Reviewing the Approaches to Hydro Optimization

In today's electricity supply market, getting more out of existing assets is paramount. Optimizing the operation of hydro assets can be accomplished at several levels: from a single unit to a series of plants. Numerous optimization methods are available that, if used appropriately, can significantly enhance the economics of hydropower generation.

By Lee H. Sheldon

In today's hydropower terminology, "optimization" means to maximize the benefits from an existing generating resource. This usually means to maximize the efficiency of energy generation, but also can mean to maximize the revenue from a generating project. In many cases, optimization can provide the lowest cost additional energy available from any generating resource.

Project optimization can be achieved in three ways: on an individual generating unit basis; on the basis of both powerhouse load apportionment and total loading; and on the basis of the contributing watershed or river basin. Although these are separate types of optimizations, the effectiveness of each is enhanced by the optimization of the others. In addition, for each of the three types, various methods are available to achieve optimization, and several additional methods are under development.

Single Unit Optimization

Single unit optimization refers to optimizing the performance of an individual generating unit. There are numerous ways in which the efficiency of a single turbine-generator unit can be improved. These include index testing and adjusting the unit's vacuum breaker setting. In addition, a dispatcher can influence single unit optimization through his or her ability to keep the unit at best gate as head changes.

A classic example of single unit optimization is indexing or conducting a relative efficiency test on a Kaplan or double-regulated turbine to determine the optimal blade-to-gate setting for a given flow and head condition. This information can be used to maximize unit output. This optimum blade-to-gate relationship for a given head is programmed into the governor as a blade-to-gate "cam curve." Indexing has been repeatedly demonstrated to provide an excellent economic rate of return (i.e., increase in generating revenue versus the cost of testing).

The rational for this testing is twofold. First, new prototype units generally have minor differences from their homologous models, which cause changes from the optimum cam curve predicted by the model. Second, as units age during their service life, particularly after weld repairs for cavitation damage, their optimum cam curves tend to change. Experience has shown that, as a rule of thumb, it is economically worthwhile to index a Kaplan turbine about every four years of service life and certainly after every major overhaul.

Another frequently overlooked means of increasing efficiency of all reaction turbines is to set the opening and closing of the vacuum breaker at the proper gate position (i.e., so that the vacuum breaker is open only when it is truly needed).

Vacuum breakers are used to allow the unit to draw atmospheric air into the subatmospheric region under the runner at low gate settings to reduce vibration and rough operation. However, by its very nature, this arrangement reduces the subatmospheric pressure under the runner and, consequently, the head differential across the runner. In turn, efficiency is reduced. Vacuum breaker valves should be set to close at the smallest gate setting that does not exacerbate rough operation.

Proper unit maintenance is another means of improving the efficiency of a single generating unit. Activities such as maintaining proper gate seal and wearing ring clearances to minimize leakage losses, keeping trashracks clean to minimize head losses, maintaining proper tailwater levels to avoid cavitation, and minimizing penstock withdrawals to proper levels for non-generating uses (such as domestic water services and shaft bearing and generator cooling) can pay dividends.

Powerhouse Load Optimization

Optimizing a powerhouse load refers to proper sharing or apportionment of total powerhouse generating load among the individual generating units, and to the total powerhouse load itself. Neither is to be confused with maximizing head (which is discussed later in this article).

Load apportionment refers to maximizing the generation output of a multi-unit power plant for any given flow rate and head. It also could refer to minimizing the flow rate for any given generation output and head. This is the newest type of optimization, for only recently have the software algorithms become available to solve the *infinite* number of possible generation combinations to find the one unique optimum solution.

For a simplistic example, consider a

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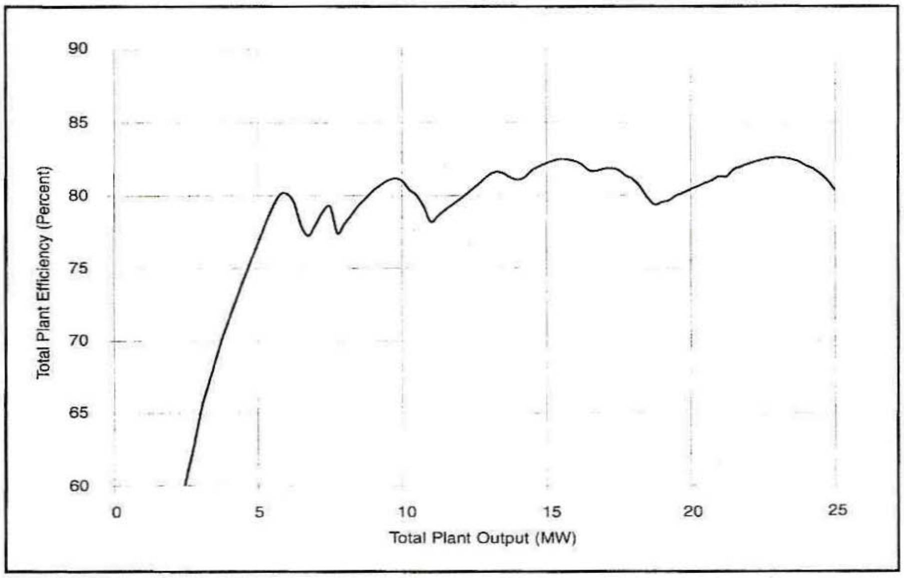

Figure 1: This graph depicts the optimum efficiency profile of an actual hydro plant with three Francis turbines (one large; two small) operating at a constant gross head. As shown from the profile, a small increase or decrease in total powerhouse load can cause a difference in total generating efficiency.

plant containing two equal-sized units with equal efficiency profiles operating at an arbitrary head and at a load where one unit is exactly at peak efficiency and the other is at some higher or lower gate opening. This combination of units is using more water than necessary to generate at that given combined power level. The unit at peak efficiency could have its load changed a small amount in the direction of the other machine's generation. Owing to the flatness of efficiency profiles around their peaks, the efficiency would decrease only slightly on this first unit. However, this would allow the second unit to change its load the same small amount in the direction of the first, but it would rise on a steeper slope of the efficiency profile. The end result is that, although their combined power output remains the same, the combined, or total, efficiency of the two units is increased (i.e., less water is now used to obtain the same power output).

For this illustration, the optimum solution is where each unit generates at a point on its efficiency profile where the slopes of the tangents are equal. However, for a powerhouse with more than two units and\or units with differing efficiency profiles and\or different size units and\or units down for maintenance and\or units kept on line for spinning reserve, the number of possible ways to share load among the units increases many fold.

As mentioned earlier, software algorithms can be used to analyze the number of combinations to find the one optimum way to share load among units for any given head, flow, and power requirement and any given availability of units.

Optimizing the total powerhouse generating load itself is a significant and unique aspect of powerhouse optimization. However, this type of optimization has only been demonstrated a few times because the large number of required optimum load-sharing solutions have only rarely been calculated to document it.

The situation is that, *even if* each individual generating unit is at its optimum *and* the total powerhouse loads at constant gross head are shared among the units in the most optimal manner, there still can be an additional large difference in total generating efficiency depending on the total plant load itself. This is because a multi-unit power plant's optimum efficiency profile is not uniform, but has "peaks and valleys."

This is best illustrated by a graphical example of the optimal efficiency profile of an actual powerhouse at constant gross head. This particular powerhouse consists of one larger and two smaller Francis turbines. The two smaller turbines have slightly differing efficiency profiles, particular with respect to the power at which peak efficiency occurs. The load-sharing problem to achieve maximum powerhouse efficiency was solved repeatedly for very close increments of total powerhouse loading. The resulting optimal efficiencies were plotted versus total powerhouse output, and are shown in Figure 1. This range of powerhouse outputs starts with the minimum load on just one unit, and includes shutting down and starting units as needed, and ends with the maximum output of all three units.

As may be noted, the optimized powerhouse efficiency profile in Figure 1 is not a constant, but has distinct, substantial peaks and valleys. In other words, a small increase or decrease in total powerhouse load can cause a difference in even the optimized total generating efficiency. Consequently, dispatching power plants at discreet total loads corresponding to the peaks, rather than randomly at arbitrary loads, can increase a power plant's generating efficiency.

System Optimization

The third type of optimization concerns optimizing a system of hydro plants in entire watersheds or river basins, particularly where there is more than one powerhouse in series, such as shown in Figure 2. The previous two types of optimizations were concerned with how to best use the fluid energy that is provided at the power plant. This type of optimization is concerned with how to provide the fluid energy to the power plant. The objective of this optimization is quite straightforward—to provide as much flow, at as high a head, for as long a period of time as possible.

It is recognized that generally maximizing head, such as operationally maintaining a full forebay, increases energy production. This is because a given volumetric flow rate of water, such as a cubic foot per second, contains more fluid energy to transfer to a turbine runner than the same quantity of water at a lower head. Conversely, spilling water at any head is the same as generating at zero efficiency.

The basic complicating factor in basin optimization is time. That is, unlike the previous two types of optimizations, cause and effect do not occur simultaneously. For instance, water released at an upstream project requires a certain travel time before it is available for generation at a downstream project. Consequently, where there is a higher revenue millage rate for on-peak generation, the water discharged from an upstream project may not reach a downstream project until off-peak rates are in effect.

A second complicating factor is uncertainty. Any basin optimization is based, to some extent, on hydrology, which, in turn, is a statistical correlation of historical events. Any such compilation necessarily has an amount of unknowns or uncertainty. Traditionally, basin optimization has been achieved by creating numerical or computer models and running a large number of simulations. However, recent advances in decision-making software logic now allow customized models to quickly arrive at an optimum simulation.

Techniques for Achieving Optimization

Each of the three types of optimization described in this article can be achieved through one or more techniques.

Single Unit Optimization Techniques

For the single generation unit, almost all methods involve performance or efficiency testing, including diagnostic evaluations.[1,2] This testing is done for two reasons: 1) to determine those adjustments that will optimize the performance of the individual tested unit; and 2) to determine the individual unit's efficiency profile for use in some method of powerhouse optimization.

Efficiency testing is classified as either absolute or relative, depending on whether the flow rate is measured in absolute terms, such as cubic feet per second, or in relative terms such as a change in some piezometric elevation or in a pressure differential. For measuring flow in absolute terms, there are on the order of a dozen methods, each with its own advantages and disadvantages for the particular application. Many of these methods, including area velocity integration (current meter), salt velocity, pressure time, and tracer dilution, are delineated in various test codes.[3,4,5]

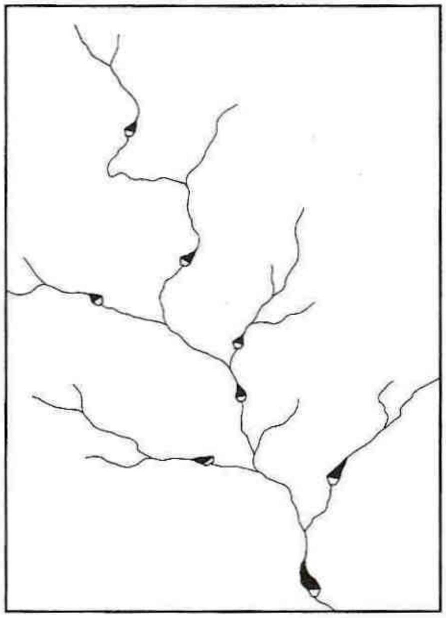

Figure 2: Several optimization tools are available for operating hydropower projects in series in a river basin, as shown in this hypothetical example.

In addition to these older methods, newer methods are continuing to be developed. Two examples are the sliding gate method and the acoustic scintillation measurement method. The sliding gate method for index testing of Francis and Kaplan units follows the general procedures for standard testing and analysis with one exception: instead of moving the turbine's wicket gate in discrete increments and collecting data for a period of time at the discrete gate positions, the gate is moved slowly and continuously through the desired range of movement. Performance data is continuously recorded during this period. Rather than determining a set of discrete points along an efficiency curve, the entire curve is delineated.[6] In the scintillation method, which is just being introduced, time for a recognizable, natural turbulence pattern within the fluid to travel a short distance is measured.[7]

The relative method of efficiency testing is generally easier and less expensive to use than the absolute method. In addition, the results still may be converted into absolute flow units, to a reasonable degree of accuracy, by calibrating the relative flow-indicating devices by an absolute flow measurement method, or by matching or comparing with the predicted performance from homologous hydraulic turbine models. Recent developments in this method have been in the area of automatic test recording equipment. Many owners of hydro facilities, including the U.S. Army Corps of Engineers, Tennessee Valley Authority, Grant County Public Utility District, and Seattle City Light, have developed test recording equipment to various degrees of automation for their own use. (See the box to the left for details about one innovative test recording device.)

There are a number of other adjustments, even to units with "nonadjustable" runners, that can be optimized by proper testing techniques and the diagnostic evaluations of the test data.[8] These include: proper settings for the vacuum breaker air valves, compensation for hysteresis in the blade and/or wicket gate control linkages, effect of head loss on the operation of adjacent units, effects of cavitation due to tailwater elevations, and effects of fish screens at the intake.

Powerhouse Optimization Techniques

For optimizing the powerhouse apportionment of loads, there are three basic methods available on the market to determine the optimum way to share load among the individual, available units.

The first method is a fixed schedule

The Little Black Box for Index Testing

One of the truly great inventions within the hydropower industry that unfortunately never made it into the marketplace is the Index Test Box developed by a technician at Woodward Governor Company. This device, which simply plugged into a Woodward governor on a Kaplan turbine, made minute changes to the blade angles while the unit was operating normally. Then, using sophisticated signal processing techniques, the device recorded the test data once all conditions were stable and constant. The data was recorded on an EPROM (Erasable, Programmable, Read Only, Memory) chip that could be removed from the Index Test Box and plugged into a data reduction software system, which then analyzed the data to determine the optimum blade-to-gate cam curve. The Index Test Box could then be moved to the next unit in the powerhouse, a new chip installed, and the next Kaplan runner index tested and optimized. All units being tested remained in normal operation, and, with a different chip dedicated to each unit, even trending information or comparisons with previous test data could be made.

The one prototype Index Test Box purchased by Portland General Electric Company and installed and tested on one of the utility's Kaplans produced an identical optimum blade-to-gate cam curve when compared to the results of a conventional, manual index test conducted simultaneously, as documented in 1989 by the utility in the report "Evaluation of Woodward Index Test Box on Portland Hydro Unit 2."

An article about this device appeared in Hydro Review, *Volume 6, No. 3, June 1987, page 36-41.*

Optimization Software

Several commercially available software packages can be used to optimize the operation of an individual hydro generating unit, a single powerhouse, and/or several powerhouses in one river basin.

HYDROPS

Distributor/Year Released: Charles Howard & Associates, Ltd., Victoria, British Columbia, Canada; 1986

Description: HYDROPS contains a real-time generation unit loading model that analyzes data for hydrology, loads, and prices, and optimizes on-line unit loading. Decisions are available for both short- and long-term operations. Uses Windows 95 or NT on a high-end standard PC.

HydroSoft

Distributor/Year Released: HydroSoft Energie Inc., Montreal, Quebec, Canada; 1992 (then named GESTEAU)

Description: HydroSoft analyzes data from one or more generating stations to automatically determine the optimal distribution of power between various power plants and the units within each power plant. Information provided can be historic, real-time, or forecasted. Uses UNIX on a UNIX server; user interface runs locally on X-terminals or PCs using Windows NT.

ICC-SHOP

Distributor/Year Released: Powel Data, Trondheim, Norway; 1996

Description: ICC-SHOP is a tool for short-term optimization of complex cascaded river systems. The module is a part of ICC-System, which integrates tools for hydro system management in a deregulated market. ICC-SHOP determines the optimal use of the water while taking into account firm load obligations and options for buying and selling in a spot market. Uses UNIX (Hewlett Packard, Dec Alpha, Sun) and Windows NT.

OPT-EASE

Distributor/Year Released: Kleinschmidt Associates, Pittsfield, Maine; 1994

Description: OPT-EASE is used to maximize plant electrical output or to minimize total plant water usage. The package provides the optimal setting for existing or future conditions based on analysis of performance data and efficiency profiles for each generating unit. Uses Windows 95 or NT on a PC (486 or better).

RunAid

Distributor/Year Released: Hydropower Technologies Inc., Palo Alto, California; 1988

Description: The package optimizes unit loading; reservoir regulation and discharge; the number of units in operation, with start/stop transitions; cascade power plants; and systems of multiple reservoirs and multiple power plants. Uses Windows NT on a standard PC with substantial memory.

SIMHYDE and VALOPER

Distributor/Year Released: Technik-Eaucan Inc., Dollard-des-Ormeaux, Quebec, Canada; 1988

Description: SIMHYDE is used to simulate the long-term operation of present and future hydroelectric plants. Detailed data input is analyzed, providing the optimal operating regime for the turbine-generator units. This regime is then input in VALOPER, which is used to make decisions on the optimum operation of the hydro plant. Uses UNIX on a high end standard PC.

Vista

Distributor/Year Released: Acres International Ltd., Niagara Falls, Ontario, Canada; 1992

Description: This seven-module package analyzes data about plant equipment, water levels, flow, value of generation, outages or maintenance, on- and off-peak periods, and other factors. Results of the analysis allow optimization of short- and long-term generation scheduling. Uses Windows NT on a high-end standard PC.

Waterview

Distributor/Year Released: Hydro Resource Solutions, L.L.C., York, Pennsylvania; 1996

Description: The package contains a main efficiency module and several optional modules including Kaplan optimization and plant optimization. Uses Windows 95 or NT on a high-end PC. Sensors for data input are available through the distributor.

WOPRO 3.0

Distributor/Year Released: Worley Consultants Ltd., Auckland, New Zealand; 1997

Description: The package provides real-time multi-reservoir operation and planning information by integrating inflow forecasting, reservoir optimization and scheduling, and optimal unit allocation. Uses Windows 95 or NT on a high-end standard PC.

—Ed Fulton

or table of pre-solved optimum solutions. The second is an on-line monitor, which measures real-time flow rate and unit efficiency, and learns or remembers the best set points encountered. The third is a new software technique that instantaneously solves for the optimum solution for any given situation, based on previously tested efficiency profiles.

The first of these, the fixed schedule, is obtained by calculating a large number of loading combinations, plotting total plant efficiency versus plant output, and identifying the envelope or optimum curve to this aggregate of solutions.[9] The advantage of this method is a high degree of confidence in the optimum answer because of the number of nearby load combinations calculated. The disadvantage is the rigidity of the method. If units are added or down for maintenance or even if turbine runners are replaced or generators rewound, the table needs to be recalculated.

The second method to optimize powerhouse loading is the on-line monitor.[10,11] This instrumented system uses a multi-path acoustic technique to measure flow rate, determine unit efficiency, and compute total plant efficiency. The best combination of loads on individual units encountered at each load set point is stored in a memory. The advantage, of course, is that this system continually monitors the real-time efficiency of each generating unit. The disadvantage is, again, inflexibility in that the system must relearn the effect of changes to an individual unit's performance or even its nonavailability. A single monitoring system is also limited by the number of generating units it can handle.

The third method to optimize powerhouse apportionment is to actually solve for the optimum load-sharing problem for any given hydraulic conditions and unit availabilities based on efficiency profiles of each generating unit.[12,13] The advantages, of course, are the nearly instantaneous response and the total flexibility of providing the optimum solution for an unlimited number of units and of any unit availability, as well as optimizing by maximizing power for a given flow rate or by minimizing water use for a given power output. The disadvantage is that each optimum solution is based on the profiles from previous efficiency tests and may not reflect the current efficiency of each generating unit. However, when new efficiency test data becomes available, it is easily incorporated.

Optimizing the efficiency of a multiunit power plant by controlling its total load often is not an option. The lack of storage for run-of-the-river plants and system demands for power more often take precedence. However, where dispatching plant loads are flexible, an increase in total plant efficiency can be achieved by the method of generating only at discreet total outputs, i.e., at the "peaks" rather than the "valleys."

River Basin Optimization Techniques

To optimize the operation of more than one powerhouse in series in a river basin, several simulation models have been developed for specific watersheds and are being successfully used to optimize operations.[14,15,16,17,18]

One of the difficulties in optimizing energy production is the number and type of environmental constraints that may be imposed on a hydro project. For instance, it is not unusual that the rate at which the tailwater elevation may be changed is restricted, which constrains the "ramp rate" at which the power plant may change load. This challenge currently is being addressed by a number of software developers.

What the Future Holds

As hydroelectric project owners look toward the future, the opportunities for optimizing plant operations are tremendous. By applying proven as well as emerging techniques for optimizing operations of a single unit, multiple units in a powerhouse, and/or a series of plants in a river basin, the hydro industry can use its existing assets smarter and more effectively than ever before. ■

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