Engineering to Achieve the Optimum Choice of Machine

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ABSTRACT

Power stations that were built early in the 20th century have turbines of type Francis even for low heads. When those stations are refurbished the natural choice of turbine is the Kaplan type. The Kaplan turbine has the advantage of high efficiency over a wide range of discharges and a relatively high rotational speed resulting in a generator with fewer poles than for a corresponding Francis turbine and thus less expensive. The higher speed makes it also easier to achieve high inertia for efficient control stability and for islanding operation. However the Kaplan turbine typically requires negative setting necessitating a lot of excavation as compared with a Francis unit. Furthermore, the low setting means risk of flooding especially during maintenance.

For the 2007 refurbishment of the Ludvika Hydropower Station in Sweden which first went into operation in 1901 the aim was to achieve a solution which would provide the lowest investment cost for the entire project while satisfying demands on efficiency, operation availability, maintainability and ergonomics, wear etc. The engineering produced capitalized values for losses, unavailability, cavitation damages and excavation work and those values were written into the specification. Those values were used for evaluation and as penalties for noncompliance.

Based on the evaluation criteria the successful vendor came to a solution with an oversized horizontal six-bladed Kaplan with positive setting which may seem strange. A couple of large vendors bid solutions with smaller size Kaplan units and faster speed but with considerably lower setting. Those solutions however resulted in a much higher evaluated costs for the project and were therefore not considered.

The paper deals with describing the project as such and the engineering efforts leading to the optimum overall longtime profitability solution. It illustrates the benefit of including several important criteria in the machine specification.

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 start-up 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 Francis machines providing 40 Hz power and one Francis 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 Francis machine for 50 Hz in 1930 and the two remainder ones by a new Francis machine at 50 Hz in 1941. The 1930 and 1941 Francis machines were in commercial operation until they were taken out of operation on January 8, 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.

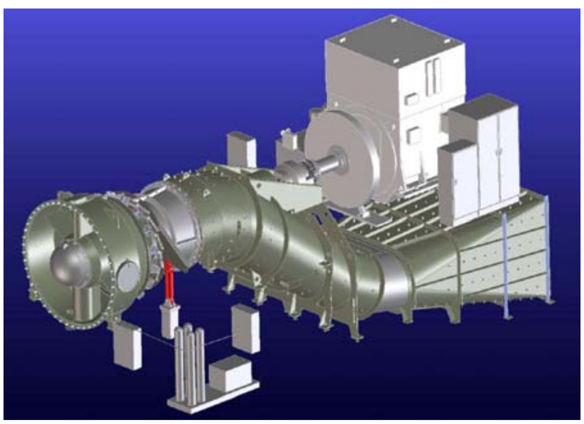

Figure 1. 3D model of the Ludvika Machine
Courtesy of Kössler, Austria

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 ISO, 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 sales volume with such certificates, 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. In 2007 about 72 % came from biomass CHP, 17 % from hydropower and 11 % from windmills. The average certificate price for 2008 was approx. $ 27 per MWh while the average price for electricity as such was approx. $ 41 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.

LEGAL GROUND

The hydropower station has operated on support from a permit issued in 1916. Such a permit is according to Swedish law valid indefinitely. However it may be tried again in court and changed. In such cases the power plant owner may suffer losses. If losses amount to 5 % or less they have to be borne by the owner. The losses in excess of 5 % are to be borne by the Swedish taxpayers. For most proposed processes so far the potential benefits of changes have been determined to be of less value than the disadvantages and therefore very few changes have materialized and thus government process funding is kept low. A refurbishment effort may take place within an old permit as long as reservoir levels are kept intact and no changes to the established usage are pursued.

PREPARATIONS

The previous machines were of type Francis. For those the combined discharge was measured at maximum wicket gate openings and found to be 24 m^3/s. At that discharge of cause the efficiency was beyond peak and considerably lower as the efficiency curve for Francis units is very peaky. The specification for the new Kaplan machine therefore called for peak efficiency at 24 m^3/s discharge and no operation beyond that discharge as to not violate the old permit and the established operation of the plant thus providing the best future use of the available water resources over time. It was also determined by measurements and calculations that discharges in excess of 24 m^3/s were not practically feasible as the losses in the 330 m long and not straight tunnel tend to be too high and the impact forces from the surge at emergency shut-down excessively high. For a very wet year like 2008 the decision to put peak efficiency at peak discharge proved very profitable with annual production of close to 19 GWh compared with 13 GWh of the average year.

DESIGN CRITERIA

The criteria below were derived from different studies and discussions:

Discharge

The demand for discharge of 24 m^3/s at peak efficiency came out of the discussion above on legal aspects and thus equals the maximum discharge for the refurbishment.

Type

Also the decision to go for a Kaplan unit was made after studies showing a corresponding Francis unit would be very large and heavy and thus costly. In general a Kaplan unit is best suited for a head as low as 17 m. Expected lifetime was set to 60 years.

Operating Pattern

The station normal operation was set to be 6 am thru 10 pm five days a week, i.e., very close to established pattern. Periods of large run-offs may demand maximal output around the clock

Islanding Operation

A Kaplan unit is also running faster than a corresponding Francis unit thus making it easier and cheaper to achieve the necessary inertia of J = 15 000 kgm^2 @ 300 rpm (J = 18 000 kgm^2 @ 273 rpm, J = 21 000 kgm^2 @ 250 rpm etc) to allow limited islanding capability. The wicket gate operating speed open/close of 8/6 s and runner operating speed open/close of 20/20 s were deemed sufficient as well as accumulator energy storage allowing full travel maneuvers close – open – close + automatic stop.

Setting

The normal setting of a Kaplan unit is negative, i.e., the runner center line is located below the tail water level, TWL, the higher the head the lower the setting. As such a setting means a lot of excavation the aim is to minimize the excavation cost. The curve below describes the cost vs depth:

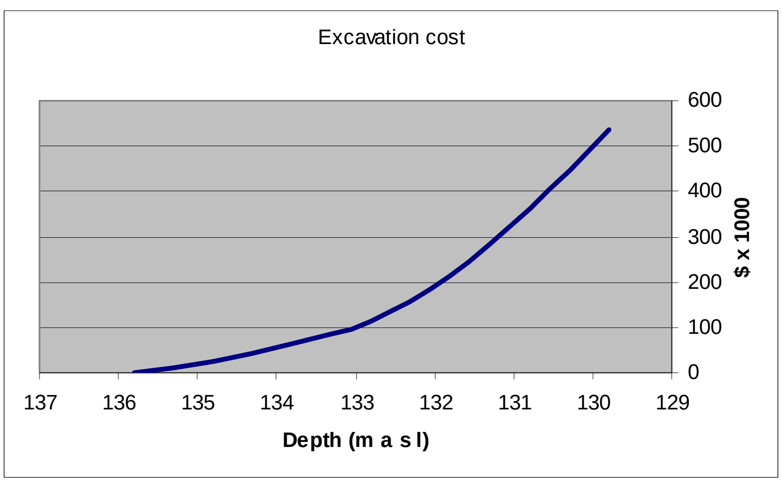

Figure 3 Excavation cost vs depth (Excavation and subsequent construction)

The curve indicates a low setting is costly.

Cavitation Damages

As the IEC norm is very lenient the more stringent Swedish norm SEN 26 80 10 was referenced to. However the criteria for cavitation damages were stiffened even more. Due to its complexity the algorithm and associated penalty clause is omitted here.

Efficiency

The capitalized values, net present values (NPV), of losses were calculated from predicted revenue values for a 60 year period and the given interest rate. For the discharges 12, 18 and 24 m3/s the values per kW thus turned out to be $ 1 250, $ 3 750 and $ 5 000 respectively.

Reliability

Aside from 15 days per year when the machine is out for inspections and maintenance the reliability was set to 99 %. Non-compliance penalty was calculated to $ 2 500 per hour.

Scope

I order to achieve as clean contract boundaries as possible the specification called for a machine comprising turbine, directly driven synchronous generator, brake, hydraulic power pack, bearing lubrication units, sensors and other necessary peripherals. Thus the client did not have to be involved in the interfaces between turbine and generator such as various forces, runaway speed etc.

Profitability calculations

The interest rate used for the calculations above was 8 %, which has to be considered high for a hydropower investment with a calculated life of 60 years. An analysis shows that when performing the net present value, NPV, 91 % of it is derived from the initial 30 years and only 9 % from the remaining 30 years. Thus by using such high interest rate there is a risk several long-term healthy projects do not get funded.

CONTRACT

At evaluation of the received bids it became clear that two large manufacturers had paid very little attention to the excavation costs. By doing so they were able to offer turbines with runner diameter 1.6 - 1.7 m and small flywheel due to relatively high rotational speed but in order to avoid cavitation damages they had to choose a low setting. The high costs for excavation kicked them out of the competition.

The successful bidder, a consortium formed by turbine manufacturer Kössler, Austria and generator manufacturer Lloyd Dynamowerke, Germany, avoided much of evaluated excavation costs by choosing a large diameter, 2.12 m, more expensive turbine. By having the discharge envelope curtailed at peak efficiency, a large diameter and six runner blades they could choose a positive setting without suffering potential cavitation damages, see Figure 4 below. The disadvantage was the lower speed resulting in a larger more expensive generator with more poles and a larger more costly flywheel to meet the inertia criterion. All together this solution proved to be the optimum for the project. The contract price was approx. $ 2 million. The rated output from the machine is close to 3 600 kW.

The refurbished station was put back in commercial operation October 19, 2007 and has been running very well. It’s too early to determine whether the reliability and cavitation damages will stay within guaranteed values as the warranty time is still in the running. However operating records and inspections so far indicate compliance with criteria. The absolute efficiency test was performed soon after commissioning. The inaccuracy of the test was less than 1 % as the Accusonic method was used and the machine passed with flying colors, see Figure 5 below. As can been noticed the peak efficiency occurs at a lower discharge than called for but reasonably close as the curve is relatively level.

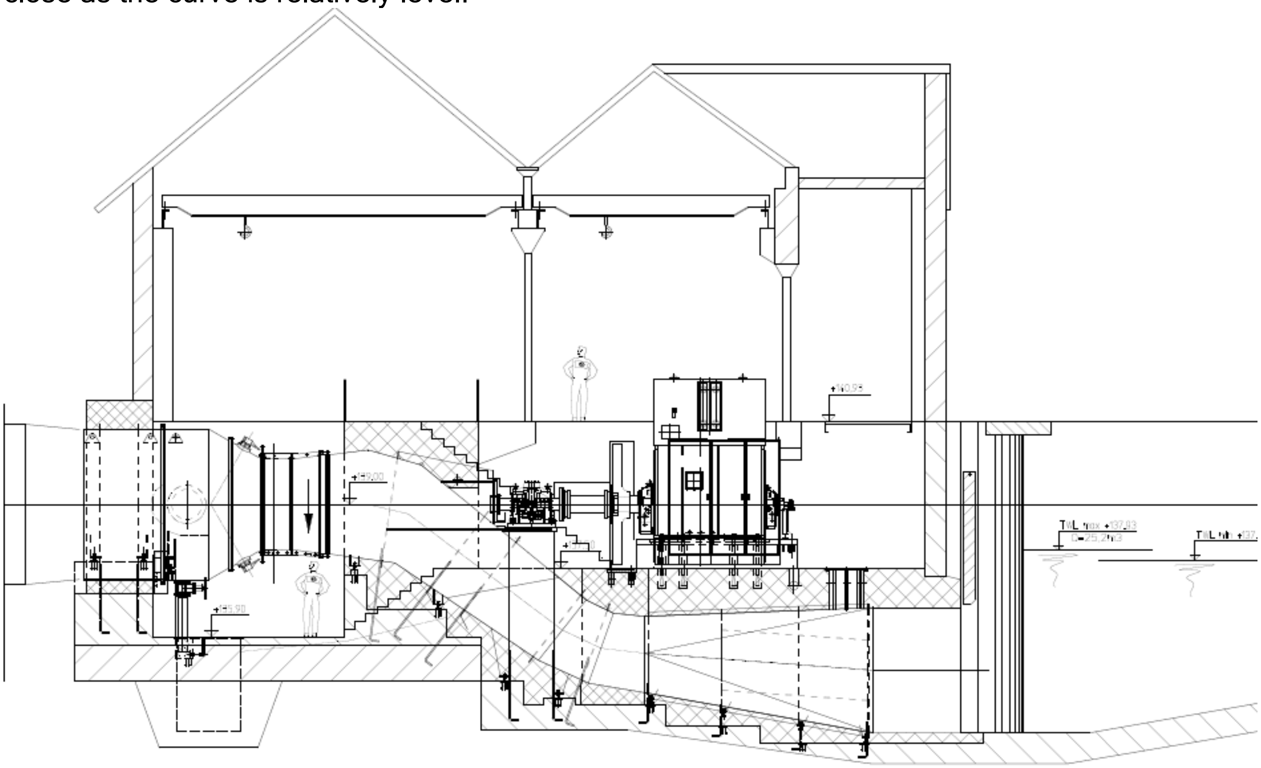

Figure 4 The runner centerline of +139.00 is located above maximum TWL of +137.93
Courtesy of Kössler, Austria

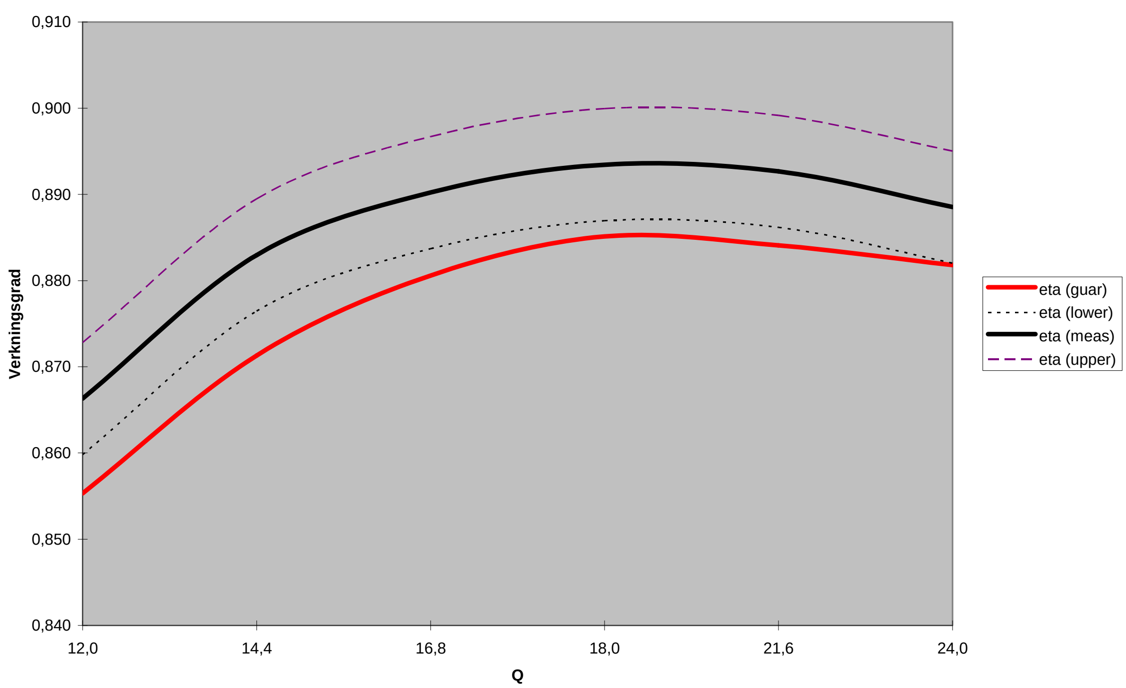

Figure 5. Measured efficiency with inaccuracy bands and guaranteed efficiency
The Accusonic method was used for flow measurements

CONCLUSION

The main aim when building a new plant or refurbishing and old one is to reach the optimum long-term profitability based on calculated values derived from present and predicted future prices for electricity and certificates, reliability, efficiency and cavitation. It can be concluded that that it pays off to engage a civil contractor to estimate costs for excavation and construction which then is used as a design criterion in the specification.

The owner of a project for a new or a refurbished plant shall not stop short of examining whether a rather un-conventional solution based on an oversized machine may be the most beneficial in the long run.

Figure 6 The Kaplan turbine in operation.

Figure 7 The synchronous generator. The cooling air is circulated through heat exchangers at top of which one is supplying warm water to a large accumulator tank. That water is used to heat the building mainly during standstill at nights and weekends.

AUTHOR

Tommy Hjort earned his MSEE from Chalmers Institute of Technology in Gothenburg, Sweden. He served for more than 20 years at Vasterberglagens Kraft AB as planning manager, production manager and concurrently as project manager for the Ludvika refurbishment project. Previously he worked for more than 14 years for ASEA/ABB in the field of High Voltage Direct Current, HVDC, transmissions in various aspects on projects in Sweden, Norway, USA, Canada, Congo and Brazil. He has now his own consulting company, Cervus Power AB.