Fine Tuning a PAT Hydropower Plant in a Water Supply Network to Improve System Effectiveness

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Abstract: The installation of hydropower plants equipped with pumps as turbines (PATs) in water supply systems has been demonstrated to be suitable and advantageous in order to both reduce pressure and recover energy. However, certain technical difficulties have delayed the widespread adoption of this innovative approach. The design of a hydropower plant within a water network should address three main problems, i.e., (1) the scarcity of information about PAT behavior; (2) the large and stochastic variability in the working conditions that can influence the efficiency and the reliability of the plant; and (3) the need to guarantee the correct operation of the water supply system. This paper presents a new regulation procedure based on the maximization of an upgraded version of the plant effectiveness, which takes into account the plant efficiency, reliability, and sustainability. Four plant regulation schemes are presented. A stochastic model is used to simulate the fluctuations of the hydraulic characteristics, while the PAT behavior has been calculated with a recently developed model that revises the turbomachinery affinity equations. A case study demonstrates the application of the new procedure with reference to a pressure reducing station in southern Italy and a semiaxial PAT. **DOI: 10.1061/(ASCE)WR.1943-5452.0000961.** *© 2018 American Society of Civil Engineers.*

Introduction

Pump turbines are commonly used in pumped storage hydropower plants, where pump turbines transfer water to a high storage reservoir during off-peak hours. The stored water can later be used to generate electricity to cover temporary peaks in demand from consumers or unplanned outages at other power plants. The power of such plants is generally of the order of hundreds of megawatts. Thus, the pump turbines are designed ad hoc, often with the help of experimental investigations because the high investment costs can be balanced by the large amount of produced energy (Deane et al. 2010). In contrast, the values of discharge and head, if compared with pumped storage hydropower plants, are generally low in urban water supply systems, where dissipation points are required to reduce pressure and leakages (Vairavamoorthy and Lumbers 1998; Tucciarelli et al. 1999). Due to the small amount of available power, dissipation valves have generally been used to date in order to dissipate the excess flow energy. The replacement of pressure reducing valves with pico- or micro-hydropower plants could be a feasible practice to achieve an effective pressure control along with energy recovery (Dannier et al. 2015; Fontana et al. 2016; Fecarotta and McNabola 2017). To accomplish this aim, several authors have presented specific hydropower devices (Paish 2002; Gaius-obaseki 2010; Sammartano et al. 2013, 2017; Sinagra et al. 2017; Carravetta et al. 2017). The use of pumps as turbines (PATs) has recently been demonstrated to be a viable and economical technical solution due to the greater availability and the lower cost of pumps when compared with classical turbines (Carravetta et al. 2014d; Fecarotta et al. 2015; Carravetta et al. 2016, Carravetta et al. 2018a, b). Despite the affinity between pumped storage machines and PATs, the two technologies are significantly different. The design of a hydropower plant within a water supply system raises three major issues relating to (1) hydraulic behavior of the device, (2) operating conditions, and (3) interactions between the plant and the water system:

- The scarcity of information about the behavior of PATs makes the design of a hydropower plant in an urban water system difficult because pump manufacturers do not usually provide the performance of their pumps operating in turbine mode (Derakhshan and Nourbakhsh 2008a).
- The operating conditions—flow rate and head drop—of pump turbines in pumped storage hydropower plants work are generally assigned and almost constant, while a PAT in a water system should deal with stochastic and variable operating conditions. In water transmission systems, with a transmission from the water source to the urban area, the discharge variability, which can be quite large (McNabola et al. 2014), is connected to long-term variations in water demand due to socioeconomic factors. In water distribution systems, such as urban networks, the variability of the operating conditions is faster and even greater due to the instability of the water demand.
- Finally, the primary purpose of an urban water system is the supply of water to the residents. Thus, the replacement of a dissipation node with a hydropower plant should not influence the behavior of the network: an effective design should take into account the energy efficiency of the plant, as well as the influence of the plant on the network and its capacity to adapt to different working conditions, in order to avoid disruptions or interruption of the water service due to mechanical failure or malfunctioning

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(Carravetta et al. 2013b). Each of these three issues has been investigated in several studies and many papers concern one or more of these aspects of energy recovery in water supply systems.

State of the Art

The PAT behavior is primarily expressed by the performance curves that relate the discharge Q^t flowing through the turbine with the head drop ΔH^t (head curve), the power P^t (power curve), and the efficiency $\eta^t = P^t/(\gamma \Delta H^t Q^t)$ (efficiency curve), γ being 9806 $\mathrm{N/m^3}$, the water specific weight. Several papers discuss the predictability of PAT curves under different hypotheses and conditions. Many authors propose experimental measurements (Gantar 1988; Fernandez et al. 2004), but such a procedure is obviously very expensive and only pump manufacturers can provide the experimental curves for the whole catalogue of their machines. Other studies demonstrate that computational fluid dynamics is a valid tool to predict the machine behavior (Rodrigues et al. 2003; Natanasabapathi and Kshirsagar 2004; Yang et al. 2012; Bozorgi et al. 2013) with a low requirement in terms of computational resources if certain precautions are adopted (Carravetta et al. 2011). However, its application requires the availability of the three-dimensional (3D) geometrical model of the machine. Thus, several one-dimensional (1D) methods, which predict the machine performance by means of algebraic semiempirical equations, have been developed. Williams (1994) described the reliability of several literature models proposed to predict the best efficiency point (BEP), i.e., the values of Q^t_B, ΔH^t_B, and P^t_B where η^t attains its maximum value η^t_B, of a PAT when the BEP in pump mode is known. Derakhshan and Nourbakhsh (2008b) proposed a model to describe the whole set of performance curves, i.e., the relationships $\Delta H^t = \Delta H^t(Q^t)$, $P^t = P^t(Q^t)$, and $\eta^t = \eta^t(Q^t)$, of a PAT when the performance curves in pump mode are available. Singh and Nestmann (2010) proposed an optimization method to predict the machine characteristics and select the optimal operation. If the performance curves of a single prototype machine are available, several authors have proposed the use of the turbomachinery affinity law and of the Suter parameters (Ramos and Almeida 2001, 2002; Carravetta et al. 2012) to simulate the behavior of a PAT when the running speed or the impeller diameters are modified. Recently, Fecarotta et al. (2016) have proposed a new model based on the relaxation of the affinity equations (RAE) to correct the errors of the classic affinity law (CAL) in the prediction of the performance of a semiaxial PAT when the running speed is modified. The correct prediction of the PAT behavior is crucial as well as the prediction of the operating conditions. The discharge and the available head in a water supply system are widely variable and a correct modeling of the whole set of performance curves of the machine, which may often operate far from the BEP, and of the hydraulic conditions is needed for the study of the interaction between the supply system and the hydropower plant. The variability of water demand in residential areas is influenced by many factors, such as the weather and climate (House-Peters and Chang 2011), economics and water pricing (Brookshire et al. 2002), and housing characteristics (Nauges and Thomas 2000). Several studies based on different approaches have been developed to model the residential water demand. Some studies relate the peak demand to the number of inhabitants (Babbitt and Baumann 1958; Rich 1980). Other researchers (Zhou et al. 2002) forecast the water consumption with a semideterministic approach that relates the demand to several climatic and nonclimatic components. In the absence of real time continuous measurements, due to the complexity of the influencing factors, the water demand can be considered as a stochastic variable (Gargano and Pianese 2000; Babayan et al. 2006). Several authors, such as Buchberger and Wells (1996), Alvisi et al. (2003), and García et al. (2004), propose statistical approaches to simulate the end-user behavior. Recently, a stochastic model based on a mixed distribution has been proposed by Gargano et al. (2016) to simulate the water demand of small towns. According to such a model, if the time-average water demand is known, the instantaneous discharge can be calculated with a Monte Carlo generator. The available head that should be dissipated in a pressure reducing valve or exploited in a hydropower plant is obviously related to the flowing discharge due to the head loss in the pipeline, but is also affected by a stochastic component (Giustolisi and Walski 2012). The hydropower plant should be designed to face the large variability of the hydraulic conditions and the study by Carravetta et al. (2011) demonstrated that any transient effect within the plant due to the flow variability can be neglected due to the slowness of such variations. According to Carravetta et al. (2013a) the PAT can be either inserted into a hydraulic circuit (HR = hydraulic regulation) with a series and a parallel valve, respectively, or regulated by a variable frequency driver (ER = electrical regulation), which modifies the input frequency of the asynchronous generator to regulate the rotational speed. In HR the series valve is used when the head to dissipate is higher than the head drop caused by the PAT, while the bypass is opened when the demand is too high. In ER mode, the rotational speed of the PAT is modified in order to change its characteristic curve and to match the values of discharge and head in the system. Carravetta et al. (2012, 2014b) proposed an optimization procedure, namely the variable operating strategy (VOS), for the optimal design of a hydropower plant in a water supply system with any of the previous regulation modes. Such a procedure allows us to select the best machine and the best operations for a given head-discharge pattern. The working conditions of the PAT influences both the efficiency of the machine and the mechanical reliability (Barringer 2003). Carravetta et al. (2013b) suggested that a correct plant design should not be based just on the maximization of the energy production but should consider other indicators to assess the whole effectiveness of the plant.

Aim of the Paper

The results of the VOS indicate the optimal specifications of a PAT, in terms of pump geometrical size and rotational speed, for a given pattern of flow rate and head drop. In practice, the installed PAT will be an industrial machine whose characteristics are close to the VOS solution. Therefore, the same PAT is used in a wide range of flow rate patterns and the assigned head drop is managed by the regulation system. In this paper, the variation of the power plant performance for an assigned PAT under the random variability of the hydraulic conditions is investigated. The daily discharge pattern is evaluated with the stochastic model presented by Gargano et al. (2016), applied to the experimental measurements of a monitoring station in southern Italy. Additionally, a probabilistic approach has been used to evaluate the available head. A semiaxial PAT has been used and the influence of a correct prediction of its behavior under a variable speed is evaluated, the results being compared with the classic affinity law and the model based on the RAE. The machine is inserted in different regulation schemes to investigate the influence of the regulation mode on the performance of the plant. The results are presented in terms of system effectiveness.

Modeling of Semiaxial PAT under a Variable Speed

However the performance of a single prototype machine is obtained, such a result can be extended to similar machines by the application of the turbomachinery affinity law. Such a model, based on a theoretical background, describes the variability of the head curve $\Delta H^t = \Delta H^t(Q^t)$, the power curve $P^t = P^t(Q^t)$, and the efficiency curve $\eta^t = \eta^t(Q^t)$, when the rotational velocity N is modified or the geometry of the machine is scaled. The turbomachinery affinity law can be expressed as follows:

$$\frac{Q^I}{Q^{II}} = \left(\frac{N^I}{N^{II}}\right)^1 \cdot \left(\frac{D^I}{D^{II}}\right)^3 \qquad \frac{\Delta H^I}{\Delta H^{II}} = \left(\frac{N^I}{N^{II}}\right)^2 \cdot \left(\frac{D^I}{D^{II}}\right)^2$$
$$\frac{P^I}{P^{II}} = \left(\frac{N^I}{N^{II}}\right)^3 \cdot \left(\frac{D^I}{D^{II}}\right)^5 \qquad (1)$$

where ΔH^I and P^I = head and the power of the prototype, having an impeller diameter of D^I, rotating at a speed of N^I, and delivering a discharge of Q^I. In this case Q^{II}, ΔH^{II}, and P^{II} are the homologous quantities for a similar machine having D^{II} impeller diameter and rotating at N^{II} speed. According to Affinity law 1, the efficiency at the BEP, η_B^{II}, of any similar machine does not depend on the rotating speed or the impeller diameter and is equal to η_B^I. This result disagrees with the real behavior of turbomachines (Simpson and Marchi 2013; Carravetta et al. 2014a, c). Usually, for a single machine rotating at different speed values, the maximum best efficiency, $\eta_B^{\max}$, is attained only at a given optimal speed value $N^{\max}$, while a decrease is observed as the speed diverges (Sárbu and Borza 1998). Additionally, the increase of the diameter produces scale effects, e.g., due to the wall roughness or the mechanical tolerances, and the efficiency is generally higher for larger machines (Paish 2002). Several studies have been developed to model the relationship between the best efficiency and the rotational speed in pump mode (Gulich 2003; Sárbu and Borza 1998; Simpson and Marchi 2013). A recent study (Fecarotta et al. 2016) has proposed a relaxation of the affinity equations (RAE) to account for the differences between the affinity law and the real behavior of a semiaxial PAT under different rotating speed values. According to this model $N^{\max}$ is dependent on some geometric parameters of the machine, namely the impeller diameter D, the stator height F, the stator diameter ϕ, and the position of the BEP (Q_B^{II}, ΔH^{II}, P^{II}, η_B^{II}) at rotating speed N^{II} depends on the ratio $N^{II}/N^{\max}$ and on the position of the BEP at $N^{\max}$ rotating speed ($Q_B^{\max}$, $\Delta H_B^{\max}$, $P_B^{\max}$, $\eta_B^{\max}$)

$$N^{\max} = a_N \cdot D^{\alpha_N} \cdot \phi^{\beta_N} \cdot F^{\gamma_N}$$
$$\frac{Q_B^{II}}{Q_B^{\max}} = a_Q \cdot \left(\frac{N^{II}}{N^{\max}}\right)^{\alpha_Q}$$
$$\frac{\Delta H_B^{II}}{\Delta H_B^{\max}} = a_H \cdot \left(\frac{N^{II}}{N^{\max}}\right)^{\alpha_H}$$
$$\frac{\eta_B^{II}}{\eta_B^{\max}} = a_\eta \cdot \left(\frac{N^{II}}{N^{\max}}\right)^2 + b_\eta \cdot \left(\frac{N^{II}}{N^{\max}}\right) + c_\eta \qquad (2)$$

where, for the analyzed machines, $a_N = 5.970 \cdot 10^{18}$, $\alpha_N = -0.4856$, $\beta_N = 31.11$, $\gamma_N = -38.63$, $a_Q = 1.004$, $\alpha_Q = 0.825$, $a_H = 0.972$, $\alpha_H = 1.603$, $a_\eta = -0.317$, $b_\eta = 0.317$, and $c_\eta = 0.707$ (dimensionless units).

The power P_B^{II} can be calculated as $P_B^{II} = \gamma \cdot \Delta H_B^{II} \cdot Q_B^{II} \cdot \eta_B^{II}$. Fecarotta et al. (2016) also proposed two new formulations to describe the dimensionless head curve $h = h(q)$ and the power curve $p = p(q)$, where $h = \Delta H^{II}/\Delta H_B^{II}$, $q = Q^{II}/Q_B^{II}$ and $p = P^{II}/P_B^{II}$

$$h = a_h \cdot q^2 + b_h \cdot q + c_h \qquad p = a_p \cdot q^2 + b_p \cdot q + c_p \qquad (3)$$

where, for the analyzed machines, $a_h = 1.61$, $b_h = -1.41$, $c_h = 0.805$, $a_p = 1.85$, $b_p = -0.858$, and $c_p = 0.00567$ (dimensionless units).

Fecarotta et al. (2016) demonstrated that the use of Eqs. (2) and (3) reduces the error in the prediction of the machine behavior, if compared with the results of Eq. (1).

Variable Operating Strategy and Upgraded Effectiveness

Generally, the backpressure (BP), i.e., the value of the head downstream of the plant, is assigned as a constant value. This usually happens when the hydropower plant is installed to replace a pressure reducing valve (PRV), which is a self-regulating valve used to set the downstream pressure to a constant value. PRVs are generally used to pursue a leakage control strategy by dividing the whole network into district metered areas (DMAs) and are widely used in water systems (Karadirek et al. 2012; Prescott and Ulanicki 2008). In contrast, the upstream head (H^u) depends on the discharge Q^d. Thus, the available head ΔH^d that should be exploited in the hydropower plant is time variable, being

$$\Delta H^d(Q^d) = H^u - BP \qquad (4)$$

When no regulation (NR) is provided, the PAT works according to its characteristic curve

$$\Delta H^t = \Delta H^t(Q^d) \qquad (5)$$

and Eq. (4) may not be satisfied. In order to regulate the plant according to the needs of the supply system, the machine can be inserted in a hydraulic and/or electric circuit, with one or two valves, an electric speed driver and a mechanical speed multiplier, as shown in Fig. 1.

In HR, when the discharge approaching the plant, Q^d, is low, H^u is high due to the lower head loss in the pipeline and the available head can exceed ΔH^t. In this case the series valve can dissipate the surplus head ΔH^v to reach the BP value. Conversely, when Q^d is high, ΔH^t can be larger than ΔH^d. In such case, an amount of the discharge Q^b can be bypassed by the parallel valve to reduce the values of both Q^t and ΔH^t

$$\begin{aligned} &\Delta H^d = \Delta H^t(Q^t) + \Delta H^v \\ &Q^d = Q^t + Q^b \\ &\Delta H^v > 0,\ Q^b = 0 \qquad \text{if } \Delta H^t(Q^t) < \Delta H^d \\ &\Delta H^v = 0,\ Q^b > 0 \qquad \text{if } \Delta H^t(Q^d) > \Delta H^d \end{aligned} \qquad (6)$$

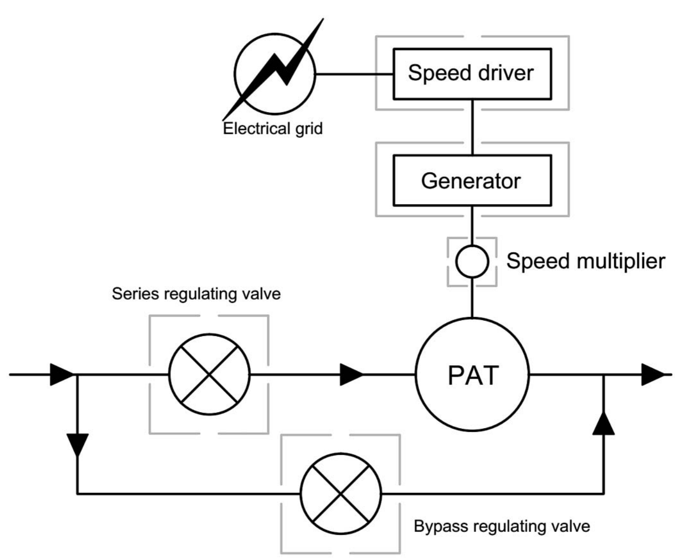

Fig. 1. Installation scheme of a hydropower plant within a water supply system.

Neither the flow bypassed through nor the head dissipated by the two valves contribute to the energy production. However, the regulation will be mandatory if a hard BP constraint is required. In the optimized design the PAT is chosen even to control the amount of energy that is dissipated or bypassed. This will be a result of the procedure proposed in this paper.

In HR mode the rotational speed of the machine is fixed because the input frequency of the asynchronous generator is constant. Nevertheless, a speed multiplier can be inserted between the pump and generator to set a constant speed value different from the rotational speed of the generator in order to optimize the performance of the plant. Conversely, if an electrical variable speed driver is used (ER), the rotational speed N^t can be varied to modify the characteristic curve of the machine and match ΔH^t with ΔH^d

$$N^t\colon \Delta H^t(Q^t, N^t) = \Delta H^d(Q^d) \tag{7}$$

The rotational speed of the generator (rpm) can be calculated according to the following equation:

$$N^t = \frac{2 \cdot 60 \cdot f}{p^o} \tag{8}$$

where f = electrical input frequency (Hz); and p^o = number of poles of the generator. The maximum value of N^t depends on the maximum input frequency, which is generally equal to 60 Hz, while the minimum rotational speed can be normally set at half the nominal speed (corresponding to the nominal frequency of the generator, usually equal to 50 Hz). Indeed, even if a speed driver would allow a further decrease in the minimum frequency of the generator (Sammartano et al. 2016), a lower running speed should be avoided if no additional fan cooling systems is installed. For example, a two poles generator can rotate between 1,500rpm and 3,600 rpm. Such a limitation in the velocity range restricts the regulation possibility of the plant because for an assigned discharge Q^d, ΔH^t is limited between a maximum and a minimum value, corresponding to the maximum and the minimum frequency, respectively. Thus, in some cases, Eq. (4) may not be satisfied in ER mode. The HR and ER can be coupled (HER) to improve the performance of the plant

$$\begin{aligned}
&\Delta H^d = \Delta H^t(Q^t, N^t) + \Delta H^v \\
&Q^d = Q^t(N^t) + Q^b \\
&\Delta H^v > 0,\ Q^b = 0 \qquad \text{if } \Delta H^t(Q^t, N^t) < \Delta H^d \\
&\Delta H^v = 0,\ Q^b > 0 \qquad \text{if } \Delta H^t(Q^d, N^t) > \Delta H^d
\end{aligned} \tag{9}$$

In such a case, the regulation of the plant, i.e., the rotating speed and the valve opening, is not unique, because different values of rotating speed and valve opening can be selected to match the values of Q^d and ΔH^d. Table 1 summarizes the equipment of each installation scheme and Fig. 2 shows their operation.

Upgraded Effectiveness

Carravetta et al. (2012, 2013a) proposed the VOS procedure to optimize the design of the hydropower plant in order to maximize the plant efficiency, i.e., the power production. Carravetta et al. (2013b) advocated replacing the efficiency with effectiveness as the maximizing function, to take into account not only the produced power, but all the components influencing the performance of the system. The same procedure can be used to select the best time operation of an existing plant. The effectiveness has been defined as (Carravetta et al. 2013b)

$$e = A_1 \cdot A_2 \ldots A_n \tag{10}$$

Table 1. Equipment of the different installation schemes

Mode	NR	ER	HR	HER
Series valve	—	—	×	×
Bypass valve	—	—	×	×
Speed multiplier	—	—	×	—
Speed driver	—	×	—	×

Note: NR = no regulation; ER = electric regulation; HR = hydraulic regulation; and HER = hydraulic and electric regulation.

where $A_1, A_2 \ldots A_n$ = indicators influencing the performance of the system. In that paper, they suggest considering, as indicators, the plant capability η_p, the plant reliability μ_p, and the plant flexibility ϕ_p.

The plant capability can be calculated as the ratio between the produced power and the available power, and is influenced by both the machine efficiency and the regulation (e.g., the head dissipated in the series valve or the bypassed discharge, which do not contribute to the energy production)

$$\eta_p = \frac{Q^t \Delta H^t \eta^t}{Q^d \Delta H^d} \tag{11}$$

The mechanical design of a turbomachine is focused on the optimization of its performance, including its reliability, in a region of operation spread near the BEP (CEN 2015). When, during the regulation, the machine operates far from its BEP, its reliability decreases, and this could lead to an increase in the maintenance costs. The reliability of the plant at a certain load condition can be estimated as the ratio between the mean time to failure ($MTTF$) calculated for that load and the $MTTF$ calculated for the BEP. Thus, its value is 1 if the machine operates at the BEP, and lower otherwise

$$\mu_p = \frac{MTTF(Q^t)}{MTTF(Q_B)} \tag{12}$$

Carravetta et al. (2013b) assumed that the relation between the reliability of the PAT and the distance from the BEP is equal to the relation obtained for the machine working in pump mode, according to the Barringer (2003) studies. In this work, the law between the distance of the operating condition from the BEP and reliability of the machine has been modified, as shown in Fig. 3. According to the efficiency curves of PATs, shock losses are higher for values of discharge lower than Q_B. Thus, a higher reliability is expected in the right-hand side of the characteristic curve.

Finally, the plant flexibility measures the reduction in the efficiency when ΔH^d is different from the design values. Such a condition can occur when the hydraulic pattern is obtained by a simplified network simulation. In this paper, as shown subsequently, the accurate modeling of the network, which takes into account the stochastic nature of Q^d and ΔH^d, makes the flexibility parameter redundant. Nevertheless, a new parameter that directly measures the differences between the required and the produced BP values has been introduced.

When the plant is provided with HR, each value of ΔH^t and Q^d can be matched by the mutual regulation of the valves opening. Conversely, when the PAT is regulated only by a speed driver, some operating points can be out of the regulation region. This results in a BP value different from the assigned one. Similarly, when no regulation is present (NR), the BP value can be reasonably different from the assigned one because of the difference between the operating points and the head curve, as shown in Fig. 2. In both cases a penalty should be considered in the optimization process, accounting for the difference between the required and the produced BP. Indeed, a BP value different from the required one can affect the

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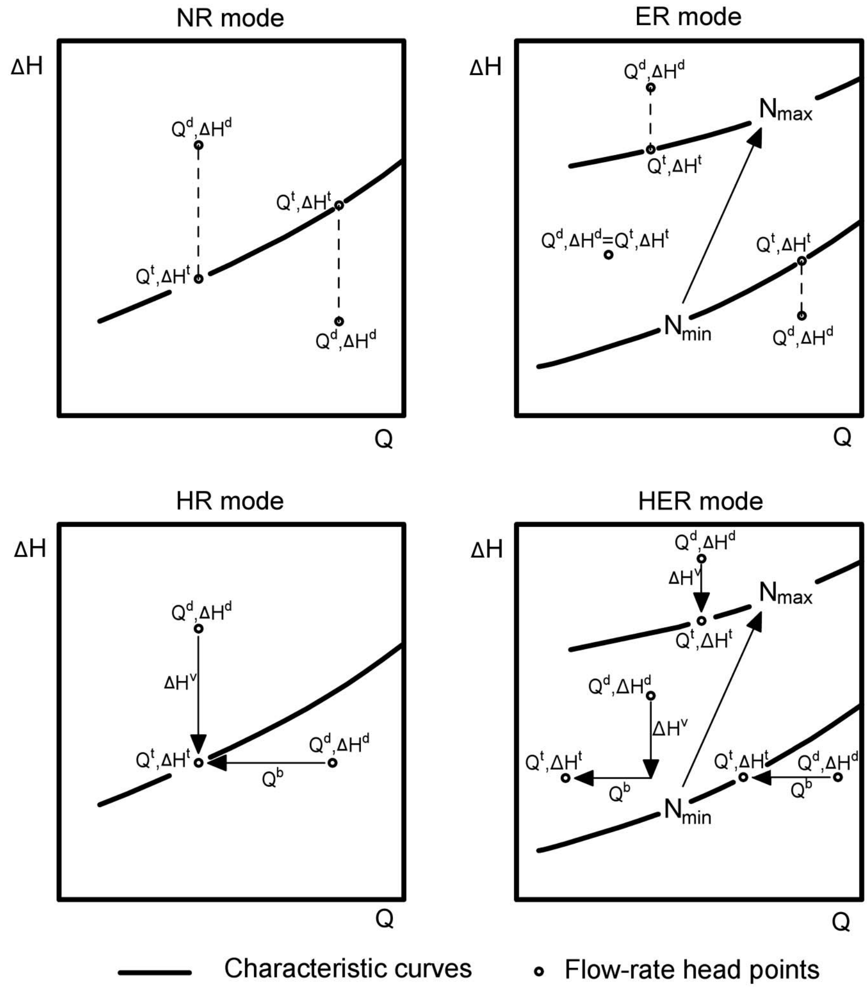

Fig. 2. Operations of the different installation schemes.

service of the network: a higher BP could lead to an increase of breakings and leakage, while a lower value could cause a reduction in the supply. Such a penalty can be included as a factor in the calculation of the effectiveness. This new factor, namely plant sustainability, χ_p, is ranged between 0 and 1 and has been defined as

$$\chi_p = \left(1 + \alpha \frac{|\Delta H^t - \Delta H^d|}{BP}\right)^{-1} \quad (13)$$

where α = coefficient influencing the decay of effectiveness when the produced net head is different from the design value. In this paper α has been arbitrarily set to 10, and thus an error equal to 10% in the BP halves the effectiveness of the plant. The three parameters are ranged between 0 and 1 and their product has been chosen as an objective function being a compromise between:

- power production, measured in terms of the capability of the plant;
- mechanical reliability of the machine, due to the modification of the MTTF on account of the variable operation; and
- operation of the water network, which can be affected by a variation of BP from the required value.

Fine Tuning of the Plant

The objective function, namely the effectiveness, is therefore defined as

$$e = \eta_p \cdot \mu_p \cdot \chi_p \quad (14)$$

Eq. (14) can be expanded as

$$e = \frac{Q^t \Delta H^t \eta^t}{Q^d \Delta H^d} \cdot \frac{MTTF(Q^t)}{MTTF(Q_B)} \cdot \left(1 + \alpha \frac{|\Delta H^t - \Delta H^d|}{BP}\right)^{-1} \quad (15)$$

The value of the effectiveness depends both on the available hydraulic characteristics and on the regulation of the plant. The objective function can be expressed as

$$\max(z) = \frac{1}{n} \sum_{i=1}^{n} e_i \quad (16)$$

where n = number of the operating points considered for the plant design; and e_i = calculated effectiveness of the ith operating point. The maximization of the objective function allows us to select the machine and set its rotational speed. In NR and HR the constant speed value can be set by a speed multiplier. Conversely, in ER and HER the rotational speed can be set for each operating point.

The plant effectiveness can be considered as a quality index, measuring the effects of the regulation system on the energy production, the mechanical reliability and the network needs. Such a quality index should be considered during the design of a PAT plant as well as other aspects (e.g., environmental and economic issues, life cicle cost, and life cicle assesment) or used to perform an effective regulation of existing plants.

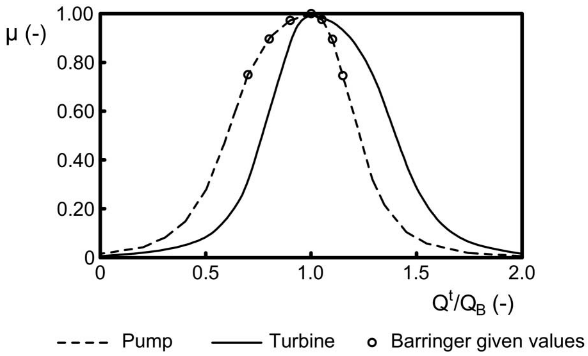

Fig. 3. Comparison between the machine reliability in pump and turbine modes.

Case Study: Head and Discharge Pattern

The case study refers to a monitoring station (Amendola, Pompeii, southern Italy) of a 10,000 inhabitants water supply network in southern Italy, where the daily pattern of upstream head and discharge was available with a sampling rate of 15 min. Fig. 4 shows the values of c_Q, i.e., the ratio between the hourly (μ_Q) and the daily ($\overline{\mu_Q}$) averaged discharge, and c_H, i.e., the ratio between the hourly (μ_H) and the daily ($\overline{\mu_H}$) averaged upstream head, versus the daily time. The pattern has been scaled in order to modify the daily averaged discharge. The relation that has been used to scale the daily pattern is the following:

$$\mu_Q(t) = \overline{\mu_Q} \cdot [1 + c_m(c_Q(t) - 1)] \tag{17}$$

where c_m = coefficient whose value was chosen in order to set to 0.1 the variation coefficient of the daily pattern, as shown by Gargano and Pianese (2000). In recent years, many water authorities or companies have adopted SCADA systems for the online monitoring and control of the operational parameters of the flow rate and pressure in water supply systems (Kara et al. 2016). Therefore, there are several studies and applications where the flow rate can be measured and evaluated very easily with short time intervals for very long periods, and full scale PAT systems have been realized based on these detailed data (Muhammetoglu et al. 2017a, b). Unfortunately, in this case study, the topology of the hydraulic network is unknown, and only the measured data of the monitoring station are available. Thus, the experimental data has been used to develop an instantaneous discharge/head prediction model. The data of the monitoring station has been used to best fit a simple quadratic relation between the discharge and the upstream head

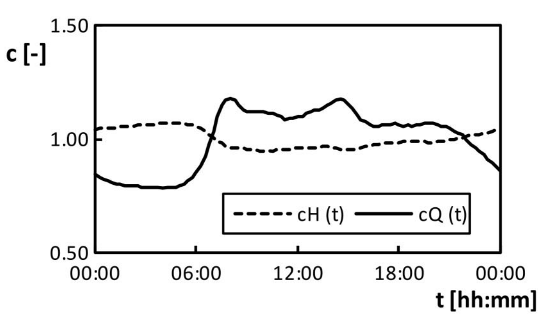

Fig. 4. Daily pattern of hourly averaged dimensionless discharge and head.

$$H^u = H_0 - K \cdot Q^{d2} \tag{18}$$

where H_0 and K have been evaluated as 91.24 m and 18,263 s^2/m^5, respectively. Such a relation can be used in the prediction of the available head when a complete hydraulic simulation of the network is not possible due to a lack of data or the complexity of the system.

The coefficient K can modeled using the Gauckler-Strickler formula for circular pipes

$$K = \frac{L}{0.0971 \cdot K_{st} \cdot (2R)^{16/3}} \tag{19}$$

where K_{st} = coefficient depending on the pipe material ($m^{1/3}/s^1$); R = radius of the pipe (m); and L = length of the approaching pipeline (m).

Instantaneous Discharge

The difference between the instantaneous discharge and the time averaged discharge can be relevant and a correct hydropower design should take into account such a variation. The instantaneous discharge can be calculated, based on the daily pattern of the hourly averaged discharge, by means of a recent probabilistic model (mixed distribution) by Gargano et al. (2016). This distribution is obtained by merging two cumulative distribution functions taking into account the probability of both a null and not null discharge. The following formulations can be used for a Monte Carlo generation:

$$Q^d = \mu_Q(t) \cdot \left(1 - \frac{\sqrt{3}}{\pi} \cdot \ln \frac{1 - F(t)}{F(t) - F_0(t)} \cdot CV(t)\right)$$

$$F_0(t) = \exp\left(-5 \cdot \frac{N_{ab}}{1000} \mu_Q(t)\right)$$

$$CV(t) = 0.1 + \frac{6}{(0.25 \cdot N_{ab})^{3/4} \cdot \mu_Q(t)^{5/4}} \tag{20}$$

where $F_0(t)$ = probability of a null discharge; N_{ab} = number of inhabitants served by the urban supply system; and $F(t)$ = probability of not null discharge, randomly generated using the Monte Carlo method. In accordance with Gargano et al. (2016), the instantaneous discharge has been calculated for each minute and plotted in Fig. 5.

Calculation of the Instantaneous Upstream Head

Eq. (18) allows us to calculate the hourly averaged value of the upstream head μ_H. The instantaneous value of $H^u(t)$ can be calculated as the sum of two components

$$H^u = \mu_H + H' \tag{21}$$

where H' = difference between the instantaneous and the hourly averaged values of the upstream head. An analysis of the experimental values of H' shows that it is a normally distributed random component, as shown by the Q-Q plot of Fig. 6, where the calculated percentiles (Weibull) are plotted versus the theoretical percentiles.

The simulated patterns of discharge and head are plotted in Fig. 5 where they are compared with the experimental data sampled each 15 min in terms of the dimensionless parameters. The picture shows a good agreement between the two patterns, even if the experimental series does not include the highest and the lowest values, probably due to the lower sampling rate.

Thus, for the simulation of the network, the upstream head has been calculated according to Eqs. (18) and (21), where H' has been calculated using a Monte Carlo generation.

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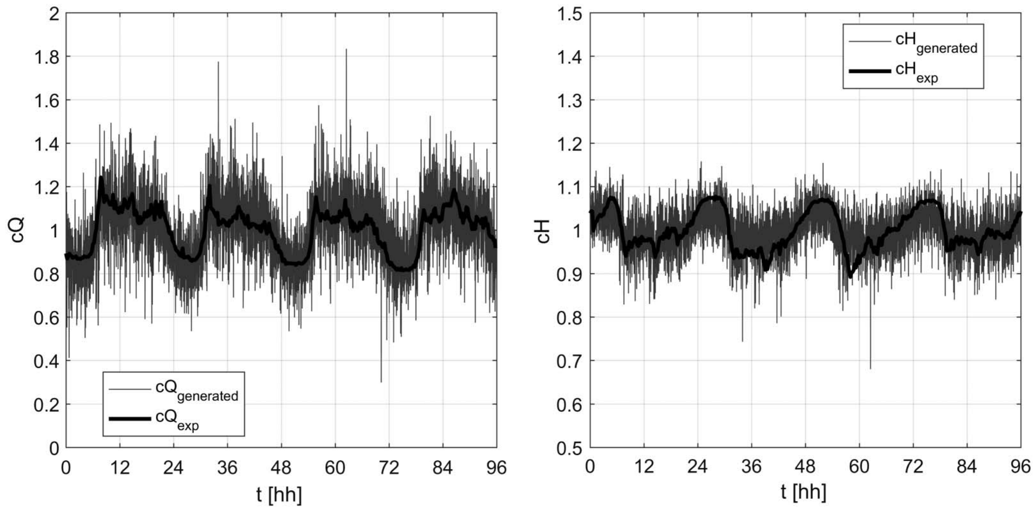

Fig. 5. Comparison between the generated discharge with a 1 min sampling rate and the measured discharge with a 15 min sampling rate.

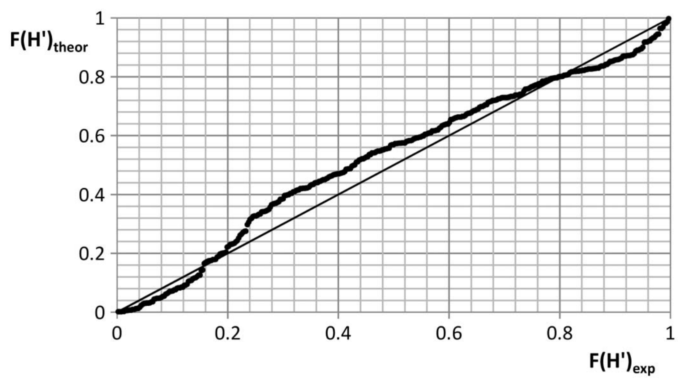

Fig. 6. Q-Q plot of H' (normal distribution).

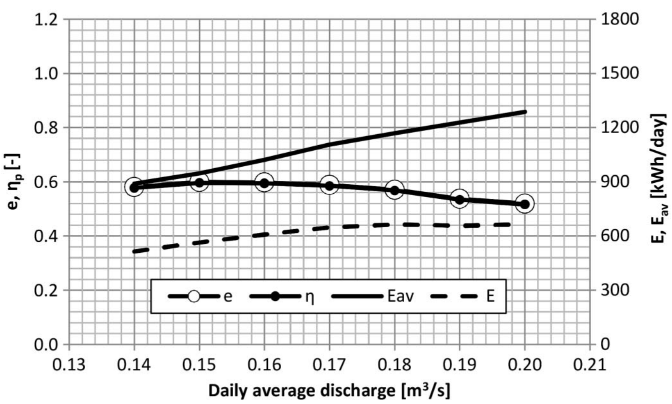

Fig. 7. Results of the design of the HER plant.

Hydropower Design

The experimental data of the monitoring station of Amendola have been used to generate a synthetic daily pattern of head and discharge for the design of the micro-hydropower plant. The discharge pattern has been scaled with respect to seven daily-averaged discharge values, ranging between 0.140 and 0.200 m^3/s. The hourly-averaged discharge has been calculated using Eq. (17) and the data of Fig. 4, while the instantaneous discharge has been calculated using Eq. (20). The instantaneous upstream head was calculated using Eqs. (18), (19), and (21). The BP was set to 60 m and the available head was calculated using Eq. (4). The selected machine is a 14 in. semiaxial pump, with a 277 mm impeller. The performance of the selected PAT has been determined for four kinds of power plant, in a range of flow conditions, differing in the regulation mode, i.e., HER, HR, ER, and NR.

HER Plant

For an assigned hydraulic pattern and machine, the VOS can be applied to regulate the plant in terms of the bypass discharge (Q^b), dissipated head in the series valve (ΔH^v) and rotational velocity of the PAT (N^t) in order to maximize the effectiveness for each operating point. The RAE equations were used to model the machine behavior under a variable speed. A four-day pattern was used for the design of the plant, with a total of 5,760 operating points, for each of the seven daily-averaged discharge values.

Fig. 7 shows the results of such a regulation in terms of effectiveness, plant efficiency, and daily available (E_{av}) and produced (E) energy, as a function of the daily average discharge. The available energy increases with the average discharge and the produced energy attains not negligible values (between 500 and 650 kWh/day). The ratio between the produced energy and the available energy (namely the plant capability) slightly decreases with the discharge. The design BP value is always attained due to the presence of the two valves, and the sustainability is therefore equal to one. Furthermore, the speed driver makes the plant rather adjustable and allows the PAT to work near its BEP, and thus the reliability of plant is about equal to one for each discharge. Therefore, the effectiveness is equal to the plant capability and reasonably high.

HR Plant

In the HR mode the rotational speed cannot be modified instantaneouslybecause the input electric frequency is constant. Nevertheless, a speed multiplier, such as a gear box, can be inserted between the generator and the PAT to select a constant speed different from the rotational velocity of the generator. Such a value is the result of the fine tuning, while the valves regulation is imposed to reach the correct BP value.

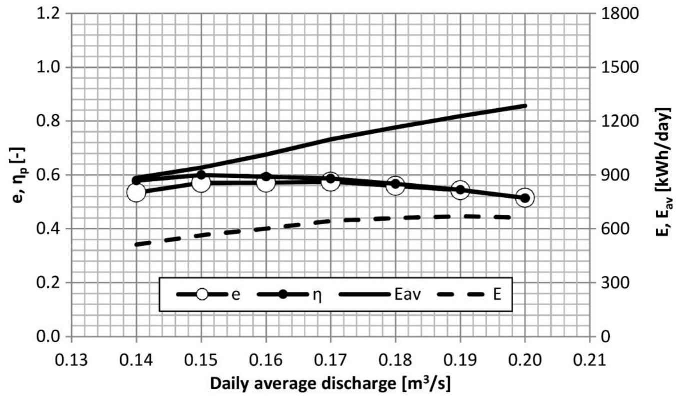

Fig. 8. Results of the design of the HR plant.

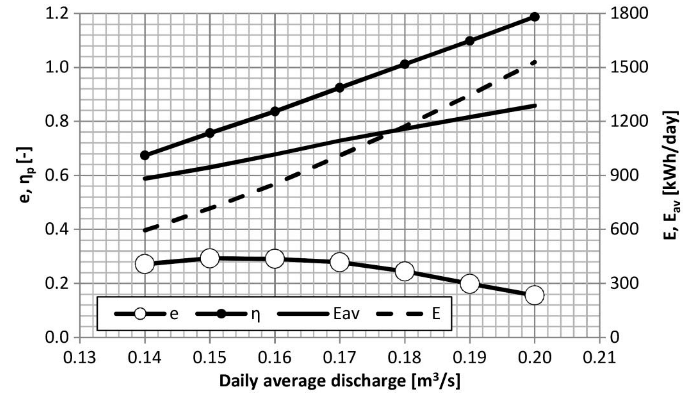

Fig. 9. Results of the design of the ER plant.

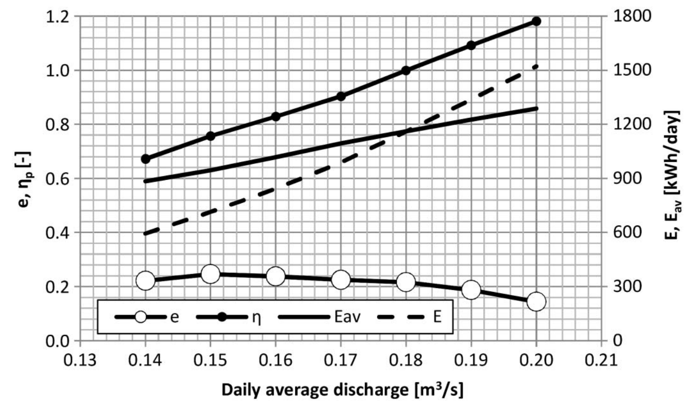

Fig. 10. Results of the design of the NR plant.

Fig. 8 shows the result of the design process for the HR plant. As in HER mode, the sustainability of the plant is always equal to 1 because the presence of the two valves ensures the correct value of BP. The reliability values are lower than in HER mode because the machine works far from the BEP and that produces slightly lower values of effectiveness. Nevertheless, the reduction in the produced energy, if compared with HER mode, is not significant.

ER and NR Plant

In the ER mode, the regulation is limited due to the constraints on the rotational speed. Thus, the BP value can be ensured only if the operating point is contained in the regulation region of the machine. Nevertheless, the introduction of the sustainability factor for the calculation of the effectiveness accounts for the differences between the real and the assigned BP during the optimization process. Furthermore, in the NR mode, the regulation of the plant is not allowed, and the BP is always different from the design value. In both cases, the sustainability of the plant is always less than 1, while the capability can be greater than 1. This happens because ΔH^t can be greater than ΔH^d with a resulting BP lower than the design value. Thus, η_p by Eq. (11) can be greater than 1. The produced energy, in both cases, is reasonably high, as shown by the high values of capability. Figs. 9 and 10 show that the effectiveness assumes very low values, due to the effect of the sustainability. Of course, such a relevant decay of effectiveness depends on the value of the α coefficient of Eq. (13), which has been arbitrarily set to 10 in this study.

In Fig. 11 the ratios $|H^u - \Delta H^t|/BP$ for the ER mode and NR modes are plotted for the first day of the pattern. A difference between the design BP and the resulting value is evident. This behavior results in low values of sustainability and effectiveness. If the BP value is considered too small by the plant designer, then the sustainability Eq. (13) can be modified in order to direct the tuning process to other solutions.

Comparison between the Regulation Schemes

In Fig. 12 the values of the calculated effectiveness for the four regulation schemes are compared. As shown previously, the effectiveness of the HER and HR plant is significantly higher than the effectiveness of the ER and NR. This behavior is primarily due to the effect of sustainability, which assumes the lowest values for the ER and NR modes. In terms of reliability (Fig. 13), the four regulation modes exhibit significant differences: the HER results are close to 1 because the working conditions of the machine are maintained close to the BEP by the double regulation for all the discharge and head values. The HR performs better than ER at high flow rates, while an opposite behavior is observed at low discharges. Finally, NR shows the lowest values of reliability due to the lack of any regulation system. Even if the performance of HER and HR are generally better than ER and NR, the final decision about the type of plant to be installed should involve economic considerations. The plant capability allows a computation of the produced power, which results in revenue due to the energy production. Therefore, the revenue should be compared with the installation costs, which are obviously maximum for a HER plant and minimum for a NR plant. Finally, the payback period or the net present value can be used to make the final decision.

Figs. 7–10 show that the plant capability is always high, even if it has not been chosen as a design parameter. Both in the HER and HR modes, where the hydraulic constraint relating to the BP value is always respected, the plant capability is really close to its maximum value, i.e., the BEP of the machine. Moreover, in the ER and NR modes, where the BP can be different from the assigned value, the capability is even higher than the BEP. These results demonstrate that the whole energy production is not considerably penalized when the effectiveness is chosen for the tuning of the system. However, in the evaluation of the capability, the energy losses due to the presence of a speed driver in HER and ER and of a speed multiplier in HR have been neglected. This means that the real capability and the real effectiveness of the plant can be slightly lower.

Effects of the Variability of Discharge and Head

In order to evaluate the influence of the variability of discharge and head in the plant design, two different design cases have been

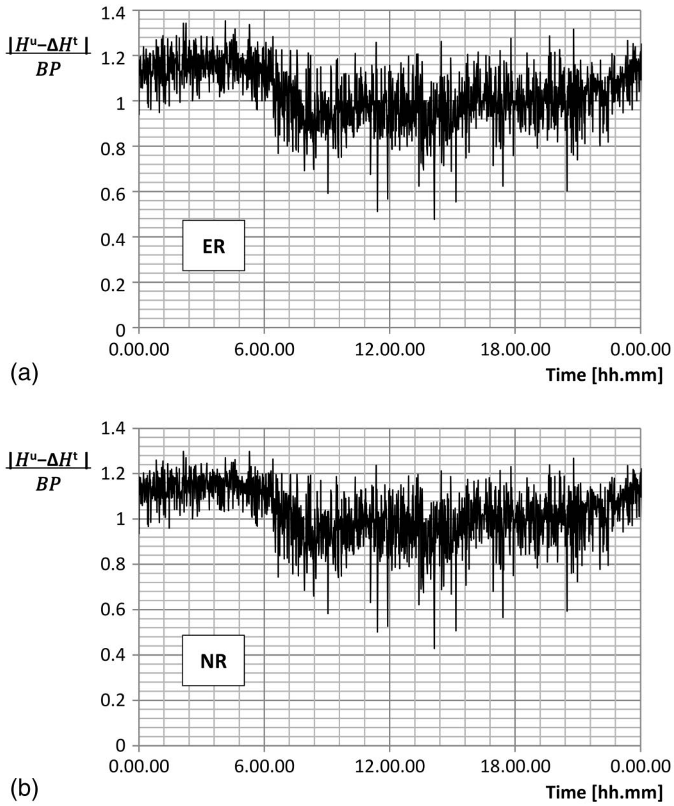

Fig. 11. *BP* values resulting from the design of ER and NR plants.

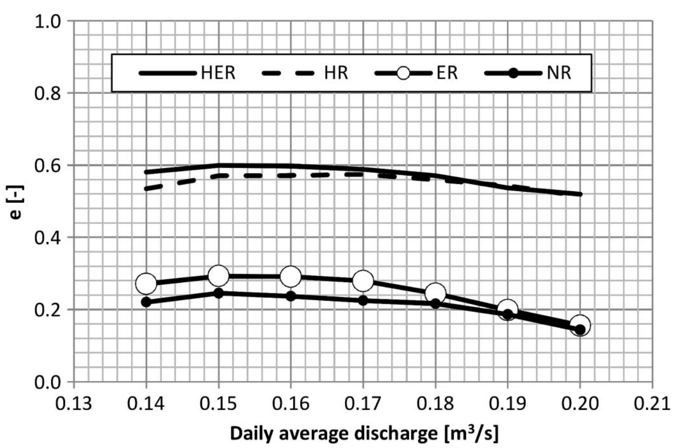

Fig. 12. Comparison between the effectiveness of the four regulation modes.

considered. As a first comparison, the design has been performed with reference to a stochastic pattern for a single day, instead of for four days. The difference in the results is not so high, as shown in Table 2, where the results are compared in terms of optimal rotational speed, capability, and effectiveness for the four regulation modes and for an average discharge of 0.140 m^3/s. For the HER and ER modes the values of optimal rotational speed shown are daily average values.

A second investigation analyses the effects of the stochastic behavior of discharge and head on the design and the predicted effectiveness. The four plants have been designed using the hourly averaged discharge as the daily pattern, without the stochastic components.

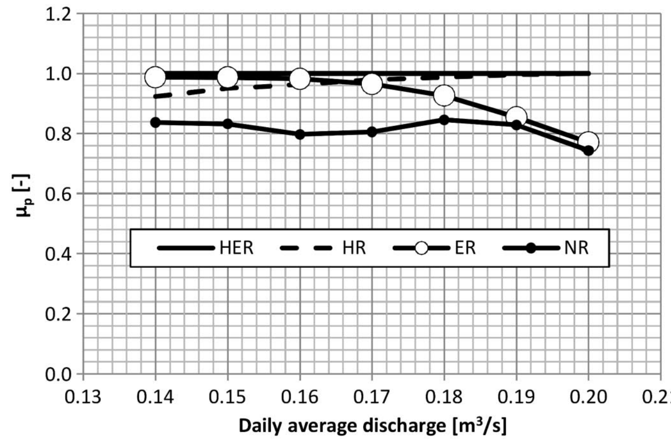

Fig. 13. Comparison between the reliability of the four regulation modes.

Table 2. Comparison between 1-day and 4-day pattern design for an average discharge of 0.140 m^3/s

	N^t (rpm)			η_p			e		
Mode	4 days	1 day	% var	4 days	1 day	% var	4 days	1 day	% var
HER	1,329	1,321	0.59	0.577	0.587	−1.76	0.577	0.587	−1.76
HR	1,244	1,232	0.97	0.579	0.579	0.05	0.534	0.529	1.07
ER	1,404	1,408	−0.28	0.674	0.678	−0.53	0.271	0.275	−1.57
NR	1,350	1,367	−1.28	0.672	0.674	−0.28	0.221	0.223	−0.98

Note: %var = percentage variation.

Table 3. Comparison between average and 4-day stochastic pattern design for an average discharge of 0.140 m^3/s

	N^t (rpm)			η_p			e		
Mode	sto	ave	% var	sto	ave	% var	sto	ave	% var
HER	1,329	1,352	−1.77	0.577	0.618	−7.17	0.577	0.618	−7.17
HR	1,244	1,300	−4.51	0.579	0.616	−6.40	0.534	0.595	−11.40
ER	1,404	1,373	2.22	0.674	0.653	3.07	0.271	0.335	−23.79
NR	1,350	1,370	−1.44	0.672	0.655	2.58	0.221	0.332	−50.29

Note: ave = average pattern design; sto = stochastic pattern design; and % var = percentage variation.

Table 3 shows that the variation in the predicted effectiveness is significant and increases as the adaptability of the plant reduces. The ER and NR mode performances are much affected by the spikes of discharge and head, and thus the effectiveness significantly decreases if the pattern duration increases.

Conclusions

This study focuses on the optimal regulation of a hydropower plant within a water supply system. The plant is provided with a pump as turbine that simultaneously reduces the pressure and produces energy. The plant should be efficient, in terms of energy conversion; reliable, in that any malfunctioning or breaking could affect the water supply; and sustainable, because it should not influence the network functionality.

The daily discharge and head pattern is evaluated with a stochastic approach applied to the average experimental measurements of a monitoring station in southern Italy, in order to simulate the random variability. A semiaxial PAT has been chosen as the working machine. Two valves and a speed driver can be combined to equip four types of regulation scheme, namely HER, HR, ER, and NR. The influence of the regulation mode on the performance of the plant has been evaluated.

The fine tuning of the plant is obtained by the maximization of the system effectiveness, which is formally defined as the product of three parameters: the plant capability (which is a measure of the efficiency of the plant), the plant mechanical reliability (which measures the decrease in the mean time-to-failure when the machine operates far from its BEP), and the plant sustainability (which measures the influence of the plant on the performance of the water network).

The results show that in terms of system effectiveness (Fig. 12) the HER plant performs better than the others because it has more regulation options, a fact which makes it more flexible. The HR plant exhibits a slightly lower effectiveness, while the lowest values are observed for the ER and NR plants. The absence of any hydraulic regulation indeed produces low values of system sustainability because the head drop produced by the PATs is often different from that required. Conversely, in terms of system capability (Figs. 7–10), ER and NR show the highest values because the head drop produced is greater than that available, with a resulting higher output power. In terms of reliability (Fig. 13), the four regulation modes behave differently. HER reliability is close to 1 because the regulation of the plant keeps the working conditions close to the BEP of the machine. The HR reliability increases with the size of the plant, while the reliability of the ER mode decreases when the average flow rate increases. Instead, the NR mode presents the lowest values of reliability for all the discharge values.

Finally, the influence of a correct prediction of the hydraulic pattern is shown. In order to investigate how the random variability of the hydraulic characteristics affects the performance of the plant, the number of working days has been reduced from 4 to 1. The results show that if only one working day is used as the base pattern, only a slight difference is observed in the predicted values of both the capability and effectiveness for all the four regulation modes. Conversely, if the probabilistic approach is neglected and only the average pattern is used for the design, a significant error in the expected performance can be observed, especially for the ER and NR modes, where the error in the predicted effectiveness reaches 24 and 50%, respectively.

Acknowledgments

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Notation

The following symbols are used in this paper:

BP = backpressure;
c_H = daily head coefficient;
c_Q = daily demand coefficient;
CV = variation coefficient;
D = impeller diameter;
E = daily produced energy;
E_{av} = daily available energy;
e = plant effectiveness;
F = stator width;
$F(t)$ = probability of not null discharge;
$F_0(t)$ = probability of null discharge;
f = generator input frequency;
H = head;
H_0 = hydrostatic head;
H' = random component of head;
H^u = upstream head;
h = dimensionless head;
I, II = prototype and similar machine;
K = resistance coefficient;
K_s = Strickler coefficient;
L = length of the pipeline;
$MTTF$ = mean time to failure;
N_{ab} = number of inhabitants;
$N^{\max}$ = rotational speed where the maximum machine efficiency is obtained;
N^t = rotational speed;
n = number of operating points;
P_B = power at best efficiency point (BEP);
$P_B^{\max}$ = power at maximum efficiency point;
P^t = power produced by the PAT;
p = dimensionless power;
p^o = number of poles of the asynchronous generator;
Q = discharge;
Q_B = discharge at best efficiency point (BEP);
Q^b = bypassed discharge;
Q^d = available discharge;
$Q_B^{\max}$ = discharge at maximum efficiency point;
Q^t = turbined discharge;
q = dimensionless discharge;
R = radius of the pipe;
t = time;
ΔH = head drop;
ΔH_B = head drop at best efficiency point (BEP);
ΔH^d = available head drop;
$\Delta H_B^{\max}$ = head drop at maximum efficiency point;
ΔH^t = head drop produced by the PAT;
ΔH^v = head drop produced by the valve;
α = sustainability coefficient;
γ = water specific weight;
η_B = efficiency at best efficiency point (BEP);
$\eta_B^{\max}$ = maximum efficiency of the machine;
η^t = machine efficiency;
η_p = plant capability;
μ_H = hourly averaged head;
μ_p = plant reliability;
μ_Q = hourly averaged discharge;
$\overline{\mu_H}$ = daily averaged head;
$\overline{\mu_Q}$ = daily averaged discharge;
ϕ = stator diameter; and
χ_p = plant sustainability.

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