ONLINE UNIT MANAGEMENT FOR OPTIMAL OPERATION OF HYDRO POWER PLANTS

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ABSTRACT

The paper presents a novel methodology for the operation of those hydro power plants provided with a single penstock by the optimal distribution of the dispatched power among its available generating units, aiming at the maximum efficiency of the whole power plant energy conversion. While previous optimization methods made use of off-line static curve and parameters or expensive flow meters, the proposed method is on-line in nature and uses a single pressure meter at the end of the power plant penstock. The method was applied to a power plant and has resulted in a higher efficiency operation under several conditions.

INTRODUCTION

Hydro power plants have been used for electricity generation for a long time due to its low operational cost, high energy conversion efficiency, and because it uses a renewable primary resource, the water. Nevertheless, water is an important resource that must be handled with care, to ensure long term sustainability. On the other hand, the self-sustainable development and the reasonable exploration of natural resources have become the great challenge of the 21st century. Hydro power plants deal with these two sides of the coin. In Brazil, where hydro power plants account for about 78% of the installed power and 92% of the gross energy generation, every tenth of a percent increase in the energy conversion efficiency is welcomed.

In the design of a hydro power plant the gross head is defined by the regional topography and by the dam height. The total power and the number of generating units is a function of economic factors and of the hydrological availability of the site. The flexibility of hydro power plants allows its operation to accommodate both base and peak loads.

When meeting the peak load the generated power must follow the load variations, therefore the loading and the number of employed units of the power plant must be chosen to provide the dispatched power with the highest efficiency. When supplying the base load all the available units are operated to generate their maximum power. Nevertheless, due to the hydrologic cycle, there is a percentage of the year, the dry season, when there is not sufficient water to push all the units of a power plant at their rated power and, again the available units must be dispatched to achieve the highest efficiency.

Few papers cover the subject of optimal operation of a single hydro power plant (Arce et al., 2002), (Finardi and Silva, 2005), (Bortoni et al., 2007), and (Cheng et al., 2009). The great majority of published material regards to the hydro cascade operation, aiming at the maximum energy generation for a given inflow scenario such as (Pereira and Pinto, 1982) and (Carvalho, S. Soares, 1987). This paper presents a novel methodology the online optimal operation of hydro power plants for its best efficiency.

1 OPTIMAL POWER PLANT OPERATION

There are many methods that can be used to obtain an optimal distribution of the dispatch power among the units of a power plant. A brief description of such methods is presented as follows.

1.1 Classical economic dispatch

As long as the efficiency of each generating unit is a function of the delivered power, the power plant optimization problem can be stated as defining the output of each unit that maximizes the total power generation efficiency or, in other words, to reach the minimum generation cost subject to system constraints to meet the demand and the capability of the machines. The simplest economic dispatch formulation is

$$\begin{aligned} &\min C_T(P_i) \\ &\text{s.t.}\ \ \Sigma P_i = P_d \\ &\quad P_{Li} \le P_i \le P_{Ui}. \end{aligned} \tag{1}$$

Notice that for hydropower plants, from now on, the cost function is considered as the water consumption as a function of the generated power, as long as the water has not a direct associated cost.

1.2 Dispatch based on efficiency tests

Unfortunately, it is well-known that each machine, even from the same manufacturer and design, has its own characteristics and the generation cost will eventually vary between like units. Therefore, a procedure for optimal load distribution among the available units of a power plant can start from the presented equal load distribution criterion, as a quasi-optimal solution, to perform an iterative process based on the efficiency curve of each unit to obtain an overall maximum efficiency.

In this case, field tests must be done to obtain the efficiency curve of each unit, which explains their efficiency behavior with the dispatched power under several operating conditions of head and flow.

Fig. 1 presents an example of an operating chart of a hydro turbine model obtained from laboratory tests. The efficiency of the hydro turbine depends on the turbine flow and net head, leading to a three-dimensional diagram, which is the unit efficiency characteristic for any load and head conditions.

Based on the knowledge of efficiency function of the units of a hydro power plant, it is possible to obtain an optimal solution that maximizes the efficiency of the entire power plant.

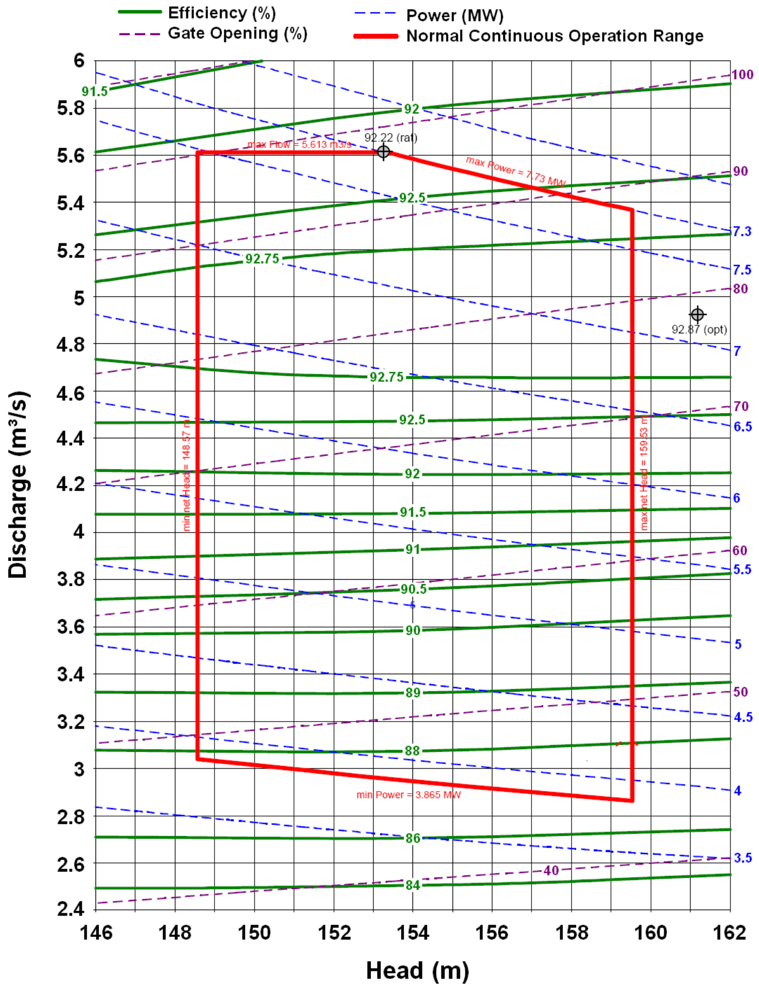

Figure 1 – Operational chart of a hydro turbine.

$$\max \eta_T$$

$$s.t.\ \ \Sigma P_i = P_d \tag{2}$$

$$P_{Li} \leq P_i \leq P_{Ui}.$$

With η_T given by:

$$\eta_T = \frac{{}_{i=1}^{n} P_i}{{}_{i=1}^{n} \frac{P_i}{\eta_i}} \tag{3}$$

Nevertheless, this efficiency curve is a single picture of the machine behavior at a given moment and does not consider eventual variations on the machine or on the power plant parameters over time. Another approach based on loss minimization rather than efficiency maximization can be applied (Arce et al., 2002), but, again, the model parameters do not depend on machine aging, temperature variation and other factors.

1.3 Dispatch based on efficiency measurement

The energy conversion efficiency is obtained by the ratio between the output and the input power. Equation (7) depicts this concept by including the related variables.

$$\eta = \frac{P \cdot 10^{-3}}{\rho \cdot g \cdot Q \cdot H} \tag{4}$$

The net head is the difference between the gross head and the hydraulic losses. Therefore, a suitable device can be conceived to determine the online efficiency of each unit based or implemented using power plant SCADA. As long as the total efficiency of the power plant depends on the efficiency of each working unit (6), the optimization of the load distribution among the available units can be accomplished according to (5).

Based on Figure 1 the net head is obtained as

$$H_L = \frac{P_1}{\gamma} + a + y + \frac{8 \cdot Q^2}{\pi^2 \cdot g} \cdot (D_i^{-4} - D_o^{-4}) \tag{5}$$

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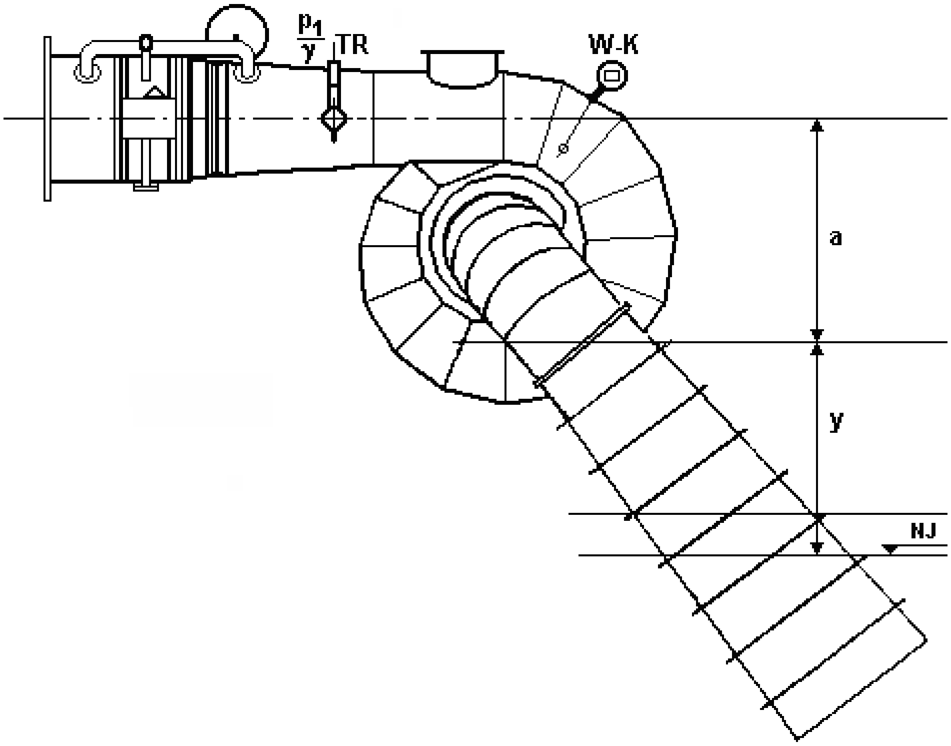


Figure 2 – Dimensions for the net head calculation.

1.4 Proposed Optimal Power Plant Dispatch

The previous methods have been implemented and tested for many years. While the first proposal is based on constant efficiency behavior, the latter is based on online efficiency measurement, which takes into account the aging of the units, penstock losses, tailrace level, and other variables. Nevertheless, the need for flow measurement constitutes a great drawback of the previous approaches. Online or off-line flow measurement in hydro power plants is a real challenge due to the large diameters involved and the required accuracy.

Therefore, entire power plant efficiency optimization using flow measurement criteria falls on the high cost of flow sensors for such large diameters. In addition, occasionally the gain in efficiency with the optimal operation is smaller than the accuracy of the flow measurement, which leads to erroneous solutions. It is proposed that the described problems can be overcome by using a gauge pressure sensor at the end of the penstock, which has much lower cost and more accurate than flow sensors.

The pressure at the penstock end is the difference between the gross head and the head losses, which is proportional to the squared flow. The following equation depicts this relationship.

$$p_0 = z - k \cdot Q^2 \tag{6}$$

Equation (5) has a central importance in the adopted approach as long as it gives an alternative way to infer the influence of the flow without really measuring it. The static pressure at the end of the penstock is the gross head, which is the vertical distance from the forebay to the pressure metering point, minus the friction losses obtained through the head loss coefficient.

One can conclude that the bigger the flow driven by the turbines, the lower the pressure at the end of the penstock will be. Therefore, maintaining the dispatched power met by the power generated by the power plant units, a reduction of the input flow means an increase in the overall power plant efficiency.

In other words, according to (6), this flow reduction is related with a pressure increase. Therefore, instead of maximizing the overall efficiency in order to obtain a global optimum, the optimization problem can be rewritten to seek for the maximum penstock end pressure:

$$\begin{aligned} &\max\ p_0 \\ &\text{s.t.}\ \ \Sigma P_i = P_d \\ &\quad P_{Li} \leq P_i \leq P_{Ui}. \end{aligned} \tag{7}$$

The proposed methodology is suitable for those power plants with several units fed by a single penstock. The process starts with all the units equally loaded to meet the demanded power. Then, the loading of each unit is slightly changed until a maximum penstock end pressure is achieved.

When applying this methodology the user does not have access to the overall efficiency value, since the flow is not measured. However, due to the concave characteristic of the efficiency curves, it is recognized that the system will work in a more economical way.

2 REAL TIME OPTIMIZATION

There are three important issues that must be taken into account when selecting the optimization method to solve the presented problem. The first is that the problem combinatorial in nature, there are infinity combinations of generated power among the available units that can meet the demanded power.

The second is that there is not a formal mathematical model to be optimized, as long as updated efficiency curves of the units are not known, but only the information of the pressure at the penstock end. The third is that it is an online, real-time, optimization problem, which must be solved as fast as possible, maintaining the system stability.

The developed algorithm considers the search as a combinatorial optimization problem (Nemhauser and Wolsey, 1998). The inputs of the model are the delivered power of each unit and the gauge pressure value at penstock end. The output is a signal to act as a reference on each speed governor and the power of each unit.

Combinatorial optimization problems can be solved using either exact methods (Nemhauser and Wolsey, 1998) or heuristics (R. C. Holte, 2001). The exact methods explore large solution space and are very time consuming, making them impractical for real-time optimization applications. The use of heuristics is very suitable for such cases, allowing for finding efficient solutions in a very reasonable execution time instead of looking for the global optimum (R. C. Holte, 2001).

The best solution search is made by applying combinations of small pre-defined disturbance steps in the generated power of each unit, keeping demanded power met, until the most efficient operation point is found.

The example shown in Figure 3 represents a small power plant with three units and has a demand of 15 MW. At time 0, the demanded power is equally divided between the units, resulting in certain penstock end pressure. At time 1, the unit #1 has its power increased by one step, while unit #3 has its power reduced by one step, thus keeping the overall generated power and leading to a new pressure. By time 3, there is a new power distribution with a new step power increase in unit #1 and a reduction of the generated power of unit #2 by one step. The total generated power is kept constant and meets the dispatched power, with some change in the overall efficiency, described by the penstock end pressure.

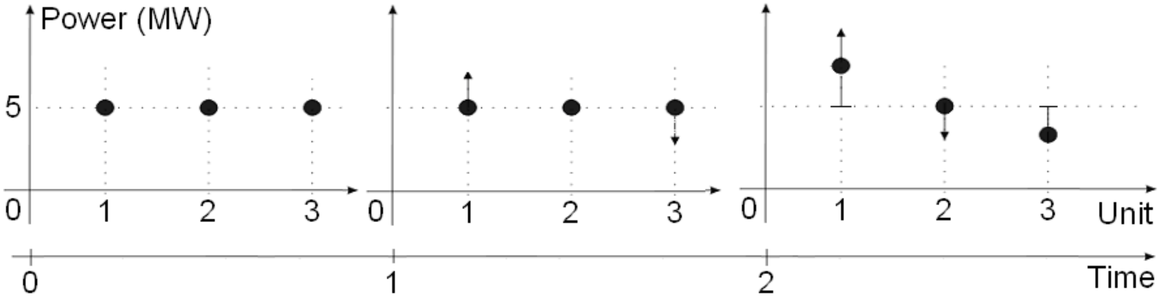


Figure 3 – Guess-and-check process of the search engine

The search algorithm must have a heuristic capable to direct the search engine to a power distribution between the available units that lead to the highest pressure and overall efficiency. Iteration is defined by a power step in the direction of the maximum positive pressure variation. The time to complete one iteration is approximately the units settling time multiplied by the number of possible combinations. The settling time depends on the power plant arrangement, which eventually will reflect the water acceleration time constant and on speed governor time constants. In general settling time is less than sixty seconds (Kundur, 1993).

The graphical results depicted in Fig. 8 exposes an interesting feature of the proposed combinatorial optimization methodology, i.e. the step changes when reaching the optimal solution. The phenomena observed between iterations 11 and 13 is a backward step to a previous more efficient stage and a reduction in the searching step as a function of an efficiency reduction, as shown in Fig. 4.

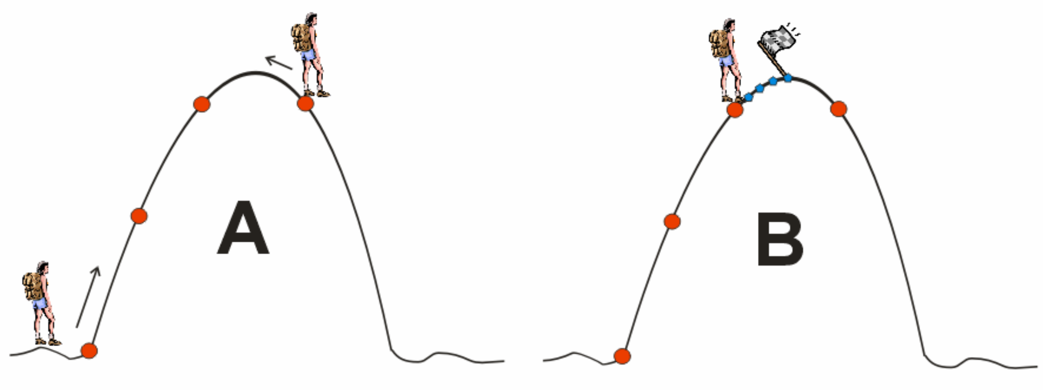


Figure 4 – searching step change due to an efficiency reduction

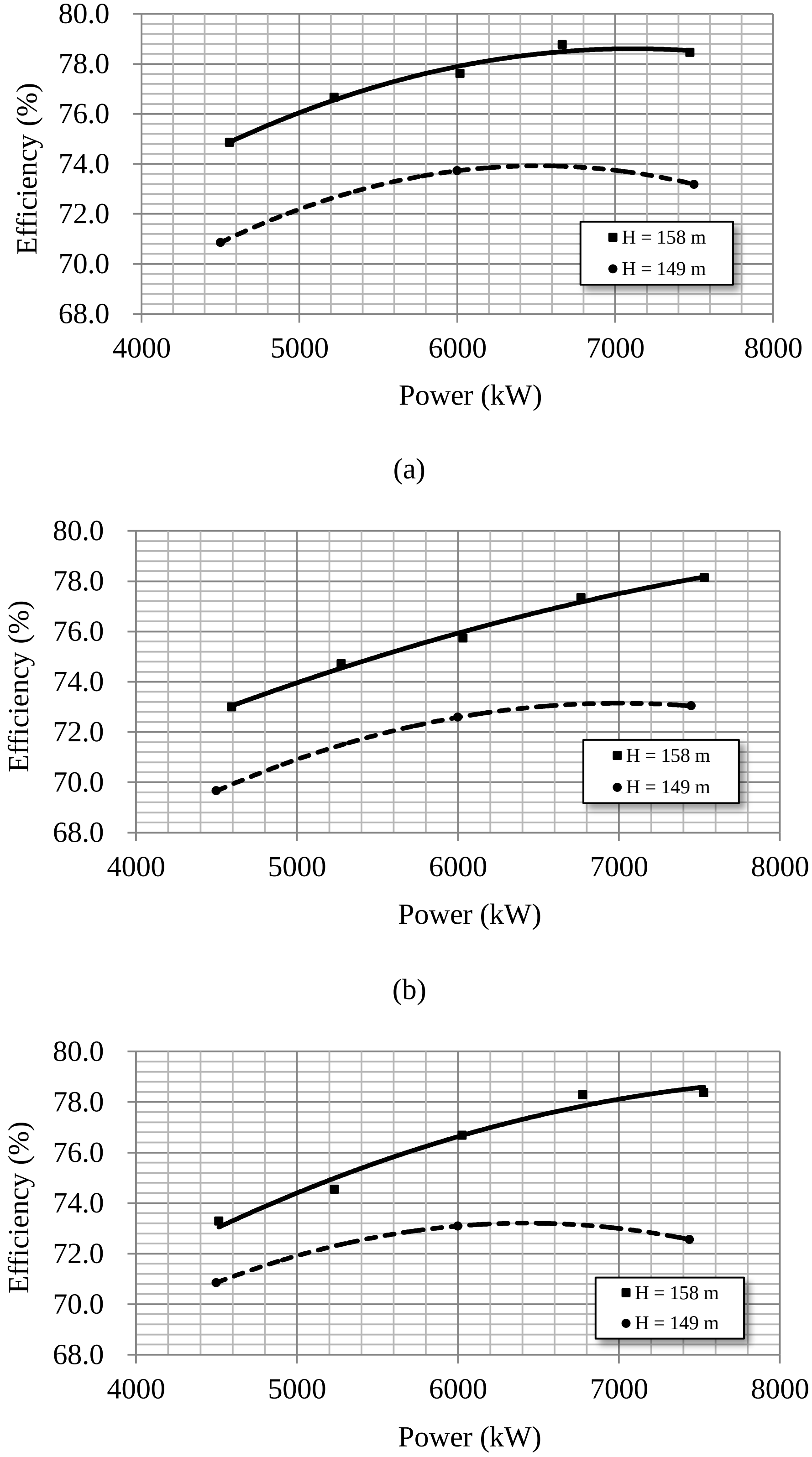
3 APPLICATION

As the first assumption, the proposed methodology is suitable for those power plants provided with a single penstock. Its application to the Rio Bonito Hydro Power Plant was selected to be explored here. This power plant has a single penstock feeding three units of 7 MW each, totalizing 21 MW. The rated gross head is 160 m and the rated flow is 15.6 m³/s.

For evaluation purposes, off-line efficiency tests were applied to the three units in the *wet* and *dry* seasons of the year. Due to the absence of rain during the dry season in relation to the wet season, the gross head was reduced from to 158 m to 149 m. The efficiency curves of the machines are shown in Figure 5 for units #1, #2, and #3, respectively.

The difference in the efficiency of the units for different gross heads is notorious, ranging from about 2 to more than 6 percentage points, reflecting the hydro turbine behavior represented by its performance chart. Such phenomenon is very difficult to model using algebraic formulations and can only be detected by using either on-line efficiency measurement or an observing variable.

A very high accuracy class smart pressure sensor was installed at the penstock end. The digital transmission of the data allowed for obtaining pressure measurements with resolution on the order of millimeters of water column.



(a)

(b)

(c)

Figure 5 – Efficiency curves of units for different gross heads.

For evaluation purposes, water flow was also measured with a non-intrusive ultrasonic flow meter. Figure 6 shows the penstock end pressure as a function of the water flow. Notice that the curve shows a negative coefficient parabola as expected (5) and that its abscissa intercept can vary according to the water upstream level.

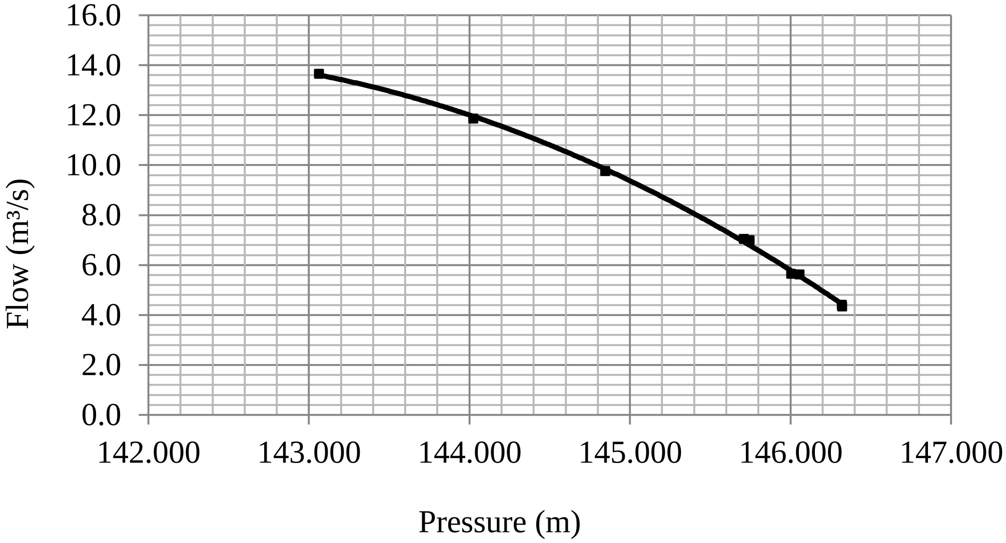


Figure 6 – Water flow rate as a function of penstock end pressure.

Due to the very large time constant of the upstream water level, it is considered constant during the optimization process. Optimal load distribution among the three units of the power plant, employing the proposed methodology, was carried out for dispatched powers of 10 MW and 18 MW, for a gross head of 149 m.

3.1 Dispatch of 10 MW

In the first case, dispatch of 10 MW, units #1 and #2 were selected to supply the load as long as each one is able to carry 7 MW. Each one was loaded with 5 MW at the beginning of the iterative process. A change of 500 kW is applied to the machines at each iteration. The best combination was obtained with machine #1 loaded with 6 MW and machine two with 4 MW. At this point the pressure was 144.890 mH2O and the flow was 9.62 m³/s. Figs. 7 and 8 presents these evolutions. The iterative process was considered finished as long as no combination was found better than the previous operating condition. A benefit of almost 1% was reached with the water flow reduction, as show in Fig. 9.

3.2 Dispatch of 18 MW

All the units were participating of the dispatch of 18 MW. In the beginning of the iterative process the load was equally divided by the three units and each one was loaded with 6 MW. After applying steps of 500 kW for each combination with the three available units. In the third iteration no combination was found better than the previous results, ending the iterative process, Fig. 12.

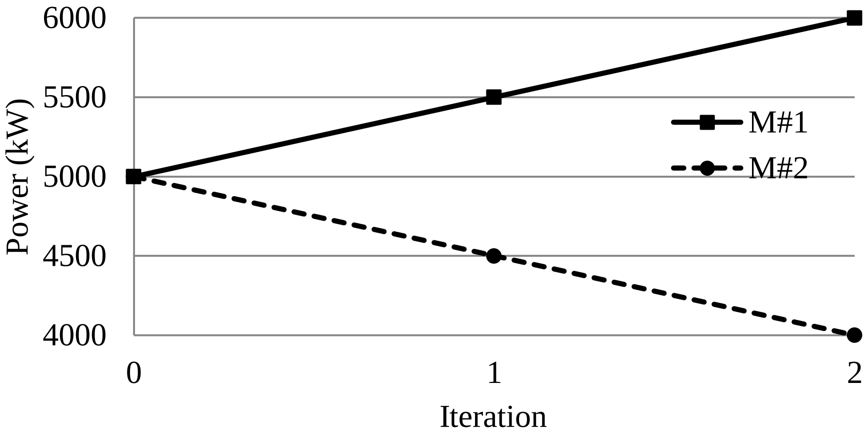


Figure 7 – Load distribution during the optimization process – 10 MW.

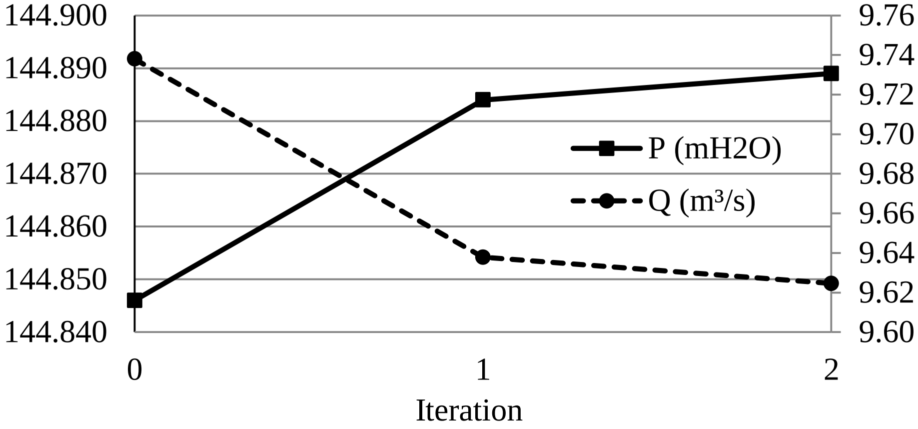


Figure 8 – Pressure and flow during the optimization process – 10 MW.

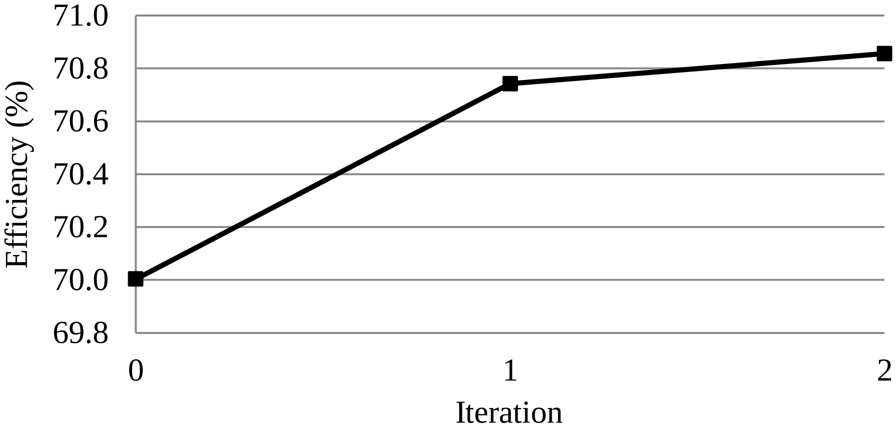


Figure 9 – Efficiency evolution during the optimization process – 10 MW.

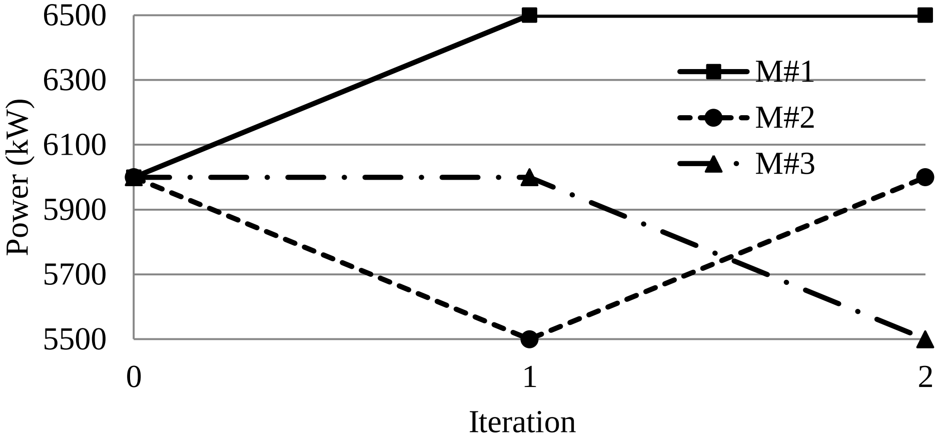


Figure 10 – Load distribution during the optimization process = 18 MW.

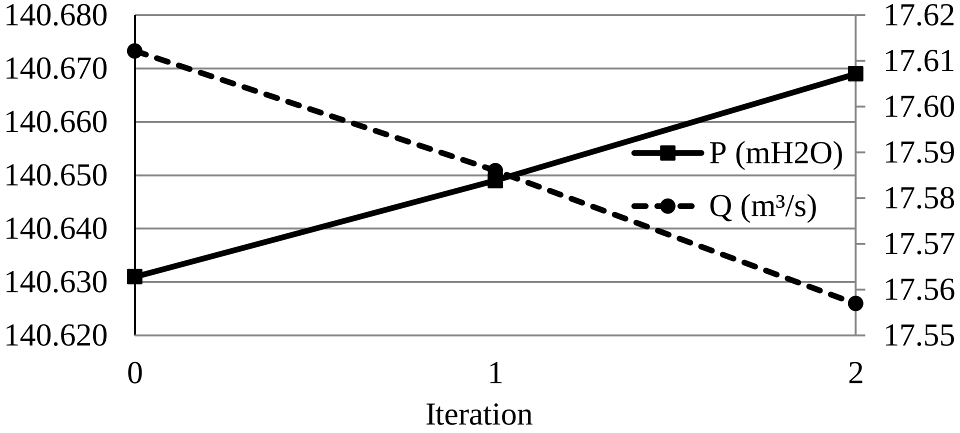


Figure 11 – Pressure and flow during the optimization process – 18 MW.

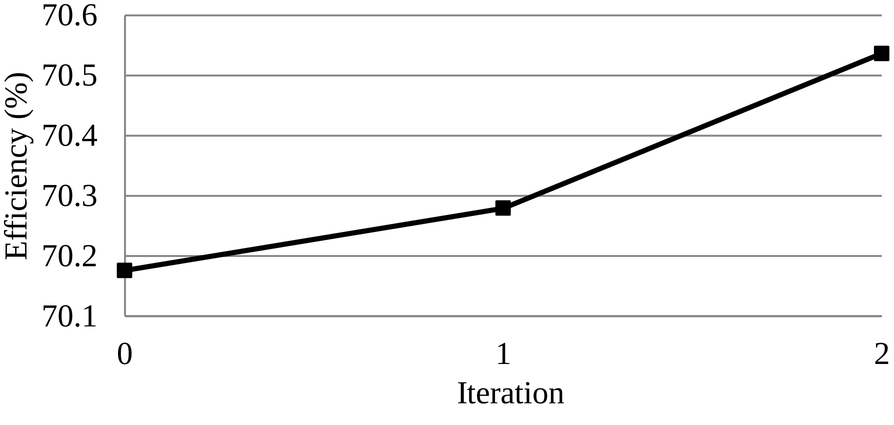


Figure 12 – Efficiency evolution during the optimization process – 18 MW.

3.3 Analysis of the results

In both dispatch conditions the combinatorial loading of the units was performed manually as a specific algorithm was not implemented in the power plant SCADA system. It was observed that the settling time was about thirty seconds for each combination and, therefore, each iteration was performed in less than five minutes. Considering a single step of 500 kW, the whole optimization process took two iterations to reach an efficient solution, i.e., less than ten minutes.

Benefits of 0.9% and 0.3% of the operational efficiency were obtained with the application of the proposed methodology for dispatching 10 MW and 18 MW respectively. Such reduction could be expected because the greater the dispatched power the lower the flexibility of operation will be. At the limit, when dispatching 21 MW, the maximum output of the power plant, there is no flexibility, all the units must work on their rated power, and there is no choice, no gain.

4 CONCLUSIONS

The work presented a novel methodology for the optimal operation of hydro power plants provided with a single penstock, leading to the optimal distribution of the dispatched power among its available units.

As long as the flow is not measured, the efficiency of the power plant cannot be determined. However, due to the concave characteristic of the optimization function, the applied algorithm will search for the highest gradient in each iteration and the power plant will converge to its maximum efficiency.

The presented application, for example, demonstrated gains that vary from zero, at full load operation, to 0.9% at half load. As long as the water availability varies during the year, establishing wet and dry seasons, the annual gain benefits can be assessed by mathematically operating the flow duration curve of the site under analysis with its gain-power curve.

In addition, considerable improvement on the presented methodology can be obtained with the construction of a data base of efficient solutions, which would allow starting the iterative process from a *quasi*-optimal solution, reducing the number of steps and iterations.

Therefore, future work includes, among others, the use of reinforced learning techniques and the study of online load distribution on those power plants provided with several penstocks.

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NOMENCLATURE

C	cost function ($)
P	power (MW)
ΣP_i	summation of all units generation (MW)
η	efficiency
ρ	fluid density (kg/m^3)
g	gravitational acceleration (m/s^2)
Q	turbine flow (m^3/s)
H	net head (m)
p_0	static pressure (m)
z	gross head (m)
k	head loss coefficient
P1	pressure on the turbine input (N/m^2)
γ	specific weight of the water (N/m^3)
D	the turbine input and output diameters (m)
a	fixed distance between the turbine input to a given reference (m)
y	variable distance from the reference to the downstream level (m)

Subscripts

T	total
d	dispatched
i	i-th unit, input
L	lower
U	upper
o	output

REFERENCES

1. A. Arce, T. Ohishi and S. Soares. *Optimal dispatch of generating units of the Itaipu hydroelectric plant.* IEEE Trans. on PWRS-17(1), Feb. 2002, pp. 154-158.
2. E.C. Finardi, E.L. da Silva. *Unit commitment of single hydroelectric plant*. Electric Power Systems Research 75 (2005) 116-123.
3. E.C. Bortoni, G.S. Bastos, L.E. Souza. *Optimal load distribution between units in a power plant*. ISA Transactions 46, 2007, pp. 533–539.
4. C. Cheng, S. Liao, Z. Tang, M. Zhao. *Comparison of particle swarm optimization and dynamic programming for large scale hydro unit load dispatch*, Energy Conversion and Management, Vol. 50(12), Dec. 2009, pp. 3007-3014.
5. M.V.F. Pereira, L.M.V.G. Pinto. *Decomposition approach to the economic dispatch of hydrothermal systems*. IEEE Trans. on PAS-101(10), 1982, pp. 3851-386
6. M.F. Carvalho, S. Soares. *An efficient hydro-thermal scheduling algorithm*. IEEE Trans. on PWRS-2(3), 1987, pp. 537-542.
7. G. L. Nemhauser, and L. A. Wolsey. Integer and combinatorial optimization. Vol. 18. New York: Wiley, 1988.
8. R. C. Holte, "Combinatorial auctions, knapsack problems, and hill-climbing search." Advances in Artificial Intelligence. Springer Berlin Heidelberg, 2001. 57-66.
9. P. Kundur, *Power System Stability and Control*. EPRI Power System Engineering Series. McGraw-Hill, Inc. New York, 1993.