

Variable Speed Hydro Generation: Operational Aspects and Control

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Abstract— The potential advantages of variable speed hydroelectric generation are discussed in this paper. Some general aspects concerning the efficiency gains in turbines and the improvements in plants operation are analysed. The main results of measurements on a test loop with an axial-flow turbine are reported. Also we describe the control scheme implemented, which is based on artificial neural nets (ANN). In order to confirm the practical interest of this technology, the operation of a run-of-the-river small-hydro plant has been simulated over a several years period. Substantial increases in the production with respect a fixed-speed plant have been found.

Index Terms—Artificial Neural Networks, operation limits of hydro turbines, regenerative frequency converters, variable-speed hydro generation.

I. INTRODUCTION

In hydroelectric power plants the speed of the generating unit must remain constant in order to keep the synchronism with the grid. Usually, hydroturbines are optimised for an operating point defined by speed, head and discharge. At fixed-speed operation only limited deviations of head and discharge are allowed. In variable-speed turbines the allowable range of variation of the hydraulic magnitudes is enlarged, giving rise to significant advantages in the plant operation. In [1] remarkable improvements in environmental, energy and hydraulic conditions are reported.

Variable-speed technologies are presently well introduced in wind generation [2], where appreciable advantages have been found. Although the power converters increase the cost of the generating facility, the improvements in operation that may result, and the potential net benefits that can be obtained make this option reasonably attractive. The aim of this paper is to discuss the possible advantages of using these techniques

in hydro generation, considering the main aspects related with the turbine, generator, control system and operational conditions.

II. VARIABLE SPEED HYDRAULIC TURBINES

Generally speaking, the potential advantages of variable speed operation are especially found in Francis turbines with high specific speed as well as in Kaplan or propeller turbines [3].

A. Francis turbines

In Fig. 1 the hill curves of a typical Francis turbine are

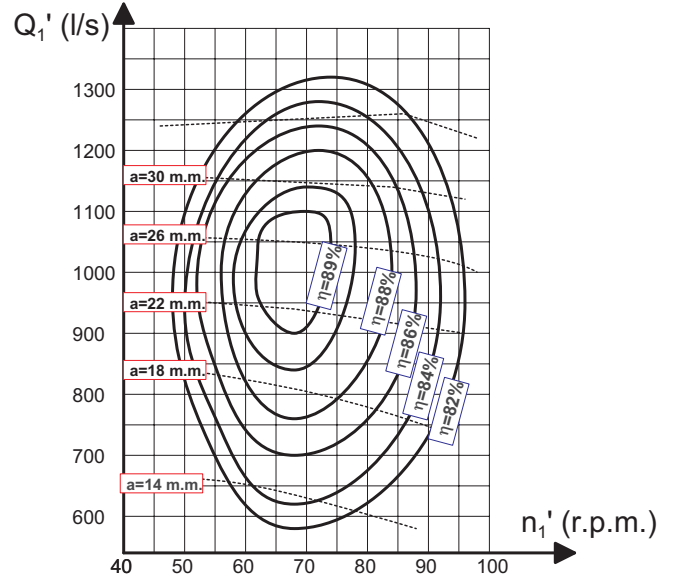


Fig. 1. Efficiency hills of a Francis turbine [4].

represented in unit values, $n_1 - Q_1$.

From this figure is clear that the efficiency drops appreciably if n_1 or Q_1 deviate from the optimal values. In a constant speed turbine this occurs when the net head H , or the discharge Q , change, as it is shown in (1).

$$\begin{aligned} n &= n_1 \sqrt{H} / D_1 \\ Q &= Q_1 D_1^2 \sqrt{H} \end{aligned} \quad (1)$$

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But if it were possible to modify the speed, n , the efficiency could be optimized for the given operating conditions.

Moreover, the speed adjustment would avoid other problems which arise when the head deviations are excessive, namely: draft tube pressure oscillations and cavitations [1], [4], [5].

B. Propeller and Kaplan turbines

The double regulation of a Kaplan turbine allows maintaining high values of efficiency in a broad range of values of head and discharge. A propeller turbine has fixed blades, its cost being appreciably lower than that of a Kaplan turbine [1]. However the efficiency drops dramatically for load values out of a narrow range in the neighborhood of rated power. As before, variable-speed operation of a propeller turbine improves substantially its performance, although keeping it below that of a Kaplan one. Moreover, in some power plant configurations it would be possible to operate without wicket gates, with the regulation provided by the speed.

Then the variable-speed propeller turbine may be a good alternative to a Kaplan turbine, because of its greater simplicity and robustness, while still maintaining good performance. The counterpart comes from the extra equipment needed for variable-speed operation on a fixed-frequency grid.

III. VARIABLE SPEED GENERATION

In medium or large size power plants a synchronous generator is generally used. Then it is possible to connect the plant to the grid through an HVDC link. This solution is very attractive in remote sites when the energy has to be transmitted across long distances [6], [7]. With this scheme the unit speed may be varied within a $\pm 25\%$ with respect to its rated value [1]. If the distances are shorter and AC transmission is used, a doubly fed generator may be used to operate at variable speed. An example of this scheme may be found in the *Compuerto* hydro plant (Spain), where the rotor of the 10 MW generator is fed by a thyristor cycloconverter [5]. Significant improvements in the power system performance, such as increased stability margin, may result in this case as reported in [8].

The recent advances in power electronics allow the application of self-commutated elements such as IGBT's, increasing the control capabilities of the converter. Double-sided inverters may work as regenerative converters [9], making it possible to raise or lower the speed. Additionally, the power factor at the grid side may be adjusted. This configuration is presently used in some wind generators.

Induction generators with short-circuited rotor, such as squirrel cage ones, are cheaper and more robust, but the rotor currents cannot be controlled as above. However in the smaller units the stator could be connected to the fixed-frequency grid through a regenerative converter, allowing the

variable-speed operation. Obviously, in these cases the converter must be sized for the total generator power. This option will be examined in the following paragraphs.

IV. EXPERIMENTAL WORK

A. Description of the test facility

In the Hydraulics Laboratory of the E.T.S. de Ingenieros de Caminos (Polytechnic University of Madrid) some tests on a tubular microturbine have been done [10]. The position of the runner blades must be maintained during operation. The turbine shaft is coupled to an asynchronous machine through a torque transducer, and both machines turn at the same speed. The electrical machine is connected to the A.C. grid through a regenerative frequency converter.

In Fig. 2 a diagram of the test loop is shown. The pump is operated by a variable speed drive. Thus, the net head applied to the turbine varies accordingly. The turbine and the asynchronous machine turn at the same speed, its value being very close to the synchronous speed. Thus it may be changed by the regenerative converter by adjusting the frequency in the

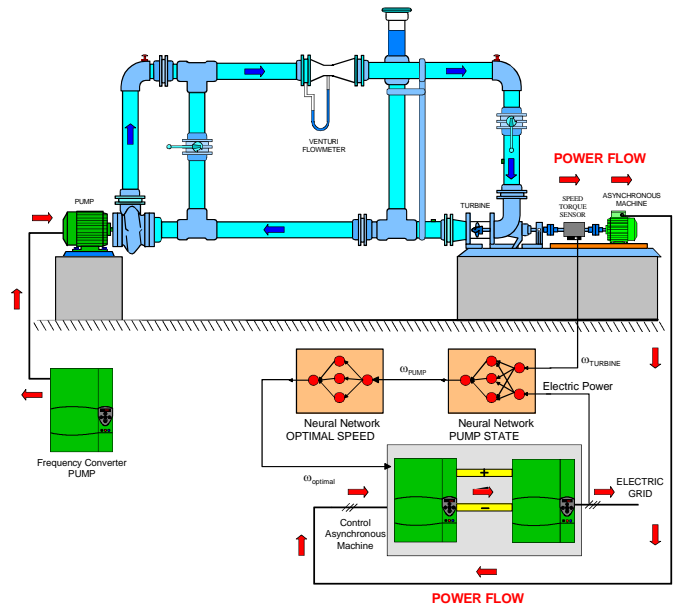


Fig. 2. Test facility.

stator side. In that way a variable-head, variable-speed turbine results. Of course the discharge through the turbine is determined by the hydraulic characteristics of this machine and the test loop, once the pump and turbine speeds are fixed.

In Fig. 3 some of the more relevant test results are shown. The discharge (Q) and the net head (H_n) are directly measured by suitable hydraulic instrumentation and define the power taken by the turbine. The efficiency value corresponds to the turbine alone and it is obtained from the mechanical power calculated from the values of the shaft speed and mechanical torque.

The $H_n - Q$ curves are fairly near to the theoretical ones; but the efficiency curves contain some irregularities, probably because of their higher sensitivity to measurement errors. In any case, the effects of varying the turbine speed are

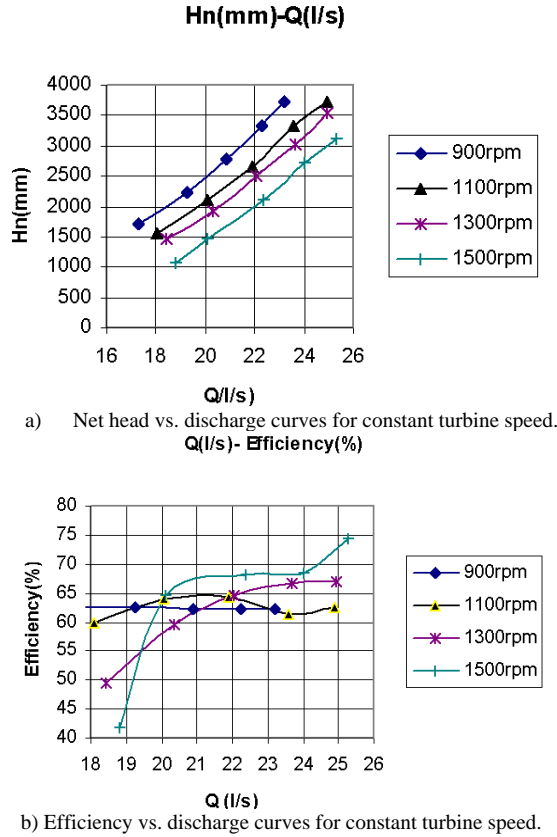


Fig. 3. Experimental results.

significant, and an optimal turbine speed may be found for each discharge value.

B. Control of the turbine speed

The axial-flow turbine installed has no wicket gates, so that the turbine speed is the unique control variable. Hydraulic operational conditions are defined by the pump speed, which determines the gross head for the turbine. A controller has been designed and implemented that selects the optimum speed for the actual conditions. The operation points included in Table I (see Appendix) are used for this task that is carried out in two steps:

- The first step is to estimate the state of the system, given by the speed of the pump. This variable should be obtained from the measured values of turbine speed and generated power.
- The second step is to find the optimal turbine speed that corresponds to the actual system state. Such value determines the desired frequency in the machine side of the regenerative converter.

Each step is performed by an Artificial Neural Network (ANN), implemented in MATLAB-Simulink®, which receives information from the system by means of a data acquisition card.

In the lower part of the Fig. 2 a diagram with the signal and power connections is included. The first step of the control

process is performed by the ANN labelled “PUMP STATE”; while the second step is carried out by the ANN denominated “OPTIMAL SPEED”.

Both Neural Networks are of the type *multilayer-perceptron* [11]. The first one has 2 neurons in the input layer, 8 neurons in the hidden layer and 1 output neuron determining the estimated pump speed. The second ANN has a similar structure with 1 neuron in the input layer, 5 neurons in the hidden layer and 1 neuron in the output layer, giving the optimal value of the turbine speed. The hidden layers of both Neural Networks are of the type *tansig*, while the output layer is linear.

The Neural Networks are trained by means of a modified back-propagation algorithm, based on the Levenberg-Marquart method [11], which allows reducing the training time and improves the convergence as compared with the

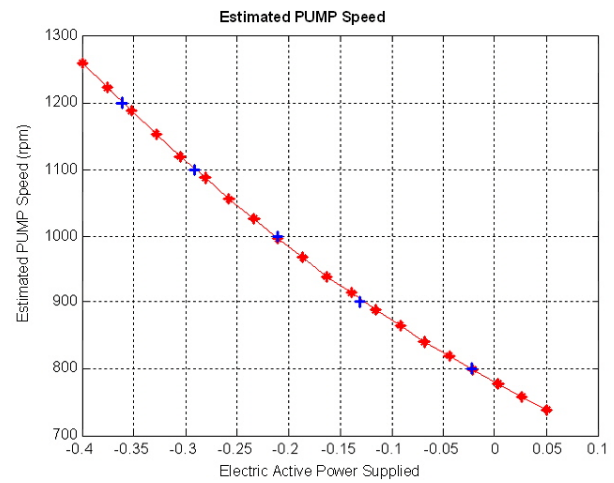


Fig. 4. Response of the Neural Network “PUMP SPEED” x : measured points ; ♦ : ANN response (the turbine speed is fixed at 1200 r.p.m.)

classical training algorithm.

Fig. 4 shows the response of the first Neural Network and the good agreement with experimental data.

The output of this ANN is considered as an estimation of the system state, which is used by the second Neural Network

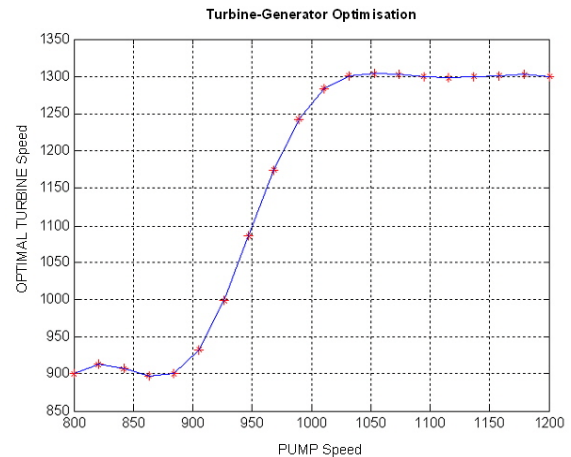


Fig. 5. Optimal turbine speed as a function of system state: + ANN response; ---: interpolated response.

to determine the turbine speed giving the highest efficiency. Fig. 5 presents the results for the tested system.

It is clearly shown that for high values of the gross head (represented here for the pump speed) the turbine speed should be adjusted in the range of 1300 rpm; while for low heads the optimum efficiency of the turbine is reached when its speed approximates the value of 900 rpm. Obviously, there

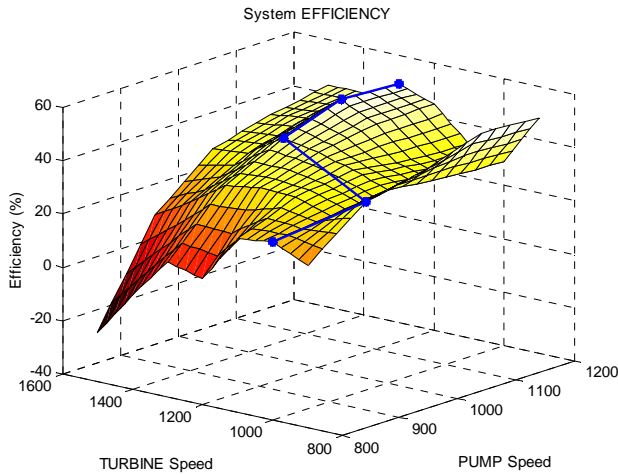


Fig. 6. Efficiency vs. turbine and pump speeds

exists a smooth transition between both regions.

The dependence of the efficiency vs. the turbine speed for each pump speed is shown in Fig. 6. The line detached on the surface links the optimum efficiency points.

The used frequency converter must be able to operate within the frequency limits imposed by the optimal turbine speed variations. In this case, assuming that the synchronous speed were 1000 rpm, the required range of frequency variation would be (+ 30% , - 10%).

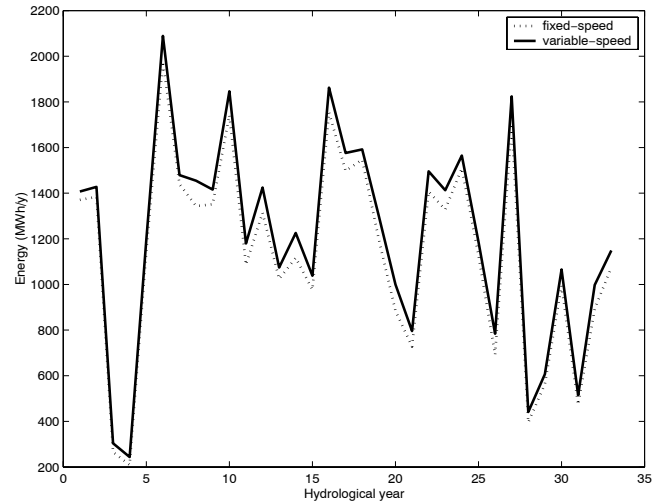
V. SIMULATION OF A RUN-OF-THE-RIVER SMALL-HYDRO PLANT

An evaluation of the improvements that may be obtained in a run-of-of the-river small-hydro plant has been done. The plant to be analysed is a low-head scheme without any storage capacity; so its environmental impact may be reduced to a minimum. The plant is located on a river in the north-west of Spain. An historical series of average daily flow along 35 years has been used.

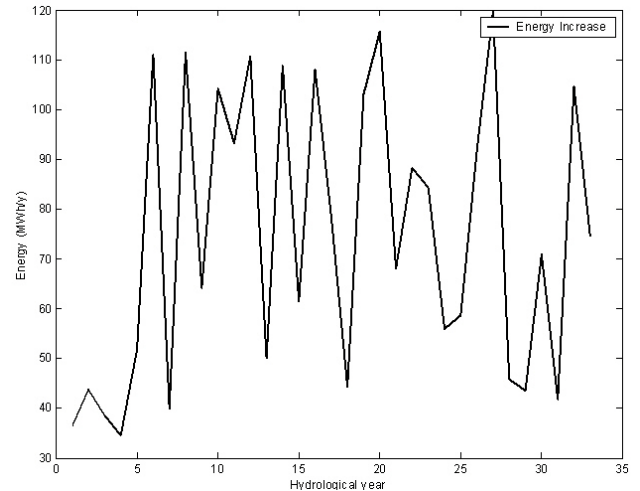
The flow available for generation corresponds to the excess of the inflow over a minimum flow required for maintaining the biological conditions in the river. As there is no storage capacity, the flow is kept constant along each interval of 24 h. The forebay elevation is supposed to be constant along the whole simulation period. The generating unit is operated when the available discharge is within turbine allowable working limits; at this respect it is worth to notice the enlargement of

the turbine allowable operating region due to variable speed.

The turbine speed is adjusted to achieve the maximum efficiency with the given values of head and flow. As this kind of power plants is usually unattended, an automatic



a) Fixed-speed vs. variable-speed



b) Energy Increase. Difference between variable-speed and fixed-speed generation

Fig. 7. Comparison of fixed-speed and variable-speed generation

controller similar to that described above should be used.

In Fig. 7a the yearly generation obtained with optimum speed is compared with that obtained with fixed-speed.

An annual average increase of 74.5 MWh is achieved, which represents 6.5 % of the average fixed-speed generation, 1136.9 MWh/y. This result corresponds to a head of 4.99 m and supposes a significant improvement in the exploitation of the resource. Additionally, it is interesting to note that with a smaller head of 4.0 m, the generated energy would be only 838.2 MWh/y, but the increase obtained with variable speed operation would reach a greater value, 114.5 MWh/y, the p.u. increase being almost twice than before.

VI. VARIABLE-SPEED OPERATION OF HYDRO PLANTS: SOME GENERAL CONSIDERATIONS

The increase in capital invested in the plant to account for the electronic converter needed for variable-speed generation, should be compensated with the improvements gained in operation. Although this question is to be analysed in detail in each particular case, some general aspects may be highlighted.

In hydro plants with some regulating capacity provided by a reservoir, if the turbine may run at variable speed, the allowable range of stored volumes for operation becomes significantly larger. This would avoid the shut down of the plant when the reservoir level is too low for normal speed operation. Moreover, it results in greater flexibility in the dispatch and more opportunities for allocating the produced energy in the electric system. Alternatively, for the same regulation capacity, the reservoir area could be reduced with the consequent benefits in the environmental impact.

Campos Barros et al. have studied the behaviour of several hydro plants of different characteristics in Brasil. The variable-speed operation of these plants has been simulated by the authors, and the results of the study are reported in [1]. In those plants with great reservoirs the preceding estimations are confirmed in that respects to the head variations; namely, either the energy generated is increased or, if the amount of energy is maintained, the flooded area may be reduced.

Concerning the run-of-the-river hydro plants, it is worth it to consider the better fit of a variable-speed unit to the river flows. The continuity in operation would be greater, resulting in a reduction of the number and duration of stops. Thus, some environmental benefits may also result downstream on the river. If the plant has a small reservoir, the head variations may be significant, and the improvements in the turbine efficiency gained running at variable speed, result in an increase of the generated energy.

VII. CONCLUSIONS

The application of variable speed generation schemes to hydroelectric power plants offers a series of advantages, based essentially on the greater flexibility of the turbine operation in situations where the flow or the head deviate substantially from their nominal values. Specifically, the following aspects may be emphasized:

- 1) In general, the improvements in the turbine efficiency are greater when the more important variations correspond to the head, rather than to the flow. Then, the variable-speed option would be more advantageous for high specific speed turbines.
- 2) The possibility of running the turbine at a variable speed, may avoid some situations with bad hydraulic conditions, giving rise to cavitations or draft tube oscillations.
- 3) In hydro plants with reservoir, the operating range of head variations can be increased, thus reducing the needs for

flooded area.

- 4) In the run-of-the-river hydro plants the continuity of operation may be increased because the higher range of allowable flows in the turbine.
- 5) A control system, based in Artificial Neural Networks has been developed to adjust automatically the speed of the turbine to the existing operating conditions.
- 6) The feasibility of this concept has been demonstrated in a small laboratory facility, where commercial frequency converters have been used.
- 7) A simulation performed on a run-of-the-river small-hydro plant confirms that significant gains in generated energy

TABLE I
MEASURED OPERATION POINTS

P_{trif} (kW)	Efficiency (%)	Turbine speed (rpm)	Pump speed (rpm)
-0,061	21,15	903	800
-0,16	37,79	903	900
-0,241	42,24	903	1000
-0,361	49,64	903	1100
-0,411	48,28	903	1200
-0,08	27,06	1000	800
-0,13	29,84	1000	900
-0,19	32,31	1000	1000
-0,23	30,02	1000	1100
-0,27	29,03	1000	1200
-0,07	25,26	1100	800
-0,14	33,75	1100	900
-0,21	36,90	1100	1000
-0,26	33,77	1100	1100
-0,3	32,84	1100	1200
-0,022	7,48	1200	800
-0,131	34,46	1200	900
-0,211	40,63	1200	1000
-0,291	44,17	1200	1100
-0,362	44,78	1200	1200

may be obtained.

APPENDIX

ACKNOWLEDGMENT

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