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Energy recovery in water systems by PATs: a comparisons among the different installation schemes

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Abstract

Pressure reducing valves are frequently used within water distribution networks to reduce pressure values. The use of a pump working as a turbine (PAT) to recover the dissipated energy is generally considered the most cost-effective solution, but PATs are not provided with any regulation device. Thus, in presence of variable hydraulic conditions, a regulation system has to be inserted in the power plant to obtain the requested backpressure value. A comparison among the feasible regulation systems for PAT regulation is discussed and the optimal solution is found by means of the power plant effectiveness, combining system capability, flexibility and reliability.

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Keywords: Water distribution networks; PATs; Energy recovery; variable operating strategy (VOS); PAT hydraulic regulation; PAT electrical regulation.

1. Introduction

Energy dissipations are widely diffused in water distribution networks due to the pressure control practice aimed to leaks reduction (Tucciarelli et al., 1999, Araujo et al., 2006). Several methods are proposed in literature for determining the optimal location of regulation valves in order to perform the best pressure control. Two different strategies for valve location are suggested. The first is the identification of a number of nodes within the whole network where to locate valves in order to reduce the pressure to target values (Araujo et al., 2006). The second is the placement of the valve at the inlet node of one or more WDN district (Carravetta et al.).

A smart energy policy would require the exploitation of the hydraulic power dissipated along the water distribution network. Several technical solutions have been proposed to replace pressure reducing valves with energy production devices (Paish, 2002, Sammartano et al., 2013) in order to allow both an efficient power conversion and a reliable network pressure regulation either within (Ramos et al., 2010) or at the inlet node of a water distribution network (Carravetta et al.).

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In water distribution networks any energy production system should face a large variability of hydraulic working conditions, i.e. the discharge and the available pressure head, due to the daily user demand pattern. Power plant design is based on the respect of the constraints of water distribution networks, i.e. the imposed backpressure or the valve closure degree, and on the hydro power plant capability, defined as the ratio between produced electrical energy and hydraulic available energy for a given demand pattern. The design of the hydropower plant can be performed by a variable operating strategy (Carravetta et al., 2012). Variable operating strategy (VOS) application demonstrated that the use of a PAT as electro-mechanical device for energy production is generally considered the most cost-effective solution. When the PAT is inserted in a series parallel circuit (HR), PAT operation can be hydraulically regulated by control valves. In electric regulation (ER) of the impeller is modified by means of an electrical device. Recently a complete design strategy has been proposed based on the plant effectiveness, which combines the energy efficiency both with the system flexibility and the mechanical reliability (Carravetta et al., 2013a). Indeed, during his life cycle, the operating condition of an energy production system could change, due to hydraulic variation in the characteristics of the network, and the flexibility of the plant is an important parameter in the design process. Furthermore, the daily working condition variability can increase the stress of the PAT and the assessment of mechanical reliability of the system is crucial in order to avoid frequent failures.

The capability of the hydropower plant was found to be reasonable, with maximum values of 0.6 for HR and 0.55 for ER (Carravetta et al., 2013b). Furthermore, HR and ER modes could be combined in the installation scheme, but with an increase of the complexity, due to the presence of a PLC based actuator. Such increase of complexity, together with the higher power plant cost, could be afforded only in presence of a reasonable increase in system capability. The analysis of the capability for any combination of HR and ER is presented herein.

2. PAT working conditions

Flow rate and pressure values can be strongly variable within the dissipation nodes of a water distribution network due to daily user demand variability. In such variable operating conditions, for a given optimal pressure value, a variable head drop is dissipated in the valve. In Fig. 1, possible node working conditions are plotted, where the flow rates ($Q$) and upstream pressure head ($PH$) are measured values in the Italian water distribution network of the town of Pompei (Campania). By replacing the PRV with a PAT the available head ($H$) for energy production is the difference between the pressures head ($PH$) and the required backpressure ($BP$).

PATs can be used in combination with asynchronous electric generator, having constant rotation speed. In such conditions the performances of the machines are described by the characteristic curves, which relates the flow rate and head drop. The device efficiency curve, depending on the discharge, presents a maximum: the corresponding values of discharge and head drop ($Q_B^P$, $H_B^P$) is called Best Efficiency Point (BEP). Both characteristic and efficiency curves can be obtained in three ways: experimentally (Gantar, 1988, Fernandez et al., 2004, Derakhshan and Nourbakhsh, 2008), by computational fluid dynamics (CFD) (Rodrigues et al., 2003, Natanasabapathi and Kshirsagar, 2004, Fecarotta et al., 2011, Carravetta et al., 2011) and by any one-dimensional method (Stepanoff, 1957, Childs, 1962, Hanckock, 1963, Grover, 1980, Sharma, 1985, Schmiedl, 1988, Alatorre-Frenk and Thomas, 1990). Once the prototype characteristic and efficiency curves are available, the results may be extended to obtain the characteristic curves of other similar devices of different runner diameter and rotation speed, by using the Suter (Suter, 1966, Wylie et al., 1993) parameters.

As shown in Fig. 1, for the presence of variable operating conditions, a PAT can be used to obtain in the dissipation node a specified energy drop only in presence of a regulation system. In the case of small power plant, Fig. 2, the modulation can be obtained both by valves, which modifies the hydraulic characteristics of the flow, and by an inverter, which regulates the rotational speed of the PAT. The two valves placed in a series-parallel circuit and the inverter connected to the machine can be combined in order to obtain additional installation schemes.

If the regulation is performed only by valves (hydraulic regulation - HR), the series valve dissipates the surplus head while the valve in the parallel branch can bypass a part of the discharge, in order to move the available Q-H points onto the characteristic curve of the PAT. Rather, for an available head, $H$, higher than the head-drop deliverable by the machine, $HT$ (points to the left of the PAT characteristic curve in Fig. 3-left), the valve in series (A) dissipates the excess pressure. Instead, when the discharge, $Q$, is larger (points to the right of the PAT characteristic curve in Fig. 3-left), the PAT would produce a head-drop higher than the available head: in this case the bypass (B valve) is opened.
to reduce the discharge flowing in the PAT from $Q_i$ to $Q_i^T$. Conversely, if the PAT is regulated only by the inverter (electric regulation - ER), the rotational speed is modified in order to move the characteristic curve of the machine, matching the required values of discharge and head (Fig. 3-middle). Furthermore, in the new schemes analyzed herein, the inverter can be used in combination with one or both valves (Fig. 3-right), obtaining the combinations reported in Table 2.

Table 1. PAT regulation schemes

<table>
<thead>
<tr>
<th>Device (Fig. 2)</th>
<th>Case I (HR)</th>
<th>Case II (ER)</th>
<th>Case III</th>
<th>Case IV</th>
<th>Case V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Valve A</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Valve B</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Under water distribution network design constraints (backpressure), the result of VOS is the selection of the optimal pump for PRV replacing. VOS was already tested for HR and ER regulations (cases I and II), by maximizing plant capability and minimizing the plant payback period. A more complete method for PAT selection by VOS includes, in addition to the electro-mechanical efficiency, also maintenance and operational aspects, by using system effectiveness (Carravetta et al., 2013a). In this paper, a complete comparison among all the installation schemes will be shown: the capability, the flexibility, the reliability and the effectiveness, which are described below, are the terms of such comparison.

3. Hydropower plant effectiveness

A complete method for PAT selection has to take in account, not only the system capability, but also the power plant reliability. Clements (1991) describes effectiveness as telling how well the product/process satisfies end user demands. System effectiveness, ranging between 0 and 1, accounts for the influence of different performance criteria of system. In the case of energy production by PAT, effectiveness equation can be written as follows:

$$E = \eta_p \cdot \phi_p \cdot \mu_p$$
where: capability, $\eta_p$, represents how the system performs its intended production activity according to expectation, flexibility, $\phi_p$, represents how the system performs for a BP variation around the design value, reliability, $\mu_p$, represents how the system operates for a given time without failure.

### 3.1. Capability

The capability is defined as the ratio between produced electrical energy and hydraulic available energy for a given demand pattern. The capability can be expressed as

$$\eta_p = \frac{\sum_{i=1}^{n} H_i^T Q_i^T \eta_i^T (N) \Delta t_i}{\sum_{i=1}^{n} H_i Q_i \Delta t_i} \text{ with } Q_i^T \leq Q_i \text{ and } H_i^T \leq H_i$$

(2)
being $\Delta t_i$ the time interval with constant hydraulic characteristics ($Q_i, H_i$), $n$ the number of points in the operating region, $H_i^T$ and $Q_i^T$ the head drop and the discharge delivered by the PAT, $\eta_i^T$ the PAT efficiency for each operating condition, depending on the rotating speed $N$.

### 3.2. Flexibility

System flexibility ($\phi_p$) gives an estimate of the power plant capability to ensure the design efficiency under back-pressure changes. The latter could result from operating conditions different the design ones, as for an inaccurate network modeling or in the case of time for changes in the water demand pattern. Considering a 10% BP variation, system flexibility will be defined as the minimum of the ratio between plant efficiency at 10% BP and design plant efficiency:

$$\phi_p = \min \left( \eta_p^{10\%} / \eta_p, \eta_p^{10\%} / \eta_p \right)$$

### 3.3. Reliability

System 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 (Tung et al., 2006). The concept of system failure rate $\lambda$, and mean time to failure $MTTF = 1/\lambda$ are used to express system resistance under a load $L$ (external forces or demand) acting on the mechanical system.

Barringer (1998) and Barringer (2003) 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, $MTTF_B$.

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

Pump reliability, and consequently $\mu$ values, depends on the quality standard of pump components and are expected to be the same in inverse use of the pump as a PAT. In Fig. 4, $\mu$ values for different values of flow discharge around the BEP for API standard are plotted.

In presence of variable operating conditions, the load $L$ (external forces or demand) acting on the mechanical system is variable in time. Under the hypothesis that the reliability of the hydro-power system is represented...
by an exponential probability distribution, it is possible to express the failure rate \( \mu_p \) by a mean time average:

\[
\lambda_{av} = \sum_{i=1}^{n} \frac{\lambda_i \Delta t_i}{T}
\]

obtaining an average mean time to failure \( MTTF_{av} = 1/\lambda_{av} \). Finally, it is possible to define \( \mu_p \) as the measure of the reliability reduction due to the life-cycle, by the expression (Carravetta et al., 2013a):

\[
\mu_p = \frac{MTTF_{av}}{MTTF_b}
\]

4. PAT geometry and system capability by VOS

Variable Operating Strategy is based on a number of specific rules allowing the definition of the hydropower plant system satisfying design constraints to obtain the best system performance. Performance is evaluated on the basis of a performance equation. The performance equation could be either system capability equation (Eq. 2) or effectiveness equation (Eq. 1).

Then the following VOS steps are suggested;

1. A PAT operating region including all working conditions is defined.
2. A system regulation scheme is selected, among cases 1-5.
3. a measured pattern of flow-rate and pressure-head conditions \((Q_i, H_i)\) is assigned and the available head is determined based on the required backpressure \((BP)\), as in Fig. 1;
4. a PAT type is considered (e.g., centrifugal, semi-axial);
5. a wide set of PAT characteristic curves is considered in the PAT operating region, by changing the impeller diameter and the rotational speed;
6. for each PAT a performance is calculated based on a performance equation;
7. the PAT that gives the best performance is considered the optimal design solution;
8. the near-optimal machine is selected from the market and its turbine mode curves are calculated in order to verify the actual performance.

In cases III-V, a trial procedure has to be inserted in the previous step 6. In fact, for each available head drop, \(H_i\), and discharge, \(Q_i\), different operating point \(H_i^T\) and \(Q_i^T\) can be specified depending on the rotating speed of the machine, which modifies its characteristic curve. Therefore, the operating point giving the best performance is determined by varying \(Q_i^T\).

5. Comparisons

The proposed design strategy has been applied on a centrifugal, single stage, PAT \((N_s^T = 44.0 \text{rpm} \cdot \text{kW}/2m – 4/3))\), using the capability as performance equation. VOS was applied to the data set of 1 for different BP values. VOS results in term of system capability \((\eta_p)\) are showed in Fig. 5-9, where the capability is plotted for each couple of backpressure and machine diameter. Furthermore, VOS results are summarized in Table 2, where for each \(BP\) value the optimal diameter is showed, together with the respective capability.

PAT optimal design produces good power plant capabilities for all regulation modes. For each required BP, a different best capability point is obtained for each case. The maximum values is obtained in cases III and V for \(BP = 30m\). Furthermore, for values of \(BP\) higher than 30 m, cases III and V present the same capability: this means that, at least for the VOS optimal machine, the series valve is not needed for the regulation of the flow.

Two properties can be discussed in the plot for each regulation mode: the extension of the feasible zone of the power plant \((\eta_p > 0)\); the location of the high capability zone \((\eta_p > 0.4)\).
5.1. Extension of the power plant feasible zone ($\eta_p > 0$)

The power plant feasible zone is the range of the PAT diameters allowing the fulfillment of the BP constraint for all flow rates. It represents the range of application of a pump family in inverse use. The extension of the feasible zone is relevant also in the values assumed by system flexibility (Carravetta et al., 2013b). The same pump family can be used in HR mode (Fig.5) in the range of low BP with smaller design diameters when compared with ER cases. In the feasible zone of HR, this kind of regulation is more economically convenient than ER. Furthermore, the extension of
the feasible zone is smallest for case II (ER) (Fig. 6): this means that few machines (i.e. few diameters) can manage all \((Q, H)\) conditions with a change in runner speed. By placing a control valve in series or in parallel with the ER a great benefit is obtained in terms of regulation and the feasible zone becomes larger (Fig. 7-8). The advantage is more appreciable for ER + valve B (case III), where the by pass allows the regulation of all \((Q, H)\) points below the characteristic curve of minimum runner speed in ER. Obviously the feasible zone is largest for case V, which includes all other cases (Fig. 9), and the maximum \(\eta_p\) is obtained.
5.2. Location of the high capability zone ($\eta_p > 0.4$)

An optimal design implies the choice of a commercial pump having geometrical dimension as close as possible to the best capability point, i.e. in the high capability zone. In Fig. 10 the limit of such a zone for the different cases are plotted.

HR is the most suitable choice for low BP, presenting an easy pneumatic regulation with low PAT cost. Given the extension of the high capability zone, the choice of a commercial pump close to the optimal design solution will not affect appreciably the energy production. ER presents the most complicate design. For the limited extension of the high capability zone, a variation of the PAT geometry from the optimal design one could lead to poor operational conditions in terms of BP and $\eta_p$. The other ER based cases present low design uncertainties but higher plant costs when compared with HR. Additionally the regulation strategy of combined ER and control valves of case III to V has never been studied deeply. Finally the use of ER and bypass (case III) seems a promising opportunity for extending the use of the PAT to the highest BP values.

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References


