

PROTOTYPE HILL CHART TESTING OF A SAXO UNIT

Emmanuel Côté

Jr. Eng., Test Engineers, Hydro-Québec,
5565, rue De Marseille, Montréal, Qc, Canada, H1N 1A4

Éric Cloutier

Eng., Test Engineers, Hydro-Québec,
5565, rue De Marseille, Montréal, Qc, Canada, H1N 1A4

SYNOPSIS

Performance tests of hydraulic turbine prototypes are often carried out at a specified net head and efficiency is assumed to be constant with head or to behave like a model. However, in a power plant where head is low and can double from a season to another, these assumptions are not accurate. Since its 10.5 MW “Saxo” turbines are operated at a net head varying from 8 to 20 meters, power plant operation would benefit having accurate performance charts based on prototype measurement for the entire net head operating range.

The main objective of the efficiency measurement was to validate contractual efficiency guarantee clauses using current meters with hydraulic conditions near the specified net head. The second objective was to extend the knowledge of the unit efficiency to all the operating net heads and reproduce the hill chart of the turbine based on prototype testing. In order to do that, a permanent measuring system was installed to measure efficiency using the transient time acoustic method calibrated with the current meters to measure the flow.

Major differences were revealed as the hill chart of the turbine was redrawn and compared with the one based on non-homologous model testing. The prototype peak efficiency is lower than expected since model testing showed an increase with net head on all the operating range while prototype testing showed a decrease in efficiency at higher heads. The peak efficiency also occurs at a lower flow than expected.

These tests now allow the operation of the power plant with knowledge of the unit’s performances over all their net head operating range, thus allowing a far more efficient power production.

POWER PLANT

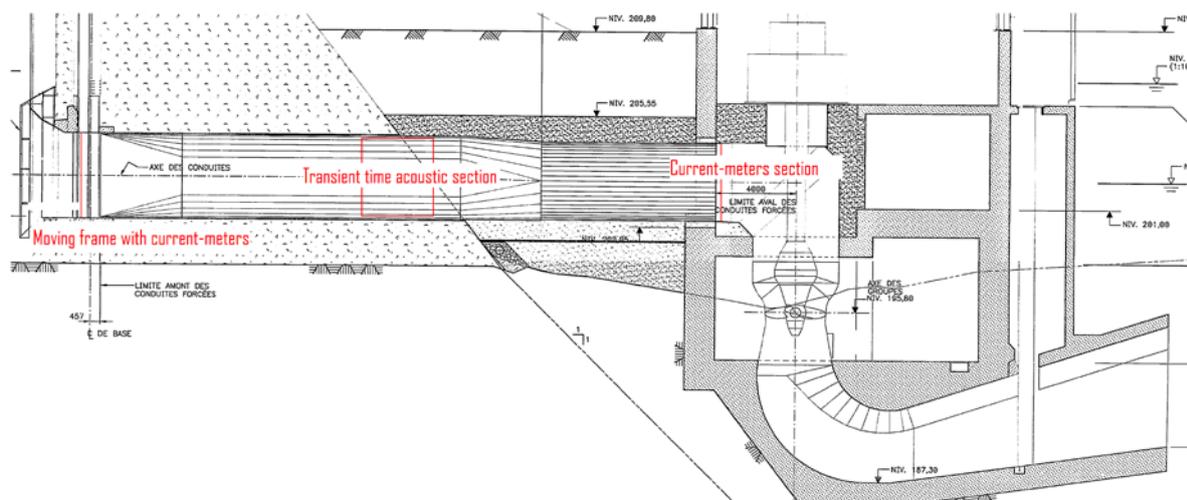


Figure 17: Unit configuration

The hydraulic power plant is located on Gatineau River near the town of Mont-Laurier in Québec, Canada. It has been commissioned in 2007 on an already existing dam and reservoir with 5 vertical axial flow Kaplan turbines. As shown on figure 1, each one of the “Saxo” turbines has its own penstock with an

elbow upstream of the fixed guide vanes and is coupled directly to its own generator rotating at 200 rpm. The water flow exits the draft tubes directly into the river. While the specified net head of the turbines is fixed at 18 meters, one particularity of this power plant is that the upstream water level changes a lot with the seasons which causes the net head to vary from 8 to 20 meters during a year.

OBJECTIVES

The contract with the generator unit supplier specified that the guaranteed unit efficiency would be for a net head of 18 meters and that the absolute testing were going to be done with a measurement set up that complies with the IEC 60041-1991 [1] as much as possible. Hence, measurements were done on the unit near the specified net head using a current meter structure in the penstock to measure the flow.

However, for the purpose of unit's operation optimisation, their characteristics also needed to be known over all their net head operating range. Therefore, efficiency testing at different net head was necessary. Since head variation plan over the year cannot be changed rapidly for unit testing, a simpler measurement set up that could be left on the unit for an extended period of time and accessed remotely was set up to carry out additional testing during the year at different head.

This paper will explain how the complete characterisation of the small "Saxo" units was done firstly by using the absolute contractual testing at the specified net head and secondly by extending the net head range with simpler testing over a variety of net heads within the operating range.

CURRENT METERS MEASUREMENTS

Flow

The current meters method was used to determine the discharge. In an ideal case, according to IEC 60041 [1] and ISO 3354 [2], the current meter section would have been installed in a straight section of conduit at least twenty pipe diameters downstream and five diameters upstream of any irregularity. However, given the geometry of the present unit's penstock illustrated on figure 1, the supporting structure was installed less than one diameter upstream of the 90° intake elbow and approximately three diameters downstream of the diverging section.

To allow accurate flow measurement in possible irregular flow conditions, 44 current meters were distributed along eight radius and six concentric circles in addition to the four current meters placed near the center (figure 2). On the outermost ring, eight small current meters with 50 mm propeller were used. The other current meters used 120 mm propeller. Using the velocity profile given by the current meters, the flow can be integrated to cover the whole section using the numerical method detailed in ISO 3354 [2].

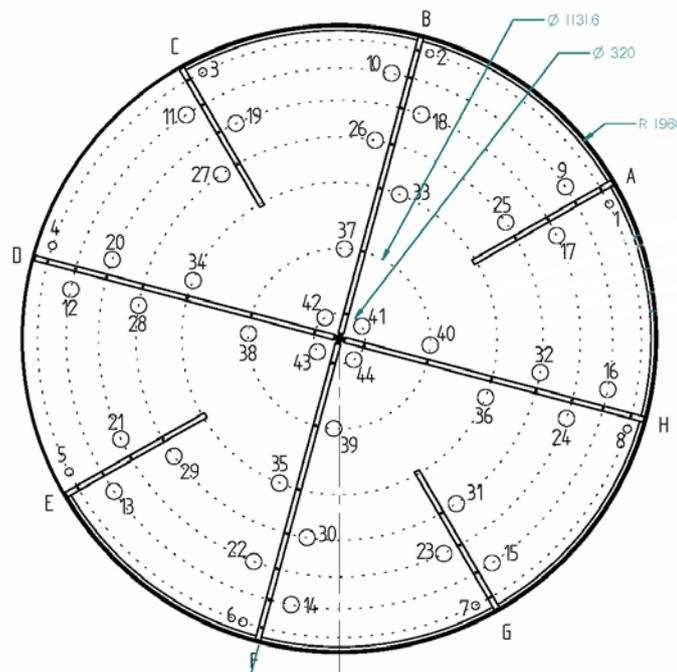


Figure 18: Disposition of the current meters

A moving frame with current meters was also installed in the stop log gate slot approximately one meter downstream of the trash racks to scan the velocity profile at the water intake. Two rows of ten current meters with 100 mm propellers were distributed on the frame shown on figure 3. This second method for measuring the flow is used for its simplicity of deployment in order to be transferred on the other units for individual performance measurements. In comparison with penstock measurements, a moving frame at the intake has the major advantage of reducing greatly the installation costs and the productions losses caused by extended unit downtime.



Figure 19: Moving frame at the intake of the unit

The results of the first three runs with this method were similar to the contractual ones measured in the penstock. The difference between the two methods is less than 0.35 % for those first three runs. Unfortunately, after those runs, current meters were damaged by logs that managed to pass through the trash racks.

The transient-time acoustic method for measuring the flow was also used in the penstock upstream of the diverging section. It will be discussed in the extended net head testing section of this paper.

Head

The net head was calculated using the four static pressure measured at the upstream contractual section between the divergent and the current meter structure, the two static pressure at the downstream section located at the end of the draft tube, the elevation of those sections as well as average water velocity at those sections. The pressure transducers for each section were placed at the same elevation in order to be independent of possible inaccuracy in the power plant reference benchmarks.

Output

The generator output was measured using the three wattmeter method with an accuracy of ± 0.1 %. To improve the accuracy of the measurement, calibrated voltage and current transformer were installed.

Correction applied

Since the current meters structure has been installed downstream of the static pressure taps, its head loss is taken into account in the net head measurement and would be imputed to the turbine if no correction would have been applied. Losses caused by the main structure, the current meters and the pipes for the wires were estimated using literature and CFD analysis. The following relation gives the correction applied as a function of the flow:

$$\Delta H_n = -9.49 \times 10^{-5} Q^2 \quad (\text{kPa})$$

Efficiency results

The performance tests lasted two days and over 60 steady state points were taken at different fixed blade position while varying the wicket gates opening. Results differ from what was expected from the

non-homologous model testing (figure 4). The difference probably lies in the imprecision of the model testing caused by the upstream 90° elbow not being correctly modelled.

As it can be seen on the 100% blade opening curve on figure 4, the efficiency dropped steeply after 10 MW on the first testing. To respect the contractual guarantee, other testing was conducted after increasing the maximal blade opening to the mechanical maximum that corresponds to 107% of the original nominal opening. That simple modification of the blade opening illustrated as the blade 107% curve on figure 4 allowed a gain of efficiency of up to 4% at higher outputs.

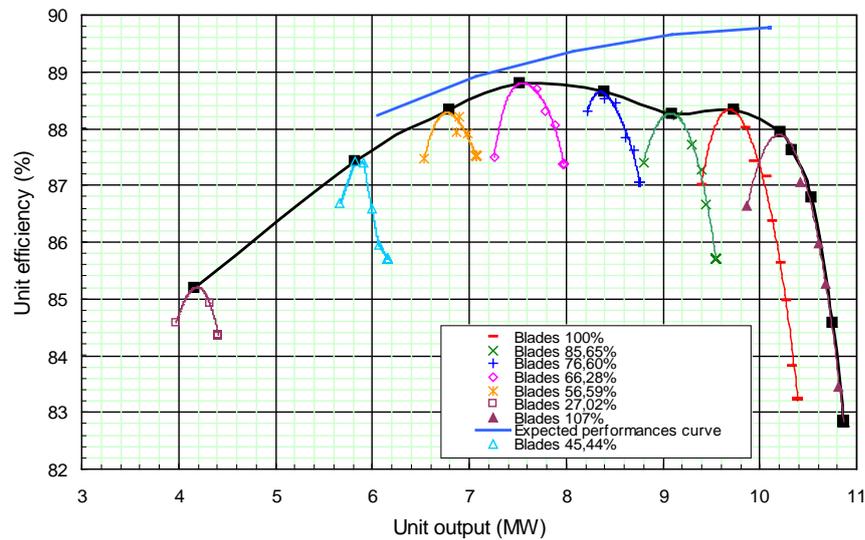


Figure 20: Efficiency vs. unit output at 18 meters

Because of the configuration of the unit’s penstock, the current meters have been installed near irregularities such as a diverging section and a 90° elbow. During the first two tests, communication was lost with one current meter at the bottom of the section. As illustrated on figure 5, the velocity profile was not very well distributed at higher flow. The mean value of the index of asymmetry as stated in ISO 3354 standard [2] is 0.053. This value is slightly higher than the recommendation, but a higher number of current meters were used to compensate. In this case, 43 current meters were measuring while the IEC 60041 recommends a number of current meters between 24 and 28.

To calculate the level of confidence in the results, an evaluation of the uncertainty caused by the number of measurement points have been done and the uncertainty on the resulting flow caused by the imperfections in the velocity distribution has been evaluated at $\pm 0.5\%$.

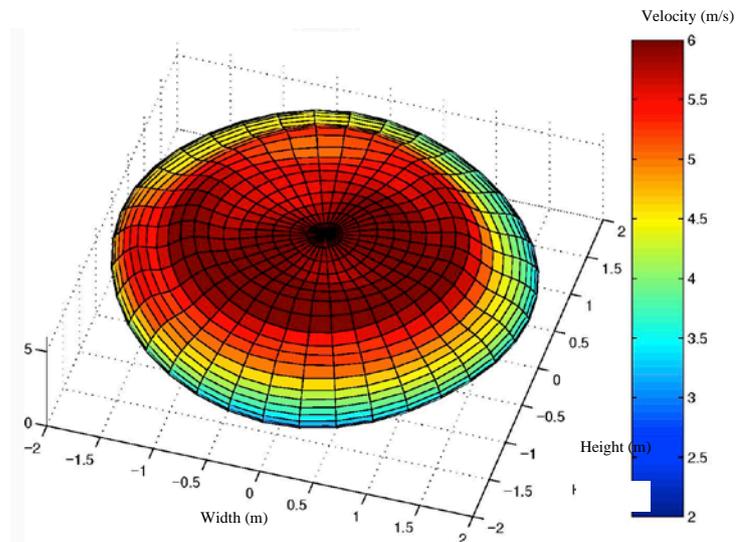


Figure 21: Velocity distribution at the measuring section

EXTENDED NET HEAD TESTING

Simplified measurement set up

Since net head is relatively low and encounters major variations during the year, assuming that the efficiency is constant with head is not accurate. Model testing could also have given knowledge of the unit's efficiency over all its operating range, but since they were done on a non-homologous model, confidence in the model's hill chart testing is quite low. Therefore, to make sure that the unit can be operated optimally, prototype efficiency testing needed to be done over a wider range of net head.

In order to be able to leave a permanent measuring system at the power plant for an extended period of time, a simplified measurement set up for relative efficiency testing was installed. Instead of the current meter structure that was not made to be left in the penstock for a long time, a transient-time acoustic system was used to measure the flow. The acoustic flowmeter computed the flow by integrating the water velocities measured by ultrasonic probes at a cross-section of the penstock along eight paths in two cross planes. More detail on the acoustic method for measuring the flow can be found in appendix J of IEC 60041 code [1]. The probes were installed before the contractual testing so their resulting flow could be compared with the one coming from the current meters and be calibrated with it as an index. The net head pressure was given directly by a differential pressure transducer connected to the upstream and downstream sections. Output power was given by permanent wattmeter while gate and blade position were also given by permanent transducers. All signals were connected to a data acquisition system which could be accessed remotely.



Figure 22: Installation of the transient time acoustic probes.

Testing method and data processing

The acquisition system was acquiring data continuously, sampling each signal at 100 Hz and saving its average every 10 seconds. That way, the net head profile could be followed and when desired conditions were reached, a testing procedure was executed. The procedure consisted of moving the wicket gates in “on cam” mode to move the blades to a given position. After a five minutes hydraulic stabilization, “off cam” sliding gates testing was done by moving the gates from -10 % to +10 % of the “on cam” gate position while the blades remained in position. Since the rate of the regulator for the opening of the gates could not be lowered to less than 0.1 % per second, a 30 seconds pause was done at every percent of gate opening to make sure hydraulic conditions were stable. The last steps were repeated for every 10 % of blade opening, starting at 20 %.

Each step of gate opening is processed and after the resulting flow and output have been converted to the average specific energy. A reversed “U” shaped curve is drawn on the efficiency chart for each blade opening. Supposing that the turbine is operated with optimal cam relationship (adjustments will be made in the regulator based on these testing), the efficiency curve at a given net head is plotted by connecting the

tangent of all the constant blade opening curves normalized at the same specific energy (figure 7). Each intersection of two curves gives an operating point with all the desired parameters that are normalized back to its measured specific energy to be placed on the prototype hill chart.

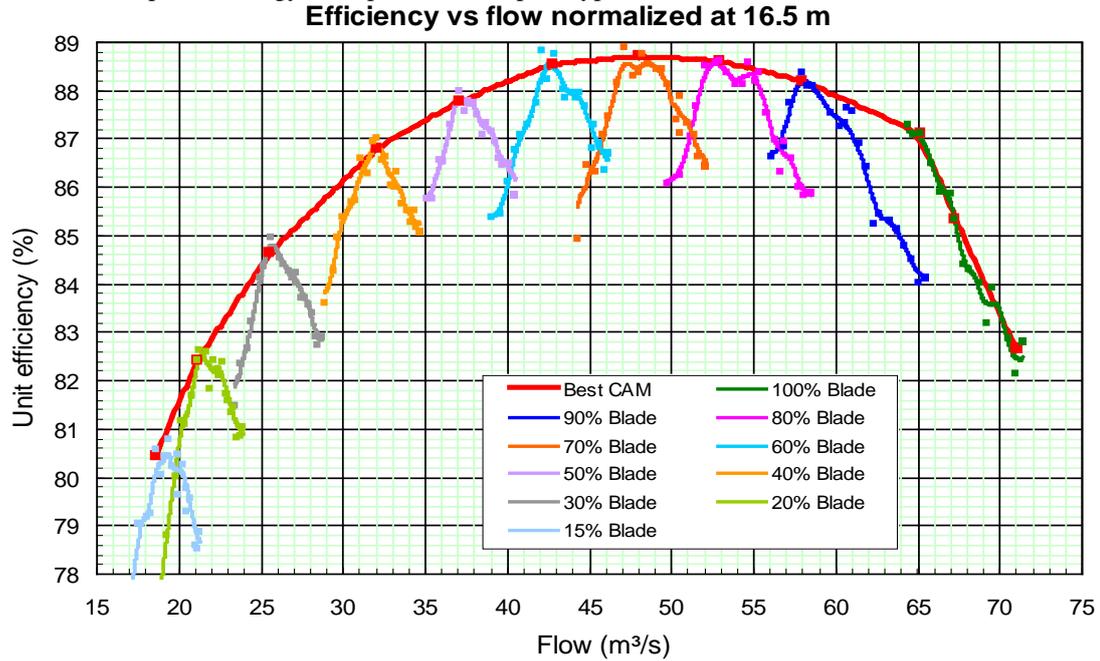


Figure 23: Off CAM parabolas and best CAM efficiency curve

Prototype hill chart

Height days of testing at six different net head were done between February and June 2009. The resulting prototype hill chart which summarise the main characteristics of the generator unit is shown at figure 8

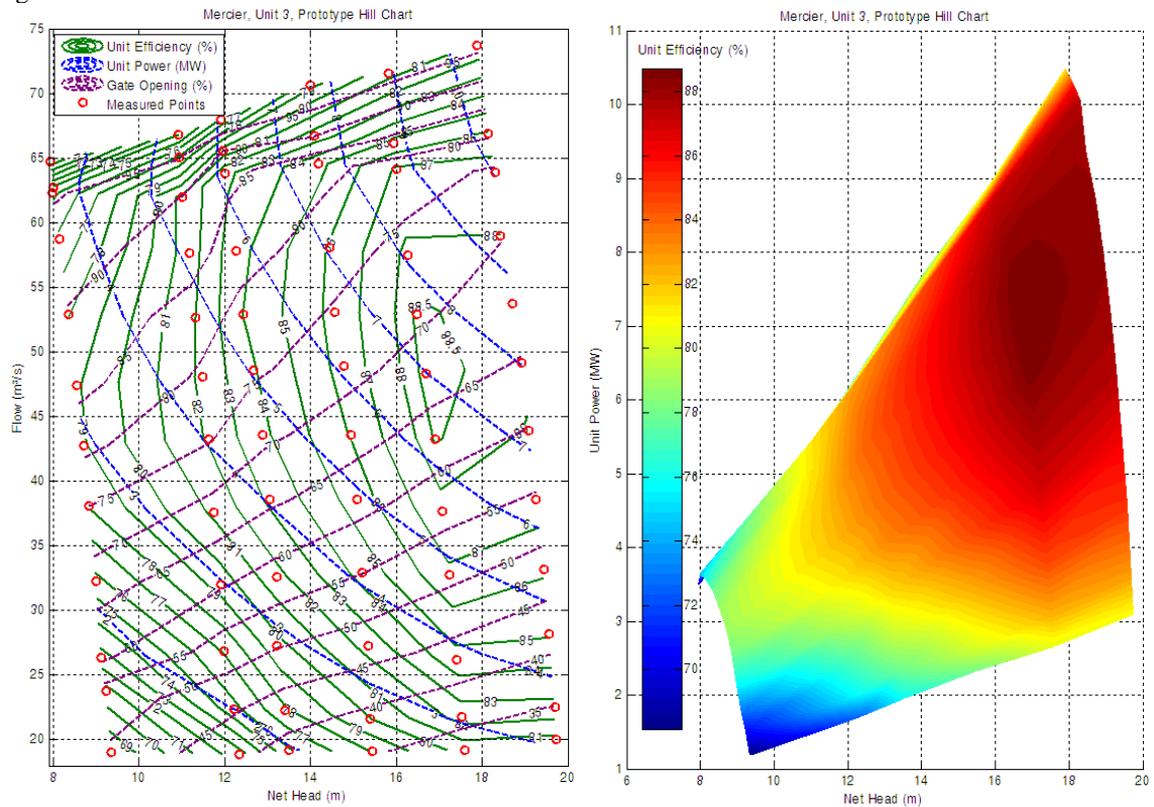


Figure 24: Prototype hill chart of the unit as measured

Since the testing, efficiency at higher flow as well as maximal flow and output have been increased by allowing the blades to be opened seven percent more.

An interesting fact observed is that at lower head, beyond a certain maximal output, more gate opening led to a decrease of output and a drastic loss of efficiency. Moreover, another important fact for operation is that regardless of the head, the peak in efficiency occurred almost at a constant flow.

Figure 9 presents a comparison between the measured prototype turbine hill chart and the one based on non-homologous model testing.

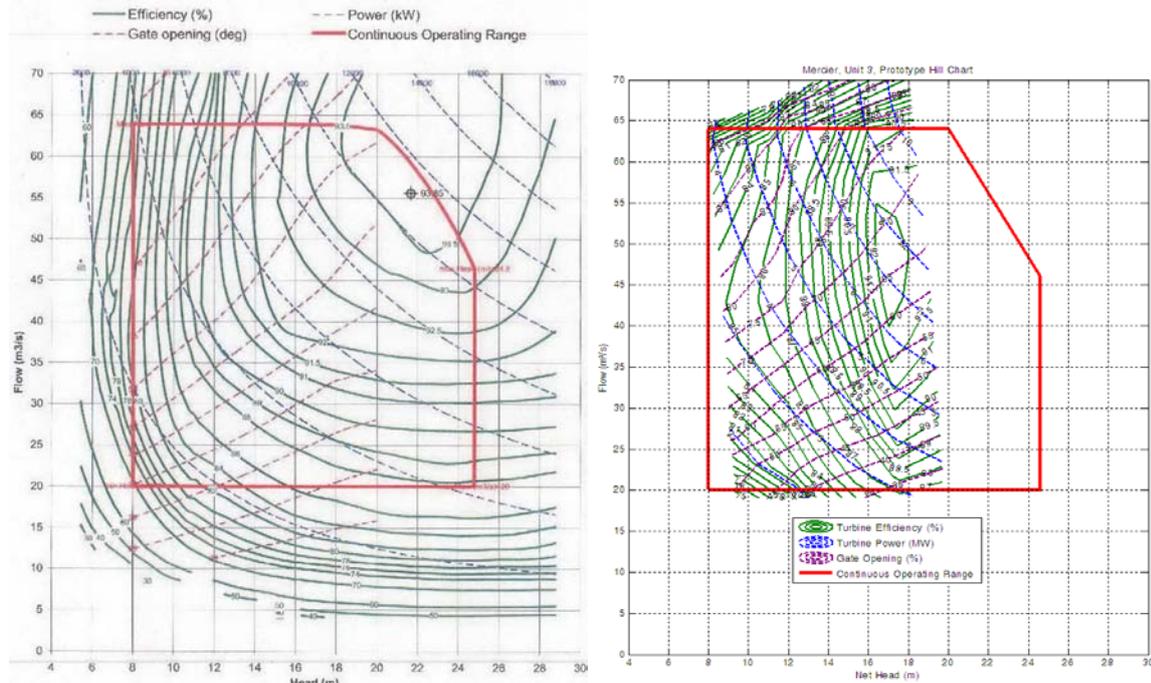


Figure 25: left: ©Voith-Siemens, 2007: Expected prototype turbine performances; right: Hydro-Québec, 2009: Measured prototype turbine performances

Major differences appear as the two hill charts are compared. It can be partially explained by the fact that the model used for the testing was not a homologous representation of the prototype. It had for instance its elbow downstream of the runner instead of upstream. Based on the model testing, efficiency should have increased with head in all of the operating range before reaching its optimum slightly before 22 m of net head. However, prototype testing showed a slight decrease in efficiency between 17 and 19 m of net head. Model also indicated that the peak of efficiency should have occurred near 55 m³/s of flow while prototype testing showed that the decrease in efficiency started between 45 and 50 m³/s.

During the contractual current meters tests, the head remained between 18.5 and 20.0 meters while the guaranteed efficiency was for the specified net head of 18.0 meters. At first, to convert the results, the model hill chart was used, but after the determination of the prototype hill, a significant correction was done to the results. When flow and output are converted to the specified net head using the prototype hill, efficiency is 0.5% higher than when converted with the model hill. Using the model hill could have caused a penalty to the manufacturer.

CONCLUSIONS

Even with unfavourable conduit configuration, the current meters method for measuring the flow has given reliable results to characterise the performances of the 10.5 MW “Saxo” turbine. Increasing the number of current-meter compensated for the irregularity of the flow. A simplified measurement set up using the transient-time acoustic method for measuring the flow also allowed measuring the turbine’s performances over all of the large net head operating range and redrawing its hill chart based on prototype measurement.

For guaranty verification purpose, the measured hill chart allowed a much more precise conversion of the results to the specified net head, the efficiency being 0.5% higher than it would have been converting with the model hill. The prototype hill chart testing will also allow doing optimal cam adjustments and like it can be seen on figure 4 and 7, cam adjustment is critical in turbine's efficiency optimisation and it was way off.

Operation will also benefit having accurate performance curve upon all the net head operating range. The information needed to get the optimal efficiency in all of the operating conditions is now accurate and it was shown that operating the unit using the model's performance characteristics would have cause an important loss of efficiency and money. For all those reason, those prototype efficiency testing will be profitable even with small units like those one.

REFERENCES

1. IEC 60041, "International Standard: Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines", third edition, 1991-11.
2. ISO 3354, "Measurement of clean water flow in closed conduits - Velocity-area method using current meters in full conduits and under regular flow conditions", second edition, 1988-07-15.
3. Éric Cloutier, "Rapport ES-2008-2018 - Groupe 03 - Détermination du rendement du groupe par la méthode jaugeage aux moulinets – Centrale ...", Hydro-Québec, 2010-04-08
4. Emmanuel Côté, Éric Cloutier, "Groupe 3 - Rendement à chutes multiples – Centrale ...", Hydro-Québec, 2010-07-19

BIOGRAPHY

Emmanuel Côté graduated in mechanical Engineering from the University of Sherbrooke in 2007. Since 2008, he works for Hydro-Québec Production's testing department. He has already performed testing of hydraulic turbine performances using the department's main methods such as: current meters, transient-time acoustic, pressure-time, thermodynamics and different index.

Éric Cloutier graduated in mechanical Engineering from the University of Sherbrooke in 1997. Since 1999, he has worked on the commissioning of Hydro-Quebec's major power plants. He has performed many performance tests using different methods and is responsible for the engineering team of the testing department.