OPTIMIZATION

As used in today's hydropower terminology, the term "optimization" means to maximize the benefits from an existing generating resource. This usually means to maximize the efficiency of energy generation, but can also mean to maximize the revenue from a generating project. Studies by the Bonneville Power Administration (BPA) have documented that optimization provides the lowest cost additional energy available from any generating resource.(Ref 1)

There are three different types of optimization - on a single generating unit basis, on the basis of powerhouse load apportionment and total loading, and on the basis of a watershed or river basin. Although these are separate types of optimizations, the effectiveness of each is enhanced by the full optimization of the others. In addition, for each of the three types, there are different methods to achieve optimization and new methods are currently under development. The purpose of this paper is to provide a compilation and description of these various types and methods.

The first type of optimization is on a single unit basis and refers to optimizing the performance of an individual generating unit. There are a number of ways in which the efficiency of a single turbine-generator unit can be improved, not counting a dispatcher's ability to keep the unit at best gate as head changes. A classic example of such optimization is indexing or conducting a relative efficiency test on a Kaplan or double regulated turbine. This is done primarily to determine the optimum blade to gate relation for a given head, which may be programmed into the governor as a blade to gate "cam curve." Indexing has been repeatedly demonstrated to provide an excellent economic rate of return or increase in generating revenue versus the cost of testing.(Ref 2) The need for this testing is basically for two reasons. First, new 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 for a rule-of-thumb, it is generally economically worthwhile to index a Kaplan about every four years of service life and certainly after every major overhaul.

Another frequently overlooked way to increase efficiency on all reaction turbines is to set the opening and closing of the vacuum breaker at the proper gate. 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 also reduces the subatmospheric pressure under the runner and consequently the head differential across the runner, which in turn reduces efficiency. Other ways to improve the efficiency of a single generating unit include maintaining proper gate seal and wearing ring clearances to minimize leakage losses; keeping trash racks clean to minimize head losses; maintaining proper tailwater levels to avoid cavitation; and minimizing penstock withdrawals to proper levels for.such nongenerating uses as shaft bearing and generator cooling, and domestic water services.

The second type of optimization, that of powerhouse loading, refers to first, the proper sharing or apportionment of total powerhouse generating load among the individual generating units and second, to the total powerhouse load itself. Neither is to be confused with maximizing head (which is discussed under the third type). The first or load apportionment refers to maximizing the generation output of a multiunit powerplant for any given flow rate and any head or to minimizing the flow rate for any given generation output and any 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, if a plant containing two equal sized units with equal efficiency profiles is presently 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 is using more flow of water than necessary to generate at that given power level. The unit at peak efficiency could have its load changed a small amount in the direction of the other machine's generation. Due to the flatness of efficiency profiles around their peaks, the efficiency would decrease only slightly on this unit, However, this would allow the second unit to change its load the same small amount in the direction of the first, but in doing so, 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 simple illustration, the optimum solution is where each unit generates at a point on its efficiency profile where the slopes 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. Only recently have a couple of different methods become available which are capable of solving the infinite 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.

The second optimization or the total powerhouse generating load itself is a very significant and unique aspect of this powerhouse optimization, which has been documented only a couple of times previously because the large number of required optimum load sharing solutions have not previously been calculated. That is, 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 optimum manner, there can still be a very large difference in total generating efficiency depending on the total plant load itself. This is best illustrated by a graphical example of the optimum efficiency profile of an actual powerhouse at constant gross head. This particular powerhouse consists of one larger and two smaller Francis turbines and 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 for very close increments of total powerhouse loading and plotted versus total powerhouse output on 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 is not a constant, but has distinct, significant peaks and valleys. In other words, a small increase or decrease in total powerhouse load can cause a significant difference in even the optimized total generating efficiency.

Consequently, dispatching powerplants at discreet total loads corresponding to the peaks rather than randomly at arbitrary loads can significantly increase a powerplant's efficiency.

The third type of optimization concerns optimizing entire watersheds or river basins, particularly where there is more than one powerhouse in series. The previous two types of optimizations were concerned with how to best utilize the fluid energy that is provided at the powerplant. This third type of optimization is concerned with how to provide the fluid energy to the powerplant. The objective of this optimization is quite straight forward - to provide as much flow without spilling, at as high a head, for as long a period of time as possible. It is not always 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 at a higher head 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. One only has to consider trying to predict reservoir evaporation rates to appreciate the concept of uncertainty. Traditionally, basin optimization has been achieved by creating numerical or computer models and running a large number of simulations. However, recent advances in generic decision making software logic now allow customized models to quickly arrive at an optimum simulation.

Editors Note - Break Point for Continuation

Each of the above three types has a number of different methods to achieve optimization. For the single generating unit, almost all methods involve performance or efficiency testing, including diagnostic evaluations.(Ref 3) This testing is done for two reasons. First, to determine those adjustments which will optimize the performance of the individual tested unit and second, to determine the individual unit's efficiency profile for use in some methods of type two or powerhouse optimization. Efficiency testing is classified as either absolute or relative, depending on whether the flow rate in 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 different methods, each with its own advantages and disadvantages for the particular application. The older methods are delineated in the various test codes(Ref 4) as well as some of the newer methods, such as acoustic. The newest method just being introduced is that of scintillation.(Ref 5) In this method, time for a recognizable, natural turbulence pattern within the fluid to travel a short distance is measured.

The relative method of efficiency testing is generally easier and less expensive to use. In addition, the results may still 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. The Corps of Engineers, Tennessee Valley Authority, Grant County PUD, and Seattle City Light, just to name a few, have developed test recording equipment to various degrees of automation for their own use. One of the truly great inventions of this hydropower industry that unfortunately never made it into the market place is the Index Test Box developed by a technician at Woodward Governor Company. This device, which simply plugged into one of their governors on a Kaplan turbine, made minute changes to the blade angles while the unit was in normal operation. Then, using sophisticated signal processing techniques it recorded the test data once all conditions were stable and constant. The data was recorded on an EPROM (Erasable, Programmable, Read Only, Memory) chip which 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 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 and installed and tested on one of their Kaplans produced and identical optimum blade to gate cam curve when compared to the results of a conventional, manual index test conducted simultaneously.(Ref 6)

Aside from the blade to gate cam curve, 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.(ref 7) These include proper settings for the vacuum breaker air valves, compensation for hysteresis in the blade and/or wicket gate control linkages, effect on head loss of the operation of adjacent units, effects of cavitation due to tailwater elevations, and effects of fish screens at the intake.

In 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 is a fixed schedule or table of presolved 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, such as available from Hydropower Technologies, Inc. now of Palo Alto, California, 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. 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, such as the Model 7530 available from Accusonics. This instrumented system uses a multipath 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 to six generating units.

The third method to optimize powerhouse apportionment is to actually solve for the optimum load sharing problem each time for any given hydraulic and unit availability conditions based on efficiency profiles of each generating unit stored in a memory. The newly developed software by Kleinschmidt Associates, called *OPT-EASE,* uses this method.(Ref 8) 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 is available, it is easily incorporated.

Optimizing the efficiency of a multiunit powerplant by controlling its total load is often 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 is flexible, an increase in total plant efficiency can be achieved by generating only at discreet total outputs.

For the third type of optimization, that of river basins with more than one powerhouse in series, there are several simulation models currently available. *HydroSoft-RMS*™ is a real-time system for the planning, dispatching, and scheduling of hydroelectric power generation by a subsidiary of Hydro-Quebec. Charles Howard and Associates of Vancouver, B.C., specializes in providing customized hydrologic models. One of the difficulties in optimizing energy production is the number and type of environmental constraints which 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 powerplant may change load. *WaterView* by the Norris Laboratory of the Tennessee Valley Authority is designed to balance peak performance with a host of potential environmental constraints. The emerging simulation and optimization system by Technik-Eaucan, Inc. combines a hydraulic simulation module, an economic value decision processor, and a powerhouse optimization module so that both type two and type three optimizations may be achieved simultaneously.

In conclusion, it is now recognized that there are three different, distinct types of optimization: single unit, powerhouse load apportionment and total load, and river basin; and that the second type is actually composed of two separate parts. Further, there are different methods to achieve each type of optimization. Some of these methods are new and just becoming available on the market. However, based on the proven economic viability of the established methods, the emerging selection of available optimization methods has the ability to significantly enhance the economics of hydropower generation.

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