Design Considerations for Hydropower Development In a Water Distribution System

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ABSTRACT
Installation of a hydraulic turbine in a water distribution system involving long pipeline reaches requires several unique design considerations. For a fixed speed unit, the selection of design points for head and flow needs to be optimized to provide an operating envelope that would maximize the return on the investment given the widely varied flow and pressure conditions imposed by the water distribution system. The selection of a turbine design speed is essential in facilitating runner design, which must minimize the hydraulic pressure transients on turbine runaway that may result in overstressing the existing pipelines. Method and approach to evaluate these considerations are outlined. Relevant results for the selected design are presented using the 4.3 MW Rancho Penasquitos Pressure Control/Hydroelectric Facility as an illustrative example. Licensing requirements for small inline hydroelectric facilities are also briefly discussed.

Introduction
The potential for power recovery from a water distribution system exists whenever water flows from a high pressure to a low pressure in such a manner that throttling occurs. San Diego County Water Authority (Water Authority) currently imports about 320,000 acre-feet of untreated water per year through a gravity flow distribution system consisting of about 270 miles of pipeline. As a result, this system requires several in-line pressure control facilities designed to regulate pressure and flow. These in-line facilities are potential sites for the installation of an inline hydropower recovery turbine. The Water Authority’s Rancho Penasquitos Pressure Control/Hydroelectric Facility (PCHF) is the largest facility of this kind in the system.

The PCHF is geographically located in the central part of San Diego County, within the northern city limits of the City of San Diego. The PCHF is connected to the Water Authority’s Pipeline 5, which is a 108-inch diameter cement mortar lined and coated steel pipeline having an overall length of about 21.6 miles. Pipeline 5 supplies untreated water to a number of local municipal water treatment plants under gravity flow, and is vented to atmosphere at several high points. As part of the PCHF project, Pipeline 5 will be converted to pressurized flow raising the hydraulic grade line upstream of the facility.

The Water Authority has developed the PCHF, currently under design, to consist of three 42-inch diameter sleeve valves and one 4.3 mega-watt (MW) Francis turbine (Black & Veatch, 1996). Three sleeve valves will provide the required pressure and flow control up to 620 cubic feet per second (cfs). Additionally, the hydroelectric turbine generator will provide flow control up to 315 cfs and also recover the energy either for sale to the electric grid or used to offset the energy requirements of operating the Water Authority’s and its member agencies’ pumping and filtration facilities. The earned power revenue would be used to amortize the capital cost of the generating facility and to offset the Water Authority’s operating and maintenance costs.

The operating flow and available pressure gradient at the PCHF will be a function of the upstream hydraulic control facility and the untreated water demands in the Water Authority’s aqueduct pipeline system located north and south of the PCHF. During normal operations, either the sleeve valves or the turbine generator (or both) would be used to control the flow and pressure. The planned PCHF configuration will allow the turbine to tap only the flows south of the PCHF in Pipeline 5, which serves primarily the demands at the Miramar, Alvarado, Otay and Sweetwater filtration plants. The upstream hydraulic control is the Twin Oaks Valley Diversion Structure, which is a 22 million gallon reservoir with a normal operating water surface elevation of 1088 feet above mean sea level (MSL). Downstream hydraulic grade line control is provided by an open vent structure (the Miramar Hill Vent Structure),
which is maintained at a constant operating elevation of 825 feet MSL. Therefore, the normal maximum gross available head for the turbine generator at the PCHF would be 263 feet.

**Maximum Power Available**

The available power \( P \) for a turbine is the product of the net head \( H \) and flow \( Q \). As the net head is the gross head \( H_i \) minus the friction head loss \( H_f \) that is a function of the flow squared \( Q^2 \) in accordance with either the Darcy-Weisbach formula or the Manning formula, the available power \( P \) is then a function of \( Q \). Taking the first derivative of \( P \) with \( Q \) and equating to zero, an arithmetical derivation for a constant \( H_i \) determines that the maximum power \( P_{max} \) is available when \( Q \) is equal to the square root of \( 1/3 \) times the maximum flow \( Q_{max} \), which is defined as the flow that would result in \( H_i \) equal to \( H_f \).

Using the PCHF data as an example:
- Gross head, \( H_i = 263 \) feet,
- Length of Pipeline 5, \( L = 21.6 \) miles,
- Diameter of Pipeline 5, \( D = 9.0 \) feet, and
- Darcy’s \( f = 0.0108 \) or Manning’s \( n = 0.0110 \)

The maximum flow \( Q_{max} \) that can be sustained by the 263-foot gross head is found to be 710.5 cfs using either the Darcy-Weisbach or Manning formula. The maximum power would occur when the flow, \( Q_{max \ power} \), is:

\[
Q_{max \ power} = \frac{Q_{max}}{\sqrt{3}} = \frac{710.5}{\sqrt{3}} = 410.2 \text{ cfs}
\]

At a flow of 410.2 cfs, the corresponding net head at the PCHF is 175.3 feet, and the maximum generator output would be 5.16 MW if the design full-gate efficiency of the turbine and the generator efficiency at the full-gate power were 0.87 and 0.975, respectively. This design would maximize the power and energy production if, and only if, the operating flow can be set at a near constant rate of about 410.2 cfs. In fact, this ideal design scenario may apply if a sizable downstream reservoir would exist and the constant power inflow could be regulated to meet the variable downstream demands. Furthermore, in this situation the turbine could be oversized to allow the constant power flow operated at or near to the best efficiency point if the marginal benefit-cost ratio were greater than one, i.e. the incremental power revenue would be greater than the incremental cost of additional capital investment.

Unfortunately, the downstream hydraulic grade line control for the PCHF is set at the Miramar Hill Vent Structure with zero storage capacity. The flows at the PCHF vary significantly on a daily basis and are stochastically dependent upon the daily demands and the availability of local water resources at the municipal filtration plants located upstream and downstream of the PCHF. A turbine designed to generate the maximum power may not be economically justified because numerous low flows would have to bypass the turbine and allow the energy of highpressure heads being wasted through the sleeve valves.

**Considerations in Turbine Selection**

For a fixed speed unit, the turbine can only operate within a certain operating envelope, in which the allowable ranges of heads and flows are prescribed. Theoretically, a variable speed unit or two units of equal or different size would increase the operating ranges and efficiencies to maximize the power and energy production. However, these arrangements would increase unit capital cost and overall complexity in operation. In this context, the criterion requirement is that the selection of turbine capacity and number of units needs to be optimized to maximize the return on the initial investment, and not the maximum power and energy production.

The ultimate turbine selection is an economic decision that depends on the range of expected operating flows and heads based on future water demand projection and the percent of time that these heads and flows are expected to occur. Economic justification, including the required return or payback for the capital investment, is determined by comparing the projected value of the energy generated during the economic life of the facility to the capital cost of procuring, installing, and maintaining the facility for the same period of time. The process used is essentially an iterative process, which requires a computer simulation of power operation for a number of turbine design alternatives, and follows with a cashflow analysis of the cost and benefit for each alternative to identify the ultimate selection that best meets the criterion requirement.

The following outlines the method and approach employed by the Water Authority to confirm the selection of a 4.3 MW Francis turbine at the PCHF:

1. **Economic Life:** The economic life was set at 20 years, which represents the book life over which the capital cost of construction would be recovered from the debt service payments. Whereas the physical life of the hydroelectric facility may be over 50 years, the choice of 20 years reflects the insignificant economic value discounted over a longer period, the limited faith in long-term projection, and the Water Authority’s conservative fiscal policy.

2. **Daily Flow Projection and System Hydraulic Analysis:** The average

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daily flow is considered adequate for the power operation study at the PCHF, as the diurnal variation of the daily untreated water demand is small and practically nil. Historical daily flows and demands in recent years were collected. Future water demand projections were developed from the historical data, population growth projections, and regional development plans. The future demand projections were prorated based on the historical daily data to generate the future daily flow sequences for use in the power operation. As the friction loss is a vital design consideration for long upstream conveyance pipelines of large diameter, the Darcy-Weisbach equation, was used to provide the needed accuracy. Values of Darcy’s $f$ vary with the pipe rugosity, diameter, flow and water temperature, and can be calculated using spreadsheet formula considering each variable. Ranges of rugosity values for a variety of pipe materials were published elsewhere (US BuRec, 1977) and are supported with extensive field and experimental evidence. As Pipeline 5 is a mortar-lined steel pipe, an average rugosity of 0.000325 feet was adopted for the purpose of power operation study, while the maximum and minimum rugosity values were often used for required conservatism for designs and hydraulic transient analysis.

3. Development of Turbine Design Alternatives and Operating Envelopes: Based on the ranges of operating heads and flows expected over the 20-year period, a number of viable turbine design alternatives were developed to include number of units, unit design head, flow and rotational speed. An operating envelope (or a head-flow-capacity-efficiency relationship) was then established for each design alternative considering the specific speed and the operating limits due to cavitation and low efficiency. Preliminary engineering was also prepared to estimate the turbine dimensions and the civil/structure space requirements needed for the cost estimate.

4. Power Operation Study: A FORTRAN computer program was coded to simulate the daily power operation using the operating envelope and the projected daily flow sequences as the inputs. The program calculated, on a daily basis, the power flow, bypass flow, net head, turbine efficiency and turbine output capacity for each design alternative. The output data were then transferred to a spreadsheet for reprocessing the monthly and yearly summaries.

5. Economic Analysis: This is a cashflow spreadsheet program, which analyzes the cost and benefit streams over the 20-year economic life to evaluate the economic parameters, including internal rate of return (IRR), net present value (NPV) and payback period. A 20-year municipal bond issue with a coupon rate of 5.0 percent was assumed to finance 100 percent of the incremental capital cost. Incremental capital cost was calculated by first estimating the direct cost of the equipments and civil/structure features at the level of vendors and contractors, and then applying allowances to cover the indirect costs. Incremental costs are defined as those additional costs that would result from incorporating hydroelectric generating capability into the planned pressure control facility at the PCHF. Annual operating and maintenance (O&M) costs were estimated based on the experience of similar installed capacity, and then escalated 3 percent annually. Market clearing prices forecast by California Energy Commission for the years 2000 through 2010 were used as the values of the energy for the initial seven years of operation starting in 2004. The energy values after the year 2010 were assumed to increase at an annual escalation rate of 1.5 percent.

Using the above methodology, a single 4.3 MW Francis unit has been selected for the PCHF operating conditions. The operating envelope used for this selection, together with the daily generation data for selected years are shown in Figures 1 and 2. The power operation assumed a conservative limit of operating capacity up to 110 percent of the design capacity at full gate and a limit of operating flow up to 105 percent of the design discharge. The generation data for year 2023 in Figure 2 tend to spread into the lower head region because the increase of future untreated water demands effectively reduce the net heads available for generation. The pertinent design data

<table>
<thead>
<tr>
<th>Table 1 – Design Data</th>
<th>Rancho Pensaquito Pressure Control Hydroelectric Facility</th>
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</thead>
<tbody>
<tr>
<td><strong>Rancho Pensaquito Pressure Control Hydroelectric Facility</strong></td>
<td></td>
</tr>
<tr>
<td><strong>English Units</strong></td>
<td><strong>Metric Units</strong></td>
</tr>
<tr>
<td>Rated generator output</td>
<td>4736 kva (pф=0.9)</td>
</tr>
<tr>
<td>Rated turbine output</td>
<td>5653 horsepower</td>
</tr>
<tr>
<td>Generator output</td>
<td>4.26 MW</td>
</tr>
<tr>
<td>Turbine output at $(H_s, P_o)$</td>
<td>4.37 MW</td>
</tr>
<tr>
<td>Design discharge, $Q_o$</td>
<td>300.0 Cfs</td>
</tr>
<tr>
<td>Design head, $H_o$</td>
<td>198.0 Feet</td>
</tr>
<tr>
<td>Selected speed, $N$</td>
<td>720.0 rpm (at 60 Hz)</td>
</tr>
<tr>
<td>Selected specific speed, $N_s$</td>
<td>74.2 (in US HP unit)</td>
</tr>
<tr>
<td>Discharge diameter of runner, $D_r$</td>
<td>3.3 Feet</td>
</tr>
<tr>
<td>Generator/turbine, $W_{RF}$ (for pф=0.9)</td>
<td>66603 lb-ft²</td>
</tr>
<tr>
<td>Average runaway speed, $N_r$</td>
<td>1320 Rpm</td>
</tr>
<tr>
<td>Spiral case longitudinal dimension</td>
<td>11.2 Feet</td>
</tr>
<tr>
<td>Spiral case transverse dimension</td>
<td>9.6 Feet</td>
</tr>
<tr>
<td>Draft tube length</td>
<td>15.3 Feet</td>
</tr>
</tbody>
</table>
and dimensions for the selected turbine are given in Table 1.

The economic results for a cash-flow analysis including energy values, O&M costs, debt service, interest payment, internal rate of return (IRR), and net present value (NPV) are summarized for selected years, as shown in Table 2. Capital investment for the facility is estimated at $8.8 million. All monetary values are in $1,000 increment with the exception of energy values, which is in $/MWHr. The resulting payback period is between 11 and 12 years, or when the NPV or the cumulative cash flow becomes positive.

The power operation study results show that the average annual generation ranges from 33,007 MWhr in year 2004 to 30,765 MWhr in year 2023. These values represent a plant factor varying from 87 percent to 80 percent. High plant factor implies high utilization of the available flow, and is another indication that the turbine selection has been reasonably optimized.

Considerations in Hydraulic Transients

Transient flow can generally be divided into controlled and uncontrolled transient flows. The controlled transient flows are planned flow changes, such as line startup by opening and closing of control valves, valve stroking to adjust flows, turbine startup, turbine shutdown, or adjustments in turbine flows for increasing or decreasing power generation. Planned flow changes are considered orderly changes of the turbine or control valve settings, and will take the operation from one steady state condition to another steady state condition through transient flow in a controlled manner.
During normal startup and shutdown of the turbine unit at PCHF, one or two of the 42-inch sleeve valves will be used to close or open in synchronous operation with the turbine wicket gates. Ideally, the net change in flow may be reduced to zero by matching the discharge characteristics of the sleeve valve with that of the turbine. However, this is usually not possible because of the non-linear flow characteristics of the turbine and valves, and because of the dead time, or delay time, between the opening (or closing) of the valves and the closing (or opening) of the wicket gates. A preliminary computer simulation of this operation at the PCHF indicated that if the valve full stroke time is longer than 15 - 20 minutes, then the transient pressure rise or drop can be minimized.

Uncontrolled transient flows are unplanned flow changes, such as caused by a sudden load rejection of the turbine due to earthquake or other events, when the generator is disconnected from the electric grid while power is being generated. Because the small inertia of the turbine/generator in relation to the water column in a long pipeline, the rotational speed of the turbine will increase from the synchronous speed to a runaway speed that could approach nearly 180 percent of the synchronous speed. Runaway is generally not a significant problem to the turbine or generator, since both can be designed to withstand this condition. However, the flow through a Francis turbine may be seriously affected by the high runaway speed. This flow change upon runaway could produce critical transient pressure conditions in the upstream and downstream pipelines since most water distribution systems are not routinely designed for such event. Surge tanks could be incorporated in the design to limit the hydraulic transients effect, but they are expensive and an appropriate site for the tank may not be obtainable. Synchronized flow bypass using control valves is not considered reliable for the emergency operation because of an unacceptable risk of mechanical failure.

Study (Harza, 1976) has shown that the change in turbine discharge on runaway depends on the design specific speed at full gate. A low specific speed turbine causes a throttling effect on flow, which would create high transient pressure upstream of the turbines. Similarly, a high specific speed turbine would cause a flow increase, which would create high transient pressure downstream of the turbine. The following is a plot of Hitachi experience curve, together with Francis turbine model test data and the associated trend line.

Figure 3
Discharge of Francis Turbines at Runaway Speed

<table>
<thead>
<tr>
<th>Specific Speed Ns (in US hp unit)</th>
<th>Ratio of Q on Runaway to Full-Gate</th>
<th>Model Test</th>
<th>Hitachi Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.3</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.7</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.9</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1.1</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>1.3</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>

It appears that the zero change in flow could be technically feasible for a specific speed ranging from 62 – 80 at full gate, which depends on individual manufacturer’s runner design. Therefore, one way to minimize the transient pressure impacts would be to require in turbine bid specifications a special provision for limiting the discharge change upon runaway, such as ± 5 percent to ±10 percent of full-gate design discharge. The bid documents should describe the turbine setting and the upstream and downstream head variations, and the design rotational speed should be left open to the bidders’ choice, to allow manufacturers full flexibility to offer designs that will best meet the special provision on flow change. Model test should be required to provide testing data points near the runaway speed, which must have the discharge characteristics within the specified limits. A computer simulation using the model test characteristics should be performed, prior to a field test, to confirm that the transient pressures generated by a full-load rejection without synchronous bypass opera-
tion would not exceed the pipe design limits.

As the mechanical and electrical equipments constitute up to 85 percent of the total construction cost, it is also necessary to have thorough, complete, and unchanged specifications for the turbine generator prepared well in advance of the final design for civil-structure components. Vendor drawings are required for the completion of the civil-structure design so that all civil-structure components would accommodate the turbine and other equipment design.

**FERC Licensing Considerations**
The Federal Energy Regulatory Commission (FERC) may issue a conduit exemption license for a generating capacity up to 40 MW for a municipal project on an existing conduit. The PCHF would qualify for a conduit exemption not only under the capacity criterion, but also meeting the other criteria in that: (1) the conduit would be constructed even if the hydroelectric facility were not; (2) the project will be located on property in which the Authority holds real property interest; (3) the project will discharge into a water supply pipeline and will not rely on the construction of a dam; and (4) power generation will be a secondary usage of the project water.

The exemption process will require an initial consultation, in which an Initial Consultation Package (ICP) would be prepared in accordance with 18 CFR 4.38, and a Draft Exemption Application would be prepared in accordance with 18 CFR 4.92. The ICP and the Draft Exemption Application would be distributed to the resources agencies for review and comments. If all the issues can be settled and the Draft Exemption Application is revised to incorporate agencies’ substantive comments, the revised Draft Exemption Application represents the Final Exemption Application, which will be filed with FERC. FERC would then issue a public notice, and if there were no intervention, the conduit exemption license may be issued in a matter of few months. Recent consultation with FERC staff has indicated that an application for exemption for a 39.6 MW installed capacity plant was approved by FERC in about two months.

**Conclusion**
Development of small hydroelectric facilities on water distribution systems is a small but significant step to promoting renewable sources of pollution-free power. A conduit hydroelectric facility is environmentally preferable to many other types of generation because it does not produce carbon dioxide, NOx, SOx, or other potentially harmful particulates that are major contributors to various pollution problems in an urban environment, and therefore, should be considered a genuine “green power” project. Fast implementation, long project life, zero fuel cost, and freedom from price volatility of fossil fuels should make similar conduit hydroelectric facilities an economic project in a competitive open market.

**References**

Black & Veatch Corporation, “Hydroelectric Feasibility Study for Pipelines 6 and 5EII”, a draft report prepared for the San Diego County Water Authority, 1996.


Harza Engineering Company, “Discharge of Francis Turbines at Runaway Speed”, a study report prepared for the Metropolitan Water District of Southern California, June 1976

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