Optimization of Hydro-Power Plants for Generation

Jim Cook
Jim Walsh

Abstract

A decision support system is presented that addresses optimal unit dispatch and load allocation in a multi-unit hydroelectric plant. The concept behind the optimization approach is explained. Estimates of the improvements this system can provide over existing plant operational methodologies are provided. Actual use of this system has provided gains of over 2% in plant performance.

Introduction

Process optimization software can be found in many forms. It can be tightly integrated as a fundamental part of an automated system or exist as an aid to guide personnel in setting system parameters for optimum operation. Software in this latter category is often referred to as decision support. A decision support system is presented here that addresses optimal unit dispatch and load allocation in a multi-unit hydroelectric plant. Initially, the concept behind the optimization approach is explained, covering its scope and approach. Then a case study examining the benefits that could be obtained over an existing plant's operational methodologies is provided. Finally, a spreadsheet tool for implementing the system is provided. In testing under actual conditions, this system has provided gains of over 2% in plant performance.

Optimization in the context of a single plant

Optimization covers a broad variety of topics when considering the performance of hydro electric plants. In run of the river schemes involving two or more plants cascaded on a river system it is common to consider timing the available energy to meet a peak load as optimizing the river system. Various types of river and plant models that deal with parameters having a system wide scope are necessary for such optimization. What is often ignored though is the performance optimization of each plant considered in isolation. This paper deals specifically with such individual plant optimization issues. Specifically, it addresses the optimal dispatching and loading of units within an individual plant to minimize that plant's discharge for a given load requirement or to maximize that plant's power for a given discharge requirement.

It should be mentioned that while this paper deals with performance improvements at the individual plant level, optimization is also often performed at an individual unit level. For instance, with Kaplan units the blade angle is optimized (on-cam) for a given head and wicket gate opening. The plant level optimization process introduced here assumes either Francis style units or "on-cam" Kaplan units are being used and focuses on the allocation of load between units to meet a specific plant output requirement.

Right from startup the operating characteristics (generation vs. flow characteristics at given heads) of new units having the same hydraulic design are slightly different. This is due to manufacturing tolerances as well as variations in the inlet and outlet arrangements at the power plant. Normal wear and tear as the units age caused by cavitation and silt erosion as well as wear and seal ring clearance degradation combined with the repair of this damage will tend to increase these operating differences, sometimes dramatically[1]. Field testing units by simultaneously measuring individual unit power and discharge at a given operating head with modern instrumentation can quantify these differences.

The operation of hydroelectric plants can be improved when these differences are known with sufficient precision. Although it is often ignored, such data is used to optimize the output of many multiple unit hydroelectric plants in the United States. The Tennessee Valley Authority (TVA), the United States Bureau of Reclamation and the United States Army Corps of Engineers all have invested heavily in optimization of their hydro generation assets at the single plant level. TVA considers such optimization a vital program and monitors all of their plants in real time to maximize power output while minimizing turbine discharge. This monitoring is performed at both “run of the river” and “storage release” plants. A crude order-of-magnitude calculation based on TVA’s experience with real-time optimization provides a convenient “rule of thumb” for estimating the production improvements to be expected if this approach is used elsewhere. It turns out that the improvement is roughly equivalent to the variation in performance among units divided by the number of units. If units have been run for several years and have had their turbines repaired, performance differences have been found to range from 1% [2] to 7% [3] [4]. So in a seven unit plant one could expect improvements of up to about 1%. The Pensacola case study presented later in this paper contains operational data suggesting that this rule might be very conservative.

More work is currently being undertaken jointly by the US Army Corps of Engineers and Bonneville Power Administration to obtain individual plant characteristics for use in optimally dispatching and allocating load on multiple unit hydroelectric plants. According to Tom Murphy at BPA[5], every 1% of efficiency improvement on the Colorado River in the Pacific Northwest is worth 3 Million dollars annually.

A study backed up with actual tests made by Niagara Mohawk at their School Street Power Station in the early 1990's also addressed single plant optimization. The School Street Power Station is in Cohoes New York and operates in a “run of the river” mode.

---

[1] Robert Karlicek, “Test Equipment And Results From 25 Hydraulic Turbine Tests using Thermodynamic Method” IGHEM- Montreal 1996.

[2] ibid.

[3] James Walsh, “Performance Tests on Pump Turbines at Salina Pump Storage Facility” November 1991.

[4] J.M Levesque, P.Lamy, C. Langvin “Field Measurement Results on Replacement Runners at Shawinigan2 and Bersimis 1 Case Study” EPRI Hydraulic Turbine Testing Workshop/ Seminar June 1987 York Pennsylvania

[5] HYDRO OPTIMIZATION AND EFFICIENCY IMPROVEMENTS presented to Environmental Protection Agency May 10 2006.

This station has 5 Francis style units with a total capacity of 34 MW. The study documented differences in unit operating characteristics that could lead to poor choices when selecting the dispatch and load allocation on various units. The report concluded that overall gains in production of up to 4.4 % were achievable[6]. In 2006 School Street Station generated 220,555 MWhrs[7]. A 4.4% gain in generation would yield 9,704 Mwhrs.. At $50 / Mwhr this would amount to over $485,000 USD annually.

<u>Visualizing the system's operation</u>

An important key to solving any problem is to find an efficient way to visualize it. We've attempted to do this in Figure 1 by plotting total plant generation vs. total plant flow for a database of different unit and associated set point choices in a three unit plant. A unit choice refers to a subset of units selected to operate when there isn't sufficient flow to operate all of the plant's units. An associated set point choice refers to the sequence of discharge settings for the chosen operating units. It's easy to notice that the plot seems to represent well defined characteristic curves. Those at low values of generation and flow represent single unit operation. Those in the mid range represent all combinations of two units. The highest curve represents all three units operating together.

This particular plant generation vs. flow plot was constructed from a database containing combinations of operating units and associated "optimum" set points. For each combination of units selected for operation the number of different set point sequences that will provide a given total plant flow is large, bounded only by the resolution to which

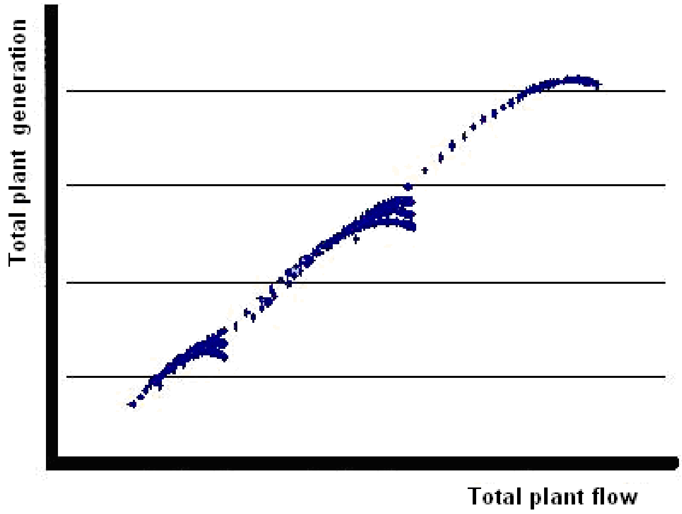

Figure 1- Total plant generation vs. total plant flow for a number of different unit and associated set point choices in a three unit plant.

[6] James Cook, James Walsh, Jamie Veitch "Improving Performance with a Hydro Control System", Waterpower '93, August 10-13, 1993

[7] United States Department of Energy.

you can reasonably measure and adjust each unit's flow. The total plant generation provided by each of these set point sequences will vary. Some set point sequences will do better than others. For any combination of units, that sequence providing the largest plant generation at the given plant flow is the “optimum” represented in Figure 1. It's interesting to observe that some “optimum” settings provide considerably more generation than others. The difference is most noticeable over ranges that can be satisfied by both n and n+1 units.

Figure 2 illustrates how the optimums of Figure 1 were obtained. The upper left plot in the figure represents the power vs flow (p vs. q) operating characteristics for each individual unit. These would have been measured in the field using data acquisition equipment and instrumentation. These unit operating characteristics can be analyzed to find the optimum set points for each unit combination at a given plant flow using a variety of heuristics. The heuristic used to develop Figure 1 is called the equal slope condition. This condition is satisfied when the slope of the unit p vs. q characteristic is the same at the setpoint of each participating unit.

Sequences of set points having this equal slope characteristic can be obtained graphically from a combined plot of the dp/dq derivatives. This is the plot immediately below the unit characteristics plot in Figure 2. The intersection of a horizontal line and the dp/dq characteristics on this plot provides a sequence of “equal slope” operating points for a given dp/dq slope. Plotting the total Power and Flow from all possible combinations of such sequences for a series of dp/dq values produced the database used to create Figure 1. In Figure 2 the process of collecting all possible equal slope combinations is illustrated graphically for one value of dp/dq by the lines running between the plots.

There are many heuristics that can be employed to provide such optimum solutions and in the aggregate provide a comprehensive solutions data base. The best approach will be largely dependent on the plant type, individual unit models, and the hydraulic arrangement of the units within the plant. While Figure 1 is an abstract illustration, the points in the plant generation vs. flow plot were pasted in from data derived from actual characteristics.

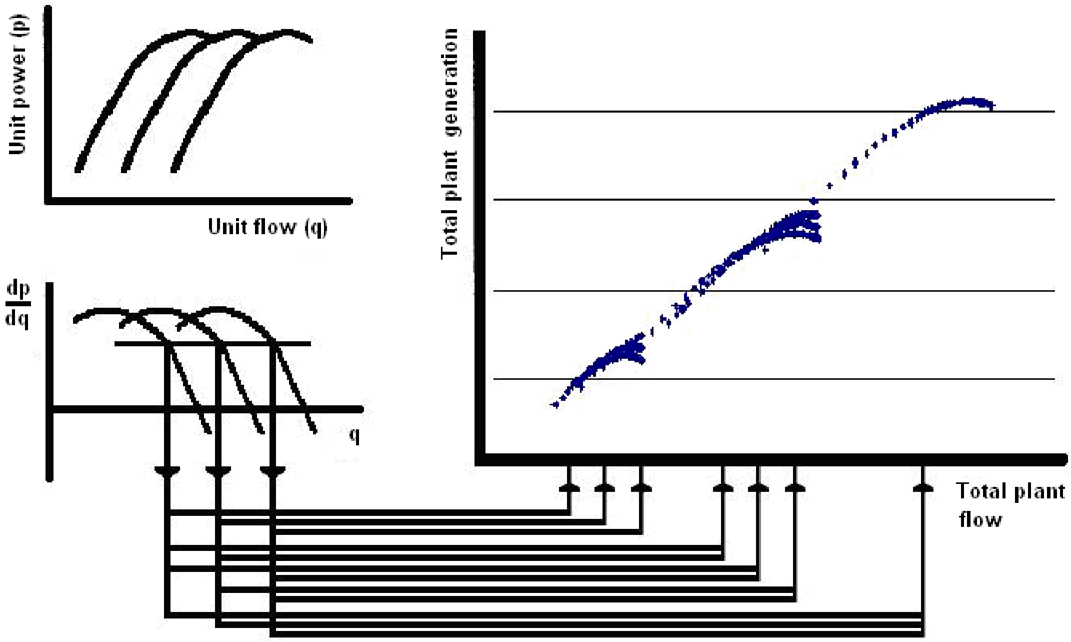

Figure 2 - An illustration of how the different unit and associated set point choices in Figure 1 were obtained.

Our single plant optimization approach begins by creating a database of a sufficient number of optimum unit and set point solutions to cover the plant's operating range. Once created, this solution database may then be used to provide the best settings under unit availability constraints for given loads or discharges. Queries on the database find the solution requiring the least flow for a target plant power or most power for a target plant discharge. This approach is applicable to both run of river or storage release type projects and lends itself to various constraints typically imposed on the plant. Another clear advantage of this approach is that it is scalable. In the construction of the unit models and solution database, rough operating zones or zones prone to cavitation damage are eliminated so the optimum solutions will not contain unit set points within these regions.

Case Study – Pensacola Power Plant in Ketchum Oklahoma

This case study was carried out at the Pensacola Power Plant owned and operated by Grand River Dam Authority in Oklahoma. Pensacola consists of 6 vertical Francis units that can generate 15 MW each. Data was collected for a 3 month period to analyze the potential for plant output improvement. The Pensacola Power Plant is typically operated as a storage release project. Thus the reservoir inflow dictates plant loading. In an average year Pensacola generates 350,000 MWhrs (excluding 2006 data) of energy[8]. In 2006 and 2007, which were drought years, the average annual generation dropped to 102,000 Mwhrs.

8 Grand Rive River Dam Authority Monthly Generation Statistics 1991-2006.

Figure 3 is a chart of actual operating performance data from this period presented as plant efficiency vs. plant power. One can see several loci of data corresponding to different numbers of committed units (ranging from one to six). One can also observe that for the same number of committed units, some combinations provided efficiencies that were a few percent better than others for the same load. Even larger efficiency ranges are evident where the loci overlap. For lower powers this difference approaches as much as 10 percent. It appears that the plant operation has room for improvement, particularly at the lower plant powers from 10 to 60 MW.

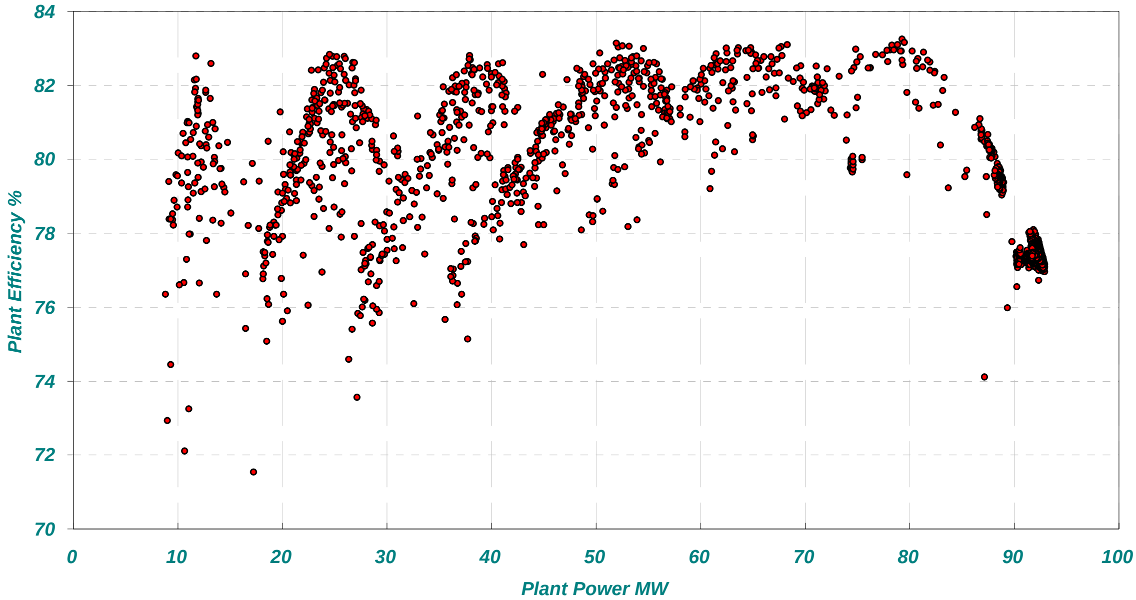

Figure 3 – Actual operation conditions Pensacola Power Plant

In Figure 4 the process followed to create a database of optimum solutions is outlined. Field measurements on each unit obtained during the same time frame (upper left worksheet) were used to construct a plant model (middle plot). From the plant model, the data base of optimum solutions (upper right worksheet showing the plant generation vs. flow plot with plant efficiency data also plotted) was created using various heuristics such as the equal slope method described above.

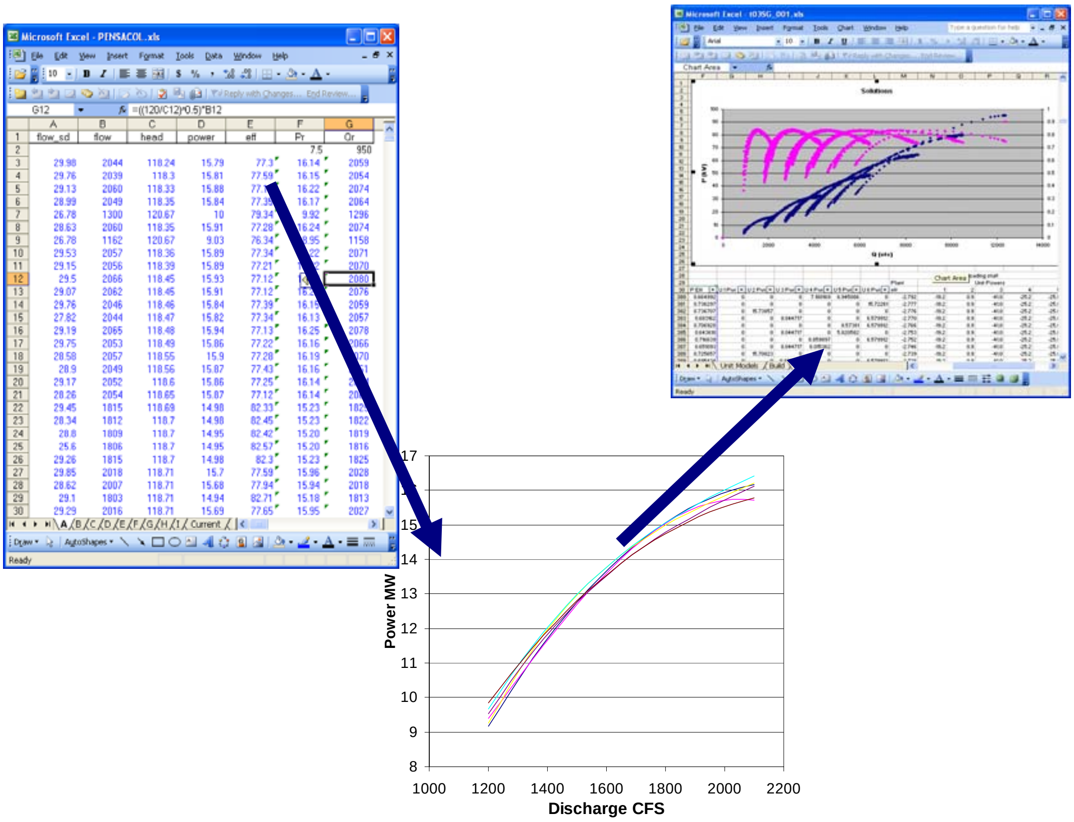

Figure 4 – A representation of the modeling process.

To graphically illustrate the potential for improvement, Figure 5 displays the efficiencies corresponding to optimum solutions superimposed on the actual operating efficiency data of Pensacola Power Plant. One can compare the average of the optimums to the actual performance over several ranges of plant powers. From this data, the expected improvement can be calculated.

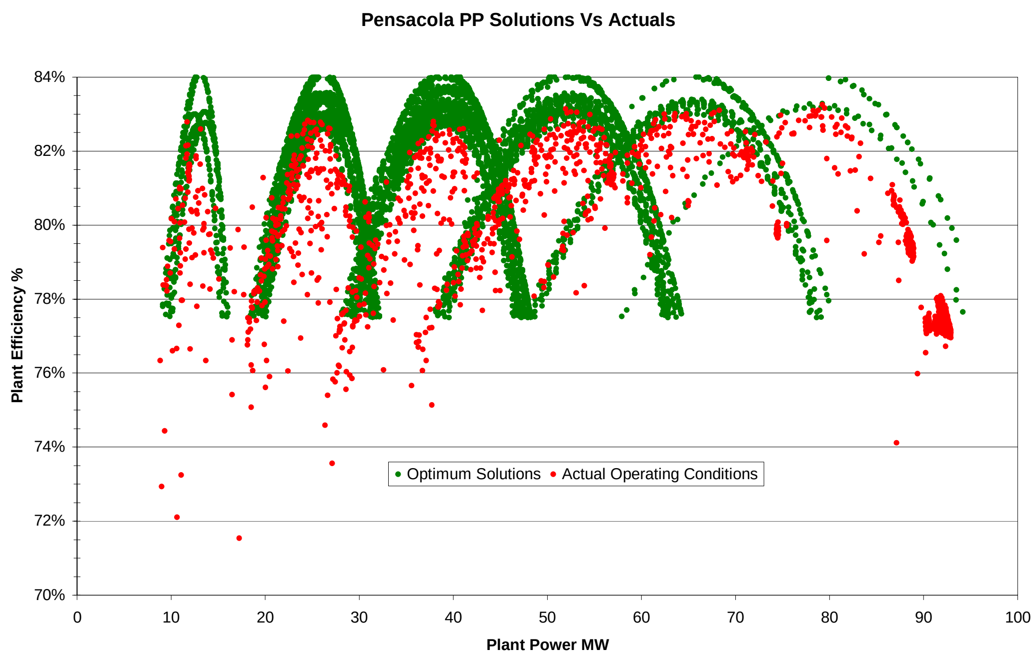

Figure 5 – Comparing optimum solutions with actual plant performance

Table 1 provides this comparison for a range of Plant powers between 22 and 55 MW (2600- 5800 CFS) which, on average, accounts for roughly 5/6 of the time the plant spends generating. It shows that on average about a 2.3% improvement is expected over the 22 to 55 MW plant operating range.

Flow	2600	3000	3400	3800	4200	4600	5000	5400	5800
Power (MW)	22	26	30	33	36	40	45	49	55
Optimums	81.29	83.24	81.85	80.04	82.73	83.25	82.38	81.84	83.08
Actual	79.79	79.96	78.87	78.74	80.11	79.84	79.84	80.31	81.29
Delta %	1.51	3.28	2.97	1.30	2.62	3.41	2.54	1.54	1.78

Table 1 – The expected improvement between actual operating conditions and optimums.

The expected improvement in average efficiency over a year can be estimated by considering the time spent at each range of plant power using historical averages as shown in Figure 6 below. At Plant Powers below 22 MW the expected improvement is minimal and to be conservative it is assumed as zero. Similarly at Plant powers above 55 MW the expected improvement is assumed to be minimal and again, to be conservative it is assumed to be zero.

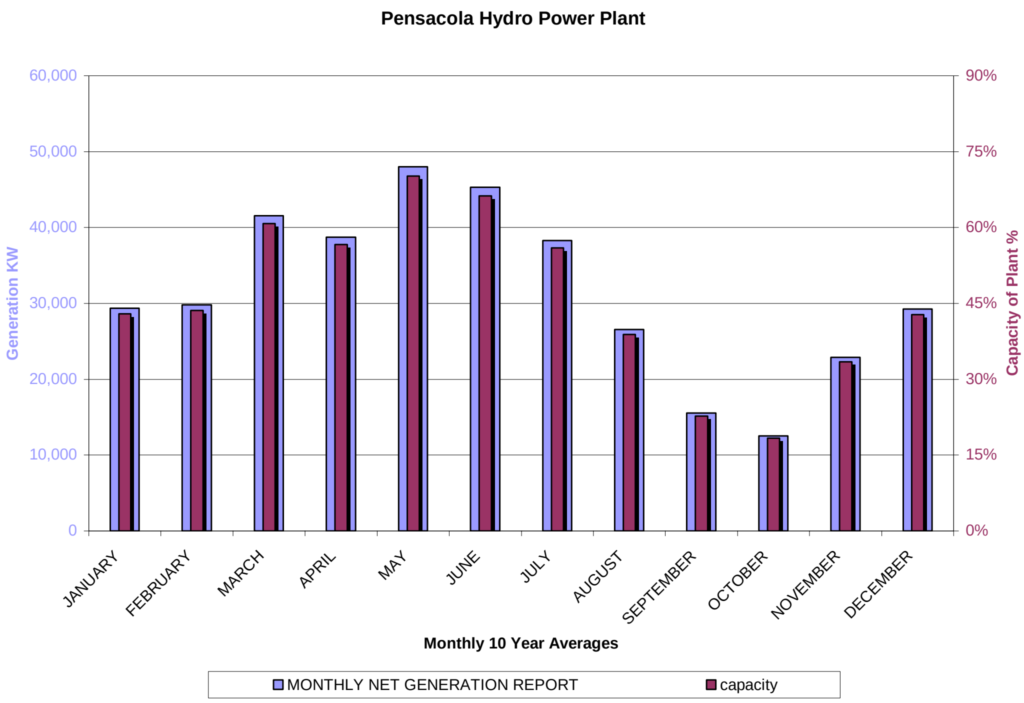

Figure 6 - Pensacola Power Plant 10 year average generation by month

Using the 10 year monthly averages, we can calculate the expected annual improvement in plant performance. This is simply a product of the possible improvement in the 20 to 55 MW range times the fraction of the year the plant operated in that range. From Figure 6 there are only 2 months out of the year where improvement is not expected, so the expected annual improvement is 2.3 * 10/12 or 1.9%. This improvement in the average annual energy from Pensacola is 1.9% of 350,000 Mwhs or 6,650 MWhrs. At 40 USD/ Mwhrs this equates to 266,000 USD annually.

The HydroAssistant tool

The key to this optimization approach is the database of optimum solutions as introduced conceptually in Figure 1. HydroAssistant™ is an Excel spreadsheet application that provides operators a simple interface to use for dispatching and optimally loading units using such a database. Operators have the ability to specify if a unit is available for commitment and if units must operate motoring or on standby. Figure 6 is a screen shot of a HydroAssistant™ set up for a six unit power plant. The worksheet contains a plot of both the P and Efficiency vs. Q for all solutions in the database followed by the actual data. Solutions can be obtained by entering constraints into the user interface for preset queries or by using Excel's Autofilter functionality directly on the database range. As shown in the user interface, the user can remove specific units from consideration and, if units must be motored, the motoring power and discharge can be factored into the solution.

This database of optimum solutions can also be integrated into automated dispatch systems for PLC use or to be accessed using OPC calls or Modbus.

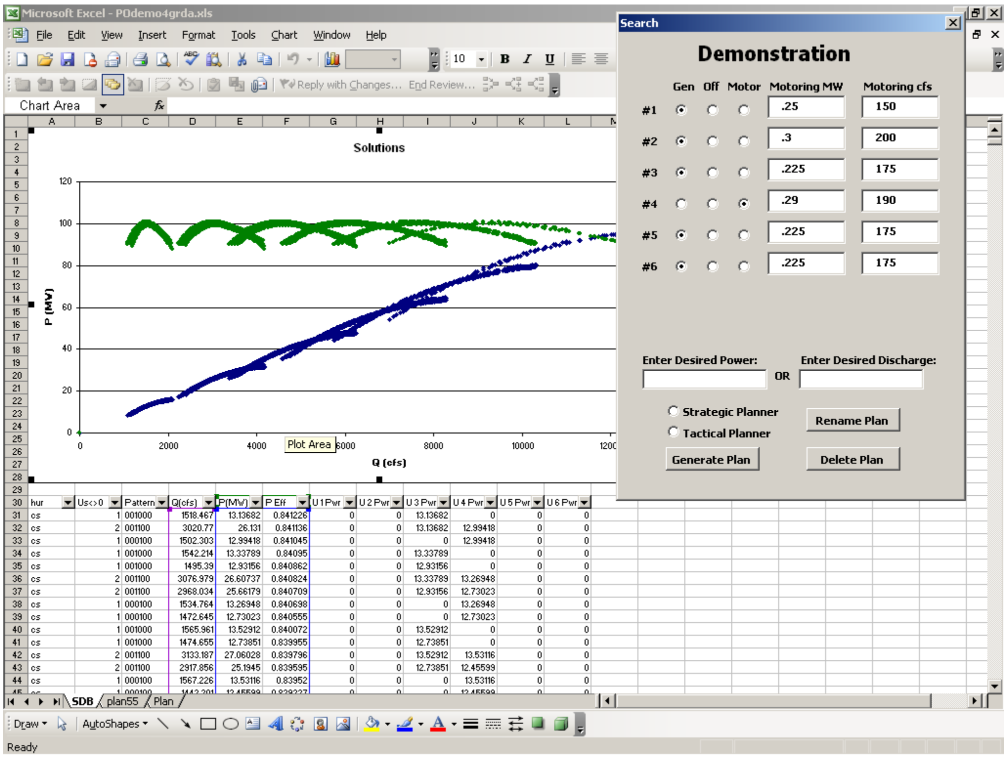

Figure 6. The HydroAssistant interface.

Conclusion

Dispatching units without considering the differences in their performance characteristics can result in degraded generation. Instrumentation is available to establish these differences with enough precision to create a database of those settings that will optimize plant output. HydroAssistant™ provides a convenient tool to query this database manually. This database may also be made available for PLC use or to be accessed using OPC calls or Modbus.

Actual use of this optimization approach has provided gains of over 2% in plant performance. This may seem like a small amount, but if similar decision support systems were used at all of the hydro sites in North America, assuming an energy value of US $40/MWh, the potential savings to the industry could reach US $107,000,000 per year. In addition to increasing revenue this represents for the industry, it would also offset more green house gas emissions from fossil power plants.