively.

Should the generating units be identical, the total power generated must be equally distributed among the units in operation, so as to maximize the efficiency, thus, optimizing the unit dispatch. When the generation units are different, the active power generation is distributed among the units using the conventional Economic Dispatch problem, similarly to the case of thermal units [6].

III. TESTS AND RESULTS

The effectiveness of the proposed methodology was evaluated through a pilot project which included a hydroelectric plant with 3 generation units and an installed capacity of 348 MW. Next, some of the results obtained will be presented.

Figure 3 shows the values obtained through the developed tool considering a pre-established measuring date. This figure shows the values corresponding to the generated active and reactive power, water discharge, water head, gate opening and runner blade opening. It also shows the unit efficiency calculated using the proposed tool. By using these values it can be established the operative limits to thereafter obtain the optimization process solution, as seen in Figure 3.

Once performed a general analysis, it was possible to verify that in the past, at certain times, the units were operating with efficiencies below of their ideal value or optimal value. This operation can result in an increased consumption of water.

Figure 4 illustrates an example where for a pre-established measuring interval the unit efficiency is below of the ideal value or optimal value.

The operation needs of the generation units without reaching their maximum efficiency can occur due to various reasons, namely: operative limits of the generation units, operative errors and operative reserve requirements.

As for the results presented in Figure 4, the optimization algorithm proposed so as to maximize the generation units efficiency, was utilized [3].

Table 1 shows the results obtained on 01/11/2006 at 21:00h. Notice the efficiency and the active power dispatched at that time. Note also that the generation could have been done with only 2 units instead of 3 generation units, thus increasing the generators efficiency and minimizing the water consumption.

Regarding the efficiency and active power dispatched, it can be concluded that the water reduction obtained, once applied the optimized dispatch could have represented approximately 7.6 MW at that time.

Once performed the previous tests, there were carried out several measurements (Table 2) similarly to Figure 5. The objective of these measurements was to perform a comparative analysis between the values obtained in site and those presented in the referred figure. The values shown in Figure 5 were obtained from the reduced model tests.

The reason why Table 2 was only partially elaborated, are: the measured values stored in the database do not contemplate all the water heads nor all the generated power values, as presented in Figure 5. Despite the generating units similar they present different operative behaviors. This difference demands the necessity for elaborating a specific table for each unit. Finally, it is also the difficulty, imposed by the System Operator, for using one or more units to simulate different operation sceneries. For these reasons, Table 2 shows only some of the values monitored for 2 different units.
Fig. 3. Solution obtained considering a pre-established measuring date - 11/01/2007.

Fig. 4. Unit efficiency obtained through the proposed methodology - 01/11/2006.

TABLE 1
Actual and optimized dispatch - 01/11/2006 - 21h.

<table>
<thead>
<tr>
<th></th>
<th>Active Power Measured (MW)</th>
<th>Efficiency Measured (%)</th>
<th>Limit Minimum Unit (MW)</th>
<th>Limit Maximum Unit (MW)</th>
<th>Active Power Optimized (MW)</th>
<th>Efficiency Optimized (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>54.2</td>
<td>0.89</td>
<td>00.0</td>
<td>100.0</td>
<td>100.0</td>
<td>0.92</td>
</tr>
<tr>
<td>Unit 2</td>
<td>54.9</td>
<td>0.88</td>
<td>00.0</td>
<td>100.0</td>
<td>64.3</td>
<td>0.91</td>
</tr>
<tr>
<td>Unit 3</td>
<td>55.2</td>
<td>0.86</td>
<td>00.0</td>
<td>100.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
IV. CONCLUSIONS

In this work, a methodology for the hydroelectric plant unit commitment was presented.

From the analysis and tests performed, it was possible to verify that there are times when some units work with efficiencies different from their ideal values or optimal values. This results in an increased water consumption and in a premature worn out of the generating units.

Should the generating agents operate their units at points different from the maximum efficiency due, for example, to the reserve allocation necessity requested by the System Operator, the agents should be entitled to request a compensation for such services rendered (Ancillary Services). Presently, this service is not remunerated in Brazil. However, it is expected that such service may at least compensate the excess of water used.

Should the generation units be operating at points different from the maximum efficiency, for instance, due to an error in the operative policy or due to operative restrictions, it will be necessary that the generation agents could overcome these deficiencies so as to avoid the waste of water and some other losses in their budget.

Additionally, measurements in both the gate opening and the runner blade opening allowed the generating agents to review the operation and maintenance policies often influenced by a possible imprecision in the instruments used.

The efficiency differences among the units showed that despite the similarities of the units they present a different operative behavior. Therefore, it will be necessary to consider these differences during the optimized dispatch process.

The differences existing between the results of the tests in the reduced model and those obtained in site suggest that the monitored variables in the database should be better supervised so as to consolidate the reliability of the obtained values, thus, adequate the table used to the generating units dispatch.

The results obtained through the optimization process showed to be satisfactory, however, there is still much work to do, mainly regarding issues like the adjustment of the restrictions imposed to the problem.

V. REFERENCES

VI. BIBLIOGRAPHIES

Thales Sousa was born on June 23, 1978. He received his B.Sc. degree from the State University of Sao Paulo (UNESP) in 2000. He obtained his M.Sc. and Ph.D. degrees at the University of Sao Paulo (USP) in 2003 and 2006, respectively. Currently, he works as a researcher at GAGTD in the Polytechnic School at the University of Sao Paulo. His fields of interest are: power system operation and planning.

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