Efficiency Tests on Ludvika Hydropower Station

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ABSTRACT

The tests showed that in-situ absolute efficiency testing of a small machine, 3500 kW, can be done within reasonable cost and with good accuracy thus may encourage the industry to perform such tests to a larger extent.

Efficiency tests were conducted after refurbishment of the hydropower station. Vattenfall Power Consultant performed the tests and the Accusonic method was used for flow measurements on the Kaplan turbine directly coupled to a synchronous generator. Eight (8) paths of ultra-sound beams were used. The same method was used successfully in 1993 on a 750 kW machine with Francis turbine owned by Vasterbergslagens Kraft.

It is tempting for suppliers of small hydropower machines to claim higher efficiency than can be obtained in reality as the cost of verification of a small machine is relatively high. At evaluation of bids, efficiency was evaluated as a major factor based on values derived from prognoses on future electricity production prices. The tests were performed as to verify the supplier-claimed efficiency values of the contract. This was to assure that Vasterbergslagens Kraft is awarding contracts only to serious vendors.

The total costs for the absolute efficiency test at Ludvika was $ 62 000.

The net present value after tax of a 1 % efficiency gain is $ 92 000 and $ 114 000 considering 60 years lifetime and interest rates of 8 % and 6 % respectively and thus worthwhile.

INTRODUCTION

The Ludvika Hydropower Station is owned by Vasterbergslagens Kraft AB, which has 11 hydropower stations and 47 dams, and commenced operation in 1893 with the world's first commercial power transmission scheme utilizing three-phase alternating current between the Hellsjon station and the iron-ore mining operations in Grangesberg 11 km away. That AC power scheme proved successful and made the hydropower industry develop at a fast pace.

The Ludvika Hydropower Station was first commissioned in 1901 to supply power mainly to the local up-start electro-technical manufacturing industry now known by the name ABB. The station featured a 330 m long raceway tunnel built as a masonry of slag-stone blocks, two 100 m long wood-stave penstocks and four machines providing 40 Hz power and one illumination machine at 100 Hz. Late in the 1920s the machines were synchronized with the evolving national grid at 50 Hz. Subsequently two of the machines designed for 40 Hz were replaced by one new machine for 50 Hz in 1930 and the two remainder ones by a new machine at 50 Hz in 1941. The 1930 and 1941 machines were in commercial operation until they were taken out of operation in January 2007. At that time field construction commenced for refurbishment of the station.

REFURBISHMENT PROJECT

The project was designed as to comply with the still governing permit from 1916 and the long-time usage pattern. Thus the regulating amplitudes of RWL and TWL and the head were kept the same and the discharge of the new machinery the same 24 m^3/s as measured as the combined discharges of the older machines.

The masonry tunnel had all the concrete joints between the slag stone blocks in the vaulted ceiling and in the walls inspected and whereas they were bad the material was sand-blasted away and replaced by new concrete of the same hydraulic-limestone type as had served well for more than 100 years. A new concrete bottom was cast for the entire length of the tunnel. New intake gate and trash rack, all in stainless steel, were put in. The two penstocks were replaced by one of surface-treated carbon steel. The two machines comprising Francis turbines and synchronous generators were replaced by one made up from a Kaplan turbine and a synchronous generator. The new control system features field-bus-connected distributed I/O units, process computer (PLC), operator-interface PC as well as primary and back-up programmable relay protections. The new medium voltage switchgear has vacuum type circuit breakers. The brick building power house has kept its exterior intact to preserve a piece of industrial history from more than 100 years ago. The interior, especially the foundation, has been heavily modified mainly to accommodate the lower setting Kaplan machine.

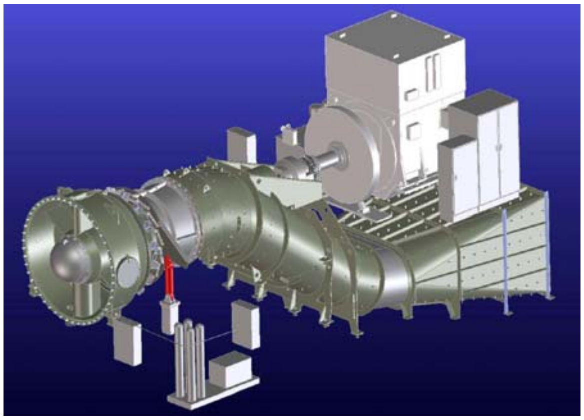

Figure 1. 3D model of the Ludvika Machine

Figure 2. Power house interior

Machine:

Six-bladed horizontal Kaplan with runner Ø = 2.12 m, H_{nom} = 17 m and Q_{max} = 24 m^3/s

Synchronous generator with rotating brush-less exciter, U = 10.5 kV, f = 50 Hz, n = 273 rpm

GREEN CERTIFICATES

Sweden has a trading system of green certificates since 2003 to promote investments in production facilities for renewable electricity. New as well as additional production is entitled to receipt of certificates during 15 years. The plants have to be approved by the Swedish Energy Agency and the hourly production from the plants is automatically and separately logged by means of electronic communication to the Swedish National Grid in the same fashion as for other plants. One certificate is issued for each MWh produced and the sellers of electricity have to cover a portion of their volume, different from year to year but close to 10 %. The certificates are traded bilaterally or through brokers and the deals are done electronically and recorded by the Swedish National Grid. So far about 73 % has come from biomass CHP, 17 % from hydropower and 10 % from windmills. The average certificate price for 2007 was $ 32.00 per MWh while the average price for electricity as such was $ 44.80 per MWh on the Nord Pool Power Exchange.

The Swedish Energy Agency awarded the Ludvika Hydropower Station certificates for 100 % of the production for 15 years. That decision made the refurbishment effort economically feasible.

PREPARATIONS

It is always very simplifying and cost-effective to do the thinking very early in a project. Thus while in horizontal position at the work shop and before surface treatment one penstock section, L = 17 m and Ø= 3.75 m, was fitted with welded supports for the Accusonic sensors and a handhole for associate cabling. After surface treatment the sensors were installed and also the protective sheet metal cable covers. Thereby undamaged surface treatment was obtained and the installation took place in short time due to the short access distance of less than 8.5 m from either end. As to assure high accuracy for the overall efficiency measurements the switchgear current and potential transformers as well as the race-water and tail-water level pressure sensors were specified early and accordingly. Also the flow-sensor penstock section was later installed as to assure more than 10 diameters straight penstock ahead of and 5 diameters after the location of the sensors.

Figure 3. Sensor installation beyond welder

Figure 4. Straight penstock down-stream surge chamber

MEASUREMENTS

The inaccuracy of the current and potential transformers are ± 0.2 % and of the power measurement bridge ± 0.15 %. The pressure transducers located right ahead of the turbine and in the tail water canal hold the inaccuracy of ± 0.08 %. The flow measurement inaccuracy was ± 0.43 % as 8 ultra-sound paths were used and the rotational pattern of the water flow was considered. Using established methods supported by norms like ISO 5168 and IEC 60041 to determine the absolute inaccuracy of the efficiency measurement including systematic and random errors we arrived at

$$\frac{\Delta\eta}{\eta} = (0.46^2 + 0.45^2 + 0.1^2)^{½} \approx 0.65 \%$$

The tests were performed at 7 different runner blade openings, 25 - 80 %, and 6 different wicket gate openings at each blade opening thus obtaining the optimum cam curve. The obtained optimum cam curve has since replaced the preliminary one in the PLC software. The software takes the actual head into account and adjusts the cam curve accordingly.

At the same tests the generator outputs were recorded and hence the efficiency curve could be established after normalizing the values to the head and discharges of the contract text. **Figure 5** shows the guaranteed efficiency curve and above it the curve derived from the measurements and its plus/minus inaccuracy bands. As the measured values exceed the guaranteed ones it can be concluded the machine supplier, i.e. consortium partners Kossler of St. Polten, Austria and Lloyd Dynamowerke of Bremen, Germany, has fulfilled its obligations in this respect.

The actual tests were conducted by Vattenfall Power Consultant of Alvkarleby, Sweden in conjunction with representatives from the client Vasterbergslagens Kraft and witnessed by a hydraulic expert from turbine manufacturer Kossler.

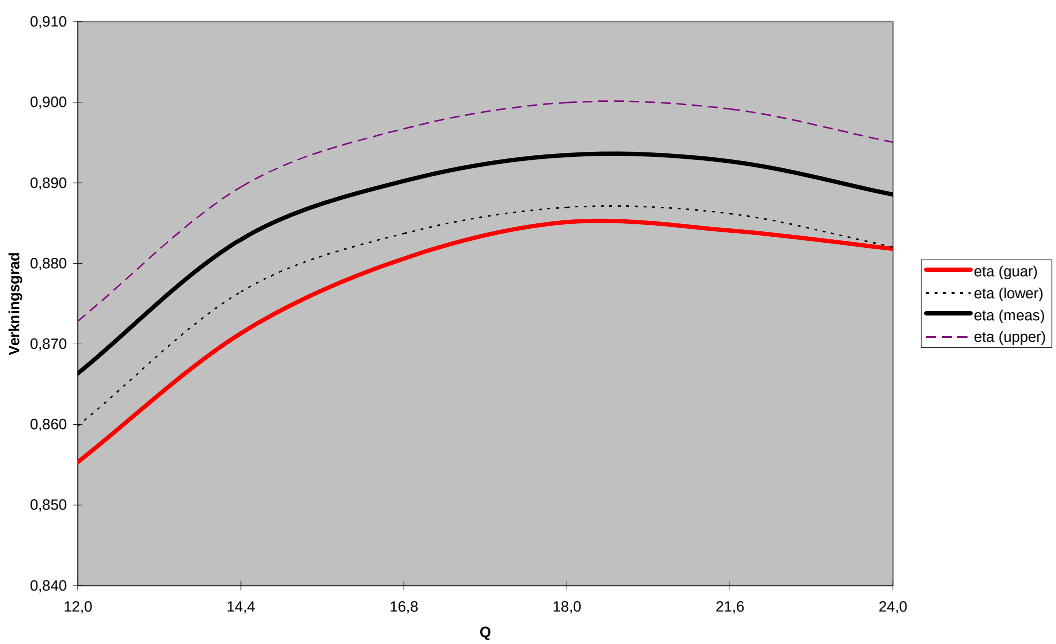

Figure 5. Measured efficiency with inaccuracy bands and guaranteed efficiency

RETURN ON INVESTMENT

The costs incurred:

Vattenfall Power Consultant (Planning, flow sensor rental and installation, testing and reporting)	$ 48 000
Vasterbergslagens Kraft (Planning, test participation, flow sensor removal and shipping)	$ 10 000
Kossler (Witnessing, however not necessary for the test as such)	$ 4 000
Total	$ 62 000

The above is the total cost for verification of the performance guarantees of the contract. At the same time the optimum cam curve was obtained. It may also be of interest to evaluate the benefit of say 1 % efficiency gain compared with the total cost for an efficiency test. By putting the 1 % gain into the refurbishment project investment calculation program with all its inputs of assumed future cost and revenue values and covering the expected lifetime of 60 years and smaller reinvestments throughout that time one arrives at post tax net present values of $ 93 000 and $ 114 000 for calculation interest rates of 8 % and 6 % respectively.

CONCLUSION

The effort at Ludvika Hydropower Station shows that verification of a supplier's guaranteed performance can be done within reasonable cost and with good accuracy, i.e. better than 99 %, even for a small turbine-generator machine.

The Kossler/Lloyd Dynamowerke consortium fulfilled and exceeded its contractual performance obligation.

It can also be concluded that it is well worthwhile to conduct such an absolute efficiency test if an efficiency gain of 1 % is considered.

AUTHOR

Tommy Hjort, MSEE, served for several years at Vasterberglagens Kraft AB as planning manager, production manager and concurrently as project manager for the Ludvika refurbishment project. He has now his own consulting company.