December 7, 2022

In reply refer to: FOIA #BPA-2022-01066-F

SENT VIA EMAIL ONLY TO: DudleyDevices@Aol.com

Douglas Albright
Actuation Test Equipment Company
3393 Eddie Road
Winnebago, IL 61088

Dear Mr. Albright,

This communication is the Bonneville Power Administration's (BPA) final response to your request for agency records made under the Freedom of Information Act, 5 U.S.C. § 552 (FOIA). BPA received your request on July 7, 2022, as a transferred FOIA request from the U.S. Department of Energy's (DOE) FOIA office. BPA accepted that transfer and acknowledged your request on July 12, 2022.

Request
"…information on Bonneville Power Administration Technology Innovation Opportunity grant for Project Number 1918-1556."

First Partial Response
Knowledgeable subject matter experts gathered 157 pages of responsive records from the agency's Technology Innovation office, and they are being released with nine pages containing minor redactions, described below.

Explanation of Exemptions
The FOIA generally requires the release of all agency records upon request. However, the FOIA permits or requires withholding certain limited information that falls under one or more of nine statutory exemptions (5 U.S.C. §§ 552(b)(1-9)). Further, section (b) of the FOIA, which contains the FOIA's nine statutory exemptions, also directs agencies to publicly release any reasonably segregable, non-exempt information that is contained in those records.

<u>Exemption 6</u>
Exemption 6 serves to protect Personally Identifiable Information (PII) contained in agency records when no overriding public interest in the information exists. BPA does not find an overriding public interest in a release of the information redacted under Exemption 6—in this case, mobile and personal phone numbers, personal email addresses, home addresses, signatures, and the name of one grant reviewer. This information sheds no light on the executive functions

of the agency, and there is no overriding pubic interest in its release. BPA cannot waive these redactions, as the PII protections afforded by Exemption 6 belong to individuals and not to the agency.

Lastly, as required by 5 U.S.C. § 552(a)(8)(A), information has been withheld only in instances where (1) disclosure is prohibited by statute, or (2) BPA foresees that disclosure would harm an interest protected by the exemption cited for the record. When full disclosure of a record is not possible, the FOIA statute further requires that BPA take reasonable steps to segregate and release nonexempt information. The agency has determined that in certain instances partial disclosure is possible, and has accordingly segregated the records into exempt and non-exempt portions.

Fees
There are no fees associated with the processing of your FOIA request.

Certification
Pursuant to 10 C.F.R. § 1004.7(b)(2), I am the individual responsible for the search and information release described above. Your FOIA request BPA-2022-01066-F is now closed, with all available responsive agency information provided.

Appeal
Note that the records and information release certified above is final. Pursuant to 10 C.F.R. § 1004.8, you may appeal the adequacy of the records search, and the completeness of this final records and information release, or/and the adequacy of the records search and the completeness of the first partial response, within 90 calendar days from the date of this communication. Appeals should be addressed to:

Director, Office of Hearings and Appeals
HG-1, L'Enfant Plaza
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585-1615

The written appeal, including the envelope, must clearly indicate that a FOIA appeal is being made. You may also submit your appeal by e-mail to OHA.filings@hq.doe.gov, including the phrase "Freedom of Information Appeal" in the subject line. (The Office of Hearings and Appeals prefers to receive appeals by email.) The appeal must contain all the elements required by 10 C.F.R. § 1004.8, including a copy of the determination letter. Thereafter, judicial review will be available to you in the Federal District Court either (1) in the district where you reside, (2) where you have your principal place of business, (3) where DOE's records are situated, or (4) in the District of Columbia.

Additionally, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services they offer. The contact information for OGIS is as follows:

> Office of Government Information Services
> National Archives and Records Administration
> 8601 Adelphi Road-OGIS
> College Park, Maryland 20740-6001
> E-mail: ogis@nara.gov
> Phone: 202-741-5770
> Toll-free: 1-877-684-6448
> Fax: 202-741-5769

Questions about this communication or the status of your FOIA request may be directed to the FOIA Public Liaison James King at jjking@bpa.gov or 503-230-7621.

Sincerely,

Candice D. Palen
Freedom of Information/Privacy Act Officer

Multi-Unit Optimization of a Hydropower Powerhouse

New Computational Methods for Unit Selection and Load Sharing

Robert Bass, Ph.D. and Lee Sheldon, PE

5/27/2011

The least expensive way to add power to the grid is to adjust the assets that are already on-line to make them more efficient. In hydro-power further gains are still possible. For peak loads and reduced flows, power systems have to do the most to maintain service during these times. The OIT hydro-power team has made significant advances in hydropower computational methods in the last year. We have assembled a team that is ready to go even further in maximizing hydropower assets.

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Volume II

Volume III

Multi-Unit Optimization of a Hydropower Powerhouse

Oregon Institute of Technology

Volume I: Technical Proposal for Evaluation Purposes by or on behalf of the Bonneville Power Administration

Robert Bass, Ph.D.
Lee Sheldon, PE
Principle Investigators

5/27/2011

1.b Summary of the proposed project

This is a one-year project to further develop an optimization algorithm for hydroelectric powerhouses. The goal of the project is to provide proof of concept on an active hydro project, develop a graphical user interface for the powerhouse operator, and increase the software's feature list. The end result will be a commercial solution for flow-to-power optimization.

Students from The Oregon Institute of Technology's (OIT) Advanced Hydropower class and follow-on independent study classes created an algorithm that optimizes unit selection and load sharing for the entire range of power output in a multi-unit hydroelectric powerhouse. Data from The Dalles Dam has been used to validate the program, and the program has been shown to match the best hand calculation by a professional engineer. It is faster than any similar program to date thanks to an optimization method that offers a more direct solution than the other iterative solutions presently in use. At this time we seek to commercialize the program by comparing the solution from the program against actual hydroelectric power plant operations.

ii. Description of the proposed project

This project provides a software solution to the problem of minimizing flow rate verses power, at a constant head, in a multi-unit hydroelectric powerhouse. The operator inputs the program with a set of performance data (empirically gathered flow vs. power data for each turbine in the powerhouse), chooses a powerhouse power output set point, and with a high degree of accuracy, the software program determines the individual unit set points and the unit selection that will provide the maximum overall efficiency. What makes this program unique from any predecessor is its speed of solution. Whereas previous programs have been able to arrive at solutions in a matter of minutes or hours, this one is capable of providing a solution within a few seconds, or even less.

Taking a non-intrusive approach, we will compare operating points with a real powerhouse. Our program can be used to validate the operator set points against a perfect solution.

iii. Discussion of how the project's technology is aligned with and addresses the gap or technology need as identified in BPA's Technology Roadmap for Hydro Power Operations

The project will address several of BPA's 2012 Power Services - Hydro Asset Management Strategy Technology Roadmap targets.

> Target 1: Operation and expansion of FCRPS power & transmission facilities to meet availability & reliability standards in the most regionally cost-effective manner
>
> > The finished product will be fully functional as both a stand-alone application and a SCADA-integratable solution. Interoperability features will include or contribute to realizing all of the items from Target 1 of the Technology Roadmap:

- Real time, system wide data measurement, collection, analysis, dissemination, and display
- Interactive and instructional displays
- High speed, secure, reliable, interoperable system wide communication
- Open source PLC technology and coding
- Data systems compatible with GDACS, AGC, and SCADA

- AGC control system compatible.

Target 3: Actively enable renewable resource integration and development through cost-effective, innovative solutions

> The algorithm rapidly solves real time models of the hydro projects in the Columbia River system. As mentioned in Target 3, “The real time hydro schedulers need a tool to enable them to rapidly simulate the hydro system as conditions change.” This tool provides a significant piece of the solution. With proper integration of this tool the Columbia Vista program, or any similar program, can see significant improvements in their speed of solution.

Target 4: Design operational and maintenance improvements to reduce costs

> The algorithm indirectly provides a maintenance solution. When turbines are operated within their maximum efficiency range, they experience less wear and tear; and require less maintenance.

Target 5: Increase generation efficiency

> The algorithm increases generation efficiency by rapidly and accurately determining the minimal flow for a given power output set point.

The finished product will:

- Enhance the future FCRPS reliability, operation, and maintenance for an increasingly complex operation.

  The algorithm is able to handle any present or future complexity in terms of numbers or differences in types, sizes, ratings, or performances of turbine generating units.

- Design operational improvements to reduce costs.

  The ability to operate at optimum efficiency will increase service life with a corresponding reduction in costs.

- Maximize existing asset use and extend useful life of assets.

  A result of operating at a condition of maximized powerhouse efficiency is a minimum of hydraulically induced vibration. This translates into reduced fatigue on the components of the generating units, minimal shaft run-out, and a reduction in the inception of cavitation. These will result in an increase in service life.

- Decrease the FCRPS environmental footprint.

  It will do this by increasing generating efficiency which is a major factor in increasing the survivability of downstream migrants passing through turbines.

- Increase generation efficiency (increased power per unit of water).

  The algorithm will inform the operator of the optimum selection of specific units to have on line and the individual load to generate with each in order for the powerhouse to generate at a maximum combined efficiency for any given head.

iv. Description of how the project applies to one or more of BPA's Focus Areas

This project addresses the Hydro & Power Services focus area. The advanced computational method used in the load sharing and unit selection algorithm greatly speeds up the determination of optimal individual unit load set points. This translates to millions of dollars earned and saved over time, in terms of both produced power and avoided maintenance. Because turbines operating at their highest efficiency produce less cavitation and have lower turbulence, they enhance fish survivability to be equal to or better than downstream migration over spill-ways.

v. The impact or unmitigated risk to BPA of not doing this project, the probability of success and technical risks of the project

The impacts of not doing this project are: to continue to forgo the additional benefits of increased generation for the same amount of water and head, to fail to increase the survivability of downstream migrants passing through turbines, and to fail to increase service life of generating units.

Success of the technical aspect of this project is guaranteed and there are no risks; the program has already been demonstrated to compute a solution as intended, and faster than any previous program. Therefore, the remaining portions of this project have a high probability of success.

vi. Discussion of related work already being done in the R&D community that is related to this project and how this project improves, advances, changes what is being or has already been done

Both BPA and the Army Corps of Engineers have worked on projects of this nature. Our understanding is that these require minutes to hours to reach a solution. The software we have developed has adopted an advanced mathematical procedure to arrive at a solution in less than a second, for a ten unit powerhouse, or around three seconds using a freeware version of the scripting platform. This makes it possible to use the program in real-time. That is, the operator can enter a set-point into the appropriate field on the graphical interface, and use the resulting data to manually arrange the turbine set-points in their most optimal configuration. Because of the speed of solution, the option also exists to adapt our program into a SCADA controlled system, where the results could directly control turbines.

vii. Where and how this project's results can be applied

The results can be applied by operators in hydroelectric powerhouses, by control center operators, or by SCADA systems. It can be applied either as an aid for the operator's choice of settings or, in the near or future term, as a SCADA output signal from a control center. This project can benefit every hydroelectric powerhouse that simultaneously runs three or more generating units. It can be used to optimize existing hydro powerhouses, because as a stand-alone application, it guides the operator's choice of unit selection and load sharing.

viii. How this project will benefit BPA. Qualitative benefits to BPA. Quantifiable benefits and estimate the cost of doing the project

According to a BPA study done by Harza Engineers, Inc., about 18 years ago, "Hydropower optimization provides the lowest cost energy available from any generating resource." Further, this additional energy is <u>firm</u> energy.

Example: “In good water years, the Columbia River Basin hydro system can produce about 18,000 average megawatts of electricity, and in poor water years, as little as 11,700 average megawatts” (excerpt from http://www.nwcouncil.org/library/2007/2007-12/power.htm).

Consider that at the very minimum this software generates a system-wide, average improvement of 1%. If the system’s collective powerhouse efficiency was a 88%, it would now be operating in the 89% range. 11700MW_avg*(.89/.87)=11833MW_avg

Put in terms of energy, this is (11833-11700)*24*365 MWh/yr, or 1165 GWh/yr of additional energy, which would garner additional annual revenue on the order of $81,527,727, assuming $70/MWh, not taking other inherent losses (lines, transformers, etc) into account.

Cost of doing the project: $234,480, of which BPA’s share would be $117,240. This includes labor, travel, ad-hoc contracting, equipment and supplies.

ix. Potential environmental impacts and/or the strategy to mitigate them

This project has only positive environmental impacts. These are primarily an increase in the survivability of downstream migrant fish passing through the hydraulic turbines.

x. List of project leaders, partners, and participants. Description of what they bring to the project and their knowledge, skills and experience as related to the project

- Principal Investigator(s) and other key personnel

  Principle Investigators:

  Lee H. Sheldon, P.E. Adjunct Professor of Engineering
  Dr. Robert Bass, PhD., Associate Professor

  Key Personnel: Students of the Advanced Hydropower Independent Study class.

- Time commitment for the Principal Investigator(s) and other key project personnel positions as a percentage of a full time employee (FTE)

  Time commitment for Principle Investigators and other Key Personnel:

  Robert Bass: 8 hours per week (0.20 FTE). Managing work schedules and overseeing reporting. Will be available to spend time finding a suitable project, and interacting with project partners. Also available to lead documentation, operational instructions, and operator training (knowledge transfer).

  Lee Sheldon, PE: 15 hours per week (0.375 FTE). Overseeing every stage of the project, especially index testing if it is required.

  Michael Curtiss: 15-20 hours per week. Time divided between scripting, researching tools and methods for attaining more of the roadmap goals. Planning to take a share of the administrative work. Committed to following reporting mechanism for technical details, accumulated expenses, time, etc.

Jonas Parker: 15 to 20 hours a week. Provide administrative support for the PI's. He will also aid in engineering, planning, research, and communicating results to BPA. He is willing to spend time traveling to find a suitable project to validate the program.

- History of the applicants' involvement in the particular technology area

  Professor Lee Sheldon, one of the two Principle Investigators, has been actively involved in hydropower optimization for at least the last 20 years. His publications on this subject are extensive; please refer to his attached resume. Two items of notable mention are in one of his works; one, he defined the five types of optimization that BPA refers to today; and two, he developed the algorithm for the very first hydropower optimization computer program and gave it to the Corps of Engineers with free license for them to use in the program they have sought to develop.

- Organizations and Personnel responsible for implementing the project

  The principle investigators are faculty mentioned above. Other parties include 3 or 4 advanced hydropower students (whose resumes and transcripts can be made available upon request by BPA) and no one else at this time.

- Identify the credentials of organization/staff to support the application

  See Lee Sheldon and Robert Bass resumes attached.

- Management structure and key managers who will be responsible for the technical work areas

  The project as proposed will follow a Professor/Graduate Student model.

  OIT considers this a special research project similar to other projects in conjunction with government or industrial sponsor. Students will be supervised by faculty, as named above, in order to meet the goals of the project.

- Brief description of the direct technology and other relevant experience of the key personnel for their responsibility areas

  All of the key personnel for this project are senior or post graduate students in the Renewable Energy Engineering curriculum at OIT. They have each taken elective courses in Basic, Advanced, and Independent Studies in Hydropower Engineering. They have also taken coursework in electromechanical energy conversion, electrical power, power systems analysis, protection & control and fluid mechanics.

- Identify contacts and references (name, title, address, telephone, and fax numbers) knowledgeable of the key participants' previous technology experience related to the project

  Students' transcripts are available upon request.

- Known and planned relationships with other utilities, developers, vendors, subsidiaries and others that will participate in the planning, development or operational phases of the project

  BPA and OIT are the only organizations involved.

- Identify the consultants and contractors you expect to use on the project

  The need for any consultants or contractors is not anticipated at this time.

- Provide pertinent examples of experience working with utility companies or federal agencies related to the technology area being studied within the last five years

  Professor Lee Sheldon, one of the two Principle Investigators, has 34 years of Federal service working as a hydropower engineer for the Corps of Engineers, BPA, Tennessee Valley Authority, and US Department of Energy. He is a graduate of USDOE's Project Management School and was certified by BPA as a Project Engineering Manager.

- Adequacy of the proposed facilities to conduct and support development of any necessary field-testing activities

  As described previously, OIT does not presently have access to a suitable multi-unit hydroelectric facility. Part of the Work Scope of this project is to identify and make contractual arrangements with such a facility.

xi. Description of the level of effort requested from BPA in support of the project

No need for assistance from BPA is anticipated, with a possible single exception. If BPA has knowledge of a hydroelectric facility that would be suitable for this project, a reference and introduction would be of assistance. BPA personnel are invited to contribute valuable information to the project as desired.

If possible, we may want to request a liaison from the Columbia Vista programming group. What we have could greatly increase that program's ability to reach a timely solution. If the rest of their algorithm is sound, it could reduce the need to tackle the entire roadmap. If there is no need to duplicate effort, it will allow us to hone our focus and achieve results that are the most beneficial to the BPA and its partners.

xii. Technology Readiness Level (TRL)

The project has reached TRL 4 – Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

Expected to reach TRL 9, "mission proven," on completion.

xiii. Additional information, with appropriate headings, that will help describe the project and plans

A complete project description is described in the next section.

Sequential Quadratic Programming to Solve Hydropower Optimization for All Generating Units in a Powerhouse

Draft

Lee Sheldon, Michael Curtiss, Jonas Parker, Gregory Ripplinger, and Parker Scoggins

Executive Summary

There is no less expensive way to add power to the grid than to adjust the machines that are already on-line to make them more efficient. One may assume that most of today's generating units have already been tuned to produce the most power at the least cost, but in hydro-power that is not the case. A little insight into the way hydraulic turbines behave; coupled with some relatively straight forward programming techniques; can yield stunning improvements in efficiency not yet realized in many systems. Optimization is the lowest cost, highest return, cleanest new energy source available today. In this paper we show how cost function minimization can be used to improve the performance of a whole hydroelectric powerhouse.

The following belongs in a sidebar

Index of Terms

Index Testing: The field testing required to determine the relative efficiency for each turbine over its entire flow range.

Unit selection: The selection of which turbines to have on-line to meet the operator set point.

Load sharing: The separate amount of load to put on each selected turbine.

Type 1 optimization: The optimization of each individual turbine in a powerhouse in terms of power output per amount of flow at constant head.

Type 2 optimization: The coordination of all the turbines in a powerhouse to achieve a power output set point using the least amount of flow. This level of optimization is the subject of this paper, and is achieved with the best possible unit selection and load sharing.

Type 3 optimization: The coordination of all the hydro powerhouses along a river or in a river basin to get the most power from the available flow.

Type 4 optimization: The coordination of a region's hydropower river basins and watersheds.

Type 5 optimization: The integration of all of a region's hydro and thermal generating units.

End of side bar

Introduction

Optimization is the process by which a system is tuned to create the best output for a given input. In hydropower that means producing the most power for a given volumetric flow rate of water or using the least water to produce a given amount of power at any given head. This process is defined as being done at a constant head since various reservoir rule curves do not provide for maximizing head.

Since all elements of a power system are connected and work together, that optimization can have many aspects. As a result, there are now five recognized Types of optimization. For example, in a Kaplan turbine, each unit needs to be optimized so that the most power is produced by the blades being at the proper angle for a given flow. This (Type 1) optimization is done by index testing and recording the best blade angle to wicket gate relationship for all possible heads for every turbine. In other kinds of turbines, such as the Francis variety, which have fixed runners, Type 1 consists of just the index test (Fig 1) to determine the relative efficiency profile.

Type 2 optimization concerns unit selection and load sharing in the whole powerhouse (Fig 4). In this paper we will discuss a newly developed method for achieving Type 2 hydropower optimization with a new, very fast computer program. This new programming algorithm also could be used to speed up higher levels or Types (i.e., 3, 4, or 5) of optimization problems as well.

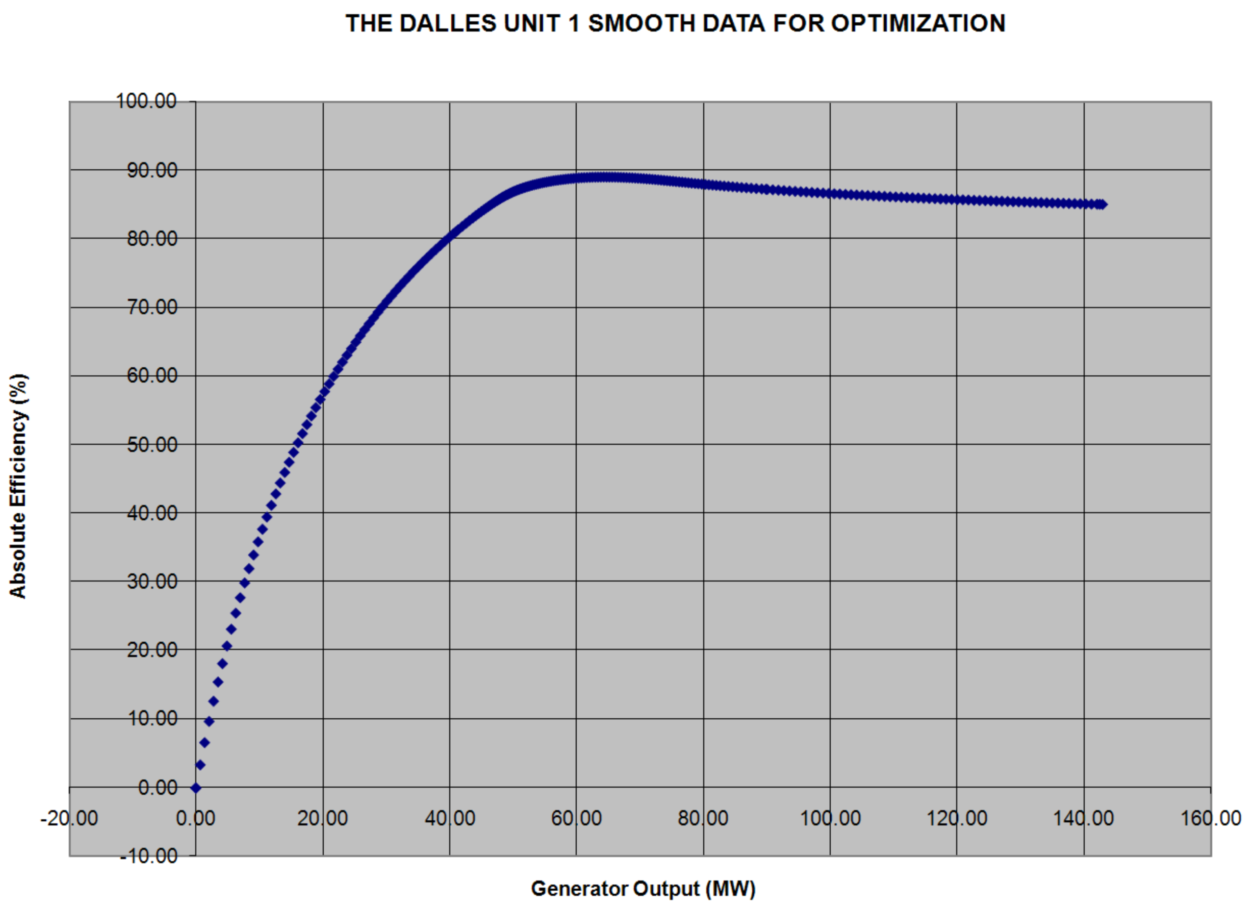

Fig. 1
The efficiency profile of a single Kaplan turbine in a powerhouse, plotted across its range of power output

Understanding Type 2 Optimization

To appreciate the value of Type 2 hydropower optimization, it first needs to be understood that every turbine in the powerhouse is slightly different. Although all the turbines in the powerhouse may be specified to be of the same design, differences in manufacturing tolerances result in differences in unit operating efficiencies, somewhere between one and five %. Further, years of operation tend to exacerbate the differences in performance between turbines. Every turbine has an efficiency profile that varies across its range of flow (Fig 2). In powerhouse documentation, the performance profiles of each individual turbine often will be available in a stored database. When the grid operator determines a mega-watt set-point for the project, the powerhouse operator can choose to have some turbines on-line and some turbines off-line, a process called **unit selection**. The next parameter to determine is **load**

sharing. The best load sharing is achieved when the wicket gate opening for each turbine is set such that the power output is met with the smallest total flow rate.

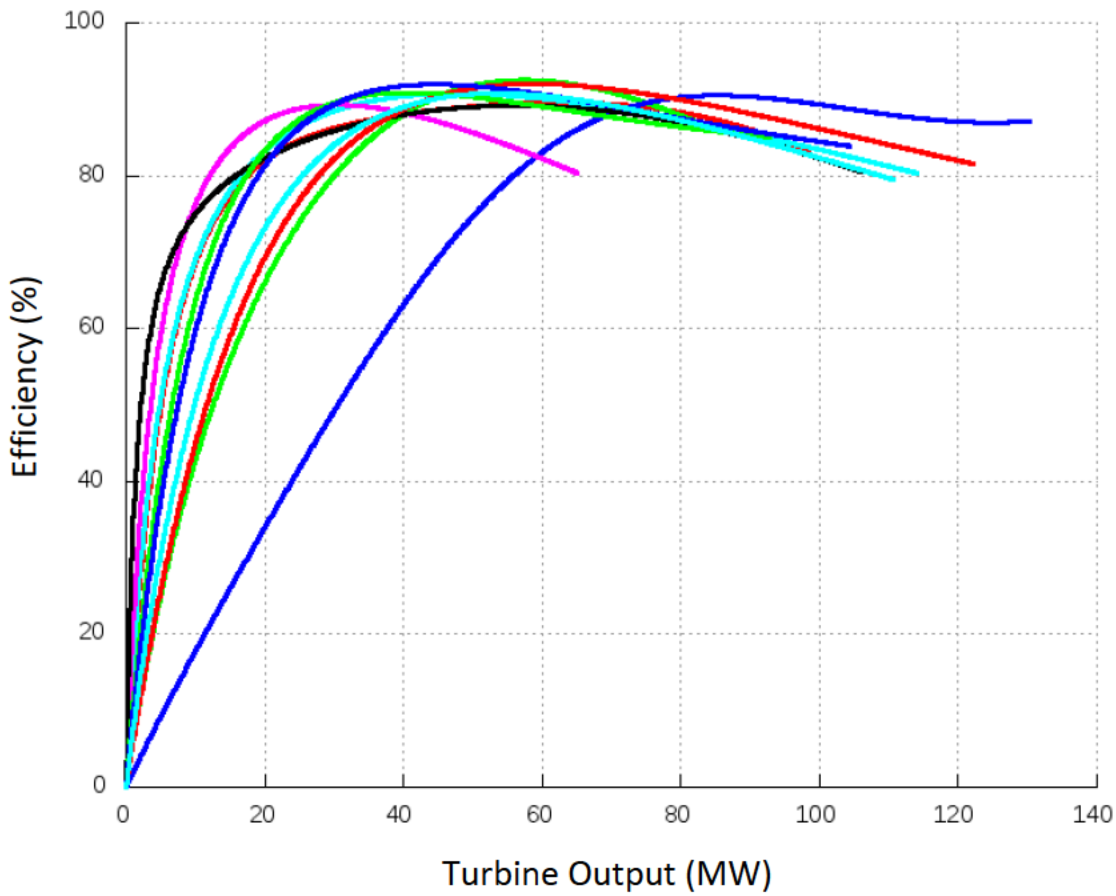

Fig. 2
Illustration of differences in efficiency profiles between individual Kaplan turbines in a powerhouse

Both decisions are much more difficult to determine than it may seem. Even a skilled operator may under utilize up to 5% of the water available for generation due to less than perfect unit selection and load sharing. During conditions where water is spilled, that 5% may not make a lot of difference. However, when the flow of the river is low enough to be insufficient to meet net energy demand, that 5% represents a corresponding loss of potential revenue. At worst a project may even lose the generation equivalent to 10% of the flow. Under many conditions that will mean a corresponding 10% loss in revenue. Even when there is plenty of water in the river, a project run at optimal power rather than at full gate can generate the same amount of power with less wear on machinery.

On the positive side, when both aspects of Type 2 optimization are done precisely, there is potential to reverse these losses for the life of the project. Another one or two % more power can usually be gained, even on a well-run powerhouse. The intent of this new computer program is to make attaining excellent Type 2 optimization within the reach of all hydropower projects and operators.

Using a Computer Algorithm for Decision Support

Computer algorithms have been developed to support the operator's decision. However, Type 2 optimization is difficult for computers to perform well. Many attempts have been made to develop software for this purpose. However, the programs often use algorithms that take too long to compute an optimal unit selection and load sharing. Programs used by large, multiunit projects for this purpose have been known to take an hour to converge on a solution. In the emerging ten minute power market, even a much smaller wait time may be unacceptable.

It must be emphasized that the program that is the subject of this paper is not meant to tie directly into the controls or SCADA systems; rather it is meant as an informational tool for the operator. However, features such as direct data acquisition could easily be added; and if there were ever a real need to add this program into the controls of a project, that would indeed be possible too.

Brute Force

The slowest way to perform the Type 2 calculation is termed the "brute force" method. A brute force computer program examines every possible unit selection and every possible load allocation among the selected units. If there are ten units in a power house, then unit selection by itself will take ten factorial (i.e. 10!, or 3,628,800) iterations to achieve. Within those ten factorial iterations, there will be as many as 100 increments of gate opening for each turbine for the program to consider. There will be a very large number of total set-point combinations that will achieve the desired power output. The program will continue until it exhausts all possible solutions. Among all possible solutions for the demanded power output, the one that requires the least flow is selected. Many programs unnecessarily use aspects of this method, which is why it takes more than an hour for some of them to finish the computation.

Method of Paired Comparisons/Hill Climbing

Faster methods are indeed possible. The method of paired comparisons begins its calculations at full power, for which there is one possible solution. It then finds the best solution for every increment of decreased power down toward zero. For every increment of decreased power, it will examine possible solutions next to the last operating point until the load-sharing that consumes the least amount of water is found. The method of paired comparisons, also called the hill climbing method, is much faster than brute force because, when possible, it chooses successive iterations in the direction of a better solution than the previous one.

Particle Swarm Combined With Hill Climbing Optimization

Different techniques can be applied to the unit commitment step and the load sharing step to speed up the hill climbing optimization. One of them is called particle swarm optimization. This modification randomly picks the number of turbines to use from the number available, then randomly picks the unit selection combination and checks to see if the maximum power is greater than or equal to the desired power. It then performs the optimal load sharing using the hill climbing method. The entire process repeats several times, after which the best unit selection and load sharing results are chosen.

Sequential Quadratic Programming (SQP) Optimization

A much faster method than particle swarm optimization combined with hill climbing, and the fastest method to date available for this purpose, is called Sequential Quadratic Programming (SQP). SQP uses Newton's Method and Taylor series expansion to directly solve a set of unconstrained, convex curves by applying a global constraint and an educated first guess. A hydro unit's flow versus power curve is sufficiently smooth such that it can be approximated with a high order quadratic polynomial. This simplified mathematical characteristic makes the hydro turbine an ideal candidate for this kind of cost function minimization. The SQP solution described by this paper was written in Octave, an open source numerical programming language. The program takes only TWO SECONDS to find optimal unit selection and load sharing for any given set-point in a powerhouse with ten turbines. This increase in computational speed may represent a breakthrough that will soon allow continual Type 2 hydropower optimization to occur in real time.

The following belongs in a side-bar

Technical Explanation of Sequential Quadratic Programming

Index of Terms for Sequential Quadratic Programming

Taylor series expansion: A linear mathematical series based on the slope of a curve around an operating point that is used to approximate the output of the function around that point.

Newton's method: A mathematical method using the derivative of a complex function and the point where the slope passes through the origin to find successively better approximations of the root of the function.

Quadratic programming: An optimization method used on a quadratic function of several variables subject to linear constraints on those variables.

Sequential quadratic programming: An optimization method using a series of algorithms to solve a quadratic function subject to non-linear constraints.

Constraints: Mathematical conditions that a solution must satisfy

Gradient: The slope (first derivative) of a function or matrix

Lagrangian Function: A function used in maximum and minimum optimization problems to represent a vector normal to a gradient function

Lagrangian Multiplier: The multiplier applied between the gradient function and the constraint function to set the magnitudes equal

Hessian: The second order partial derivative matrix of a gradient function

To reiterate, Type 2 optimization is essentially the problem of minimizing water flow through the turbine units of a powerhouse for a given power set point. In terms of flow and power, individual units are characterized by sets of nonlinear curves, depending on the head across the unit. If head is assumed constant, the constraints for this minimization problem reduce to (1.) the total power demanded and (2.) the upper and lower power limits of each unit. Since this is basically a constrained, nonlinear optimization problem with multiple variables, the use of quadratic programming (QP) is appropriate. By using QP, the constraints can be brought into the objective function, which describes the power-flow curves. This results in a Lagrangian function, $L(p, \lambda_n)$, where p is a vector of the individual units' power set points, $g_n(p)$ are the n constraints as a function of the power set point, and λ_n is a scalar multiplier known as the Langrange Multiplier of the nth constraint.

$$L(p, \lambda_n) = q(p) - \lambda_n(g(p))$$

The objective function, $q(p)$, is the flow to be minimized. The partial derivative of the Lagrangian then gives the conditions under which the optimum can be found. These conditions are typically known as the Karush-Kuhn-Tucker (KKT) conditions, named after the major contributors to their derivation. Stated in terms of $L(p, \lambda_n)$, the KKT conditions for Type 2 optimization would be:

$$\nabla L(p) - \lambda_n \nabla g_n(p) = 0$$
$$\lambda_n g_n(p) = 0$$
$$g_n(p) \leq 0$$

Furthermore, subject to the KKT conditions, a local minimum is found by applying a Quasi-Newton method.

The Quasi-Newton method begins with a second order Taylor series expansion, which gives a local, quadratic approximation of $L(p, \lambda_n)$:

$$L(p_{i+1}) \approx L(p_i) + \nabla L(p_i)(p_{i+1} - p_i)^T + \frac{1}{2}(p_{i+1} - p_i)^T H (p_{i+1} - p_i)$$

H is the Hessian, $L''(p_{i-1})$, where p_{i-1} is the is the power set point at iteration, $i - 1$. Taking the derivative of this local approximation with respect to p_i, setting to zero, and solving for p_i gives:

$$\nabla L(p_i) \approx \nabla L(p_{i-1}) + H(p_i - p_{i-1}) = 0$$

$$p_i = p_{i-1} - H^{-1} \nabla L(p_{i-1})$$

If, $p_{i-1} = p_i$, then the extreme has been found; however, if $p_{i-1} \neq p_i$, then the iteration must be continued until a minimum solution is found. Furthermore, the above term, $H^{-1} \nabla L(p_{i-1})$, is a vector that describes a segment of a path from the current operating point p_i to the minimum, which ensures that the step lengths between operating points are chosen in the direction of a minimum at each iteration. However, to calculate the full Hessian for each iteration is unnecessary and computationally costly.

In the Quasi-Newton method, an approximate Hessian is used and updated upon iteration. There are several update methods available, but the update method of Broyden-Fletcher-Goldfarb-Shanno (BFGS) has proven reliable and is used in the program described in this paper:

$$H_i + \frac{L(p_i) - H_i(p_{i+1} - p_i)}{(p_{i+1} - p_i)^T (p_{i+1} - p_i)} (p_{i+1} - p_i)^T$$

This kind of successive updating and solving of quadratic programming problems is collectively known as Sequential Quadratic Programming (SQP).

In sum, SQP solves constrained, nonlinear, optimization problems by iteratively solving for a zero gradient of the objective function to be optimized. Also at each iteration, a check is performed to ensure that the constraint conditions have not been violated, and an updated approximate Hessian is calculated, which is used to determine the step length and direction of the stepped changes in the operating point upon iteration.

Further Reading on Sequential Quadratic Programming

1. A SEQUENTIAL QUADRATIC PROGRAMMING ALGORITHM FOR DISCRETE OPTIMAL CONTROL PROBLEMS WITH CONTROL INEQUALITY CONSTRAINTS
   J.F.O. De 0.Pantoja D.Q. Mayne
   Department of Mathematics, Department of Electrical Engineering,
   Federal University of MaranhHo, Imperial College,
   SHo Luis, MaranhHo, Brazil. London. SW7 2BT

2. SOLVING THE HYDRO UNIT COMMITMENT PROBLEM VIA DUAL DECOMPOSITION AND SEQUENTIAL QUADRATIC PROGRAMMING
   Erlon Cristian Finardi and Edson Luiz da Silva*, Senior Member, IEEE*
   IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 21, NO. 2, MAY 2006

3. IMPROVED SEQUENTIAL QUADRATIC PROGRAMMING APPROACH FOR OPTIMAL DISTRIBUTION GENERATION SIZING IN DISTRIBUTION NETWORKS
   *M. F. AlHajri*1, *M. R. AlRashidi*1, *M. E. El-Hawary*2
   1Electrical Engineering Technology Department, College of Technological Studies, Paaet, Kuwait
   2Electrical Engineering Department, Dalhousie University, NS, Canada

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Case Study

The application of this proposed program to perform Type 2 optimization has been validated against a Type 2 optimization study performed by Lee H. Sheldon, P.E. With a MS in Fluid Mechanics and Hydraulics and over 40 years experience, he has authored some 26 technical papers, including several on hydropower optimization. He is presently a university professor teaching basic and advanced hydropower engineering, as well as fluid mechanics, at the Oregon Institute of Technology (OIT). His Type 2 Optimization study was based on data measured by flow meters from 14 hydraulic turbines located at the powerhouse in The Dalles, Oregon, on the Columbia River.

The original data from the 14 turbines was provided to the authors by Sheldon. This data was then organized into 14 separate xlsx (or CSV) files, each containing only 2 columns of data, measured power and measured flow. SCRPS imports and processes the data files automatically. Figure 3 shows the results calculated by Sheldon and those obtained by SCRPS for the same data set.

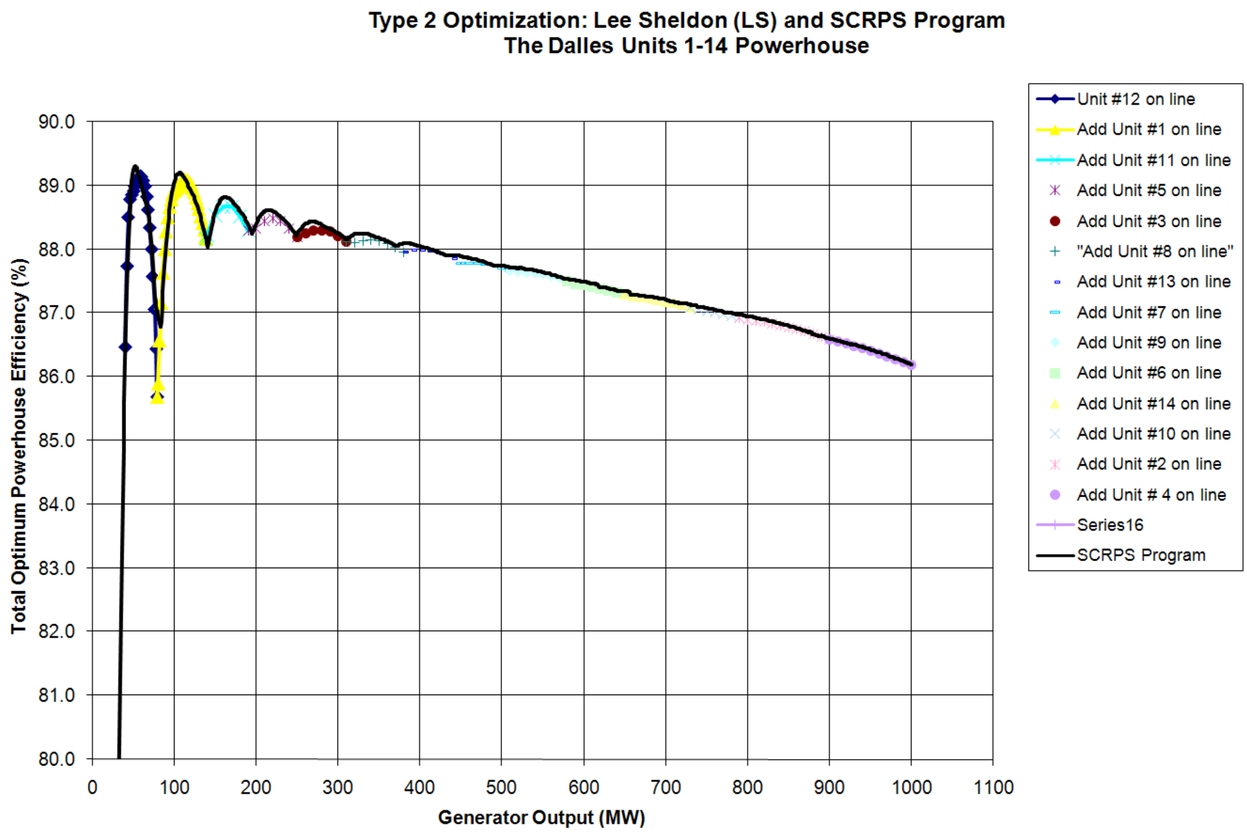

Fig. 3

The colored line is Lee Sheldon's Type 2 unit selection and load sharing calculation done by hand. The black line is the result of an optimization using the same data, performed by the SQP program written in Octave numerical programming language.

In Figure 3, the cumulative efficiency is shown on the graph, and it changes across the range of power outputs as optimum load sharing and unit selection are performed for every possible set-point between minimum power and full power. At full power the efficiency drops off because all turbines are turned on past their point of peak efficiency. At the left part of the curve, as the least efficient turbines have been turned off, there are spikes in efficiency that represent a few of the single most efficient turbines running at their peak efficiencies. At the far left there is a quick drop off in efficiency as the last, most efficient turbine is dropped below its peak efficiency.

Comparing the results, the SCRPS total optimum powerhouse efficiency precisely matched that of Sheldon's study. The study done by Sheldon required two weeks of hand calculation; whereas the SCRPS results were accomplished in a matter of minutes, including the time taken to organize and file the turbine data. Both the speed of the solution and its similarity to an exact hand calculation provide confidence that the method employed by the SCRPS Program is both practical and accurate.

Comparing the optimum to “typical” load sharing and unit selection

As a demonstration of the benefit of applying a Type 2 optimization program like SCRPS, the data from The Dalles Dam was run through another program that equivocates in unit selection and load sharing, simulating a powerhouse that has no optimization program at its disposal. Rather than finding the best solution for every set-point, this sub-optimal program selects turbines according to a random list. As more power is needed, the next turbine on a list is turned on instead of the best turbine among all those remaining. In addition, among those turbines that are on-line at one time, the load is shared evenly instead of optimally (Fig.4).

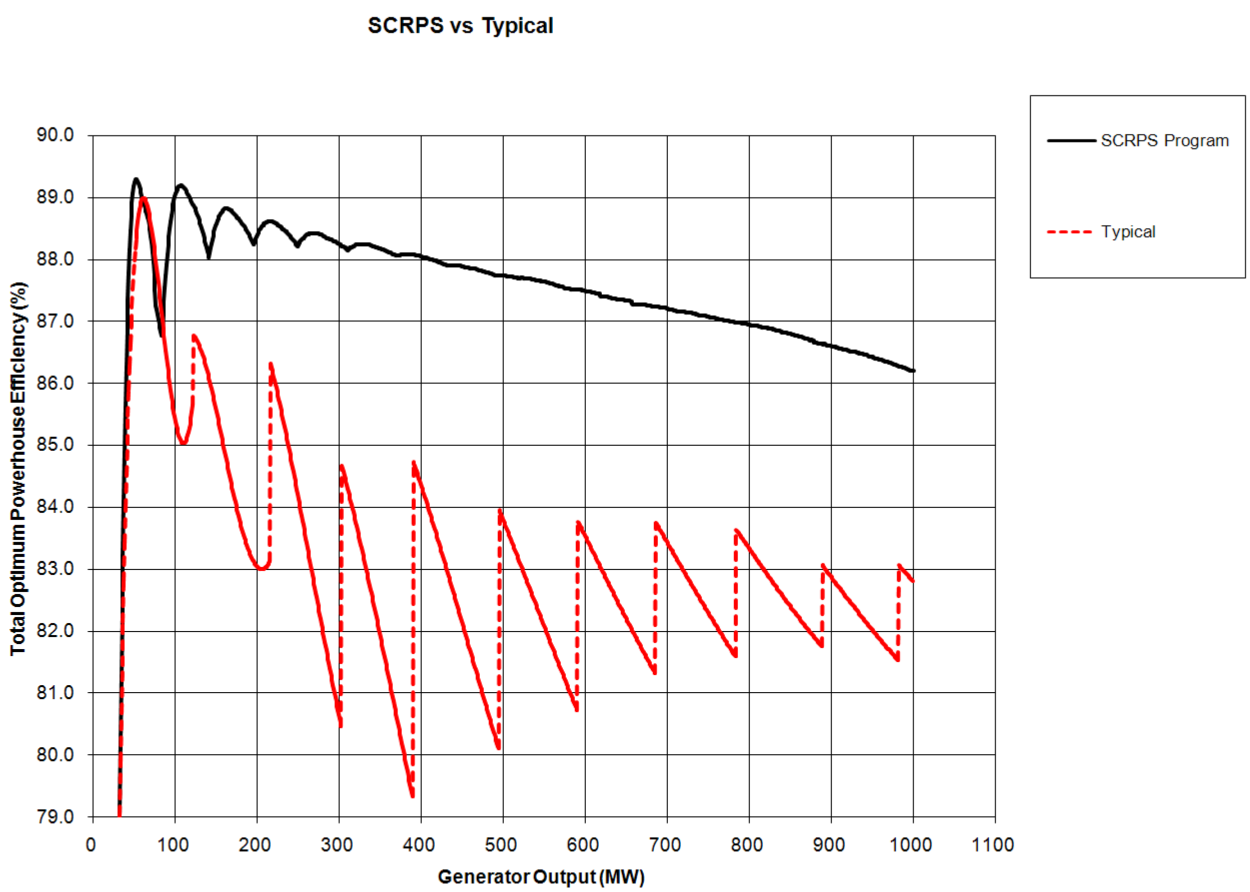

Fig. 4

“Typical” powerhouse efficiency simulation plotted against SCRPS optimal solution

The difference between the SCRPS powerhouse efficiency optimization and the “typical” unit selection and load sharing simulation is considerable. At most the “typical” simulation lost 7.9% of the efficiency that was available to the powerhouse. The average difference is around 5%, no small matter whenever sufficient water flow is valuable. There are sharp peaks at the point where individual turbines are dropped off and the units remaining on-line must share that dropped amount of load equally. The simulation is similar to the way the many powerhouses at hydro projects are actually run.

Conclusion

In the past, powerhouses have been run below maximum efficiency because Type 2 hydropower optimization programs have been either too expensive, too slow, or both. If no Type 1 optimization has been done, the loss in efficiency would be even greater. The lack of knowledge about individual turbine efficiency has left operators blind in the area of unit selection and load sharing. Even with some knowledge about the efficiencies of individual units, optimal load sharing was still doubtful.

This new program solves all the above problems, provided that a good Type 1 optimization has previously been performed. Type 1 optimization can be achieved economically and maintained with the help of automatic index testing systems such as the Index Testing Box designed by Actuation Test Equipment Company, Inc. That achieved, every project can now have some sort of Type 2 made available to the operator. Having done so, the project owners can expect a noticeable increase in the net energy produced and increased equipment service life as well.

Again, the program that is the subject of this paper is not meant to tie directly into the controls of the project; rather it is meant as a tool for the operator. The program will aid the operator in making the most economical decision for every set point, and will make an easy job of operating the project more efficiently.

Further Reading on Hydropower Optimization

"Field testing and optimizing efficiency of hydro turbines"
L.H. Sheldon
Water Power & Dam Construction, January 1982

"Optimizing Efficiencies of Multi-Unit Hydro Plants,"
Lee Sheldon
ASCE Transactions of Waterpower '95, July 1995.

"Reviewing the Approaches to Hydro Optimization"
Lee Sheldon
Hydro Review, June 1998.

"Optimizing the Generating Efficiency of Entire Powerhouses"
Lee Sheldon
HCI Transactions of HydroVision 2008, July 2008.

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Renewable Energy Engineering BS Program
Department of Electrical Engineering and Renewable Energy
Oregon Institute of Technology
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Academic Degrees

Ph.D., Electrical Engineering, University of Virginia (2004)
M.S., Electrical Engineering, University of Virginia (2000)
B.S., Electrical Engineering, University of Virginia (1997)

Academic Experience

2010 pres. Associate Professor (tenured) and Program Director, Renewable Energy Engineering, Oregon Institute of Technology, Portland
2005 10 Assistant Professor and Program Director, Renewable Energy Engineering, Oregon Institute of Technology, Portland

Principle Achievement

Designed and implemented OIT's Renewable Energy Engineering bachelors degree program (BSREE), the first engineering program of its kind in North America. The BSREE program is now the largest program within OIT's ETM School, with over 210 students, seven faculty members and $3M+ in external funding. The program is on track to achieve ABET EAC accreditation by Summer 2011.

Professional Experience

Industrial experience:
2000 01 Electronics Equipment Engineer, Automobile Safety Laboratory, Impact Biomechanics Program Department of Mechanical Engineering, University of Virginia, Charlottesville, Virginia
2000 Software Development Engineer, MonsterBook.com, San Francisco, California

Consulting Experience:
2004 05 RF Engineer, National Radio Astronomy Observatory & The University of Virginia

Current Projects

Workforce Training for the Electric Power Sector (DE FOA 0000152) (PI)
Sponsored by US DOE, STEPS Grant, $2,865,000
Four objectives: 1) hire faculty; 2) strengthen curriculum; 3) equip laboratories; 4) extend industry engagement.
Central Project: Design, development and implementation of a 20kVA, three phase 208VAC power system. Implementation of stochastic loads and generation, coupled to demand responsive loads and generation via a networked communication system and dynamic market mechanism. Team of 16 engineering students

Development of a NH_3 CaCl Adsorption Chiller for Solar Thermal Applications (PI)
Sponsored by Oregon Renewable Energy Center, $15,000
Team of 5 engineering students

LED Street Lighting Feasibility and Lifecycle Analysis (PI)
Sponsored by Portland General Electric, $4,000
Feasibility study of outdoor LED lighting for streets, parking lots and parking garages
Student: Darin Kite, BSREE Winter 2011

Past Projects

David Douglas High School Power Systems Monitoring Project (PI)
Sponsored by Portland General Electric, $9,000
Power production and weather monitoring system design for a wind/PV microgeneration site

City of St Helens, Sand Island Renewable Energy Project (PI)
Partnership with City of St. Helens, OR
Off grid photovoltaic power system for non potable water pumping and marine lighting.

Solar Water Heating in Oregon: Field Testing for Performance Verification (PI)
Performance testing of installed residential solar thermal systems, analysis and comparison to SRCC data.

Oregon City Hydroelectric Feasibility Study (PI)
Sponsored by Portland General Electric and Clackamas Soil and Water Conservation District, $20,000
Feasibility study of the Potential for Rainwater harvesting for micro hydroelectric power generation.

The Gilbert Creek Project: Innovative and Commercially Viable Micro Hydro (PI)
Power system integration and control system design for a grid tied microhydro driven induction generator.

Business of Biofuels & Ocean Renewable Power Course Development (Co PI), $10,500
Oregon Science and Technology Partnership Funding

Scholarly Activities

2010	Invited Speaker, American Physical Society, APS March Meeting
2009	Invited Speaker, University of Oregon Summer Sustainability Series
2008	Invited Speaker, OIT Foundation Reception
2008	Invited Speaker, Oregon State Fair Continuing Education in Renewable Energy
2008	Invited Speaker, University of Oregon Summer Sustainability Series
2008	Invited Speaker, HOPES Conference
2008	Invited Panelist, InnoTech Conference
2007	Invited Speaker, BASE Summit (Business Alliance for Sustainable Energy)

Professional Service

2011 pres	Board Member, Smart Grid Oregon
2009 pres	BEST Leadership Team Member
2009 2010	Oregon University System Energy Task Force Member
2009 2010	Oregon University System Committee Member, Sustainability Initiatives Committee
2009	Oregon University System Committee Member, Technical Advisor, Oregon Sustainability Center
2008 pres	Advisory Board Member, Clackamas Community College, MET Program
2008 2009	Reviewer, 2009 ASEE Annual Conference and Exposition
2008 2009	Judge, Intel Northwest Science Expo
2008	Reviewer, IEEE Transactions on Applied Superconductivity
2007 pres	Advisory Board Member, Lane Community College, Energy Programs
2007	Gladstone High School ATC Advisory Board
2006 pres	Advisory Board Member, Portland Community College, Electronics Engineering Technology

Professional Society Memberships

Member	IEEE, Power Engineering Society, Education Society
Member	ASEE, Energy Conversion & Conservation Division

Institutional Service

2009 2010	Chair, REE Portland Faculty Search Committee
2009	Member, REE Klamath Falls Faculty Search Committee
2008	Chair, EET Portland Faculty Search Committee
2008	Chair, REE Portland Faculty Search Committee
2008	Member, Presidential Search Committee (Appointed by OUS Chancellor Pernsteiner)
2007	Member, Portland Librarian Search Committee
2007	Co Chair, RES/MMET Faculty Search Committee

Awards

Faculty Achievement Award, Oregon Institute of Technology, 2008 (annual award for excellence in teaching, service to the university)
Wilson Award recipient for Outstanding Graduate Teaching, 2004

Publications

R.B. Bass, T. White, "Curriculum Changes Resulting In A New Bachelors Of Science In Renewable Energy Engineering," 2009 ASEE Annual Conference and Exposition, Austin, TX

M. Aboy, R.B. Bass, Y. Guran "New Engineering Careers and the Need for Renewable Energy Engineers," International Congress on Engineering and Computer Education 2009, Buenos Aires, Argentina, March 8 13, 2009

J. Schultz, D.L. Herald III, H. Xu, L. Liu, R.B. Bass, R.M. Weikle, II, A.W. Lichtenberger, "The Design, Fabrication and Test Results of a 1.6 THz Superconducting Hot Electron Bolometer Mixer on SOI," IEEE Transactions on Applied Superconductivity, 2009

R.B. Bass, "A Bachelors Degree Program in Renewable Energy Engineering," 36th ASEE/IEEE Frontiers in Education Conference, San Diego, CA, October 2006

R.B. Bass, J. Yarbrough, "A New, Open Source Bachelors of Science Degree Curriculum in Renewable Energy," International Conference on Renewable Energy for Developing Countries, Washington, DC, April 2006

J.C. Schultz, A.W. Lichtenberger, R.M. Weikle, C. Lyons, R.B. Bass, E. Bryerton, S. K. Pan, C. Groppi, J.W. Kooi, C.K. Walker, "Application of Ultra Thin Silicon Technology to Submillimeter Detection and Mixing," Invited Ninth World Multi Conference on Systemics, Cybernetics and Informatics, Orlando, FL, July 2005
R.B. Bass "Hot Electron Bolometers on Ultra thin Silicon Chips for a 585GHz Receiver," Presented to the Faculty of the University of Virginia as a PhD Dissertation, May 2004

R.B. Bass, A.W. Lichtenberger, R.M. Weikle, S. K. Pan, E. Bryerton, C.K. Walker, "Ultra Thin Silicon Chips for Submillimeter Wave Applications," Fifteenth International Symposium on Space THz Technology, Northampton, MA, April 2004

R.B. Bass, A.W. Lichtenberger, "Microcontact Printing with Octadecanethiol," Applied Surface Science, 226 (4), pp. 335 340, April 2004

R.B. Bass, A.W. Lichtenberger, R. Weikle, J.W. Kooi, C.K. Walker, S. K. Pan, "Ultra Thin SOI Beam Lead Chips for Superconducting Terahertz Circuits," Proceedings of the 6th European Conference on Applied Superconductivity, Sorento, Italy, September 14, 2003

R.B. Bass, A.W. Lichtenberger, G. Narayanan, "Fabrication of Diffusion Cooled Hot Electron Bolometers using Electron Beam Lithography," Proceedings of the 6th European Conference on Applied Superconductivity, Sorento, Italy, September 14, 2003

R.B. Bass, L.T. Lichtenberger, A.W. Lichtenberger, "Effects of Substrate Preparation on the Stress of Nb Thin Films", IEEE Transactions on Applied Superconductivity, 13 (2), pp. 3928 3300, 2003

R.B. Bass, J.C. Schultz, A.W. Lichtenberger, C. Walker, J. Kooi, "Beam Lead Fabrication Using Vacuum Planarization," Fourteenth International Symposium on Space THz Technology, Tucson, AZ, April 2003

J.W. Kooi , C.D. d'Aubigny , R.B. Bass, C. Walker, A.W. Lichtenberger, "Large RF Bandwidth Waveguide to Thin Film Microstrip Transitions on Suspended Membrane for use in Silicon Micromachined Mixer blocks at THz Frequencies," Fourteenth International Symposium on Space THz Technology, Tucson, AZ, April 2003

R.B. Bass, "Diffusion Cooled Hot Electron Bolometers on Beam Lead Chips for a 585GHz Receiver," Presented to the Faculty of the University of Virginia as a PhD Research Proposal, March 2003

R.B. Bass, "Hot Electron Bolometer Fabrication," Presented to the Faculty of the University of Virginia for a PhD Qualifying Exam , February 2003

R.B. Bass, J.Z. Zhang, W.L.. Bishop, A.W. Lichtenberger, S. K. Pan, "Beam Lead Quartz Chips for Superconducting Millimeter Wave Circuits," Astronomical Telescopes and Instrumentation 2002: Topics in Astronomy: Information Technologies, MMW and Sub MMW Detectors, Solar Astrophysics, Non EM Astronomy, Exo Planet Detection, and Astrobiology, Waikoloa Village, HI, August 2002

R.B. Bass, W.W. Clark, J.Z. Zhang, A.W. Lichtenberger, "Use of a Focused Ion Beam for Characterization of SIS Circuits," IEEE Transactions on Applied Superconductivity, vol. 11, no. 1, March 2001

R.B. Bass, J.Z. Zhang, A.W. Lichtenberger, "Machine Aligned Fabrication of Submicron SIS Tunnel Junctions Using a Focused Ion Beam," IEEE Transactions on Applied Superconductivity, pp 3240 3243, vol. 9, no. 2, June 1999

R.B. Bass, A.W. Lichtenberger, "Techniques for Submicron SIS Tunnel Junction Fabrication," Proceedings of the International Semiconductor Research Symposium, Charlottesville, VA, December 1999

R.B. Bass, J.Z. Zhang, A.W. Lichtenberger, "Fabrication of Submicron Nb/Al AlOx/Nb Junctions Using a Focused Ion Beam," SPIE International Symposium on Optical Science, Engineering, and Instrumentation, San Diego, CA, July 1998

R.B. Bass, A.W. Lichtenberger, "Machine Aligned Fabrication of Submicron Nb/Al AlOx/Nb Junctions Using a Focused Ion Beam," Proceedings of the International Semiconductor Device Research Symposium, Charlottesville, VA, December 1997

Donations

- Instrumentation Society of America, Portland Chapter, Fall 2009, Winter 2008 $1000
- Energy Trust of Oregon, PVPowered & Xantrex Inverters, Fall 2009 $3500
- Renewable Products Development Labs, Milwaukie, OR, Winter 2009, Winter 2008: Biofuels related equipment $48,000
- Suzlon Wind Energy, Winter 2009, 6.5' foot long section of a turbine blade
- Imagine Energy, Portland, OR, Fall 2007: Copper Cricket Solar Thermal Collector System $3500
- Christine and Jason Pompel, Oregon City, OR, Fall 2007: Four Solar Thermal Collector Systems $6000
- VetEnergy, Carson City, NV, Fall 2005: PV Array, inverter, charge controller, battery bank $8000

Internal Competitive Funding
Engineering Fee Fund Grant (Internal OIT Funding) (Winter 2009)
Title: Equipment to Support Engineering & Technology Programs in Electronics, Renewable Energy, Manufacturing, and Mechanical Engineering Technology
Amount: $38,000
R. Bass, M. Aboy, C. Crespo (Co PI's)

Engineering Fee Fund Grant (Internal OIT Funding) (Winter 2007)
Title: Laboratory Equipment and Lecture Space for the RES, MET and MAN Programs, Portland East Campus

Amount: $32,109
R. Bass (PI)

Resource Fee Commission Grants

General Renewable Energy Engineering Laboratory Support, (Fall 2009), $8,500, R. Bass (PI)
Senior Project Energy Surveying and Auditing Equipment, (Fall 2008), $6,758, R. Bass (PI)
A Photovoltaic and Solar Thermal Testing Lab, (Fall 2008), $5,800, R. Bass (PI)
Equipment in Support of a Controls & Instrumentation Lab (Fall 2008), $5216, R. Bass, F. Rytkonen (Co PIs)
Equipment in Support of a Instrumentation Course (Winter 2008), $5,000, R. Bass, F. Rytkonen (Co PIs)
Equipment in Support of a Biofuels Laboratory (Winter 2008), $6,800, R. Bass (PI)
Expansion of the Electrical Power Laboratory (Winter 2008), $6,800, R. Bass (PI)
Electronics, Renewable Energy and Physics, West Campus (Winter 2008), $3989, M. Aboy (PI), R. Bass
Physics Equipment, East Campus (Winter 2008), $3,989, M. Aboy (PI), R. Bass
Fuel Cell Chemistry (Winter 2007), $3,414, R. Bass (PI)
Electric Power Controls (Winter 2007), $3,721, R. Bass (PI)
Physics Equipment, East Campus (Fall 2006), $7,000, M. Aboy (PI), R. Bass
LabView Equipment for Online Course (Spring 2006), $4,134, R. Bass (PI), M. Aboy
Hydrogen Storage and Fuel Cell Equipment (Spring 2006), $3100, R. Bass (PI)
Electronics Equipment (Spring 2006), $11,644, R. Bass (PI)
Electrolyzer for Fuel Cell Lab (Winter 2006), $4,500, R. Bass (PI)
Power Equipment (Winter 2006), $10,042, R. Bass (PI)
LabView Equipment (Fall 2005), $3,740, R. Bass (PI), M. Aboy
Open source Curriculum Development (Fall 2005), $6,930, R. Bass (PI)

Lee Howard Sheldon
[redacted]
[redacted]
[redacted]

SUMMARY

Licensed as a Professional Engineer, holding a Master of Science Degree and with extensive experience in the mechanical, environmental, and civil aspects of hydroelectric power and also experienced in shipyard engineering. Primary expertise is due to more than 30 years experience in the design, procurement, installation and testing of hydraulic turbines, including having been head of the turbine design section of the US Army Corps of Engineers (COE). Additional experience is from managing the construction of twenty hydroelectric projects for the US Department of Energy (DOE). Authored publications include almost two-dozen technical papers and a college textbook on hydropower engineering, as well as being a member of a technical publisher's advisory board. Presentations include organizing a number of seminars and conferences and teaching at the university level. The shipyard experience is by virtue of having achieved the designator as a Naval Reserve Engineering Duty Officer (EDO) and working in the construction, alteration, conversion and repair of naval ships.

SIGNIFICANT EXPERIENCES

- Developed a technique to determine the optimum manner to share load among generating units in a powerhouse so that the total or combined efficiency is maximized.
- Managed the research and development program for the Bonneville Power Administration (BPA), which successfully introduced several new technologies, including variable speed – constant frequency generation.
- Managed the construction of twenty hydroelectric projects around the country to demonstrate the economic viability of small-scale hydropower.
- Developed new equipment and a number of new diagnostic techniques to evaluate hydraulic turbine performance.
- Designed and developed state of the art fish screening systems and other environmental enhancements for hydropower.
- Developed and published the academic instruction materials for university courses, as well as conferences and seminars on hydropower.

- Received the first Naval Reserve designator as an Engineering Duty Officer in the state of Oregon.

CAREER EXPERIENCE

May 2, 2008-Presant

Consulting engineer in private practice. Also, Adjunct Professor of Fluid Mechanics and Basic and Advanced Hydropower Engineering, Oregon Institute of Technology, Portland, Oregon, eastside campus.

2002-May 1, 2008, US Army Corps of Engineers, Hydroelectric Design Center, Portland, Oregon

Reemployed on a term basis as a senior hydro mechanical engineer in the Hydroelectric Design Center of the US Army Corps of Engineers to evaluate and test new methods of measuring flow rate in hydraulic turbines and to develop new computer software programs to maximize the combined generating efficiency of multiunit powerhouses.

1998-2002, ENRON Engineering & Construction Company, Houston, Texas

Employed as an engineering specialist in hydropower to economically evaluate potential hydroelectric projects for acquisition.

1994-1998, Kleinschmidt Associates, Pittsfield, Maine

As a senior hydromechanical engineer with an engineering consulting firm, worked extensively in the forensic analysis of hydraulic turbine failures. In addition, was involved in the study and design of hydraulic turbine installations, field testing of hydromechanical equipment, site development, optimization studies, hydraulic modeling, and performing analytical studies related to advanced hydropower-generating concepts.

Temporarily assigned for one year to the Tennessee Valley Authority (TVA), which has a long-term program to replace 80 turbine runners at more than a dozen projects. Worked in the hydromodernization program by reducing and analyzing all the field test data and preparing the turbine efficiency and performance test reports.

1982-1994, Bonneville Power Administration

Positioned as the senior hydropower engineer in charge of the technical direction and administration of BPA’s research, development, and demonstration program in hydropower. This included performing analytical studies, evaluating proposals, negotiating and administrating contracts, monitoring laboratory research, and conducting field tests and prototype evaluations.

As part of this position, worked extensively in the environmental aspects of hydropower. This included: designing and studying models of fish ladders, designing turbines to aerate discharges, developing the hydraulic analysis of the Eicher Fish Screen, designing other state of the art fish screening systems, optimizing the efficiency of both hydraulic turbines and entire powerhouses to facilitate downstream migration, conducting workshop sessions on fish passage through turbines, and serving on the technical committee of DOE's Advanced Hydro Turbine System Program Committee.

<u>1979-1982, US Department of Energy, Idaho Operations Office, Idaho Falls, Idaho</u>

Served as the project manager for the construction of twenty hydroelectric demonstration projects located throughout the nation.

<u>1971-1979, US Army Corps of Engineers, Hydroelectric Design Center, Portland, Oregon</u>

As head of the turbine design section, performed site development and optimization studies, water hammer analyses, contract management, field-testing and oversaw construction and equipment installation. Additional duties included preparation of equipment specifications, procurement of turbines, pumps, valves, and related mechanical equipment. During the course of employment, worked on the design, construction, capital improvement, and/or O&M of every Corps hydropower project in the Pacific Northwest.

<u>1969-1971, US Army Corps of Engineers, Division Hydraulic Laboratory, Bonneville, Oregon</u>

Worked on the design, construction, operation and evaluation of hydraulic models of various civil structures, rivers, canals, conduits and outlets.

<u>1963-1986, US Navy, Active and Reserve Duty</u>

Early active duty and reserve activities in the US Navy included: hydrography, amphibious forces, Seabees, submarines, and inshore undersea warfare. When promoted to the rank of Commander, simultaneously earned the designator of a fully qualified Engineering Duty Officer. Consequently, before retiring from the Navy, spent fifteen years in shipyards on the construction, conversion, alteration, and repair of naval ships. Having been a boiler officer on active duty, received a subspecialty designation in ship's hulls and propulsion systems.

EDUCATION

Bachelor of Science in General Engineering, University of California at Los Angeles, 1963.

Master of Science in Mechanical Engineering, California State College at Los Angeles, 1969.

LICENSES

Registered as a Professional Engineer, Mechanical, Oregon, #7150, 1970.

HONORS AND AWARDS

Elected to membership in Tau Beta Pi (Engineering Honor Society), 1962.

Elected to membership in Phi Kappa Phi (Scholastic Honor society), 1968.

Secretary of the Army Energy and Water Management Award for New Technology in FY 2006.

AFFILIATIONS

Current member of the Publisher's Advisory Board of Hydro Review, published by HCI Publications.

Current member of the US Department of Energy's Advanced Hydro Turbine System Program Committee.

Past chairman of the Hydro Working Group of the Electric Power Research Institute (EPRI).

PUBLICATIONS

1. "Cost Analysis of Hydraulic Turbines," International Waterpower and Dam Construction, June 1981.
2. "Field Testing and Optimizing the Efficiency of Hydraulic Turbines," International Waterpower and Dam Construction, January 1982.
3. "Model to Prototype Efficiency Step-Up for Francis Turbines," presented to and published in the Transactions of the ASME Second Symposium on Small Hydro-Power Fluid Machinery, November 1982.
4. Co-author of "Determining the Net Head Available to a Turbine," presented to and published in the Transactions of the ASME Second Symposium on Small Hydro-Power Fluid Machinery, November 1982.
5. "An Analysis of the Benefits to be Gained by Using Variable Speed Generators on Francis Turbines," presented to DOE/EPRI Variable Speed Generator Workshop in Denver, Colorado, May 1983.

6. One of four contributing authors to the text Hydropower Engineering, published by Prentice-Hall, Inc., in 1983.
7. “An Analysis of the Applicability and Benefits of Variable Speed Generation for Hydropower,” presented to and published in the Transactions of the ASME Third Symposium on Small Hydro-Power Fluid Machinery, December 1984.
8. “Performance Differences: Turbine Models and Full-Scale Prototypes,” Hydro Review, Summer 1985.
9. “Installation of a Marine Thruster as a Hydroelectric Turbine at Eagle Creek National Fish Hatchery,” BPA Final Report DOE/BP-22105 1, November 15, 1986, available from the National Technical Information Service.
10. “Flow Measurement by Three Different Methods: Winter-Kennedy Piezometers, Traveling Screen, and Weir,” presented to and published in the Transactions of the EPRI/BPA Hydraulic Turbine Testing Workshop/Seminar, York, Pennsylvania and Portland, Oregon, June 1987.
11. “Performance Differences Between a Model and a Homologous Prototype,” presented to and published in the Transactions of the EPRI/BPA Hydraulic Turbine Workshop/Seminar, York, Pennsylvania, and Portland, Oregon, June 1987.
12. “Can a Marine Thruster be Used as a Hydroelectric Turbine?,” Hydro Review, Special Waterpower ’87 issue, August 1987.
13. Co-author of “Pump Turbines, Trends and Status,” presented to and published in the Transactions of the International Renewable Energy Conference, Honolulu, Hawaii, September 1988.
14. Co-author of “Variable Speed Pump/Turbines,” Hydro Review, Special Waterpower ’89 issue, August 1989.
15. “Q&A, Is Your Hydrogenerator Speeding? A Look at Overspeed, Runaway Speed,” Hydro Review, Special Waterpower ’95 issue, July 1995.
16. “Optimizing Efficiencies of Multi-Unit Hydro Plants,” presented to and published in the ASCE Transactions of Waterpower ’95, July 1995.
17. “Q&A, The Choice Between Reaction and Impulse Turbines,” Hydro Review, February 1997.
18. “Diagnostic Evaluation of Turbine Efficiency Profiles and Data,” presented to and published in the ASCE Transactions of Waterpower ’97, August 1997.

19. “Reviewing the Approaches to Hydro Optimization,” Hydro Review, June 1998.
20. “Modern Errors in Winter-Kennedy Piezometers,” presented to and published in the Transactions of the Second International Group for Hydraulic Efficiency Measurement (IGHEM) Conference, Reno, Nevada, July 1998.
21. “The Bernoulli Theorem: Sharing its History and Application,” Hydro Review, August 2000.
22. Co-author of, “Draft Tube Velocity Head Correction Factor,” presented to and published in the HCI Transactions of Waterpower ’05, July 2005.
23. Co-author of, “Improving Turbine Efficiency Calculations through Advanced Velocity Measurements,” Hydro Review, June 2007.
24. “A New Form of a Calibration Equation for the Winter-Kennedy Piezometer System,” presented to and published in the HCI Transactions of Waterpower XV, July 2007.
25. “Optimizing the Generating Efficiency of Entire Powerhouses,” presented to and published in the HCI Transactions of HydroVision 2008, July 2008.
26. “New Method to Determine Turbine Absolute Flow and Absolute Efficiency Data,” Hydro Review, July 2010.

Multi-Unit Optimization of a Hydropower Powerhouse

Oregon Institute of Technology

Volume II: Project Description for Evaluation Purposes by or on behalf of the Bonneville Power Administration

Robert Bass, Ph.D.
Lee Sheldon, PE
Principle Investigators

5/27/2011

2.b Project Description

1. Goal and Scope of this Agreement

The Goal of this Agreement is to develop the most effective software possible for multilevel hydropower optimization. The Scope is limited to utility-scale hydropower projects with ten or more turbines. The first six Tasks concern only a stand-alone decision support tool. Success of Tasks 1 through 6 will fulfil criteria for all five Roadmap Targets for Hydropower:

- Enhance the future FCRPS reliability, operation, and maintenance for an increasingly complex operation
- Design operational improvements to reduce costs
- Maximize existing asset use and extend useful life of assets
- Decrease the FCRPS environmental footprint
- Increase generation efficiency (increased power per unit of water)

Extending the project into a possible Task 7, the program would be incorporated into an adaptive controller, which is a very feasible step that would require working together with utility operators and engineers.

2. Background

Optimization is the process of tuning a system to create the best output for a given input. In hydropower that means producing the most power for a given volumetric flow rate of water; or using the least water to produce a given amount of power at any given head. When discussing the various levels of hydropower optimization, we assume a constant head since various reservoir rule curves do not provide for maximizing head.

Since all elements of a power system are connected and work together, that optimization has several levels. There are now five recognized Types of optimization. For example, Kaplan turbines produce the most power when the blades are at the proper angle for a given flow. This (Type 1) optimization requires index testing and recording the best blade angle-to-wicket gate relationship for all possible heads for every turbine. Other kinds of turbines, such as the Francis variety, have fixed runners. For these turbines, Type 1 consists of just the index test to determine the relative efficiency profile. Lee Sheldon, PE, one of two Principle Investigators in this team has decades of experience performing Type 1 optimization.

Type 2 optimization concerns unit selection and load sharing in the whole powerhouse. We recently developed a new method for calculating Type 2 hydropower optimization with a new, very fast computer program.

To appreciate the value of Type 2 hydropower optimization, it helps to understand that every turbine in a powerhouse is slightly different. Although all the turbines in a powerhouse have the same specifications by design, differences in manufacturing tolerances result in differences in unit operating efficiencies in the range of somewhere between one and five percent. Further, years of operation tend to exacerbate the differences in performance between turbines. Every turbine has an efficiency profile that varies across its range of flow. In powerhouse documentation, the performance profiles of each individual turbine are often available in a stored database. When the grid operator determines a mega-watt set-point for the project, the powerhouse operator can choose to have some turbines on-line and some turbines off-line, a process called **unit selection**. The next parameter to determine is **load sharing**. The best load sharing is achieved when the wicket gate opening for each turbine is set such that the power output is met with the smallest total flow rate.

Both decisions are much more difficult to make than it may seem. Even a skilled operator may underutilize up to 5% of the water available for generation due to less than perfect unit selection and load sharing. During conditions when water is spilled, that 5% may not make a lot of difference. However, when the flow of the river is low enough to be insufficient to meet net energy demand, that 5% represents a corresponding loss of potential revenue. At worst a project may even lose the generation equivalent to 10% of the flow. Under many conditions that will mean a corresponding 10% loss in revenue. Especially from late August to October, with future potential of further reduced flow, **maximizing optimization algorithms for hydro-power can essentially help build generating power for these times**. Even when there is plenty of water in the river, a project run at optimal power rather than at full gate can generate the same amount of power with less wear on machinery.

3. Location of Project (if site-specific)

Part of the program validation, index testing, and training will happen at a suitable hydro-power project at site as determined in Task 1. Such a project will preferably be located within the BPA service area of the Pacific North West, but not limited to that area.

Other parts of the Project such as data reduction, computer programming, engineering, documentation, and so on will happen at OIT campuses in Portland and Hillsboro, Oregon; or elsewhere (such as at home) as desired by Key Members.

4. BPA-Furnished Property or Services

No part of the Project requires that BPA furnish any property or services, but we welcome consultation with BPA personnel as desired by BPA and its members. BPA may elect to make its own research facilities open to certain members of the OIT hydropower team if desired, but doing so would not be necessary to the success of the Project.

5. Recipient-Furnished Property or Service

OIT will furnish standard University type services to members of this Project; such as access to buildings, computers, software, testing equipment, and administrative support. Such facilities will be open to BPA members as well should they choose to collaborate on this project. Again, nothing is required of BPA personnel for the success of this project. The OIT hydropower team itself will make use of its own previously developed software to perform optimization.

6. Definitions and Acronyms

Index Testing: The field testing required to determine the relative efficiency for each turbine over its entire flow range.

Unit selection: The selection of which turbines to have on-line to meet the operator set point.

Load sharing: The separate amount of load to put on each selected turbine.

Type 1 optimization: The optimization of each individual turbine in a powerhouse in terms of power output verses flow rate at constant head.

Type 2 optimization: The coordination of all the turbines in a powerhouse to achieve a power output set point using the least amount of flow. This level of optimization is the subject of this paper, and is achieved with the best possible unit selection and load sharing.

Type 3 optimization: The coordination of all the hydro powerhouses along a river or in a river basin to get the most power from the available flow.

7. Documentation

The OIT Hydropower Team will commit to documentation consistent with the desired format and regularity requested by BPA for TI Projects.

8. General Requirements

Successful completion of the project will require the team to locate a suitable hydro-power project. In the event that a suitable project is impossible to access, it is conceivable that the project could still be made meaningful by using historical data, working on Task 7, and so on. However, it is much preferred that we find an actual dam with which to perfect the computer program. Since we have tested the program, and also due to Lee's decades in hydropower optimization, the Project has the highest probability of success if we have a hydro-power project to work with.

9. Methods to be Used

Methods to be used include Index Testing (if necessary), data reduction and organization in Excel, MATLAB and Octave scripting, Java and PHP programming, SCADA design, OPC or IEC 61850 connectivity, calculations by hand and more traditional engineering tools, and research using all available media.

10. Specific Requirements

A. Objectives

1. Identify a hydropower project for index testing, and collect data
2. Manually determine optimal load sharing and unit selection, for low, medium (if possible), and high head
3. Validate the computer algorithm using the hand-calculated results
4. Modify script to incorporate more features: curvilinear interpolation, block loading, alarms
5. Develop a graphical front end for stand-alone use and also demonstrate as a SCADA solution
6. Documentation, operational instructions, and operator training. Explore commercialization.

First, the team will validate the computer program that it has created to date. The program inputs power versus flow data for all the individual turbines in a power-house. It outputs recommended gate openings that will meet a given demanded power output using the least amount of flow. Presently the program is a stand-alone tool that provides decision support. We would like to further test the accuracy of that decision support. Then we will modify the program according to the needs of the operator, and finally provide the necessary documentation and training. The validation will follow the Tasks outlined below. A future stage will be to integrate the algorithm into a controller.

B. Description of tasks

1. Identify a Suitable Hydro-power Project

A suitable project will have a minimum of three Kaplan or Francis type turbines. Ideally the turbines will have their index tests up to date. Team members will communicate with dam owners and travel to suitable projects. After visiting multiple sites, the team will choose the best hydro-power project. The team expects that it may take considerable time and effort to find a facility that has both the desired characteristics and consent of the owner. In the best case the team will already have identified a hydro-power dam before the work begins. The team will make a contract with the owners of the dam to get the work done.

2. Obtain Performance Data

If the project has undergone a recent index test, performance data should exist for each turbine. If no data or only limited data is available, the optimization team is prepared to perform and index test. To perform an index test, Principle Investigator Sheldon and a few students will use operating data to record power versus flow for each turbine. An index test will significantly increase the long term efficiency of the dam should we need to perform one.

3. Verification Phase: Validate Algorithm

The OIT Hydropower Team will use the performance data to verify the program. During this phase, we will compare gate openings that the program recommends to the actual set-points used by the operator on each turbine. The computer program will calculate the difference in efficiency in terms of power versus volumetric flow rate.

4. Front End Development

Having verified the back end of the program, the team will modify the front end of the program to suit the user (hydro-power dam operator.) When we get to this point we will know what these front-end modifications may entail. For instance, the operator may prefer that the program express turbine set-points in terms of servo-stroke instead of power output, though the two quantities are directly linked computationally. Various modifications to the computer program can be made to suit the particular dam. The same algorithm can be applied to other important variables in the power system: such as the electrical dead-band in the generators; and improved load forecasting for the dam using a neural networking program.

5. Documentation

The team will document the test (Gate 3) and also document the newly modified code that resulted from Gate 4. The OIT Hydropower team will formally transfer all knowledge gained from the first four Tasks to the owners and operators of the hydropower project and to BPA. The documentation will follow Operator and BPA guidelines respectively.

6. Training

If the project is successful according to the needs of the dam and/ or BPA, the OIT Hydropower team will provide training to make the knowledge useful to both parties. Training a few engineers and operators on simple user friendly software will not consume very much time. We have a working manual already to date, and will publish an updated version when we get to this step.

7. Future Development of an Adaptive Controller

In a future seventh stage, possible in FY2012 but not required, the team will build an adaptive controller for the program. The controller could be used in a SCADA integrated system. Key members of the team know how to adapt software to generator controls, but this stage needs careful coordination with the utility. The team is capable of incorporating the following features as desired by BPA and the owners of the dam:

- Real-time, system-wide data measurement, collection, analysis, dissemination, and display
- Interactive and instructional displays
- High speed, secure, reliable, interoperable system wide communication
- Open source PLC technology and coding
- Data systems compatible with GDACS, AGC, and SCADA
- AGC control system compatibility

C. Project Management Protocols

i. Communications plan

All Key members and the Principle Investigators will meet once a week to discuss progress. Members will each produce a short report for each meeting, or longer if required for that week. The team will produce full reports for OIT and BPA at each Stage Gate. While work is in progress, members will stay in contact with each other on a daily basis. Above describes the internal communication schedule similar to the one The OIT Hydropower Group currently follows, and the internal part of the Communications Plan that we will follow during the Project.

The OIT Hydropower Team will publish any significant or interesting details of the project in a journal such as Hydropower Review, or may present results at conferences such as Hydrovision. Such will be the external Communications Plan (unless it is requested to be otherwise by BPA, in which case we will gladly oblige.)

In addition, the OIT Hydropower Team will commit to any schedule and format for reporting to BPA that BPA requests.

ii. Contingency plan

If unable to gain access to an active hydropower project:

The least certain part of the project is Task 1, identifying a suitable hydro-power project with the consent and contractual agreement with the owner of the dam. We have allotted significant man hours to this task. In the event that Task 1 is not attainable, the Project will continue using historical data from another dam besides the The Dalles Dam. In this contingency, since there will be no real dam for which to modify the program, nor anyone to train, the Project will use historical index test data and skip to Task 4: Frontend Development.

iii. Stage Gates

Three critical Stage Gates have been identified:

Stage Gate 1: Following Task 1, we will evaluate the success of locating a hydro project and obtaining index test data. If no, we may choose to divide efforts and continue the search, postponing tasks 2 and 3 and continuing on to task 4, front end development.

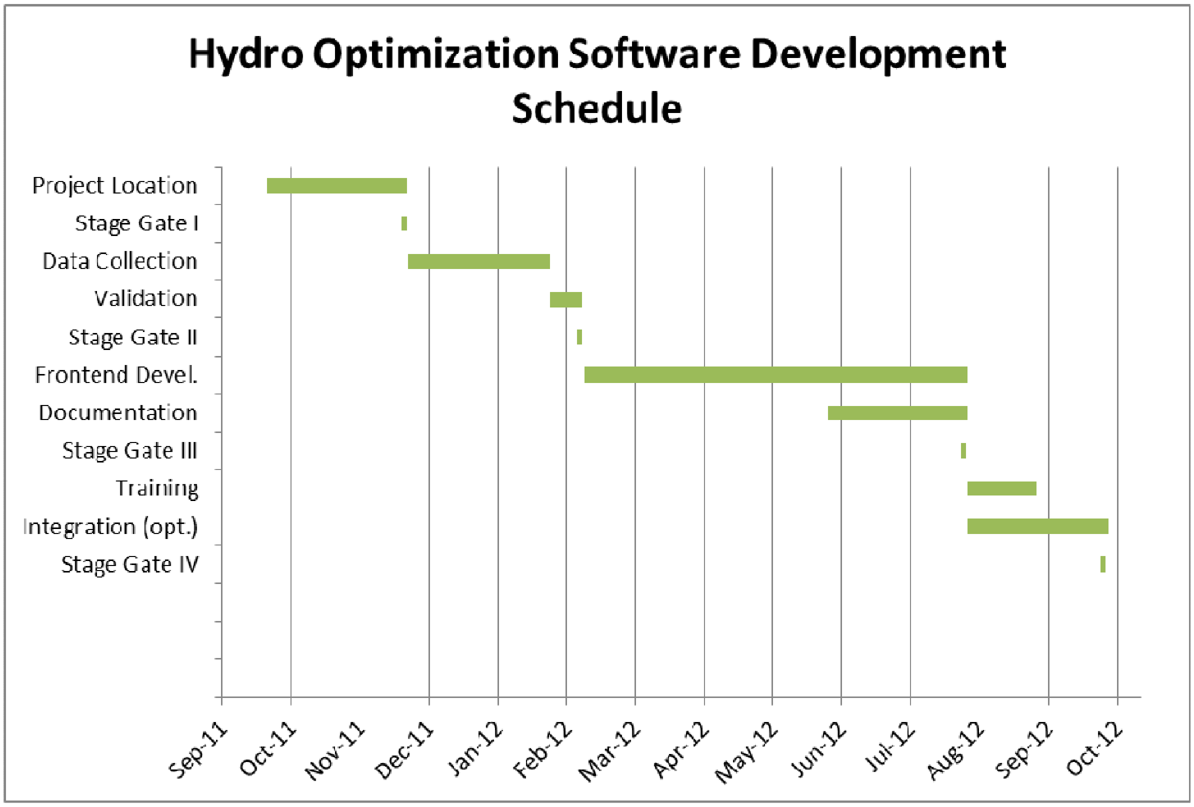
Stage Gate 2: Following Task 3, we will have proof of concept, and any newly identified functionality will have been built into the back end. The remainder of the project will be focused on building the Graphical User Interface (i.e. the software front end).

Stage Gate 3: Evaluate progress of the Graphical User Interface, and assess any issues that may have arisen. Determine whether the option for integration into existing systems is available. Tasks 5 and 6, Documentation and Training, begin.

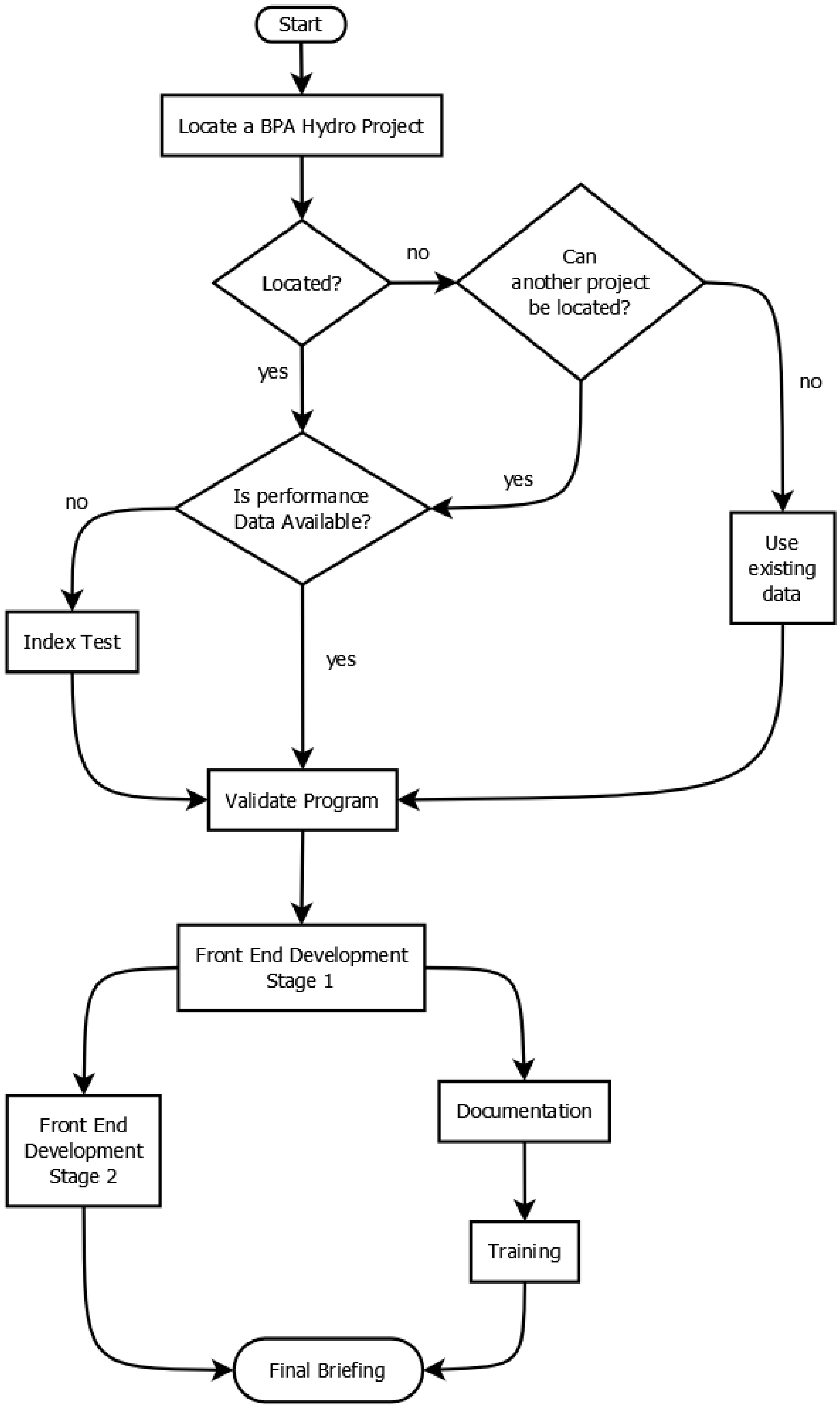
The following are illustrated on a Gantt timeline, in the next section:

Task 1: Identify a Suitable Hydro-power Project
Stage Gate 1
Task 2: Obtain Performance Data
Task 3: Verification Phase: Program Validation
Stage Gate 2
Task 4: Front End Development
Stage Gate 3
Task 5: Documentation
Task 6: Training

iv. Gantt Chart



v. Process Flowchart



vi. Technology Transfer

The OIT Hydropower will transfer to BPA the means and methods by which to optimize any similar hydro-power project. From previous experience and testing, we believe the results will be efficient and excellent, especially for hydro projects that experience reduced flow during some part of the calendar year. Ownership of previously written computer code will be protected, and is soon to be under patent. However, BPA will have the means by which to use the software in the manner originally intended, legally and materially. BPA will be entitled to ownership of any additional code we generate during this project.

D. Deliverables

1. Updated and Modified Type 2 Hydropower Optimization Software
    - Ownership of previous code is protected. However, the newest version containing all necessary useable code will be made available for use
    - Several formats/ programming languages available including Web based program and executable files
    - Includes user-friendly Graphical User Interface (GUI)
2. Systematized Hydropower Optimization Methodology, Type 1 and Type 2
    - Includes training personnel from BPA and from selected dam
    - Includes Operator Manual
3. Standard Deliverables as Expected by BPA including but not limited to:
    - All supporting data in an electronic format acceptable to BPA
    - Expected functionality and support of any hardware and/or software as applicable along with full documentation of its use and repair, as acceptable to BPA
    - Expected performance standards
    - How the proposed project will be integrated into BPA's Power Delivery System
    - How established utility processes and procedures will be impacted
    - The appropriate testing and/or evaluation methodology if applicable
    - A final report including next steps for the project or potential follow-on projects

E. Time Schedule

Task 1: Identify a Suitable Hydro-power Project
60 days
Task 2: Obtain Performance Data
62 days
Task 3: Verification Phase: Program Validation
14 days
Task 4: Front End Development
164 days (Overlaps with Documentation)
Task 5: Documentation
61 days
Task 6: Training
30 days

Total 29 Weeks= 7 Months and One Week

11. Technical Exhibits

See attached paper entitled “Sequential Quadratic Programming to Solve Hydropower Optimization for All Generating Units in a Power House.”

Multi-Unit Optimization of a Hydropower Powerhouse

Oregon Institute of Technology

Volume III: Cost Share and Budget for Evaluation Purposes by or on behalf of the Bonneville Power Administration

Robert Bass, Ph.D.
Lee Sheldon, PE
Principle Investigators

5/27/2011

3.b Cost Share Contribution

The Cost Share Contribution will come from in-kind labor contribution from the applicants. Faculty and key student members will add labor to this project as the sole Cost Share Contribution. This labor is expected to reach 53% of the value of the project.

3.c Task Budget

Stage Gate Budget	Labor	Fringe Benefits (OPE)	Travel	Equipment/ Supplies	Other indirect costs (tuition)	Indirect costs	BPA Share	Project total
Task 1	$17,949.48	$2,397.32	$6,000.00	$15,100.00	$7,288.00	$7,970.46	$35,570.70	$56,705.26
Task 2	$17,949.48	$2,397.32	$2,500.00		$7,288.00	$7,970.46	$16,970.70	$38,105.26
Task 3	$14,957.90	$1,997.76	$0.00		$7,288.00	$6,642.05	$12,463.81	$30,885.71
Task 4	$11,966.32	$1,598.21	$0.00		$7,288.00	$5,313.64	$10,456.91	$26,166.17
Task 5	$11,966.32	$1,598.21	$0.00		$7,288.00	$5,313.64	$10,456.91	$26,166.17
Task 6	$11,966.32	$1,598.21	$3,500.00		$7,288.00	$5,313.64	$13,753.95	$29,666.17
Total	$86,755.83	$11,587.04	$12,000.00	$15,100.00	$43,728.00	$38,523.87	$99,672.98	$207,694.74

3.d Budget Justification Narrative

A. Labor

Personnel Costs

There are two pay tiers associated with this project, Faculty and Student. For Faculty, base pay plus OPE comes to $57.66 per hour which is a comprehensive hourly figure that includes all overhead. Student pay comes to $21.98 per hour, including all overhead.

There are a total of four students and two faculty that can work on this project. Graduate students are limited to a maximum of 0.49 FTE, slightly less than 20 hours per week. Robert Bass, faculty member and PI, has committed 0.20 FTE (8 hours per week) to the project. Lee Sheldon has committed 0.35 FTE (15 hours per week).

Over the period of the project, the labor costs are expected to come in around $86,756. OIT and BPA will split the labor costs for Lee Sheldon and the graduate students on a 50/50 basis. OIT will assume full responsibility for for the labor costs of Robert Bass.

B. Fringe Benefits (OPE)

Fringe Benefits (OPE), where applicable, are included in the amount proposed above in part 3.d.A as covered by OIT. The percentage above base pay is 53% for faculty and 9% for students. As done with the labor costs, OIT and BPA will split the OPE costs for Lee Sheldon and the graduate students on a 50/50 basis. OIT will assume full responsibility for for the OPE costs of Robert Bass.

C. Travel

Travel is a moderate expense for this project, especially in Task 1 when Key Members are identifying a suitable hydropower site. Key members will be driving to sites after making appointments with interested owners. $6000 dollars has been allocated for travel expenses for Task 1.

Task 2 requires working at the dam identified in Task 1 for a limited time. $2500 in travel expenses is allocated for Task 2.

Training in Task 6 will require travelling to the dam and to meet BPA officials for as long as it takes to fully transfer all knowledge. $3500 in travel expenses is allocated for Task 6.

Total travel expenses are expected not to exceed $12,000.

Travel will be billed to the project at the appropriate rate similar to the way any business accounts for travel when deducting the expense on federal and state taxes. The OIT hydropower team will account for travel in the exact same way according to federal law. All travel costs will be assigned to BPA.

D. Subcontracts

There are no subcontracts anticipated for this project.

E. Equipment/Supplies

All supplies are in the software category. The project needs a one year commercial license for MATLAB and other Mathworks products, including a compiler so that the computer program can be compiled into an executable file during the knowledge transfer during Task 6. There are $15,100 of supplies needed. All equipment/supplies costs will be assigned to BPA.

F. Other Direct Costs

OIT has liability insurance for this project. Costs associated with photocopying and printing will be very small. Funds have been designated to support the graduate students' classes during the project year. OIT and BPA will split the tuition costs, with OIT assuming 2/3rd of the tuition costs and BPA 1/3rd.

G. Indirect Costs (General and Administrative Costs)

This project has the benefit of association with a University, so all administrative costs are contained in the overhead of the hourly rate for faculty and student members. An indirect rate of 52.5% has been used to calculate indirect costs based on the graduate student salaries and Lee Sheldon's salary. OIT and BPA will share these indirect costs on a 50/50 basis.

1918-1556: Multi-Unit Optimization of a Hydropower Powerhouse
Reviewer Name [redacted]

Evaluation Criteria #1: **Roadmap Technology**

The degree to which proposed research addresses a technology need described in BPA's Technology Roadmaps and the degree to which it addresses a gap identified in the Roadmaps. (Refer to pg 1 for more Roadmap information)

1	2	3	4	5
Project meets no technologies in the Roadmaps or does not state any link to the Roadmaps at all.	Some information was provided to identify the technology or gap but very little analysis.	Acceptable responses to address Roadmap technologies.	Clearly demonstrated a technology need and/or gap in the Roadmap(s) with supporting detail.	Excellent identification and analysis of the projects links to the Roadmap's and supporting detail.

Score : 4
Comments: The proposal clearly identifies the target areas although some descriptions appear optimistic in the level of integration & benefit provided.

Evaluation Criteria #2: **Multiple Roadmap Technologies**

The degree to which the project fills multiple technology needs or gaps identified in a Roadmap or is directly linked to more than one Roadmap.

1	2	3	4	5
Project does not address a roadmap technology and received a 1 for Criteria #1.	Project fills only one technology need or gap.	Project will address more than one technology in the same Roadmap.	Project will address at least one technology in more than one Roadmap.	The project has specific links to multiple Roadmaps and technologies.
Score : 3				

Comments: Provides potential optimization improvements and possible software tools

Evaluation Criteria #3: **Focus Area**
The extent to which the application addresses any of the Focus Areas.

1	2	3	4	5
Proposal does not address a focus area.	Proposal does address a focus area but is unstated.	Proposal identifies a focus area connection but is unclear to what extent.	Proposal addresses a focus area with some supporting detail.	Proposal clearly addresses a focus area with sufficient explanation and supporting detail.

Score : 4

Comments: The proposal clearly addresses computational advances in generator control optimization. Will need to include Corps or Bureau for a fully-successful project.

Evaluation Criteria #4: **Technical Success**
The probability of the project being a technical success.
(High Risk/Reward projects will be identified through other evaluation criteria. The projects should be evaluated solely on the likelihood of success.)

1	2	3	4	5
The project is very unlikely to succeed.	The project has a small chance of technical success.	The project has a reasonable chance of success.	Project success is likely.	Project success is extremely likely.

Score : 4

Comments: High likelihood of success from a computational standpoint, however success in implementation is less certain. Would require training of project operators and recognition of other constraints on system.

Evaluation Criteria #5: **Successful Application to BPA**
The probability of near or long term successful application to BPA.

1	2	3	4	5
The project is very unlikely to be applicable to BPA.	The project has a small chance of applicability to BPA.	The project is likely applicable to BPA.	The project is very likely to be successfully applied at BPA.	The successful application at BPA is extremely likely.

Score : 2
Comments: Would need to be accepted by Corps and Bureau. Given operational constraints, application would be limited to a handful of projects. Reference to CV unclear.

Evaluation Criteria #6: **Magnitude of Expected Benefit**
Magnitude of the quantitative/qualitative expected benefit to cost ratio, as applied system-wide, assuming this project is a technical success.

1	2	3	4	5
The project is very unlikely to have benefit to BPA.	The project would have little benefit to BPA.	The project would be moderately beneficial to BPA.	The project would provide a substantial benefit to BPA.	The project would have an extremely large benefit to BPA system-wide.

Score : 2
Comments: Note: Stated cost of doing project is $234,480 w/ BPA sharing ½ of the total. Budget Table (3.c) shows total budget of $207,694.74 Potential Benefits seem overstated in proposal as the calculation used a large # of projects and high energy price.

Evaluation Criteria #7: **Stage Gates**
The degree to which proposed Stage Gates (go/stop decision points) reflect real options and choices for project decisions, and relate to real discovery, science, and/or achievement thresholds.

1	2	3	4	5
No Stage Gates identified.	State Gates identified are arbitrary or lack key elements of effective go/stop decision points. Supporting detail for why they were chosen is lacking.	Stage Gates are reasonable but could have been placed at better points. Additional Stage Gates may also be needed. Little supporting detail for why they were chosen is provided.	The Project stage gates are described with sufficient detail and reflect real options and choices for project decisions.	Project stage gates are well thought and out and explained. They are at exactly the key places for go/stop decisions points.

Score : 4.5
Comments: In addition to the stopping points the proposal identifies alternatives if roadblocks are encountered along the way.

1918-1556: Multi-Unit Optimization of a Hydropower Powerhouse	
Reviewer Name:	

Evaluation Criteria #1: **Roadmap Technology**
The degree to which proposed research addresses a technology need described in BPA's Technology Roadmaps and the degree to which it addresses a gap identified in the Roadmaps. (Refer to pg 1 for more Roadmap information)

1	2	3	4	5
Project meets no technologies in the Roadmaps or does not state any link to the Roadmaps at all.	Some information was provided to identify the technology or gap but very little analysis.	Acceptable responses to address Roadmap technologies.	Clearly demonstrated a technology need and/or gap in the Roadmap(s) with supporting detail.	Excellent identification and analysis of the projects links to the Roadmap's and supporting detail.

Score : 3
Comments:

Evaluation Criteria #2: **Multiple Roadmap Technologies**
The degree to which the project fills multiple technology needs or gaps identified in a Roadmap or is directly linked to more than one Roadmap.

1	2	3	4	5
Project does not address a roadmap technology and received a 1 for Criteria #1.	Project fills only one technology need or gap.	Project will address more than one technology in the same Roadmap.	Project will address at least one technology in more than one Roadmap.	The project has specific links to multiple Roadmaps and technologies.
Score : 5				

Comments:

Evaluation Criteria #3: **Focus Area**
The extent to which the application addresses any of the Focus Areas.

1	2	3	4	5
Proposal does not address a focus area.	Proposal does address a focus area but is unstated.	Proposal identifies a focus area connection but is unclear to what extent.	Proposal addresses a focus area with some supporting detail.	Proposal clearly addresses a focus area with sufficient explanation and supporting detail.

Score : 3
Comments:

Evaluation Criteria #4: **Technical Success**
The probability of the project being a technical success.
(High Risk/Reward projects will be identified through other evaluation criteria. The projects should be evaluated solely on the likelihood of success.)

1	2	3	4	5
The project is very unlikely to succeed.	The project has a small chance of technical success.	The project has a reasonable chance of success.	Project success is likely.	Project success is extremely likely.

Score : 3
Comments: Technical goal of fast unit optimization at constant head has a reasonable chance of success

Evaluation Criteria #5: **Successful Application to BPA**
The probability of near or long term successful application to BPA.

1	2	3	4	5
The project is very unlikely to be applicable to BPA.	The project has a small chance of applicability to BPA.	The project is likely applicable to BPA.	The project is very likely to be successfully applied at BPA.	The successful application at BPA is extremely likely.

Score : 1-2
Comments: Similar project already implemented (NRTO), so no apparent additional benefits to be gained. Furthermore, assumption is constant head, which is not valid in real-life and maximizing efficiency is not always the objective (frequently we need to maximize flexibility)

Evaluation Criteria #6: **Magnitude of Expected Benefit**
Magnitude of the quantitative/qualitative expected benefit to cost ratio, as applied system-wide, assuming this project is a technical success.

1	2	3	4	5
The project is very unlikely to have benefit to BPA.	The project would have little benefit to BPA.	The project would be moderately beneficial to BPA.	The project would provide a substantial benefit to BPA.	The project would have an extremely large benefit to BPA system-wide.

Score : 1-2
Comments: Benefits of increase in annual revenue of $81.5 million are absurd. I seriously doubt that there is additional efficiency to be gained after implementing NRTO. Furthermore, seeking most efficient generation set points is not necessarily the correct objective function. With uncertainty due to flows, loads and wind, operating the system to maximize generation is not necessarily the correct objective function. Instead, maximizing flexibility should be considered as well.

Evaluation Criteria #7: **Stage Gates**
The degree to which proposed Stage Gates (go/stop decision points) reflect real options and choices for project decisions, and relate to real discovery, science, and/or achievement thresholds.

1	2	3	4	5
No Stage Gates identified.	State Gates identified are arbitrary or lack key elements of effective go/stop decision points. Supporting detail for why they were chosen is lacking.	Stage Gates are reasonable but could have been placed at better points. Additional Stage Gates may also be needed. Little supporting detail for why they were chosen is provided.	The Project stage gates are described with sufficient detail and reflect real options and choices for project decisions.	Project stage gates are well thought and out and explained. They are at exactly the key places for go/stop decisions points.

Score : 4
<u>Comments:</u>

1918-1556: Multi-Unit Optimization of a Hydropower Powerhouse
Reviewer Name:

Evaluation Criteria #1: **Roadmap Technology**
The degree to which proposed research addresses a technology need described in BPA's Technology Roadmaps and the degree to which it addresses a gap identified in the Roadmaps. (Refer to pg 1 for more Roadmap information)

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Project meets no technologies in the Roadmaps or does not state any link to the Roadmaps at all.	Some information was provided to identify the technology or gap but very little analysis.	Acceptable responses to address Roadmap technologies.	Clearly demonstrated a technology need and/or gap in the Roadmap(s) with supporting detail.	Excellent identification and analysis of the projects links to the Roadmap's and supporting detail.

Score :
<u>Comments:</u>

Evaluation Criteria #2: **Multiple Roadmap Technologies**
The degree to which the project fills multiple technology needs or gaps identified in a Roadmap or is directly linked to more than one Roadmap.

1	2	3	4	5
Project does not address a roadmap technology and received a 1 for Criteria #1.	Project fills only one technology need or gap.	Project will address more than one technology in the same Roadmap.	Project will address at least one technology in more than one Roadmap.	The project has specific links to multiple Roadmaps and technologies.
Score :				

Comments:

Evaluation Criteria #3: **Focus Area**
The extent to which the application addresses any of the Focus Areas.

1	2	3	4	5
Proposal does not address a focus area.	Proposal does address a focus area but is unstated.	Proposal identifies a focus area connection but is unclear to what extent.	Proposal addresses a focus area with some supporting detail.	Proposal clearly addresses a focus area with sufficient explanation and supporting detail.

Score :
Comments:

Evaluation Criteria #4: **Technical Success**
The probability of the project being a technical success.
(High Risk/Reward projects will be identified through other evaluation criteria. The projects should be evaluated solely on the likelihood of success.)

1	2	3	4	5
The project is very unlikely to succeed.	The project has a small chance of technical success.	The project has a reasonable chance of success.	Project success is likely.	Project success is extremely likely.

Score :
Comments:

Evaluation Criteria #5: **Successful Application to BPA**
The probability of near or long term successful application to BPA.

1	2	3	4	5
The project is very unlikely to be applicable to BPA.	The project has a small chance of applicability to BPA.	The project is likely applicable to BPA.	The project is very likely to be successfully applied at BPA.	The successful application at BPA is extremely likely.

Score :
<u>Comments:</u>

Evaluation Criteria #6: **Magnitude of Expected Benefit**
Magnitude of the quantitative/qualitative expected benefit to cost ratio, as applied system-wide, assuming this project is a technical success.

1	2	3	4	5
The project is very unlikely to have benefit to BPA.	The project would have little benefit to BPA.	The project would be moderately beneficial to BPA.	The project would provide a substantial benefit to BPA.	The project would have an extremely large benefit to BPA system-wide.

Score :
<u>Comments:</u>

Evaluation Criteria #7: **Stage Gates**
The degree to which proposed Stage Gates (go/stop decision points) reflect real options and choices for project decisions, and relate to real discovery, science, and/or achievement thresholds.

1	2	3	4	5
No Stage Gates identified.	State Gates identified are arbitrary or lack key elements of effective go/stop decision points. Supporting detail for why they were chosen is lacking.	Stage Gates are reasonable but could have been placed at better points. Additional Stage Gates may also be needed. Little supporting detail for why they were chosen is provided.	The Project stage gates are described with sufficient detail and reflect real options and choices for project decisions.	Project stage gates are well thought and out and explained. They are at exactly the key places for go/stop decisions points.

Score :
<u>Comments:</u>

UNITED STATES GOVERNMENT	CONTRACT	BONNEVILLE POWER ADMINISTRATION

Mail Invoice To:

.See Page 2

Contract : 00056104
Release :
Page : 1

Vendor:
PORTLAND STATE UNIVERSITY

1721 SW BROADWAY
PORTLAND OR 97207

Please Direct Inquiries to:

MATTHEW L. DELONG
Title: CONTRACT SPECIALIST
Phone: 503-230-7549
Fax : 503-230-4508

Contract Title: **TIP 254: MULTI-UNIT OPTIMIZATION OF A HYDROPOWER POWERHOUSE**

Total Value : **$59,103.00** **** NOT TO EXCEED ****
Pricing Method: **COST SHARE (NO FEE)** Payment Terms: % Days Net 30
Performance Period: **01/17/12 - 09/30/12**

(b) (6) [redacted] Christina E. Frost
Contract Officer
Printed Name/Title
5/16/12
Date Signed

(b) (6) [redacted]
5/16/12
Date Signed

BONNEVILLE Power Administration	Continuation Sheet

COOPERATIVE AGREEMENT # 56104

TECHNOLOGY INNOVATION PROJECT # 254
PORTLAND STATE UNIVERSITY
MULTI-UNIT OPTIMIZATION OF A HYDROPOWER POWERHOUSE

BPA Financial Assistance Officer	Matthew DeLong	(503) 230-7549	mldelong@bpa.gov
BPA Project Manager/Technical Representative	Jim Irish	(503) 230-5914	jtirish@bpa.gov
Principal Investigator	Bob Bass	(503) 725-2818	robert.bass@pdx.edu

SUMMARY
The cooperative agreement is hereby awarded according to agreement between the Bonneville Power Administration (BPA) and Portland State University.

1. Cooperative Agreement contents:

   Signature Page
   Signature Page Continuation Sheet
   Unit 1 – Terms and Conditions
   Unit 2 – Project Description
   Unit 3 – Stage Gate Budget

2. The period of performance is from the January 17, 2012 through September 30, 2012.

3. BPA's total award amount is $59,103 which shall not be exceeded without written authorization of the Financial Assistance Officer.

4. This award document may contain both Financial Assistance clauses, as well as BPA Purchasing clauses, as allowed by both the Bonneville Financial Assistance Instructions (BFAI) and the Bonneville Purchasing Instructions (BPI). It is BPA's intent that these clauses be used interchangeably and Contractors and/or Financial Assistance recipients abide by the clause's legal requirements regardless of the use of the specific words: "contract," "contractor," "subcontractor," "grant," "cooperative agreement," "recipient," or "sub-recipient."

5. Recipient shall submit monthly reimbursement requests by budget category in accordance with proposal budget, to the PM, via e-mail. Reimbursement requests shall include total spend to date and cost share reporting.

6. This agreement incorporates by reference 2 CFR Part 220, Cost Principles for Education Institutions (OMB Circular A-21) to be used to determine allowable, allocable, and reasonable costs for reimbursement.

7. This agreement also incorporates by reference Administrative requirements from 2 CFR 215 (A-110) which apply to Higher Education, Hospitals, and Other Non Profit Organization recipients and sub-recipients.

(END OF CONTINUATION SHEET)

COOPERATIVE AGREEMENT

TABLE OF CONTENTS

UNIT 1 – TERMS AND CONDITIONS

REGULATIONS APPLICABLE TO BPA FINANCIAL ASSISTANCE (4-1)
(BFAI 4.10) (SEP 04)

The Bonneville Power Administration's financial assistance function is managed and executed solely in accordance with the Bonneville Financial Assistance Instructions (BFAI). The BFAI is available without charge on the Internet at http://www.bpa.gov. Copies of the BFAI may be obtained for $15.00 each. Requests and comments should be sent to Head of the Contracting Activity - HCA, Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208. Subscriptions are not available.

NONDISCRIMINATION IN FEDERALLY ASSISTED PROGRAMS (4-2)
(BFAI 4.10) (SEP 04)

The recipient shall comply with 10 CFR Chapter II, Section 600.39 which provides that "...no person shall on the ground of race, color, national origin, sex, handicap, or age be excluded from participation in, be denied the benefits of, be subjected to discrimination under, or be denied employment, where the main purpose of the program or activity is to provide employment or when the delivery of program services is affected by the recipient's employment practices, in connection with any program or activity receiving Federal assistance from ..." BPA.

EXAMINATION OF RECORDS (4-3)
(BFAI 4.10) (SEP 04)

(a) The recipient shall maintain books, records, documents, and other evidence and accounting procedures and practices, sufficient to reflect properly all direct and indirect costs of whatever nature claimed to have been incurred and anticipated to be incurred for the performance of this award. The Financial Assistance Officer or a representative shall have the right of access to any books, documents, papers, or other records of recipients and subrecipients which are pertinent to the award, in order to make audits, examinations, excerpts and transcripts.

(b) Such material shall be made available at the office of the recipient, at all reasonable times, for inspection, audit or reproduction, until the expiration of 3 years from the date of final payment under this award or for such longer period, if any, as is required by applicable statute. If any litigation, claim, negotiation, audit or other action involving the records has been started prior to the expiration of the 3 year period, the records must be retained until completion of the action and resolution of all issues which arise from it, or until the end of the regular 3 year period whichever is later.

REPORTING PROGRAM PERFORMANCE (4-4)M
(BFAI 4.10)(JAN 11)

(a) Frequency. Unusual events having a negative impact on the project shall be reported by the Recipient to the Project Technical Representative (PTR) as soon as they are discovered. A progress report is due quarterly no later than the first Friday after the last day of the quarter. BPA quarters end on December 31, March 31, June 30, and September 30. A final report on the project must be submitted no later than 90 days after completion of the project.

(b) Contents. The report shall contain a comparison of the actual accomplishments to those planned for the period, and the findings of the principal investigator. If the project is not on schedule, a brief explanation of the reason is required. Unusual situations encountered which impacted the costs or effectiveness of the project should be identified and explained. Include the following information:

1. Planned Project Deliverable(s) list format with status.

    a. Track entire list from start to finish of project.

b. Track Status: status may include submitted, accepted, in progress, delayed, and rescheduled.

2. Activities/Accomplishments: Work performed this reporting period tracked at task/deliverable level. Include status of stage gates this reporting period

3. Challenges/Discoveries: Describe problems encountered and what discoveries made. Link to tasks and deliverables

4. Actions Taken on Challenges/Discoveries: Describe your response or proposed response. Include actions taken, results achieved, people informed, etc

5. Planned Activities: Describe activities planned for next quarter. If appropriate, include next stage gate, when is it and what expectations are to be met

6. Schedule Status: Do you anticipate meeting, or missing, the planned completion date for upcoming tasks and deliverables? Explain any variance. Explain your basis for this determination.

7. Financial Status: Describe the actual project expenditures at the stage gate level. BPA understands that final expenditure information may not be immediately available at the end of each quarter. Reasonably estimate the expenditures.

8. Proposed Project Changes

   a. Track list of proposed project changes from start to finish of project. Describe any changes to project scope, schedule, budget or work element.

   b. Track status of project changes submitted. Status may include submitted, accepted, revised, declined, in progress, delayed.

(c) Format: Deliver the report in electronic format to the PTR in Microsoft Word or Adobe Portable Document Format.

REIMBURSEMENT PAYMENT AND FINANCIAL REPORTING REQUIREMENTS (4-6)M
(BFAI 4.10)(MAR 11)

(a) Payment for services performed under this award will be reimbursed by Vendor Express payment after performance of the services. Recipient requests for reimbursements, and recipient financial reporting requirements shall be made as follows:

(1) Reimbursements. Standard Form 270e, Request for Advance and Reimbursement or equivalent, shall be used when requesting reimbursement for costs incurred on the project. Each request for reimbursement shall include the costs broken out for each budget category (Personnel, OPE, subcontract, etc…) represented in the Unit 3 Award Budget. Requests should not be made more frequently than monthly. An electronic copy should be submitted to the Project Manager (PM) and Project Technical Representative (PTR).

(2) Final Cost Report. The final cost report shall be submitted to the PTR within 90 days after the end of the effective period. It shall be submitted in the same format as the budget as awarded. The final cost report shall compare the amounts allocated in the award budget to the amounts expended for each budget element. This may be included with the final project report as indicated in Reporting Clause 4-4M.

ENVIRONMENTAL PROTECTION (4-7)
(BFAI 4.10)(SEP 04)

The recipient shall insure that the facilities under its ownership, lease or supervision which will be utilized in the accomplishment of the project are not listed on the Environmental Protection Agency's (EPA) list of Violation

Facilities and that it will notify BPA of the receipt of any communication from the Director of the EPA Office of Federal Activities indicating that a facility to be used in the project is under consideration for listing by the EPA.

ACKNOWLEDGMENT OF SUPPORT (4-9)
(BFAI 4.10)(SEP 10)

Publication of the results of this award is encouraged. The recipient shall include in any article or other announcement that is published an acknowledgment that the project was supported, in whole or in part, by BPA (award number may be included), but that such support does not constitute an endorsement by BPA of the views expressed therein.

DISPUTES (4-10)
(BFAI 4.10) (SEP 04)

(a) Except as otherwise provided in this award, any unresolved dispute concerning a question of fact arising under this award shall be decided by the Financial Assistance Officer (FAO), who shall reduce that decision to writing and mail, or otherwise furnish a copy thereof to the Recipient. The decision of the Financial Assistance Officer shall be final and conclusive. The FAO's decision may be appealed to the BPA HCA. The decision of the BPA HCA shall be final and conclusive.

(b) This clause does not preclude consideration of law questions in connection with decisions provided for in paragraph (a) above; provided, that nothing in this award shall be construed as making final the decision of any administrative official, representative, or board, based on a question of law.

(c) The use of alternate disputes resolution processes are encouraged, and may be used as negotiated between the parties.

TRAVEL (4-11)
(BFAI 4.10)(SEP 04)

(a) Domestic travel may be an appropriate charge to this award, and prior authorization for specific trips is not required. In accordance with the applicable cost principles, reasonable, necessary, and allowable travel costs may be charged on an actual basis or per diem basis in lieu of actual costs incurred, provided the method used results in charges consistent with those normally allowed by the organization in its regular operations and travel is at less than business class common carrier fare, unless otherwise approved in advance by the Financial Assistance Officer.

(b) Foreign travel may be charged to this award without prior approval if detailed in the approved budget. If foreign travel is required, but not detailed in the approved budget, it must be approved in writing by the Financial Assistance Officer prior to beginning the travel. Foreign travel will be reimbursed on the same basis as domestic travel.

PROJECT TECHNICAL REPRESENTATIVE (4-13)
(BFAI 4.10)(SEP 04)

(a) The Project Technical Representative (PTR) is the authorized representative of the Financial Assistance Officer (FAO) for technical actions performed in relation to the award. This includes the functions of (1) review of work performed; and (2) interpretation of technical program requirements.

(b) The PTR is not authorized to act for the FAO in the following matters: (l) modifications that change the amount of award, technical requirements or time for performance; (2) suspension or termination of the recipient's right to proceed; and (3) final decisions on any matters subject to appeal.

COST REIMBURSEMENT BASIS (4-15)
(BFAI 4.10)(SEP 04)

This award is funded on a cost reimbursement basis without fee or profit, not to exceed the amount awarded as indicated on the face page and is subject to a refund of unexpended funds to BPA.

SUSPENSION OR TERMINATION (4-17)
(BFAI 4.10)(SEP 04)

(a) Definitions.

(1) "Suspension" is an action by BPA that temporarily suspends BPA support under the award pending corrective action by the Recipient or pending a decision by BPA to terminate the award.

(2) "Termination" means the cancellation of BPA sponsorship, in whole or in part, at any time prior to the date of completion.

(b) Suspension or Termination for cause.

(1) Notice of Suspension. Prior to issuing a suspension notice, efforts will be made by BPA and the recipient to informally resolve disagreements. If informal efforts fail, BPA may issue a notice of suspension that specifies the date on which the suspension will take effect. During the suspension, BPA may withhold further payment and prohibit the recipient from incurring additional obligations of funds pending corrective action by the recipient or a decision by BPA to terminate. BPA shall allow all necessary and proper costs that the recipient could not reasonably avoid during the period of suspension provided that they would otherwise be allowable.

(2) Notice of Termination for Cause. Prior to issuing a termination notice, efforts will be made by BPA and the recipient to informally resolve disagreements. If informal efforts fail, BPA may issue a notice of termination that will take effect as stated in the letter. The Financial Assistance Officer shall determine the severity of the violation that caused the termination for cause, and determine what costs are appropriate for reimbursement.

(c) Termination for convenience. BPA or the recipient may request that the award be terminated in whole or in part when both parties agree that the continuation of the project would not produce beneficial results commensurate with the further expenditure of funds. The two parties shall agree upon the termination conditions, including the effective date and, in the case of partial terminations, the portion to be terminated. The recipient shall not incur new obligations for the terminated portion after the effective date, and shall cancel as many outstanding obligations as possible. BPA shall allow full credit to the recipient for the BPA share of the noncancellable costs, properly incurred by the recipient prior to termination.

(d) Authority to issue notices. The Financial Assistance Officer is the only person authorized to suspend or terminate the award.

CHANGE OR ABSENCE OF THE PRINCIPAL INVESTIGATOR OR DESIGNATED KEY PERSONNEL (4-18)
(BFAI 4.10)(SEP 04)

Since BPA funding of this project is based, to a significant extent, on the qualifications and level of participation of the Principal Investigator(s), or key personnel, a change of Principal Investigator(s), or key personnel, or their level of effort is considered a change in the approved project. The approval of BPA must be obtained prior to any change of the Principal Investigator or key personnel who have been identified as key personnel. In addition, any continuous absence of the Principal Investigator or key personnel in excess of 3 months, or plans for the Principal Investigator or key personnel to become substantially less involved in the project than was indicated in the approved application requires BPA prior approval. The recipient must contact the Financial Assistance Officer (FAO) immediately upon becoming aware that any of these changes are likely and must receive FAO approval before effecting any such change.

Robert Bass, Principal Investigator

Lee Sheldon, Co-Principal Investigator

REQUIREMENT FOR AUDIT (4-21)
(BFAI 4.10)(SEP 04)

The recipient is required to obtain an audit in accordance with OMB Circular A-133.

BUDGET CHANGES AND LINE ITEM TRANSFERS (4-26)M
(BFAI 4.10) (MAR 11)

If unanticipated project needs arise, the recipient is authorized to make Award Budget line item transfers not exceeding twenty (20%) percent of the total project buget. Reallocation of funds exceeding this amount must have the prior written approval of the FAO. The recipient shall send a written request for such budget changes to the FAO through the PM or PTR. The FAO will respond to the request within 30 days.

Recipients or subrecipients shall obtain prior approval whenever any of the following changes are anticipated:

(a) Changes in the scope or the objective of the project or program that will require a budget revision.

(b) The need for additional funding.

PERFORMANCE PERIOD (4-100)
(BFAI 4.10) (MAR 11)

(a) The work to be performed under the Cooperative Agreement shall commence on January 17, 2012 and shall continue to September 30, 2012.

(b) MULTIPLE STAGE GATES (Decision points)

(1) Stage gates are decision points for deciding whether the project should go ahead, be delayed, stopped or re-scoped. Stage gates occur at least once before the end of a project. Stage gates are based upon the essential performance elements (breakthroughs) that have to happen for the rest of the project to be worth doing and before the project can go any further.

(2) BPA will authorize performance of subsequent stage gates identified in the Project Description. In the event a determination is made to exercise a subsequent stage gate, the PTR or PM will issue a written authorization to proceed with work included in the subsequent stage gate. The PM/PTR's stage gate authority is limited to stage gates that have been funded. In the event of concurrent task or stage gate paths, multiple stages may be approved to proceed with in advance. For example, in the incorporated project description, tasks/stage gates 2, 3, 4 shall be approved to proceed once Stage Gate 1 has been approved. Budget available for reimbursement will be limited to the stages that have been approved.

(3) BPA's Technology Innovation Summit week is also a stage gate. During the week, project presentations are provided to BPA's Technology Confirmation Innovation Council by the principal investigators and should include project status, issues, next steps, financial status, etc... The Council will make a decision about whether the project should continue based on its progress and expectations of future progress.

(4) The decision to exercise a stage gate is a unilateral option reserved for BPA.

COST SHARE (4-101)
(BFAI 1.3.3) (OCT 11)

(a) BPA shall not pay any fee or profit to the Recipient for performing this project.

(b) The Recipient's cost share and any third party cost share contribution shall be verified by BPA before the BPA Cooperative Agreement is executed.

(c) BPA may fund up to 50 percent of a project's total cost to the Recipient or the amount identified in Unit 3 – Stage Gate Budget, whichever is less.

(d) Recipient shall notify the FAO in writing immediately in the event of a change to the cost share type, amount, or source.

(e) In the event of a reduction in the cost share, Recipient shall immediately notify FAO in writing and provide an action plan to secure replacement cost sharing. The notification shall indicate if the Recipient plans to either continue the project with a reduction in scope or end the project in the absence of cost sharing.

(f) Failure to obtain and maintain the required level of cost share during the project period of performance is grounds for Termination with Cause. BPA may Terminate this Cooperative Agreement for Cause per Clause 4-17 without notice if the Recipient is unable to obtain and/or maintain the required level of cost share during the project period of performance.

RESTRICTION ON CERTAIN FOREIGN PURCHASES (9-8)
(MAY 11) (BPI 9.3.2)

(a) Except as authorized by the Office of Foreign Assets Control (OFAC) in the Department of the Treasury, the Contractor shall not acquire, for use in the performance of this contract, any supplies or services if any proclamation, Executive order, or statute administered by OFAC, or if OFAC's implementing regulations at 31 CFR Chapter V, would prohibit such a transaction by a person subject to the jurisdiction of the United States.

(b) Except as authorized by OFAC, most transactions involving Cuba, Iran, and Sudan are prohibited, as are most imports from Burma or North Korea, into the United States or its outlying areas. Lists of entities and individuals subject to economic sanctions are included in OFAC's List of Specially Designated Nationals and Blocked Persons at *http://www.treas.gov/offices/enforcement/ofac/sdn*. More information about these restrictions, as well as updates, is available in the OFAC's regulations at 31 CFR Chapter V and/or on OFAC's website at *http://www.treas.gov/offices/enforcement/ofac*.

(c) The Contractor shall insert this clause, including this paragraph (c), in all subcontracts.

AUTHORIZATION AND CONSENT-RESEARCH, DEVELOPMENT, AND DEMONSTRATION CONTRACTS (17-1.1)
(OCT 11)(BPI 17.6.4.1.1)

(a) BPA authorizes and consents to all use and manufacture of any invention described in and covered by a United States patent in the performance of this contract or any subcontract at any tier.

(b) The terms of this clause shall apply to subcontracts at any tier whether or not incorporated into such subcontracts.

PATENT RIGHTS - OWNERSHIP BY THE CONTRACTOR (17-2.1)
(OCT 11)(BPI 17.4.1.1, BPI 17.5.2.8.1)

(a) Contractor's rights.

(1) Ownership. The Contractor may retain ownership of each subject invention throughout the world in accordance with the provisions of this clause.

(2) License. The Contractor shall retain a nonexclusive royalty-free license throughout the world in each subject invention to which the Government obtains title, unless the Contractor fails to disclose the invention within the times specified in paragraph (b) of this clause. The Contractor's license extends to

any domestic subsidiaries and affiliates within the corporate structure of which the Contractor is a part, and includes the right to grant sublicenses to the extent the Contractor was legally obligated to do so at contract award. The license is transferable only with the written approval of the agency, except when transferred to the successor of that part of the Contractor's business to which the invention pertains.

(b) Contractor's obligations.

(1) The Contractor shall disclose in writing each subject invention to the CO within 2 months after the inventor discloses it in writing to Contractor personnel responsible for patent matters. The disclosure shall identify the inventor(s) and this contract under which the subject invention was made. It shall be sufficiently complete in technical detail to convey a clear understanding of the subject invention. The disclosure shall also identify any publication, on sale (i.e., sale or offer for sale), or public use of the subject invention, or whether a manuscript describing the subject invention has been submitted for publication and, if so, whether it has been accepted for publication. In addition, after disclosure to the agency, the Contractor shall promptly notify the CO of the acceptance of any manuscript describing the subject invention for publication and any on sale or public use.

(2) The Contractor shall elect in writing whether or not to retain ownership of any subject invention by notifying the Contracting Officer within 2 years of disclosure to the agency. However, in any case where publication, on sale, or public use has initiated the 1-year statutory period during which valid patent protection can be obtained in the United States, the period for election of title may be shortened by the agency to a date that is no more than 60 days prior to the end of the statutory period.

(3) The Contractor shall file either a provisional or a non-provisional patent application on an elected subject invention within 1 year after election. However, in any case where a publication, on sale, or public use has initiated the 1-year statutory period during which valid patent protection can be obtained in the United States, the Contractor shall file the application prior to the end of that statutory period. If the Contractor files a provisional application, it shall file a non-provisional application within 10 months of the filing of the provisional application. The Contractor shall file patent applications in additional countries or international patent offices within either 10 months of the first filed patent application (whether provisional or non-provisional) or 6 months from the date permission is granted by the Commissioner of Patents to file foreign patent applications where such filing has been prohibited by a Secrecy Order.

(4) The Contractor may request extensions of time for disclosure, election, or filing under paragraphs (b)(1), (b)(2), and (b)(3) of this clause.

(c) Government's rights—

(1) Ownership. The Contractor shall assign to the agency, on written request, title to any subject invention—

(A) If the Contractor fails to disclose or elect ownership to the subject invention within the times specified in paragraph (b) of this clause, or elects not to retain ownership; provided, that the agency may request title only within 60 days after learning of the Contractor's failure to disclose or elect within the specified times.

(B) In those countries in which the Contractor fails to file patent applications within the times specified in paragraph (b) of this clause; provided, however, that if the Contractor has filed a patent application in a country after the times specified in paragraph (b) of this clause, but prior to its receipt of the written request of the agency, the Contractor shall continue to retain ownership in that country.

(C) In any country in which the Contractor decides not to continue the prosecution of any application for, to pay the maintenance fees on, or defend in reexamination or opposition proceeding on, a patent on a subject invention.

(2) License. If the Contractor retains ownership of any subject invention, the Government shall have a nonexclusive, nontransferable, irrevocable, paid-up license to practice, or have practiced for or on its behalf, the subject invention throughout the world.

(d) Contractor action to protect the Government's interest.

(1) The Contractor shall execute or have executed and promptly deliver to the agency all instruments necessary to—

(A) Establish or confirm the rights the Government has throughout the world in those subject inventions in which the Contractor elects to retain ownership; and

(B) Assign title to the agency when requested under paragraph (d) of this clause and to enable the Government to obtain patent protection for that subject invention in any country.

(2) The Contractor shall require, by written agreement, its employees, other than clerical and nontechnical employees, to disclose promptly in writing to personnel identified as responsible for the administration of patent matters and in the Contractor's format, each subject invention in order that the Contractor can comply with the disclosure provisions of paragraph (c) of this clause, and to execute all papers necessary to file patent applications on subject inventions and to establish the Government's rights in the subject inventions. The disclosure format should require, as a minimum, the information required by paragraph (c)(1) of this clause. The Contractor shall instruct such employees, through employee agreements or other suitable educational programs, as to the importance of reporting inventions in sufficient time to permit the filing of patent applications prior to U.S. or foreign statutory bars.

(3) The Contractor shall notify the Contracting Officer of any decisions not to file a nonprovisional patent application, continue the prosecution of a patent application, pay maintenance fees, or defend in a reexamination or opposition proceeding on a patent, in any country, not less than 30 days before the expiration of the response or filing period required by the relevant patent office.

(4) The Contractor shall include, within the specification of any United States nonprovisional patent and any patent issuing thereon covering a subject invention, the following statement, "This invention was made with Government support under Agreement 56104 awarded by the Bonneville Power Administration. The Government has certain rights in the invention."

(e) Reporting on utilization of subject inventions. The Contractor shall submit, on request, periodic reports no more frequently than annually on the utilization of a subject invention or on efforts at obtaining utilization of the subject invention that are being made by the Contractor or its licensees or assignees. The reports shall include information regarding the status of development, date of first commercial sale or use, gross royalties received by the Contractor, and other data and information as the agency may reasonably specify. The Contractor also shall provide additional reports as may be requested by the agency in connection with any march-in proceeding undertaken by the agency in accordance with paragraph (f) of this clause. The Contractor also shall mark any utilization report as confidential/proprietary to help prevent inadvertent release outside the Government. As required by 35 U.S.C. 202(c)(5), the agency will not disclose that information to persons outside the Government without the Contractor's permission.

(f) March-in rights. The Contractor acknowledges that, with respect to any subject invention in which it has retained ownership, the agency has the right to require licensing pursuant to 35 U.S.C. 203 and 210(c), and in accordance with the procedures in 37 CFR 401.6 and any supplemental regulations of the agency in effect on the date of contract award.

(g) Subcontracts. The Contractor shall include the substance of this clause in all subcontracts.

PATENT AND COPYRIGHT INFRINGEMENT NOTICE (17-13)
(OCT 11)(BPI 17.6.4.3.1.1)

(a) The Contractor shall report to the CO, promptly and in reasonable written detail, each notice or claim of patent or copyright infringement based on the performance of this contract of which the Contractor has knowledge.

(b) In the event of any claim or suit against BPA on account of any alleged patent or copyright infringement arising out of the performance of this contract or out of the use of any supplies furnished or work or services performed under this contract, the Contractor shall furnish to BPA, when requested by the CO, all evidence and information in the Contractor's possession pertaining to such claim or suit. Such evidence and information shall be furnished at the expense of BPA except where the Contractor has agreed to indemnify BPA.

(c) The terms of this clause shall apply to subcontracts at any tier whether or not incorporated into such subcontracts.

UNIT 2 – PROJECT DESCRIPTION

1. GOAL AND SCOPE OF THIS AGREEMENT

The Goal of this Agreement is to develop the most effective software possible for multilevel hydropower optimization. The Scope is limited to utility-scale hydropower projects with three or more turbines. The first six Tasks concern only a stand-alone decision support tool. Success of Tasks 1 through 6 will fulfill criteria for all five Roadmap Targets for Hydropower:

- Enhance the future FCRPS reliability, operation, and maintenance for an increasingly complex operation
- Design operational improvements to reduce costs
- Maximize existing asset use and extend useful life of assets
- Decrease the FCRPS environmental footprint
- Increase generation efficiency (increased power per unit of water)

2. BACKGROUND

Optimization is the process of tuning a system to create the best output for a given input. In hydropower that means producing the most power for a given volumetric flow rate of water; or using the least water to produce a given amount of power at any given head. When discussing the various levels of hydropower optimization, we assume a constant head since various reservoir rule curves do not provide for maximizing head.

Since all elements of a power system are connected and work together, that optimization has several levels. There are now five recognized Types of optimization. For example, Kaplan turbines produce the most power when the blades are at the proper angle for a given flow. This (Type 1) optimization requires index testing and recording the best blade angle-to-wicket gate relationship for all possible heads for every turbine. Other kinds of turbines, such as the Francis variety, have fixed runners. For these turbines, Type 1 consists of just the index test to determine the relative efficiency profile. Lee Sheldon, PE, one of two Principle Investigators in this team has decades of experience performing Type 1 optimization.

Type 2 optimization concerns unit selection and load sharing in the whole powerhouse. We recently developed a new method for calculating Type 2 hydropower optimization with a new, very fast computer program.

To appreciate the value of Type 2 hydropower optimization, it helps to understand that every turbine in a powerhouse is slightly different. Although all the turbines in a powerhouse have the same specifications by design, differences in manufacturing tolerances result in differences in unit operating efficiencies in the range of somewhere between one and five percent. Further, years of operation tend to exacerbate the differences in performance between turbines. Every turbine has an efficiency profile that varies across its range of flow. In powerhouse documentation, the performance profiles of each individual turbine are often available in a stored database. When the grid operator determines a mega-watt set-point for the project, the powerhouse operator can choose to have some turbines on-line and some turbines off-line, a process called **unit selection**. The next parameter to determine is **load sharing**. The best load sharing is achieved when the wicket gate opening for each turbine is set such that the power output is met with the smallest total flow rate.

Both decisions are much more difficult to make than it may seem. Even a skilled operator may underutilize up to 5% of the water available for generation due to less than perfect unit selection and load sharing. During conditions when water is spilled, that 5% may not make a lot of difference. However, when the flow of the river is low enough to be insufficient to meet net energy demand, that 5% represents a corresponding loss of potential in revenue. At worst a project may even lose the generation equivalent to 10% of the flow. Under many conditions that will mean a corresponding 10% loss in revenue. Especially from late August to October, with future potential of further reduced flow, **maximizing optimization algorithms for hydro-power can essentially help build generating power for these times**. Even when there is plenty of water in the river, a project run at optimal power rather than at full gate can generate the same amount of power with less wear on machinery.

3. LOCATION OF PROJECT (IF SITE-SPECIFIC)

Part of the program validation, index testing, and training will happen at a suitable hydro-power project at site as determined in Task 1. Such a project will preferably be located within the BPA service area of the Pacific North West, but not limited to that area.

Other parts of the Project such as data reduction, computer programming, engineering, documentation, and so on will happen on the PSU and OIT campuses.

4. DOCUMENTATION

The Hydropower Team will commit to documentation consistent with the desired format and regularity requested by BPA for TI Projects.

(The Team consists of Lee Sheldon and Robert Bass, the Co-PIs; Michael Curtiss and Jonas Parkers, PSU Research Associates; and Greg Ripplenger, an OIT Undergraduate Research Assistant. Responsibilities of the Hydropower Team members are detailed in section 3.d.A.)

5. GENERAL REQUIREMENTS

Successful completion of the project will require the team to locate a suitable hydro-power project. In the event that a suitable project is impossible to access, the project stops in accordance with Stage Gate 1 criteria. Since we have tested the program, and also due to Lee's decades in hydropower optimization, the Project has the highest probability of success if we have a hydro-power project to work with.

6. METHODS TO BE USED

Methods to be used include Index Testing (if necessary), data reduction and organization in Excel, MATLAB and/or Octave scripting, Java and PHP programming, calculations by hand and more traditional engineering tools, and research using all available media.

7. SPECIFIC REQUIREMENTS

A. Objectives

1. Identify a hydropower project for index testing, and collect data
2. Manually determine optimal load sharing and unit selection, for low, medium (if possible), and high head
3. Validate the computer algorithm using the hand-calculated results
4. Modify script to incorporate more features: curvilinear interpolation, block loading, alarms
5. Develop a graphical front end for stand-alone use and also demonstrate as a SCADA solution
6. Documentation, operational instructions, and operator training. Explore commercialization.

First, the team will validate the computer program that it has created to date. The program inputs power versus flow data for all the individual turbines in a power-house. It outputs recommended gate openings that will meet a given demanded power output using the least amount of flow.

Presently the program is a stand-alone tool that provides decision support. We would like to further test the accuracy of that decision support. Then we will modify the program according to the needs of the operator, and finally provide the necessary documentation and training. The validation will follow the Tasks outlined below.

B. Description of tasks

1. Identify a Suitable Hydro-power Project

A suitable project will have a minimum of three Francis-type turbines. Ideally the turbines will have their index tests up to date. Team members will communicate with dam owners and travel to suitable projects. After visiting multiple sites, the team will choose the best hydro-power project. The team expects that it may take considerable time and effort to find a facility that has both the desired characteristics and consent of the owner.

2. Obtain Performance Data

If the project has undergone recent index testing, performance data should exist for each turbine. If no data or only limited data is available, the optimization team is prepared to perform index testing. To perform index testing on all units within the powerhouse, Lee Sheldon, with assistance from Parker and Ripplenger, will use operating data to record power versus flow for each turbine.

3. Verification Phase: Validate Algorithm

The Hydropower Team will use the performance data to verify the program. During this phase, we will compare gate openings that the program recommends to the actual set-points used by the operator on each turbine. The computer program will calculate the difference in efficiency in terms of power versus volumetric flow rate.

The program will be judged successful based on two criteria. First, the program must be able to compute acceptable unit allocation and load sharing solutions in a timely manner; ie. the program solution should arise in near-real time such that an operator can implement the program recommendations prior to changes in head/flow and power conditions. Second, for a given mega-watt set point, the program should provide allocation/sharing solutions that maximize powerhouse efficiency. As a metric, the program output needs to be compared to the allocation/sharing decided upon by operators. Figure 1 compares optimized to a simulation of random unit selection and identical load sharing between turbines, clearly a non-optimized set of solutions. Development of a proper metric will require an understanding of the efficiency curves achieved by current allocation/sharing practice.

Figure 2 depicts the original sixteen units at The Dalles as they were tested by current meters in about 1967. The upper curve is the optimum unit selection and optimum load sharing. In other words, it is the very best that powerhouse could have done. (This curve was calculated by hand by Lee Sheldon, and is the same as the black curve in Figure 1 that was calculated using the SQL algorithm). The lower curve is the optimum load sharing, but with the worst unit selection. Where the two lines join, every unit is on line and therefore unit selection is no longer relevant. If one assumes a random probability of unit selections, then the average operation is the difference between the two. This graph therefore shows the benefit from knowing which units to bring on and off line at a particular powerhouse load set point. The difference between these curves is shown in Figure 3 (blue dotted data set, black trend line). The efficiency gains when the powerhouse output is less than around 700 MW are therefore likely to be greater 0.25-0.5%. Optimum load sharing versus average load sharing would show a similar magnitude of benefit.

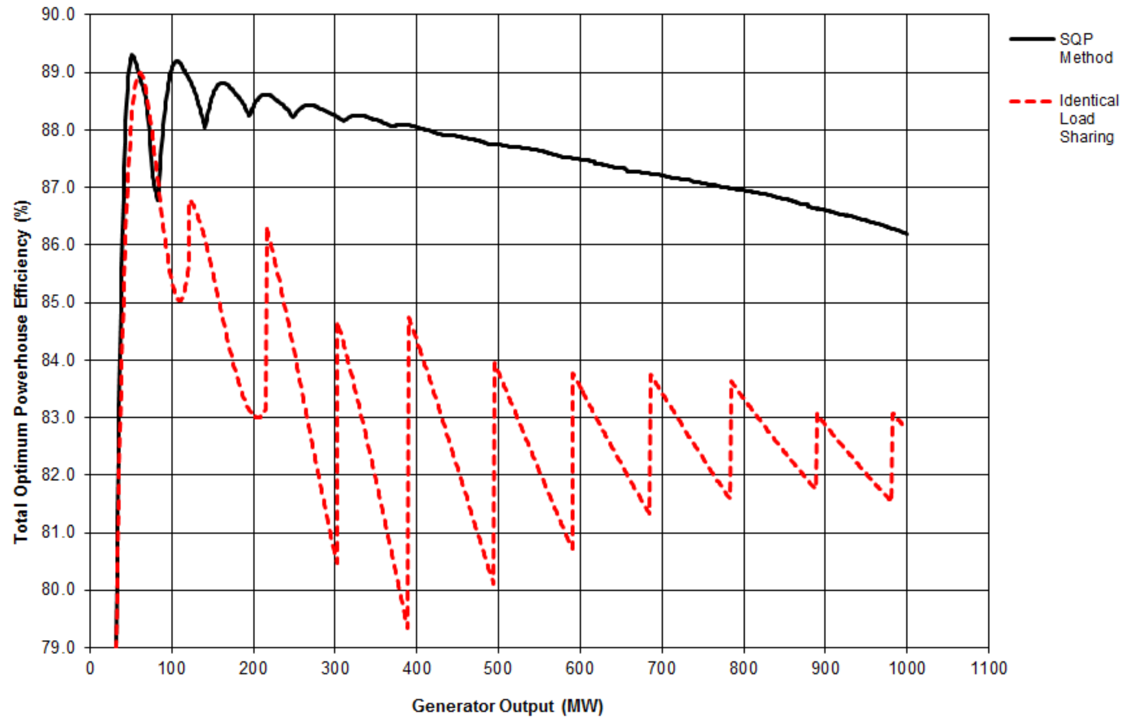

Figure 1 Simulation of identical load sharing between turbines (dashed red) plotted against the optimal solution achieved by the SQP algorithm (solid black).

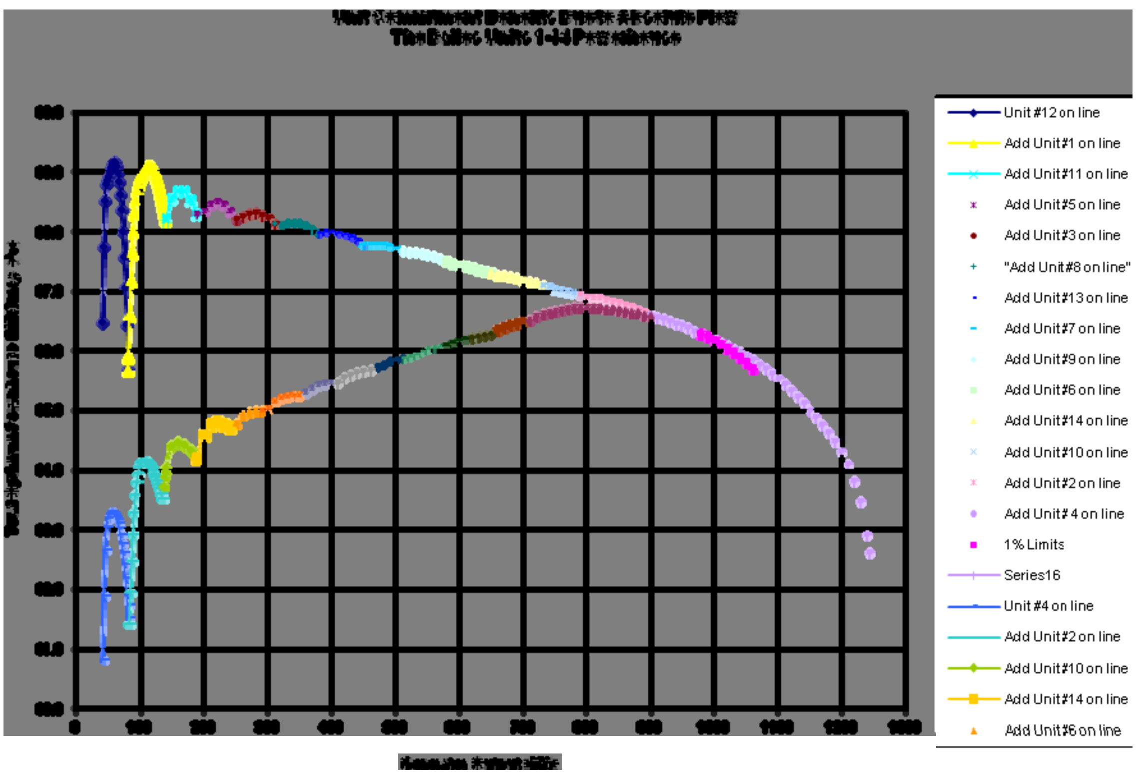

Figure 2 Efficiency curves for optimal unit selection (top curve) and worst-case unit selection (bottom curve). In both cases, load sharing is optimized. Non-optimal unit selection would result in a curve between these two extremes.

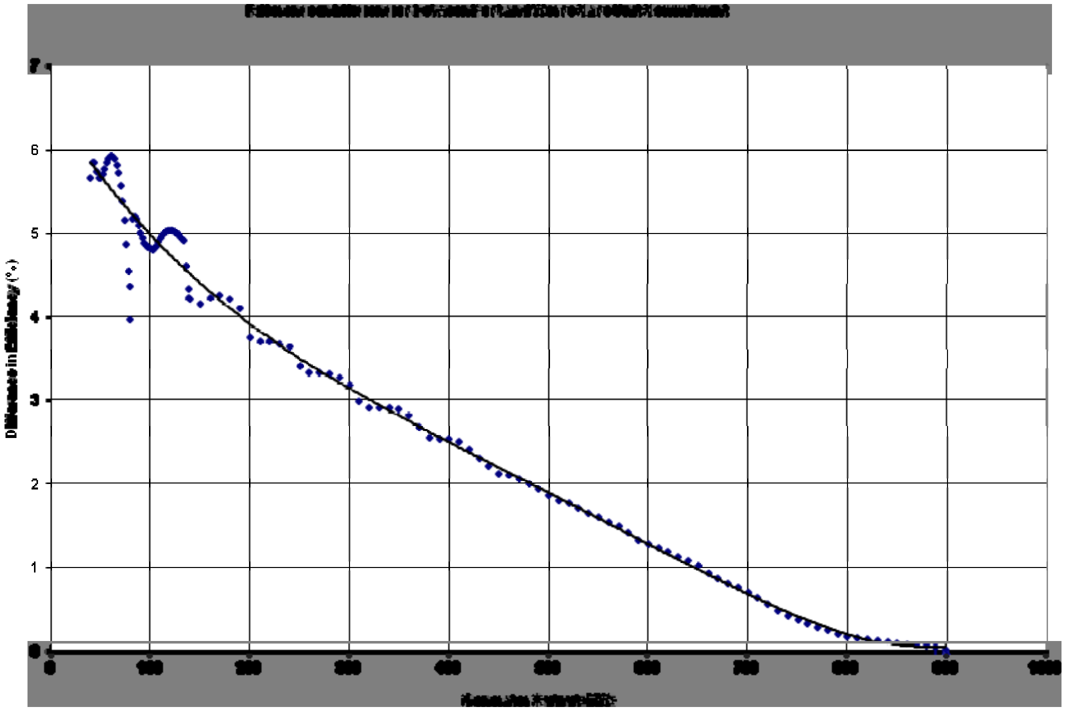

Figure 3 Difference in efficiency between best case and worst case unit selection (load sharing optimized in both cases). Efficiency gains are significant when powerhouse output is less than 700 MW.

Regarding fish survivability, studies by Milo Bell and others have noted that powerhouses running near optimal turbine efficiency maximize survivability. This research was the motivation behind Judge Redden's decision within the 2008 FCRPS Biological Opinion to require powerhouse output to run within 1% of peak turbine efficiency. Improvements in efficiency should lead to increased survivability.

4. Front End Development

Having verified the back end of the program, the team will modify the front end human-machine interface (HMI), of the program to suit the user (hydro-power dam operator). When we get to this point we will know what these front-end modifications may entail. For instance, the operator may prefer that the program express turbine set-points in terms of servo-stroke instead of power output, though the two quantities are directly linked computationally. Various modifications to the computer program can be made to suit the particular dam. The same algorithm can be applied to other important variables in the power system: such as the electrical dead-band in the generators; and improved load forecasting for the dam using a neural networking program.

For the design of the program HMI, cooperation between the Hydropower Team and hydro facility engineers and operators will be essential. The HMI will be designed to accommodate their requirements and address their concerns. We envision this program as a tool for everyday use by system operators, so the HMI design must focus on enhancing their productivity.

One such feature to include is a setpoint for maintaining some amount of spinning reserve. From the HMI, an operator could set a reserve margin, defined either as some fraction of peak power or a specific MW capacity. The algorithm would then optimize unit selection and load allocation based on this additional constraint.

5. Documentation

The team will document the test (Gate 3) and also document the newly modified code that resulted from Gate 4. The Hydropower team will formally transfer all knowledge gained from the first four

Tasks to the owners and operators of the hydropower project and to BPA. The documentation will consist of an 'Operator's Guide' that details the program operation and describes the HMI.

6. Training

If the project is successful according to the needs of the dam and/ or BPA, and if time permits, the Hydropower team will provide on-site operator training to system operators.

C. Project Management Protocols

1. Communications plan

All Key members and the Principle Investigators will meet once a week to discuss progress. Members will each produce a short report for each meeting, or longer if required for that week. The team will produce full reports for BPA at each Stage Gate.

The Hydropower Team will publish any significant or interesting details of the project in a journal such as Hydropower Review, or may present results at conferences such as Hydrovision.

In addition, the Hydropower Team will commit to any schedule and format for reporting to BPA that BPA requests.

2. Contingency plan

If we are unable to gain access to data from an active hydropower project:

The least certain part of the project is Task 1: identifying a suitable hydropower project and the consent of the owner of the dam. We have allotted significant time to this task. In the event that Task 1 is not attainable, the project will stop.

3. Stage Gate Requirements

Four critical Stage Gates have been identified:

Stage Gate 1: Identify a suitable Multi-unit hydroelectric facility and execute a contractual agreement with the Corps, BOR, PGE, Pacific Corp or another dam-owning entity within 60 days. If no project is identified, the project stops.

Acceptance Criteria:
- Hydro-power project identified – include a schedule for specific activities.
- Description of test procedure for acquiring index test data
- Understanding of S/W (front and back end) ownership
- Understanding of ownership of index data
- Document our ability to modify S/W for multiple/any BPA hydro project

Stage Gate 2: Obtain Performance Data

Acceptance Criteria:
- Document test cases
- Provide algorithm results for each test case and compare to known solutions. Determine if this is acceptable performance
- Compare against acceptance criteria established in Task #3

Stage Gate 3: Following Task 3, we will have proof of concept, and any newly identified functionality will have been built into the back end.

Acceptance Criteria:

- Back-end functionality suitable for providing near-real unit allocation and load sharing solutions.
- Efficiency of the SQP solution compared to results from current operational procedures.

Stage Gate 4: Evaluate progress of the HMI, and assess any issues that may have arisen. Determine whether the option for integration into existing systems is available.

Acceptance Criteria:

- Front-end functionality meets the need of hydro facility operators and engineers

Stage Gates 5 and 6: Documentation and Training.

Acceptance Criteria:

- Report delivered to BPA discussing in detail the progress made during Stage Gates 1 through 4.
- Training packet provided to operational personal interested in using the program. The training packet, the 'Operator's Guide' would consist of an operator manual and documentation describing the operation of the software and the HMI.
- If time permits, on-site training program will be provided to explain the operation of the software and HMI. If so desired, a seminar describing SQP theory could be offered.

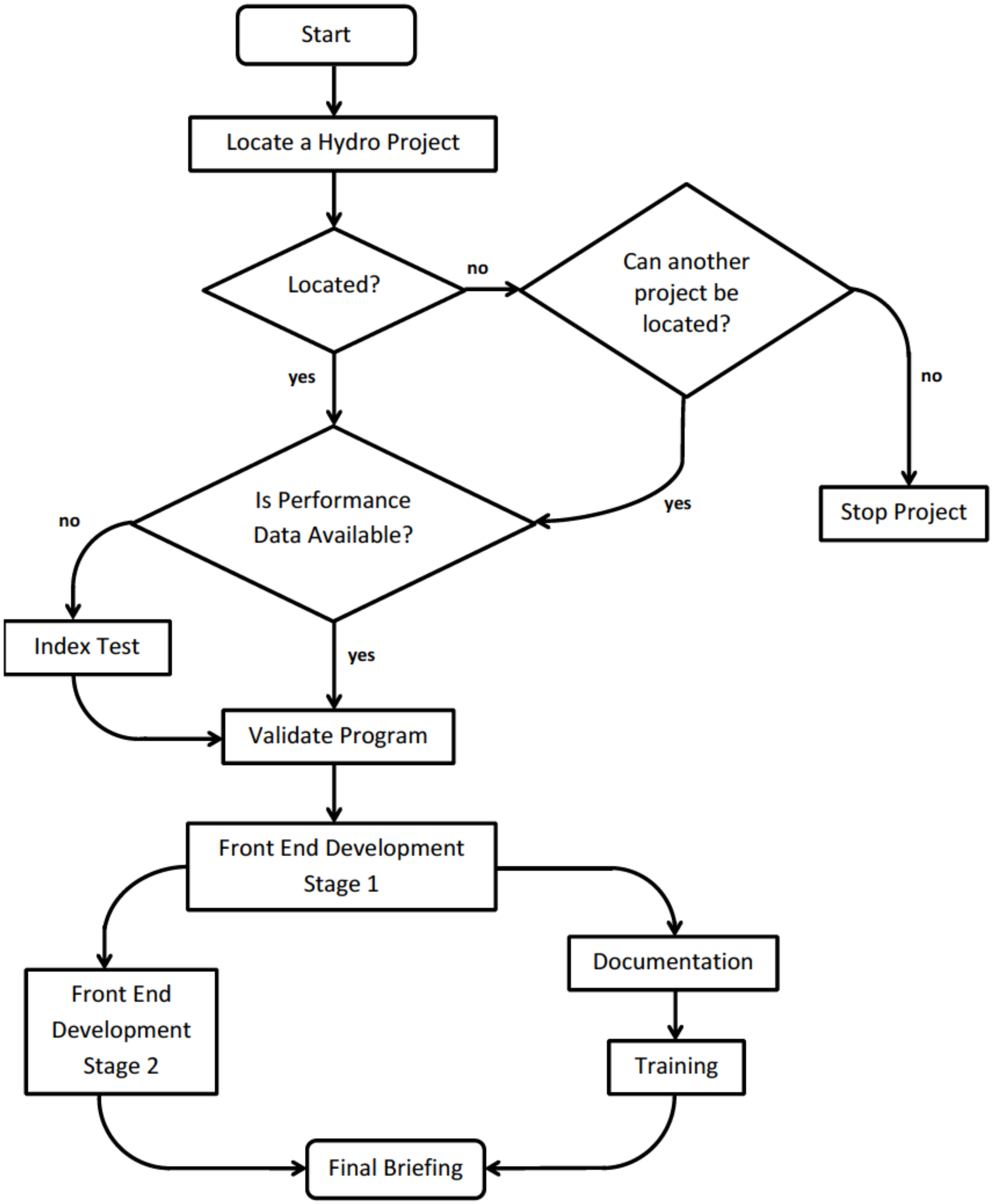

Figure 4 Process flow chart

Stage gate criteria are clearly noted in Section C.3 on pages 18/19.

4. Technology Transfer

The Hydropower group will transfer to BPA the means and methods by which to optimize any similar hydro-power project. From previous experience and testing, we believe the results will be efficient and excellent, especially for hydro projects that experience reduced flow during some part of the calendar year. Ownership of previously written computer code is protected by a provisional patent. However, a new HMI and new functionality will be developed during the term of this project, which BPA will have the right to use. The package consisting of the previously-developed core code, the new HMI and the additional functionality constitute the technology innovation that is the focus of this project. Any future use of the deliverables will be in accordance with the terms and conditions of the agreement and the project description.

D. Deliverables

1. Updated and Modified Type 2 Hydropower Optimization Software
   - Ownership of previous code is protected. However, the newest version containing all necessary useable code will be made available for use by BPA via license agreement in accordance with the terms and conditions.
   - Several formats/ programming languages available including Web-based program and executable files
   - Includes user-friendly Graphical User Interface (GUI)

2. Knowledge Transfer of Hydropower Optimization Methodology, Type 1 and Type 2
   - Includes training personnel from BPA and from selected dam, if time permits
   - Includes 'Operator's Guide'

3. Standard Deliverables as Expected by BPA including but not limited to:
   - All supporting data in an electronic format acceptable to BPA
   - Expected functionality and support of any hardware and/or software as applicable along with full documentation of its use and repair, as acceptable to BPA
   - Expected performance standards
   - How the proposed project could be integrated into BPA's Power Delivery System
   - How established utility processes and procedures will be impacted
   - The appropriate testing and/or evaluation methodology if applicable
   - A final report including next steps for the project or potential follow-on projects

E. Time Schedule

Task 1: Identify a Suitable Hydro-power Project, 60 working days/12 wks
Task 2: Obtain Performance Data, 62 working days/12.4 wks
Task 3: Verification Phase: Program Validation, 14 days working
Task 4: Front End Development, 164 working days (Overlaps with Documentation) = 30 working days/6 wks
Task 5: Documentation, 10 workin gdays/2 wks
Task 6: Training, 30 workn gdays/6 wks
Total project duration is six months (several tasks overlap)

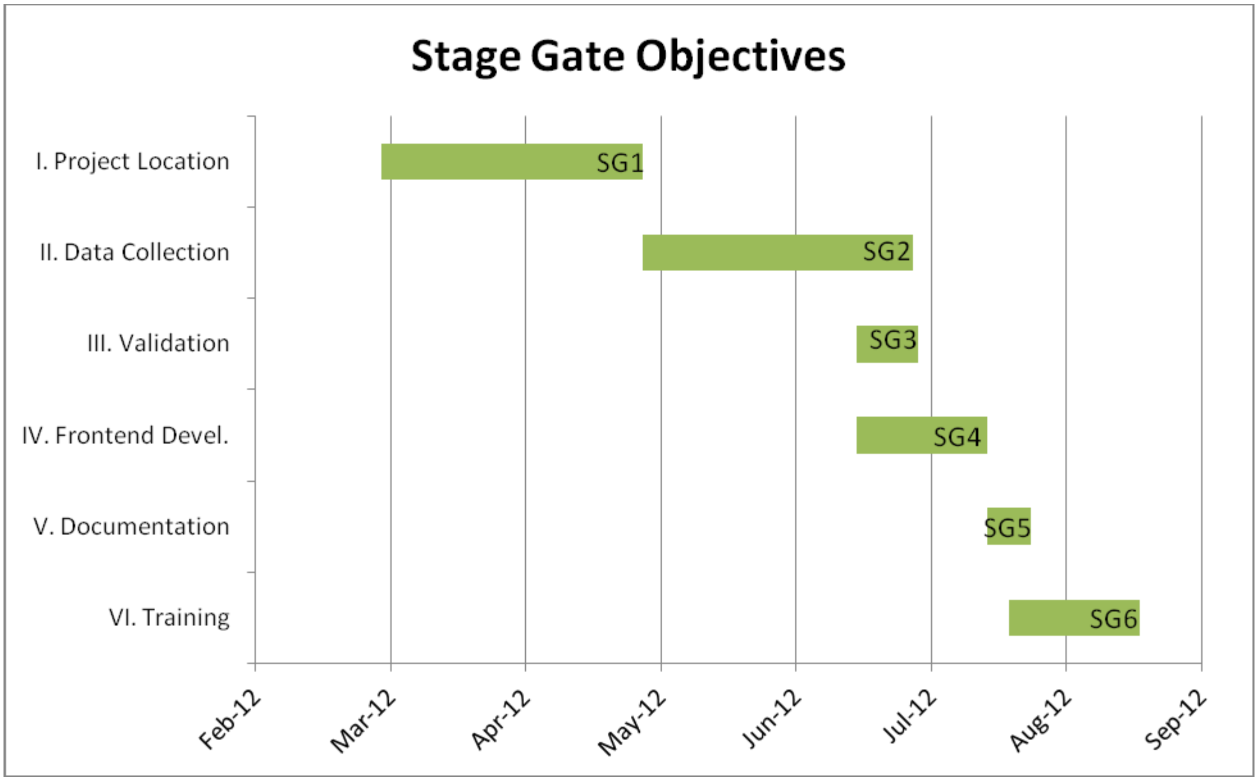

Figure 5 Gantt Chart outlining the six stage gate activities.

UNIT 3 – BUDGET

COST SHARE CONTRIBUTION

Project Year	Requested BPA Cost Share Contribution	Offerors Cost Share Contribution	Third Party Cost Share Contribution – Cash	Third Party Cost Share Contribution – In Kind	Total Project Cost
1	$59,103	$60,092	$0	$0	$119,195
Total	$59,103	$60,092	$0	$0	$119,195

STAGE GATE BUDGET (For estimates of spend by Stage)

Stage	Labor	Fringe Benefits (OPE)	Travel	Subcontract	Equipment/ Supplies	Indirect costs	BPA Share	Project total
Task 1 – 60 Work Days from Award – **Stage Gate 1**	$5,678.00	$1,319.00	$6,000.00	$ 5,534.56	$15,100.00	$13,251.47	**$17,346.00**	$46,883.03
Task 2 – 62 Work Days from the end of Task 1	$5,678.00	$1,318.00	$2,500.00	$ 5,534.57	$0	$5,129.52	See below	See below
Task 3 – 14 Work Days	$4,731.00	$1,098.00	$0.00	$ 4,611.18	$0	$3,472.98	See below	See below
Task 4 – 30 Work Days	$3,785.00	$878.00	$0.00	$ 3,689.23	$0	$2,778.38	See below	See below
Stage Gate 2,3,4 Subtotal							**$25,177.00**	$45,203.86
Task 5 - 10 Work Days from the end of Task 4 **Stage Gate 5**	$3,785.00	$878.00	$0.00	$ 3,689.23	$0	$2,778.38	**$5,744.00**	$11,130.61
Task 6 – 30 Work Days	$3,785.00	$878.00	$3,500.00	$ 3,689.23	$0	$4,125.27	**$10,836.00**	$15,977.50
Total	$27,442.00	$6,369.00	$12,000.00	$26,748.00	$15,100.00	$31,536.00	**$59,103.00**	$119,195.00

AWARD BUDGET

	Cost Share	BPA Share	Total
Personnel	$18,162.00	$ 9,280.00	$ 27,442.00
Fringe	$ 5,538.00	$ 831.00	$ 6,369.00
Travel	$ -	$12,000.00	$ 12,000.00
Subcontract	$ 8,238.00	$18,510.00	$ 26,748.00
Equipment	$15,100.00	$ -	$ 15,100.00
Supplies	$ -	$ -	$ -
IDC	$13,054.00	$18,482.00	$ 31,536.00
	$60,092.00	$59,103.00	$119,195.00

Index Testing and Multi-Unit Optimization of a Hydropower Powerhouse

BPA TI Opportunity FY12, Phase 1 Application

Jonas Parker, Principle Investigator

5/5/2011

There is no less expensive way to add power to the grid than to adjust the machines that are already on-line to make them more efficient. One may assume that most of today's generating units have already been tuned to produce the most power at the least cost, but in hydro-power that is not the case. A little insight into the way hydraulic turbines behave; coupled with some relatively straight forward programming techniques; can yield stunning improvements in efficiency not yet realized in many systems. Optimization is the lowest cost, highest return, cleanest new energy source available today. In this paper we show how cost function minimization can be used to improve the performance of a whole hydroelectric powerhouse.

B.1 CONCEPT PAPER

The Oregon Institute of Technology Renewable Energy Engineering Department has a team of one Professor and four students that is now uniquely qualified and prepared to perform and formalize perfect, **multilevel optimization of hydropower powerhouses**.

The ideal optimization of a powerhouse is two-fold. **First, an index test must be performed on every turbine** in the powerhouse. **Second, an algorithm needs to be calculated to optimize all the turbines in the entire powerhouse** so they work together to meet the load at the least flow.

An index test does two things: it perfects the blade angle of a Kaplan turbine for every possible flow, and generates an efficiency profile for every turbine in a power house. Professor Lee Sheldon, former BPA and Army Corps of Engineers employee, has performed this procedure on about fifty dams.

Since the efficiency profiles for the many turbines in a power house are a little different from each other, there always needs to be a way of determining how they should share the load for all possible power outputs for the whole dam. Every turbine will have a different set of power outputs across the range of possible gate openings. Thus, each turbine will also have its own efficiency profile. When the grid operator determines a mega-watt set-point for the project, the powerhouse operator can choose to have some turbines on-line and some turbines off-line, a process called unit selection. The next parameter to determine is load sharing. The best load sharing is achieved when the wicket gate opening for each turbine is set such that the power output is met with the smallest total flow rate.

One of Lee's hydropower students, Michael Curtiss, succeeded in finding a direct solution to this problem; that accomplishment stands in contrast to the usual iterative solution used by other programs. A two hour computational problem (even for professional software at this time) was reduced to a matter of seconds. Subsequently, the program was translated into an open source computing language, and a group of 4 students continued on to write a paper on the program that has been submitted to Hydro Review, the international magazine on hydropower.

This program has been tested directly against accepted optimizations done by hand, and it succeeds every time with a high level of speed and accuracy. We show the results in the attached paper.

It is now time to formalize a procedure for optimizing entire hydropower power-houses. This procedure will include performing the index test as well as providing the decision support tool for coordinating turbines in the entire powerhouse.

The first step is to find a suitable project with multiple generating units. We shall perform an index test on all the turbines in a dam. Lee has spent his career perfecting this procedure and will provide references to that effect. Little will be required in the way of materials, and the labor will be provided by

Professor Sheldon and students for this step. All guidelines regarding index testing per the various regulatory bodies will be followed.

After completing the index test the second level of optimization will be performed. This (Type 2) optimization consists of coordinating all the turbines in a powerhouse to meet any power output set-point. The team will provide a program on a laptop that aids the operator in finding the right gate openings amongst all the turbines available for use. The program will show the operator how to meet the power demand while using the least amount of water, which will be very useful at all times but of greatest value during the summer and other times of reduced flow.

 A technology or a technology gap identified in a technology Roadmap

FCRPS Targets Addressed

1. Maximize existing asset use and extend useful life of assets

Index testing and Type 2 optimization both have the added benefit of lengthening the life of the runners. Operators will no longer need to run individual turbines at their maximum to achieve the desired power output. Eliminating the vibrations that come from running systems at full power will reduce wear and tear on wicket gates, turbines, seals, controls, housing, and so forth.

2. Increase generation efficiency (increased power per unit of water).

There is no less expensive way to add power to the grid than to adjust the machines that are already on-line to make them more efficient. One may assume that most of today's generating units have already been tuned to produce the most power at the least cost, but in hydro-power that is rarely the case. A little insight into the way hydraulic turbines behave; coupled with some relatively straight forward programming techniques; can yield stunning improvements in efficiency not yet realized in many systems. Optimization is the lowest cost, highest return, cleanest new energy source available today. In this project we will demonstrate how cost function minimization can be used to improve the performance of a whole hydroelectric powerhouse.

Technology Gaps Addressed

1. Software tools for system performance and online real time operations

The SQP solution already achieved by this group was written in Octave, an open source numerical programming language. The program takes only TWO SECONDS to find optimal unit selection and load sharing for any given set-point in a powerhouse with ten turbines. This increase in computational speed may represent a breakthrough that will soon allow continual Type 2 hydropower optimization to occur in real time.

2. Advanced optimization

Index testing is an extremely worthwhile procedure which has not been performed on most dams. The index test is a foundation for further levels of optimization.

A second level of optimization requires advanced programming techniques to achieve perfect unit selection and load sharing. The fastest method to date available for this purpose is called Sequential Quadratic Programming (SQP). SQP uses Newton's Method and Taylor series expansion to directly solve a set of unconstrained, convex curves by applying a global constraint and an educated first guess. A hydro unit's flow versus power curve is sufficiently smooth such that it can be approximated with a high order quadratic polynomial. This simplified mathematical characteristic makes the hydro turbine an ideal candidate for this kind of cost function minimization. **The students of this team have already perfected such a solution** in a computer program that has been verified.

B.2 SUMMARY OF THE WORK PLAN

Research and Development Phase

Completed Already this 3/2011

Demonstration Phase

Week 1-2

Identify a suitable project with multiple generating units. Since most projects do not have performance profiles to a high degree of accuracy, index testing a select group of units will likely be necessary.

Week 3-4

Perform Index Test on the project that was selected

Weeks 4-6

- Run the Type 2 optimization program using data from the Index Test
- Verify the Results
- Load the results on a laptop for operator use
- Publish a manual for operator to use
- Publish procedure for BPA use
- Publish the Results of Generation Increases for BPA and for Hydropower Conferences

B.3 COST SHARE

The required 50% cost-share for the project will be addressed by in kind labor contributions by OIT Professor Lee Sheldon and three other students.

The labor offset provided by us will be calculated according to industry standard for work done by the PE, and also for work done by technical staff (two or three students.)

If the project takes 6 weeks, each member expects to provide 3 weeks of free engineering time.

B.4 STATEMENT OF QUALIFICATIONS

Applicant Organization:

OIT Office of Strategic Partnerships
OIT Portland East
7726 SE *Harmony* Road
Portland, OR 97222

Principle Investigator:

Jonas Parker
Senior REE at OIT
Jonas.parker@oit.edu
[redacted]

This team is particularly qualified to providing both Type 1 and Type 2 levels of optimization for three reasons:

1. Professor Sheldon's lifetime of experience and success at this process
2. The ability of students to put that expertise into fast, accurate computer programs
3. The outputs of the program matches the best hand calculation exactly

The further verification of the procedures developed by this team on a real dam has the highest probability of success for the dam itself and for the continuing development of hydropower optimization within the BPA.

The proof of the high likelihood of success is offered in the following ways:

1. Lee Sheldon's distinguished working record at the Army Corps of Engineers among other organizations listed in his resume
2. In the attached paper that documents how sequential quadratic programming techniques have been brought to bear on some of Lee's experience
3. The Type 2 optimization program that itself is available for a live demonstration upon request.

Overview of the applicant organization and the project team

Applicant Organization:

OIT Office of Strategic Partnerships

The mission of the OIT Office of Strategic Partnerships is to build partnerships with industry, business, and education partners that result in applied research and learning opportunities for students and faculty. The Office of Strategic Partnerships strives to add value for industry partners, increase revenue for the university, and build greater awareness about OIT and the expertise of its students and faculty.

The Office of Strategic Partnerships is responsible for:

1. Developing public-private partnerships that result in tangible institutional, industry, and community benefits
2. Catalyzing applied research projects and investments in laboratories and industry-university collaborations
3. Promoting contract education, professional development and faculty consulting opportunities with industry partner companies and their employees
4. Cultivating industry-relevant scholarships and internships for OIT students in partnership with OIT Career Services and the Oregon Tech Foundation
5. Increasing community access to faculty expertise, collaborations, and publications
6. Raising business awareness about OIT, its mission, programs, quality, and statewide presence

Lita Colligan
Associate Vice President - Strategic Partnerships
Oregon Institute of Technology
Portland Campus
7726 SE Harmony Rd.
Portland, OR 97222
503.821-1247work
503.786-5040 fax
(b) (6) [redacted]

Project Team Includes:

Expert Hydropower Engineer: **Lee Sheldon, PE**
Faculty Member

Optimization Programmer: **Michael Curtiss, BS REE, Spring 2011**
Student Member

Principle Investigator: **Jonas Parker, BS REE, Spring 2011**
Student Member

Participating Student: **Gregory Ripplinger, BS REE, Spring 2012**
Student Member

Professional resumes for project team members;

See Professor Sheldon's Resume in Attached Files

Resume's of student members are available on request

Abilities, skills, qualifications, and specialized experience of staff

Summary of qualifications is included in Lee Sheldon's resume in the attached files

Working experience with BPA, DOE, or other government entities:

Professor Sheldon:

Primary expertise is due to more than 30 years experience in the design, procurement, installation and testing of hydraulic turbines, including having been head of the turbine design section of the US Army Corps of Engineers (COE). Additional experience is from managing the construction of twenty hydroelectric projects for the US Department of Energy (DOE).

Managed the research and development program for the Bonneville Power Administration (BPA), which successfully introduced several new technologies, including variable speed – constant frequency generation.

B. 5 REFERENCES

List three references for projects of similar scope and complexity that were completed by the Applicant. Include the names, telephone numbers, and email addresses of contact persons from the agencies or organizations that sponsored the project.

For Professor Lee Sheldon

1. US Army Corps of Engineers, Hydroelectric Design Center, Portland, Oregon
   (503) 808-4200 or -4219 cenwp-dll-webmaster@usace.army.mil

2. Tennessee Valley Authority
   Hydro-modernization Program
   (865) 632-2101 tvainfo@tva.gov

3. BPA's former research, development, and demonstration program in hydropower
   (503) 230-5527

References for the student members are available on request

Lee Howard Sheldon

(b) (6) [redacted]

(b) (6) [redacted]

SUMMARY

Licensed as a Professional Engineer, holding a Master of Science Degree and with extensive experience in the mechanical, environmental, and civil aspects of hydroelectric power and also experienced in shipyard engineering. Primary expertise is due to more than 30 years experience in the design, procurement, installation and testing of hydraulic turbines, including having been head of the turbine design section of the US Army Corps of Engineers (COE). Additional experience is from managing the construction of twenty hydroelectric projects for the US Department of Energy (DOE). Authored publications include almost two-dozen technical papers and a college textbook on hydropower engineering, as well as being a member of a technical publisher's advisory board. Presentations include organizing a number of seminars and conferences and teaching at the university level. The shipyard experience is by virtue of having achieved the designator as a Naval Reserve Engineering Duty Officer (EDO) and working in the construction, alteration, conversion and repair of naval ships.

SIGNIFICANT EXPERIENCES

- Developed a technique to determine the optimum manner to share load among generating units in a powerhouse so that the total or combined efficiency is maximized.
- Managed the research and development program for the Bonneville Power Administration (BPA), which successfully introduced several new technologies, including variable speed – constant frequency generation.
- Managed the construction of twenty hydroelectric projects around the country to demonstrate the economic viability of small-scale hydropower.

- Developed new equipment and a number of new diagnostic techniques to evaluate hydraulic turbine performance.
- Designed and developed state of the art fish screening systems and other environmental enhancements for hydropower.
- Developed and published the academic instruction materials for university courses, as well as conferences and seminars on hydropower.
- Received the first Naval Reserve designator as an Engineering Duty Officer in the state of Oregon.

CAREER EXPERIENCE

<u>May 2, 2008-Presant</u>

Consulting engineer in private practice. Also, Adjunct Professor of Fluid Mechanics and Basic and Advanced Hydropower Engineering, Oregon Institute of Technology, Portland, Oregon, eastside campus.

<u>2002-May 1, 2008, US Army Corps of Engineers, Hydroelectric Design Center, Portland, Oregon</u>

Reemployed on a term basis as a senior hydro mechanical engineer in the Hydroelectric Design Center of the US Army Corps of Engineers to evaluate and test new methods of measuring flow rate in hydraulic turbines and to develop new computer software programs to maximize the combined generating efficiency of multiunit powerhouses.

<u>1998-2002, ENRON Engineering & Construction Company, Houston, Texas</u>

Employed as an engineering specialist in hydropower to economically evaluate potential hydroelectric projects for acquisition.

<u>1994-1998, Kleinschmidt Associates, Pittsfield, Maine</u>

As a senior hydromechanical engineer with an engineering consulting firm, worked extensively in the forensic analysis of hydraulic turbine failures. In addition, was involved in the study and design of hydraulic turbine installations, field testing of hydromechanical equipment, site development, optimization studies, hydraulic modeling, and performing analytical studies related to advanced hydropower-generating concepts.

Temporarily assigned for one year to the Tennessee Valley Authority (TVA), which has a long-term program to replace 80 turbine runners at more than a dozen projects. Worked in the hydromodernization program by reducing and analyzing all the field test data and preparing the turbine efficiency and performance test reports.

<u>1982-1994, Bonneville Power Administration</u>

Positioned as the senior hydropower engineer in charge of the technical direction and administration of BPA’s research, development, and demonstration program in hydropower. This included performing analytical studies, evaluating proposals, negotiating and administrating contracts, monitoring laboratory research, and conducting field tests and prototype evaluations.

As part of this position, worked extensively in the environmental aspects of hydropower. This included: designing and studying models of fish ladders, designing turbines to aerate discharges, developing the hydraulic analysis of the Eicher Fish Screen, designing other state of the art fish screening systems, optimizing the efficiency of both hydraulic turbines and entire powerhouses to facilitate downstream migration, conducting workshop sessions on fish passage through turbines, and serving on the technical committee of DOE's Advanced Hydro Turbine System Program Committee.

1979-1982, US Department of Energy, Idaho Operations Office, Idaho Falls, Idaho

Served as the project manager for the construction of twenty hydroelectric demonstration projects located throughout the nation.

1971-1979, US Army Corps of Engineers, Hydroelectric Design Center, Portland, Oregon

As head of the turbine design section, performed site development and optimization studies, water hammer analyses, contract management, field-testing and oversaw construction and equipment installation. Additional duties included preparation of equipment specifications, procurement of turbines, pumps, valves, and related mechanical equipment. During the course of employment, worked on the design, construction, capital improvement, and/or O&M of every Corps hydropower project in the Pacific Northwest.

1969-1971, US Army Corps of Engineers, Division Hydraulic Laboratory, Bonneville, Oregon

Worked on the design, construction, operation and evaluation of hydraulic models of various civil structures, rivers, canals, conduits and outlets.

1963-1986, US Navy, Active and Reserve Duty

Early active duty and reserve activities in the US Navy included: hydrography, amphibious forces, Seabees, submarines, and inshore undersea warfare. When promoted to the rank of Commander, simultaneously earned the designator of a fully qualified Engineering Duty Officer. Consequently, before retiring from the Navy, spent fifteen years in shipyards on the construction, conversion, alteration, and repair of naval ships. Having been a boiler officer on active duty, received a subspecialty designation in ship's hulls and propulsion systems.

EDUCATION

Bachelor of Science in General Engineering, University of California at Los Angeles, 1963.

Master of Science in Mechanical Engineering, California State College at Los Angeles, 1969.

LICENSES

Registered as a Professional Engineer, Mechanical, Oregon, #7150, 1970.

HONORS AND AWARDS

Elected to membership in Tau Beta Pi (Engineering Honor Society), 1962.

Elected to membership in Phi Kappa Phi (Scholastic Honor society), 1968.

Secretary of the Army Energy and Water Management Award for New Technology in FY 2006.

AFFILIATIONS

Current member of the Publisher's Advisory Board of Hydro Review, published by HCI Publications.

Current member of the US Department of Energy's Advanced Hydro Turbine System Program Committee.

Past chairman of the Hydro Working Group of the Electric Power Research Institute (EPRI).

PUBLICATIONS

1. "Cost Analysis of Hydraulic Turbines," International Waterpower and Dam Construction, June 1981.
2. "Field Testing and Optimizing the Efficiency of Hydraulic Turbines," International Waterpower and Dam Construction, January 1982.
3. "Model to Prototype Efficiency Step-Up for Francis Turbines," presented to and published in the Transactions of the ASME Second Symposium on Small Hydro-Power Fluid Machinery, November 1982.
4. Co-author of "Determining the Net Head Available to a Turbine," presented to and published in the Transactions of the ASME Second Symposium on Small Hydro-Power Fluid Machinery, November 1982.
5. "An Analysis of the Benefits to be Gained by Using Variable Speed Generators on Francis Turbines," presented to DOE/EPRI Variable Speed Generator Workshop in Denver, Colorado, May 1983.
6. One of four contributing authors to the text Hydropower Engineering, published by Prentice-Hall, Inc., in 1983.
7. "An Analysis of the Applicability and Benefits of Variable Speed Generation for Hydropower," presented to and published in the Transactions of the ASME Third Symposium on Small Hydro-Power Fluid Machinery, December 1984.

8. "Performance Differences: Turbine Models and Full-Scale Prototypes," Hydro Review, Summer 1985.
9. "Installation of a Marine Thruster as a Hydroelectric Turbine at Eagle Creek National Fish Hatchery," BPA Final Report DOE/BP-22105 1, November 15, 1986, available from the National Technical Information Service.
10. "Flow Measurement by Three Different Methods: Winter-Kennedy Piezometers, Traveling Screen, and Weir," presented to and published in the Transactions of the EPRI/BPA Hydraulic Turbine Testing Workshop/Seminar, York, Pennsylvania and Portland, Oregon, June 1987.
11. "Performance Differences Between a Model and a Homologous Prototype," presented to and published in the Transactions of the EPRI/BPA Hydraulic Turbine Workshop/Seminar, York, Pennsylvania, and Portland, Oregon, June 1987.
12. "Can a Marine Thruster be Used as a Hydroelectric Turbine?," Hydro Review, Special Waterpower '87 issue, August 1987.
13. Co-author of "Pump Turbines, Trends and Status," presented to and published in the Transactions of the International Renewable Energy Conference, Honolulu, Hawaii, September 1988.
14. Co-author of "Variable Speed Pump/Turbines," Hydro Review, Special Waterpower '89 issue, August 1989.
15. "Q&A, Is Your Hydrogenerator Speeding? A Look at Overspeed, Runaway Speed," Hydro Review, Special Waterpower '95 issue, July 1995.
16. "Optimizing Efficiencies of Multi-Unit Hydro Plants," presented to and published in the ASCE Transactions of Waterpower '95, July 1995.
17. "Q&A, The Choice Between Reaction and Impulse Turbines," Hydro Review, February 1997.
18. "Diagnostic Evaluation of Turbine Efficiency Profiles and Data," presented to and published in the ASCE Transactions of Waterpower '97, August 1997.
19. "Reviewing the Approaches to Hydro Optimization," Hydro Review, June 1998.
20. "Modern Errors in Winter-Kennedy Piezometers," presented to and published in the Transactions of the Second International Group for Hydraulic Efficiency Measurement (IGHEM) Conference, Reno, Nevada, July 1998.
21. "The Bernoulli Theorem: Sharing its History and Application," Hydro Review, August 2000.

22. Co-author of, “Draft Tube Velocity Head Correction Factor,” presented to and published in the HCI Transactions of Waterpower ’05, July 2005.
23. Co-author of, “Improving Turbine Efficiency Calculations through Advanced Velocity Measurements,” Hydro Review, June 2007.
24. “A New Form of a Calibration Equation for the Winter-Kennedy Piezometer System,” presented to and published in the HCI Transactions of Waterpower XV, July 2007.
25. “Optimizing the Generating Efficiency of Entire Powerhouses,” presented to and published in the HCI Transactions of HydroVision 2008, July 2008.
26. “New Method to Determine Turbine Absolute Flow and Absolute Efficiency Data,” Hydro Review, July 2010.

Sequential Quadratic Programming to Solve Hydropower Optimization for All Generating Units in a Powerhouse

Draft

Lee Sheldon, Michael Curtiss, Jonas Parker, Gregory Ripplinger, and Parker Scoggins

Executive Summary

There is no less expensive way to add power to the grid than to adjust the machines that are already on-line to make them more efficient. One may assume that most of today's generating units have already been tuned to produce the most power at the least cost, but in hydro-power that is not the case. A little insight into the way hydraulic turbines behave; coupled with some relatively straight forward programming techniques; can yield stunning improvements in efficiency not yet realized in many systems. Optimization is the lowest cost, highest return, cleanest new energy source available today. In this paper we show how cost function minimization can be used to improve the performance of a whole hydroelectric powerhouse.

The following belongs in a sidebar

Index of Terms

Index Testing: The field testing required to determine the relative efficiency for each turbine over its entire flow range.

Unit selection: The selection of which turbines to have on-line to meet the operator set point.

Load sharing: The separate amount of load to put on each selected turbine.

Type 1 optimization: The optimization of each individual turbine in a powerhouse in terms of power output per amount of flow at constant head.

Type 2 optimization: The coordination of all the turbines in a powerhouse to achieve a power output set point using the least amount of flow. This level of optimization is the subject of this paper, and is achieved with the best possible unit selection and load sharing.

Type 3 optimization: The coordination of all the hydro powerhouses along a river or in a river basin to get the most power from the available flow.

Type 4 optimization: The coordination of a region's hydropower river basins and watersheds.

Type 5 optimization: The integration of all of a region's hydro and thermal generating units.

End of side bar

Introduction

Optimization is the process by which a system is tuned to create the best output for a given input. In hydropower that means producing the most power for a given volumetric flow rate of water or using the least water to produce a given amount of power at any given head. This process is defined as being done at a constant head since various reservoir rule curves do not provide for maximizing head.

Since all elements of a power system are connected and work together, that optimization can have many aspects. As a result, there are now five recognized Types of optimization. For example, in a Kaplan turbine, each unit needs to be optimized so that the most power is produced by the blades being at the proper angle for a given flow. This (Type 1) optimization is done by index testing and recording the best blade angle to wicket gate relationship for all possible heads for every turbine. In other kinds of turbines, such as the Francis variety, which have fixed runners, Type 1 consists of just the index test (Fig 1) to determine the relative efficiency profile.

Type 2 optimization concerns unit selection and load sharing in the whole powerhouse (Fig 4). In this paper we will discuss a newly developed method for achieving Type 2 hydropower optimization with a new, very fast computer program. This new programming algorithm also could be used to speed up higher levels or Types (i.e., 3, 4, or 5) of optimization problems as well.

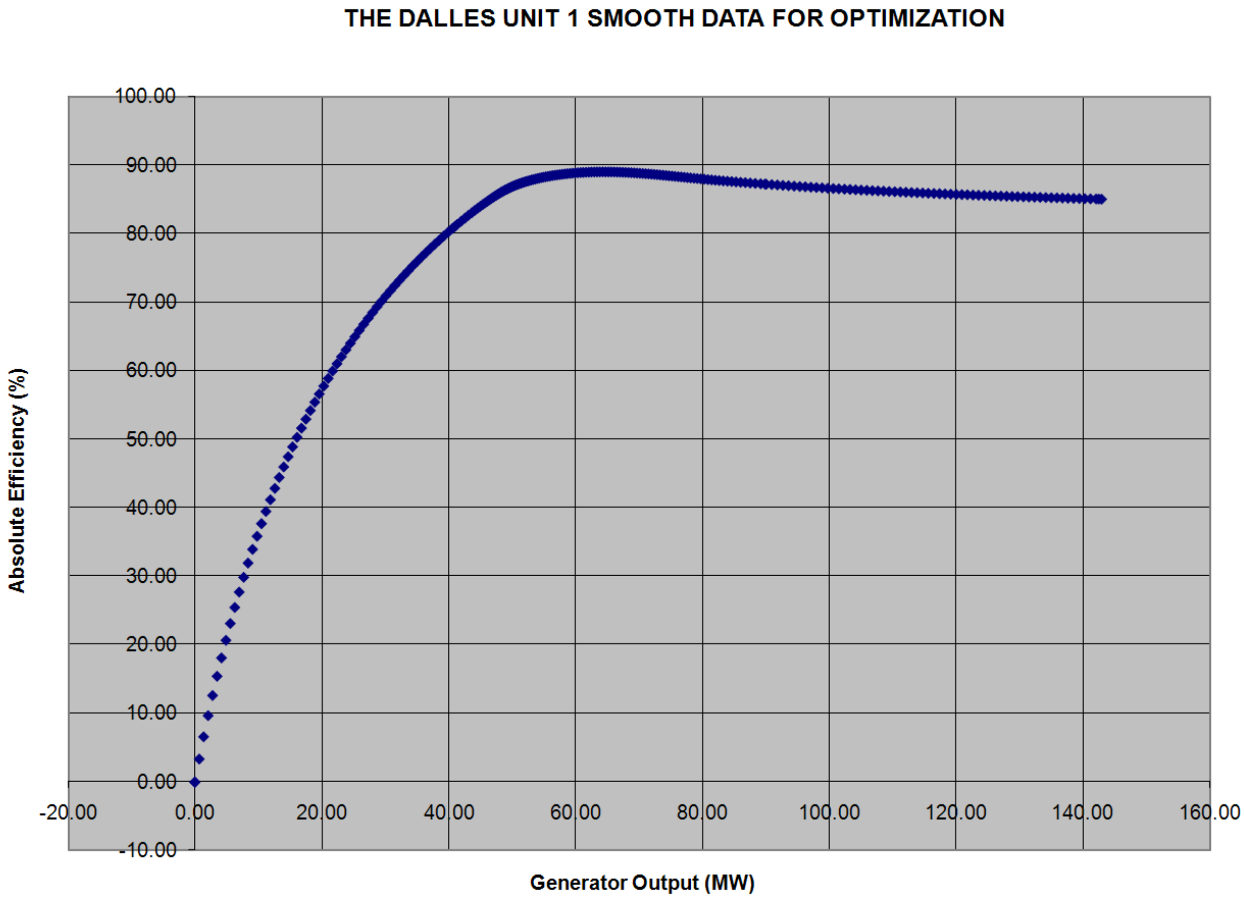

Fig. 1
The efficiency profile of a single Kaplan turbine in a powerhouse, plotted across its range of power output

Understanding Type 2 Optimization

To appreciate the value of Type 2 hydropower optimization, it first needs to be understood that every turbine in the powerhouse is slightly different. Although all the turbines in the powerhouse may be specified to be of the same design, differences in manufacturing tolerances result in differences in unit operating efficiencies, somewhere between one and five %. Further, years of operation tend to exacerbate the differences in performance between turbines. Every turbine has an efficiency profile that varies across its range of flow (Fig 2). In powerhouse documentation, the performance profiles of each individual turbine often will be available in a stored database. When the grid operator determines a mega-watt set-point for the project, the powerhouse operator can choose to have some turbines on-line and some turbines off-line, a process called **unit selection**. The next parameter to determine is **load**

sharing. The best load sharing is achieved when the wicket gate opening for each turbine is set such that the power output is met with the smallest total flow rate.

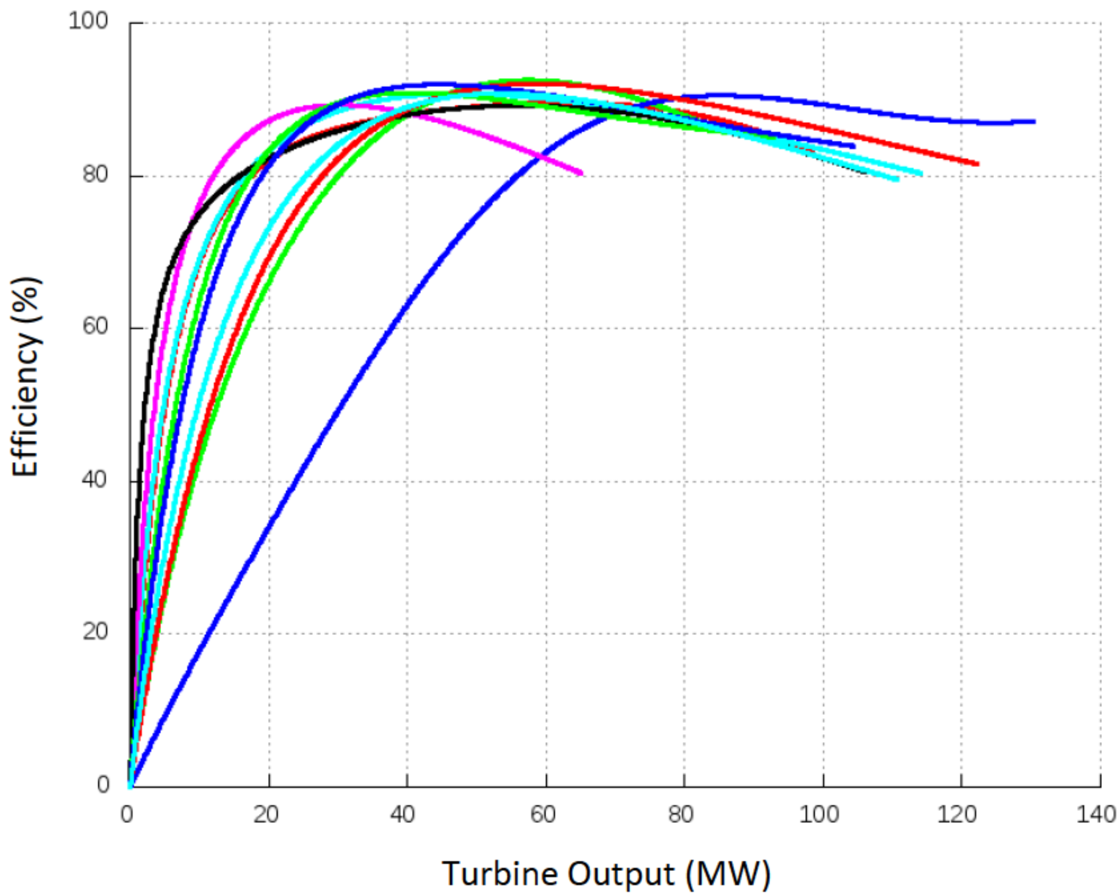

Fig. 2
Illustration of differences in efficiency profiles between individual Kaplan turbines in a powerhouse

Both decisions are much more difficult to determine than it may seem. Even a skilled operator may under utilize up to 5% of the water available for generation due to less than perfect unit selection and load sharing. During conditions where water is spilled, that 5% may not make a lot of difference. However, when the flow of the river is low enough to be insufficient to meet net energy demand, that 5% represents a corresponding loss of potential revenue. At worst a project may even lose the generation equivalent to 10% of the flow. Under many conditions that will mean a corresponding 10% loss in revenue. Even when there is plenty of water in the river, a project run at optimal power rather than at full gate can generate the same amount of power with less wear on machinery.

On the positive side, when both aspects of Type 2 optimization are done precisely, there is potential to reverse these losses for the life of the project. Another one or two % more power can usually be gained, even on a well-run powerhouse. The intent of this new computer program is to make attaining excellent Type 2 optimization within the reach of all hydropower projects and operators.

Using a Computer Algorithm for Decision Support

Computer algorithms have been developed to support the operator's decision. However, Type 2 optimization is difficult for computers to perform well. Many attempts have been made to develop software for this purpose. However, the programs often use algorithms that take too long to compute an optimal unit selection and load sharing. Programs used by large, multiunit projects for this purpose have been known to take an hour to converge on a solution. In the emerging ten minute power market, even a much smaller wait time may be unacceptable.

It must be emphasized that the program that is the subject of this paper is not meant to tie directly into the controls or SCADA systems; rather it is meant as an informational tool for the operator. However, features such as direct data acquisition could easily be added; and if there were ever a real need to add this program into the controls of a project, that would indeed be possible too.

Brute Force

The slowest way to perform the Type 2 calculation is termed the "brute force" method. A brute force computer program examines every possible unit selection and every possible load allocation among the selected units. If there are ten units in a power house, then unit selection by itself will take ten factorial (i.e. 10!, or 3,628,800) iterations to achieve. Within those ten factorial iterations, there will be as many as 100 increments of gate opening for each turbine for the program to consider. There will be a very large number of total set-point combinations that will achieve the desired power output. The program will continue until it exhausts all possible solutions. Among all possible solutions for the demanded power output, the one that requires the least flow is selected. Many programs unnecessarily use aspects of this method, which is why it takes more than an hour for some of them to finish the computation.

Method of Paired Comparisons/Hill Climbing

Faster methods are indeed possible. The method of paired comparisons begins its calculations at full power, for which there is one possible solution. It then finds the best solution for every increment of decreased power down toward zero. For every increment of decreased power, it will examine possible solutions next to the last operating point until the load-sharing that consumes the least amount of water is found. The method of paired comparisons, also called the hill climbing method, is much faster than brute force because, when possible, it chooses successive iterations in the direction of a better solution than the previous one.

Particle Swarm Combined With Hill Climbing Optimization

Different techniques can be applied to the unit commitment step and the load sharing step to speed up the hill climbing optimization. One of them is called particle swarm optimization. This modification randomly picks the number of turbines to use from the number available, then randomly picks the unit selection combination and checks to see if the maximum power is greater than or equal to the desired power. It then performs the optimal load sharing using the hill climbing method. The entire process repeats several times, after which the best unit selection and load sharing results are chosen.

Sequential Quadratic Programming (SQP) Optimization

A much faster method than particle swarm optimization combined with hill climbing, and the fastest method to date available for this purpose, is called Sequential Quadratic Programming (SQP). SQP uses Newton's Method and Taylor series expansion to directly solve a set of unconstrained, convex curves by applying a global constraint and an educated first guess. A hydro unit's flow versus power curve is sufficiently smooth such that it can be approximated with a high order quadratic polynomial. This simplified mathematical characteristic makes the hydro turbine an ideal candidate for this kind of cost function minimization. The SQP solution described by this paper was written in Octave, an open source numerical programming language. The program takes only TWO SECONDS to find optimal unit selection and load sharing for any given set-point in a powerhouse with ten turbines. This increase in computational speed may represent a breakthrough that will soon allow continual Type 2 hydropower optimization to occur in real time.

The following belongs in a side-bar

Technical Explanation of Sequential Quadratic Programming

Index of Terms for Sequential Quadratic Programming

Taylor series expansion: A linear mathematical series based on the slope of a curve around an operating point that is used to approximate the output of the function around that point.

Newton's method: A mathematical method using the derivative of a complex function and the point where the slope passes through the origin to find successively better approximations of the root of the function.

Quadratic programming: An optimization method used on a quadratic function of several variables subject to linear constraints on those variables.

Sequential quadratic programming: An optimization method using a series of algorithms to solve a quadratic function subject to non-linear constraints.

Constraints: Mathematical conditions that a solution must satisfy

Gradient: The slope (first derivative) of a function or matrix

Lagrangian Function: A function used in maximum and minimum optimization problems to represent a vector normal to a gradient function

Lagrangian Multiplier: The multiplier applied between the gradient function and the constraint function to set the magnitudes equal

Hessian: The second order partial derivative matrix of a gradient function

To reiterate, Type 2 optimization is essentially the problem of minimizing water flow through the turbine units of a powerhouse for a given power set point. In terms of flow and power, individual units are characterized by sets of nonlinear curves, depending on the head across the unit. If head is assumed constant, the constraints for this minimization problem reduce to (1.) the total power demanded and (2.) the upper and lower power limits of each unit. Since this is basically a constrained, nonlinear optimization problem with multiple variables, the use of quadratic programming (QP) is appropriate. By using QP, the constraints can be brought into the objective function, which describes the power-flow curves. This results in a Lagrangian function, $L(p, \lambda_n)$, where p is a vector of the individual units' power set points, $g_n(p)$ are the n constraints as a function of the power set point, and λ_n is a scalar multiplier known as the Langrange Multiplier of the nth constraint.

$$L(p, \lambda_n) = q(p) - \lambda_n(g(p))$$

The objective function, $q(p)$, is the flow to be minimized. The partial derivative of the Lagrangian then gives the conditions under which the optimum can be found. These conditions are typically known as the Karush-Kuhn-Tucker (KKT) conditions, named after the major contributors to their derivation. Stated in terms of $L(p, \lambda_n)$, the KKT conditions for Type 2 optimization would be:

$$\nabla L(p) - \lambda_n \nabla g_n(p) = 0$$
$$\lambda_n g_n(p) = 0$$
$$g_n(p) \leq 0$$

Furthermore, subject to the KKT conditions, a local minimum is found by applying a Quasi-Newton method.

The Quasi-Newton method begins with a second order Taylor series expansion, which gives a local, quadratic approximation of $L(p, \lambda_n)$:

$$L(p_{i+1}) \approx L(p_i) + \nabla L(p_i)(p_{i+1} - p_i)^T + \frac{1}{2}(p_{i+1} - p_i)^T H(p_{i+1} - p_i)$$

H is the Hessian, $L''(p_{i-1})$, where p_{i-1} is the is the power set point at iteration, $i - 1$. Taking the derivative of this local approximation with respect to p_i, setting to zero, and solving for p_i gives:

$$\nabla L(p_i) \approx \nabla L(p_{i-1}) + H(p_i - p_{i-1}) = 0$$

$$p_i = p_{i-1} - H^{-1} \nabla L(p_{i-1})$$

If, $p_{i-1} = p_i$, then the extreme has been found; however, if $p_{i-1} \neq p_i$, then the iteration must be continued until a minimum solution is found. Furthermore, the above term, $H^{-1} \nabla L(p_{i-1})$, is a vector that describes a segment of a path from the current operating point p_i to the minimum, which ensures that the step lengths between operating points are chosen in the direction of a minimum at each iteration. However, to calculate the full Hessian for each iteration is unnecessary and computationally costly.

In the Quasi-Newton method, an approximate Hessian is used and updated upon iteration. There are several update methods available, but the update method of Broyden-Fletcher-Goldfarb-Shanno (BFGS) has proven reliable and is used in the program described in this paper:

$$H_i + \frac{L(p_i) - H_i(p_{i+1} - p_i)}{(p_{i+1} - p_i)^T (p_{i+1} - p_i)} (p_{i+1} - p_i)^T$$

This kind of successive updating and solving of quadratic programming problems is collectively known as Sequential Quadratic Programming (SQP).

In sum, SQP solves constrained, nonlinear, optimization problems by iteratively solving for a zero gradient of the objective function to be optimized. Also at each iteration, a check is performed to ensure that the constraint conditions have not been violated, and an updated approximate Hessian is calculated, which is used to determine the step length and direction of the stepped changes in the operating point upon iteration.

Further Reading on Sequential Quadratic Programming

1. A SEQUENTIAL QUADRATIC PROGRAMMING ALGORITHM FOR DISCRETE OPTIMAL CONTROL PROBLEMS WITH CONTROL INEQUALITY CONSTRAINTS
   J.F.O. De 0.Pantoja D.Q. Mayne
   Department of Mathematics, Department of Electrical Engineering,
   Federal University of MaranhHo, Imperial College,
   SHo Luis, MaranhHo, Brazil. London. SW7 2BT

2. SOLVING THE HYDRO UNIT COMMITMENT PROBLEM VIA DUAL DECOMPOSITION AND SEQUENTIAL QUADRATIC PROGRAMMING
   Erlon Cristian Finardi and Edson Luiz da Silva*, Senior Member, IEEE* IEEE
   TRANSACTIONS ON POWER SYSTEMS, VOL. 21, NO. 2, MAY 2006

3. IMPROVED SEQUENTIAL QUADRATIC PROGRAMMING APPROACH FOR OPTIMAL DISTRIBUTION GENERATION SIZING IN DISTRIBUTION NETWORKS
   *M. F. AlHajri*1, *M. R. AlRashidi*1, *M. E. El-Hawary*2
   1Electrical Engineering Technology Department, College of Technological Studies, Paaet, Kuwait
   2Electrical Engineering Department, Dalhousie University, NS, Canada

End of text in sidebar

The following is part of normal text, not in sidebar

Case Study

The application of this proposed program to perform Type 2 optimization has been validated against a Type 2 optimization study performed by Lee H. Sheldon, P.E. With a MS in Fluid Mechanics and Hydraulics and over 40 years experience, he has authored some 26 technical papers, including several on hydropower optimization. He is presently a university professor teaching basic and advanced hydropower engineering, as well as fluid mechanics, at the Oregon Institute of Technology (OIT). His Type 2 Optimization study was based on data measured by flow meters from 14 hydraulic turbines located at the powerhouse in The Dalles, Oregon, on the Columbia River.

The original data from the 14 turbines was provided to the authors by Sheldon. This data was then organized into 14 separate xlsx (or CSV) files, each containing only 2 columns of data, measured power and measured flow. SCRPS imports and processes the data files automatically. Figure 3 shows the results calculated by Sheldon and those obtained by SCRPS for the same data set.

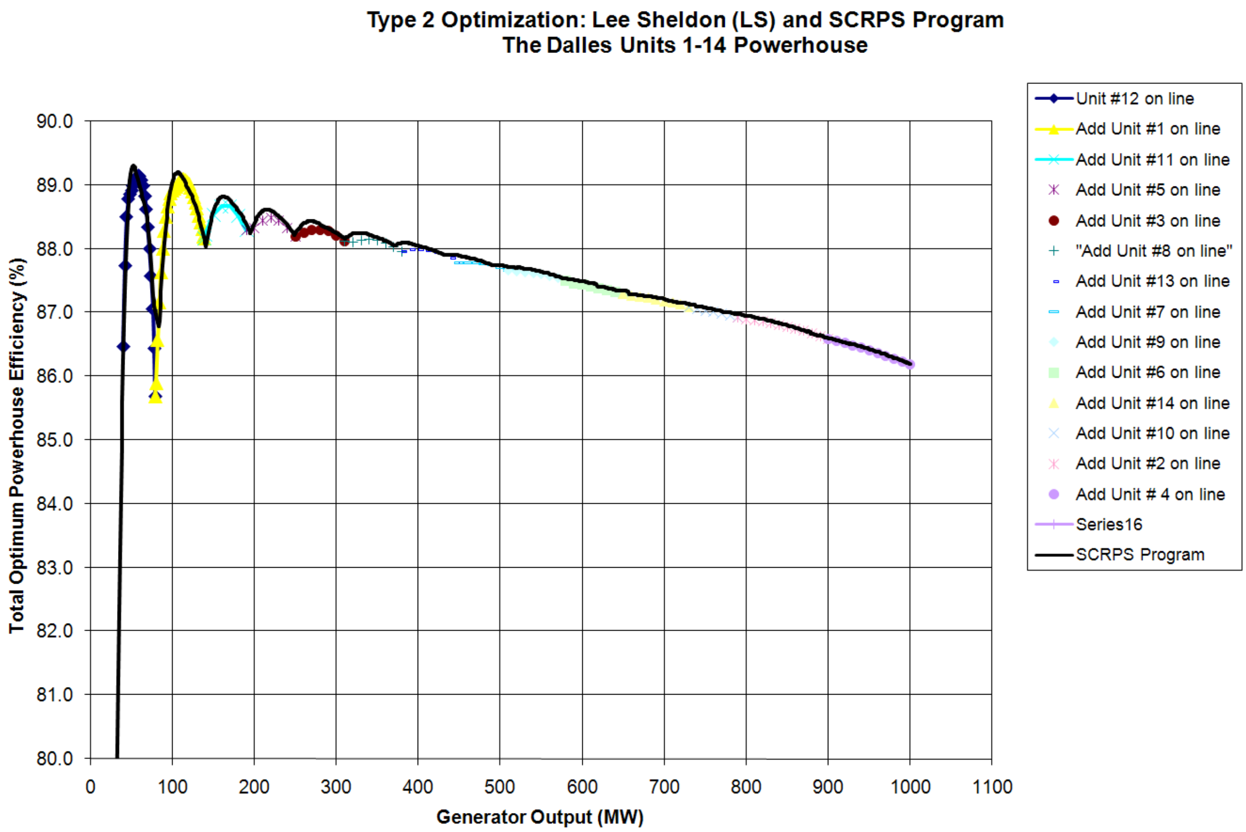

Fig. 3

The colored line is Lee Sheldon's Type 2 unit selection and load sharing calculation done by hand. The black line is the result of an optimization using the same data, performed by the SQP program written in Octave numerical programming language.

In Figure 3, the cumulative efficiency is shown on the graph, and it changes across the range of power outputs as optimum load sharing and unit selection are performed for every possible set-point between minimum power and full power. At full power the efficiency drops off because all turbines are turned on past their point of peak efficiency. At the left part of the curve, as the least efficient turbines have been turned off, there are spikes in efficiency that represent a few of the single most efficient turbines running at their peak efficiencies. At the far left there is a quick drop off in efficiency as the last, most efficient turbine is dropped below its peak efficiency.

Comparing the results, the SCRPS total optimum powerhouse efficiency precisely matched that of Sheldon's study. The study done by Sheldon required two weeks of hand calculation; whereas the SCRPS results were accomplished in a matter of minutes, including the time taken to organize and file the turbine data. Both the speed of the solution and its similarity to an exact hand calculation provide confidence that the method employed by the SCRPS Program is both practical and accurate.

Comparing the optimum to "typical" load sharing and unit selection

As a demonstration of the benefit of applying a Type 2 optimization program like SCRPS, the data from The Dalles Dam was run through another program that equivocates in unit selection and load sharing, simulating a powerhouse that has no optimization program at its disposal. Rather than finding the best solution for every set-point, this sub-optimal program selects turbines according to a random list. As more power is needed, the next turbine on a list is turned on instead of the best turbine among all those remaining. In addition, among those turbines that are on-line at one time, the load is shared evenly instead of optimally (Fig.4).

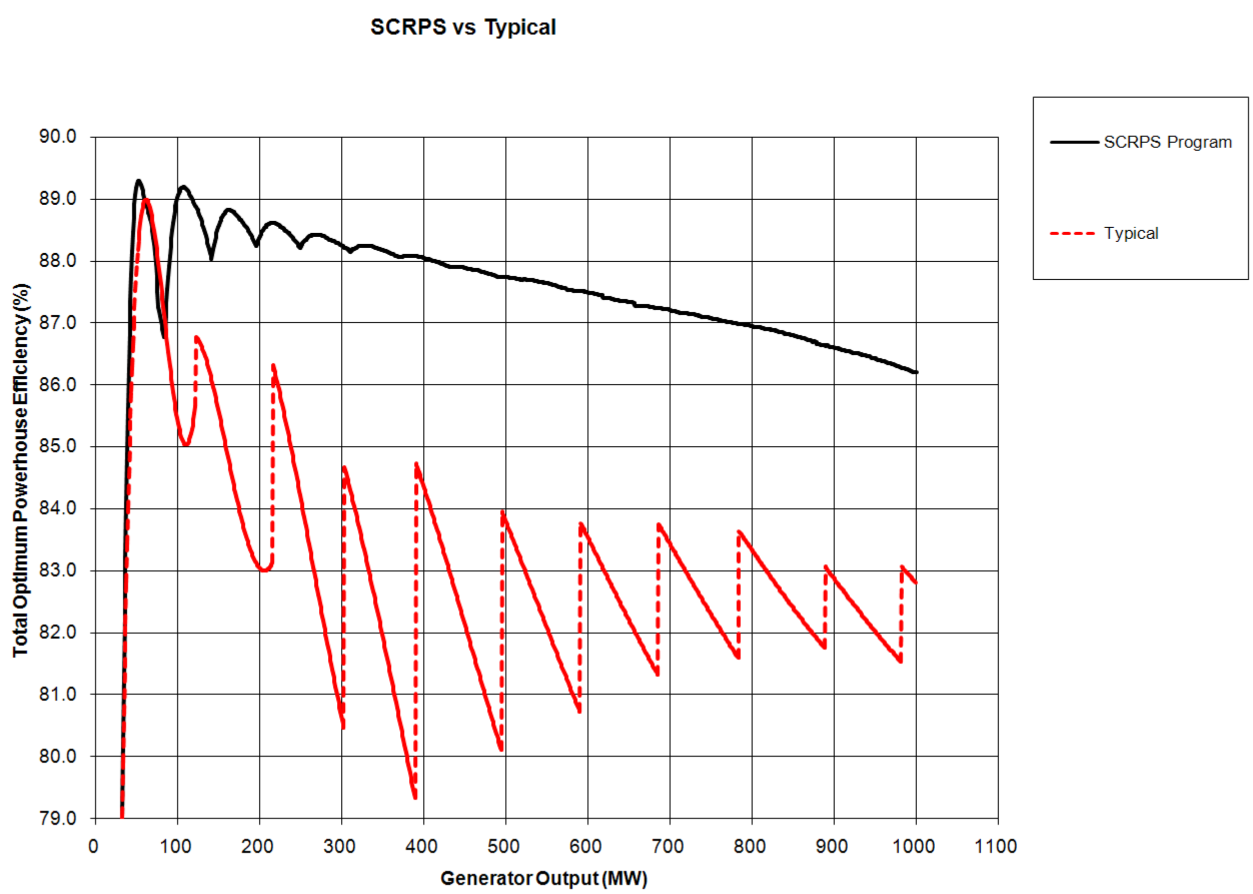

Fig. 4

"Typical" powerhouse efficiency simulation plotted against SCRPS optimal solution

The difference between the SCRPS powerhouse efficiency optimization and the "typical" unit selection and load sharing simulation is considerable. At most the "typical" simulation lost 7.9% of the efficiency that was available to the powerhouse. The average difference is around 5%, no small matter whenever sufficient water flow is valuable. There are sharp peaks at the point where individual turbines are dropped off and the units remaining on-line must share that dropped amount of load equally. The simulation is similar to the way the many powerhouses at hydro projects are actually run.

Conclusion

In the past, powerhouses have been run below maximum efficiency because Type 2 hydropower optimization programs have been either too expensive, too slow, or both. If no Type 1 optimization has been done, the loss in efficiency would be even greater. The lack of knowledge about individual turbine efficiency has left operators blind in the area of unit selection and load sharing. Even with some knowledge about the efficiencies of individual units, optimal load sharing was still doubtful.

This new program solves all the above problems, provided that a good Type 1 optimization has previously been performed. Type 1 optimization can be achieved economically and maintained with the help of automatic index testing systems such as the Index Testing Box designed by Actuation Test Equipment Company, Inc. That achieved, every project can now have some sort of Type 2 made available to the operator. Having done so, the project owners can expect a noticeable increase in the net energy produced and increased equipment service life as well.

Again, the program that is the subject of this paper is not meant to tie directly into the controls of the project; rather it is meant as a tool for the operator. The program will aid the operator in making the most economical decision for every set point, and will make an easy job of operating the project more efficiently.

Further Reading on Hydropower Optimization

"Field testing and optimizing efficiency of hydro turbines"
L.H. Sheldon
Water Power & Dam Construction, January 1982

"Optimizing Efficiencies of Multi-Unit Hydro Plants,"
Lee Sheldon
ASCE Transactions of Waterpower '95, July 1995.

"Reviewing the Approaches to Hydro Optimization"
Lee Sheldon
Hydro Review, June 1998.

"Optimizing the Generating Efficiency of Entire Powerhouses"
Lee Sheldon
HCI Transactions of HydroVision 2008, July 2008.

Department of Energy
Bonneville Power Administration (BPA)
P.O. Box 3621
Portland, Oregon 97208-3621

January 17, 2012

Portland State University
Attn: Bob Bass
Assosiate Professor
ECE Department
Post Office Box 751
Portland, OR 97207-0751
bobbass@ece.pdx.edu

By Email

Subject: Pre-Award Authorization for TI Project # 254

This letter constitutes an authorization for you to commence work on TI Project #254, Multi-Unit Optimization of a Hydropower Powerhouse. This authorization is subject to the following conditions:

1. A maximum of $17,346 in costs may be incurred (Stage Gate 1 - Task 1 Budget) from BPA's share in additional to PSU/OIT's agreed upon share. Expenditures above that amount are not authorized and are at your risk.
2. This authorization is subject to the cost principles described in 2 CFR Part 220 and Administrative Requirements of OMB Circular A-110.
3. When the Cooperative Agreement is provided, it will be a cost-reimbursement cost-share type agreement.
4. Authorized expenditures cannot be made until the new Agreement is signed and fully executed by both parties.
5. The BPA Project Manager and Project Technical Representative is Jim Irish whose authority with respect to this project/agreement is outlined in the attached delegation memorandum.
6. All work shall be done in accordance with the updated Project Description and Budget submitted on January 5, 2012. I expect the new agreement to be sent to PSU by January 27, 2012 and then review/negotiations may take a few weeks before execution.

If you have questions regarding this authorization, please feel free to give me a call at (503) 230-7549. Thank you for your assistance in this effort.

Sincerely,

(b) (6) [redacted]

Matthew DeLong
Financial Assistance Officer

Cc: Jim Irish, Project Manager/Project Technical Representative

Enclosures

TIP #254: Multi-Unit Optimization of a Hydropower Powerhouse

Project Start: N/A

End Date: N/A

Total Project Budget: $119,195

- BPA Budget: $59,103
- Cost Share: $60,092

BPA Project Actuals (project start to date): N/A

BPA FTE Budget: N/A

BPA FTE Actuals (project start to date): N/A

BPA PM: James Irish

Principal Investigator/Contractor: Bob Bass (PSU), Lee Sheldon (OIT)

Project Stakeholders: BPA, PSU, OIT

Project Synopsis: Team - PIs

- Lee Sheldon, PE
  - 41 years as a hydropower engineer (ACE, BPA, TVA, USDOE). Graduate of USDOE's Project Management School. Certified by BPA as a Project Engineering Manager.
  - (0.3 FTE)
  - Overseeing stage gates (mile stones?), index testing, program validation.

- Robert Bass, PhD
  - Associate Professor, Portland State University
  - (0.15 FTE)
  - Managing work schedules, reporting, interacting with project partners, advising on technical aspects.

Project Synopsis: Team - Engineers

- Michael Curtiss
  - Practicing power engineer. Research Associate at PSU.
  - (0.2 FTE)
  - Scripting, HMI development, researching tools and methods for roadmap goals.

- Jonas Parker
  - Practicing power engineer. Research Associate at PSU.
  - (0.2 FTE)
  - Provide administrative and engineering support, aid in engineering, planning, research, assist with index testing, program validation.

- Greg Ripplenger
  - Engineering student, OIT.
  - (0.2 FTE)
  - Assist with engineering, planning, index testing, program validation.

Project Synopsis: Project Description

- Type 1 - optimization of individual generating unit
- **Type 2 - optimization of entire powerhouse**
- Type 3 - optimization of multiple powerhouses sharing the same river basin or watershed
- Type 4 - optimization of an entire geographic region containing several river basins or watersheds
- Type 5 - optimization of hydro-thermal integration

Project Synopsis: Type-2 Optimization

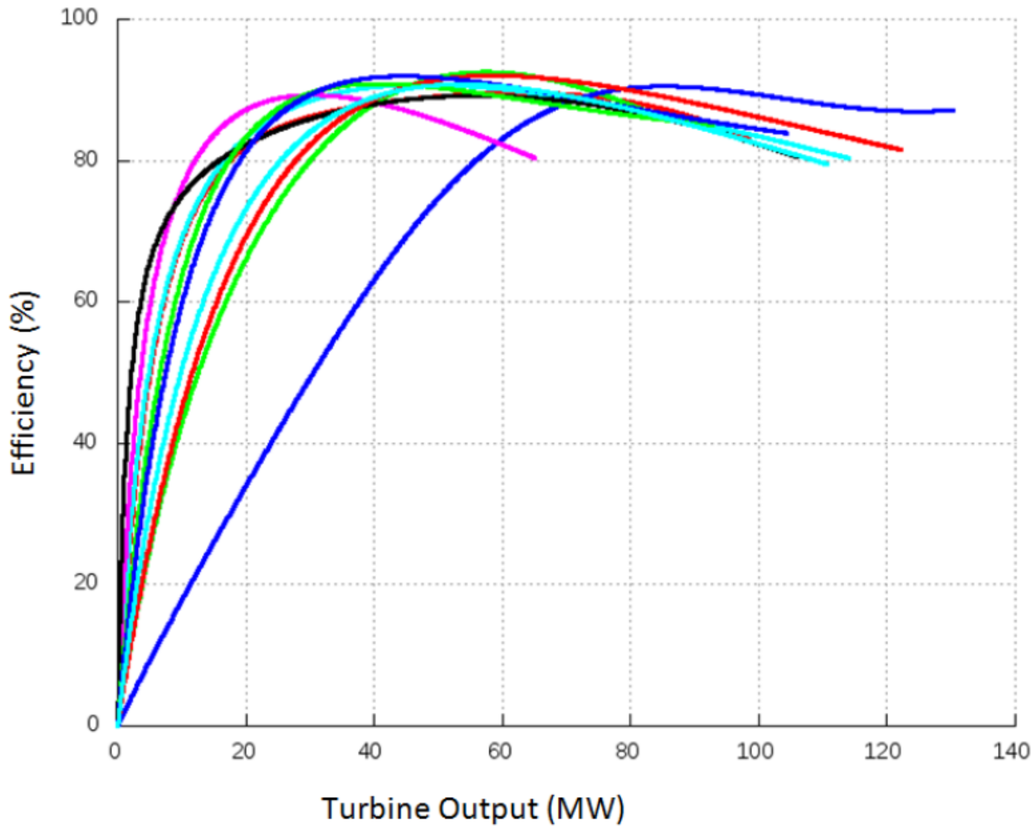

Figure 1 Illustration of differences in efficiency profiles between individual units in a powerhouse.

Project Synopsis: Type-2 Optimization

- Every turbine has efficiency profile that varies across its range of power and flow

- Performance profiles of each turbine available in a stored database

- Based on power set-point and available head:
  - **Unit Selection:** Operator chooses to have some turbines on and others off
  - **Load Sharing:** Operator sets wicket gate openings for turbines individually

- **Goal: Power output is met using the minimum overall flow rate at any head.**

Project Synopsis: Type-2 Optimization

- **Unit Selection (Unit Commitment)**
  - powerhouse unit selection resulting in the highest combined maximum efficiency for a given power set point.

- **Optimal Load Sharing (Economic Dispatch)**
  - different generation level for each unit resulting in a maximum combined efficiency
  - select power level so that the slope of each unit's flow to power curve is equal so that any flow diverted to another unit would result in the same combined power output

Project Synopsis: Optimization

- Brute Force
  - Very accurate results
  - For 10 turbines with 100 set points:

$$iterations = \frac{100!}{(100! - 10!)} = 6.28 \times 10^{19}$$

- Other methods: hill climbing, particle swarm, etc
  - Computationally efficient (converge < several minutes)

- Sequential Quadratic Programming (SQP)
  - Very accurate results
  - Convergence < 1 second

Project Synopsis: SQP Optimization

- "Cost" function minimization

  Minimize $f(x) \quad x \in \Re$

  Subject to $c_i(x) = 0$

  $h_j(x) \geq 0$

- Polynomial curve fitting to define $f(x)$

- Use Lagrangian multipliers and build KKT conditions

- Iterative method, employing Newton-Raphson

Project Synopsis: Initial Results

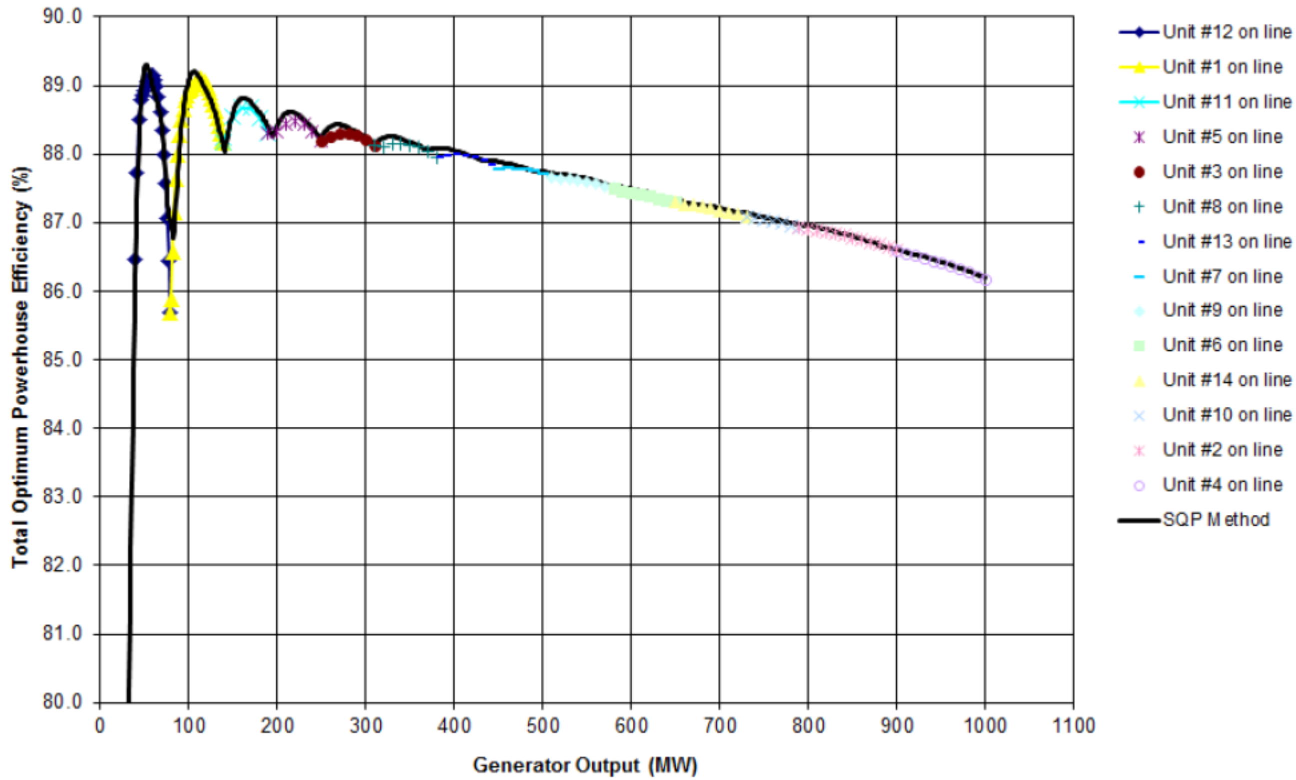

Figure 2 Optimization study based on measured data from 14 hydraulic turbines located at the powerhouse in The Dalles. Colored line is each stage of Lee Sheldon's Type 2 unit selection and load sharing done by hand. Black line is the results of an optimization using the same data performed by the SQP algorithm.

Project Synopsis: Project Description

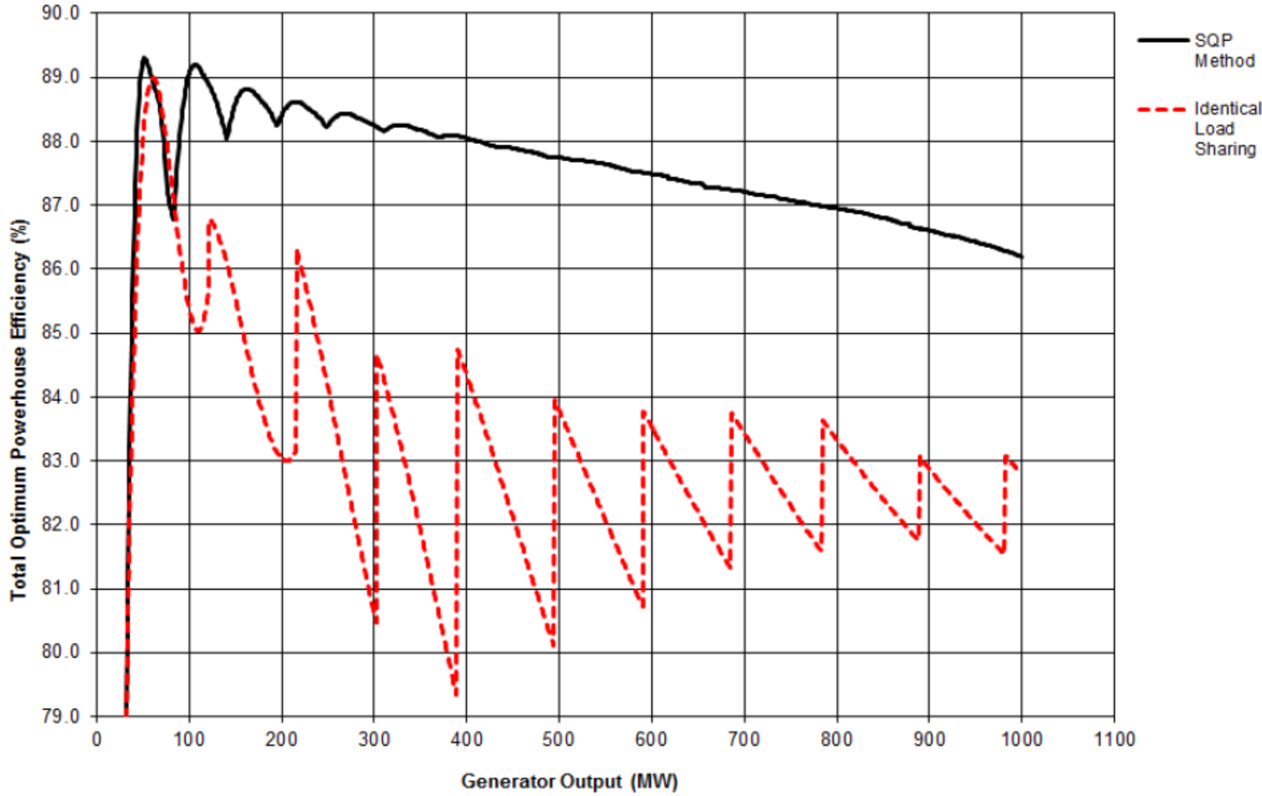

Figure 3 Simulation of identical load sharing between turbines (dashed red) plotted against the optimal solution achieved by the SQP algorithm (solid black).

Project Synopsis: Project Description

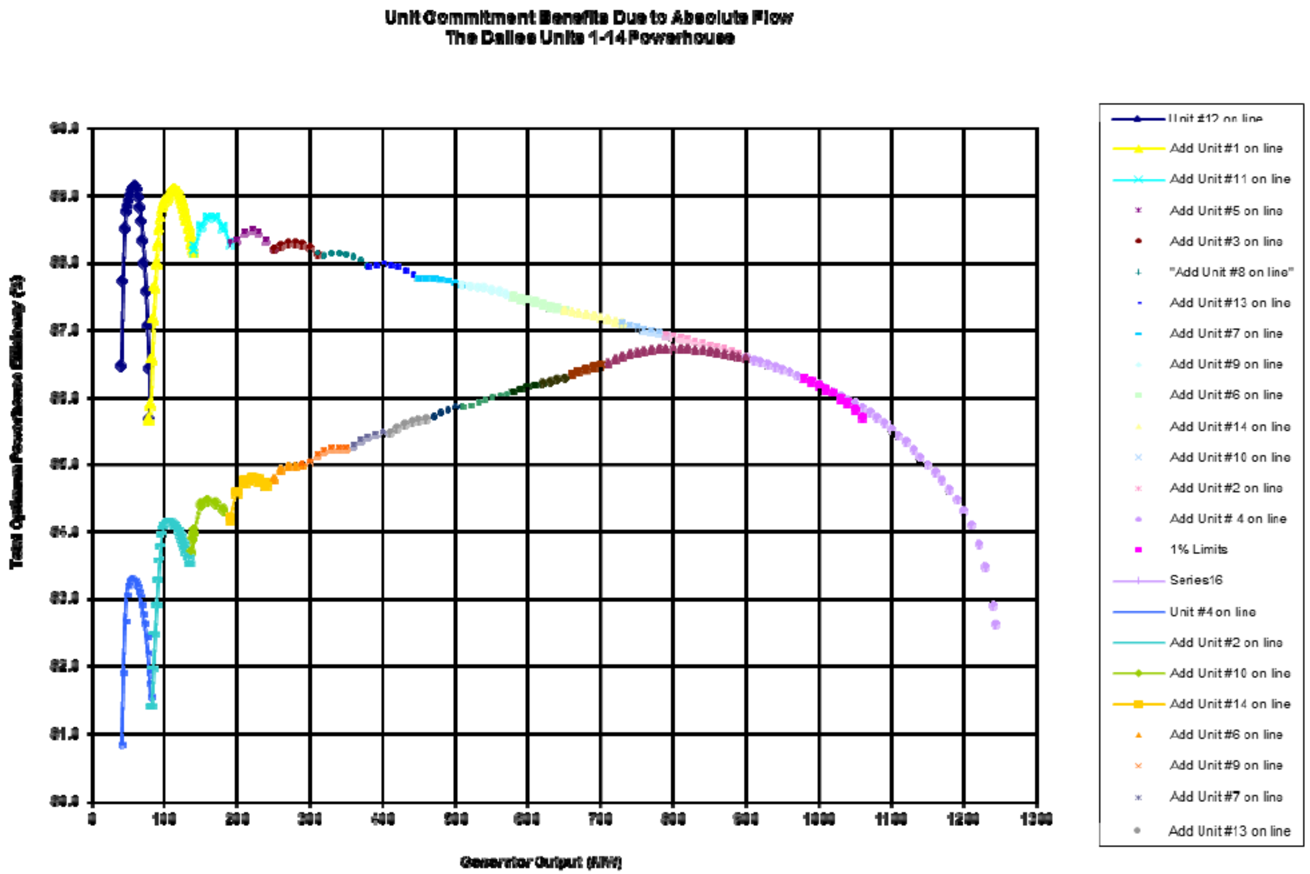

Figure 4 Efficiency curves for optimal unit selection (top curve) and worst-case unit selection (bottom curve). In both cases, load sharing is optimized. Non-optimal unit selection would result in a curve between these two extremes.

Project Synopsis: Project Description

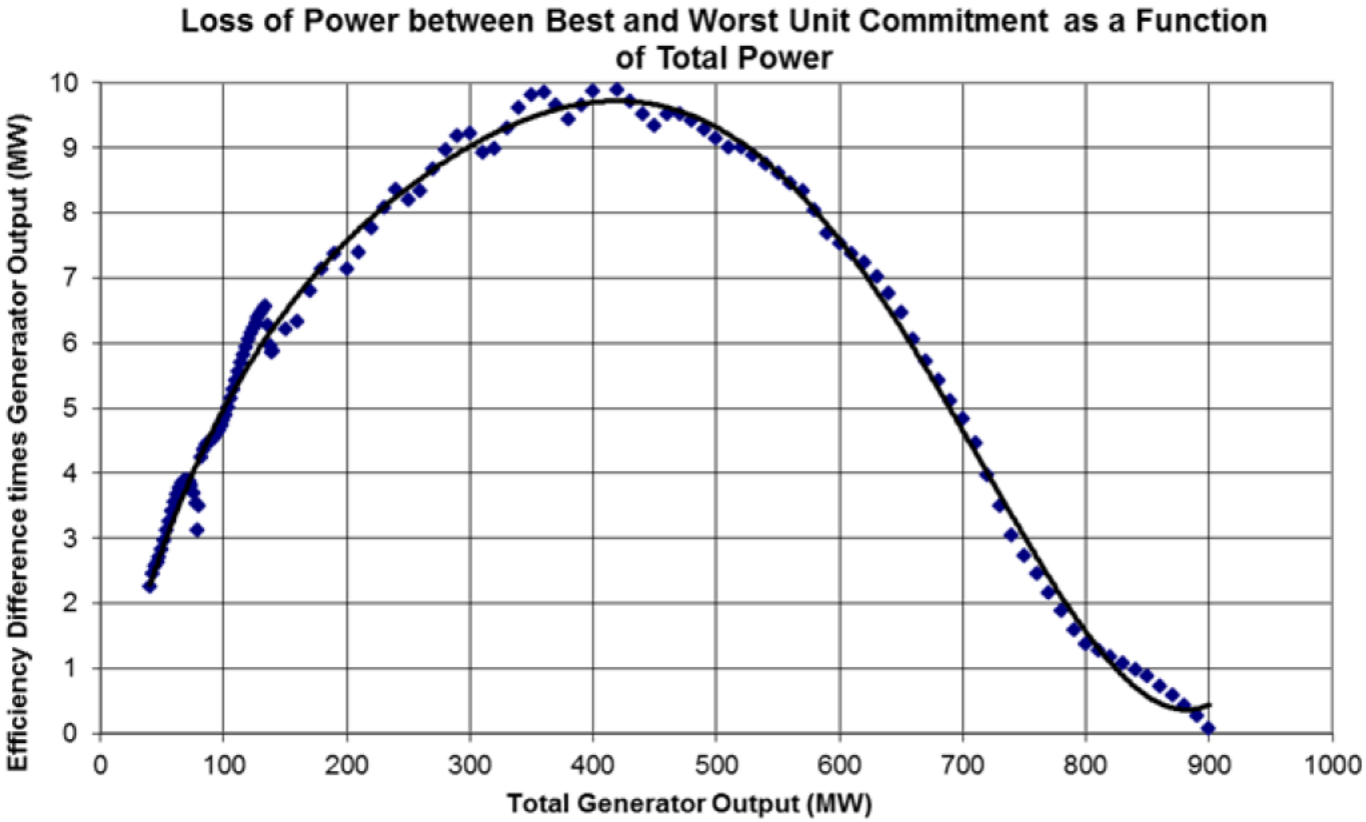

Figure 5 Difference in efficiency timer generator output between best case and worst case unit selection (load sharing optimized in both cases). Efficiency gains are significant when powerhouse output is less than 700 MW. Black line is the 6th-order polynomial trend.

Current Program Features

- User Inputs
  - Power
  - Turbine online status
  - Head and tailwater elevations
  - Specific weight

- Indicators (overall and/or per turbine)
  - Power
  - Flow
  - dQ/dP (inverse “demand rate”)
  - Efficiency

Project Synopsis: Project Objectives

1. Identify a suitable hydropower project
2. Obtain performance data
3. Verification Phase: validate algorithm
4. Incorporate operator-specified features. ex. curvilinear interpolation, block loading, alarms, spinning reserves
5. Develop GUI
6. Documentation, operational instructions, and operator training.

Project Synopsis: Project Objectives

- Major planned deliverable:

A stand-alone optimization application for a specific hydroelectric facility that demonstrates a measurable increase in powerhouse performance

Accomplishments (Plans)

1. Identify a Suitable Hydro - power Project
2. Obtain Performance Data
3. Verification Phase: Validate Algorithm
4. Development of HMI, Features
5. Documentation & Training

Possible Additional Developments

- Incorporate centralized project management tools
- Six hour-ahead prediction
- Graphical elements
  - Gate percentage indication
  - Graphical representation of actual vs. optimal
  - Operator settings display (SCADA for actual plant values)
- Historical data logging
- Incremental Excel data updates
- User manual and documentation
- Set up PLC hooks
- Export to standalone application

Expected Project Benefits

- Enhance FCRPS reliability, operation and maintenance
- Design operational improvements to reduce costs
- Maximize existing asset use and extend useful life of assets
- Decrease the FCRPS environmental footprint
- Increase generation efficiency (increased power per unit of water)

Expected Benefits

"Estimate the value of increased revenue and/or reduced costs for BPA."

•Estimate the increase in firm energy and increased revenue due to SQP Optimization

- 2011 BPA total hydro generation 5 minute data
- Scaled data down to The Dalles 14 units @ 78MW
- Applied smooth spline fit on Figure 5 data
- Calculated firm energy (MWh) savings from SQP optimization
- Calculated revenue using 2011 Mid-C average, $29.11/MWh

•Scale to estimate savings at The Dalles, all units

~ $1.4M/yr (42 MWh/yr)

•Scale to estimate savings across FCRPS

~ $9.4M/yr (324 MWh/yr)

Technology Transfer/Application to BPA

- Currently negotiate with project stakeholders regarding technology transfer

From: Estep,Judith A (BPA) - ST-3
Sent: Tuesday, April 24, 2012 2:34 PM
To: Irish,James T (BPA) - PGF-6; DeLong,Matthew L (BPA) - NSSP-4
Cc: Jones,Mark A (BPA) - PGF-6; Estep,Judith A (BPA) - ST-3
Subject: RE: BPA TI #254 Stage Gate 1 Update Response

Hi Jim: Please see comments from both Matt and me. Let us know if you have any questions comments.

From: Irish,James T (BPA) - PGF-6
Sent: Tuesday, April 24, 2012 11:44 AM
To: DeLong,Matthew L (BPA) - NSSP-4
Cc: Jones,Mark A (BPA) - PGF-6; Estep,Judith A (BPA) - ST-3
Subject: BPA TI #254 Stage Gate 1 Update Response

DRAFT – Please review for what we discussed at yesterday's meeting.

Matt,

In review of the requirements of Stage Gate #1 as stated on Page 8 of the Pre-award Authorization dated 01/17/2012 and the Memorandum received from Mr. Robert Bass dated April, 13, 2012, I would like to ask for the specifics as to the stated requirements:

- The requirement states to "Identify a suitable Multi-unit hydroelectric facility and execute a contractual agreement with the Corps, BOR, PGE, Pacific Corp or another dam-owing entity within 60 days" . Please provide the contractual agreement. (good)
- Hydro-power project identified – including a schedule for specific activities. (specify that we are only looking for a schedule of specific activities since they already identified Grand Coulee as the project)

Regarding the following requirements – Can you add a sentence about the information we feel wasn't addressed in the SG #1 "report"? We think it would be helpful to provide some details about what we think was not addressed.

- Description of test procedures for acquiring index test data.
- ~~Understanding of S/W (front and back end) ownership.~~ Not an issue – potential licensing options have been resolved.
- Understanding of ownership of index data.
- Document our ability to modify S/W for multiple/any BPA hydro project.

I would like to have the requested information submitted within thirty days after receipt of this request.

Thank you.

Sincerely,

Jim Irish

Jim Irish
Project Manager / COTR / ANS Program Coordinator - PGF-6
Bonneville Power Administration
905 NE 11th Ave
PO Box 3621
Portland, OR 97208
(503) 230 - 5914 - Office
[redacted] - Cell

From: DeLong,Matthew L (BPA) - NSSP-4
Sent: Monday, April 16, 2012 11:59 AM
To: Estep,Judith A (BPA) - ST-3
Subject: FW: BPA TI #254 - Stage Gate 1 Update
Attachments: Stage Gate 1 - Irish.pdf

FYI

Matt DeLong
Contract Specialist - NSSP
DOE - Bonneville Power Administration
503-230-7549 | mldelong@bpa.gov

From: Bob Bass [mailto:rbass2@pdx.edu]
Sent: Friday, April 13, 2012 8:49 AM
To: Irish,James T (BPA) - PGF-6
Cc: DeLong,Matthew L (BPA) - NSSP-4;(b) (6) [redacted]
Subject: BPA TI #254 - Stage Gate 1 Update

Hello Jim,

Attached is a memo concerning the status of BPA TI project #254, Multi-unit Optimization of a Hydropower Powerhouse. Particularly, the memo articulated our completion of Stage Gate 1.

I look forward to hearing from you.

-Bob

--
Robert Bass, Ph.D.
Associate Professor
Electrical & Computer Engineering
Portland State University
Portland, OR 97201
robert.bass@pdx.edu

Multi-Unit Optimization of a Hydropower Powerhouse: New Computational Methods for Unit Selection and Load Sharing

Final Report
BPA TI Project 1918-1556
September 17th, 2012

Robert Bass, Ph.D.
Michael Curtiss
Lee Sheldon, PE
Jonas Parker

Abstract

This paper presents results from verification testing of a hydropower optimization algorithm. The algorithm, utilizing sequential quadratic programming (SQP), is a decision support tool that optimizes the unit selection and load sharing between individual units within a hydroelectric powerhouse, while simultaneously accommodating multiple equality and inequality constraints unique to the powerhouse. As a means for demonstrating the efficacy of the algorithm, we modified the program to accommodate the 24-unit Grand Coulee hydroelectric facility. We then compared the algorithm results to four days of actual operational data and verified adherence to constraints. Further, we found the execution time is sufficiently fast to aid hydropower operations in real-time.

Index terms – Sequential quadratic programming, hydropower optimization, unit commitment, load sharing, performance optimization

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1 Introduction

We have developed a decision support tool designed to aid hydropower operations with unit selection and load sharing in a multi-unit hydropower powerhouse, with the objective of minimizing water flow for a given power request. The tool, originally described by Curtiss, et al, utilizes sequential quadratic programming (SQP) to minimize the objective function, flow as a function of power set-points, while adhering to several varieties of constraints pertinent to a specific powerhouse. [1]

In this paper, we present a case study to demonstrate the efficacy of the algorithm. This case study consists of operational data from four days of operation at the Grand Coulee hydroelectric facility (Coulee). The U.S. Bureau of Reclamation (USBR) provided our research group with characteristic data from Coulee, including unit capability curves and nominal capacities, condensing capabilities, unit dispatch priorities, discharge equations for four groups of units within the facility, as well as a set of operational notes. USBR also provided four complete days of operational data from Coulee, against which we compared the unit selection and load sharing solutions from our algorithm. USBR has implemented optimization at Coulee only recently; these operational data were recorded prior to regular use of optimization at Coulee.

This paper begins with a review of optimization methods and a discussion of Type 2 hydropower optimization. This is followed by a discussion of SQP and constraints specific to hydropower optimization problems. We conclude with a discussion of our results from the Coulee case study.

2 Theory of Type II Optimization

Five types of optimization pertaining to hydroelectric power have been defined. These are: Type 1, the optimization of individual turbines within a powerhouse; Type 2, the collective coordination of turbines within a powerhouse; Type 3, the coordination of all hydroelectric powerhouses within a river basin; Type 4, the coordination of multiple river basins within a wider region; and, Type 5, the coordination of all generating sources within a region. [1] [2]

While this paper focuses on Type 2 optimization, each successive type of optimization is dependent upon those before it. Type 2 optimization is dependent on first achieving Type 1 optimization. Type 1 optimization is achieved by determining a unit's absolute optimum efficiency profile, i.e. power output, p, per unit of flow, q, at a given head. Methods of achieving Type 1 optimization vary based on turbine type and powerhouse configuration. For Francis, Kaplan and fixed-blade propeller turbines, a table of power versus flow relationships is assembled at increments of head. Kaplan turbines also require characterization of their blade-to-gate relationship in order to determine optimal blade positioning. For each individual turbine, regardless of type, these data are compiled in a two-column table of efficiency versus power output. Using these data, a third column is derived, dq/dp, the rate of change of flow with respect to power. This is an important step in preparation for Type 2 optimization since equality of dq/dp is the criteria for Type 2 optimization.

The term dq/dp is the inverse of a term dp/dq that has been in use in conjunction with surge tanks for several decades and is named "demand rate." The nature of this parameter may be examined by taking its total derivative by the chain rule of differentiation. The result is Equation 1:

Equation 1

$$dq \big/ dp = \frac{q}{p}\left[1 - \frac{p}{h}\left(\frac{dh}{dp}\right) - \frac{p}{\eta}\left(\frac{d\eta}{dp}\right)\right]$$

The derivative in the latter term, $d\eta/dp$, is the "efficiency droop." At powers greater than the power at peak efficiency, it is negative and the whole term becomes positive. In that power regime, the whole term adds to the amount of flow required to gain an incremental increase power. The reason the total derivative, dq/dp, applies to any mix of different sized machines is because the efficiency droop is multiplied by power, p. That is, a given value of efficiency droop affects a machine of any size equally on a proportional basis. The other term does not apply when optimization is done on a constant head (h) basis. However, in the stability of surge tanks, it causes the lowest head to be the least stable. This is because the inverse derivative, dp/dh, is easily shown by the Affinity Laws to always be positive. That is power always increases as head increases. Therefore, in accordance with the orthogonal rule for gradients dh/dp must always be negative. Thus, the lower the head, the larger this positive whole term becomes. Also, again this term is multiplied by power, p, so it applies to any mix of different sized units.

Type 2 optimization involves two actions, unit selection and load sharing, and concerns coordination of both actions for all units within a powerhouse to achieve a total powerhouse power set point using a minimal amount of flow. Load sharing involves selecting wicket gate openings such that the derivative of flow with respect to power output (dq/dp) is equal for all units. If all units in a powerhouse were identical, these actions would be trivial since their efficiency profiles would be identical. However, though the turbines may be of the same design, the efficiency profile of each is slightly different due to both abnormalities in manufacturing and variation of the placement of the units within the powerhouse. Wear-and-tear over years of operation can exacerbate these differences. These abnormalities can result in peak unit operating efficiency differences and shifts in peak efficiency points of between two and ten percent, as demonstrated in Figure 1. Optimization algorithms take advantage of these differences by proper unit selection and load sharing, given a power set-point and known head. Unit selection involves choosing to bring on line some turbines while leaving others off-line. When the powerhouse is under the control of a human operator, unit selection and load sharing decisions are based on the heuristic knowledge of the operators. Experienced operators are able to make these decisions with impressive results, though as our analysis shows, there is room for additional improvement through the use of an efficient optimization algorithm.

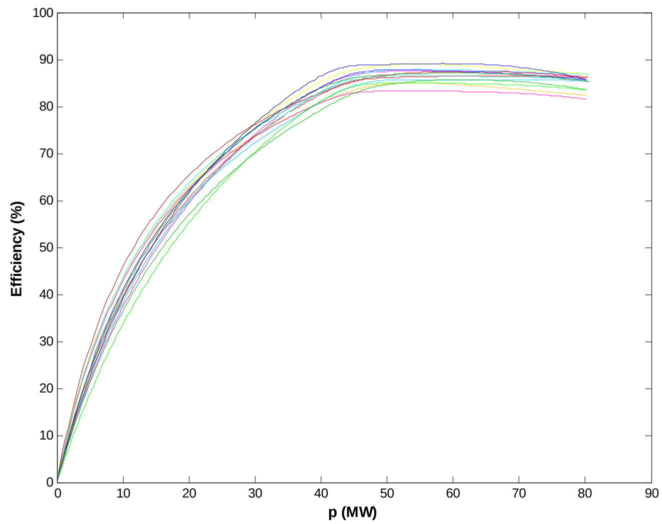

Figure 1 Identical units within a powerhouse exhibit variations in their efficiency profiles, specifically the peak efficiency and the power at peak efficiency. The above shows the variations in efficiency profiles between fourteen otherwise identical 78 MW units.

For the Coulee case study presented in this paper, the USBR provided discharge equations characterizing groups of units rather than individual units. Discharge equations provide flow, *q*, as a function of power set-point, *p*, and head, *h*. Equation 2 presents a generalized form of these equations. The coefficients *A* through *J* are characteristics of the turbine groups.

Equation 2

$$q(p,h) = A + Bp + Ch^{-1} + Dp^2 + Eh^{-2} + Fph^{-1} + Gp^3 + Hph^{-2} + Jp^2h$$

The USBR and the Bonneville Power Administration (BPA) use these discharge equations in the day-to-day operation of Coulee as well as for planning and modeling. The groups (units 1 through 9, 10 through 18, 19 through 21 and 22 through 24) are each characterized by a unique discharge equation. It is from these discharge equations that we derive the dq/dp curves, Equation 3.

Equation 3

$$dq/dp = B + 2Dp + Fh^{-1} + 3Gp^2 + Hh^{-2} + 2Jph$$

To maximize operational gains, each unit would have its own characteristic dq/dp curve, thereby taking advantage of the variation between all turbines in order to achieve optimal unit selection and load sharing, rather than characterizing units more generally in groups. Nonetheless, the use of group discharge equations proved to be sufficient test the capabilities of our algorithm.

3 Sequential Quadratic Programming

Sequential quadratic programming (SQP) is a non-linear, computationally-efficient optimization technique used for minimizing an objective function subject to equality and inequality constraints. SQP has been applied to various aspects of power systems, such as the design of distribution systems, placement of VAR compensators, power systems control, frequency control, optimal power flow, as well as unit commitment for hydroelectric power [3] [4] [5] [6] [7] [8] [9].

For Type 2 hydropower optimization, the objective function $q(p)$, subject to m equality and inequality constraints $c(p)$ and $h(p)$, is the total flow to be minimized, and p is a vector of independent variables representing the individual units' power set-points. SQP determines the p vector of power set-points such that $q(p)$ is minimized.

Equation 4

$$\text{minimize } q(p) \quad p \in \Re^n$$

$$\text{s.t. } c_i(p) = 0 \quad i = 1, \ldots, m_c$$

$$\text{and } h_i(p) \geq 0 \quad i = m_c + 1, \ldots, m$$

Vectors of Lagrange multipliers, λ for the equality constraints and π for the inequality constraints, are used to constrain the objective function according to $c(p)$ and $h(p)$, resulting in a Lagrange function. The Lagrange function is simply a constrained version of the objective function $q(p)$.

Equation 5

$$L(p, \lambda, \pi) = q(p) - \sum_{i=1}^{n} \lambda_i c_i(p) - \sum_{i=1+n}^{m} \pi_i h_i(p)$$

The gradient of the Lagrangian when set to zero then gives the conditions under which the optimum may be found, Equation 6.

Equation 6

$$\nabla L(p, \lambda, \pi) - \lambda \nabla c(p) + \pi \nabla h(p) = 0$$

An iterative quasi-Newton method is then applied to solve for p, λ and π. The quasi-Newton method uses a 2nd-order Taylor series expansion to provide a quadratic approximation of the Lagrangian at iteration $k+1$,

Equation 7

$$L(p_{k+1}) \cong L(p_k) + \nabla L(p_k)(p_{k+1} - p_k)^T + \frac{1}{2}(p_{k+1} - p_k)^T H(p_k)(p_{k+1} - p_k)$$

$$\text{s.t. } c(p_k) + \nabla c(p_k)^T (p_{k+1} - p_k) = 0$$

$$\text{and } h(p_k) + \nabla h(p_k)^T (p_{k+1} - p_k) \geq 0$$

where $H(p_k)$ is the Hessian of the Lagrange function. For quasi-Newton methods, an approximate Hessian is updated after every iteration; calculating a full Hessian is not necessary. Using these steps, SQP can be used to solve constrained nonlinear problems in a computationally efficient manner. Provided with reasonable initial guesses for the arguments of the Lagrange function, the algorithm should converge within a practical number of iterations.

4 Constraints

Unit commitment and load sharing of synchronous turbines within a powerhouse are subject to numerous constraints, such as minimum loading, up-margin, condensing/motoring, run and down times, and start-up/shut-down priorities. In order to properly optimize the operation of a powerhouse, these constraints must factor into the optimization algorithm. For discussion sake, we categorize these constraints within three headings: non-temporal inequality constraints, temporal inequality constraints, and equality constraints. Constraints that do not fit within these categories are lumped under the heading of 'others.'

4.1 Non-temporal Inequality Constraints

Non-temporal inequality constraints, $h(p)$, confine the search space for the minimized solution to $q(p)$ by modifying the Lagrangian as shown in Equation 5. These constraints are time-independent. Note, if a constraint has both an upper and lower bound, say $h_{min} \leq h(p) \leq h_{max}$ such as for minimum and maximum loading, then it is redefined as two constraints $h_a(p) = h(p) - h_{min} \geq 0$ and $h_b(p) = h_{max} - h(p) \geq 0$ to match the form specified in Equation 4.

4.1.1 Rough Zones / Cavitation Zones Constraints

Also known as "Exclusion Zones", these constraints define bands of operation where the turbine run-out and/or cavitation is high. When operating a unit within these zones, the goal is to ramp through as quickly as possible; a unit should never be operated in one of these zones for an extended duration.

Exclusion zone constraints may be addressed in two ways. One, if the best solution places a turbine within an exclusion zone, the solution would be thrown out and then the next-best solution would be chosen. This process would iterate until the best solution was found that did not place any turbines within an exclusion zone. Or two, inequality constraints defining exclusion zones for every generator would be included within the definition of the Lagrangian. The optimal solution would then be calculated based on these constraints. The latter approach is more computationally efficient since it restricts the search space for the solution to the objective function and does not require multiple iterations to determine a second-best solution.

4.1.2 Steady-State Unit Constraint

When a unit is generating, its load must not be changed. A steady-state constraint is handled by setting the unit's power output, subtracting that output from the powerhouse power set-point, and then excluding it from unit selection within the optimization algorithm.

4.1.3 Minimum Loading Constraint

When a unit is operating, it must be running at or above a defined generation load. This is the same as an exclusion zone boundary extending from 0 MW to the given lower MW bound.

4.1.4 Up-Margin Constraint

Up-margin represents how much additional power can be generated from a power plant without starting another unit. Up-margin reserve may be built in to the program as an upper-bound constraint. When additional power is needed, the upper-bound constrain would be shifted upwards. The load-sharing portion of the algorithm would then be re-run (excluding the unit-selection portion) to determine new power set-points for all units given the new powerhouse set-point.

4.1.5 Shared Penstock Constraint

If multiple generators share a single penstock then the discharge rate of each unit can be dependent upon the loading of the other units on the same penstock. This could be accounted for in the optimization algorithm by allowing for multiple discharge equations for a single generator since the maximum penstock flow rate is an inequality constraint, and the two turbines can share load freely within it. When the constraint begins to affect efficiency one or both units will initially be dropped. Whichever of the two is the better choice will return, individually, if it happens to fit into the solution.

4.2 Temporal Inequality Constraints

Temporal inequality constraints are a time-limited form of the inequality constraints $h(p)$. These constraints enter into the Lagrangian if a solution is sought within some specified time frame. The time frame is triggered by an event, specifically either a shut-down or start-up of a unit. After the time frame has expired, the constraint is removed from the Lagrangian.

Four temporal inequality constraints are applied to multi-unit hydropower optimization. These are the Minimum Run-Time constraint, which dictates how long a unit must be run prior to being shut down again; the Maximum Run-Time, which dictates the maximum time a unit may be run before it must be shut down; the Minimum Down-Time constraint, which dictates the minimum time a unit must stay shut down before being started again; and the Maximum Down-Time constraint, which dictates the maximum time a unit can be shut down before it must be restarted.

Because of the temporal nature of these constraints, any optimization algorithm employing them would have to be run on a continuous loop and incorporate an internal clock. As a stand-alone decision support tool, the current version of our optimization algorithm does not account for temporal inequality constraints. However, it would be straight-forward to modify the software to incorporate these constraints. This could be done by monitoring the on/off status tag of each turbine via hooks to the powerhouse SCADA system, which would then be used to include or remove the appropriate constraints within the Lagrangian.

4.3 Equality Constraints

Equality constraints, $c(p)$, also confine the search space for the minimized solution to $q(p)$. These constraints either set specific required values for $c(p)$ that modify the Lagrangian, or they result in a unit being removed from unit selection consideration.

4.3.1 Must-Run Constraint

A constraint must be made if the unit should not be shut down. Example 1: A pump is electrically tied to a specific generator. While pumping, that generator must remain generating. Example 2: A unit or group of units is armed for Gen Drop, which is a mechanism that can be used by a Power Marketing Agency to quickly shed generation if a problem occurs with the transmission system.

There are two possibilities for implementing this constraint. First, if there is a specific required output such as with gen drop, the unit can be "fixed" to generate a specific output and excluded from the optimization matrix using an equality constraint. Second, if a specific output is not required but the unit must stay on, then the unit would be a required part of the solution but its load sharing would be optimized. In the case of Example 1 for instance, a minimum *inequality* constraint would be set to ensure sufficient power was available to meet the needs of the pump.

4.3.2 Motoring / Condensing Constraints

Units may be motored or condensed instead of shut down. This could be done for operational issues or voltage support issues. Motoring refers to keeping a unit spinning while not producing power. This may be done in order to limit cycling on breakers, for example. Condensing refers to keeping a unit online specifically to provide reactive power support; units are often used to buck VARs from the system during light loading periods.

To implement these constraints, the real power consumption of the unit when it is in a condensing or motoring state (ie. not part of the unit selection vector) is added to the powerhouse power set-point such that additional power from adjacent units is available to meet both the power requirements set by dispatch and the real power consumption of the condensing units.

4.3.3 Ancillary Services Constraints: Spinning Reserve, Voltage Control, Frequency Control

Spinning Reserve - In most cases, this is the exact same as Up-Margin. There are a few exceptions where condensing units might contribute to spinning reserve.

Voltage/Frequency Reserve - Operation of a plant to meet voltage / frequency control requirements. This control is typically driven by a unit's governor. Example: Run a unit at speed-no-load only for VAR support and not real power generation.

These constraints can all be handled by fixing generation levels of selected units outside the optimization matrix. Units which are in condensing service would simply be noted as such and not enter the optimization matrix, as discussed above.

4.4 Others

Two other constraints are employed in the optimization algorithm, but do not fall within the equality or inequality definitions pertinent to Equation 4. These are the Priorities Start-up constraint and the Priorities Shut-down constraint. These constraints are simply definitions of priorities that should be used when determining an order upon which to stop or start units. Example 1: Try to always start Unit A before Unit B because of a bus issue, or physical unit location. Example 2: try to shut down Unit B before Unit A.

These constraints are handled by withholding a unit from being added/removed prior to its paired unit. For Example 1, Unit B would be withheld from the solution until Unit A has come online, understanding that Unit B would not necessarily be the next unit added; similarly with Example 2.

5 Results

Through our case study of the Grand Coulee facility we have demonstrated potential flow savings in the range of around one to two percent. A decrease in flow within this range may be possible if operators use this SQP-based algorithm as a decision support tool. Further, the algorithm can calculate results in real-time, allowing operators to make unit selection and load sharing adjustments without delay. Each of the four sets of data from Coulee contained over 8600 data points; adjustments to unit selection and/or load sharing were made roughly every ten seconds. The algorithm returns results for the 24-unit Coulee facility in less than one second.

Figure 2 shows flow as a function of time for Coulee on August 11th, 2007 (called hereafter the "Actuals") in comparison to the flow that would have resulted if the algorithm were used as a decision support tool. For this data set, use of the algorithm would have resulted in the use of 0.92% less water than what was actually realized. The difference in flow between the Actuals and the Algorithm is presented more clearly in Figure 3. This difference has an energy value of around 734 MWh_Q (water potential energy) over the span of the day.

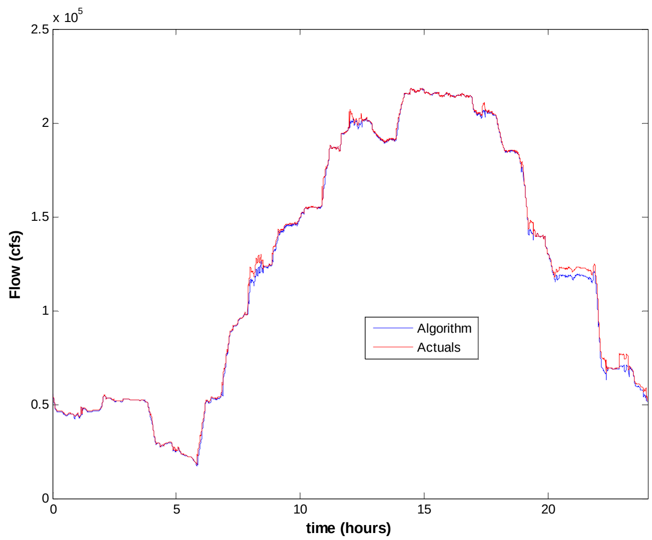

Figure 2 Shown are the actual flow (Actuals, red) for Grand Coulee Dam on August 11th, 2007 and the flow that would result if unit selection and load sharing were determined by the optimization algorithm (blue).

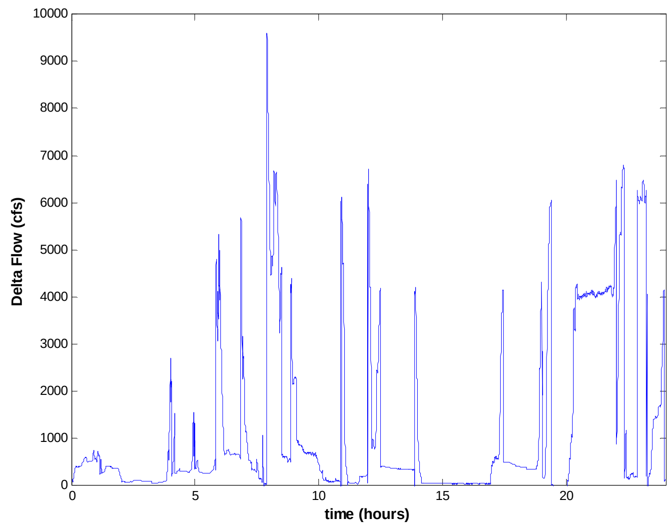

Figure 3 Difference in flow as a function of time between the Actuals and the algorithm. This difference has an energy value of around 734 MWh_Q (potential energy), or 663 MWh_E (electrical energy) over the span of this data set (one day).

Table 1 presents a summary of the results from the four sets of performance data against which the algorithm was verified. Each set of performance data included information on MW request, up-margin, forebay and tailbay elevations (head), individual generator status (online or offline) and generator MW output (generators in condensing mode present a negative MW number), with an update provided roughly every ten seconds throughout the day. Using the MW request and head set-points, the algorithm was set to determine unit selection and load sharing for each of these time intervals, thereby producing its own generator status profiles and MW output values. Using the group discharge equations, we compare the flow resulting from the Actuals to the flow resulting from the algorithm set-points. Table 1 presents these results in terms of energy per day of flow (MWh_Q), from which we derive an estimate of the electricity "savings" (MWh_E) based on the moment-by-moment efficiency of the powerhouse. Recognizing the power set-point in both cases is identical, we know there are no actual electrical energy savings. Rather, the translation of the conserved flow to MWh_E allows us to place a momentary price signal on the water savings, provided a reasonable price per MWh_E such as the Mid-Columbia on-peak spot price.

Table 1 Presented below is a summary of results from the four sets of operational data used to verify the algorithm. Column two presents the electrical energy requested by dispatch over the range of the data set (one day). The third column shows the actual water flow energy consumed per data set. The fourth column shows the flow energy that would have been consumed were the algorithm implemented as a decision support tool. The fifth column shows the difference between the actual and algorithm flow energies per data set. The sixth column estimates the value of the saved flow energy in terms of electrical energy, which may then be evaluated in dollar terms based on a metric such as the average on-peak Mid-Columbia (Mid-C) spot price. This was calculated based on the moment-by-moment water flows and efficiencies throughout the day.

Data Set	Electrical Energy Demanded (MWh_E)	Flow Energy, Actuals (MWh_Q)	Flow Energy, Algorithm (MWh_Q)	Difference (MWh_Q)	Difference (MWh_E)
061025	39,362 (CF = 0.24)	44,133	43,283	850 (1.9%)	764 (1.9%)
061217	53,131 (0.33)	59,010	58,423	587 (1.0%)	531 (1.0%)
070811	71,955 (0.45)	79,729	78,995	734 (0.92%)	663 (0.92%)
070823	65,601 (0.41)	72,858	72,242	616 (0.85%)	551 (0.84%)

5.1 Verification of Adherence to Constraints

The USBR performance data describe unit operation under a set of constraints. These include the following non-temporal inequality and equality constraints: up-margin, shut-down and start-up priorities, motoring/condensing, minimum loading and rough zones. With the exception of rough zones, all of these constraints were incorporated into the algorithm (temporal constraints were not incorporated into this version of the algorithm). The algorithm's adherence to these constraints was verified by analyzing the results for constraint violations, as discussed below.

5.1.1 Up-margin

The optimization program can be set to provide up-margin for the powerhouse. To validate, the output data files were examined to ensure that the powerhouse up-margin was not violated; the sum of MW output and the up-margin request should never exceed the powerhouse nameplate capacity minus all offline units. For all four data sets, this was found to be the case, as illustrated in Figure 4.

5.1.2 Shut-down & Start-up priorities

Specific to Coulee, two specific units should be started first and stopped last. The program was modified to ensure these two units adhered to these priorities. Doing so results in these units being removed from the unit selection part of the optimization algorithm. To validate, data output files were examined to ensure these units were the first to be started and last to be stopped. For all four data sets, this was found to be the case.

5.1.3 Minimum Loading

Specific to Coulee, units 1 through 21 must not be set to less than 50 MW and units 22-24 must not be set to less than 25 MW. We wrote the program to allow an operator to input minimum loading constraints for every generator. To validate, the algorithm output for each generator was checked to ensure the power did not drop below the minimum loading threshold. Figure 5 visually illustrates this evaluation; for units 1 through 21, the algorithm never selects a power set-point below 50 MW, while units 22 through 24 are never set below 25 MW. For all four data sets, this was found to be the case.

5.1.4 Motoring/condensing

Specific to Coulee, units 19 through 24 should never be shut down. Rather, they should be made available for motoring/condensing. In which case, the MW losses incurred while motoring/condensing must be accounted. To verify, the algorithm output was checked to ensure the prescribed motoring/condensing powers were subtracted from the total powerhouse output when these units were not part of a unit selection solution. Figure 5 demonstrates this constraint was met for Units 19-24 on August 11, 2007. When taken offline, the units are set to motor/condense, in which case they consume power (negative power). For all four data sets, this was found to be the case.

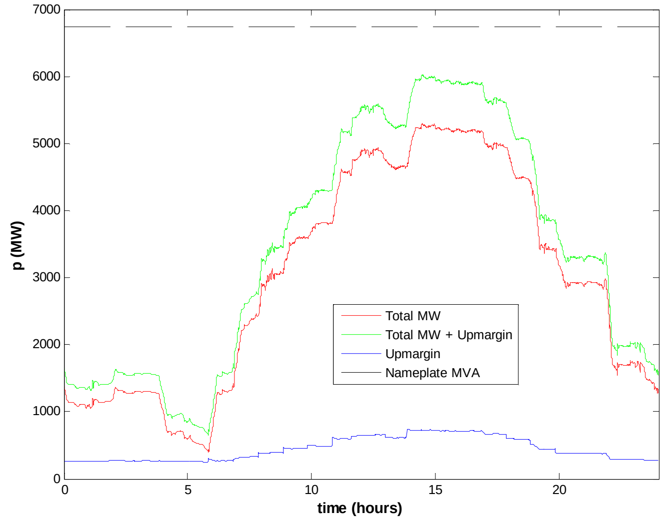

Figure 4 Adherence to the up-margin constraints was evaluated by ensuring the MW dispatched plus the up-margin request did not exceed the nameplate capacity of the powerhouse (6735 MVA, upper dashed line). On August 11, 2007, the sum of peak MW output and the up-margin request was 5,561 MW, significantly less than the powerhouse nameplate.

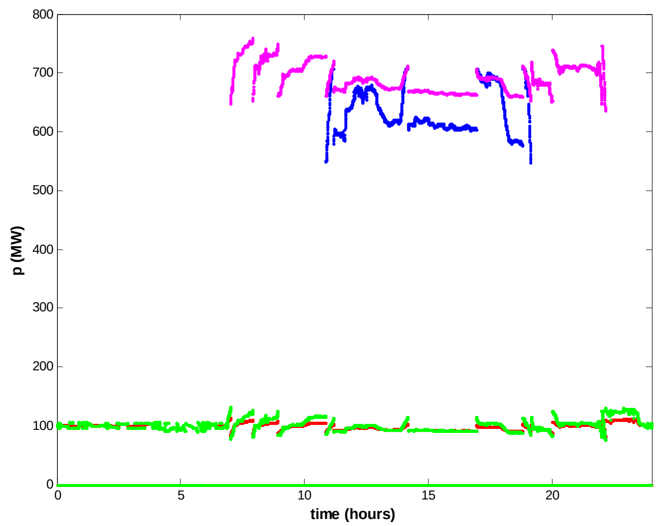

Figure 5 Power output for groups 1 through 4 on August 11, 2007. Groups 1 and 2 are noted in green and red, lower curves. Groups 3 and 4 are noted in magenta and blue, upper curves. Note none of the units were assigned set points below 50 MW (Groups 1, 2 and 3) or 25 MW (group 4) unless the unit was taken offline. Units in Groups 3 and 4 are set to motor/condense when taken offline, causing them to become consumers of power (not shown).

5.2 Verification of Optimization

Multi-unit hydropower optimization may be easily understood initially in terms of the parameter, $d\eta/dp$, the rate of change of efficiency, η, with respect to power, p. If this derivative is equal to zero, the tangent to a curve of efficiency versus power is parallel to the power axis. The point of intersection between the tangent and the efficiency curve is the location of peak efficiency. However, if two identical units are operating, their combined efficiency is maximized if they are both operated such that the slopes of the derivatives are equal, and not necessarily zero. In this way, an infinitesimal flow rate cannot be taken away from one machine and given to another in any way which would result in an increased combined efficiency. If the units are of different size (or even different efficiency profiles) an increase of efficiency on the larger machine produces a greater increase on the combined efficiency than the same increase on the smaller machine. In other words, the value of the derivative must be weighted on the basis of size. Equation 8 describes the basic definition of fluid power, p_{HP}, in units of water horsepower at a constant head, h, and specific weight of water, γ.

Equation 8

$$p_{HP} = \eta q \left(\gamma h \big/ 550\ ft \cdot lb / s \right)$$

This equating of weighted $d\eta/dp$ curves between units is equivalent to equating dq/dp curves; q provides the weighting.

If the algorithm recommends optimized unit selection and load sharing, then the dq/dp values for every online unit within the powerhouse will be equivalent. For the Coulee case study, the algorithm does result in equivalent dq/dp values for all units at all set-points, as demonstrated graphically in both Figure 6 and Figure 7.

In Figure 6, we compare the difference between the dq/dp results from the algorithm and those from the Actuals at every set-point throughout a day. The degree of optimization is visible when one overlays the dq/dp curves of several units. When overlaid, and if optimized, the dq/dp curves should all overlap. As shown in Figure 6A, the overlay of dq/dp from the Actuals shows there are variations in dq/dp over time between the various units. While the Actuals efficiency performance is very good, there is room for improvement. In Figure 6B, the overlay shows nearly identical dq/dp curves at all times, indicating the algorithm is behaving according to theory.

In Figure 7, we show the derivative of the group discharge equations for the four turbine groups (solid lines). Overlapping these curves are four loci of dq/dp values derived from the algorithm results. The curves and the data share the same head of 312 feet; recall the units' discharge equations, Equation 2, and therefore the dq/dp curves (Equation 3), are functions of head. Each locus derives from a different power set-point. Note all the data points within each locus share the same dq/dp value, indicating that the algorithm has optimally allocated load sharing between the units, and that all online units are adhering to their respective discharge equation curves.

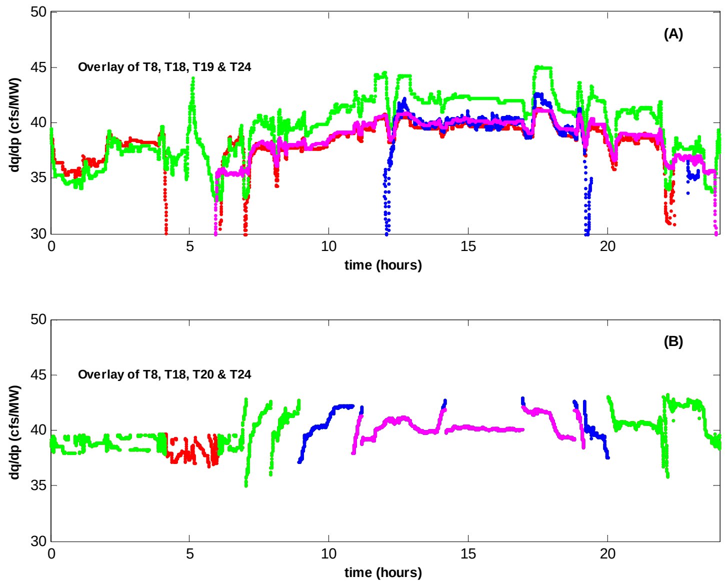

Figure 6 (A) Overlay of *dq/dp* data from four representative Grand Coulee units, one from each of the four groups, derived from actual performance data recorded on August 11th, 2007. The overlay demonstrates that load sharing is not optimized since the units do not share the same *dq/dp* at all times. (B) Overlay of *dq/dp* data from four representative units, one from each of the four groups, based on suggested unit selection and load sharing from the algorithm. Optimization was based on actual head, reserve margin, unit availability and MW request set points from August 11th, 2007. This overlay demonstrates load sharing is optimized; all units have nearly identical *dq/dp* values when they are online. The results from T20 (magenta) overlay those of T24 (blue), which overlay those from T8 (green) and then T18 (red).

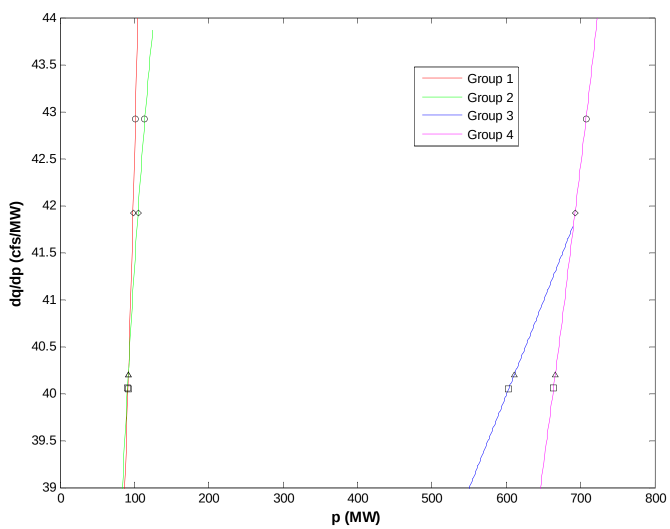

Figure 7 Derivative of the group discharge equations (*dq/dp* vs *p*) for the four turbine groups at Grand Coulee at 312 ft of head. The loci of *dq/dp* values are bound by the limits of the discharge equations for the units that are online. Four loci can be noted in this curve, each for a different power set-point. All the online units within a locus should have the same *dq/dp* value if the algorithm is properly allocating load sharing. The top two loci, circles and diamonds, have *dq/dp* of 42.9 and 41.9 cfs/MW and power set-points of 2132 and 2065 MW, respectively. Note in both cases only three of the four turbine groups are being used for unit selection; the Group 3 units are offline and the *dq/dp* values for these two loci are beyond the range of those units' *dq/dp* equation. For the bottom two sets, triangles and squares, with *dq/dp* values of 40.0 and 40.2 cfs/MW and power set-points of 2138 MW and 2156 MW respectively, units from all four turbine groups are being used for unit selection.

6 Conclusion

Through the Grand Coulee case study, we demonstrated powerhouse efficiency may be improved if operations are complimented with an SQP-based decision support tool. It must be noted however, that these gains were achieved using group discharge equations rather than unit-specific efficiency curves for every unit within the powerhouse, suggesting further improvements may be possible if all the units within the powerhouse are individually characterized. Ideally, every unit would be uniquely characterized such that variations between units may be exploited to maximize optimization. Such characterization could be done via absolute index testing of every unit within the powerhouse in order to ascertain absolute performance characteristics for each unit. [10] [11] Nonetheless, the use of group discharge equations proved to be sufficient to suggest possible operational gains in the range of 1 to 2%. Grossly extrapolating based on the four data sets presented in the case study, and using the 2011 average on-peak Mid-Columbia wholesale spot price of $30/MWh, the approximately 627 MWh per day saved through optimization amount to an annual savings of around $6.9M.

In order to realize such gains, a decision support tool must be able to return results in significantly less time than the mean hold time of the head and power set-points. We found the algorithm returns results for the 24-unit Coulee facility in less than one second. Given that adjustments in unit selection and load sharing in the Coulee datasets occur roughly every ten seconds (8600 adjustments per day), the algorithm is sufficiently fast to serve as a decision support tool.

7 Acknowledgements

The authors wish to thank Toby Steves and his colleagues at the U.S. Bureau of Reclamation for their generous support, specifically in providing operational information and performance data for the Grand Coulee powerhouse. This work was partially supported by the Bonneville Power Administration though a Technology Innovation Opportunity grant, project number 1918-1556.

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Quarterly Status Report

Project Manager	Jim Irish	**Status for period ending**	1Q FY12
Project Name		**TI Project No:**	254
COTR	Jim Irish	**Contract Nos:**	None
Contractors		**Team Members:**	

Overall	G Y R	1.Working on getting contract written so work on the project phase
Stage Gate	G Y R	1.Work has not started so SG#1 has not been met which is critical
Budget	G Y R	1.Contract has not been issued but CO has the authority to give a get start now until contract is issued and signed

Description
Green *Project is on scope, schedule and cost with no significant issues.*
Yellow *Issues exist which may affect scope, schedule, or budget by more than 10%*
Red *Issues exist which may affect scope, schedule, or budget by more than 20%*

Key Accomplishments This Period
Include status of Stage Gates

Hopefull reconcillation between the splitting of the original project proposers and the issuance of a contract.

Key Activities Planned for Next Period

Issuance of start work order and preliminary work toward completion of SG #1

Schedule Status
Do you anticipate meeting or missing the planned completion date. Provide explanation

It is anticipated that the completion date will be met however that is optimistic and if SG#1 is achieved then the project may meet it's end date but that is optimistic and will probably look toward out year continuation.

Project Budget

FY12 Budget is dependent upon final approv

Current Issues

Problems / circumstances that have impacted or are currently impacting the project

Issue	Impact (Hi/Med)	Action Taken / Next Steps
No contract and IP agreement	HI	Working towards resolution

Impact definition:
Med: Impacting schedule, scope, or budget by more than 10%
Hi: Impacting schedule, scope, or budget by more than 20%

Risks

Potential issues that are not currently impacting but could impact the project

Risk	Probability Lo/Med/Hi	Impact Lo/Med/Hi	Mitigation
Completing Contract schedule	Hi	HI	Meet SG#1 or terminate

Probability definition:	Impact definition:
Lo: <50%	Would affect scope, schedule, or budget by less than 10%
Med: 50% to 75%	Would affect scope, schedule, or budget by more than 10%
Hi: >75%	Would affect scope, schedule, or budget by more than 20%

TIP 254: Multi-Unit Optimization of a Hydropower Powerhouse, New Computational Methods for Unit Selection and Load Sharing

Context

The least expensive way to add power to the BPA grid is to adjust assets that are already online to make them more efficient. Hydropower is the largest of BPA's present resources; therefore, any verifiable improvement that maximizes hydropower delivery is hugely significant. This project provides software -- an algorithm -- that rapidly solves real-time models of the hydro projects in the Columbia River system. It uses empirically gathered flow vs. power data for each turbine in a powerhouse, and with a high degree of accuracy determines individual unit set points and unit selection that will provide maximum overall efficiency, with astounding speed of solution -- within a few seconds, or even less. That means additional power for the same amount of water. It also provides increased life for generating units and increased survivability of downstream migrant fish passing through turbines. The program has already been demonstrated to compute a solution as intended. Therefore, the remaining portions of this project have a similarly high probability of success.

Description

This is a one-year project to further develop an optimization algorithm for hydroelectric powerhouses. The goal is to provide proof of concept on an active hydro project, develop a graphical user interface for the powerhouse operator, and increase the software's feature list. The end result will be a commercial solution for flow-to-power optimization. Students from The Oregon Institute of Technology's (OIT) Advanced Hydropower class and follow-on independent study classes created an algorithm that optimizes unit selection and load sharing for the entire range of power output in a multiunit hydroelectric powerhouse. Data from The Dalles Dam has been used to validate the program, and it has been shown to match the best hand calculation by a professional engineer. It is faster than any similar program to date, thanks to an optimization method that offers a more direct solution than the other iterative solutions presently in use. Now the direction is to commercialize the program by comparing the program solution against actual hydroelectric power plant operations. Taking a nonintrusive approach, operating points will be compared with a real powerhouse. The program can be used to validate operator set points against a perfect solution.

Why It Matters

According to a BPA study done by Harza Engineers, Inc., about 18 years ago, "Hydropower optimization provides the lowest cost energy available from any generating resource." Further, this additional energy is firm energy. Example: "In good water years, the Columbia River Basin hydro system can produce about 18,000 average megawatts of electricity, and in poor water years, as little as 11,700 average megawatts" (excerpt from http://www.nwcouncil.org/library/2007/2007-12/power htm). Consider that at the very minimum this software generates a system-wide, average improvement of 1%. That would amount to 1165 GWh/yr of additional energy, and additional annual revenue on the order of $81,527,727, assuming $70/MWh -- an astounding return for very little investment.

Goals and Objectives

1. Identify a hydropower project for index testing, and collect data
2. Manually determine optimal load sharing and unit selection, for low, medium (if possible), and high head
3. Validate the computer algorithm using the hand-calculated results
4. Modify script to incorporate more features: curvilinear interpolation, block loading, alarms
5. Develop a graphical front end for stand-alone use and also demonstrate as a SCADA solution
6. Documentation, operational instructions, and operator training. Explore commercialization.

Deliverables

1. Updated and modified Type 2 hydropower optimization software
   a. Ownership of previous code is protected. However, the newest version containing all necessary useable code will be made available for use
   b. Several formats/ programming languages available including Web-based program and executable files
   c. Includes user-friendly graphical user interface (GUI)

2. Systematized hydropower optimization, Methodology Type 1 and Type 2
   a. Includes training personnel from BPA and from selected dam
   b. Includes operator manual
3. Standard deliverables as expected by BPA including but not limited to the following:
   a. All supporting data in an electronic format acceptable to BPA
   b. Expected functionality and support of any hardware and/or software as applicable along with full documentation of its use and repair, as acceptable to BPA
   c. Expected performance standards
   d. How the proposed project will be integrated into BPA's Power Delivery System
   e. How established utility processes and procedures will be affected
   f. Appropriate testing and/or evaluation methodology if applicable
   g. A final report including next steps for the project or potential follow-on projects.

Project Start Date: January 2012

Project End Date: September 2012

BPA Funding

Total Project Cost: $208,695

BPA FY2012 Budget: $100,673

BPA FY2012 FTE: 0.15

Participating Organizations

Oregon Institute of Technology Hydropower Group

For More Information Contact

BPA Project Manager:

James Irish
jtirish@bpa.gov