Maximum Efficiency Point Tracking for Adjustable-Speed Small Hydro Power Plant

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***Abstract*— The paper presents the general scheme and the relevant implementation of a Maximum Efficiency Point Tracking (MEPT) system for a Small Hydro Power (SHP) plant equipped with a variable-speed generator. This last consists of a Doubly Fed Induction Generator (DFIG) and a power electronic converter that independently controls both the rotor speed and the generator power factor. The MEPT is designed to be used with a propeller turbine with adjustable runner blade angle and it is coupled with the headwater level regulator. Such a regulator imposes the water flow to the turbine. The conceived MEPT periodically tries to improve the production efficiency by solving a constrained optimization problem, subject to the feasibility operating constraint of the SHP unit and to the equality constraint which forces to meet the water flow value provided by the headwater regulator.**

***Index Terms*—Hydro power plant, adjustable-speed generation, maximum efficiency point tracking.**

I. NOMENCLATURE

Parameters

D	turbine reference diameter;
g	acceleration of gravity;
$\Omega_{\alpha,\beta,n}$	set of the admissible values of α, β, and n;
Q_{min}	minimum values of the turbine discharge;
Q_{max}	maximum values of the turbine discharge;
ΔQ_{max}	maximum allowed Q rate variation;
ρ	water density.

Variables

t	period of time;
α	wicket gate opening;
β	runner blade angle;
η_T	efficiency of the turbine;
η_G	efficiency of the generator;
f_h	function representing the relationship between net head, headwater and tailwater levels and water flow;
f_q	function providing the value of water flow Q_b released through the weir spillways;
H_b	water level at the weir that should be kept above concession level $\bar{H}_b$;
H_{bc}	level in the small reservoir (i.e., the headwater level);
H_s	turbine tailwater level;
H	turbine net head;
n	turbine speed;
P	plant power output;
pf	power factor;
Q	turbine water flow rate;
u	1-0 binary variable that identifies if the plant is in operation or not.

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II. INTRODUCTION

SMALL hydro power (SHP) installations are supported by several programs for the development of renewable resources. Whilst large hydropower stations involve large-scale environmental integration activities, these problems are, in general, not very significant for the case of SHP installations up to 10 MW. On the other hand, modern SHP applications require dedicated equipment to improve the generation efficiency, taking into account the need to limit the environmental impact.

Usually, the superior characteristics of synchronous generators force to choose to operate hydraulic turbines at fixed speed. However, the efficiency of these production units can be increased by using variable speed generators [1-13]. As shown in Fig. 1, for the case of constant head H, when the water flow varies from Q_a to Q_b it is more convenient to run the unit at speed n_b rather than n_a, in order to operate at a better efficiency point. Moreover, the variable speed operation may alleviate draft tube surging and cavitation problems. Adjustable speed hydro plants may also provide additional means for the enhancement of power system stability [9,10].

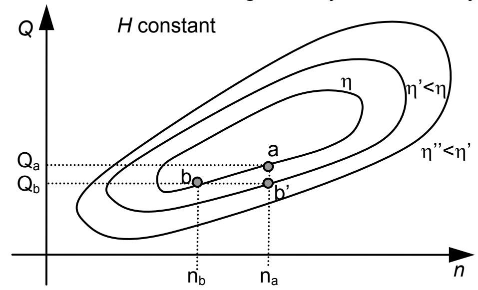


Fig. 1. Example of a efficiency hill diagram of a turbine for constant net head H, with contours of equal efficiency η. [1]

[1], The turbine hill diagram are usually represented by using the so-called unit variables Q_1 and n_1, defined according to similarity laws ($Q_{11} = Q \big/ \left(D^2 \sqrt{H}\right)$ and $n_{11} = n \cdot D \big/ \sqrt{H}$, where D is the turbine reference diameter) [16].

Especially for the case of large production units with pumping capability, among different possible solutions, adjustable speed hydro units are often conceived with Doubly-Fed wound-rotor Induction Generators (DFIG) fed on the rotor side either by cycloconverter [2,7] or by two PWM inverters, which are back-to-back connected [12]. For power plants located in remote sites becomes also sometimes convenient the connection to the grid through a High Voltage Direct Current (HVDC) link that allows a unit speed variation of ±25% [3,5]. For small applications, other solutions are also proposed in the literature, namely the use of two cascaded induction generators [11] or the connection of a short-circuited rotor induction generator to the grid through a regenerative PWM converter sized for the total generation power [13].

This paper deals with the problem of the optimal selection of the operating control variables of an adjustable speed hydro unit. In particular, we consider the case of a low-head river power plant with a double regulated axial tubular turbine (TT), in which both wicket gate opening α and runner blade angle β should be controlled. The considered control variables, therefore, are three: n, α and β. The conceived Maximum Efficiency Point Tracking (MEPT) system starts from an initial non-optimal condition and tries to improve the production efficiency by applying the steepest gradient method [14]. The selection of the steepest gradient method has been chosen as a first option and based on its relative simplicity and minimal computational cost of each MEPT iteration.

The MEPT is also coupled with the water level control system. In fact, river power plants are commonly sited where there the storage capability is mimimal and where flows can fluctuate widely as a function of normal and abnormal precipitation, snow melting, and releases from upstream plants. Therefore, in order to maintain a reasonable head on the turbine, the unit should operate almost at the same water flow that enters the system. Otherwise, there is a waste of energy associated to the spilling of unused water or the headwater is drawn down to an unacceptable level with respect the concession level imposed by the Authorities. The commonly employed control concept for the regulation of the water level consists of a Proportional-Integral (PI) controller, with an additional feed-forward term in case of available information on the incoming river water flow at some distance upstream of the SHP plant. For the case of cascades of several power plants, in which also the damping of the discharge variations must be considered as an additional objective in the controller design, Model Predictive Control (MPC) schemes have been proposed (e.g., [15]).

The structure of the proposed paper is the following. Section III presents the formulation of the problem. Section IV presents the scheme of the MEPT system. The paper contains, in Section V, the validation of the proposed MEPT implemented in a PC based Data Acquisition and Control (DAQ) system coupled with a real time emulator of a 400 kW SHP unit realized with the DS-1104 dSpace DSP [17]. The emulator model refers to a power plant recently built, whose characteristics have been inferred from experimental measurements and for which the MEPT has been designed. The conclusion of the paper identifies the topics that need a further research effort.

III. THE PROBLEM

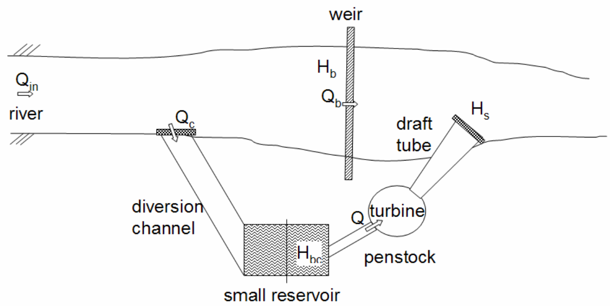


Fig. 2. Scheme of a river power plant, where the turbine is located in a man-made channel in parallel to the natural river course.

With reference to the scheme of Fig. 2, the general problem can be stated as

$$[\alpha_t,\beta_t,n_t] = \arg\max_{\alpha,\beta,n} \int P_t dt \tag{1}$$

subject to

$$H_{b,t} \geq \bar{H}_b \tag{2}$$

$$\alpha_t,\beta_t,n_t \in \Omega_{\alpha,\beta,n} \tag{3}$$

$$u_t\,\mathrm{Q}_{\min} \leq Q_t \leq u_t\,\mathrm{Q}_{\max} \tag{4}$$

$$-\Delta\mathrm{Q}_{\max} \leq Q_t - Q_{t-1} \leq \Delta\mathrm{Q}_{\max} \tag{5}$$

with

$$P_t = \rho g\, H_t\, Q_t\, \eta_T\left(\alpha_t,\beta_t,n_t,H_t\right)\eta_G\left(P_t,n_t,pf_t\right) \tag{6}$$

$$H_t = f_h\left(H_{bc,t},H_{s,t},Q_t\right) \tag{7}$$

$$Q_{b,t} = f_q\left(H_{b,t}\right) \tag{8}$$

where subscript t indicates a period of time.

H_b, H_{bc} and H_s can be calculated by using a hydraulic model of the river [15], as a function of the river water flow value Q_{in}.

IV. SCHEME OF THE CONCEIVED MEPT

In the following, we consider an efficiency function η that aggregates both η_T and η_G. Moreover, we suppose operating conditions at constant value of pf.

Under the assumptions, which should be verified for each application, that P always increases with the increase of the value of Q, i.e.

$$\bar{Q} = \arg\max P\left(H,Q,\eta\right) \quad \forall Q \leq \bar{Q}, \tag{9}$$

we can write for each period t

$$[\alpha,\beta,n] = \arg\max_{\alpha,\beta,n} P \; = \arg\max_{\alpha,\beta,n} \eta\left(\alpha,\beta,n,H\right) \tag{10}$$

subject to constraints (3) and to the equality constraint

$$Q = \bar{Q} \tag{11}$$

where $\bar{Q}$ is provided as solution of the following optimal control problem of H_b

$$\left[\bar{Q}_t, u_t\right] = \arg\min_{Q_t, u_t} \int \left(H_{b,t} - \bar{H}_b\right)^2 dt \qquad (12)$$

subject to (2), (4) and (5).

The above described scheme is illustrated in Fig. 3.

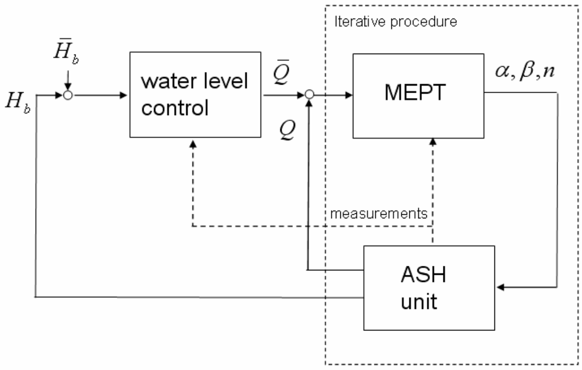


Fig. 3. Scheme of the conceived MEPT.

In what follows, problem (10) is indicated as MEPT problem.

The MEPT procedure starts from non-optimal SHP condition, characterized by values α_0, β_0, n_0, and tries to improve the production efficiency by applying the gradient method.

If, at a time t, the error on the constraint (11) becomes excessive, the MEPT algorithm is bypassed and the water level control acts directly to α and β.

For the solution of the MEPT problem, two different conditions can be distinguished:

A) low value of river water inflow Q_{in} ($Q_{in} \leq Q_{max}$): in this condition water level H_b is kept equal to the concession level $\bar{H}_b$ by limiting the water flow Q discharged by the hydro unit;

B) high value of river water inflow Q_{in} ($Q_{in} > Q_{max}$): in this condition $H_{b,t} > \bar{H}_b$ and therefore, under hypothesis (9), the plant should operate at $Q = Q_{max}$, being the limits on the value of α, β and n, as represented by (3), sufficient to guarantee the safety of the hydro unit.

The following paragraph describes in detail the procedure for the more complex case of operating condition A). In condition B) the MEPT algorithm is simpler than for the previous condition, as does not include equality constraint (11).

A. Constrained MEPT procedure

Starting from operating point $\alpha=\alpha_0$, $\beta=\beta_0$ and $n=n_0$, when $Q=Q_0$ and $\eta=\eta_0$, the efficiency gradient components are experimentally determined as the unit response to small control variable variations

$$\nabla_{\eta,\alpha} = \left.\frac{\partial \eta}{\partial \alpha}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}}, \; \nabla_{\eta,\beta} = \left.\frac{\partial \eta}{\partial \beta}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}}, \; \nabla_{\eta,n} = \left.\frac{\partial \eta}{\partial n}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}} \qquad (13)$$

Then, the MEPT procedure increases the initial values of the control variables following the direction of the gradient components multiplied by a positive factor k

$$\Delta\alpha = k \left.\frac{\partial \eta}{\partial \alpha}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}}, \; \Delta\beta = k \left.\frac{\partial \eta}{\partial \beta}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}}, \; \Delta n = k \left.\frac{\partial \eta}{\partial n}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}} \qquad (14)$$

For a sufficiently small value of k, the variations given by (14) correspond to an increment of the unit efficiency, and, therefore, by repeating experimentally the gradient component determination and the application of the variations provided by (14), allows to reach the maximum efficiency operating point.

In order to take into account the equality constraint (11), the procedure determines also the gradient components of Q through the same three tests used to obtain the η-gradient components

$$\nabla_{Q,\alpha} = \left.\frac{\partial Q}{\partial \alpha}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}}, \; \nabla_{Q,\beta} = \left.\frac{\partial Q}{\partial \beta}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}}, \; \nabla_{Q,n} = \left.\frac{\partial Q}{\partial n}\right|_{\substack{\alpha_0\\ \beta_0\\ n_0}} \qquad (15)$$

Constraint (11) can be written as

$$\nabla_{Q,\alpha}\Delta\alpha + \nabla_{Q,\beta}\Delta\beta + \nabla_{Q,n}\Delta n = -\left(Q_0 - \bar{Q}\right) \qquad (16)$$

with the objective of correcting the initial flow mismatch. It links the value of the control variable to the values of the other two.

It appears convenient, as it will be shown later, to chose a variable whose variations has a significant influence on Q. As such an influence is dependent on the current value of the variables, at each MEPT iteration such a variable is selected as the one characterized by the largest value among the Q-gradient component (15). We report here the equations relevant to the case in which variable α has the largest value of $\nabla_{Q,\alpha}$. The equations relevant to the other two cases have the same structure.

By stating α as a function of β and n,

$$\Delta\alpha = B_{\alpha\beta}\Delta\beta + B_{\alpha n}\Delta n - \left(Q_0 - \bar{Q}\right)/\nabla_{Q,\alpha} \qquad (17)$$

where

$$B_{\alpha\beta} = -\frac{\nabla_{Q,\beta}}{\nabla_{Q,\alpha}}, \; B_{\alpha n} = -\left.\frac{\nabla_{Q,n}}{\nabla_{Q,\alpha}}\right| \qquad (18)$$

the efficiency variation is:

$$\begin{aligned}\Delta\eta &= \nabla_{\eta,\alpha}\Delta\alpha + \nabla_{\eta,\beta}\Delta\beta + \nabla_{\eta,n}\Delta n = \\ &= \left(B_{\alpha\beta}\nabla_{\eta,\alpha} + \nabla_{\eta,\beta}\right)\Delta\beta + \left(B_{\alpha n}\nabla_{\eta,\alpha} + \nabla_{\eta,n}\right)\Delta n \\ &\quad -\left(Q_0 - \bar{Q}\right)\nabla_{\eta,\alpha}/\nabla_{Q,\alpha}\end{aligned} \qquad (19)$$

and, therefore, the variations of the control variables are

$$\Delta\beta = k\left(B_{\alpha\beta}\nabla_{\eta,\alpha} + \nabla_{\eta,\beta}\right) \qquad (20)$$

$$\Delta n = k\left(B_{\alpha n}\nabla_{\eta,\alpha} + \nabla_{\eta,n}\right) \qquad (21)$$

where k is the gain of the applied variations, whilst $\Delta\alpha$ is given by (17).

If one of the variables reaches the maximum limit or the minimum one, the gradient control algorithm is applied to the remaining two variables.

Once the direction for the modification of variables α, β and n is found, the control algorithm keeps updating the variables until the efficiency increase becomes smaller than a predefined percentage of the expected variation provided by (19) or the violation of constraint (11) becomes larger than a predefined value.

The MEPT action is also stopped and the α, β and n values are kept constant when the η-gradient components and constraint (11) current violation are lower than a predefined tolerance.

When the MEPT action is too slow to follow rapid variations of the river flow Q_{in}, MEPT is stopped and control variables α and β are adjusted by a traditional PI level regulator through a α-β coordinating relationship, whilst n is kept constant.

B. MEPT procedure for large values of river water flow

In operating condition B), as already mentioned, the efficiency maximization may be replaced by a unit-output unconstrained maximization procedure, if concession limits imposed directly on the value of Q are neglected.

V. MEPT TUNING AND VALIDATON BY MEANS OF A REAL TIME EMULATOR OF AN AJUSTABLE-SPEED SHP UNIT.

A preliminary version of the proposed MEPT algorithm has been implemented in a computer based Data Acquisition and Control System (DAQ), composed by two 6062E PCMCIA National Instruments boards, by using the LabView programming environment.

The MEPT tool has been validated by means of its coupling with a digital real time emulator of a SHP unit realized with the DS-1104 dSpace DSP [17].

This section describes the SHP-unit dynamic model and the tests carried out for a first MEPT validation and tuning of the main algorithm parameters.

A. Dynamic model implemented in the SHP unit emulator

The emulator refers to a recently built hydro power plant for which the MEPT has been designed. The power plant has the structure illustrated in Fig. 2 and it is equipped with a near-weir 700 kW DFIG SHP unit, with maximum water flow Q_{max} of about 9 m^3/s and a net head at Q_{max} equal to 8.4 m.

The weir forms a small upstream reservoir whose extension is estimated as 6400 m^2. The concession water level at the weir $\bar{H}_b$ is equal to 10.51 m. The man made channel is 30 m long, with a section area equal to 8 m^2. At the end of the channel is located a 150 m^2-large stilling basin with volume equal to 570 m^3. A 35 m long penstock, with a diameter of 2.2 m feeds a vertical axis propeller turbine, which is, as mentioned, a double regulated axial tubular turbine (TT), in which both wicket gate opening α and runner blade angle β are adjustable. From the turbine, the water is discharged to the river trough a 30 m-long 90°-curved draft tube and tailrace.

The model has been developed in Matlab-Simulink and implemented as a real time process in the dSpace DSP. The model includes the upstream reservoir dynamic behavior for the calculation of the water level at the weir H_b, the estimation of the overflow discharged through the weir Q_b, the calculation of the tailrace elevation H_s and penstock head loss for the estimation of the net head H. The dynamic model of the elastic water column in the penstock is introduced [18] whilst the short man-mad channel dynamics are neglected. The model of the turbine is based mainly on two look-up tables having as independent variables the angular position of the fixed and of the rotating vanes (i.e., α and β) and the rotational speed n, as illustrated in Fig. 4. These tables provide the efficiency η_T and the discharge of the hydro-turbine Q, respectively, and have been inferred from experimental measurements carried out in a SHP similar to the one considered in this paper [19], as described in the following paragraphs. The model of the power plant is completed by a simple model of the adjustable speed generator that allows n-variations between 350 rpm and 400 rpm, taking into account the rotor dynamic, and by the model of the PI level regulator, which includes the delays introduced by the electro-hydraulic servo drives for the α and β variation.

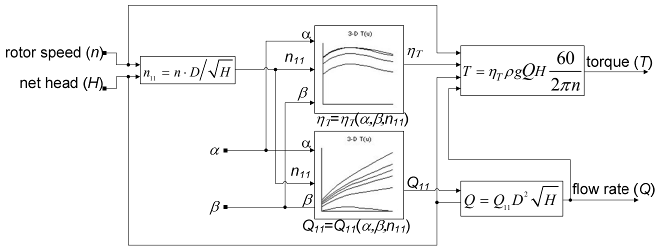


Fig. 4. Hydro turbine model block diagram.

The performances of the hydro turbine were calculated according to European standards [20-22], by measuring the net electrical output power and taking account for the losses in the electrical generator obtained by separated tests performed. The incoming hydraulic power was calculated by measuring the pressure drop through the hydro turbine by means of two pressure transducers placed respectively before the turbine input flange and at the exit of the drat tube. The flow rate was measured by an ultrasonic flow device having double track, embedded in the penstock.

The possibility of adjusting the guide vanes independently of the impeller blades allowed to obtain a full set of working points and to individuate the best configuration in a wide range of values of the flow rate, as illustrated in Fig. 5, but for a single value of the rotational speed only, as the turbo generator under test is equipped with a synchronous generator. In order to have a first estimation of the behavior of the hydro-turbine within the expected range of the rotational speed, transposition rules based on similarity laws were applied.

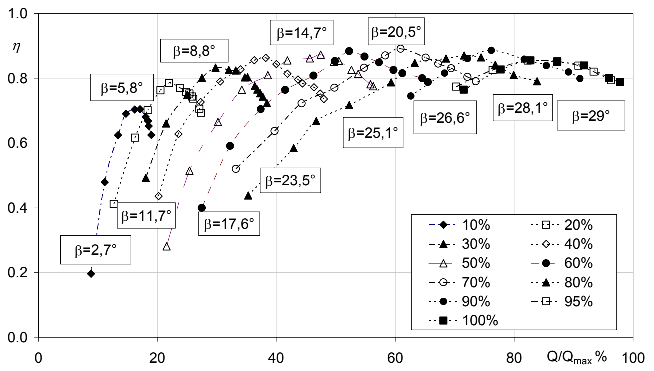


Fig. 5 Hydro turbine efficiency η_T at constant speed as a function of the flow rate Q. Single curves are obtained by varying wicket gate opening degree for a fixed propeller blade angular position.

B. Examples of validation tests results

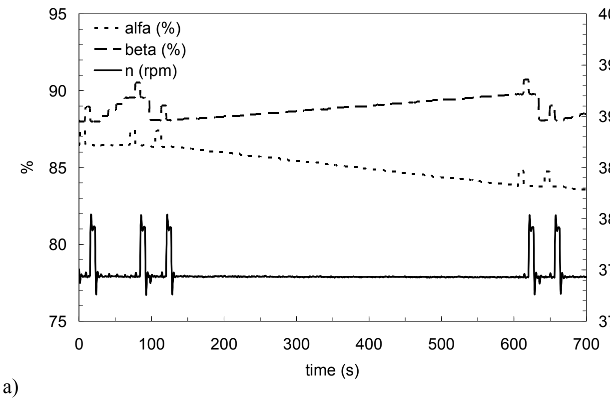
Several tests have been carried out in order to set up and validate the MEPT algorithm. We here present a typical result relevant to the application of the developed MEPT algorithm that makes reference to the conditions in which $Q_{in} \leq Q_{max}$. We have found similar results starting from different non-optimal steady state conditions of the SHP. Field tests are needed to tune the proposed MEPT algorithm taking into account the presence of measurement fluctuations and errors.

Fig. 6 shows the behavior of the MEPT algorithm starting from the following non-optimal steady state condition: $Q_{in}=\bar{Q}=Q=7$ m^3/s, $Q_b=0$, $H_b=10.51$ m, $\alpha=86.5\%$, $\beta=88.1\%$, $n=375$ rpm, $P=541$ kW, $\eta=81.7\%$.

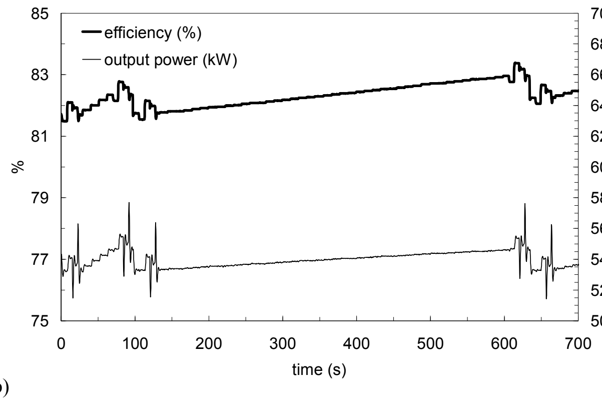
As shown in the first 20 s of Fig. 6a), the MEPT algorithm applies three small subsequent variations to the control variables α, β, and n equal to 1%, 1%, and 5 rpm, respectively. After each variation, a delay is applied before storing the relevant updated values of η and Q in order to reach the SHP efficiency and water flow steady state conditions. For the implemented model, the delay of 6 s has been found to be the minimum adequate delay to satisfy the above condition.

After the accomplishment of all the three tests, the η and Q-gradient components are calculated and control variable β, characterized by the largest value of Q-gradient component, is selected to adjust the Q value taking into account the reference value $\bar{Q}$. Then, the values of $\Delta\alpha$, $\Delta\beta$, and Δn are calculated by using the equations reported in the previous section.

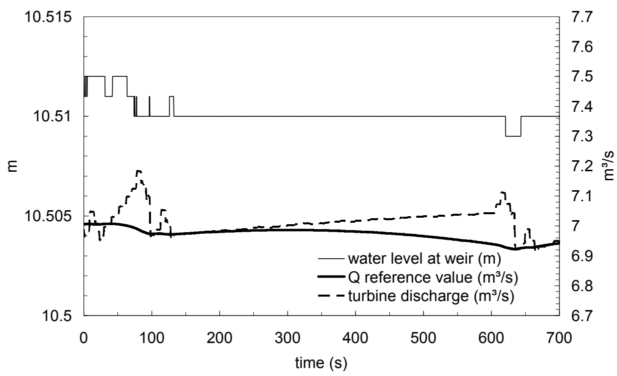
Fig. 6 shows that after the first control cycle, the MEPT algorithm keeps updating the control variable, every 6 s, along the same direction until, as shown in Fig. 6c), the difference between Q and $\bar{Q}$ becomes larger than 0.1 m^3/s. Then, the MEPT applies again two times the procedure estimate the η and Q gradient components. The first MEPT cycle permits to find new $\Delta\alpha$, $\Delta\beta$, and Δn values that adjust the Q value, whilst the second cycle finds the new direction for the efficiency increase (see Fig. 6b). This last direction is kept unchanged until 606 s when the difference between Q and $\bar{Q}$ becomes again larger than 0.1 m^3/s.



a)



b)



c)

Fig. 6. SHP behavior during MEPT action starting form non-optimal steady state condition: a) α, β, and n variations, b) η and P behaviour, c) Q , $\bar{Q}$ and H_b behavior.

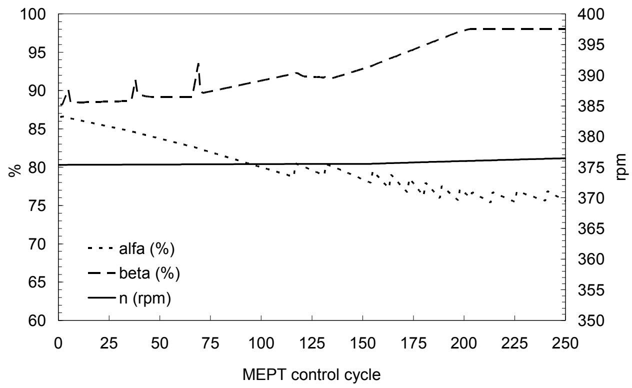
Fig. 7 shows the values of the SHP quantities at the end of each MEPT cycle starting from the same initial condition of Fig. 6.

Fig. 7b) shows that the METP action is able to reach a new steady state condition characterized by higher values of both efficiency and power output, namely 87.8% and 577 kW. For this case, as shown in Fig. 7a), β control variable reaches its maximum value of 98% in correspondence of the reaching of the maximum efficiency and the n-variations are negligible for the efficiency hill diagram considered in the turbine model.

Fig. 7c) shows that during the METP tracking action the water level variations at the weir are kept lower than 1 cm.

Starting from the final optimal condition of Fig. 7, Fig. 8 reports the value of the SHP quantities at the end of each

MEPT cycle during three step variations of the river water flow Q_{in}, namely from 7 m^3/s to 7.5 m^3/s applied at the 32nd cycle, from 7.5 m^3/s to 7 m^3/s at the 71st cycle, from 7 m^3/s to 6.5 m^3/s at the 151st cycle.



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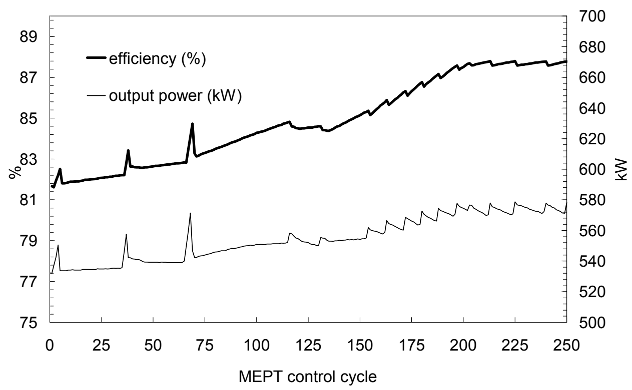

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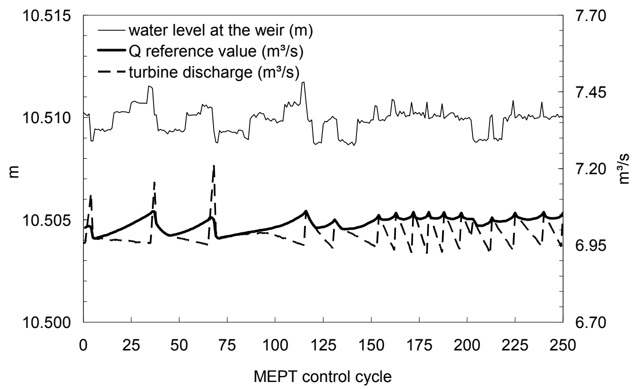
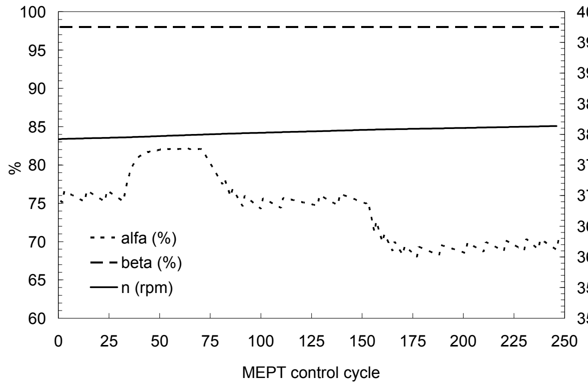


c)

Fig. 7. SHP quantities at the end of each MEPT cycle starting form non-optimal steady state condition: a) α, β, and n, b) η and P, c) Q , $\bar{Q}$ and H_b.

Fig. 8a) shows that β control variable is kept at its maximum value. Therefore the main control action is played only by α that mainly tries to track the $\bar{Q}$ variations requested by the water level control, as illustrated by Fig. 8c).

Fig. 8b), however, shows that the efficiency reduction, in correspondence of Q_{in} increase, is lower than 1% and that there is also an efficiency increase when the Q_{in} decreases, due to the non linear shape of the turbine hill diagram for the considered set of operating conditions. Indeed, also Fig. 7 shows that, in similar operating conditions, an α reduction results in a efficiency increase.



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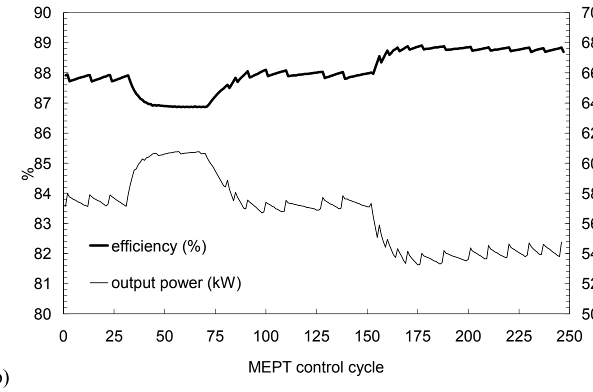

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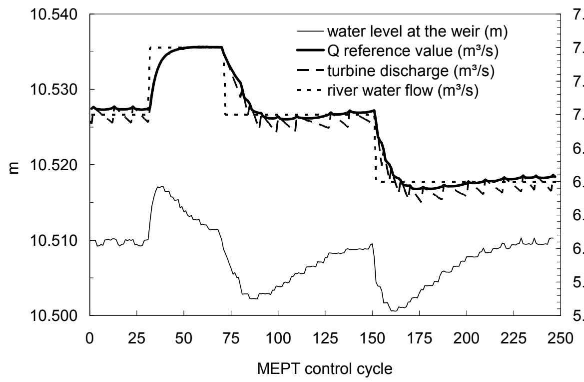

c)

Fig. 8. SHP quantities at the end of each MEPT cycle during three 0.5 m^3/s step variations of the Q_{in} value, starting form the final optimal condition of Fig. 7: a) α, β, and n, b) η and P, c) Q , $\bar{Q}$, Q_{in}, and H_b.

VI. CONCLUSIONS

The proposed MEPT algorithm, based on the application of the steepest descent gradient method, appears to be a promising tool for the exploitation of mini-hydro resources. This has been verified by implementing the proposed algorithm in a PC based DAQ system and by the tests carried out by using a real time emulator of a 400 kW SHP unit realized with the DS-1104 dSpace DSP.

The proposed MEPT algorithm allows the maximum SHP energy production from the water source taking into account the constraints relevant to the water level at the weir. In case of water levels larger than the concession one, the plant operates at its maximum water flow.

The advantages relevant to the adoption of an adjustable speed hydro unit will be also quantified by the field results obtained on a new SHP plant in which the described MEPT tool is being installed.

Further studies to improve the robustness of the MEPT algorithm will take into account the adoption of improved optimization methods (e.g. conjugate gradient).

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