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Optimization-Based Hydro Performance Indicator

by

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INTRODUCTION

In *What Management Is*, Joan Magretta writes, "It may be the oldest saw in the book, yet it remains absolutely true: What gets measured gets managed. Without measurement, there is no performance." Typically, the performance measures for a hydroelectric generating facility or system include readily measured items such as expenditures and schedules for major capital projects, reductions in overall operations and maintenance expenses, and improvements to the equivalent forced outage rate. Although electricity generation is a primary production element, generation is typically tracked, but not used as a performance measure. Wide variations in annual hydrology, changing operational patterns due to market conditions, a variety of power system needs, and regulatory requirements for instream flows, recreational flows, fish spills, etc., can obscure the "line of sight" between individual actions, unit operations, plant operations, water resource system operations, and overall power system production.

The Tennessee Valley Authority (TVA) is a federal public power corporation, created by an Act of Congress in 1933. TVA's hydro facilities along the Tennessee River and its tributaries include twenty-nine hydroelectric dams and a large pumped-storage plant. TVA operates this power and reservoir system for optimal balance among a variety of objectives, including navigation, flood control, power production, water supply, water quality, and recreation. TVA recognizes that a sustained commitment is required to ensure accurate unit performance characteristics and to ensure the appropriate use of the available performance information for properly operating the units. With the advances in electronics and computers over the past several decades, many hydro systems, including TVA's, now have on-line operating data for every unit. Indicators can be constructed from these data to provide the performance of the hydro system at any desired level of detail.

This paper describes a hierarchical, optimization-based hydro performance indicator (OHPI) with two components, the operation efficiency and the correlation efficiency. Both components can be viewed at different levels to understand performance at the unit level, the plant level, or the overall system level. The OHPI and these component indicators are computed using plant operational data, an optimization engine, and an automated data analysis system. The operation efficiency uses archival unit performance characteristics, derived from numerical and physical model tests, index (i.e., relative efficiency) tests, and field absolute efficiency tests, to determine how closely the actual dispatch matches the optimized dispatch. The correlation efficiency uses measured unit performance characteristics, based on continuous, real-time monitoring data, to determine how closely the measured unit characteristics match the expected unit characteristics. These component indicators can be displayed in easily understood units, including lost energy opportunity (LEO, in MWh), water conservation opportunity (WCO, in acre-feet), and lost revenue opportunity (LRO, in $).

The OHPI provides an efficient means for benchmarking, prioritizing, and troubleshooting performance issues for a hydro plant or a system of plants, whether fully automated, partially automated, or manually operated. This ensures that limited human resources can identify and correct the most significant problems. The OHPI and its two component indicators are described in the following section. As examples, the paper presents OHPI results for a system with two hydro plants: (1) Plant 1, a plant with four Kaplan units; and (2) Plant 2, a plant with eighteen Francis units and three propeller units. The resulting analyses and subsequent test results demonstrate how these indicators can be used in ranking the plants and units in a hydro system to rapidly determine the largest contributors to lost energy production and to provide information for determining the root causes of the lost efficiency.

OPTIMIZATION EFFICIENCY, CORRELATION EFFICIENCY, AND OHPI

The optimization efficiency compares the measured plant efficiency to the optimized plant efficiency while meeting the actual plant generation. The optimization engine is used to compute the optimized plant efficiency with archival data. For each time step of the archival data, the optimization engine apportions the total plant load among the units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the measured plant load; operating each unit within minimum and maximum power limits; and meeting reactive power requirements). Note that the deficit in operation efficiency (i.e., 100 minus the operation efficiency) represents the efficiency gain achievable by continuously optimizing the plant load.

The efficiency gain from optimized unit dispatch is converted into three measures: (1) lost energy opportunity (LEO); (2) lost revenue opportunity (LRO); and (3) water conservation opportunity (WCO). The lost energy opportunity represents the additional energy that would have been generated if the plant dispatch were optimized to meet the same load. This is computed by assuming that the water saved by optimized dispatch is used to produce energy at the same plant head and optimized plant efficiency for the computational time step. LRO is the corresponding revenue that would have been gained from the additional energy, based on the spot market price for the given time step. The WCO represents the water that could have been saved by optimized dispatch and stored rather than used to produce additional energy. These measures represent gains from achievable plant improvements in units that are directly relevant to management and plant personnel (i.e., energy, money, and water).

Optimized plant dispatch depends on accurate unit characteristics and instrumentation, which are evaluated with the correlation efficiency, the second component of the OHPI. At each time step and for each unit within the system, a unit correlation efficiency deficit is computed as the absolute value of the difference between the expected unit characteristics used by the optimization engine and the measured unit characteristics acquired by on-line measurements of unit load, unit flow, unit gate and blade settings, headwater, and tailwater.

Linking the deficit in unit correlation efficiency to the efficiency losses associated with plant dispatch and caused by errors in unit characteristics is an important step in computing the correlation efficiency. With this link established, the energy losses for each unit can be computed, and the units within a system responsible for the largest energy losses can be identified. Currently, the simplifying assumption is made that a one percent correlation efficiency deficit will produce a corresponding one percent unit efficiency loss. In reality, the effects of errors in unit characteristics on optimized plant dispatch will depend on the plant configuration, the 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 is an upper bound.

The OHPI is computed by first summing, for the entire system, the energy losses derived from the operation and correlation efficiencies. The total system energy, which is the total energy that would have been generated if all units in all plants were optimized based on unit characteristics with no errors, is also required. The OHPI is computed from these terms by subtracting the summed losses from the total energy and then dividing the resulting value by the system energy. This result, created from data for all units within a system for the time period of interest, represents how well the system has been optimized.

The supporting analyses for both the operation efficiency and the correlation efficiency mirror the hierarchical structure of the hydro system. For example, Figure 1 presents the structure that is used for the correlation efficiency analysis. The data used are individual unit data, separated into head intervals which are within a Zone 1 tolerance as defined in the ASME PTC 18-1992 performance test code for hydroturbines (ASME, 1992), allowing the application of the appropriate affinity relationships to flow and power data. For a given head level, the data are presented in a series of plots comparing expected performance to measured performance. The LEO, LRO, and WCO indicators are computed at the head level and summed to the unit, plant, and system level. The hierarchical data structure enables a performance engineer to rapidly rank the plants and units by performance, to identify the poorest performing plants and units, and to establish root causes for the poor performance.

The multi-level structure is adapted to a specific system by adding nodes at each level in a manner similar to adding file directories within widely used file management programs for personal computers. For example, Figure 2 presents a four-level structure adapted to a hypothetical two-plant system with each plant containing a different number of units and with one nominal head interval for each unit. Most systems are considerably more complex but even complex systems can be easily configured and analyzed with this approach.

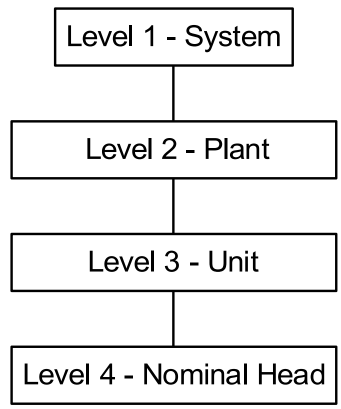

Figure 1: Four-Level, Hierarchical Data Analysis Structure

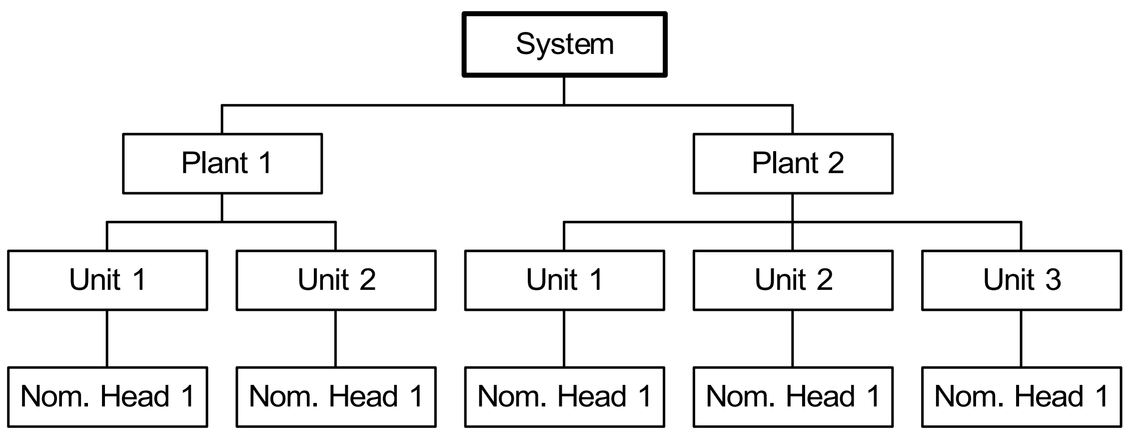

Figure 2: Four-Level Structure Configured for a System

Figure 3 presents a process diagram for the data analyses. DataWolff™, an Excel-based general-purpose program for automated data analyses, performs the overall OHPI analyses. DataWolff is configured with an analysis script that creates the hierarchical structure and defines the analysis steps (e.g., defining the data to import, defining the filters, specifying the calculations, and defining which plots to create). Because all calculation procedures are contained in external libraries, analysis scripts can support a wide variety of computations. Within the OHPI analysis script, the WaterView® optimization module computes optimized plant efficiencies for the operational efficiency indicator. Once the script is created, the data analyses can be fully automated. The analysis results are contained in a series of Excel workbooks corresponding to the hierarchical structure of the analyses.

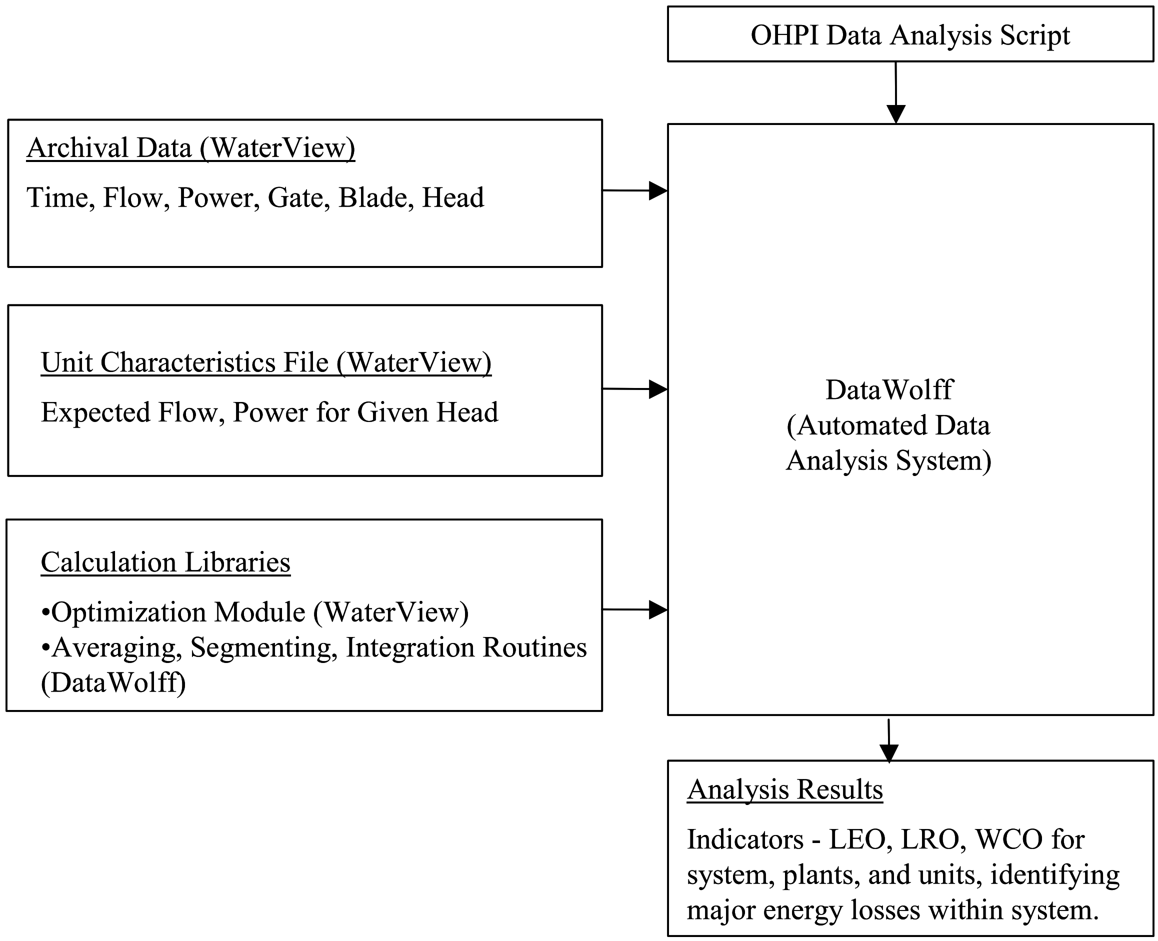

Figure 3: Data Analysis Process Diagram

RESULTS FROM INDICATOR ANALYSES AND SUBSEQUENT TESTS

The following results illustrate the use of the OHPI for a hydro system with two hydro plants: (1) Plant 1, a plant with four Kaplan units; and (2) Plant 2, a plant with eighteen Francis units and three propeller units. Archival data, which consisted of instantaneous readings acquired at 15-minute intervals for one year, was used for these analyses. The following discussion demonstrates the application of the OHPI results to rapidly identify and rank the more poorly performing plants and units within a system and to troubleshoot the root causes for the various performance losses.

The system level of the analysis contains the overall OHPI, which has a value of 93.1% for the year. This represents a deficit of 6.9% from a fully optimized system and merits further investigation. Figure 4 shows three plots that separate the OHPI into the operation and correlation efficiencies at both the system level and the plant level. The system operation efficiency of 97.3% shows that improvements in optimization are possible.

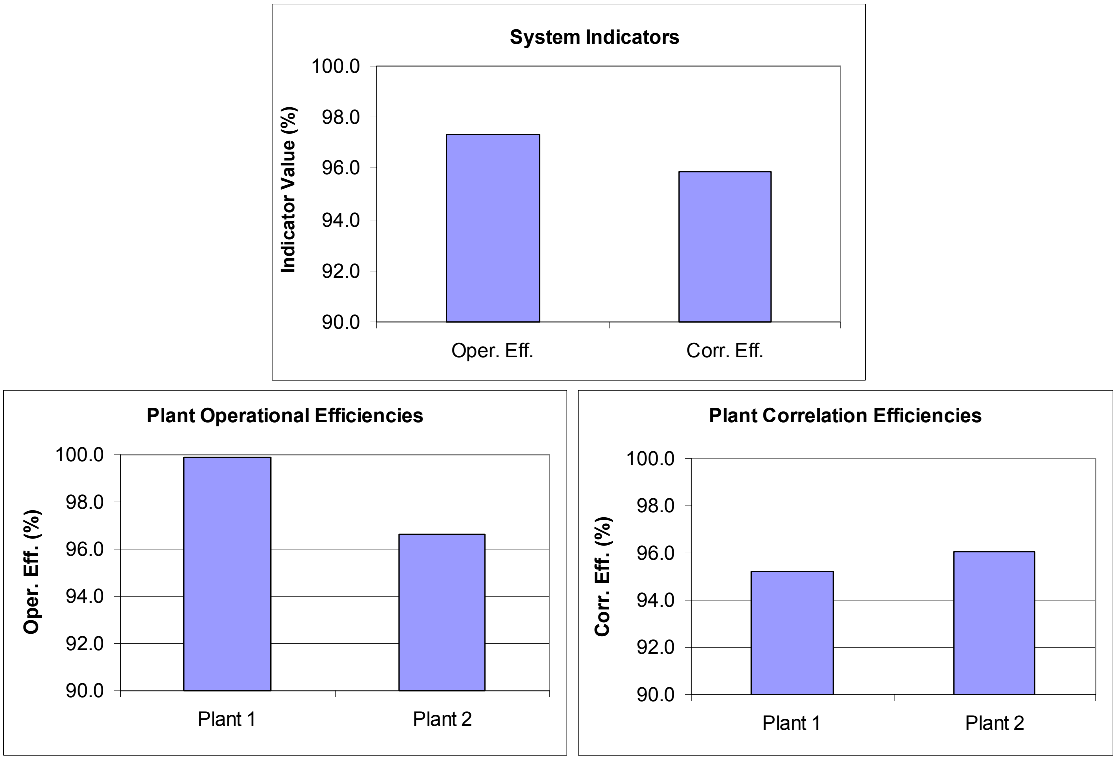

Figure 4: System and Plant Indicators

The operation efficiencies for Plant 1 and Plant 2, presented in Figure 3, are 99.9% and 96.6%, respectively, with corresponding LEO values of 500 MWh and 73,500 MWh. The LEO for Plant 2 of 73,500 MWh corresponds to a LRO of $1,740,000 and a WCO of 731,000 acre-feet. This demonstrates that there is significant room for improvement at Plant 2, while little optimization gain appears to be achievable at Plant 1. Plant 1's high operation efficiency, approaching 100%, can be readily understood by examining Figure 5, which presents unit characteristics for Plants 1 and 2 for a given head. Because all units in Plant 1 have almost identical unit characteristics, which are relatively flat over most of the operating region, optimized plant dispatch is achieved easily. In contrast, Plant 2 includes multiple units with significantly different characteristics, so this plant presents a much greater challenge in optimizing the generation.

Plant 2, which is used extensively for automatic generation control (AGC), has been typically set to operate with a base load and a participation (swing) load. The individual units were manually configured to match the plant's overall AGC requirements. Typically, the base load remains constant, and an AGC control signal varying between –1 and +1 controls the swing load. The minimum control setting can decrease each unit's base load up to the swing load, and the maximum control can increase the base load up to the swing load.

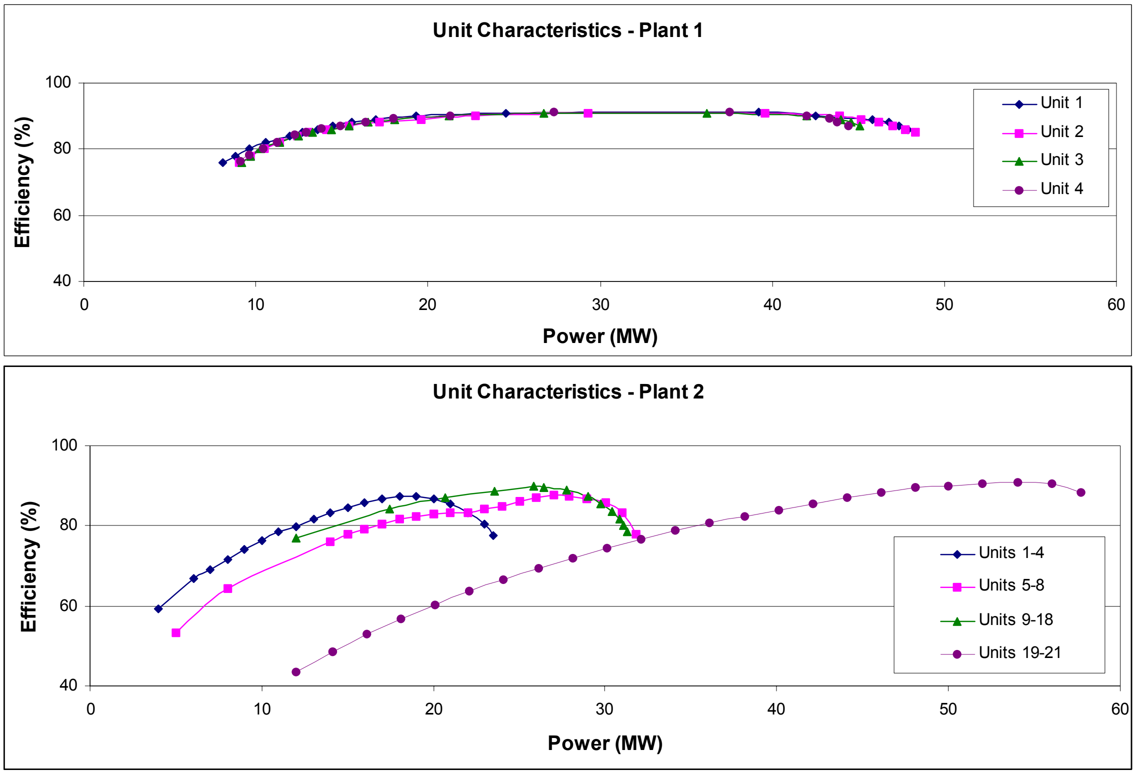

Figure 5: Representative Unit Characteristics for Units within Two Plants

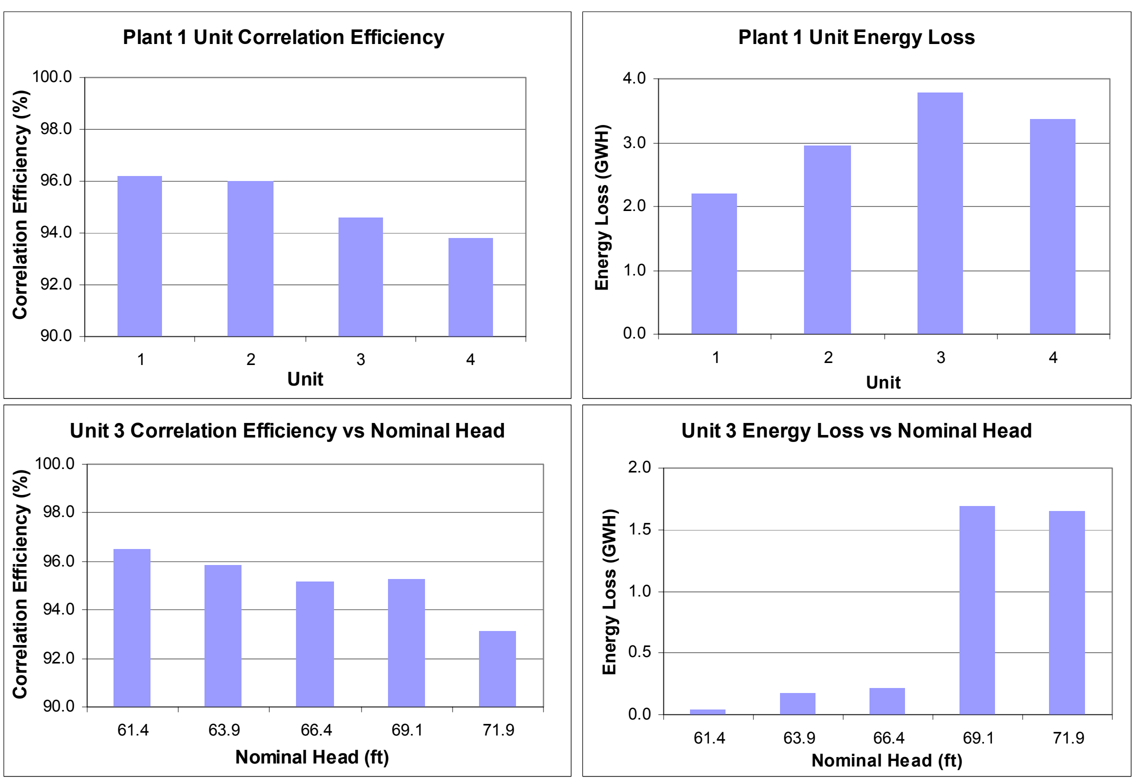

Figure 6: Unit and Nominal Head Indicators for Plant 1, Unit 3

Optimizing a diverse set of units is readily achievable with optimization programs and automation systems (Adams et al., 1999). Re-computing the optimized plant dispatch on a continual basis as the plant load request changes and setting the load for each unit accordingly provides more efficient means for providing automatic generation control. This approach is called optimization-based automatic generation control, or OGC (Giles et al., 2003). Additional analyses indicate that Plant 2's operations under the current form of AGC are responsible for approximately 60% of the plant's avoidable energy losses (Wolff et al., 2002).

The second major component of the OHPI is the correlation efficiency. For the plants used in this example, the correlation efficiency has a system value of 95.9% and values of 95.2 and 96.1% for Plants 1 and 2, respectively. Figure 6 presents correlation efficiencies versus unit for Plant 1, showing that Unit 3 has a correlation efficiency of 94.6% with an associated LEO of 3,800 MWh. This unit was chosen for further investigation because it has the highest energy loss and thus had significant potential for improvement, as demonstrated by the low correlation efficiency. Figure 6 also shows the energy losses and the correlation efficiencies versus nominal head. A nominal head of 69.1 ft contains the largest energy loss, indicating that the unit operated for a large portion of the time at this head and that a significant amount of data exists for this head interval.

Figure 7 presents plots of efficiency versus power, flow versus power, power versus gate, and blade versus gate for a nominal head of 69.1 ft. The efficiency and flow versus power curves clearly indicate that there is a discrepancy between the expected flow in the unit characteristics and the measured flow from the Winter-Kennedy flow meter.

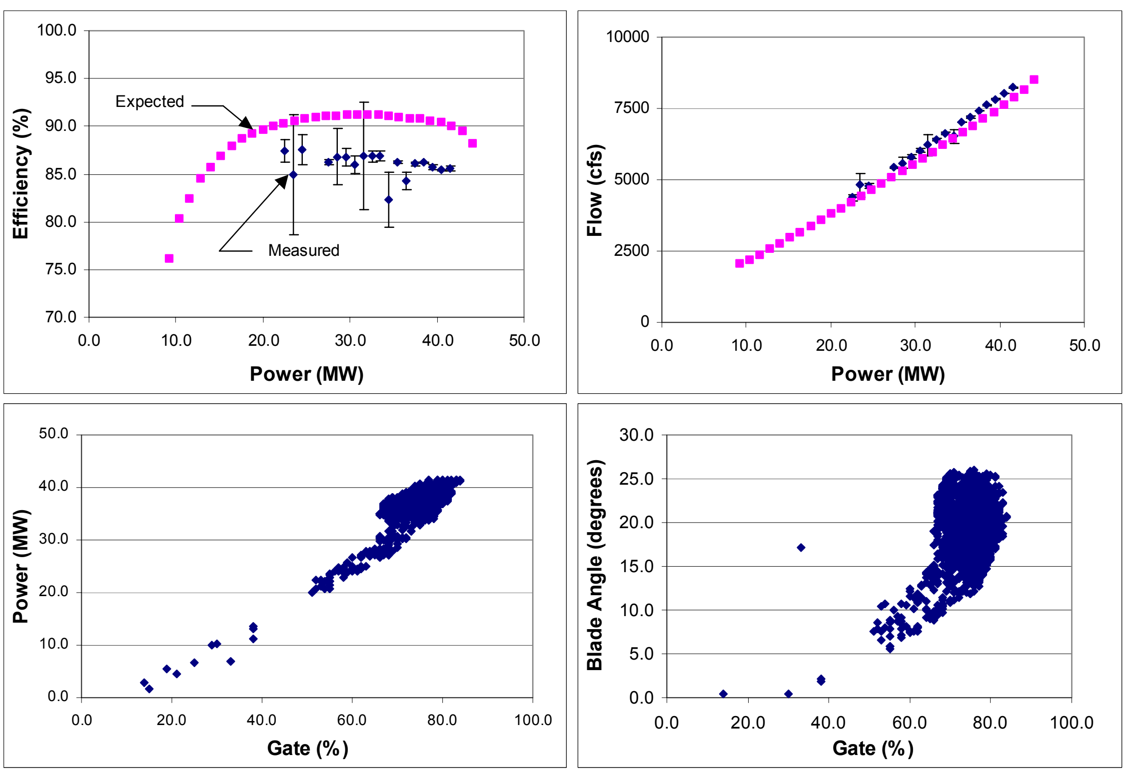

Figure 7: Unit 3 Data for Nominal Head of 69.1 ft

In addition, the blade versus gate curve shows other probable causes for the poor correlation efficiency. For a given head, the blade-gate curve should be a well-defined line, and this is not the case, suggesting problems with either the blade and gate instrumentation or improper operation of the blade-gate cam. Because the power versus gate curve demonstrates similar scatter, it was judged likely that the problems were associated with the cam rather than with the instrumentation.

Performance engineers conducted follow-up testing to further investigate the poor correlation efficiencies computed for Plant 1's Unit 3. Two remote index tests were conducted. For these tests, the data were acquired in five-second intervals from the WaterView monitoring system while the unit was stepped through several gate settings and held at each gate setting for approximately five minutes. Prior to the tests, the unit's instrumentation was checked (e.g., inspecting the blade-gate cam, bleeding air from the Winter-Kennedy piezometer lines, checking calibrations).

Figure 8 presents the results from the remote index test. These results are consistent with the OHPI analyses based on the WaterView archival data. Both archival analyses and the remote index test results demonstrate a similar discrepancy between the measured and expected efficiencies, which is a primary cause of the low correlation efficiency.

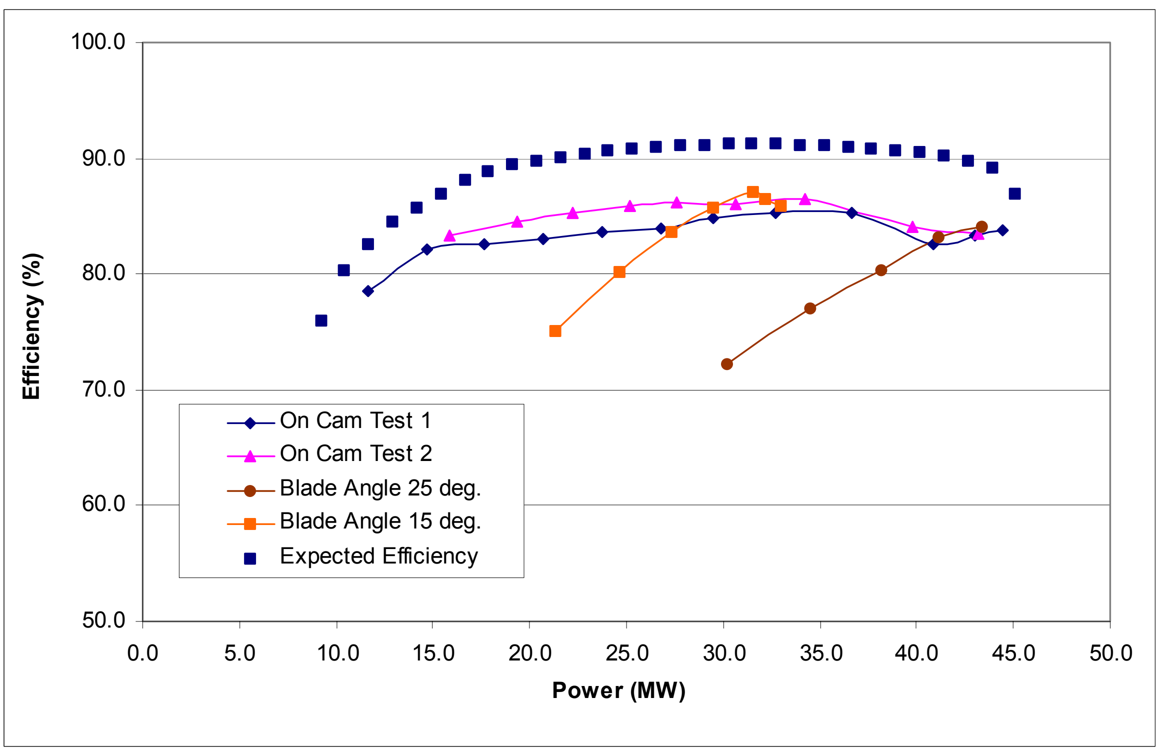

Figure 8: Unit 3 Index Test Results

The remote index tests also confirmed that this unit would benefit from more emphasis on proper cam maintenance. The two on-cam tests were conducted when the head levels were close enough to apply ASME Zone 1 corrections. However, the on-cam efficiency versus power curves are different. The blade versus gate relationship changed in the time interval between the two on-cam tests, as verified by blade versus gate plots from the two tests. In addition, the fixed-blade tests demonstrated higher peak efficiencies than the on-cam tests, indicating that a properly optimized cam was not in place for either of the on-cam tests.

Significant improvements in unit characteristics are also possible for Plant 2 as indicated by the relatively low correlation efficiency of 96.1% shown in Figure 3. Figure 9 presents the correlation efficiencies versus unit power level and demonstrates that Units 19-21 have the lowest correlation efficiencies and the highest energy losses. Unit 19 was chosen to further demonstrate the utility of the correlation efficiency because it produced one of the largest energy losses and because it was available for testing.

Figure 9 also presents energy loss for Unit 19 as a function of nominal head. The largest energy loss occurred at a nominal head of 90.7 ft, indicating that the unit operated a large portion of the time at that head and that a significant amount of data exists.

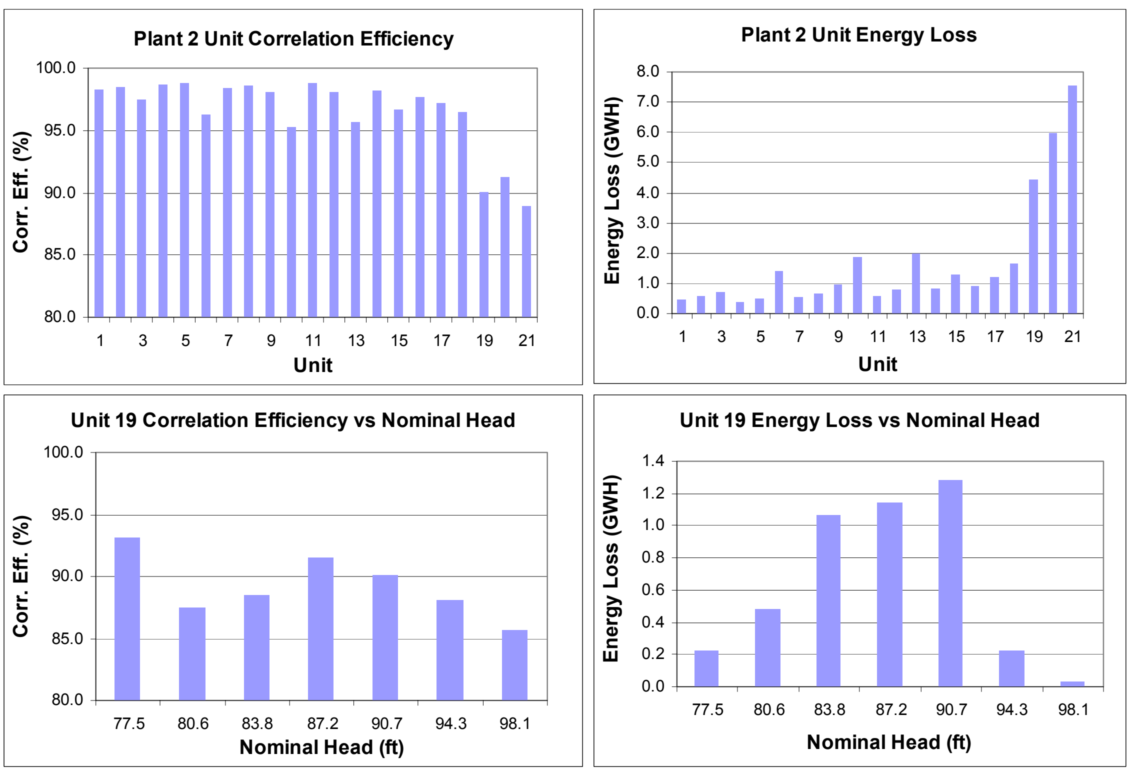

Figure 9: Unit and Nominal Head Characteristics for Plant 2

Figure 10 presents efficiency versus power results from a remote index test of Plant 2's Unit 19 and the expected efficiency versus power from the archival unit characteristics data. These plots demonstrate that the primary cause for the low correlation efficiency is a discrepancy between the measured flow rate and the expected flow rate.

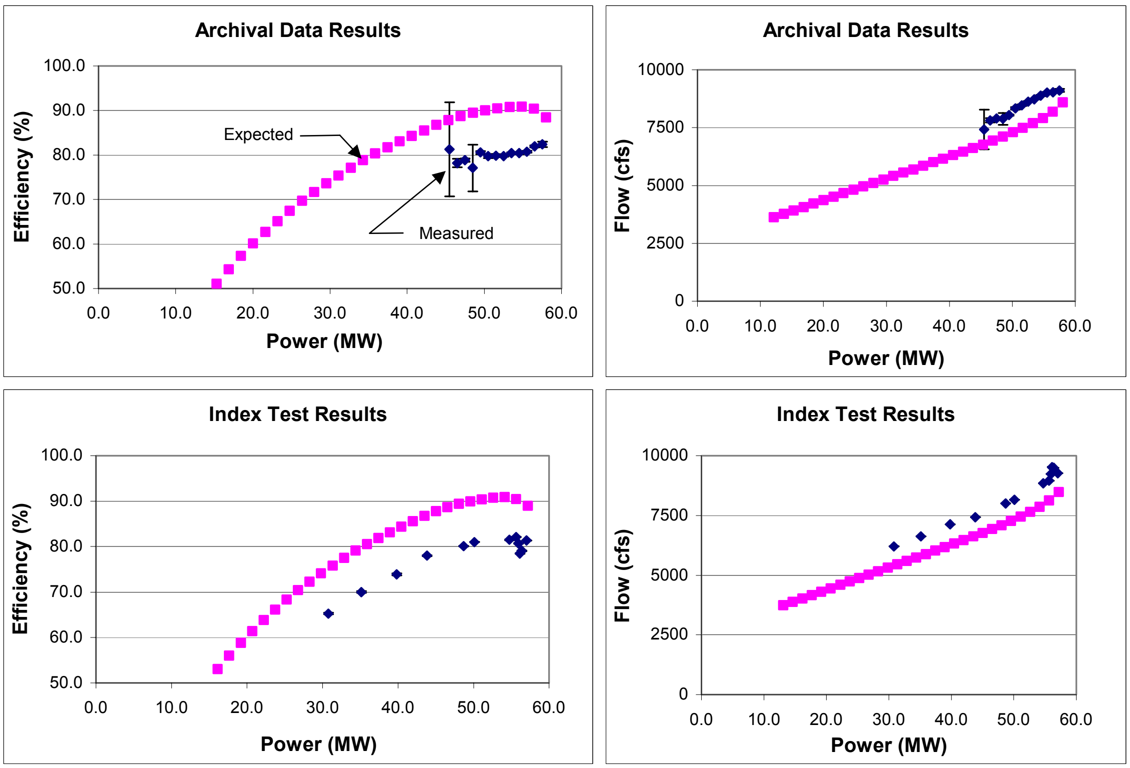

Figure 10: Comparison of Archival Analysis and Index Test, Unit 19, Plant 2

CONCLUSIONS

The optimization-based hydro performance indicator (OHPI) provides an effective means to measure and manage a hydro system, ensuring that each unit and plant is producing energy as efficiently as possible. There are two primary components of this indicator, the operation efficiency and the correlation efficiency. The operation efficiency measures how efficiently all of the units in all of the plants within a system are operated to meet the requested loads, while the correlation efficiency evaluates the accuracy of all unit characteristics and related instrumentation within the system.

WaterView archival data and the WaterView optimization engine are used in conjunction with DataWolff automated data analysis software for the OHPI analyses. The analyses are based on a comprehensive data set with high temporal resolution, including power, flow, headwater, tailwater, gate, and blade (for Kaplan units) data from every unit within the system. A key feature of the OHPI is that the structure of the hydro system is mirrored in the hierarchical structure of the data analyses. For example, the correlation efficiency is based on a four-level structure that summarizes performance at the system level, at the plant level, at the unit level, and at various levels for nominal head. The hierarchical structure enables a performance engineer to rank the plants and units within a given system by avoidable energy losses and to diagnose the root causes of the energy losses.

OHPI results from one year of archival data for two plants demonstrate the utility of this indicator. The operation efficiencies for the 21-unit Plant 2 show that significant gains are achievable with improved optimization. The correlation efficiencies for both plants provide an effective tool for locating the units within a plant that produce the highest energy losses in plant dispatch due to errors in their unit characteristics and associated instrumentation. This approach was used to identify a unit with an improperly operating blade-gate cam and two units that demonstrate significant discrepancies in the measurements of flow rate. Subsequent index testing confirmed the problems first identified from the archival data using the OHPI and its components, the operation efficiency and the correlation efficiency.

REFERENCES

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

ASME, *Hydraulic Turbines: Performance Test Code PTC 18-1992*, New York, New York: American Society of Mechanical Engineers, 1992.

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, July 2003.

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