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Article

Pump as Turbine (PAT) Design in Water Distribution Network by System Effectiveness

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Abstract: Water distribution networks face several problems related to leakages, where the pressure control strategy is a common practice for water loss management. Small-scale hydropower schemes, where pumps as turbines replace pressure reducing valves, can be considered an interesting technical solution, which ensures both economic convenience and system flexibility. Due to the water networks' variable operating conditions, a new methodology to model the effectiveness of pumps as turbines was developed based on the efficiency and the mechanical reliability of the hydropower device and the flexibility of the plant. System effectiveness is proposed as the objective function in the optimization procedure and applied to a real system, enabling one to emphasize that the hydraulic regulation mode of the plant is better than the electric regulation mode for American Petroleum Industry (API) manufacturing standards of pumps.

Keywords: pump as turbine (PAT); water distribution networks; Variable Operating Strategy (VOS); PAT hydraulic regulation; PAT electrical regulation; effectiveness

1. Introduction

Among the different sources of hydropower, small-scale hydroelectric power systems can be considered very interesting [1,2], but in order to make them economically feasible, they require low cost hydraulic and electric equipment. The strategy of pressure containment for leakage reduction is a common practice management of water distribution networks, because water loss increases with pressure values [3–5]. The first strategy for pressure containment is the reduction of pipe diameters, which also leads to a cost reduction [6–8]. When high pressure variability occurs within a water distribution network, pressure reducing valves (PRV) can be inserted for lowering water pressure to target levels [9–12]. Different numerical methods have been proposed for PRV placement design according to valve possible regulations [13]. Water demand satisfaction is the main design constraint of the model proposed by Araujo *et al* [4]. In 2006 [4], such a constraint was obtained in a two-step procedure, by determining, firstly, the best PRV location, then the best time distribution of PRV opening. An entropy-based method was used by Liberatore and Sechi in 2009 [14] for the solution of an optimization processes for PRV placement based on the target pressure values at nodes with fixed PRV backpressure values. PRVs can be considered the cheapest and a simpler solution to reduce pressure, but in the framework of a virtuous energy strategy, any PRV regulation should be converted in order to produce energy [15–17]. Traditional turbines can be considered a solution in order to control pressure and produce energy with high efficiencies, but the limited power available in a water distribution network, together with the high cost of a miniaturized turbine, could excessively extend the payback period of the machine [18]. Among the different alternatives of special turbines that have been suggested to face small and variable power [19–21] pumps as turbines (PATs) can be considered a compromise, having lower efficiencies and lower costs, and presumably, their use can be a worthy choice [22–25].

The difficulty of energy recovery in water networks consists in the variability of the available power, which is dependent on the user demand pattern. Operating conditions with large variability are a widely diffused issue among different production systems of renewable energy, with different problems and solutions depending on the source, such as waves, tides and wind [26–32]. In the field of water distribution networks, a specific design procedure, named the Variable Operating Strategy (VOS), for variability in time conditions of both flow discharge and pressure drop, was recently developed for power plants using a PAT as a production device [33–35]. Two PAT regulation modes were considered in VOS, hydraulic or electrical regulation, to obtain an optimal flow/pressure modulation in the power plant, *i.e.*, a suitable equivalence between PRV and PAT for pressure control management. The geometrical parameters of the PAT to be used in substitution of the PRV, plant efficiency and daily energy production are the main results of VOS application. Due to variable working conditions (e.g., flow and pressure), the electromechanical device could operate even far from the best efficiency point (BEP), thus resulting in a decrease of system reliability. Moreover, effective working condition could be slightly different from the design values, often based on network simulations. At the moment, there is no study in the literature on the effect of these factors on the lifecycle costs of a pump used as a turbine, and this aspect could prevent a large diffusion of PATs. To obtain an estimate of PAT maintenance costs, a methodology for the computation of PAT effectiveness was developed accounting for three different factors:

- The capability of the PAT performance in hydraulic or electrical regulation;
- The flexibility of the PAT under working conditions slightly different from the design values;
- The reliability of the PAT based on the lifecycle of its components.

The introduction of the overall mechanical effectiveness increases VOS potentiality. Due to the lack of experimental data in the field of PATs, their behavior is modeled herein by one-dimensional methods: the performances curves of the PATs with different diameters and rotational speeds are calculated by the affinity law of turbomachinery and the Suter [36] parameters, and the methodology is deeply described by Carravetta *et al*. 2012 [33]. The lacks of this approach have been highlighted by several authors [37,38], but whereas extensive experimental data about PAT performances will be available, the procedure can be improved in order to obtain more precise results. Similarly, PAT reliability depends on several factors, *i.e.*, the operating conditions, the manufacturing standards, the installation, the typology of water, *etc*. Unfortunately, due to the rarity of PAT installation, there is not a database of failures, and any statistical approach would be very difficult. In this paper, the authors refers to the Barringer reliability model [39,40], which only considers the hydraulic conditions and the manufacturing standards.

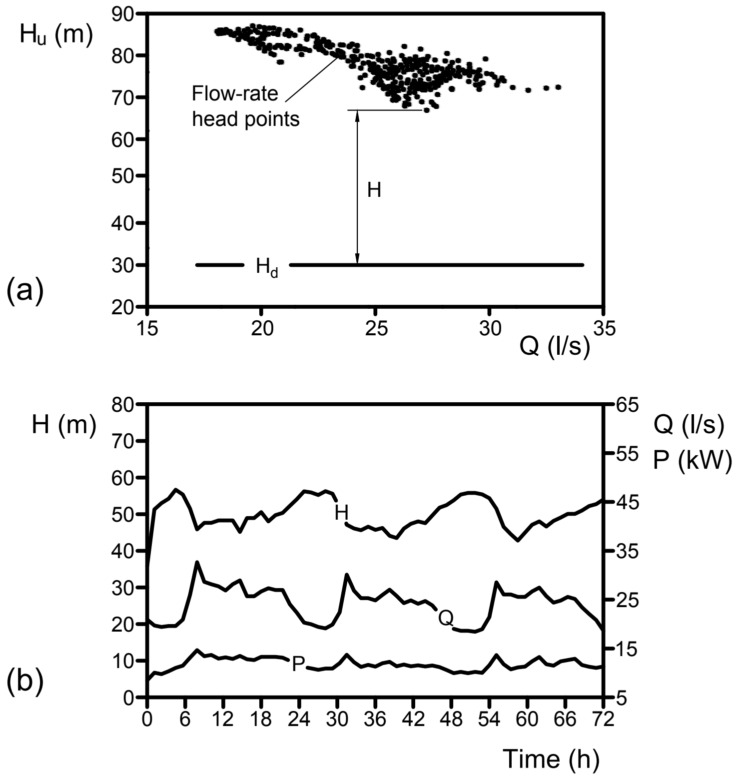
2. PAT Design Skills

A proper approach for the management of water distribution networks is the achievement of minimum standards of service. User satisfaction in terms of water quantity and quality requirements, as well as an active leakage control for reducing water loss, are among the primary management concerns, including cost savings. In absence of a direct action for physical leak reduction, namely, pipe replacement or rehabilitation, an appreciable reduction of water leakage can be obtained by means of an effective control of the head patterns in water distribution networks. The use of pressure control in systems is limited by the cost of the required valves.

In some cases, this strategy gives better results when used in combination with the division of the water distribution network into district meter areas [41], where a smaller number of valves occurs for pressure management. Unfortunately, this result is obtained with a reduction of system flexibility in the case of pipe failure. A new opportunity for pressure control can be given by the introduction of PAT in place of PRV. In this case, the costs of the electromechanical equipment are balanced in a small payback period by the income for energy production [34]. Additionally, system flexibility can be enhanced, because, in the case of pipe failure, the PAT working conditions can be changed. When the dissipation point locations are assigned within a water distribution network, flow rate (Q) and pressure head (H_u) daily patterns are hydropower plant design constraints, together with the backpressure (H_d) value, namely, the pressure head value downstream of the hydropower plant. The H_d value is determined as the optimal pressure head value for the network management in order to ensure both water demand and water loss reduction. The difference between the H_u pattern and H_d constitutes the net-head ($H = H_u - H_d$) daily pattern. The values of H_u and Q measured in an existing Italian PRV station located in Pompei (Campania), together with the daily pattern of Q, H and the available power, P, are plotted in Figure 1, with reference to a fixed $H_d = 30$ m.

The proposed design procedure involves the evaluation of the best performing PAT geometry, given the characteristic and efficiency curve of a single pump type working in inverse mode. PAT selection can be obtained with different power plant regulation systems, in particular, either with a hydraulic (HR) or an electric regulation (ER). In HR mode, the pump is connected in a series parallel hydraulic circuit, composed of two branches; the first branch is a dissipation/production branch, where the PAT and a PRV are placed in series; the second branch is a bypass regulated by another PRV. In ER mode, the PAT is connected to an inverter, ensuring variable rotational speed to the pump shaft [33,34].

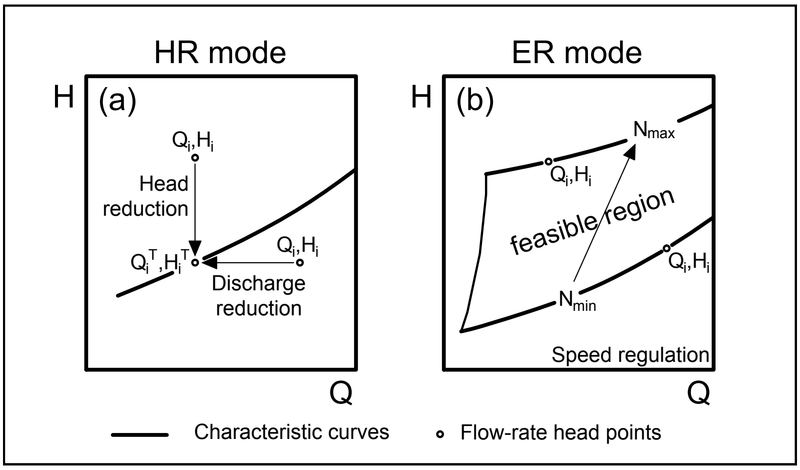
Figure 1. (**a**) Measured pressure head (H_u) and flow rate (Q) values; and (**b**) daily patterns of net-head (H), flow rate (Q) and available power (P) with a given backpressure value ($H_d = 30$ m).



In Figure 2, working conditions in ER and HR modes are plotted. In HR mode, for a net-head, H_i, higher than the head-drop deliverable by the machine, H_i^T (pointing to the left of the PAT characteristic curve in Figure 2), the valve in series dissipates the excess pressure. Instead, when the discharge, Q_i, is larger (pointing to the right of the PAT characteristic curve in Figure 2), the PAT would produce a head-drop higher than the available net-head: in this case, the bypass valve is opened to reduce the discharge flowing in the PAT from Q_i to Q_i^T. Thus, for each working condition, the electric power is different from the maximum available hydraulic power, because of flow rate/head reduction in the series parallel circuit. Conversely, in ER mode, the operating speed (N) of the generator is changed to match the load conditions determined by the instant flow discharge and head drop values; namely, the PAT characteristic curve is modified to match the available head. HR allows it to operate in all working conditions, due to the bypass regulation system. Conversely, ER does not ensure such a regulation, and therefore, PAT selection depends on the wideness of its feasible region to cover all the working condition points (PAT feasible region of Figure 2).

Each point of the characteristic curve, both in HR and ER mode, is related to a different value of machine efficiency (η_i). The performances curves of the machine depend on its geometrical characteristics. Thus, for a given machine, which can be identified by the pump type (centrifugal, semi-axial, ...) and the diameter, D, of the impeller, a different power would be produced, depending on the pattern of hydraulic conditions and on the regulation mode (hydraulic or electric). The Variable Operating Strategy (VOS) allows one to identify the type and the diameter, D, of the PAT, which maximizes the energy production for a given hydraulic demand pattern, either in HR or in ER mode. The choice between HR and ER modes is not simple and case-dependent, and the final design decision cannot disregard an economic evaluation of capital costs and payback period. A deep economical analysis was performed by Carravetta *et al.* in 2012 [34] for the data set of Figure 1a, and the payback period of the electro-mechanical components in HR mode were shorter than in ER mode. The comparison referred to a centrifugal, single stage pump, having specified a speed of $N_s^T = 44.0$ (rpm, kW). Anyway, it is not a general result, and the manager choice can vary, depending on the hydraulic conditions. In this paper, ER and HR will be compared also in terms of flexibility and mechanical reliability.

Figure 2. Pump as turbine (PAT) operating conditions in (**a**) hydraulic; or (**b**) electrical regulation.



3. System Effectiveness

In the framework of a more complete method for PAT selection, including not only the electro-mechanical efficiency, but also reliability, the effectiveness equation can be taken into account [42–44]. In 1991, Clements [45] describes effectiveness as telling how well the product/process satisfies end user demands. System effectiveness, ranging between zero and one, accounts for the influence of the different performance criteria of the system. The effectiveness equation can be written as follows:

$$E = A_1 \cdot \ldots \cdot A_i \cdot \ldots \cdot A_n = \prod_{i=1}^{n} A_i \qquad (1)$$

where $A_1, ..., A_i, ..., A_n$ are the n performance indicators of the system influencing its overall effectiveness. For PAT design, three indicators have been considered in evaluating E ($n = 3$): capability (η_p), flexibility (ϕ_p), reliability (μ_p). They represent, respectively, how the system:

- performs its intended production activity according to expectation;
- performs for a H_d variation around the design value;
- operates for a given time without failure.

Thus, Equation (1) specifies:

$$E = A_1 \cdot A_2 \cdot A_3 = \eta_p \cdot \phi_p \cdot \mu_p \tag{2}$$

3.1. System Capability

The capability is a direct result of VOS, since it can be defined as the ratio between produced electrical energy and hydraulically available energy for a given demand pattern. It can be differently calculated for HR mode or ER mode. In HR mode [33]:

$$\eta_p = \frac{\sum_{i=1}^{n} H_i^T\, Q_i^T\, \eta_i^T\, \Delta t_i}{\sum_{i=1}^{n} H_i Q_i \Delta t_i} \quad \text{with } \; Q_i^T \le Q_i \; \text{ and } \; H_i^T \le H_i \tag{3}$$

while in ER mode [34]:

$$\eta_p = \frac{\sum_{i=1}^{n} H_i\, Q_i\, \eta_i(N)\, \Delta t_i}{\sum_{i=1}^{n} H_i Q_i \Delta t_i} \tag{4}$$

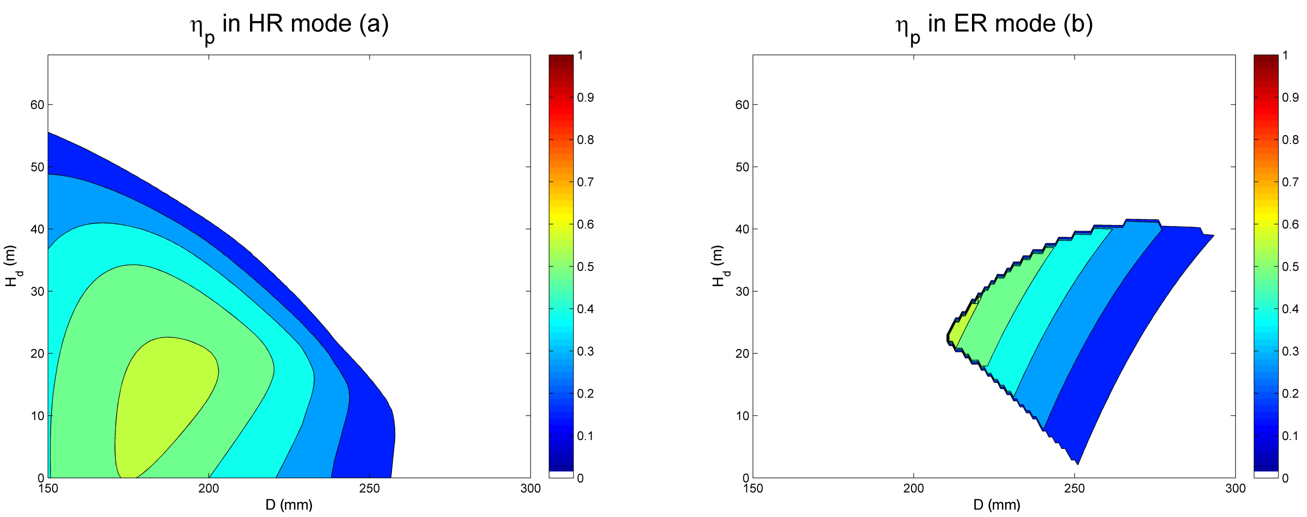
Δt_i being the time interval with constant hydraulic characteristics (Q_i, H_i).

It is interesting to stress that, in ER mode, the system capability corresponds to the average machine efficiency. In ER mode, the efficiency of the machines with a feasible region that does not include all the operating points is considered equal to zero.

Some previous studies [33,34] showed that the capability of a hydropower system with hydraulic regulation is higher than the capability of an electric regulated system, with maximum values of about 0.6 for HR and 0.55 for ER. Obviously, such values are strongly case-sensitive, because they depend on the variability of the hydraulic conditions.

In Figure 3, the calculated capabilities, η_p, of both ER and HR modes are plotted *versus* the diameter, D, of the machine and the backpressure, H_d. In HR mode, capability values larger than 0.4 are obtained in a wide range and for the smaller diameter values; this means that PAT of different diameters can be used with high capability. Conversely, in ER mode, such values are attained in a smaller area of the plot. Furthermore, it is important to observe that, in HR mode, the range of feasible backpressure values is wider than in ER mode.

Figure 3. η_p values resulting from the Variable Operating Strategy (VOS): (**a**) HR mode; and (**b**) ER mode.



3.2. System Flexibility

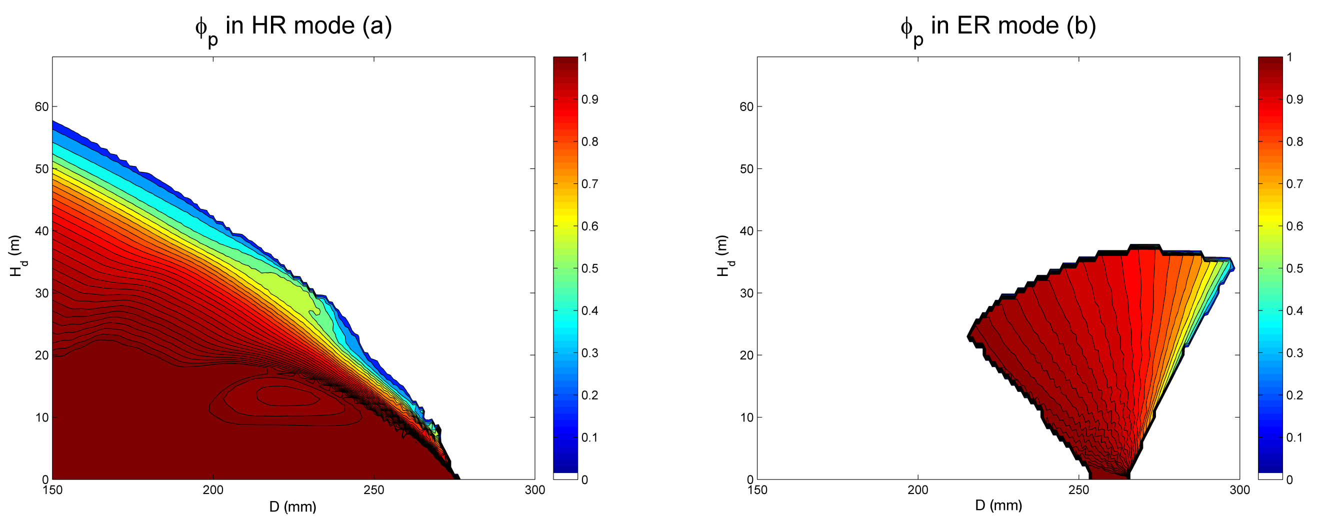
Network conditions in the power plant node, in terms of flow rates and pressures, cannot be always assumed as true values. During operations, real H_d values can be different from the design ones. Other times, flow rate and H_d may vary in time for changes in the water demand pattern. Even in the presence of measured design parameters, the introduction of a PRV or of a PAT may induce a substantial change in the water distribution network working conditions. In all these cases, PAT efficiency will vary during the power plant life, and system productivity could be lower than expected [34]. System flexibility (ϕ_p) gives an estimate of the power plant capability. Considering a $\mp 10\%$ of H_d, system flexibility will be defined as the minimum of the ratio between plant efficiency at $\mp 10\%$ H_d, namely, $\eta_p^{\mp 10\%}$ and design plant efficiency:

$$\phi_p = min\left(\frac{\eta_p^{+10\%}}{\eta_p}, \frac{\eta_p^{-10\%}}{\eta_p}\right) \tag{5}$$

System flexibility is, therefore, an important design parameter: the closer ϕ_p is to one, the less the global efficiency will vary around the design efficiency in the presence of unexpected H_d variations.

In Figure 4, the calculated capabilities, ϕ_p, of both ER and HR modes are plotted *versus* the diameter, D, of the machine and the backpressure, H_d. As a consequence of the capability plots of Figure 3, the system flexibility plot is very flat in the HR mode, but not in the ER mode, where larger gradients are observed.

Figure 4. ϕ_p values resulting from VOS: (**a**) HR mode; and (**b**) ER mode.



3.3. System Reliability

Reliability is the probability that a component, system or process will work without failure for a specified length of time when operated correctly under specified conditions [46]. Failure of an engineering system happens when the load, L (external forces or demand), exceeds the resistance, r, of the system for a specified duration, Δt. Thus, the reliability, R, of the system can be defined as the probability, p, that, during Δt, the load does not exceed the resistance:

$$R = p(L < r)|_{\Delta t} \tag{6}$$

Alternatively, if the load, L, can be considered constant for specified conditions during Δt, reliability can be defined as the probability that the time to failure, TTF, is smaller than Δt:

$$R(t) = p(TTF > \Delta t)|_L \tag{7}$$

The reliability of an engineering system is often represented by an exponential probability distribution [47]:

$$R(t) = e^{-\lambda t} \tag{8}$$

where λ is the failure rate, equal to $1/MTTF$, namely, the mean time to failure [48].

Barringer [39,40] showed how the flow rate has a marked impact on pump reliability. When a pump is operating away from its BEP, its reliability is lower than at BEP. Because $MTTF$ is a simple precursor of reliability, the latter is estimated by deriving a $MTTF$ curve showing it as a function of dimensionless flow discharge, $MTTF(Q/Q_B)$, where Q_B is the flow rate at BEP. $MTTF$ at a flow discharge away from the BEP is a fraction of the $MTTF$ at BEP, $MTTF_B$.

$$\mu = \frac{MTTF(Q/Q_B)}{MTTF_B} \tag{9}$$

Pump reliability and, consequently, μ values, depend on the quality standard of pump components. In Table 1, μ values for three industrial standards and for six different values of flow discharge around the BEP, respectively, -10% and $+5\%$ of BEP, -20% and $+10\%$ of BEP and -30% and $+15\%$ of BEP, are reported, based on the maintenance data of Barringer [39,40]. Barringer values are based on single pump component (impeller, housing, pump bearings, seals, shafts, coupling, motor bearings, motor windings, motor rotor and motor starter) reliability and are expected to be the same in inverse use of the pump as a PAT. In Figure 5, the $\mu(Q/Q_B)$ curve is plotted together with the dimensionless characteristic curves of a pump in direct and inverse mode, $h(Q/Q_B)$, h being equal to the ratio between the head drop at a given discharge and the head drop at BEP, ($h = H^T/H^T_B$).

The authors propose herein a procedure in order to evaluate the reliability of the PAT in variable operating conditions, based on the pump reliability data of Table 1: let us consider a cycle of operations whose period is T and with constant conditions for each Δt_i time interval, as shown in Figure 6.

Table 1. μ values for different manufacturing standards at different flow rates.

Q/Q_B	American National Standards Institute (ANSI)	Enhanced ANSI	American Petroleum Industry (API)
0.7	0.70	0.73	0.75
0.8	0.88	0.89	0.90
0.9	0.97	0.97	0.98
1.05	0.97	0.97	0.98
1.10	0.88	0.89	0.90
1.15	0.70	0.73	0.75

Figure 5. Plot of $\mu(Q/Q_B)$ and $h(Q/Q_B)$.

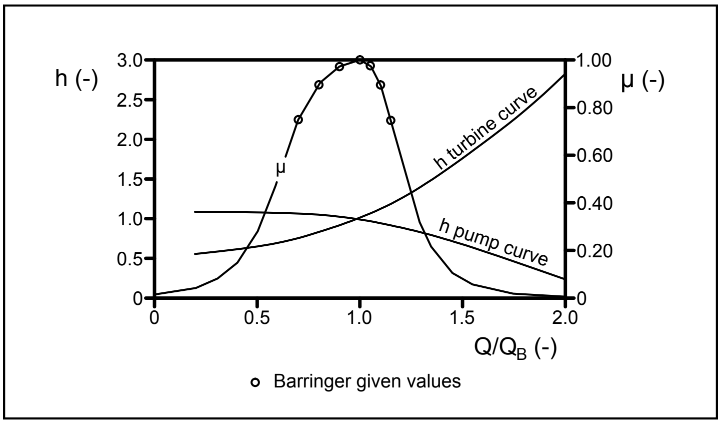
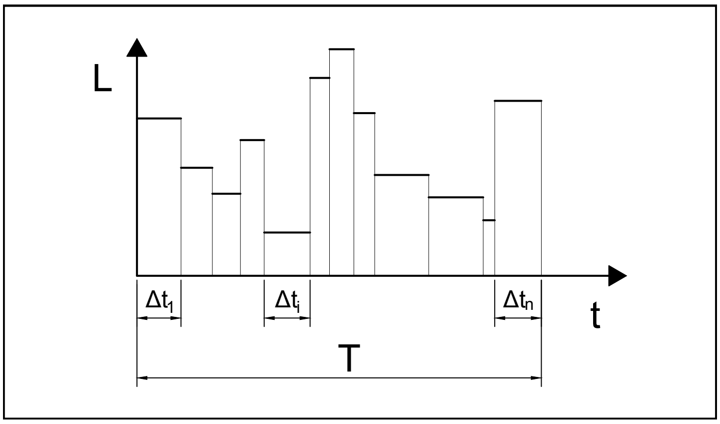


Figure 6. Load L variation during the period, T.



The reliability or the probability that the machine works without failure for the whole period, T, $R(T)$, equals the probability that the machine does not fail in any of the Δt_i intervals:

$$R(T) = p(TTF_1 \geq \Delta t_1)|_{L_1} \cap \ldots \cap p(TTF_i \geq \Delta t_i)|_{L_i} \cap \ldots \cap p(TTF_n \geq \Delta t_n)|_{L_n} \tag{10}$$

If the reliability is time-independent, *i.e.*, the effect of the aging of the machine is neglected or is the same, a correct maintenance program is carried out; Equation (10) equals to:

$$R(T) = R(\Delta t_1)|_{L_1} \cdot \ldots \cdot R(\Delta t_i)|_{L_i} \cdot \ldots \cdot R(\Delta t_n)|_{L_n} = \prod_{i=1}^{n} R(\Delta t_i)|_{L_i} \tag{11}$$

If Equation (8) is considered in order to express the reliability, then:

$$R(T) = \prod_{i=1}^{n} R(\Delta t_i)|_{L_i} = \prod_{i=1}^{n} e^{-\lambda_i \Delta t_i} = e^{-\Sigma_{i=1}^{n} \lambda_i \Delta t_i} \tag{12}$$

Being:

$$\lambda_{av} = \frac{\sum_{i=1}^{n} \lambda_i \Delta t_i}{T} \tag{13}$$

Yields:

$$R(T) = e^{-\lambda_{av} T} \tag{14}$$

Such an equation shows that the reliability of the machine in variable conditions is still described by an exponential distribution, with an average failure rate equal to λ_{av}. Thus, the average mean time to failure, $MTTF_{av}$, can be calculated as $1/\lambda_{av}$. In 1994, Carderock Division [49] showed the dependency of failure rate on load, namely $\lambda = \lambda(L)$. In the case of a PAT, the average failure rate can be derived from Equation (13) and a polynomial curve, $\lambda = \lambda(Q/Q_B)$, fitted to the values of Table 1, given the manufacturing standards. Thus, for an assigned pattern of flow characteristics, VOS application allows one to calculate:

$$MTTF_{av} = \frac{1}{\lambda_{av}} \tag{15}$$

Finally, the third term of E can be calculated:

$$\mu_p = \frac{MTTF_{av}}{MTTF_B} \tag{16}$$

where μ_p is a measure of the reliability reduction, due to the life-cycle.

Reliability plots of Figure 7 show that the reliability of HR mode is higher for the smaller diameter values, while in ER mode, high values can be attained only in a small region.

Figure 8 shows the contour plots of effectiveness, E, both for the HR and ER modes. The effectiveness of the HR mode is higher, and its feasible region is wider than ER mode.

Figure 7. μ_p values resulting from VOS: (**a**) HR mode and (**b**) ER mode.

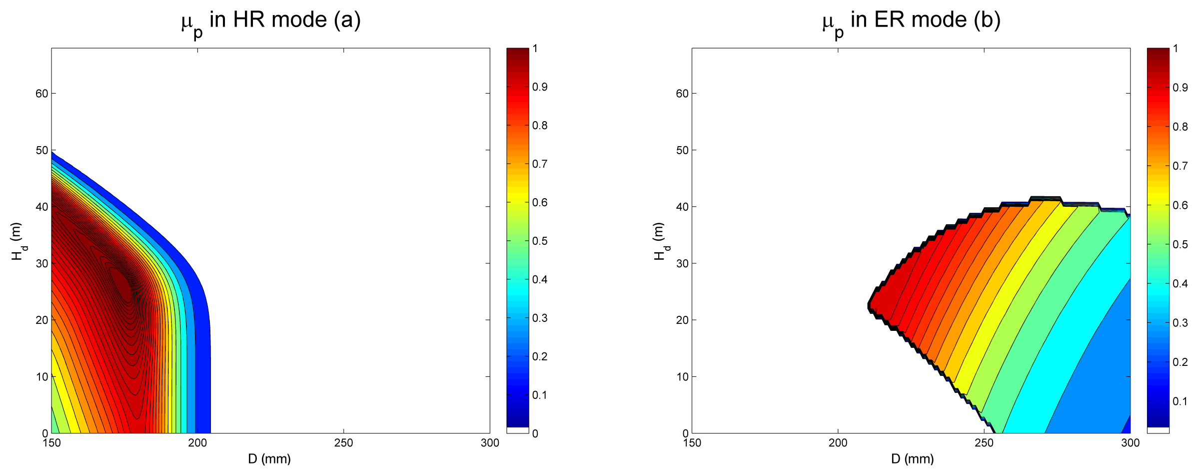
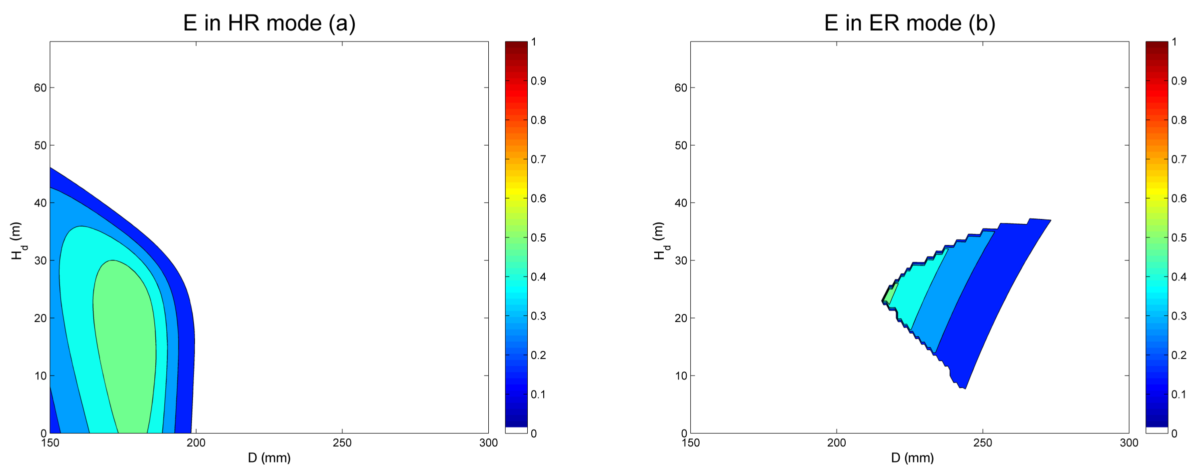


Figure 8. E values resulting from VOS: (**a**) HR mode and (**b**) ER mode.



4. PAT Design by System Effectiveness

The Variable Operating Strategy is a machine selection procedure. The last steps of the procedure consist in an optimization, in order to find the optimal PAT machine. Carravetta *et al*. [34] proposed the overall efficiency as maximizing objective function (VOS$_\eta$), while, herein, the system effectiveness (E) is proposed as maximizing objective function (VOS$_E$). The VOS$_E$ procedure has been applied to the design conditions of Figure 1, both in HR and ER mode for a centrifugal, single stage pump, having specific speed of $N_s^T = 44.0[rpm, kW]$ and for API pumps standards (Table 1). In Tables 2 and 3, the best design solution (namely, the impeller diameter, D) of VOS$_E$ is compared with the design solution of VOS$_\eta$. For a complete overview, all the parameters that influence the effectiveness are presented in Tables 2 and 3, respectively, for the optimal machines. As a first comment, it is important to stress that VOS$_\eta$, in ER mode (Table 3), indicates a machine that is not flexible at all; this is due to the particular position of the maximum efficiency (Figure 3b), which lies on the edge of the feasible region for ER. Such behavior was already emphasized by Carravetta *et al*. [34], who also modified VOS$_\eta$ results in order to increase the system flexibility.

Table 2. VOS results in hydraulic (HR) mode.

VOS	$H_d\ (m)$	**10**	**20**	**30**	**35**
VOS$_\eta$	$D\ (mm)$	186	191	181	176
	$\eta_p = A_1$	0.590	0.595	0.532	0.483
	$\phi_p = A_2$	0.997	0.984	0.952	0.893
	$\mu_p = A_3$	0.878	0.666	0.868	0.603
	E	0.517	0.390	0.440	0.260
VOS$_E$	$D\ (mm)$	179	178	171	163
	$\eta_p = A_1$	0.567	0.549	0.499	0.439
	$\phi_p = A_2$	0.999	0.990	0.956	0.923
	$\mu_p = A_3$	0.933	0.976	0.98 5	0.971
	E	0.529	0.531	0.471	0.394

Table 3. VOS results in electric regulation (ER) mode.

VOS	$H_d\ (m)$	**10**	**20**	**30**	**35**
VOS$_\eta$	$D\ (mm)$	237	216	222	234
	$\eta_p = A_1$	0.313	0.527	0.549	0.513
	$\phi_p = A_2$	0.000	0.000	0.000	0.000
	$\mu_p = A_3$	0.704	0.914	0.917	0.899
	E	0.000	0.000	0.000	0.000
VOS$_E$	$D\ (mm)$	239	221	231	250
	$\eta_p = A_1$	0.298	0.495	0.495	0.410
	$\phi_p = A_2$	0.977	0.976	0.957	0.924
	$\mu_p = A_3$	0.686	0.894	0.891	0.809
	E	0.199	0.432	0.422	0.306

Furthermore, it is interesting to observe that the system capability decreases only slightly if VOS$_E$ is adopted instead of VOS$_\eta$, while a sensible increase of E is realized. It is also important to emphasize that, with the new procedure (VOS$_E$), the E in HR mode is better than in ER mode for all considered H_d values. This is due to the smaller values of both efficiency and reliability in ER mode, while the flexibilities are quite comparable. Another important result consists in the diameters of the optimal machines: in HR mode, the optimal machines have diameters much smaller than in ER mode, and this obviously influences the cost of the machines, with a sensible reduction for the smaller diameter PATs.

The results of Tables 2 and 3 can be explained by means of contour plots of Figures 3, 4, 7 and 8, where system efficiency, flexibility, reliability and the resulting effectiveness are plotted for each H_d value and PAT diameter, both for HR and ER modes. System capability plot is very flat in HR mode, but not in ER mode, where larger gradients are observed. The same trend is also visible in both the flexibility and the reliability plot. This is a very important result, because at the end of VOS, the network manager must choose a near-optimal machine from the pump market, and a small variation of the system effectiveness of the real plant from the design conditions is desirable.

From the peculiar form of the terms combining in system effectiveness (Figures 3–8), it comes out that by an accurate design of the power systems, a strong benefit can be obtained in terms of system reliability and, consequently, in terms of system lifecycle costs. The maintenance benefit can be obtained without an appreciable decay in electromechanical efficiency. The reliability analysis proposed herein seems very case-sensitive, depending both on system regulation and pump manufacturing standards.

5. Conclusions

The Variable Operating Strategy (VOS), first presented by [33], is an optimization procedure, which allows one to select the optimal PAT (pump as turbine) to be used both for pressure control and for energy recovery in water distribution networks. The variable operating conditions can be faced by either a hydraulic (HR) or electrical regulation (ER) of the PAT.

The new concept of system effectiveness (E), based on the capability, flexibility and reliability of a PAT system, has been presented, and it has been used as an objective function of the VOS procedure. This innovative objective function adds mechanical reliability and system flexibility in the design procedure of a hydropower plant in a water network.

The Variable Operating Strategy was therefore developed for an assigned demand pattern, measured in a pressure reducing station located in southern Italy. It is interesting to observe that the overall design capability of the plant is not affected by the use of the new objective function, while a sensible increase of E is realized. It is also important to emphasize that, with this new methodology, the E in HR mode is always better than in ER mode for the case study situation. In the HR mode, system capability values are high in a wide range and for smaller diameter values. Hence, different diameters of PATs can be used with high capabilities. Conversely, in ER mode, such values are hardly attained. System flexibility is very flat in HR mode, but not in ER mode, where larger gradients are observed. The same trend is also visible in the reliability contour. These results are quite important, since they can help the near-optimal PAT choice from the pump market, with a desirable small variation of the system effectiveness from the design conditions. Another important result consists in the diameters of the optimal machines: in HR mode, the optimal machines have diameters much smaller than in ER mode, with obvious consequences in terms of costs.

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Conflict of Interest

The authors declare no conflict of interest.

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