FORWARD

The following is a description of the latest version of the Index Test Box (ITB) and its capability as an instrument to advance the state of the art in monitoring hydroelectric generating units. It is designed to optimize the performance of individual generating units powered by either Kaplan or Francis turbines and to monitor their performance and alert an operator whenever there is a degradation in performance that indicates a need for maintenance. The original device was developed to be connected to the governor and in an unattended manner to collect operational data and sort the data for analysis. It was field tested several times and compared to manually conducted index tests and found to work perfectly. In fact, it produced data with virtually no uncertainty or scatter.

The instrumentation technician invented the software while working at Woodward Governor Company. Evaluation of signal composition in the frequency domain led to the development of a nonlinear digital filter to glean steady-state data from the noisy continuous data streams emanating from the machine. Unfortunately, the ITB project did not achieve commercial success for Woodward Governor Company. Some familiarity at index testing is necessary to fully appreciate the ITB's accuracy and laborsaving value. There are scant few engineers with such expertise, especially in management/procurement positions.

Development work continued on the device, particularly on the aspect of being able to feed recorded data from the power station SCADA (Supervisory Control and Data Acquisition System) directly into the ITB as though it was actual field data. Playback is sped up to over 100 times normal speed. The sorting process to decide what to keep and what is too noisy is fully automated. This remote index testing capability was demonstrated to function perfectly in the Dorena field-tests for index testing a Kaplan turbine. A long-term condition monitoring system is available to track operational performance of generating units over time so that maintenance may be scheduled on an as needed basis.
Lee Sheldon, P.E.

The Index Test Box and Hybrid Index Testing Method are Diagnostic Tools for Optimizing and Condition Monitoring of Hydroelectric Turbines

Abstract

The Index Test Box (ITB) and Hybrid Index Testing (HIT) method combine to become HIT/ITB; a Diagnostic Tool for Index Testing and Optimizing Kaplan Turbine 3-D Cam Surfaces and Condition Monitoring of Hydroelectric Turbines. The ITB was developed as an accessory for Woodward's 505-H Kaplan governor to collect field data for index testing.

Available diagnostics are dual purpose and multi-function. The first purpose is to check-out the governor, 3-D Cam (if the turbine is a Kaplan) and electro-hydraulic actuators to verify the control system is working properly. The second is turbine efficiency analysis and index testing to optimize Kaplan turbine 3-D Cam surfaces and capture overall efficiency profiles for input to Type-2 optimization systems. The greatest advantages of the ITB and HIT Method for index testing are cost and time saving and improved data coherence and elimination of the drudgery of capturing field data by hand.

Scope

This proposal covers only Kaplan and Francis turbine index testing, optimization and condition monitoring. It is most likely this methodology will work on a Pelton type as well, but won't claim it until it's been done.

The foci of this proposal are index testing to:

- Tune-up individual Kaplan turbine head and gate to blade 3-D Cam data surfaces to maximize its individual operating efficiency all across its operating envelope.
- Capture an on-cam gate-sweep to characterize the *Overall Efficiency Profile* for input to a higher-level powerplant-wide optimization scheme.
- Define the baseline benchmark for comparison during subsequent trending of operating efficiency.
- Condition monitoring to alarm the operators if operating efficiency gets out of limits.

The purpose ofthis is to introduce the HIT method and the ITB, which is a test instrument especially designed for tuning-up and monitoring hydroelectric turbines. The ITB is used to evaluate governor and blade control system operation and aid in setup, calibration, maintenance and monitoring of these machines. The ITB is an instrument created at Woodward Governor Company in 1984 to facilitate installation, commissioning and diagnosis of hydroelectric turbine control systems by providing a means of getting better field data back to the engineers at Woodward when problems arise. Although the ITB was always found to be a useful tool for collecting field data for optimizing Kaplan turbines it was not a commercial success for Woodward.

Although it was originally designed for Kaplan turbines the ITB can be used on any type of hydroelectric generator. the original work assignment for the ITB project was when Woodward's hydro engineering manager, George Mittendorf* handing me a copy of Lee Sheldon's 1982 tutorial on Kaplan index testing and optimization with the directive, "Make us something that does this." George said to do the Kaplan turbine first, the rest of them will be easy after the ITB can do a Kaplan.

***(Woodward Hydro Engineering Manager in 1984 is credited twice in the current 2011 ASME PTC-18 Standards and PTC-18 Committees pg. viii)**

The ITB is a labor-saving data collection tool designed as an accessory to Woodward's Kaplan governor. The ITB has been validated by parallel field-testing with conventional index tests on 5-separate occasions. Each field test validation consists of:

1. using the ITB to index test a Kaplan turbine at a single head to derive the overall efficiency curve and optimize, or tune-up the 3-D Can head and gate to blade surface,
2. repeat the index test and optimization using the traditional testing methods and then
3. the results were compared and evaluated by government hydropower experts.

Each and every time the ITB results were deemed to be in full agreement with the traditional method.

ITB Features and Functions

- Stripchart recorder
- X-Y Plotter
- SteadyState filter
- Remote Viewing of data
- All standard PC-type utilities are still available

Introduction

The most recent developments to the ITB are a 5th successful field-test to validate both the ITB and the new HIT method for index testing a Kaplan turbine. In this new era of *Social Distancing*, crowd avoidance and other biological exposure concerns, a way to remotely index test and diagnose hydroelectric turbine control systems (i.e. without going to the dam) would be a welcome addition to a control-engineer's tool kit. This is precisely what the Index Test Box (ITB) and Hybrid Index Testing (HIT) method are for... The Canada/US Border is expected to be closed for months to come. This remote testing capability will become handy to have at some point when it is needed most. The ITB was originally designed as a maintenance tool to be used by Woodward's hydro engineering department to get diagnostic field-data instantly viewable back in the shop during troublesome startups. In today's contagion conscious climate, it would be helpful to be able to index test and diagnose control system problems across-borders without the hassles of crossing borders. With the ITB and Internet communications this capability exists now and can reach out to anywhere in the world.

How HIT Works

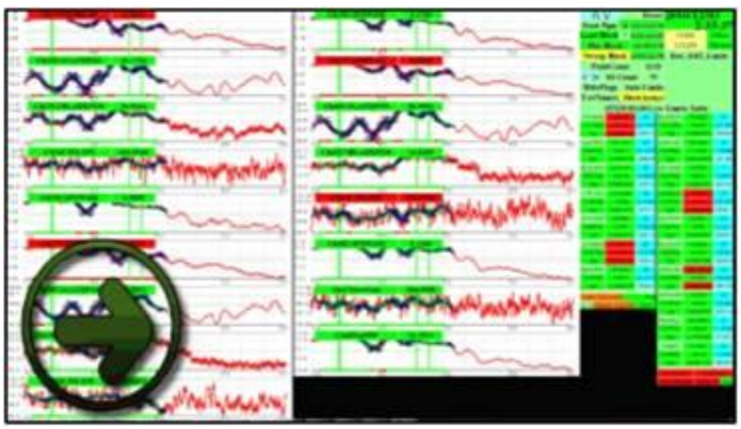

Figure 1 Click Image to see a short video about the ITB at a 3-unit plant in Canada.

The HIT method permanently reconfigures the powerplant's existing instrumentation, SCADA system and datalogger to set up for turbine efficiency measurements. By maintaining NIST Traceability* on all sensors at all times, an index test can be performed at any time and trended back to the initial benchmark data to evaluate degradation when considering refurbishment.

Every scan of data is of excellent quality and suitable for index testing and optimization.

The HIT Method breaks-down the setup steps for an index test so it can be accomplished as a series of routine task-orders carried out by regular powerplant personnel during the normal daily work schedule. This alleviates the need for index-testing specialists to go to a dam to setup and execute an index test and reduces out-of-pocket costs for an index test by approximately 90%.

According to Lee, the reduced data from the ITB has less scatter than traditionally collected index test data. A side benefit of the HIT method is that the powerplant personnel get greater familiarity with the optimization methods and equipment to perform index testing field work. When the setup is complete, execution of an index test becomes a simple task for the operators to perform as a scheduled task somewhere between annually and quinquennially. Routine maintenance of the instrumentation will maintain NIST Traceability on all sensors used for the index test measurements so every scan of data is equally accurate and valid as any other.

The workload to run an index test

Running an index test using the HIT method is not difficult or all-engaging. An index test consists of 25 or more manual setpoints for gates and blades with an 8-minute dwell at each gate-blade position pair. Assume 10 minutes per test point for these estimates. Total time for task-order – 10 minutes each for 25 test pointes = 250 minutes = 4.1 Hours. While running the test, the operator does not need to record any data or calculate any answers, just set the gates and blades and wait 8 minutes while the datalogger records scans to memory. (In truth, with the HIT method the two most important accessories for running an index test will become a minute-timer and a book or magazines to read while waiting for the next data point.)

Exercising the turbine for an index test would best be accomplished by an automatic programmed cycle in the turbine control system. (This was how it was planned at Woodward, but office politics…) It could be A virtual “Drum-Program” created in software to output setpoints to gates and blades automatically on a time schedule. The Drum Program code could reside in either the SCADA system or the governor PLC. This process reduces the cost of a Kaplan turbine index test to $1/10^{th}$ the cost of a traditional index test.

ITB Is Now a Service Over the Internet

The ITB in 2020 has evolved into a service over the Internet. The powerplant personnel get a checklist of signals to setup and a set of gate-blade pairs to execute and all the Internet and telephone assistance they need to get the test *up-and-running*. No out of pocket expenses are incurred for the setup and data collection parts of the index test because the powerplant’s own equipment and personnel are used exclusively throughout. The customer only pays ATECo for the data reduction and analysis work that ATECo actually does.

The data files recorded during execution of the gate-blade pairs are uploaded to ATECo for analysis and reduction to a new optimum 3-D Cam surface that will achieve the highest possible efficiency from the unit under any conditions of head and flow. After the new 3-D Cam surface is installed in the machine another on-cam sweep of the machine is analyzed to verify results. The final test report will quantify the efficiency improvements from the index testing and optimization procedures.

Index testing using the HIT Method is a neat, clean *no-travel-required* way to maximize electrical output while minimizing environmental harm and wear and tear on the turbines.

Remote Testing Method

Field-testing experience with the ITB and hydro-electric turbines has revealed a better way to index test a turbine that does not require that the test engineers go to the dam to run the test personally, saving both money and time. Today with viral exposure concerns everywhere the alleviation of any need to go anywhere is a plus. The Hybrid Index Testing (HIT) method of index testing has evolved as a natural progression of form follows function. The original reason that remote index testing was needed was to get one-way data communication from the powerplant's SCADA system into the ITB with no possibility of a computer virus getting fed back into the SCADA system from the ITB. The *no-go-to-the-dam* feature is especially desirous in these days of social distancing to avoid potential exposure to infectious viruses and such. (Who'd a thunk that 14 years later the anti-computer-virus technique would become useful again, but this time to protect from biological viruses? The HIT method will work equally well for this situation.)

A happy circumstance in this is that by saving many thousands on logistics (travel, lodging meals etc.) and getting back the travel time normally spent going to and coming from the dams, many more turbines can be index tested and optimized within the same Maintenance Budget.

Using this new Hybrid Index Testing (HIT) method all index testing can be accomplished from a central location working with either *live over the internet* data or canned pre-recorded data.
If the governors were programmed to execute the set of gate-blade pairs designated for the index-test, an automatic index test could be accomplished.

Remote Viewing of Data

- The technician the field sets up the instrumentation and data recorder, exercises the machine while collecting the data. Data is offloaded to a thumbdrive and then is uploaded to the ITB located back at the shop. The data can be played back in the ITB in the shop and the engineers there can see the stripchart and X-Y Graph displays with only a few minutes delay.
- If the ITB in the field is allowed to be connected to the Internet while connected to the hydro unit, it's display can be ported to the ITB back in the shop and the engineers there can see it live at the same time.

The SteadyState detector

What makes remote index testing possible is the SteadyState algorithm that is the key-element in the ITB program, a non-linear digital filter designed in the frequency domain to sift through the dense spectral content in the time domain. This non-linear algorithm was written specifically for this purpose utilizing a 2-pass statistical analysis routine comprised of Linear Regression (LR) and Standard Deviation (SD) calculations to quantify slope (SteadyState-*ness*) and SD (Noisiness) values as "figures of merit" for the average value.
Comparison of the Slope and SD values to preset limits determines if the unit is running, "steady-state." Data points captured and deemed to be steady-state are renamed "SteadyState data points."
SteadyState data is collated into a separate data file for subsequent reduction to a new 3-D Cam surface by hand.
The SteadyState data gleaned by this process is delivered in the same format as the traditional method data.

SteadyState Algorithm
utilizing Linear Regression (Slope) and Standard Deviation (SD) to "SteadyState-ness" of a data point. A SteadyState data point consists of an average value accompanied by Slope and SD values as "figures of merit." The Slope and SD are compared to operator preset limits to sort the SteadyState data from the noisy continuous data streams.

The HIT method index test at Dorena is the example being put forward now to show how your Kaplans can be optimized.

Why these tests were run at Dorena

These tests were wanted by the new owners when this recently commissioned generating equipment changed hands. In addition to the seller hiring ATECo to index test the unit 4-times to optimize the 3-D Cam surface profile by mapping the unit's entire operating envelope, the buyer hired Hatch Inc., a big-league consulting outfit to run Load Reject and index tests on the units at 102 ft head which serves to validate our work.

How the Maintenance Program Will Work - First, an index test to benchmark unit performance
The turbine testing process starts with a thorough checkout of the gate and blade control systems for dynamic responsiveness and steady state accuracy because after all – if you can't put the gates and blades where you want them, *there's no point in index testing.*

A one-time setup is needed to check out the available input and output signals and make any necessary additions or adjustments. For example, operators must be able to manually control gates and blades to exercise the machine to the prescribed gate and blade positions for index testing. Many turbine governors do not have manual gate and blade controls. Most do not have an external readout of blade position. These modifications are best accomplished by the governor supplier.

The overall Maintenance Program will utilize the new Hybrid Index Testing (HIT) method that was demonstrated recently at Dorena Dam. Index test data is used not only to tune-up Kaplan turbine head and gate to blade 3-D Cam surfaces to maximize an individual machine's efficiency performance but also to characterize its overall efficiency profile for unit Condition Monitoring, Trending and to prepare source data for plant-wide optimization schemes for multi-unit powerplants. The objective was to optimize the entire head-and-gate-to-blade 3-D Cam surface for a Kaplan turbine. To keep costs down and get greater familiarity with their equipment, the powerplant staff setup the instrumentation for the index tests.

For this test at Dorena the governor vendor was brought in to modify the governor to get manual control of gates and blades for index testing and to setup the SCADA system for continuous 2-Hz scans with the desired channel listing and order. (Forebay, tailwater, gate stroke, blade angle, flow in cfs and power in MW). Whenever it was appropriate a specimen of the stripchart data was uploaded to ATECo for evaluation and critique.

This is where the thorough control system checkout comes in

Turbine control systems have 2 modes of operation. Manual and automatic. Index testing is conducted using Manual control, but the machine normally runs under Automatic control. It is important that the automatic mode gets thoroughly checked out during its normal operation. After the optimization is complete and the control system is back on automatic, double-check to make sure it's doing what it's supposed to be doing. _In this case it was not._

A problem was found, *right off the bat*

There was a bug in the vendor's blade control software that caused inexplicable erratic behavior on startup when the blades mounted the 3-D Cam. The machine had been running for over a year with this problem and no one had noticed it - a good argument for having an ITB around to allow viewing these things.

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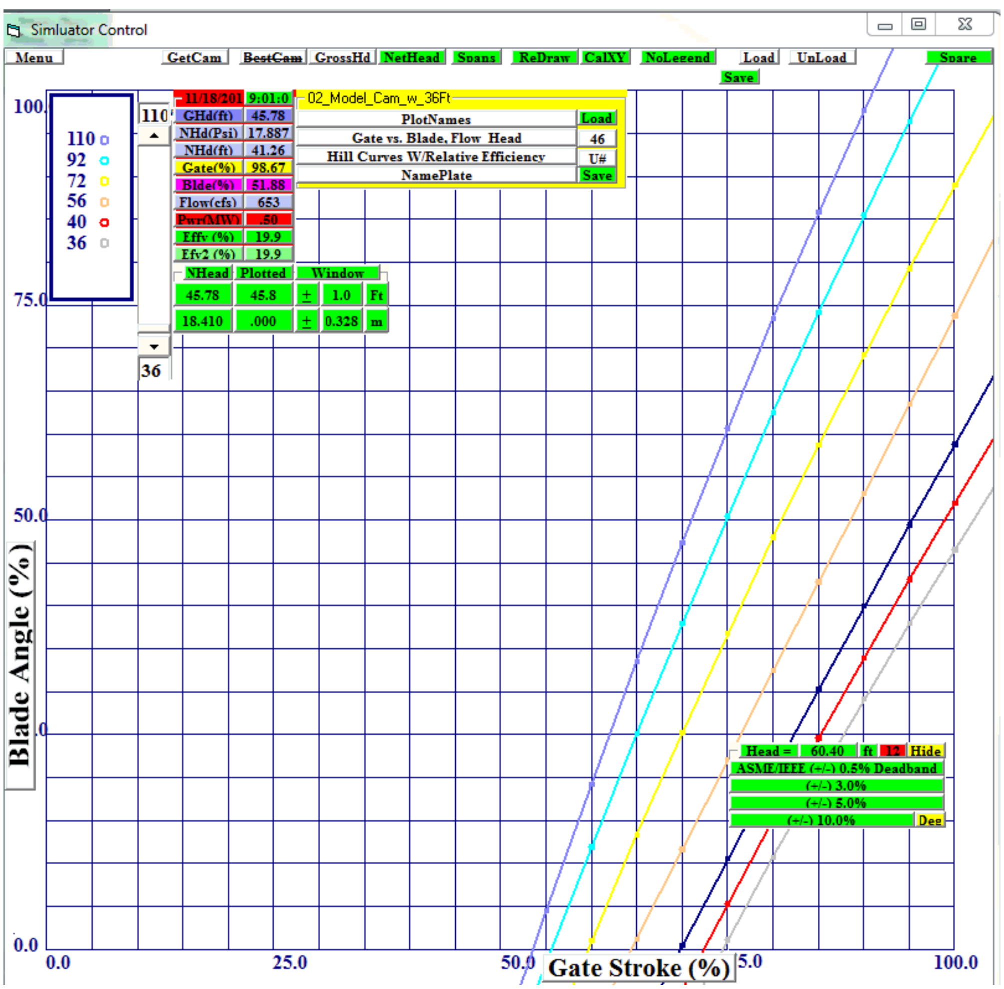

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Figure 2 Cartesian coordinate animated display of ITB monitor during Dorena Dam Kaplan startup

This is the Cartesian coordinate display of Blade vs Gates the first time the ITB got some StripChart data from Dorena. When the computer programmer who wrote the 3-D Cam program saw what it was really doing, he recognized the problem and immediately knew how to fix it. The program got fixed and a new was copy installed the next day. This problem was never seen again. This demonstrates the utility value of the Cartesian coordinate display format.

The vendor's cam surface (on the left, below) that came with the turbine from China was only an approximation of the final optimized surface. Its only purpose was to allow the new owner to startup and run the machine. After the unit is up and running it should be optimized. Four separate index-tests, each optimizing the gate to blade relationship at a single head were run at 69, 48, 85 and 102 ft head. These 4 gate-to-blade curves were assembled into a 3-D surface to map-out the entire operating envelope for the turbine (Fig. 4).

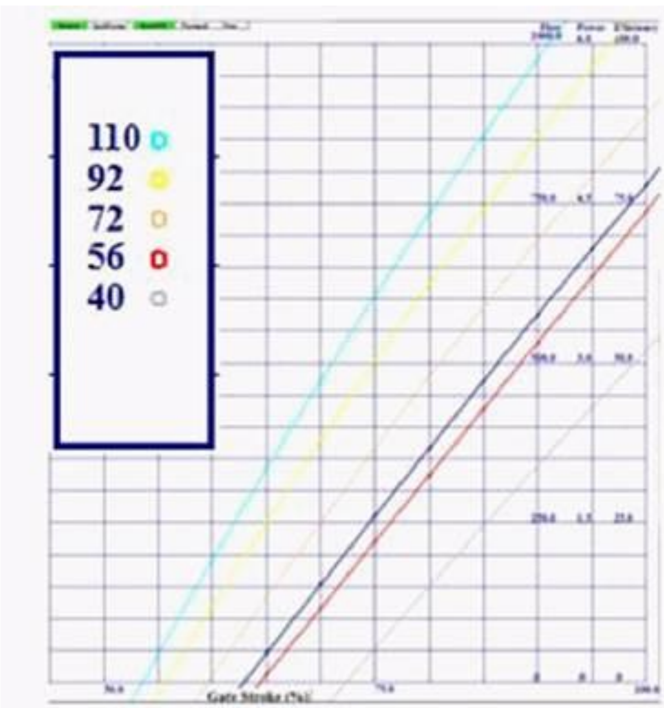

Fig 3. Vendor's Model Cam

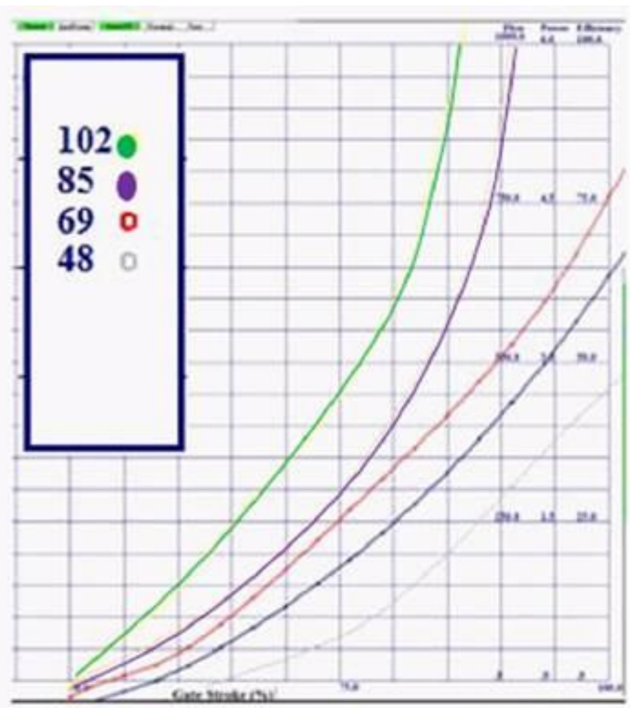

Fig 4. Optimized Cam from 4 Index Tests

The Dorena Dam Kaplan optimization project consisted of 4 separate index tests at 4 different heads to characterize the Optimum Cam curves across the full head-range of the machine.

Data Chain of Custody for ITB Hybrid Index Test Method data
This boon came along quite by accident. Ordinarily acquiring an independent commercial index test of this sort to validate the ITB would be an expensive proposition ($50k and upwards), but this time we got lucky. ATECo was hired by the seller to tune-up the 3-D Cam surface in the governor before closing the deal. On behalf of the buyers, Hatch Inc ran the Load Reject and a separate independent Index Test using the traditional methods. Unbeknown to Hatch Inc. engineers, while they ran their Load Reject and index tests for the buyer the powerplant datalogger was still streaming 2 Hz scans to memory. (If they'd have known they'd probably have shut it off.) The recorder was always left on and recording by the powerplant operators to capture anything interesting that may happen to the unit… The owners and Northbrook Energy wanted to see the second index test results so they shared the stripchart data. When asked, Hatch shared a copy of their test report and the test data spreadsheet they used for this commercial index test.

The operators wanted the datalogger always recording scans at 2Hz so it captured the Hatch's Load Reject and index tests. A few weeks later this data was uploaded to ATECo for analysis, and then the results were compared with Hatch's index test results. Because the input data was exactly the same for both tests, the results from the two tests were also exactly the same after the hair-splitting was sorted out.
(except for a 0.4% peak efficiency difference described below)
2017-05-16 Index Test at 102 ft gross head.wmv
Hatch Kaplan Index Test Report.pdf
This comparison was discussed in detail with Peter Rodrigue, a senior engineer at Hatch who signed off on the report.
Comparison of ITB and Hatch Dorena results with Peter Rodrigue.htm
My answer and Hatch's answer for the peak unit efficiency were different by 0.4%. Contract guarantees ride on this percentage so it's critical to get it right. When Peter and I finished our fine-toothed comb treatment of the two sets of calculations the conclusion was that the ITB was right and Hatch's number was 0.4% too high. It was dismissed as a typo because the point was moot - there was no Contract Guarantee in force so no harm, no foul.

The question remains: After the head and blade to gate Kaplan turbine 3-D Cams are tuned up and their efficiency profiles are delineated, what next?

Constant Efficiency Monitor
The example data for this next part of the presentation is a small 2-unit Francis plant that had undergone runner refurbishment and was being restored to service. A series of index tests were run to get data to justify going after the Energy Tax

Credit, but learned a bit more than they bargained for. This example shows how index testing for diagnostics is a valuable protection from loss and that a continuous efficiency monitor would have paid for itself many times over. This video explains further: Francis Continuous Monitor Pitch.wmv

The ITB has a Condition Monitor mode that inputs from discreet sensors and/or a SCADA system to compute real-time operating efficiency and then plots it on top of the previously determined *benchmark* efficiency profile for the existing head. The Condition Monitor will set off alarms if efficiency gets outside of operator-preset limits above and below the benchmark. These animated images show the screens on the Condition Monitor with various displays in action.

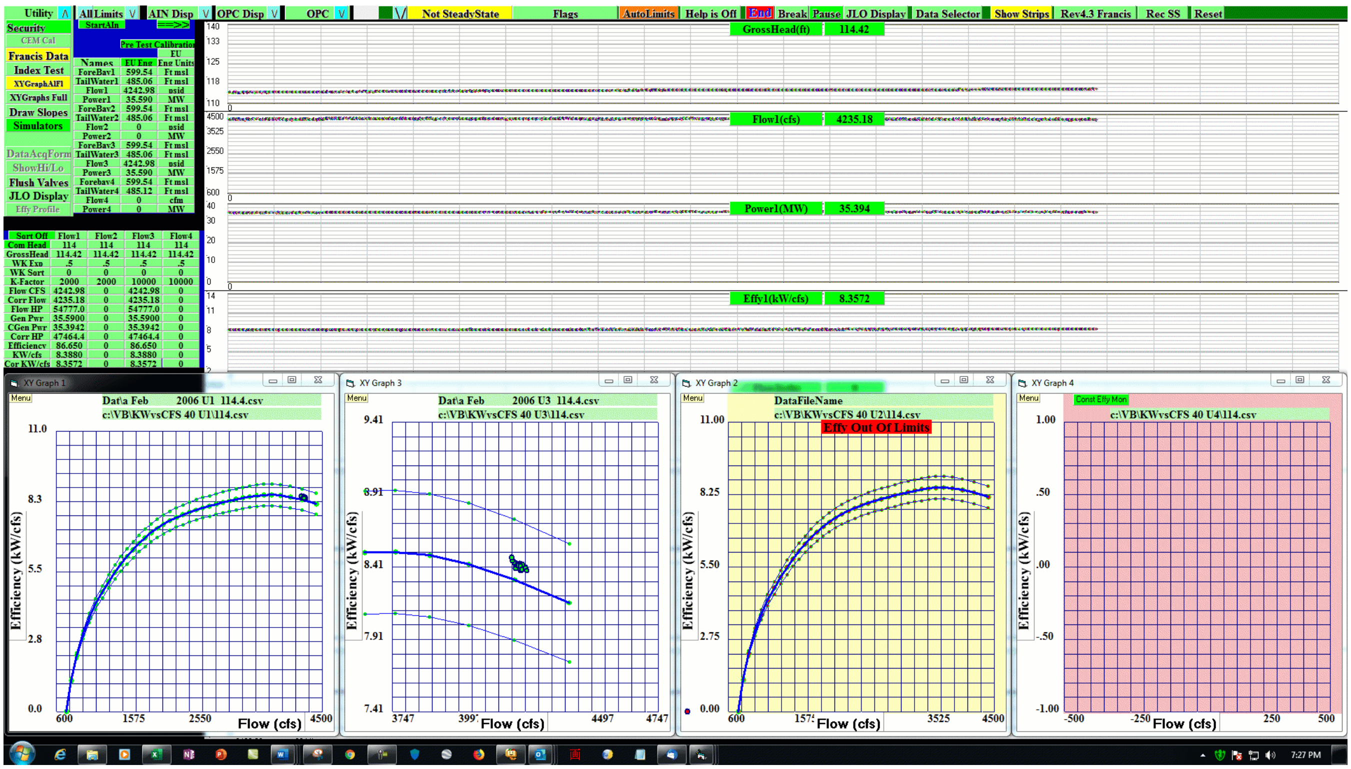

Fig 5. Condition Monitor Display for 2 40 MW Francis turbines

The Condition Monitor display above shows 4 stripcharts and 4 Cartesian coordinate X-Y Displays of efficiency (kW/cfs) vs. flow (cfs). There are 2 units in this powerplant so the X-Y graph displays were setup 2 per turbine to show both full-range and zoom-in displays. The heavy center-line is the benchmark efficiency profile extracted from the unit's prior running data. The two lighter lines above and below are computed operator-set limits boundaries. If the computed efficiency gets outside of these limits, the dot changes color from Green to Red and operator alarms are raised.

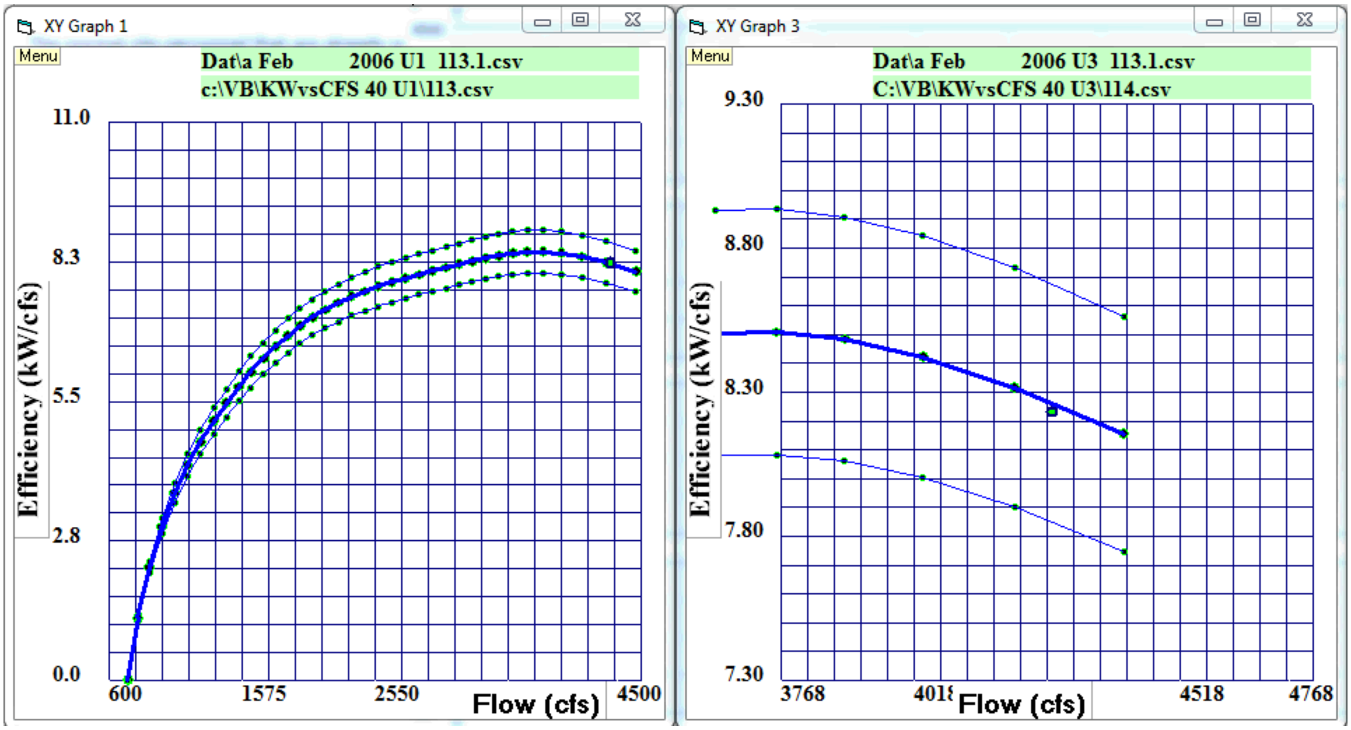

Fig 6. Condition Monitor Display for 1 40 MW Francis turbine

Here is a closeup of the PI Recorder Data for one unit from this powerplant with 2 ea. 40 MW Francis units. The data scans are at 1-minute intervals 24/7. This condition monitor shows at a glance the anticipated efficiency based on prior running and the immediate real-time efficiency computed from current data in real time.

Origin and Test History of ITB

The ITB was created as a new product at Woodward Governor Company in 1984 and has been under continuous development ever since. Thus far on 5 separate occasions the ITB has run side-by-side tests connected in parallel with traditional index tests conducted and/or evaluated by government hydropower engineers. In every case the ITB and traditional test results are in complete agreement.

The ITB was 1st validated by field testing when its test results agreed closely with a USACE Kaplan turbine acceptance test that had been run 2 weeks earlier at Clarence Cannon Dam.
1986-03-26 ITB Detailed Field Test (Albright)
1985-09-18 Clarence Cannon Test Report (Sachs)

A 2nd validation occurred 2-years hence when Lee Sheldon (while working as a Hydropower Specialist at BPA) bought the first ITB from Woodward as a

commercial product to test at a dam near Portland Oregon. That demonstration test went very well as reported by Portland General Electric (PGE) Sr. Staff Engineer Gary Hackett who was a "Disinterested 3rd Party" who participated in the test at Bull Run Dam (PGE-PHP-2).
1987-09-01 PGE-PHP-2 Report (Gary Hackett).
1988-05-28 PHP2 Classic Test (Sheldon)
1987-12-01 PGE-PHP-2 Report (Terry Bauman)

And then Woodward exercised their Patent to quash all activity and the ITB project languished on the back-burner. When the Patent expired in 2004 the ITB project was resurrected to become a front-burner product for Actuation Test Equipment Company.

The 3rd validation was by an index test on Unit 9 at USACE's McNary Dam in December 2015 that was compared to prior index testing conducted by
ASL and HDC.
2005-12-12 McNary Field Test (Wittinger)
2006-01-16 McNary Field Test (Albright)

The 4th validation was by concurrent index testing at Ice Harbor Dam by USACE HDC engineers. The government setup and ran an index test normally with the ITB connected in parallel to record streamed data to memory, functioning as a simple datalogger. The ITB was mis-programmed so that it recorded a test point every few seconds instead of deriving a single steady-state data point for 5 minutes of running time. When the data was received here the ITB was reprogrammed to read this recorded data as if it were live field-measurements. This method worked much better than expected and has evolved into the Hybrid Index Testing (HIT) method.
http://www.actuationtestequipment.com/USACE_Docs/2006-03-28_ATECo_Ice_Harbor_Analysis.pdf
2006-03-28 ATECo Ice Harbor Analysis
2006-02-01 Ice Harbor data (Ramirez)

The 2 demonstrations for the government at McNary and Ice Harbor were deemed a success but they chose not to buy it from ATECo.
2006-03-03 HOT Meeting PowerPoint (HDC).htm

The 5th validation was during the recent 4-head index test at Dorena Dam when a traditional index was conducted by test by Hatch Inc. with the powerplant

datalogger recording 2 Hz scans. The ITB analyzed the datalogger files used the HIT method and Hatch's index test used the traditional methods. The data for the exact same time intervals that Hatch took their measurements was analyzed with the ITB. With the exact same source data the computation routines in both methods gave the exact same answer.
2017-05-16 Index Test at 102 ft gross head.wmv
Hatch Kaplan Index Test Report.pdf
This comparison was discussed in detail with Peter Rodrigue, a senior engineer at Hatch who signed off on Hatch's test report.
Comparison of ITB and Hatch Dorena results with Peter Rodrigue.htm

The Next Step

Regarding the maintenance program for 6 small hydro plants:

Here's a suggestion of how this could work:

Your personnel will:

1. setup your existing instrumentation for an index test, adding new sensors as necessary to get the required signal set.
2. Reprogram your datalogger (or get one if you don't have one) to record 2-Hz Scans.
3. Exercise the unit through the requisite gate-blade pairs to execute an index test, dwelling for 3-minutes settling time and another 5-minutes for data to record at each gate-blade pair.
4. At any step in this process send a sample of the datalogger recording to ATECo for spot-evaluation and critique. (There is no charge for these.)
5. Send the index test data to ATECo for analysis and evaluation. (Up until this point no charge because the work as all been done by your personnel).
6. When a full set of turbine data is reduced to a new cam-surface Best-Cam line for the tested head, the final evaluation to get the 2-D Cam profile curve to put in the 3-D Cam costs $5k.
7. This new cam curve will be merged into the existing 3-D Cam, profile and returned. Send me as sample of your data format and the new data will match it.
8. As soon as you install the new cam surface in the machine, rerun the index test procedure and upload the data to ATECo.
9. This new data will be analyzed and computed with the before data for the unit to demonstrate how muck the index test and optimization had helped.
10. The deliverables ATECo will provide will be:

- A report of diagnostic observations from the stripchart and X-Y Plotter
- A data table of the SteadyState data points gleaned from the continuous data recordings
- A new on-cam curve to plug into the 3-D Cam for the tested head
- If you provide your entire current surface a new surface profile will be created by morphing the new data curve for the tested head into it.
- Before and after efficiency profiles for the unit
- Stripchart data.

How to begin
The first step is to inventory the turbine equipment.

1. What kind of turbine is it?
2. How many units are in the powerplant?
3. What kind of governors do they have?
4. Is there a SCADA system?
5. Is there a Data Logger?

And then let's talk about it and make a more specific plan.

Best regards,
Douglas Albright
Actuation Test Equipment Company
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