Structuring a Hydroturbine Testing Program to Measure and Maximize Its Benefits

by

Paul J. Wolff, Patrick A. March, R. Keith Jones, and David B. Hansen

Introduction

Real-time efficiency monitoring and optimization systems are commercially available and increasingly used in the hydropower industry. Real-time efficiency monitoring systems continuously measure key unit operating information that includes unit power, unit flow, headwater level, tailwater level, blade angle, and gate settings. The optimization systems apportion the requested plant load among the available individual units to optimize the overall plant energy generation, subject to various constraints. These systems have increased the efficiency of many hydro plants, resulting in significant increases in energy generation and revenue (March, 2001).

Effective optimization systems require accurate unit performance characteristics (Adams et al., 1999; March et al., 2005). Errors in unit characteristics produce corresponding errors in optimized unit dispatch, reducing overall plant efficiencies. An effective hydroturbine testing program is important in ensuring that unit characteristics are as accurate as possible. However, the availability of both qualified personnel and sufficient funding typically limit the number of tests and the scope of tests that can be performed within any organization.

This paper presents a methodology for computing analyses and indicators to track and maximize the benefits of a hydroturbine testing program and describes techniques for unit testing to minimize testing costs. On-line measurements of unit power, headwater, and tailwater can be used in conjunction with unit characteristics to quantify the energy and revenue losses associated with non-optimized plant dispatch. With the addition of an on-line flow measurement, differences between the expected and measured unit characteristics can be computed, thereby providing an overview of the accuracy of the unit characteristics. Representative examples are presented for several plants. A similar approach can be used to structure a comprehensive test program for a hydro utility or agency.

Background

The following discussion presents the components for structuring and tracking a hydroturbine testing program. The initial assessment of a hydro system requires archival data containing individual unit power data, headwater, tailwater, and the unit characteristics that are being used to determine the unit dispatch. With these data, multiple analyses can be performed, including: (1) operation efficiency analyses; (2) sensitivity analyses to evaluate the energy and revenue losses that errors in the unit characteristics would produce; (3) scheduling efficiency analyses; and, with the addition of a real-time flow measurement for each unit, (4) correlation efficiency analyses.

Operation Efficiency Analyses – An initial step in evaluating the potential benefits from a hydroturbine testing program is to evaluate how effectively the plant is being dispatched based on a given set of unit characteristics. The operation efficiency compares the measured plant efficiency to the optimized plant efficiency while meeting the actual plant generation. The archival data should be instantaneous readings rather than averaged values with sampling frequencies that depend on how the unit is dispatched. In most cases, five minute data has been found to be sufficient. However, data of higher frequency may be required, depending on how frequently the plant load changes and the accuracy requirements of the analysis.

At each time step of the archival data, an optimized plant efficiency is computed that apportions the total plant load among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the measured plant load, matching the net head, and operating each unit within minimum and maximum power limits). The optimized plant efficiency is compared to the actual plant efficiency, as operated, to evaluate the potential gain that could be achieved for that time step. Operation efficiencies very close to 100% should be achievable with optimized automation systems. Deviations of several percent in an operation efficiency analysis indicate that gains from improvements in unit characteristics may not result in appreciable improvements in overall plant efficiency. In this case, initial attention needs to focus on optimized dispatch, then on improved characteristics.

Sensitivity Analyses - Absolute flow rates through a unit are typically the most difficult and expensive data to acquire (March and Almquist, 1995). Often, the only flow rates available for on-line systems are provided by Winter-Kennedy pressure differentials, which are often based on model tests, not calibrated using absolute flow measurements. Poorly or incorrectly calibrated Winter-Kennedy taps could produce significant errors in optimized unit dispatch. However, the magnitude of errors cannot be quantified unless absolute flow measurements are made.

Sensitivity analyses can be used to estimate the energy losses and revenue losses associated with flow measurement errors. These losses are evaluated by performing an operation efficiency analysis with the unit characteristics that are currently in use and comparing the results to an operation efficiency analysis using a modified set of unit characteristics. The unit characteristics can be shifted in level by an amount that simulates the potential errors in Winter-Kennedy or other flow measurements. Both results from correlation efficiency analyses, discussed in a subsequent section, and the performance team's collective judgment should be used in determining the magnitude of the "perturbation" in the modified characteristics.

Once the modified unit characteristics are created, the approach for computing energy and revenue losses is similar to the approach described above. For each time step, the power distribution among the units is computed with the unit characteristics that are used for dispatch. This power distribution is then used in subsequent analyses for which the optimized dispatch is computed using the modified characteristics.

Scheduling Efficiency Analyses - The scheduling efficiency, which evaluates how closely actual plant loads align with the peak efficiency points for a plant, is an additional consideration when considering unit characteristics. Figure 1 presents individual unit efficiency curves and an overall plant efficiency curve. The individual unit characteristics combine to create an overall plant efficiency that is the maximum plant efficiency achievable for any given load with optimized plant dispatch. This curve shows that there are operating regions with plant efficiencies a few percent higher than the cusps of the curve. By scheduling plant loads to align with peak operating efficiency regions, more efficient energy generation is achieved. When significant changes are made to the unit characteristics, peak efficiency points may shift. Therefore, scheduling efficiency analyses should also be performed when modifying unit characteristics. Details of these analyses and related analyses are presented elsewhere (March and Wolff, 2004).

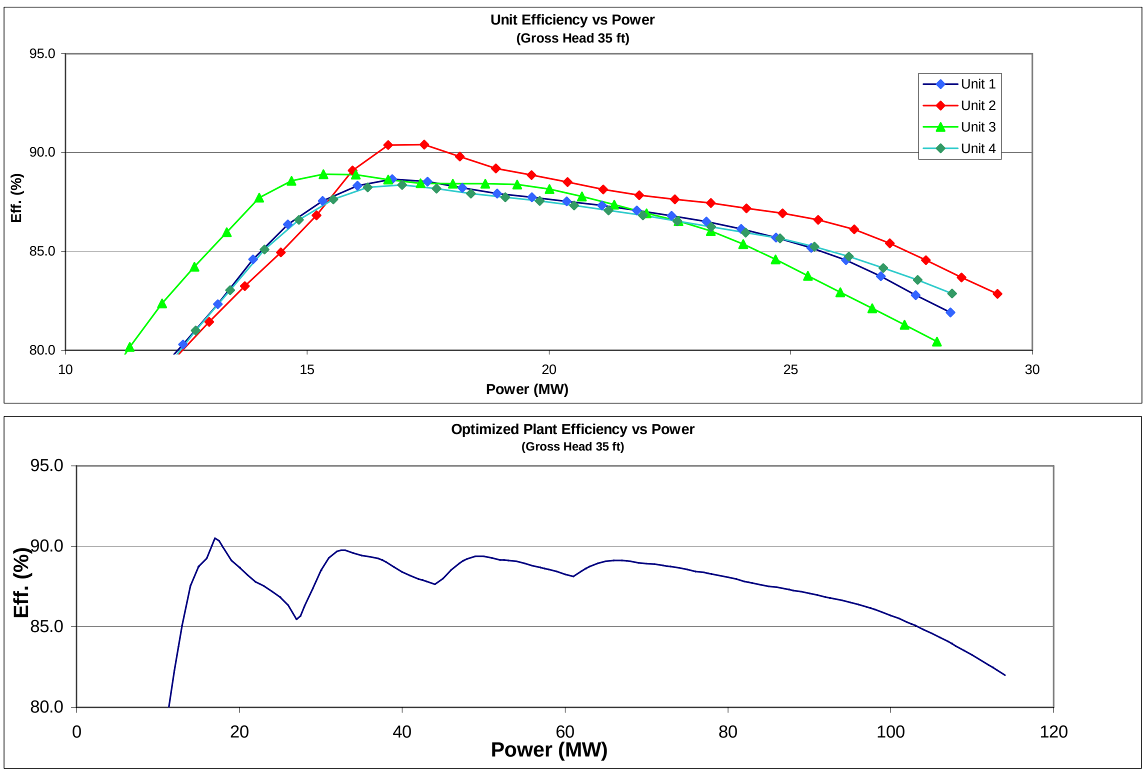

Figure 1: Individual Unit and Optimized Plant Efficiency Curves

Correlation Efficiency Analyses - With the addition of an on-line flow measurement, the correlation efficiency can be computed to compare the measured efficiency with the expected unit performance characteristics. Computing the correlation efficiency requires that the measured efficiency, based on archival data, is compared at each time step of data to the expected unit characteristics. The energy loss at each time step is computed by assuming that a 1% efficiency difference produces a corresponding 1% energy loss. Linking the efficiency difference to energy is important because it enables the prioritization of attention for units within a system. Analyses and testing can then be focused on the units with the largest potential for improvement. In reality, the effects of errors in unit characteristics on optimized plant dispatch will depend on the plant configuration, the specific schedule request, and the distribution of the correlation efficiency deficit among the units. A previous analysis, which examined the effects of errors in unit characteristics on optimized dispatch, suggests that the assumption of direct correspondence is an upper bound.

More detailed economic analyses can be computed if higher accuracy in energy and revenue losses is required. One approach is to use the archival data to create a secondary set of unit characteristics. These secondary characteristics can be targeted to specific power outputs and head levels for a unit corresponding to the primary power and head ranges in which it was operated. The archival data can be filtered to include only data within the primary operating range. Given this set of filtered archival data, optimized dispatch for the original characteristics can be computed to determine the individual unit power settings for each unit. These power settings are then used in a second operation efficiency analysis in which each unit's characteristics are assumed to be the modified values. This analysis can quantify the energy loss, assuming that the automation system uses the original characteristics and the modified characteristics are the actual unit characteristics.

<u>On-Line Performance Testing</u> - Traditionally, unit performance tests have been performed with test personnel on-site. However, because many units have all of the required readings in on-line systems, remote tests can be easily performed. The correlation efficiency described above is one form of a remote index test that is targeted to the power output and head levels that occur as part of routine operation. Index tests can also be performed with the assistance of an operator, or in some cases an automation system, to cover a wider operating range. A pretest instrumentation checkout can provide enhanced accuracy. Several of the tests were performed to verify the results from analyses of archival data. Prior to the test, the zero offsets were checked for blade and gate readings, and Winter-Kennedy pressure lines were bled. The operator then stepped the unit through predetermined blade and gate settings while all data were acquired with an on-line monitoring system. These tests were low in cost, and the tests were performed with minimal impact to plant operation. The tests covered the desired range of operation and, in general, provided data with lower noise than the archival data.

<u>Automated Data Analyses</u> - Automated computation of results is essential for supporting the analyses described above, due to the quantity of data, the number of different analyses required to gain a comprehensive overview, and the time required for manual data processing. Two key requirements for streamlined computation are that the computation should be structured to mirror the structure of the data and of the hydro system and the data processing steps should be readily modified due to the diverse requirements for different analyses and different hydro systems. DataWolff™, an Excel-based data analysis engine, and the WaterView® optimization engine were used in creating the results presented below. Further details are presented elsewhere (Wolff et al., 2002; March and Wolff, 2003; March and Wolff, 2004).

Results

For a given utility, system-wide analyses can be performed to quantify and prioritize potential improvements on a plant and unit basis. This would be the most comprehensive approach if a utility is structuring a test program. However, because the analyses and indicators previously described are incremental, they can also be applied to individual plants and units. The following results are based on the latter approach, in which selected results from plants and units in different systems are presented.

Operation Efficiency Analyses - Figure 2 presents operation efficiency analyses for four different plants for various years of operation. For the data presented in Figure 2, the 4-unit Kaplan and 2-unit Francis plants were manually dispatched while the 21-unit Francis and 4-unit pumped-storage plants were dispatched using automatic generation control (AGC) with manual settings. The operation efficiencies range from 96.7% to 100% with associated revenue losses that range from almost $3,000,000 to almost zero.

Although the operation efficiency provides the initial insight into how efficiently a given plant is being dispatched, it is important to obtain as much background information as possible to provide additional insight. For example, the 2-unit Francis plant is a tributary plant with two primary operating modes during the time when these data were acquired, namely most efficient load and the maximum sustainable load. The plant's management played a very active role in providing directives to ensure that the plant was operated at best efficiency when maximum sustainable load was not required. This plant directly benefits from the attention paid to developing accurate unit characteristics curves.

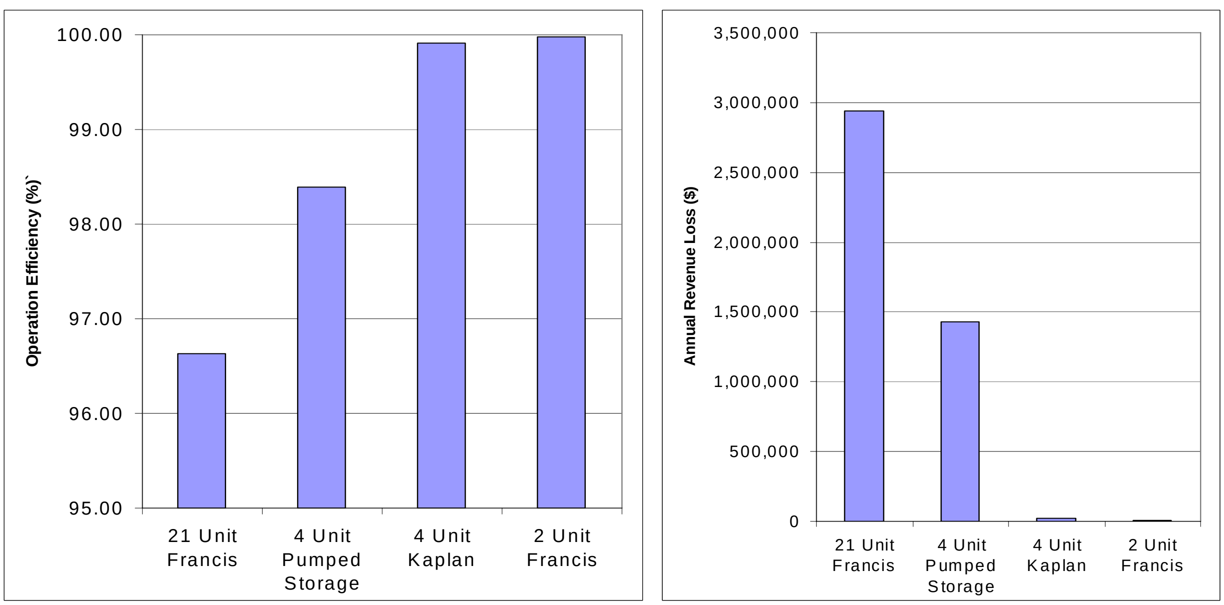

Figure 2: Operation Efficiency and Annual Revenue Loss

The operation efficiency analysis of the 4-unit Kaplan plant is based on unit characteristics which are all flat and of almost identical magnitudes. Achieving optimized dispatch for this plant is relatively straightforward. If a testing program were initiated and the unit characteristics changed, it would be important to periodically check the operation efficiency to ensure that the unit characteristics were being properly used.

For the 4-unit pumped-storage plant and the 21-unit Francis plant, the operation efficiencies can be improved. With automation systems, operation efficiencies can be very close to 100%. The combined annual benefit for achieving an operation efficiency of 100% for these plants is $4,370,000, based on an average energy price of $40/MWh. Therefore, the first priority for these plants should be optimizing the plant dispatch. In both cases, this improvement could be achieved by switching from conventional AGC to optimization-based AGC (Giles et al., 2003).

Sensitivity Analyses - Sensitivity analyses which estimate potential revenue gains are important for structuring and justifying a test program. Figure 3 presents the results from sensitivity analyses for two different plants, including: (1) a plant with six conventional Francis units; and (2) a 6-unit pumped-storage plant. The operational data for the Francis units was based on a time period of 12.5 months while the operational data for the pumped-storage units was based on a time period of only 5 days. The results below are scaled to annual values. Note that the small time period for the pumped-storage data set will produce additional uncertainty when scaled to annual values.

For plant 1, five different sensitivity analyses were performed. These analyses included comparing the unit characteristics being used by the automation system to a set of unit characteristics consisting of six identical characteristics based on a detailed absolute performance test for a single unit, and sets of characteristics with 2.5% and 5.0% offsets introduced between the most and least efficient units. A set of characteristics with offsets was created by first computing the energy generated by each unit and ranking the units accordingly. The maximum energy loss was computed by assuming that the unit that produced the largest amount of energy was the least efficient unit, the one producing the least energy was the most efficient, while the characteristics for the other units varied uniformly between the minimum and maximum. The minimum energy loss was computed by assuming that the units that produced the most and least amounts of energy were the most and least efficient, respectively. The analyses for the pumped-storage plant are based on assumed unit characteristics with a 2% offset between the most efficient and least efficient units.

Figure 3 demonstrates that there is a significant economic penalty for errors in unit characteristics. For example, given an error band represented by the 2.5% offset for the plant with six Francis units, the annual revenue loss is between $1,700,000 and $2,600,000. For the pumped-storage plant, the annual revenue loss is between $2,100,000 and $4,700,000.

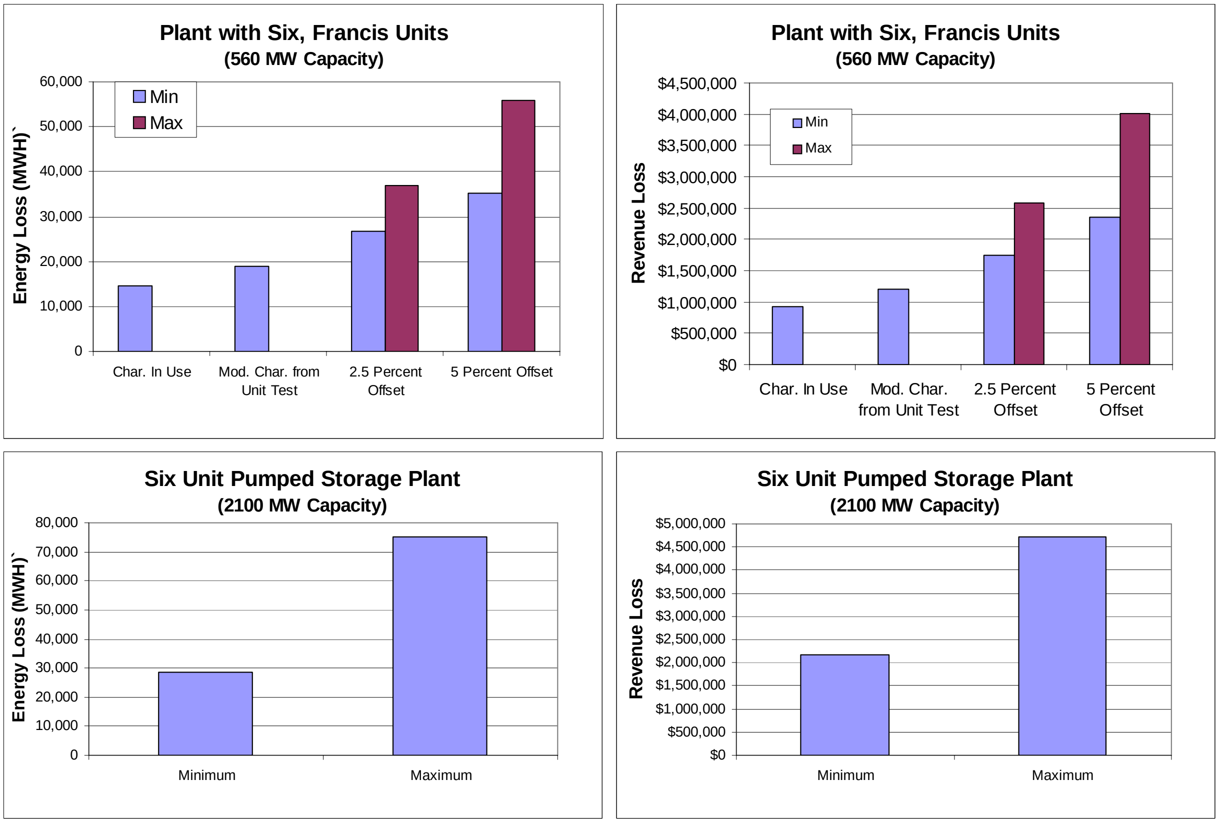

Figure 3: Sensitivity of Energy Production and Revenue to Errors in Unit Characteristics

<u>Scheduling Efficiency Analyses</u> - Scheduling efficiency is an additional consideration when modifying unit characteristics. The following example illustrates this for the 6-unit Francis plant discussed above. Figure 4 presents this plant's energy production versus power and, in addition, two overall plant efficiency curves corresponding to two different sets of unit characteristics (the set in use by the plant's automation system and the set of identical characteristics based on the performance test results). This figure shows that the loads at which the plant produced peak amounts of energy correspond closely with the peak plant efficiencies based on the unit characteristics that were in use at the time. The operation efficiency for this time period was 99.3%. The 0.7% deviation was due to several factors, including differences in the optimization algorithms, simplified constraints for the operation efficiency analysis, and transient effects in the operation efficiency analysis.

The plant efficiency curve based on the characteristics in use deviates significantly in magnitude from the one based on the single unit test data. In addition, the peak plant efficiency points shift for the modified unit characteristics and no longer coincide with the peak energy production points. This highlights the point that when significant changes in unit characteristics occur, the scheduling efficiency should also be evaluated.

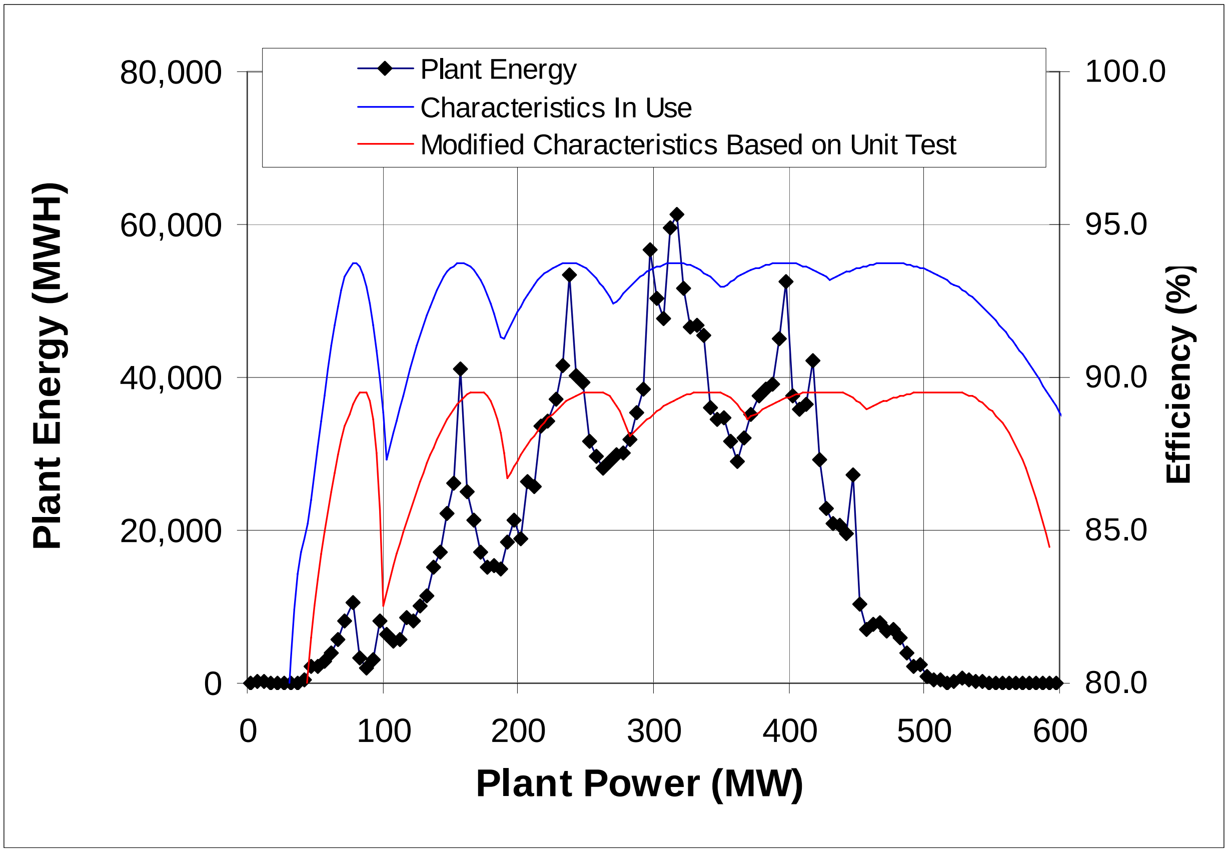

Figure 4: Power Production versus Peak Plant Efficiency Curves

<u>Correlation Efficiency Analyses</u> - Computing correlation efficiencies is the next step for evaluating the accuracy of a plant's unit characteristics. Figure 5 presents the correlation efficiencies and associated energy losses for a 4-unit Kaplan plant on a plant basis and for an individual unit, Unit 3, versus nominal head. The correlation efficiencies were computed with a simplified approach assuming that a deviation of 1% between the expected and actual efficiency produced a 1% energy loss. These correlation efficiencies all deviate significantly from 100%.

Figure 6 presents efficiency vs. power for a nominal head of 69.1 ft. Also shown in this figure are flow vs. power, power vs. gate, and blade vs. gate. The efficiency vs. power and flow vs. power curve demonstrate one of the factors producing the low correlation efficiencies. The measured flow does not agree closely with the expected flow in the unit characteristics.

The plots of blade angle versus power and gate in Figure 6 display a great deal of scatter. These plots demonstrate an additional problem with Unit 3 operation. The blade does not appear to be consistently on-cam. This problem should be addressed first, because implementing optimized unit dispatch for a Kaplan unit requires the units to be on-cam.

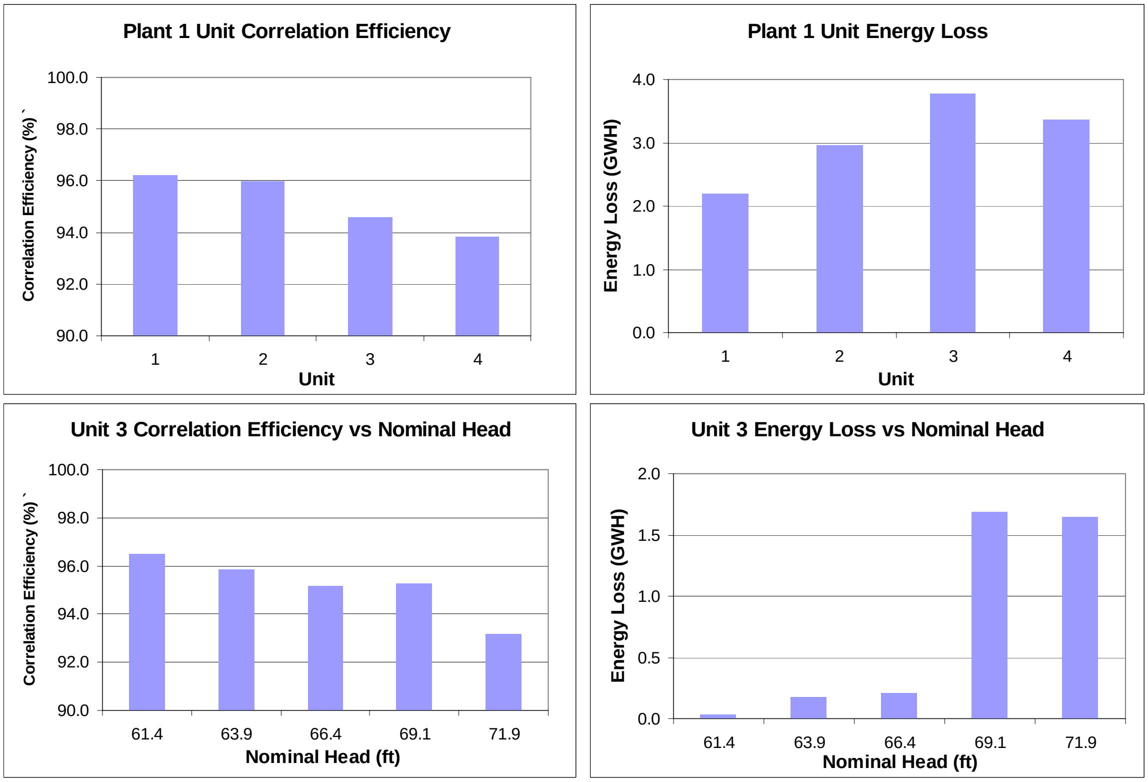

Figure 5: Correlation Efficiencies for the 4-Unit Kaplan Plant

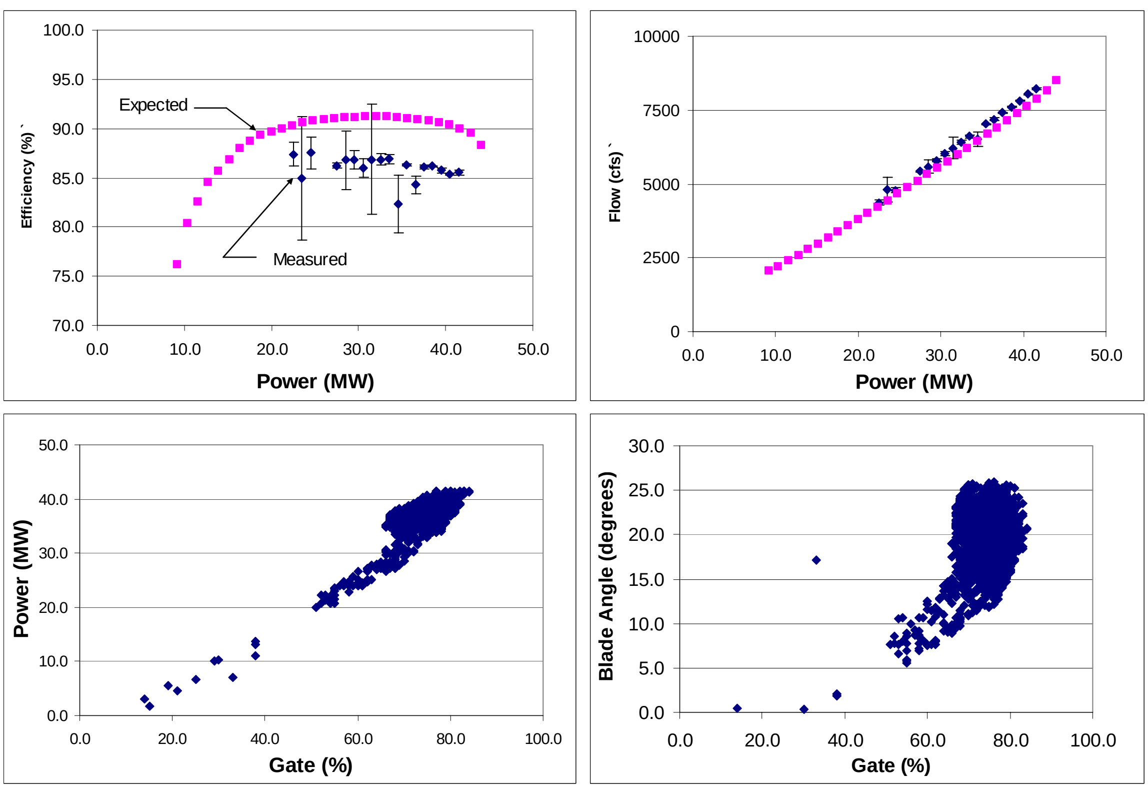

Figure 6: Unit 3 Data for Nominal Head of 69.1 ft.

<u>On-Line Performance Testing</u> - Figure 7 presents results from a remote index test. These data were acquired with an on-line monitoring system while a remote operator stepped through the requested blade and gate settings. Prior to the test an instrumentation check was performed that included bleeding the Winter-Kennedy pressure lines and resetting zero offsets. These tests confirm the results from the analyses based on archival data. The measured efficiency is several points lower than the expected efficiency. This figure also shows that some efficiency improvement can be gained by ensuring that the blade-gate cam contains the proper relationship and that it is continually used.

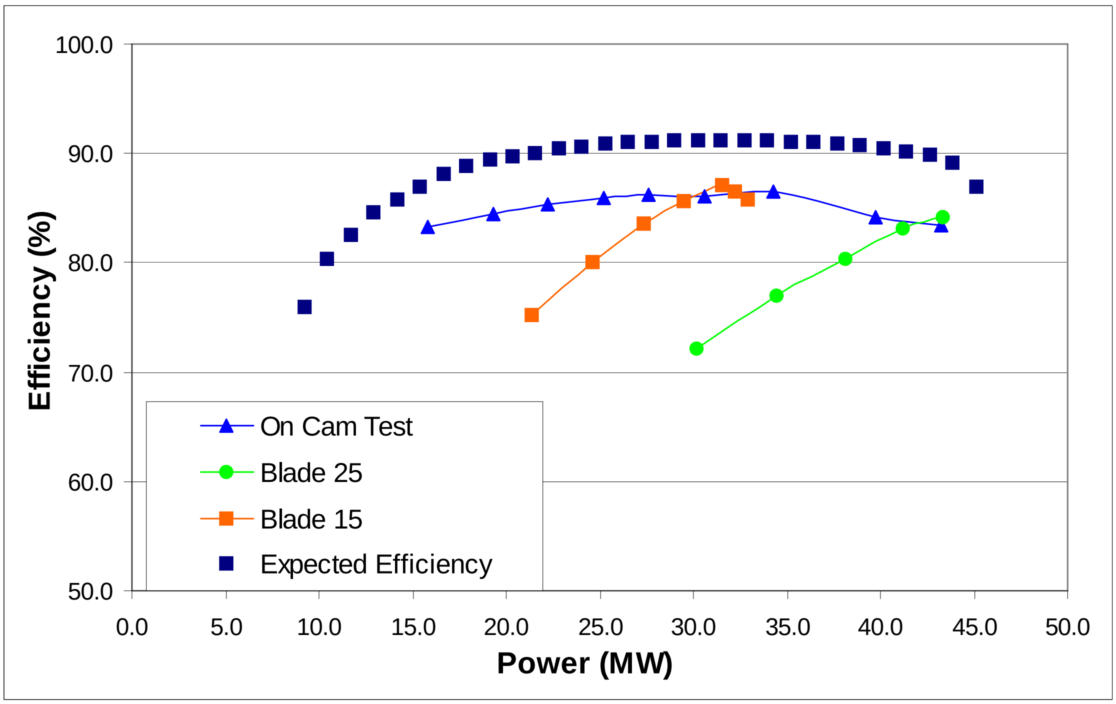

Figure 7: Unit 3 Remote Index Test Results

Conclusions

Archival data containing individual unit power outputs and headwater/tailwater readings are used with the unit characteristics in conducting multiple analyses, including operation efficiency analyses, which quantify how well a plant's dispatch is continuously optimized; sensitivity analyses, which quantify the revenue losses produced by errors in the unit characteristics; and scheduling efficiency analyses, which evaluate how closely a plant's load schedule coincides with its peak efficiency points. With the availability of real-time flow measurements, correlation efficiency analyses compare the accuracy of the expected unit characteristics to the measured unit characteristics. The deviations are quantified in terms of energy and revenue loss.

Typical results from these analyses are presented to demonstrate the analyses and to show how these analyses can provide key information for structuring a comprehensive hydropower testing program. The analyses also include calculation of indicators that can be used to benchmark the current status of a hydro system and to quantify improvements, on an energy and revenue basis, as a testing program is implemented.

References

Adams, J. S., J. M. Braden, J. E. Giles, D. B. Hansen, R. K. Jones, P. A. March. W. J. Terry, "Integrating Hydro Automation and Optimization," *Proceedings of WaterPower 99*, New York, New York: American Society of Civil Engineers, 1999.

Giles, J. E., P. A. March, and P. J. Wolff, "An Introduction to Optimization-Based AGC," *Proceedings of WaterPower XIII*, Kansas City, Missouri: HCI Publications Inc., July 2003.

March, P. A., "Knowledge Management System for Water Resources Optimizes Energy and Environment," *Proceedings of the Fourth Inter-American Dialogue on Water Management*, Paraná, Brazil, September 2001.

March, P. A., and C. W. Almquist, "Flow Measurement Techniques for the Efficient Operation of Hydroelectric Power Plants," National Institute of Standards and Technology, Metrology for the Americas Conference, Miami, Florida, November 1995.

March, P. A., and P. J. Wolff, "Component Indicators for an Optimization-Based Hydro Performance Indicator," HydroVision 2004, Montréal, Québec, Canada, August 2004.

March, P. A., C. W. Almquist, and P. J. Wolff, "Best Practice Guidelines for Hydro Performance Processes," *Proceedings of Waterpower XIV*, Kansas City, Missouri: HCI Publications, July 2005.

Wolff, P. J., J. S. Adams, J. M. Braden, J. E. Giles, D. B. Hansen, R. K. Jones, P. A. March, "Enhanced Hydro Plant Unit Operation and Data Reliability through Knowledge-Based Data Analyses," Norris, Tennessee: Tennessee Valley Authority, TVA ER&TA Project Report, October 2002.

Authors

Paul J. Wolff is President of WolffWare, Ltd., in Norris, Tennessee. He can be reached at pjwolff@wolffwareltd.com.

Patrick A. March is Principal Consultant with Hydro Performance Processes Inc. in Maryville, Tennessee. He can be reached at pamarch@hydroppi.com.

R. Keith Jones is a Mechanical Engineer for the Tennessee Valley Authority in Knoxville, Tennessee. He can be reached at rkjones@tva.gov.

David B. Hansen is an Operations Analyst for the Tennessee Valley Authority in Knoxville, Tennessee. He can be reached at dbhansen@tva.gov.