OPTIMIZING THE GENERATING EFFICIENCY OF ENTIRE POWERHOUSES

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Executive Summary

This paper describes the current programmatic efforts to maximize the efficiency of hydroelectric generation. It covers the various types and classifications of efficiency optimization. In particular, it describes the results of developing new techniques to optimize the performances of individual generating units and separate techniques to optimize the performance of entire multiunit powerhouses.

Purpose

The purpose for optimization is due to the value it provides. A number of studies, including reference (1), have found that, in today's regulatory environment, optimization can provide the lowest cost, additional energy available from any generating resource.

It is the intended purpose of this paper to document the current state of the art in the field of optimization or maximizing generation efficiency, and to provide a common basis for the various newer terms used in this field. Therefore, this paper will entail providing several descriptive definitions.

Basic Optimization

As a computer term, "optimization" is defined in the dictionary as, "to rewrite a program to obtain maximum efficiency." This term is now used in the hydropower industry to mean to change operations to obtain maximum generating efficiency. That is, converting the most power in a fluid column into mechanical shaft power. From the definition of fluid power, efficiency is the constant of proportionality between the fluid power entering the hydraulic turbine and the mechanical power out of a turbine,

$$HP = E(Q\gamma H/550)$$

where HP is the turbine output in horsepower, E is the efficiency in decimal form, Q is the volumetric flow rate in cubic feet per second, γ is the specific weight of water in pounds per cubic foot, and H is the net head in feet. The product of $Q\ \gamma$ is the weight flow rate in pounds per second. Therefore, $Q\gamma H$ is the power in the fluid column in foot-pounds per second. Since there are 550 foot-pounds per second in a horsepower, $Q\gamma H/550$ is the horsepower available in the fluid column.

This definition applies to an individual generating unit or to an entire powerhouse, containing multiple units. The complexity of this optimization subject can be observed simply by noting that every unit in a powerhouse may be adjusted to operate at its optimum performance. However, if a multiunit powerhouse is to operate at its maximum efficiency, with the exception of a load set point, no individual unit will be operating at its peak efficiency.

Optimization also provides other benefits. Maximum generating efficiency tends to prolong the operational life of generating equipment by minimizing mechanical vibration and stresses, and also to increase the survivability of downstream migrant fish.

Head

Historically, increasing generation efficiency has been synominous with increasing head. This is because as head is increased, the power that can be developed from a given flow rate generally increases. However, the head that can be made available for generation at many hydroelectric projects is constrained by other factors such as reservoir rule curves. Flood control projects, in particular, are operated primarily for flood control and secondarily for power generation. Therefore, their reservoir elevations are dictated by the need to provide storage to adsorb seasonal high flows or runoffs. Therefore, the current definition of optimization has come to exclude head considerations and to mean maximizing efficiency at any given head.

Types of Optimization

Since optimization is applicable to various aspects of hydroelectric generation, this emerging technology has categorized optimization into five types. These are:

Type 1 refers to optimizing a single or individual generating unit,
Type 2 refers to optimizing an entire powerhouse that contains multiple units,
Type 3 refers to optimizing a river basin or watershed that contains more than one powerhouse,
Type 4 refers to optimizing a geographic region that contains more than one river basin or watershed, and
Type 5 refers to optimizing hydro-thermal integration.

An example of Type 1 Optimization is the index testing of a Kaplan turbine to determine the optimum blade to gate relation to input to the governor's control system. This is the only type of optimization that may be accomplished by measuring either relative or absolute flow rates. The other four types of optimization require absolute flow measurements.

Type 2 is optimizing entire or complete multiunit powerhouses. This type of optimization is composed of two parts. Although these will be described further later, to establish their definitions, the first is the selection of the proper units to have both off and on line to share the powerhouse load set point. Borrowing a term from the thermal generation industry, this is referred to as "unit commitment." The second part of Type 2 is the different amount of load that each unit is to share so that their combined efficiency, that is the powerhouse efficiency, is maximized. Again, from the thermal industry, this is referred to as "economic dispatch." However, as applied to the hydroelectric industry, there are two kinds of economic dispatch – constrained and unconstrained. Unconstrained means that no operational restrictions are imposed on the optimum solution. This results in maximum generating efficiency. Constrained means that other conditions are imposed and the optimum solution applies only to that limited condition.

An example of a constraint is one in which the end units in a powerhouse must remain on line and at a high discharge in order to provide fish attraction water.

Whereas in the first two types of optimization the optimum solution is for an instantaneous condition, in Type 3 the element of time is introduced. This is because of water travel time. That is, the time for a changed flow condition to travel from one powerhouse to the other, either downstream or upstream. However, in this type of optimization, the powerhouses do not necessarily need to be in series, downstream or upstream of each other, but may in fact be on separate river basins.

In Type 4, the element of load demand is introduced. That is, the efficiency of generation is optimized so it meets the load that is demanded from the grid or distribution system. This type of optimization includes such aspects as load shaping, peak demand, spinning reserve, and power purchase agreements.

In Type 5, the element of mixed generating resources is introduced. Hydroelectric generation has a very fast speed of response to meeting changes in load demand in comparison to the slower thermal generating systems. This is due to the large amount of stored mechanical energy in hydro generators because of their large rotating inertia (WK^2). This allows for the nearly instantaneous following of small load variations with very small changes in synchronous speed. The control system then changes the wicket gate setting to restore exact synchronous speed. Therefore, a common method of operating a hydro-thermal system is to base load the thermal generating resources at their peak fuel rate efficiency and to load follow with designated hydroelectric generating resources.

Other Classifications of Optimization

Besides types, there are two other common classifications of optimization. These actually address a method and a goal of optimization. As to the first of these, optimization is achieved by either an on-line or off-line method. Using Type 2 as an example, in an on-line method, the flow rate in each unit is measured in real time and the load sharing is altered until a maximum combined efficiency is achieved. In an off-line Type 2 optimization, the efficiency profiles of each unit are stored in a data base and that is used to calculate the amount of the powerhouse load set point to be shared by each unit. The on-line method has an advantage in that its optimization is based on the current condition of the generating equipment. The off-line method has an advantage in that it allows a “look ahead” capability. That is, it can determine optimum operation to meet future load demands. Other than index testing, which is an on-line Type 1 method, the Corps of Engineers has concentrated its optimization efforts in off-line methods.

In hydropower there are two sought after goals in optimization. One is to minimize the amount of water, or flow rate, needed to generate a given power and the other is to maximize the power generated for a given flow rate. The value of the first is that the saved water may be stored and used to generate power at a later time. The value of the second is the instantaneous increase in generated power. Since, the Corps operates its plants to follow load demand, their efforts are directed towards the first goal of minimizing the amount of water needed to generate a given power level.

Current Activities in Optimization

Various government agencies and utilities are currently involved in the different types of hydropower optimization. The US Army Corps of Engineers (USACE) through its Hydroelectric Design Center (HDC) is conducting Research, Development and Demonstration (R, D & D) in Types 1 and 2. The Bonneville Power Administration (BPA) is developing Type 3 computer programs and is also working on Type 4. The Tennessee Valley Authority (TVA) is active in Type 5 Optimization.

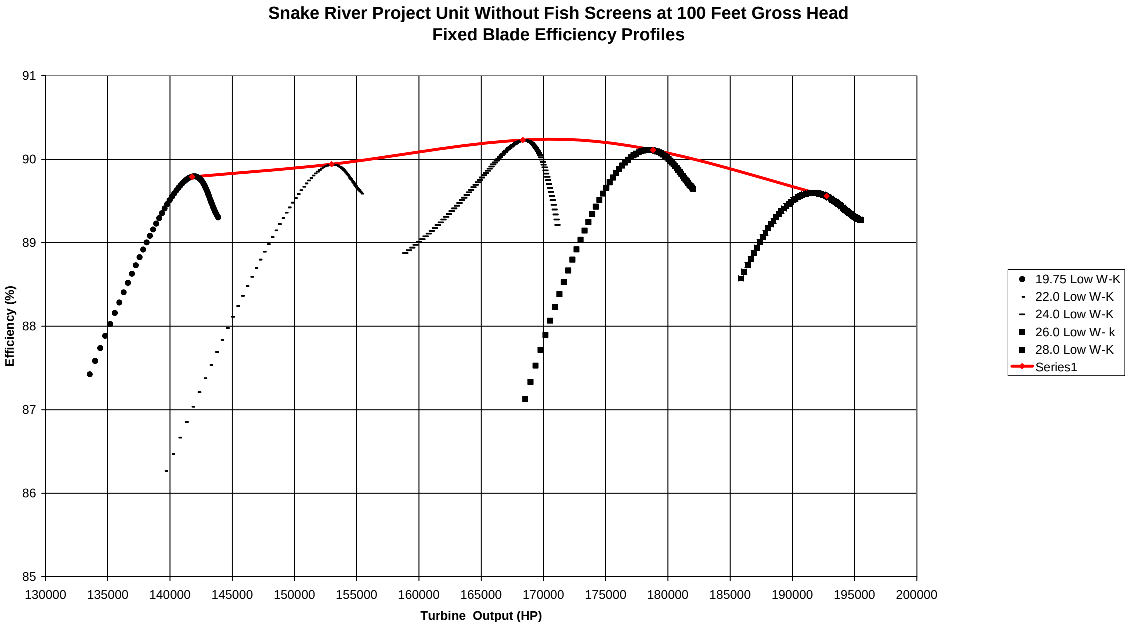
Type 1 Optimization

The remainder of this paper will concentrate on the efforts of the Corps of Engineers in Types 1 and 2 Optimization. As noted above, Type 1 Optimization refers to optimizing the efficiency of individual units. This is being done in three ways – equipment configuration, sensor improvements, and index testing.

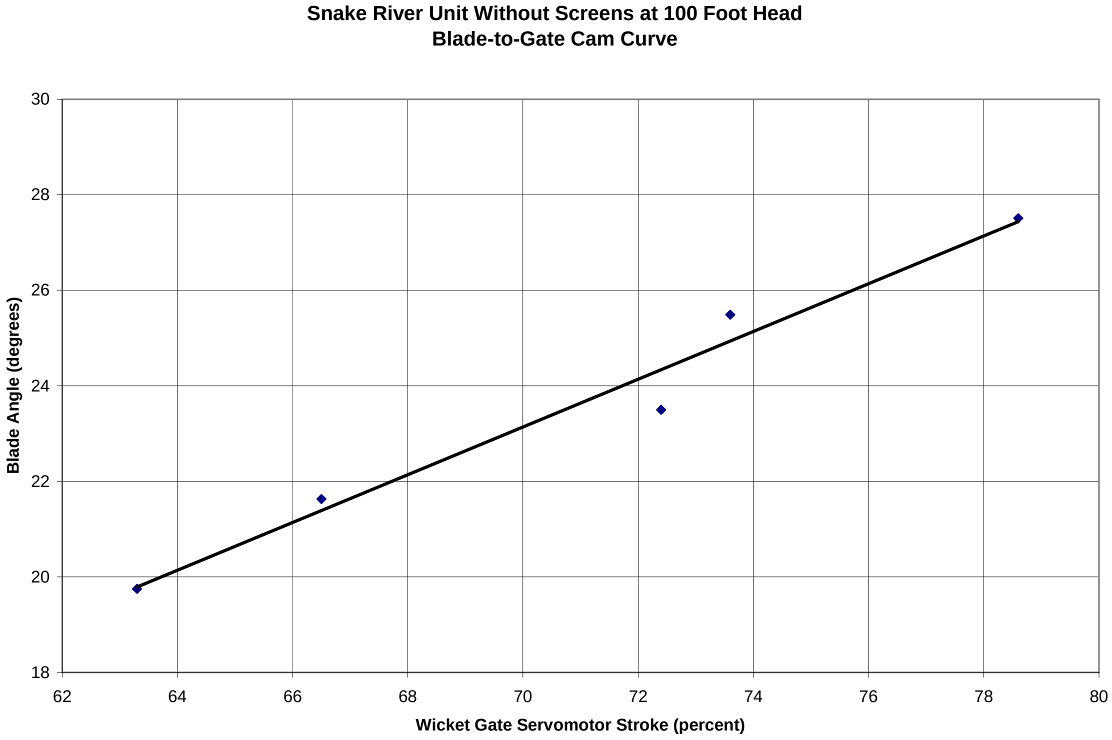
In terms of equipment configuration, the Corps has been experimenting with improving the smoothness of turbine water passages. In one effort, a relative efficiency test was performed on an older prototype Kaplan turbine and then its entire corroded water passages were sandblasted, ground smooth and repainted. However, in comparison with a subsequent relative efficiency test, the results were inconclusive. It was deduced that the calibration of the Winter-Kennedy piezometer system used to measure relative flow had been, in fact, altered by the smoothing changes to the flow passages. Subsequently, experiments were conducted in a hydraulic laboratory with a specifically roughened model. This found that an improvement in excess of two percent could be achieved by smoothing a turbine's water passages and in particular, it was found that the smoothness of the runner was by far the most critical contributor to the efficiency improvement. Other, different, model experiments have been performed on the positional relationship or orientation between wicket gates and stay vanes. In fact, the Corps received a patent on an efficiency improving configuration where the wicket gates are in the flow "shadow" of the stay vanes. In a third effort, Minimum Gap Runners (MGR) are being installed as replacement runners on Kaplan turbines. Primarily intended to minimize the mortality of downstream migrant fish, MGR's also have improved efficiency due to the reduced leakage in the gaps of blade to hub and blade to discharge ring. In a fourth effort, older governors of Kaplan turbines are being replaced with modern electronic, digital, 3-D governors. (3-D stands for the three dimensions of gate, blade and head). The older governors control the blade to gate relation at discreet heads. Thus, if the operating head happens to be at some intermediate or in-between head, there is a control error in positioning the blade angle for maximum efficiency. The new governors utilize electronic lookup tables that interpolate for the correct blade angle control at any head.

Improvements in the accuracy of the various sensors which control the generation of hydroelectric units also result in improved generation efficiency. Rather than a single gross head sensor for a powerhouse, individual unit head sensors have been installed at selected projects. It has been found that at some projects the head varies across the length of the powerhouse. This is particularly prevalent where run-of-the river projects span a river just downstream of a major sharp bend in the river. Centrifugal effects cause a super-elevation, where the water surface rides up on the outside of the curve. The accuracy with which the wicket gate opening and blade angle of Kaplan turbines is measured and controlled is directly related to the efficiency of their generation. A blade angle measuring system that measures the exact angle of each blade, each rotation of the runner, has been developed and successfully model tested. It is now being installed on a prototype Kaplan turbine for field evaluation. The system uses two vertical, relatively closely spaced, very high frequency proximity transducers in the discharge ring. The vertical separation is micro metrically measured. Since the turbine rotates at a fixed synchronous speed, velocity triangulation allows the calculation of the exact blade angle. The field test is being done to evaluate factors that may affect the transducer readings, such as blade end leakage cavitation. Rather that relying on the position of a wicket gate operating ring, the concept of monitoring the rotational position of each, individual gate stem is being explored.

An “index test” is a relative efficiency test, since the flow is measured in relative terms. Index testing has been used for decades to determine the optimum blade to gate relation or “cam curve” to input to the governor for Kaplan unit control, as well as the shape of the efficiency profile. In the traditional method, the blades are blocked in a series of fixed angles and the wicket gates sequentially opened. This yields a series of efficiency profiles at the different fixed blade angles. A tangent curve to these profiles depicts the shape of the efficiency profile and by an interpolative technique allows the derivation of the optimum cam curve at the given head. A typical index test relative efficiency profile and resulting cam curve are shown on Graphs 1 and 2.



Graph 1



Graph 2

However, conventional index testing tends to be labor intensive and time consuming as well as having to operate the unit manually, rather than being able to leave it on AGC (Automatic Generation Control). A newer technique has been developed that provides for the automatic index testing of Kaplan turbines while they remain in normal, load following, operation. This newer indexing method can not be done manually. Instead, it relies on a feature of the governor to hold power constant and then by a perturbation process causes the blades to rotate to a slightly different angle. The wicket gates are then repositioned by the governor to maintain constant power. The relative efficiency at this new blade position is compared to the previous blade position and if it is improved, the blades are moved again in the same direction. If the efficiency is reduced, the blades are moved in the opposite direction. Eventually, a blade to gate relation, which results in maximum efficiency at that given power level, is determined. This data then becomes a point on the optimum performance profile as well as a point on the blade to gate cam curve.

Type 2 Optimization

Type 2 Optimization may be thought of as load sharing optimization. That is, assigning a different generation level to each individual unit so that their combined efficiency is a maximum. This optimum load sharing among a given group of units is referred to as "economic dispatch." A multiunit powerhouse may be composed of units all from the same "family." That is, they may have been procured under the same specifications, based on the same model test, and fabricated by the same manufacturer.

However, their performances will differ to a lesser or greater extent. These differences are due to a number of factors, including: manufacturing tolerances, differing lengths of operational service, cavitation weld repair, etc. As a consequence, there is one unique way to divide any powerhouse load set point among a given group of units such that their combined efficiency is maximized.

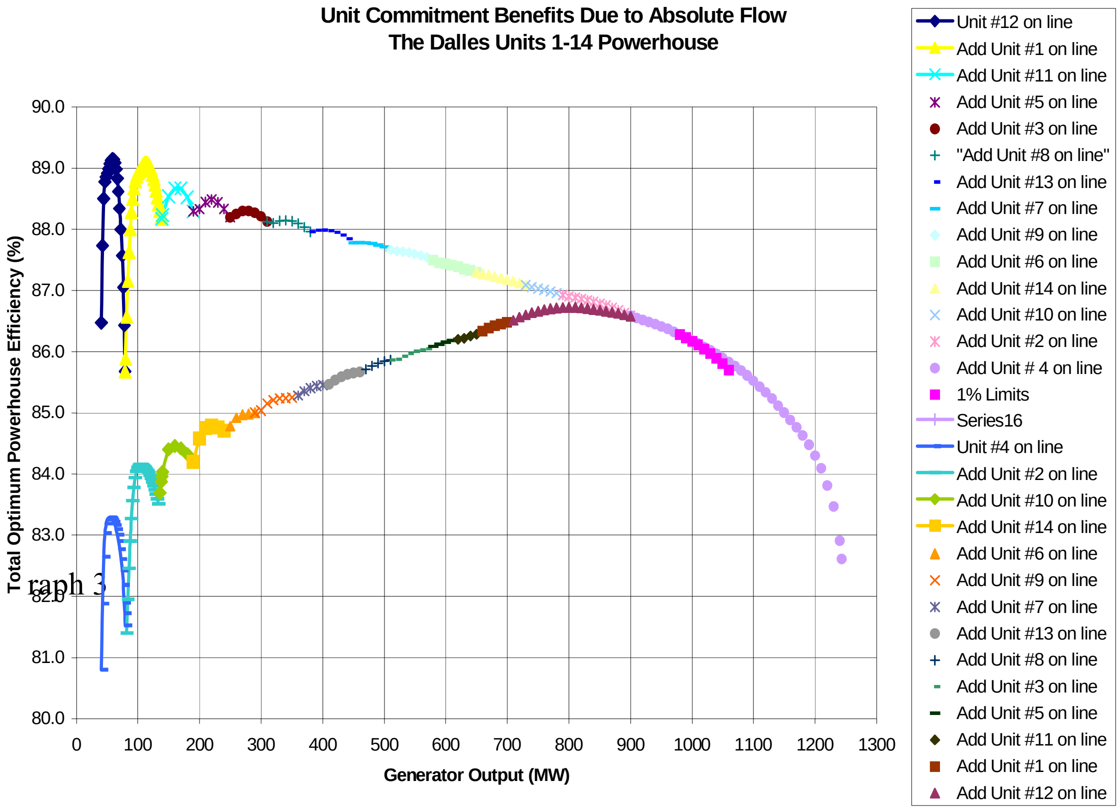
For hydraulic turbines, the criterion for maximum combined efficiency is for each machine to be operated at a power level where the slopes of the flow to power curves are equal. That is, where dQ/dMW is equal for each unit. This criterion applies to different units in a group of families as well as to different units within the same family. The physical interpretation of this criterion is that if each machine is at this same derivative, then taking an infinitesimal amount of flow rate from any one machine and giving it to any another will not increase the combined power output. Therefore, the combined efficiency of all the units must be at a maximum.

It is pointed out that this criterion is not exactly the same as equating the derivatives of efficiency with respect to power, dE/dMW. Mathematically, the two derivatives are not equalities. Applying the chain rule of differentiation to the definition of fluid power, $MW = Q\gamma HE/[550(1.3411)]$, shows that, $dQ/dMW = Q[(1/MW) - (1/E)(dE/dMW)]$. Therefore, the derivative of dQ/dMW does depend on the derivative of efficiency with respect to power, but it also depends on the flow rate, generator output, and efficiency at the point of consideration.

Algorithms have been developed to solve the optimization matrix and find the load level for each unit at which the individual derivatives of flow with respect to power are equal. The Corps of Engineers has developed a proprietary algorithm as part of their T2 Optimization program that solves this matrix with discrete tabular values in an iterative method known as a "series of infinitely paired comparisons." This is an off-line program that uses stored data of the performance profiles of each individual machine. A separate release of the program is tailored for each powerhouse. The Bonneville Power Administration (BPA) has developed a program known as NRTO, which stands for Near Real Time Optimization. This is also and off-line program, but solves the optimization matrix algebraically by replicating the performance profiles with polynomials. NRTO is actually a hybrid of Types 2 and 3 in that it covers every powerhouse in a river basin. It is intended that the two programs will work in unison. That is, NRTO will determine the load set point for each powerhouse and then the T2 program in each powerhouse would calculate the individual load to be applied to each machine. The output of each T2 would then be fed back to NRTO to close the loop.

The foregoing economic dispatch applies to load sharing among a given group of units. However, there is another part of this T2 optimization process. Different groups of even the same number of units from the same powerhouse will usually yield a different combined maximum efficiency. The prior selection of the particular group of units to enter the optimization matrix that will result in the highest combined maximum efficiency is known as, "unit commitment." This is the more difficult problem to solve, for it is similar to knowing the answer before solving the problem. However, there are actually ways in which the current optimization programs do solve the problem. First, the Corps' algorithm is capable of calculating which units to drop off line or pick up on line as needed to form the optimum group, or in other words to calculate a unit commitment. However, this requires exact information on the performance profiles down to speed-no-load. Such data is normally not available. Another way, known as the “brute force” method, is to solve the economic dispatch for all possible combinations of units and then select that group with the highest maximum efficiency.

An example of the value of T2 optimization is shown on Graph 3. At The Dalles Dam on the Columbia River, all 14 Kaplan turbines in the powerhouse in the late 1960’s were efficiency tested by the current meter method. This data set was input into the T2 program and a simulation study of reference (2) conducted. On this graph of total optimum powerhouse efficiency versus total generator output, the upper curve is the very best efficiency of which this powerhouse was capable. It shows the optimum unit commitment, and optimum economic dispatch for each group of units. In other words, the most efficient units are brought on-line first and kept on-line in each group. At 900 MW and higher, all 14 units are on-line and a unit commitment solution is not applicable, only an economic dispatch solution. The lower curve shows the worst case of unit commitment, but with optimum economic dispatch. In other words, the least efficient units are brought on first and kept on in each group, but optimum economic dispatch is still calculated for whatever units are in each group.



Graph 3

It is immediately evident that optimum unit commitment can significantly increase the efficiency of an entire powerhouse. However, this graph also shows two other efficiency gains that can be achieved from optimum economic dispatch. First, it is noted, particularly with relatively few units on line, that the optimum powerhouse efficiency curve is actually "bumpy" with definite hills and valleys. With knowledge of this, dispatchers could shift small loads to upstream or downstream projects to maintain the generation of each powerhouse at one of the peaks, rather than in a valley. Secondly, the red segment between 980 MW and 1,060 MW represents the operation of the powerhouse under the constraint of the one percent (1%) limits. That is, during the downstream fish migration season on the Columbia and Snake Rivers, the Corps is required to operate their Kaplan turbines within one percent of peak efficiency, to try to minimize the mortality of fish passing through the turbines. This, of course, reduces a unit's capacity. Therefore, the red segment represents the reduced powerhouse capacity as the optimum economic dispatch sequentially loads each unit up to its individual upper one percent limit. However, what is also noted is that, except for one or possibly two unit operation, optimum economic dispatch keeps all units operating within their one percent limits. Further, one or two unit operation is not of significance since that would be less than the minimum recorded river flow.

Conclusions

The five types of optimization can provide significant increases in the generation efficiency of our existing hydroelectric resources. This can be achieved without consideration of changes in head. Besides the Corps of Engineers, other federal agencies, including the Bonneville Power Administration and Tennessee Valley Authority, are actively engaged in the various types of optimization. Type 1 optimization refers to optimizing the performance of an individual generating unit. Within the Corps of Engineers, this is presently being done by changes in equipment configuration, sensor improvements, and index testing. Type 2 optimization refers to optimizing an entire multiunit powerhouse. In cooperation with the Bonneville Power Administration, the Corps of Engineers is developing computer programs to calculate the optimum manner to share a given powerhouse load set point among the various on-line generating units. This is referred to as economic dispatch. These programs also calculate the optimum unit commitment. That is, determining which units to have on-line for a given total powerhouse load.

References:

(1) "Hydro System Efficiency: Potential for Improvements in the Pacific Northwest System," Bonneville Power Administration, April 1986.

(2) "A Preliminary Case Study of the Effects of Having Absolute Flow Data on Run of the River Kaplan Turbines," Hydroelectric Design Center, Portland District, US Army Corps of Engineers, July 2007.

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