COMPARISON IN THE APLICATION OF THE EXPLOITATION BY OPTIMAL HEAD MODEL TO HYDROELECTRIC POWER STATIONS IN RUN-OF-THE-RIVER SYSTEMS EQUIPPED WITH DIFFERENT TYPES OF TURBINES

J.M. Blanco Barrero[1], J.C. Sáenz-Díez Muro[1], E. Jiménez Macías[1] and M. Pérez de la Parte[2]

[1] Department of Electrical Engineering. [2] Department of Mechanical Engineering
E.T.S.I.I., University of La Rioja. Luis de Ulloa, 20. 26004. Logroño (Spain)
Phone/Fax number: +34 941 299502, +34 941 299478, ,
e-mail: {juan-carlos.saenz-diez; juan-manuel.blanco; emilio.jimenez}@unirioja.es

Abstract

Hydroelectric power plants in diversion scheme systems utilize the water flowing through the river, since they present the necessary facilities and infrastructures to channel and harness the water, without having in their initial conception any storage systems.

This type of power stations are designed and automated to operate between certain limits of water head, working with "constant head", using the heads available at any moment. The operating limits are determined by the "nominal flow" for which the power plant has been designed and the "minimal technical flow" which corresponds to the minimum value of the flow with which the plant can work, which depends on each type of turbine.

By means of the presented optimization algorithms we can take advantage of those periods of time with low levels of flow (low water levels) to utilize the channels in the power station as storage elements of flow under the technical minimum, making the power plant undergo sequential cycles of emptying/filling of channels, allowing for the energetic exploitation, that will be denoted as "optimal flow".

In this article, we intend to determine how we can adapt each type of turbine to the new optimization algorithms proposed, establishing the increments in production obtained for each type of turbine and the possibility of applying the "optimal flow" algorithms.

Key words

Renewable energies, hydroelectric power plants, optimisation, Automation, Regulation.

Optimization model

The turbines represent the limiting factor of operation of the hydroelectric plants, since their limitations are determined by the maximum operating flow (flow of equipment) and a minimum flow that is limited by a minimum value of the turbine performance, 70%. The flows that set the minimum vary between 10%, 25% and 40% of rate of plant equipment, depending on the type of turbine used.

In the figure below, the curves for various types of hydraulic turbines can be observed, which, in the case of Pelton turbine, the technical minimum is at about 10% of the nominal flow, while for the Francis turbine the technical minimum flow is about 40% of the nominal flow.

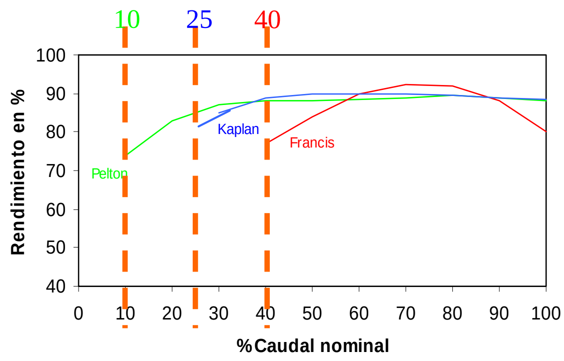


Fig. 1 Performance characteristic of different turbine types, applied the technical minimum flow.

For the range of flow rates of the turbines, the energy use obtained is:

$$E = \int_T Pa \cdot dt$$

Fig. Performance characteristic of different turbine flow applied technical minimum.

Where the power (Pa) can be obtained depending on the head (Hn) and flow (Q) parameters.

$$Pa = Q \cdot \rho \cdot g \cdot Hn \cdot \eta t$$

Expression in which the head is considered constant. Moreover, the average performance at this stage of calculation can be estimated at around 80%; thus, the above expression yields:

$$E = \rho \cdot g \cdot Hn \cdot \eta t \cdot \int_T Q \cdot dt \quad \rightarrow \text{Volume}$$

$$E = \rho \cdot g \cdot Hn \cdot \eta t \cdot V$$

Function that determines that for obtaining maximum energy, turbines must harness the largest volume of water flowing through the river.

The plant design chooses a flow value that enables maximum utilization of the flows to achieve maximum generation of energy. This flow is chosen by a hydrological study. On the other hand, if apart from the normal operation of the diversion scheme hydroelectric flowing plants (constant head), the algorithms presented in this paper are used, the volume harnessed by the turbine can increase and therefore the power generated.

Performance analysis

Let's start analyzing the behavior of the plant accordingly to its conventional mode of operation at constant head. It is necessary to know the data of circulating flow through the river.

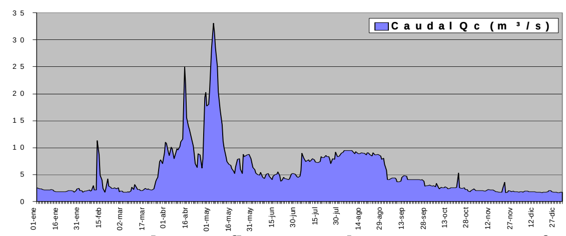


Fig. 2a Circulating flows in the Iregua river for an average year (2007). Source (CHE, Confederación hidrológica del Ebro, Ebro hydrological confederation).

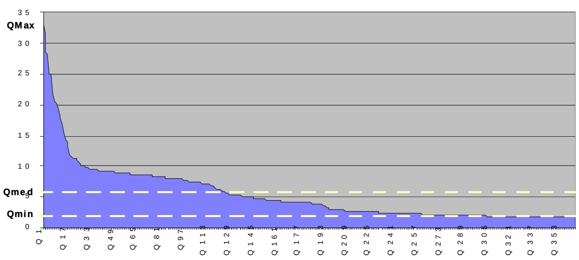


Fig. 2b Flow duration curve. Average year 2007.

From the graph of circulating flows and their management the classified flow curve is obtained (Fig 2b).

The maximum energy is obtained when all the volume represented by the "classified flow curve" is harnessed, but everything will not be able to be profitable, as there are flows that will not be able to turbine due to different causes:

1) Environmental flows: minimum flow circulating through the river to allow the river's habitat;
2) flows greater than the nominal flow: flows that exceed the nominal flow should not be used;
3) technical minimum flow (Q_mt): Minimum flow of operation of the turbine, because the performances are not acceptable under these flows.

The optimization strategy focuses on the last type of flows, because flows above nominal can not be subtracted and the ecological flow must be guarantied. Therefore, only is possible to take advantage of the flows under the technical minimum flow, during periods of time during which we could not produce power under normal conditions, as shown in the graphics.

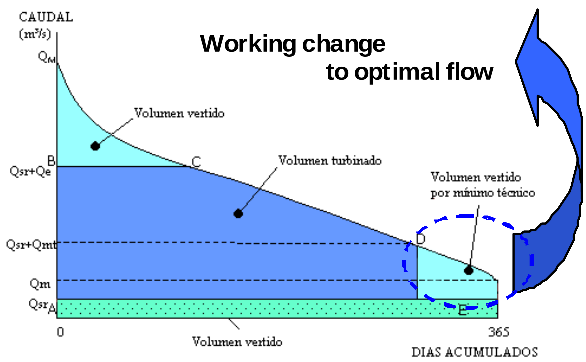


Fig. 3 Optimization policy

In the model of optimal flow operation, the hydroelectric plant uses the storage capacity of its canals and conductions to make a cyclic emptying and filling of these pipes. The plant, from the river flows and the utilization characteristics (type of turbine, existing canals and volumes that can be stored in the canals) determines a flow of work that allows using these flows and maximizing the energy production.

Operating limitations

In the mode of operation for optimum flow, conductions are filled / drained periodically. This leads to having to determine the operating limits. To determine the volume to harness in optimum flow operation mode, the following limitations will be taken into account:

- The maximal drain of conductions.
- The Volumes lost in the start-stop of the machines.
- Performance losses due to head reduction.

Limits of the conductions empting

Depending on the existing turbine at the station, the minimum level of head variation in the central is established.

- Pelton turbines. They can work with small head differences (the minimum head is 90% of the nominal head), while maintaining acceptable yields.

- Francis turbines. Operation is limited by a head of at least 65% of the nominal head.

  If turbines are open chamber, the minimum head limit has to consider a limiting factor in performance, although in this type of turbine, as they have a suction tube, head limitations have also to be considered in order no avoid cavitation.

- Kaplan turbines. They work with a head of at least 65% of nominal.

Table 1. Net heads range recommended for each type of turbine. Source [US Bureau, 1976] and the author.

Tipo de Turbina	H mínimo (%)
Pelton	90
Francis	65
Kaplan	65

Volumes lost by start-stop machine

When starting the turbine will consume a volume of water stored in the pipes to carry the turbine at rated speed and proceed with its interconnection. In addition, once interconnected, and until the optimum flow of operation, part of the volumes stored are turbined with a yield lower than that obtained by optimal flow in the electromechanical equipment.

Time values, openness and acceleration ramps set from the data shall be:

Turbina	Apertura distribuidor en conexión (%)	Tiempo alcanzar la conexión (s)	Rampa de aceleración una vez acoplada hasta 50%
Pelton	2,5	60	30 s
Francis Espiral	5-10	90	60 s
Francis Cámara Abierta	20-30	90	35 s
Kaplan	15	120	90 s

Every time the central is stopped there is a period of time for closing regulatory elements. The volume evacuated by the turbine until its total closure is considered lost, since the machine is no longer connected, and it should be procured to be the minimum necessary without water hammer problems.

Performance losses by head reduction

The mentioned performance curves represent their variation as the flow varies, with a constant value of the net head and the speed of rotation of the turbine. In addition, as shown in the figure below, the performance also depends to a greater or lesser extent on the head available for the turbine, depending on the type of turbine, being lower this performance as greater is the loss of head.

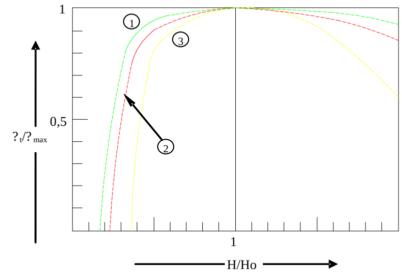


Fig 4. Performance characteristics depending on the head variation. (1) Kaplan; (2) Francis; (3) Pelton; Source [Vivier, L.. 1966].

Determination of Q_Optimo.

To determine the Q_Optimo, the performance curves of the electromechanical equipment of the plant have been modeled, obtaining for each type of plant a global performance curve, which will serve as a basis for studying the various operational flows and the application to the model. Then, the limitations of model performance are applied, such as the starting and connection times, performance loss due to head reduction, and minimum run time.

Tests for different types of turbines and hydroelectric plants were performed, from the flow data obtained from the station No. 36 in Islallana, located in Iregua River basin (part of the Ebro basin). A reference series of 40 years (1969-2008), from the total available hydrological information considered, obtaining as average year the year 2007, which will be used for application of the models presented.

High head stations, penstock, with spiral case

Within this first model, the plant where the algorithms for optimal flow control are implemented is a diversion scheme hydroelectric plant with the following characteristics:

- Concrete canal
- Penstock.
- Head of 20 m.
- Nominal flow (Qn) of 6 m3/s.

Applying the optimal flow function, and comparing it with control at a constant head, in the figure below can be seen, for each of the circulating flows that run through the river (blue function), the flow of work for conventional operating with head (green function) and work flows in a run with the new algorithms implemented, working with optimum flow (red function).

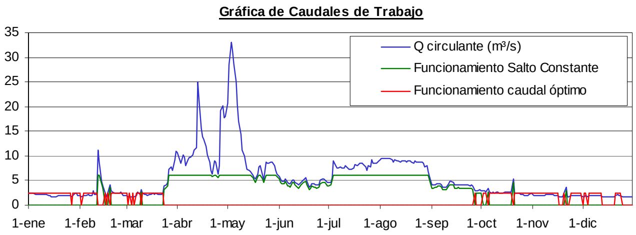


Fig.5 Comparison of work flow to operate at constant head vs. Optimal flow in 2007 (average year) Francis turbine spiral case.

The proposed operating model for optimal flow rate allows the central working during the days of not working in the traditional model, producing an increase in energy production of 19.34%, and an increase of the annual utilization of 8.21%. The volume turbined by optimum flow is 18.70 hm ³, 11% of the total turbine.

Considering the use of hydroelectric type as both modes of operation, the central fixes annual use 50.66%. The turbined volume increase is 20.98% regarding the volume with constant head.

The classified produced energy for the considered average hydrological year (2007), obtained from the classified flow curve, is depicted in the Figure below, where there are performances by constant head and optimal flow modes.

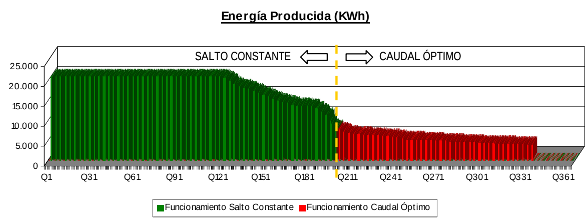


Figure 6. Classified produced energy for a power station equipped with Francis turbine of spiral chamber(average year).

High head stations with Pelton turbines.

Plant information:

- Concrete canal
- Penstock.
- Head of 120 m.
- Nominal flow (Qn) of 1 m3/s.

For implementation of operating models for constant head and optimum flow the flow of work for each exploitation model is depicted in the figure below for each flow rate by the river.

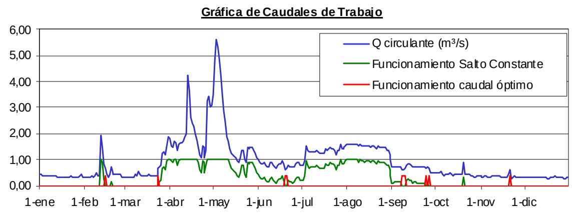
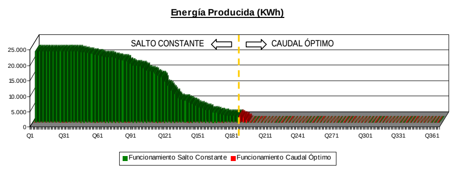


Fig. 7 Representation of work flow with constant head operation in 2007 (average year). Pelton turbine.

Considering the use of hydroelectric power as both modes of operation, the central works for optimum flow for 0.17% of annual use. The plant produces nearly in this optimal flow mode 0.52% of the energy obtained from constant head.

From the results can be determined that, in the exploitation willing Pelton turbine, due to the low value of the technical minimum flow (10%), the central nearly does not work in optimum flow mode, and due to the low yields obtained, it is not advisable to work with this type of turbines in that mode.

Representing the energy from the flow duration, the representation of the energies in classified form is obtained, where the low production by the optimal flow operating model can be observed.



Figur8 Classified produced energy for a power station equipped with Pelton turbine (average year).

Low head stations, with open case turbines. Francis turbine.

Plant information:

- Concrete canal
- Head of 9 m.
- Nominal flow (Qn) of 9 m3/s.

From the Figure of circulating flows, for each proposed operating model the working flows are determined, as can be seen in the Figure.

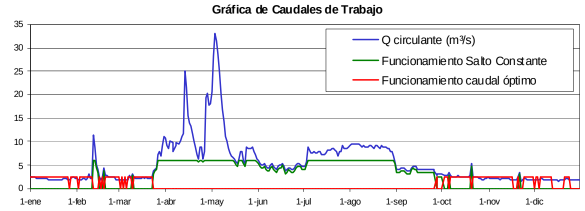


Fig. 9 Comparison of working flow to operate at constant head vs. Optimum flow. 2007 (average year).

The proposed operating model for optimal flow produces an increase in energy production of 18.54%. The turbined volume is 18.59 hm³, slightly lower than the case of turbine-powered penstock due to the largest dealer opening in the mesh. The increase in energy production is slightly lower, due to being lower than the previous head, has a greater influence on yield loss emptying due to loss of head.

Classified form productions are represented in the chart below.

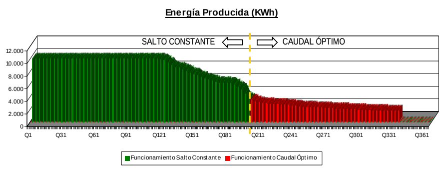


Figure 10. Classified produced energy for a power station equipped with Francis turbine of open chamber (average year).

Using Kaplan turbines.

Plant information:

- Concrete canal
- Head of 9 m.
- Nominal flow (Qn) of 6 m3/s.

Applying the optimal flow function comparing it with control at a constant head, in the figure below can be seen, for each of the circulating flows that run through the river (blue function), the working flow for conventional operating with constant head (green function) and the working flows with the new algorithms implemented, working with optimum flow (red function).

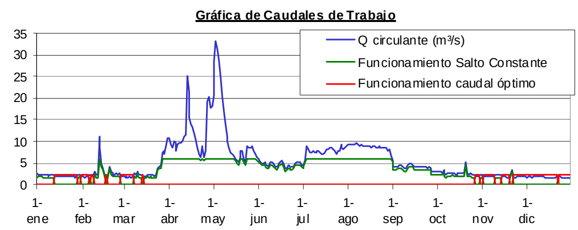


Figure. 11 Comparison of work flow to operate at constant head vs. optimum flow rate; year 2007 (average year).

The proposed operating model for optimal flow produces an increase in energy production of 9.37%, much lower than that obtained if the use was provided with Francis turbines. The turbine optimum flow volume is 9.60 hm³. This is due to technical minimum flow Kaplan turbine which favors the traditional model.

Considering the use of hydroelectric power as both modes of operation, the central works for 365 days a year and a total turbine 110.54 hm ³. I.e., it runs continuously throughout the year, a 75.34% with constant head and 24.66 % with optimal flow.

From the classified flow curve, the ratio of energy produced in the use can be obtained in a classified form, noting the production by constant head (traditional operating model) and by the optimum flow (operating model proposed).

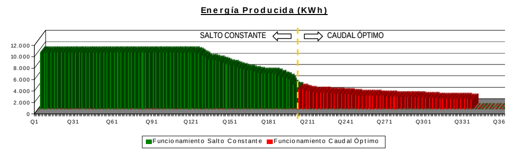


Figure 12. Classified produced energy for a power station equipped with Kaplan turbine (average year).

Conclusions

From the operation model developed by optimum flow and its application to various types of exploitations, different behaviors are observed and different production increase, depending on the type of plant and its configuration.

In the case of use of open chamber or spiral case Francis turbines, large increases in production are obtained.

The difference in the obtained productions for open chamber and spiral chamber turbines, for the same volumes in the optimum flow operating model, is due to the head difference. In the case of plants with open chamber turbines, the established head is 9 meters, rising up to 20 meters if the plant is equipped with spiral case turbines. For the same drain of conductions, the plant with lower head presents a higher percentage of loss of head, which leads to greater loss of performance.

In addition, the application of the model to Francis turbines, it can be observed that in the open chamber turbines the lost volumes until the coupling of the turbines are higher than for the spiral case turbine; thus, a better use of power plants with penstock is obtained, in addition to the previous performance improvement due to the higher head.

Plants equipped with Pelton turbines presents very low production increases, with a very low advantage derived from the implementation of the proposed operational model.

Kaplan turbines present an intermediate increase in energy production. This increase in the percentage of energy production is due to the technical minimum flow of this type of turbine, which is set at 25% of the nominal flow, which favors the implementation of the proposed model.

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