INDEX TEST BOX

A REPORT ON THE PROOF OF CONCEPT DEMONSTRATION

BACKGROUND

In the early 2000's both the Corps and BPA began placing increased value on optimization of hydroelectric generation. Several programs were initiated to increase the efficiency of generation. One of these is referred to as Type 1 or (T1), which stands for the optimization of individual generating units. In particular, this refers to determining the optimum 3-D cam surface to input into the governor to position the blades relative to gate opening and head for optimum efficiency.

The usual method by which the optimum cam is determined is by conducting a relative efficiency test. The term relative efficiency denotes that the flow is measured in relative terms or it is indexed against another, known parameter. Hence, these tests are more commonly called "index tests."

A program had been under way for manually indexing one unit of each family of Kaplan units for both with and without fish screens in place. Some years prior, a device known as an Index Test Box (ITB) had been developed that could provide automatic, unattended index tests of Kaplan turbines while they remained in normal operation. However, this device had never entered the commercial market. Woodward Governor Company, who held the original patent, had allowed it to expire. Consequently, the inventor of the original ITB was located and contacted. It turned out he was no longer employed by Woodward, but was in fact an independent contractor, doing business as Actuation Test Equipment Company (ATECo). Negotiations were begun to procure a modernized version of an ITB, particularly one using the more powerful and versatile computers now available. Because of the past success in developing a working prototype of an Index Test Box, a sole source procurement process was initiated.

BASIC METHOD OF OPERATION

The manner the original ITB conducted its unattended index tests differed from the manner conventional index tests are conducted. The ITB used a feature of the governor to hold power exactly constant. It then caused the blade angle to vary slightly and using signal processing techniques, identified steady state conditions before recording a data point. The data was stored on an EEPROM (Electronically Erasable Programmable Read Only Memory) chip that was used to transport the raw data to a separate software program to derive the 3-D cam surface, which was then programmed into an EPROM (Erasable Programmable Read Only Memory) chip. It was intended that there would be one dedicated EPROM chip for each unit and one ITB for each powerhouse. Data reduction was to be done at and by Woodward engineering.

CONTRACT

Due to prior success in developing an Index Test Box, a sole source procurement process with ATECo was initiated. This resulted in a time and material contract for the procurement of one prototype, proof of concept, Index Test Box. This contract also provided for the option to purchase up to 320 additional ITBs.

A unique feature of this contract concerned pre-existing software for the Index Test Box that was considered proprietary by ATECo and for which a Copyright had been obtained. The contracts provided that ATECo could protect this proprietary software by providing it in modular form only, but it did need to be identified by form, fit and function.

SIGNAL INPUT

The original ITB had used its own linear motion transducers for the gate and blade measurement and its own pressure transducers for headwater, tailwater and the Winter-Kennedy piezometer system.

However, in the intervening years, the Corps had developed GDACS (Generic Data Acquisition and Control System) and installed it in every powerhouse on the Columbia River. This system already contained electronic signal data on the blade, gate, head and power output. Only the pressure differential from the Winter-Kennedy piezometers was not available as a GDACS signal. However, there is a separate program underway to add the Winter-Kennedy differential as an electronic signal to the GDACS.

An index test is not only a relative test, but also a complete system optimization procedure that includes the turbine, generator and powerhouse instrumentation. Therefore, the accuracy of an index test depends, in part, on using the same data signals that are input to the governor for turbine-generator control. Consequently, it was decided early on to have the ITB access the GDACS system to be able to read these data signals. In addition, it was also decided to have the ITB simply send a request signal for the GDACS to reposition the blade angle. ATECo was in favor of these two decisions because it meant the ITB was not responsible for input calibrations and controlling the generating unit during the index test.

INITIAL GOALS

What was desired to primarily achieve from this contract was a proof of concept demonstration of a modernized version of an Index Test Box using the latest computers. Specifically, it was desired to demonstrate that the ITB could record suitable test data in an automatic, unattended mode of operation and that this data could be analyzed to determine the optimum cam and resulting efficiency profile. A secondary goal was to achieve a design of an Index Test Box that could be integrated into GDACS.

To that end, besides the basic delivery of one prototype ITB, the contract provided for delivery of:

- a complete source code listing for any code developed under this contract. Any pre-developed code was to be as self-contained modules and identified by form, fit and function, including inputs and outputs,
- parts list with drawings,
- instruction manual, and
- required software and hardware to reduce and analyze the recorded test data.

The contract further provided that:

- only the existing powerhouse instrumentation was to be used by the ITB,
- the ITB was to be capable of being integrated into the existing GDACS system,
- the Contractor was to supervise and participate in the installation, and
- the Contractor was to demonstrate the device by having it conduct a complete index test, both with and without fish screens.

BENCH TESTING

The Index Test Box hardware and the latest Release of the ITB software were hand delivered to HDC in May, 2005. Due to security concerns relative to protecting GDACS from any computer virus or contamination, it was decided to not take any release of the ITB software into the field until it had been checked on the GDACS test stand in HDC. This consisted of operating the ITB in a simulation mode and also running a Norton antivirus check. During a series of simulations on Release 16, an intermittent error was found in the ITB blade perturbation logic. For a given set of circumstances, the ITB erroneously sent a zero value as the amount of blade bias. This caused the ITB to be unable to perturbate the blades to an off cam angle. A fix for this was input on the GDACS side called the “zero snatcher.” As the name implies, whenever a zero appeared in the blade bias window, it was immediately removed or snatched away. Although this fixed the primary problem, it had a secondary effect of preventing the ITB from being able to record performance data with the blades in the on cam position, which is a blade angle of zero bias.

FIELD TESTS

There have been a total of four field tests. The first two field tests were on unit #5 at McNary. On the first, a broken wire in the circuitry for the Winter-Kennedy transducer signal prevented recording a complete set of performance data. On the second, it was noted that the Winter-Kennedy piezometric differential was much lower than on previous tests. It was thought at the time that one of the piezometer lines was leaking and therefore the differential had no value as a data item. Consequently, a concentrated effort to record data for relative efficiency was not made. In actuality, even though the piping drawings were checked on site, it was not known at the time that the two inside Winter-Kennedy piezometer lines had been reversed during construction and the drawings were never corrected. Therefore, the differential that was being recorded was actually a correct value, but for the low deflection tap set.

The third field test in December, 2005, was on unit #9 at McNary and was considered to be a successful proof of concept of the Index Test Box. There had been difficulties both before and during the test. First, was the fix in the GDACS that precluded the ITB from being able to record data with the blade angle in the on cam position. In addition, due to safety concerns, the ITB was constrained to operate within a window in which the blade angle was within $\pm$2 degrees of the on cam blade position. Further, the governor control system exhibited an inordinate amount of time to settle out at a given condition and then had difficulty maintaining a constant load. However, in spite of these, it was successfully demonstrated that the ITB had the capability to conduct an index test on a Kaplan turbine in an unattended manner.

The fourth field test was at Ice Harbor where a conventional, manual index test was being conducted. There the ITB was connected to record performance data, but the blade perturbation logic system was disenabled. Again, the ITB demonstrated that it could successfully record and store, steady state, performance data.

DATA ANALYSIS

A general data analysis software to reduce performance data recorded by the ITB still needs to be developed. It was originally perceived that the governor would be able to hold the unit at a constant power level while the blades were perturbated to different angles. Consequently, a Government deliverable in the original contract was a separate data reduction program to analyze the performance data recorded by the ITB. However, it was found that the governors at McNary could not hold power on a unit sufficiently constant while the blades were being perturbated. Consequently, the contract was verbally changed so that the contractor was still responsible to provide a data analysis routine for constant power, but HDC became responsible to provide an analysis routine for non-constant power. This latter, a general analysis program still needs to be developed. The draft of a solicitation for procurement of such an analysis routine has been prepared.

McNary Unit #9

During the data collection period on unit #9 at McNary, which was the third field test, an operator manually maintained fairly constant power on the unit as the blades were perturbated. This allowed ATECo to demonstrate and display on Graph 1 the first version of their recently developed data analysis program for constant power. In the format of this graph, the x-axis is wicket gate servomotor stroke, the left hand y-axis is blade angle, and on the right hand side, there are three vertical axes: flow, power and efficiency.

First, the family of cam curves that are presently programmed into the governor are plotted and connected by faint, different colored, thin, dashed lines. Next, the "smooth curves" are plotted. These are curves of the recorded data of power and separately flow, both plotted versus gate servo stroke. Power is plotted as the red data points, connected by a thin red line, and flow as the blue points, connected by a thin blue line. The extent to which power was held constant may be judged by how horizontal and uniform the red data points are plotted. Next, the loci of the blade and gate servomotor points are plotted, which look like a thicker black line convex upward. Finally, the relative efficiency points for each series of constant power data points are plotted in green and look like the inverted fish hooks. It turns out that the restriction on the blade perturbation not exceeding ±2 degrees from the programmed cam curve prevented recording data on the other side of the individual relative efficiency curves for each of the constant power series. That is, the programmed cam curves in the governor differ by more than two degrees of blade angle from the optimum cam curves. In order to effect a presentation of this data and method of analysis, ATECo was allowed to extrapolate the data. This extrapolation is shown in magenta on both the relative efficiency profiles and the blade-gate convex curves.

The final steps in this graphical solution method are just the same as used on conventional, fixed blade, relative efficiency tests. First, an optimum performance curve is drawn by constructing a tangent curve to the individual relative efficiency curves. Then, the intersected points of tangency are projected downward intersecting the two smooth curves of power and flow versus gate and then the blade-gate convex curves. Finally, the points of intersection are connected by three separate lines. The line connecting the points on the blade-gate convex curve is the optimum cam curve. The other two intercept connecting lines are the corresponding power-gate line and the flow-gate line.

Ice Harbor Unit #3

The results of the conventional index test, as recorded by the ITB, are plotted on Graph 2. This is the same format as Graph 1 with the following exceptions. First, the family or blade to gate cam curves, presently programmed into the machine, were not plotted. Secondly, for this conventional index test, the blades were held constant in a series of fixed blade angles. Therefore, the blade to gate curves are not convex, but horizontal straight lines. Thirdly, ATECo has errored in identifying the resulting optimum cam curve. On Graph 2 it is depicted as a line connecting the drop down intercepts from the points of peak relative efficiency. In actuality, it is the penciled line connecting the intercepts from the penciled tangent curve to the relative efficiency lines. As part of a conventional index test, test runs are made to identify the programmed cam curve on which the machine is presently operating. This cam line is identified as the solid black line on the positive 45 degree angle. The comparative result of this graph shows the optimum cam is 1.7 degrees flatter, at the same gate opening, than the presently programmed blade to gate cam curve.

Future Improvements

This new graphical format does allow for plotting of the performance data recorded by the ITB when power can be held at or near a constant value. However, there are two improvements that will further enhance its utility. First, the smooth curves of power and flow versus gate may be plotted as polynomial curves. Then, from the equations of these polynomials, the relative efficiency profiles may be constructed as a loci of points by computing a relative efficiency every 0.1% of gate servo stroke. This will smooth the graphical presentation and increase the accuracy of identifying the optimum cam curve. Secondly, IF sufficient numbers of the series of either constant powers or fixed blade angles are recorded, these may be used to construct the isoefficiency (constant efficiency) contours of the “hill curve.” This is done by intercepting the relative efficiency curves by a series of horizontal lines at different values of relative efficiency. Then these are projected down until they intercept their respective series of either constant power or fixed blade angles. Connecting the points with the same efficiency values provides the contours of the isoefficiency hill curves.

UNFINISHED ITEMS

Ultimately, the proof of concept was successfully demonstrated. However, there are several unfinished items from the original contract, including its three subsequent modifications, which still need to be addressed in order to be able to assemble a complete Index Test Box system. Much of this is due to ATECo’s diversion of time and effort from the primary goal of demonstrating the concept, to designing the device to be initially integrated into GDACS. Since this was a time and material contract, the Hydroelectric Design Center (HDC) directed these diversions to achieve this initial integration. Besides the general data analysis program, these unfinished items include the source code listing of the co-developed software, an automatic Winter-Kennedy flushing system, a tutorial user's manual, and a non-GDACS version of the ITB.

The original contract provided that the pre-developed, proprietary software was to be delivered with the co-developed software in a self contained modular form. A source code listing of the latest release of the co-developed software has been received. However, rather that the self contained, modular form with identified inputs and outputs, the pre-developed code is scattered throughout the co-developed code. This code listing needs to be reformatted before a new, in-house, contractor can use it to assemble a complete ITB system.

When actually conducting an index test, the Winter-Kennedy piezometers need to be flushed or bled down on a periodic basis. This is needed for two reasons. The first is to remove any bubbles caused by gases coming out of solution and the second is to keep the water in the piezometer lines from warming up to powerhouse ambient temperature causing a decrease in specific weight (density). In order for the Index Test Box system to truly be an automatic data measuring system, the Winter-Kennedy's need to flushed automatically. Consequently, an automatic flushing system needs to be designed and fabricated. Such a system had been verbally added to the original contract, but was later verbally removed as other priorities took precedence in preparing for the field tests.

The requirement in the original contract for delivery of a User's Manual is considered to have been met. However, this manual, as delivered, is a compilation of different sections on the technical features of the ITB. As such, these different features are not linked together. This lack of continuity means this manual is not really suitable for use as an instruction manual, such as for new index test operators. Therefore, an item considered to be in the unfinished category is a self study, tutorial or instruction manual on using the Index Test Box.

LESSONS LEARNED

The complexity of this research, development and demonstration project has lead to a number of lessons learned to date.

- A project that is research, development and/or demonstration oriented is better administered under a research type contract.
- For any computer system that will interact with GDACS, the security requirements of the GMT, including methods of accessing into GDACS, should be delineated in the procurement contract.
- The dynamics of a governing system of a generating unit selected as a test unit should be evaluated and described in any procurement contract.

CONCLUSIONS

It has been successfully concluded that an Index Test Box is capable of conducting automatic, unattended index tests on Kaplan turbines. It can accomplish this by asking GDACS to perturbate the blade angle while it selectively records the performance data. The data recorded as a series of either fixed blade angles of as a series of constant powers may be reduced with present graphical routines. It was further concluded that such a device may be integrated into GDACS.

RECOMMENDATIONS

In view of the foregoing, it is recommended that development of a complete, prototype Index Test Box system be continued. This will include: the hardware, including computer, transducers, piping and wiring; software, including all of the source code; complete documentation, including drawings, schematics, parts list, users manual and instruction manual; an automatic Winter-Kennedy flushing system; and a complete data analysis and graphing routine.

This development can be best achieved by contracting for in-house, engineering support services to work under HDC supervision. Such support services will be obtained through a competitive solicitation.

Determining Turbine Efficiency With an Index Test

An index test is a method of measuring the relative efficiency of hydraulic turbines. It is different from an absolute test, where the flow rate is measured in absolute terms, i.e., cubic feet per second. Index testing measures flow rate by relative comparison to another parameter.

Any type of hydraulic turbine can be index-tested. When the process is applied to Kaplan turbines, it determines the optimum blade-to-gate relation. This allows the complete turbine/generator/governor unit to operate at peak efficiency.

Although generally less expensive and quicker than an absolute test, an index test requires a significant number of man-hours in recording field data. In addition, the test operator must have local control of the unit, which can cause conflicts with required load and discharge schedules.

To eliminate some of these obstacles and facilitate use of index testing for Kaplan turbines, Woodward Governor Company developed an Index Test Box (ITB) (*Hydro Review*, June 1987, "Black Box Developed for Index Testing of Kaplan Turbines"). When used with the newer electronic governors, the ITB automatically conducts index tests while the generator and turbine remain in the normal generation mode. The ITB can also store performance data for comparison with subsequent tests.

Portland General Electric, with partial funding from the Bonneville Power Administration, purchased and installed the first ITB at the city of Portland's Hydro Plant #2. After the ITB recorded and analyzed the single unit's performance, a separate manual index test was conducted to verify the ITB results. Test comparisons showed the ITB to be accurate.

A final report of the ITB evaluation is available at no charge. Contact Lee Sheldon (Code RMGB), Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208.

Turbine Repair With Robotic Systems

Laboratory prototypes of a compact robotic system for hydraulic turbine repair will soon be ready for field testing. Laboratory experiments and testing are complete under a Canadian Electrical Association (CEA) project, "Development of a Prototype Robotic System for the In-Situ Repair of Hydraulic Turbine Runners" (419 G 485). The research was conducted jointly by Hydro Quebec and Ontario Hydro.

Research began in 1985, and was co-funded by CEA. The research was conducted under strict size and weight limits. The need for adaptability to unforeseen conditions and restraints was also added. Limited operator involvement and broad application to current manual repair practices was required.

Laboratory tests were conducted on a mock-up of a Francis turbine with two blades.

Although development of two prototypes showed some success, several problems were encountered. Welding problems included periodic arc-start failures, requiring a more sophisticated power supply control interface. Final surface grinding has not been implemented. Details of the constant stick-out technique also need to be resolved.

Information is also lacking in the technical, economic, and human factors involved in the field implementation. Present plans include field testing with the current prototypes, once the faults have been corrected. The research concludes that the system is still a valuable tool, even without full capability.

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