Performance Monitoring and Artificial Intelligence for Hydro Plant Efficiency Improvement

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Abstract

Hydroelectric powerplant operations offer a unique opportunity for performance improvement through the use of on-line flowmeter, level and power measurement instrumentation. A system developed to exploit this opportunity in multi-unit hydroprojects using acoustic flowmeters with an off-line expert system is described. Depending on powerplant size and condition, overall improvements of 0.5-5% are anticipated, together with improved unit performance characteristics for higher quality unit condition monitoring.

Introduction

In 1985, the total hydro generation within the United States was approximately 300,000 GWh (*Water Power & Dam Construction, 1986*). If this generation could be increased on the average by even half a percent, about 1,500 GWh of additional energy (enough to power Albany, New York for more than four months) would be realized from this resource. Since most hydro plants were designed and built in the early part of this century, improvements on this scale can realistically be obtained by applying modern instrumentation and computer technology to improve their operational efficiency.

Accusonic has been addressing this opportunity by developing the control technology to fully exploit the potential of the system performance information provided by its acoustic flowmeters. It has teamed with IIT Research Institute and the Niagara Mohawk Power Corporation to develop a Hydro Control System (HCS) which is a tailorable hardware-software platform for hydroproject control and application of operational strategies. The Hydro Advisor System described here resulted from the initial research and development to test some of the key concepts to be included in the HCS. The Hydro Advisor addresses the task of allocating discharge within multi-unit hydroprojects to optimize operational efficiency. It can be either a stand-alone PC-based system or it can be combined with a real-time data acquisition system to provide the plant operator with the tools to improve the overall efficiency of the plant.

Background

In multi-unit hydroprojects operating under less than maximum generation, operational decisions are complex. They include choosing which units to use for generation, which to keep as spinning reserve, whether to take units off line entirely, and how often to make adjustments to the loading of units. In addition, the discharge allocation to those units in use for generation must be set to optimize the overall plant performance. All this must be

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accomplished while satisfying various requirements and constraints such as the required spinning reserve, future generation requirements, and present and future headwater and tailwater levels and variation limits. Also, undesirable gate settings, frequency of gate changes allowed, and accommodation of units which are out of service need to be considered.

These operational decisions are complicated further by the dynamic nature of the turbine performance characteristics. Small differences can be important when trying to optimize the combined performance of multiple turbines. It is generally accepted that turbines of the same design do not perform identically, especially after years of service and maintenance. Turbines are constantly undergoing maintenance for cavitation repair or, in the extreme case, are replaced with new turbines. When turbines of different capacities are placed in the same powerhouse, the choices of optimal control strategies are more subtle. In fact, some choices defy intuition.

Thus in order to maintain optimum efficiency continuously, plant performance characteristics must be monitored and stored, at least occasionally and at best continuously. This performance information must include water levels, power generation, inlet/outlet canal characteristics, and "forbidden ranges", all as a function of the discharge from individual turbines. Having this data available in a database enables an accurate model of the system to be kept current. From this model operational decisions can be made for the best performance under constantly changing conditions of load, head, unit availability, and other important constraints.

Before the advent of high accuracy multipath chordal acoustic flowmeters, there was no practical way to perform this monitoring. Earlier methods, including the Gibson method, Current meters, Allen Salt velocity, Dye dilution and Winter-Kennedy taps suffered not only from a lack of repeatability, but they were one-time measurements not suitable for continuous automatic monitoring. Furthermore, several of these techniques were not capable of being permanently installed in the turbine or penstock, and were subject to long term drift and/or maintenance problems.

The acoustic flowmeter, on the other hand, is ideally suited for this purpose. It is a microprocessor based system and is inherently easy to interface to other control systems. It can be built with internal self checking and verification logic to assure that its output is good, and it can be designed with self-diagnostics to allow rapid repair in the event of failure. In some cases, these meters can be built with redundant features further to increase reliability and availability.

Other advantages include:

- Continuous flow measurements
- Wide choice of output formats
- High stability and repeatability
- High "Dry Calibrated" accuracy.
- Suitability for flow measurement in relatively unfavorable locations, such as immediately downstream of elbows, valves, near transitions, etc with minimal loss of accuracy.
- Easily controlled by external computer
- Data logging
- No head loss
- No moving parts
- Suitable for a wide range of penstock sizes, shapes and configurations.

It is the synergistic combination of acoustic flow measurement and low cost microprocessor based expert systems which makes it possible to automate hydroelectric powerplant optimization process.

An example of a data acquisition system and operation is provided in an unpublished report prepared for GRDA, Reference 1, parts of which are excerpted here.

"As part of a specification for the supply, installation and commissioning of multi-path acoustic flowmeters, pump and turbine efficiency tests were performed at Salina Pump Storage Plant for Grand River Dam Authority in Oklahoma in May of 1991.

"Pump and turbine efficiency measurements were performed on each unit at Salina at 860 feet reservoir level (241 Gross head) with the exception of Unit 3 which was out of commission. Additionally, Units 1 and 6 were tested at reservoir levels of 855 and 865 feet during May 1991. In all, 16 separate pump/turbine efficiency tests were performed in 20 days.

"The tests were performed in accordance with I.E.C. standard publication 41 - 1963 and ASME PTC 18, 1949, with the exception of the acoustic flowrate measurements which used two crossed chordal four path measurement planes in penstocks Number 1 and 6 and single 4 path chordal planes in the remaining units.

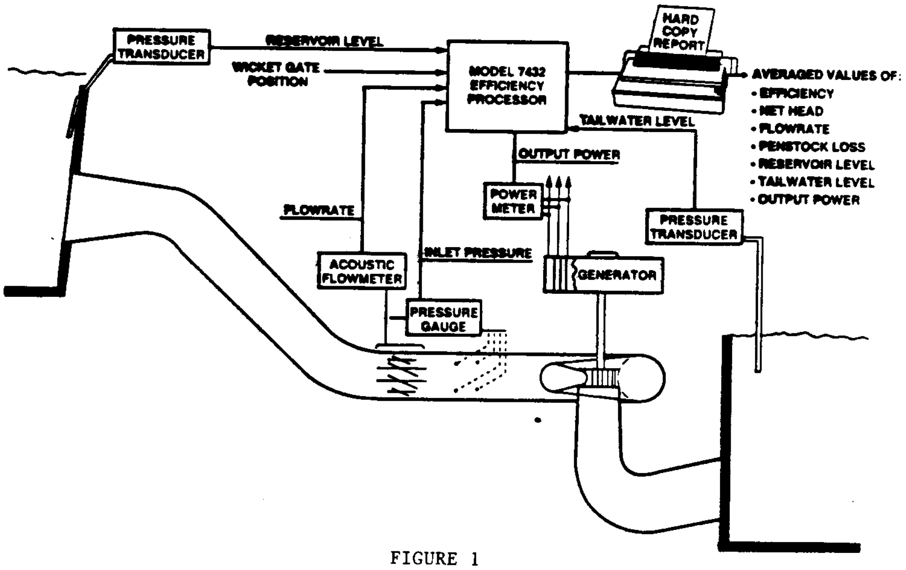

FIGURE 1
EFFICIENCY MONITORING SYSTEM

"The acoustic flowrate measurement method was found to provide highly repeatable flowrate and efficiency measurements." The Accusonic Turbine Efficiency Monitoring System (refer to Figure 1) is designed for use on many types of hydroelectric turbines.

The G.R.D.A. system comprised:

- A four path acoustic travel time flowmeter
- A three-phase power meter
- A digital pressure gauge
- Passive pressure transducers
- A central controller and data logger for storing the above data and inputs for recording the following analog information:
  - Tailwater elevation
  - Forebay level
  - Wicket gate opening

The data in this case was used to generate performance maps similar to Figure (2).

Performance Optimization Considerations

The allocation of discharge in a multi-unit hydroproject is the primary control decision affecting performance. It is a complex process for which many factors need to be considered. Foremost are the operational goals of the system. The Hydro Advisor provides for two types of operational goals, head-following and power-following.

Head-following:

A head-following operation would be used in a "run of the river" plant. It involves specifying target head values to be attained at fixed points in time. The collection of these points are referred to as the target head profile. A possible target head profile would be one that would keep the head constant at or near the top of the dam. Since power generation is proportional to the head, this approach would provide the most potential power at any time. There are other situations, however, in which keeping the head constant might not be the best approach. If an expected increased inflow is going to exceed the total maximum generation capacity of the plant and operation to maximize the total energy conversion is desired, one would probably attempt to lower the head enough just prior to the expected increase to provide for storing the excess. Otherwise the excess will be spilled and its energy will be lost.

Following a target head profile requires the calculation of the required amount of plant discharge necessary to fill or draw down the reservoir as specified in the target head profile. This calculation must consider the characteristics of the reservoir, the current head level, and most importantly the projected reservoir inflow. How often discharge is recalculated depends on the rate of change of the target head profile, and the rate of change of the reservoir inflow. For an optimized solution, the final step is to allocate the calculated discharge between units to maximize power production.

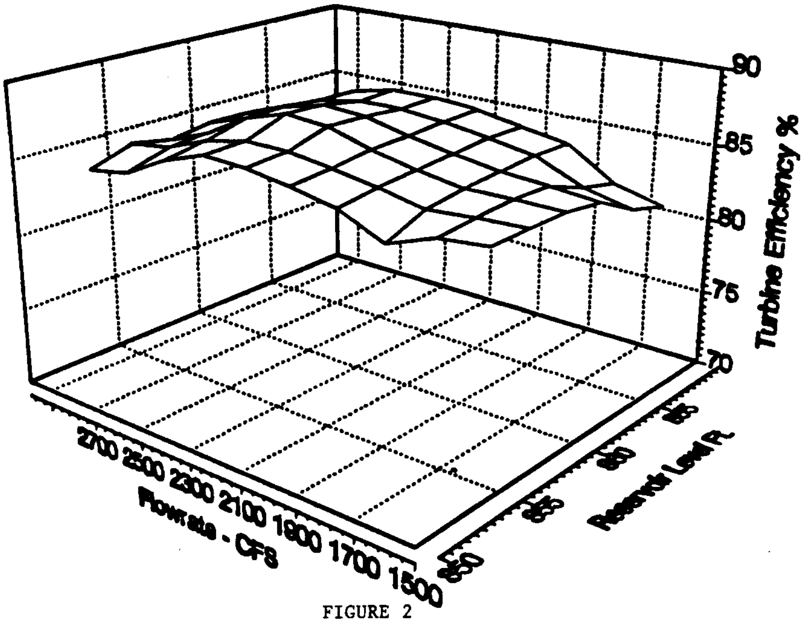

FIGURE 2
SALINA PUMP/STORAGE UNIT 1 GENERATION
PERFORMANCE MAP

Power following:

A power following operation would most likely be found in a "storage release" plant. Following a target power profile requires, for an optimum solution, finding the minimum amount of plant discharge necessary to deliver the specified power. This may be accomplished by proper allocation of the power generation requirement between units. The head, flow, and efficiency characteristics of each unit must be considered. How often the minimum amount of discharge must be recalculated primarily depends on the rate of change of the target power profile.

Alternatively, in applications where a major goal of the powerplant is to meet downstream water requirements for irrigation, a discharge following operation would be used, again with the objective of meeting the discharge requirements while optimizing power generation.

Once the operational approach is chosen, performance optimization is a matter of picking which units to utilize, determining their operating points, and deciding how frequently these are to be adjusted. There are some rather obvious constraints on these decisions, such as equipment availability, maintenance scheduling and cycling limits necessary to prevent excessive wear on the equipment. Beyond these obvious constraints the problem becomes complex, sometimes leading to counter-intuitive solutions. For instance, if the total flow required to keep a constant head happened to be the exact sum of the discharge of units A and B at best gate in a three unit system, one would think setting each of these units at best gate (and the third shutdown) would provide the best performance. It happens that this is the best approach in some cases. If the characteristics of the two units are somewhat different, however, improved performance can often be obtained by setting one unit slightly above its best gate and the other slightly below. Even when the two units are identical, replacing one with the third unit might provide even better performance depending on the characteristics of the third unit.

The key data required to be able to determine the best particular combinations are the efficiency characteristics for each unit as a function of flow and head. Although many multi-unit hydroprojects consist of similar units, age, use and maintenance cause them to change. Also, significant variations can occur in the efficiency curves between the model and actual unit. Factors such as manufacturing irregularities and flow anomalies in the water conveyance structures can affect individual performance characteristics of identically designed units. In addition, maintenance and upgrades tend to change the actual performance of units over time. Thus units that were originally designed having identical characteristics change relative to each other. Figure 3 shows a graph of power vs. efficiency that compares a unit before and after runner replacement. As such changes occur in units over the years significant operational advantages can be obtained by changing operational approaches accordingly.

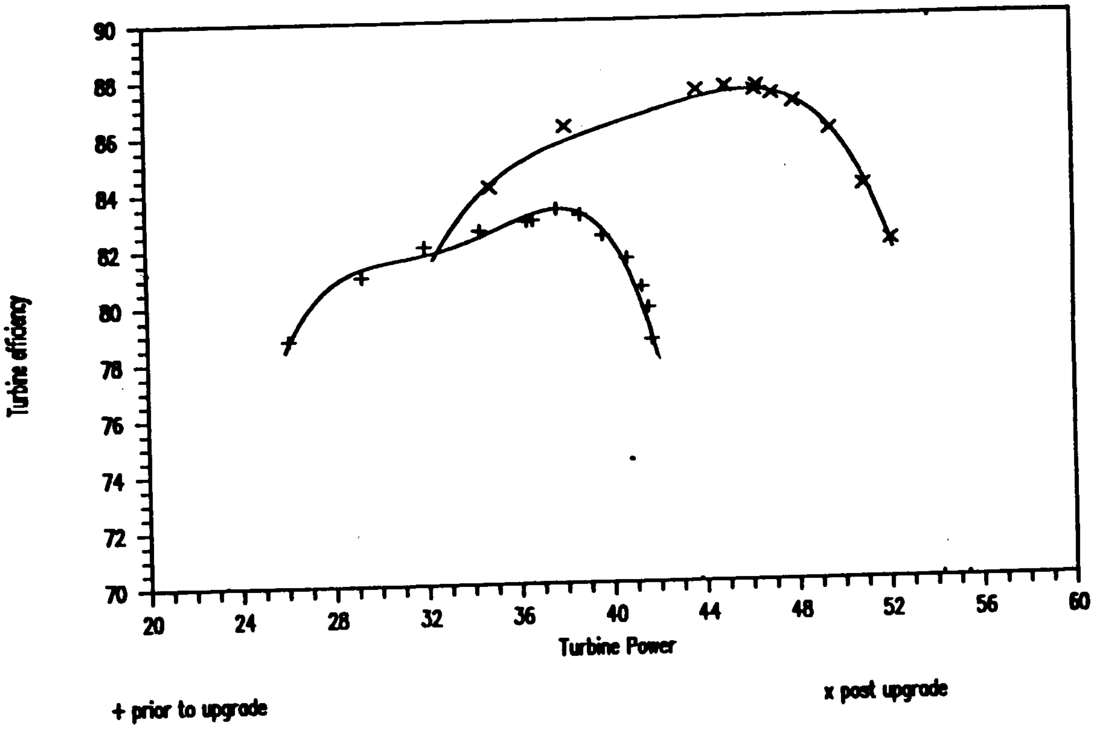

FIGURE 3
UNIT 6 EFFICIENCY VERSUS TURBINE POWER
BEFORE AND AFTER UPGRADE

Optimization Methods

The most important element of the Hydro Advisor is the automated technique used to find the best combination of units and operating points to produce a required flow or power. A knowledge-base approach is used to do this, allowing the processor intensive steps in the solution to be performed off-line. This not only enables the technique to scale up well to large numbers of units, it also provides great flexibility in finding solutions which also satisfy additional constraints.

A simplified description of the technique for a head following goal is that a database is generated to hold, for every flow and head requirement, all potential combinations of the unit settings which can generate that flow efficiently. Actually, two databases are generated for each of a selection of head levels to address both head and power following goals. One has, for each possible required flow at the given head, a complete selection of possible unit combinations (including each unit to be used, its operating point, and the total power generated by that combination) which generate the required flow. The second database is of a similar format, however it is indexed by power instead of flow, and includes the total flow associated with each combination. These databases, coupled with a rule based look-up engine constitutes the expert system.

The presence of this database reduces the process of picking the optimum unit/operating point combination for a particular flow or power requirement to a table look-up. In addition, since a number of potential combinations are made available for each requirement, picking the best solution while meeting other constraints such as unit availability, spinning reserve, or minimum discharge is greatly facilitated. The current version of Hydro Advisor enables considerations of unit availability to be incorporated. Expanding the system to handle additional constraints will be added in future releases.

Separating the development of the solutions database from the real time operation opens up many possibilities for off-line tuning of the solutions to address requirements particular to a given installation. In addition, as long as the tuning is done by automated processes, a complete reconstitution of the solutions database to account for characteristics which have changed due to maintenance operations or because better test results have been obtained, is straightforward.

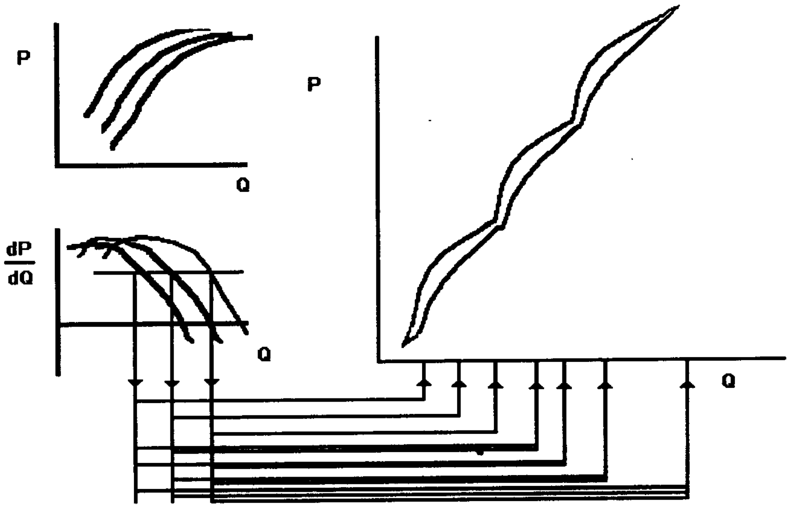

FIGURE 4
GENERATION OF COMBINATION DATABASE

Initial tests have shown this technique to be fast and reliable, however, populating the database has proved to be a significant challenge. A five unit system could easily involve well over 500 million operating point combinations if a sufficiently small resolution is desired. Many of these operating points are not needed, however, and the Hydro Advisor employs several heuristic techniques to generate a database that contains only the more promising of these combinations.

One of the most useful of these heuristics is based on the constant dP/dQ criteria which has been used for years as part of hydropower optimization strategies. References 4,5 and 6, for example, all contain optimization discussions involving this principle.[1] This heuristic uses the simple observation that when distributing the flow between two or more units with convex P vs. Q characteristics, the most economical operation results when slopes of the power vs. flow curves are equal at the operating points.

Figure 4 provides a somewhat stylized illustration of the manner in which this heuristic is applied to help fill out the solutions database for flow requirements. In the upper left part of the figure the P-Q characteristics of three units at a specific head are shown. Just below that are the slope curves (dP/dQ) associated with these characteristics. The plot on the right side of the figure is meant to represent the locus of P,Q pairs for the recommended solutions at this head.

Graphically, one could identify a selection of potential solutions by drawing a line across these slope characteristics, as shown, and reading the flow intercepts for each unit. The associated powers for the Q intercept for each unit could then be read from the P-Q characteristic above.

These represent partial solutions which can be combined to make 2^3 = 8 different optimum solutions for the database. Only seven of these are shown in the figure since the null solution is discarded. For instance, one valid combination would be to use only the first unit. For this combination in the figure imagine that the associated power

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[1] Voaden (Ref 1) provides a citation for this criteria (F.H. Rogers and L.F. Moody, "Inter-Relation of Operation and Design of Hydraulic Turbines," Engineers and Engineering, Vol. 42, July 1925, pp. 169-187) which may be one of the earliest discussions of it in reference to hydroelectric optimization. Unfortunately, the authors have not been able to obtain a copy of this article.

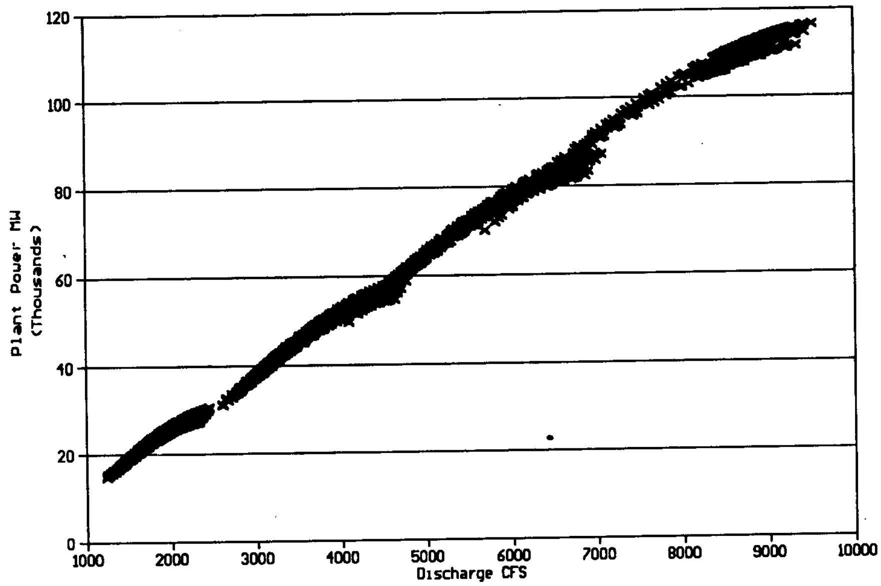

FIGURE 5
HYDRO ADVISOR DATABASE

is marked above the corresponding flow on the rightmost plot of the P,Q loci. Another valid combination would be to use all units. This provides the solution for the largest flow.

If this procedure were continued, i.e., moving the line from the top of the dP/dQ characteristics down until all possible intercepts were obtained, the loci of the powers available for each valid solution would form a thick area such as that illustrated.

In the computer this process is done by manipulating records in databases, and when the P,Q pairs are plotted from the final database the result looks similar to that in the figure. Nearly every pixel is covered by a line going from one solution to another as all solutions are plotted.

Various heuristics such as these have been known for years. They have been used to set up general guidelines for operation, often represented as curves or rules of thumb for operators to use. The advent of good instrumentation coupled with inexpensive computational resources makes it possible to exploit them to a much greater degree now, however, making available opportunities for increased performance which would have been impractical in the past.

Performance Comparisons

To illustrate the potential advantages available through the use of the Hydro Advisor, Tables 1 through 3 illustrate inputs and outputs for simulation runs of a typical 4 unit hydroelectric dam. The operating strategy is to run on a daily basis to offset energy costs during peak times. This hydroelectric dam has three older Francis type turbines (units 2-4) and one new Francis type turbine (unit 1). This is a typical hydroelectric plant where the owner is currently studying the feasibility of upgrading the remaining units.

As mentioned earlier, the generation of the possible combination database is a key aspect of the Hydro Advisor. Figure 5 graphically shows a database generated for a hydro plant. The plot shows that from a discharge flow of 3500 CFS to 8000 CFS a very rich set of combinations exist which provide a given discharge flow. It is obvious from the plot that the different solutions provide powers which can vary by several percent for the same flow. It is important to note that this graph represents only the more promising solutions to the flow allocation problem, not all of the solutions. This graph illustrates that even when selecting the more promising solutions, significant

Unit (#)	Gate (%)	Flow (CFS)	Power (KW)	Head (FT)	Plant Eff. (%)
1	98	2383	29,367		
2	0	0	0		
3	96	2339	27,519		
4	92	2282	27,586		
Total		7004	84,471	174.0	82.1

Table 1.
Manual Setting 1.

Unit (#)	Gate (%)	Flow (CFS)	Power (KW)	Head (Ft)	Plant Eff (%)
1	76	2383	26,186		
2	74	1971	25,332		
3	56	1537	19,144		
4	54	1487	18,347		
Total		7014	89,008	174.0	86.3

Table 2.
Manual Setting 2.

Unit (#)	Gate (%)	Flow (CFS)	Power (KW)	Head (Ft)	Plant Eff (%)
1	70	1924	25,067		
2	64	1749	22,504		
3	58	1594	20,041		
4	64	1733	22,517		
Total		7000	90,129	174.0	87.3

Table 3.
Hydro Advisor Results.

gains in power generation can be realized by taking care to search for the best.

To illustrate the results further we have applied the Hydro Advisor to a typical operational scenario at this power plant. In order to make the comparisons from exactly the same perspective, we used the Hydro Advisor to simulate the results of both the manually selected solutions and the recommended solutions. The Hydro Advisor was initialized for plant operation at 174 feet with a discharge flow of approximately 7000 CFS of flow. The first two solutions generated use different strategies for manually allocating the flow in order to discharge the required 7000 CFS of flow.

The first manual setting (Table 1) was set up to operate with the minimum number of units. The combinations database was searched to find the best solution involving only three units. The Hydro Advisor was set up in the manual mode, and was asked to simulate the results based on these manual settings. The results were as shown in Table 1.

The second manual setting (Table 2) approach was to set unit 1, largest and most efficient unit, at best gate. There was also enough flow remaining to set unit 2 at best gate. The remaining flow was allocated to units 3 and 4 by distributing the flow approximately evenly between them. The results were as shown in Table 2.

Finally, the Hydro Advisor was asked to make a recommendation to the problem based on the combination database previously created, and then simulate the results based on its recommendations. The results were as shown in Table 3.

There are two important points that need to be recognized from this example. First, that the Hydro Advisor was able to select a better solution than the manually picked choices, and it chose a solution that is counter-intuitive, since none of the units were set at best gate. Even though this point demonstrates the effectiveness of the system in recommending and "optimum solution", it may not be the most significant conclusion. What is also important to note is that even when efficiency characteristics between units are similar, the range of possible solutions for allocation of flow is immense, and picking the "optimum solution" without the aid of an automated tool like the Hydro Advisor, may be impossible.

Summary and Conclusion:

The combination of acoustic flow measurement (for initial unit performance data acquisition and routine maintenance of the computer model) and expert system technology (for optimal allocation of flow between units) has resulted in the development of systems which can increase the efficiency of hydroelectric powerplant operations. An example has shown the potential gain at an existing powerplant, where the system produced efficiency improvements of 1% above a possible "best guess" allocation, and over 5% over a "minimum number of units" allocation.

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