Active Draft Tube Control Gates for Increased Generation

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Abstract

New runners have been installed in the four turbines at Electricity Corporation of New Zealand's 200 MW Tokaanu power station. This has increased the output from 51.5 MW to 61.5 MW. The turbine setting is very high by modern standards and with the existing tailwater level there was a risk of severe cavitation at high outputs . To solve the problem, draft tube gates were installed to increase the pressure at the runner discharge. These gates are lowered and raised as necessary to provide the pressure required at high outputs and to allow efficient operation at lower outputs.

The paper describes the development, installation and testing of these draft tube gates.

1 Background

Electricity Corporation of New Zealand's 200 MW, 190 m head Tokaanu power station makes an important contribution to generation and frequency control in the North Island. It can operate in base load, peaking and spinning reserve modes. The station, which was commissioned in 1973 has four units which could generate up to 55 MW.

The original runners suffered from cavitation damage and, by modern standards, were not very efficient. These runners were replaced by new runners with 3% higher efficiency and with a potential output of 60 MW. As the turbine centreline is above tailwater level - which is very high by modern standards - there is a risk of severe cavitation if the new runners are operated at high outputs. To avoid cavitation damage, the turbine output must be limited to 51.5 MW when operating at the existing tailwater level.

To enable the turbine to operate safely at 60 MW, the effective tailwater level has been increased by the installation of draft tube gates. These gates effectively increase the tailwater level and so eliminate the risk of cavitation damage. The gates are lowered at high outputs to provide the back pressure required and raised at lower outputs so that the station can operate at maximum efficiency.

To our knowledge, this is the first scheme of its type in the world.

Leyland Consultants and their sub-consultant Brian Wilson were engaged to carry out the feasibility study followed by detailed design and commissioning.

Eight options for increasing the tailwater level by installing a regulating gate in the stoplog slots were considered during the initial stages of the feasibility study and several were found to be technically feasible. However, structural investigations by Brian Wilson showed that the draft tube portion of the powerhouse would be severely overloaded and that strengthening the powerhouse would be very expensive. Leyland Consultants then proposed a radically different solution which eliminated many of the problems and reduced the cost.

A cross-section of the station is shown in figure 1 below.

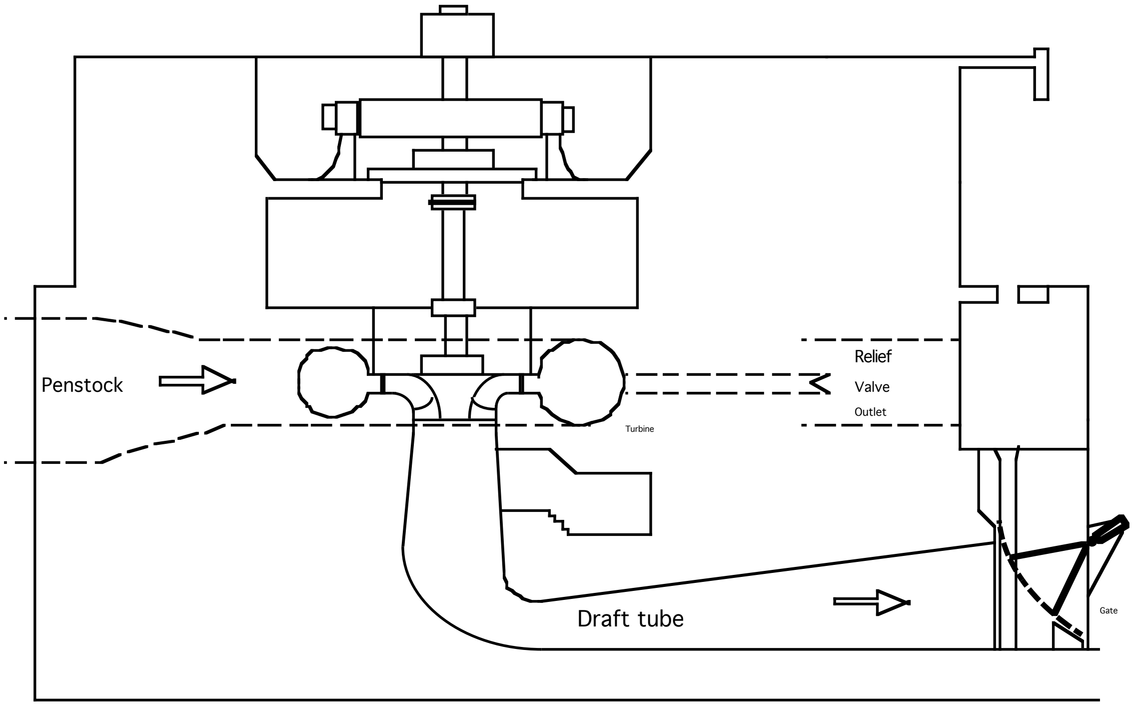


Fig.1 Tokaanu Power Station Schematic

Even the best of modern runner designs could offer little more than the existing rating at the existing setting. It became clear that to get more output, the turbine back pressure would need to be artificially increased to limit cavitation.

A nominal uprating to 61.5 MW at 185 m was considered feasible, but it required a back pressure of at least 6 metres. Several options were considered:

- a fixed or adjustable tailrace weir;
- extraordinary runner design and draft tube modifications;
- the admission of a large quantity of air into the draft tube;
- gates regulating the outlet from the draft tubes.

Adjustable tailrace weirs were dismissed as too expensive and too disruptive to the station operation. A major factor was the possibility of flooding the powerhouse. A fixed weir would result in a 3% drop in efficiency all the time.

The desired output at the existing setting would have been possible with a greatly enlarged (15% increase) runner discharge diameter, with the draft tube cone modified to a convergent/divergent shape. This option was dismissed as too expensive and because the far from optimal runner and draft tube would seriously reduce efficiency at all outputs.

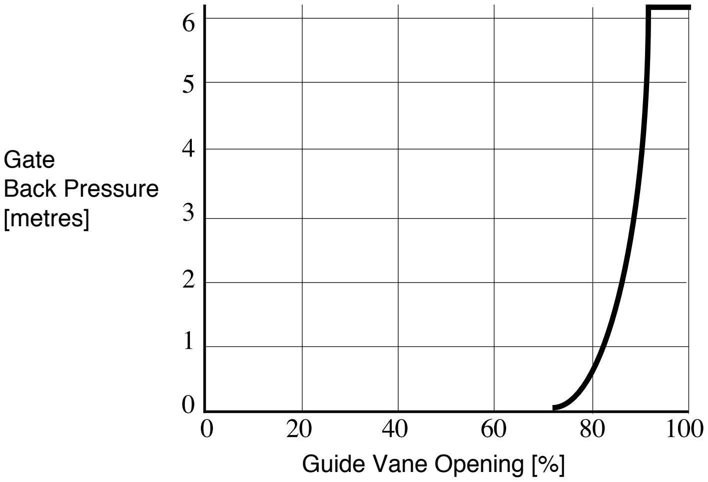
Large scale draft tube air admission was in use at other ECNZ stations to reduce suction by up to 3 m subsequent to re-runnering and uprating, but this technique, although theoretically possible, was considered too risky for the 6 m reduction required at Tokaanu. Lack of easy access to the draft tube cone was a major cost factor.

Regulating gates at the draft tube exit were therefore investigated and found to be feasible and economically attractive. Tenders were called for the runners on the basis that it would be possible to provide the equivalent of a tailwater level 2.6 m above turbine centre line. Voith Hydro, USA, was awarded the contract for the runners.

Voith Hydro conducted model tests which included a vertical gate partially blocking the draft tube exit. The tests demonstrated that:

- the draft tube gate could achieve the same effect as an increased tailwater level without any anomalous effects on turbine performance, including hydraulic stability and cavitation;
- the equivalent tailwater level could be reliably and consistently derived from a set of draft tube piezometer points upstream of the model gate;
- an output of 67.5 MW at 185 m was possible, but it would require a tailwater level about 7 m above turbine centre line. However, in reality, the additional conduit and draft tube gate losses would reduce the head to 177 m, thus reducing output to 63 MW. (This increased output/tailwater was seriously considered, but was ruled out at the gate design stage because of the excessive hydraulic loads that the gates would transmit to the powerhouse structure.)

The model tests confirmed that the contract tailwater requirements were appropriate, and slightly conservative. These requirements were used to prepare a performance specification for the gate, which included a curve specifying the required tailwater level vs. output for different heads.



Note:
This curve varies with changes in tailwater level

Fig.2 Gate Back Pressure Curve

2 Functional Requirements

ECNZ set out a number of requirements for the gate. The gate must respond to variations in the guide vane position and generate the back pressure determined by the manufacturer. In normal operation the guide vanes can move from zero to maximum in approximately six seconds. The design of the gate must ensure that back pressures greater than 7 m cannot be generated and that failure of the lifting gear or control system will not prevent continued operation. At outputs below 52 MW the gate should cause no significant increase in back pressure. Each of the four turbines has a relief valve discharging just above the draft tubes. The gate must not obstruct the operation of the relief valve which operates suddenly and without warning. The gate must not obstruct the existing stoplog which drop into a vertical slot immediately downstream of the draft tube outlet. Tokaanu power station is located in the middle of an important trout fishing area. The design of the gate and the operating mechanism must minimise the possibility of waterway pollution.

3 Options Considered

The owner's initial concept involved installing a vertical gate in the existing stoplog slots. It soon became obvious that this was not acceptable because the gate would obstruct the relief valve outlet when it was open. After a "brain storming" session the following variations on the vertical gate theme were identified:

- double hung gate;
- draft tube flap gate;
- multivane gate;
- chaffcutter gate.

Their basic features were similar in that they were all underwater mechanisms using existing stoplog slots. Their construction would be heavy and they difficult to remove for stoplog installation. Also the multiple moving parts would be susceptible to vibration:

Investigations into the powerhouse structure showed that the stoplog slots were not able to carry the gate loads of up to 1600 kN in a downstream direction. It was concluded that post-tensioned anchors would be needed along the full length of the stoplog slots and a temporary cofferdam would be needed during installation. This was a major problem as the construction costs were very high and there would also be a large loss of revenue while each turbine was out of service while the cofferdam was in place.

At this point Leyland Consultants' gate designer suggested a radial gate with its pivot above the lowest tailwater level. With this arrangement, the anchors could be installed without the need for a cofferdam.

The radial gate concept represented a major breakthrough as the costs and complications of the vertical lift gates seriously affected the economics of the project.

A negative aspect of the radial gate proposal was that there was a greater risk of a hydraulic jump and increased down stream turbulence at low tail water levels because the radial gate would not dissipate as much energy as the vertical gates. This was not realised until the gate was ready for construction. It was decided that it would be necessary to carry out model testing to evaluate the problem and to establish the best solution.

An important aspect of the model testing was the need to minimise the tailrace turbulence caused by a concentrated jet of water emerging from underneath the radial gate at partial openings. This turbulence could cause uplift of the concrete slabs downstream of the draft tubes.

After consideration of a number of options, it was decided that perforating the gate was likely to be the best way of dissipating the energy and limiting turbulence. The gate design featured internal baffles and guide fins to straighten the flow leaving the gate and baffle blocks to break up the concentrated jet emerging from underneath the gate. The gate illustrated in figure 3 was designed and model tested.

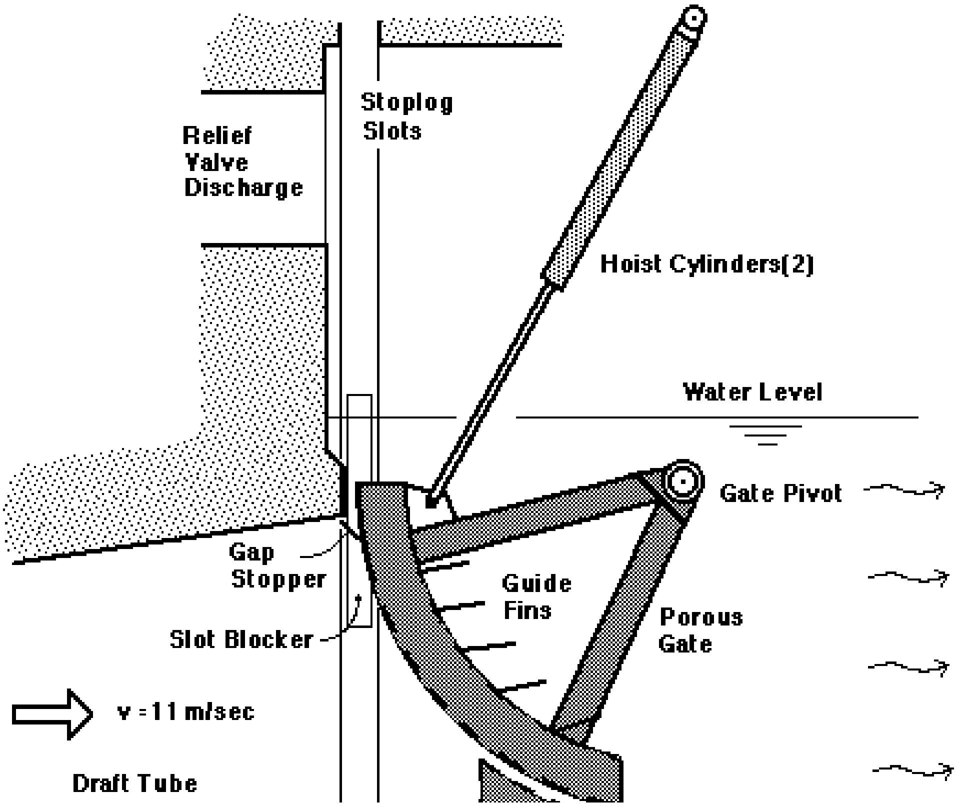


Fig.3 Gate Cross Section

4 Model Testing

Introduction

A series of model tests were carried out, by Works Consultancy, to evaluate the optimal energy dissipation and to assess the effect of the turbulent water on tailrace water levels and uplift on the slabs.

The tests established:

a. the differential head developed across the gate at varying flows and varying gate openings;

b. the drop in water level, or setdown, on the downstream side of the gate (the greater the magnitude of the setdown the greater the uplift forces on the tailrace slab);

c. the magnitude of downstream tailrace turbulence caused by the gate;

d. There was no risk of a full hydraulic jump.

A 2-dimensional model to a scale of 1:20 was constructed to evaluate items a. and b. To evaluate item c. a 3-dimensional model to a scale of 1:50 was constructed.

4.2 2 Dimensional Model Tests

A 2 dimensional model of a 1 m wide slice through the full sized gate was constructed from transparent polycarbonate so that the flow pattern and downstream water level profile could be studied. The injection of dye made it possible to study the effects of various gate configurations.

The porous gate had many energy dissipating chambers followed by guide fins to direct the emerging highly turbulent water in a horizontal direction. (Without the fins it was found that the water would leave the gate with a significant upwards velocity component, resulting in a standing wave downstream of the gate. The standing wave caused undesirable pressure fluctuations on the tailrace concrete slab.)

The parameters involved in optimising the performance of the gate were:

- the porosity of the skinplate (proportion of the skin area open to water flow) and the number of holes;
- the configuration of the mixing chambers;
- the angle and length of the guide fins;
- the configuration of baffle blocks fixed to the tailrace slab.

The model tests clearly showed that the more holes in the gate skin and the more energy dissipating chambers, the better the performance.

The effect of the baffle blocks was studied and the porosity of the blocks was adjusted to provide a smooth transition from the gate fully closed position to the gate fully open position.

4.3 3 Dimensional Model Tests

The function of the 3 dimensional model was to study the effect of a gate on the whole area of the tailrace and in particular evaluate the fluctuation of water levels on the concrete tailrace base-slab. Water velocities in the rock lined canal downstream of the concrete lined tailrace were also assessed. Model tests simulating the characteristics of the preferred porous gate design confirmed that the tailrace turbulence was acceptable and that the maximum anticipated setdown in tailwater levels was approximately 100 mm.

5 Gate Design

5.1 Structural Design

Vibration was a major concern in the design because of the high velocities involved and the need for the gate to perform over a range of flows.

Vibration has been minimised by:

- ensuring that all plates on the gate are well supported and rigid;
- fitting seals to the gate sides to prevent a high speed stream of water from passing around the sides of the gate;
- ensuring that there are no bolted panels that can work loose under vibration.

The weight of the gate is limited by the lifting capacity of the existing 13 tonne stoplog hoist which is used to lift the gate clear of the stoplog slots. Special lifting strops have been fitted to the gate for raising the gate to the "umbrella" position so that the stoplogs can be lowered into the slots.

5.2 Turbulence Control

At full output each gate must dissipate about 2.2 MW in order to prevent uplift on the concrete slabs and excessive turbulence. The concrete tailrace slab is 500 mm thick and high water velocities would result in a net uplift of the tailrace slab. This uplift could cause the slab sections to lift and require major repair work. Therefore, it was decided to limit any reduction in water level to a maximum of 200 mm.

Energy dissipation has been achieved within the gate itself by having the water pass through 112 separate holes in the gate skin. Each water jet enters a mixing chamber where it strikes a baffle plate and then emerges from the rear of the gate with a low mean velocity.

The need to vary the gate opening to provide the variable back pressure means that when the gate is partially closed some of the water can escape under the gate as a solid jet. To prevent the jet causing surging water levels in the tailrace, fixed baffle blocks are mounted on the concrete slab immediately upstream of the gate. When the gate is fully down the gate skinplate covers the upper curved surface of the baffle blocks, forcing water to flow through the mixing chambers within the blocks and then pass through the rear openings.

Model tests showed the need for 112 mixing chambers in the gate to minimise the turbulence downstream of the gate. The design of the mixing chambers and guide fins was carried out in parallel with model testing. The design concept was based on high speed water jets (11 m/sec) from the skinplate holes impacting onto flat steel baffle plates. Following massive turbulence in the mixing chamber, the water emerges from the rear of the gate through the guide fins as a well distributed mass flow with a reasonably uniform velocity profile.

This process is illustrated in figure 4 below.

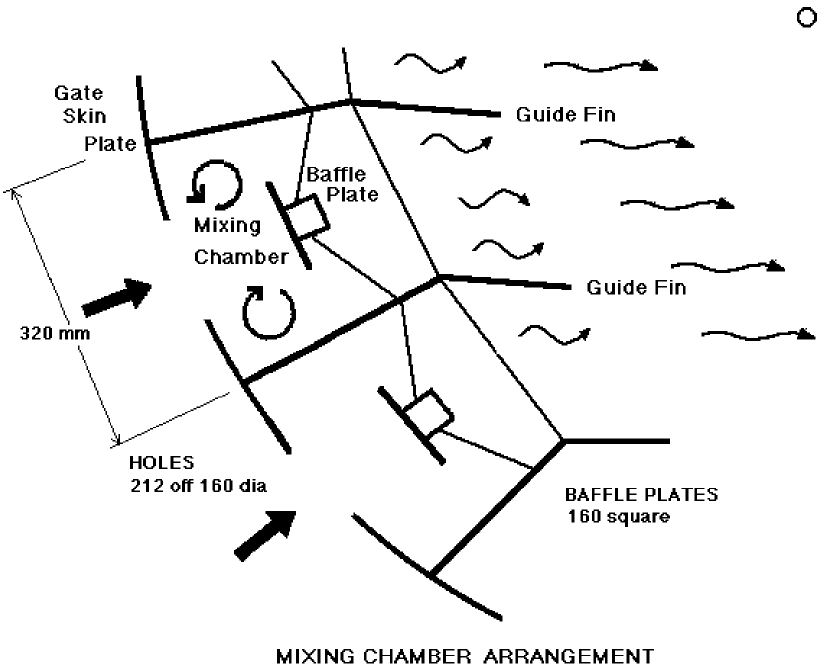


Fig.4 Mixing Chamber Arrangement

5.3 Hoisting Equipment

A pair of hydraulic cylinders raise or lower the gate in response to variations in the turbine guide vane position. Dual cylinders are fitted to provide security against the possibility of cylinder failure. Counterbalance valves fitted to each cylinder ensure that the gate cannot drop if a hydraulic hose bursts. A conventional hydraulic power pack with three identical hydraulic pumps powers the gate. Combinations of the three pumps provide for high or low speed operation.

Environmentally friendly vegetable oil is used to minimise any pollution in the event of a spill and, in addition, each cylinder is fitted with a special neck bush chamber to ensure that any oil leakage is intercepted and returned to tank without contaminating the water.

5.4 Gate Seals

Flap seals are fitted to each side of the gate to prevent long term erosion of the concrete walls which could result from a high speed jet of water escaping between the gate and the concrete side walls. They also act as dampers and minimise gate vibration.

To prevent rubbish collecting in the critical wedge shaped gap between the top of the gate and the draft tube top sill, a gap stopper sealing flap is fitted to the top of the draft tube. The gap stopper also prevents an undesirable jet of water from escaping through the top sill gap.

Removable slot blockers are fitted into the stoplog slots to prevent the escape of water past the side of the gate.

These are illustrated below in figures 5 and 6.

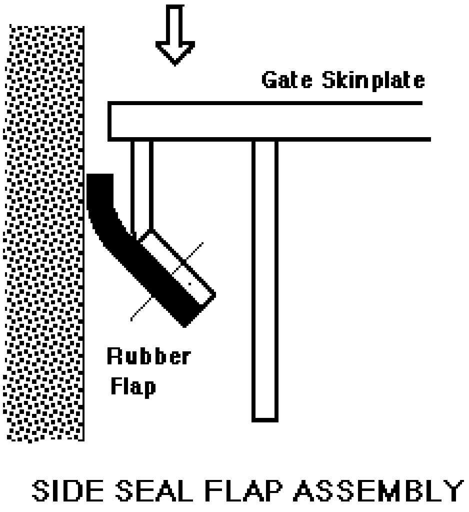


Fig.5 Side Seal Flap Assembly

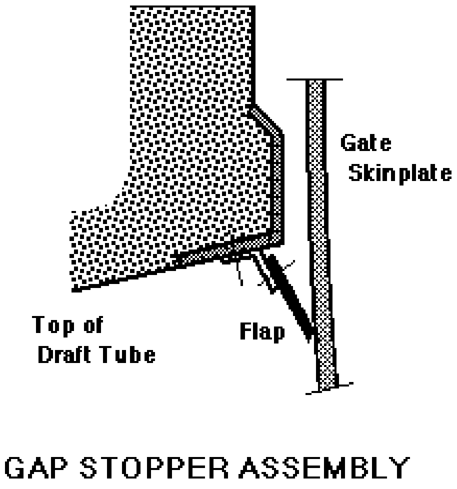


Fig.6 Gap Stopper Assembly

5.5 Gate Control System

The gate control system is integrated with the other machine control functions in the Unit Programmable Logic Controller (PLC).

The gate control objectives are:

- To position the Draft Tube Gate under differing conditions of Turbine Nett Head, Guide Vane (Wicket Gate) Position and Tail Water Level to achieve a Draft Tube Pressure that will meet the requirements set down in the turbine runner cavitation performance curves, to prevent excessive turbine runner cavitation.
- Generate alarms to warn an operator if any sensors are faulty, or if the gate is not responding to controls.
- Provide manual controls for gate positioning and maintenance.

Digital indicators display the Unit MW, Guide Vane position and DT Gate position at the Hydraulics Control Panel and also on the stoplog platform level. Unit MW and DT Gate position displays are also located on the Generator Turbine Auxiliary Panel (GTAP) on the operating floor.

5.6 Unit PLC Control Strategy

The PLC initially positions the gate to a conservative position which provides a back pressure slightly higher than that required by the manufacturers data. The gate position required to achieve this is determined by lookup tables based on the guide vane position only. To prevent excessive gate movements for fluctuations in guide vane position, a GV hysteresis is included in the PLC.

The current tail water level and draft tube pressure transmitter setting level is used in the PLC calculation to determine the draft tube pressure increase required to be achieved by the gate, in the range 0 – 6.55 mWG. This pressure is divided into 13 equal steps of 0.5 mWG increments and used as a pointer to lookup tables. The lookup tables output is the conservative Draft Tube Gate position for the current Guide vane position.

The gate is positioned to within a small dead band of approximately 1% of the conservative Draft Tube Gate Position by Raise/Lower control signals to the hydraulic pumps and solenoid valves.

5.7 PI Controller operation

Once the initial conservative draft tube gate position has been reached the Unit PLC PI controller adjusts the gate position to achieve the Required Draft Tube Pressure. The PLC monitors the machine MW and Spiral Case (Scroll Case) pressure, then calculates the machine nett head. From this information and the machine MW, lookup tables provide the required turbine tailwater level, which is the elevated tailwater level that the gate has to produce to avoid excessive runner cavitation.

Two submersible pressure transmitters are installed in the draft tube, just upstream of the gate. These measure the draft tube pressure and the two signals are averaged and filtered in the PLC to provide a stable signal.

To avoid incorrect gate operation, the PI controller is inhibited for the following conditions:

- if the actual tailwater level is greater than the desired TWL;
- if the GV position is less than 55%;
- for 60 seconds after the Gate Control Panel is selected to AUTO;
- during and for 3 minutes after the Guide Vane rate of change is greater than 2.5% in 10 seconds.

The Unit PLC incorporates additional lookup tables to produce a Nett Head corrected desired Turbine Tailwater Level . These controls are based on the Voith tailwater level vs machine MW cavitation curves for continuous turbine operation at different Nett Heads. To prevent excessive gate movements for fluctuations of Scroll case pressure and machine MW, each analogue signal is filtered in the PLC. The filtered scroll case pressure also has a hysteresis included.

Velocity Head H_V correction for net head calculation is based on GV position.

The Machine MW/desired Turbine Tailwater Level lookup tables are provided for Nett Heads of 185, 190, 195 and 200 mWG respectively, taken directly from the Voith graphs. The MW pointer range is 45 - 75 MW in 0.5 MW increments.

The Unit PLC incorporates a PI controller using the desired turbine tailwater level as the Set Point (SP) and the average draft tube pressure as the Process Variable (PV). The controller output is the Draft Tube Gate position. The gate is then positioned to achieve the desired draft tube backpressure that is equivalent to the elevated tailwater level Set Point.

The gate is positioned to within a small dead band of approximately 1% of the Corrected Draft Tube Gate Position by Raise/Lower control signals to the hydraulic pumps and solenoid valves.

5.8 Gate Positioning

The gate is controlled via twin hydraulic cylinders, a 5 port double acting (Raise/Lower) solenoid valve, two Emergency close solenoid valves, two hydraulic pumps and two pump loading solenoid valves. The pumps start only when the solenoid valves are required to be energised to raise or lower the gate. A pump run-on timer is set to 20 seconds to limit the frequency of pump starts.

5.9 Draft Tube Overpressure Protection

Should the gate positioning system fail, the gate will lower by gravity to the fully down (closed) position. To prevent excessive forces being transmitted from the gate to the station structure, an over pressure switch and relay logic governor control is provided to reduce the turbine flow to a safe value if the draft tube pressure exceeds 8 metres.

Should the draft tube pressure reach the setting of the level switch located above the gate (approximately 8 metres above the tail water level), relays in the GTAP will latch and cause the governor to be switched to manual and the load limit motor energised to reduce the load limit to about 52.5 MW or 67% guide vane setting.

The load limit initiation is shown on the GTAP as a red illuminated push-button labelled "DTG load limit over ride".

6 Civil Construction

The civil work consisted of mounting robust concrete beams capable of handling the maximum gate load of 2000 kN. These pre-cast pre-tensioned beams are of complex design because of the need to resist a combination of horizontal, vertical and torsional loads.

The 14 tonne beams are supported on vertical columns and stressed to the powerhouse structure by boring sloping 10 m long, 150 mm diameter holes into concrete and grouting the strands in place.

Care was required to achieve the required accuracy of the submerged mounting brackets. The underwater baffle beams were mounted on the concrete slab with the aid of a temporary pivoting frame to ensure accurate location prior to gate installation.

7 Installation and Commissioning

To minimise loss of generation, all civil and mechanical work was carried out at night. At times it was necessary to close down all four turbines so that divers could carry out accurate positioning work.

The installation of the gate and controls was completed at night over a two week period.

Commissioning consisted of increasing the generation level in steps and measuring the effect on turbine back pressure as the gate was lowered from the full open position to the fully down position. At each new position the degree of tailwater turbulence was monitored.

Recording vibration monitors were fitted to the gate skin and to one of the arms so that a relative measure of vibration could be obtained.

8 Performance

At high flows the gate exhibits some minor vibration. Results from the first commissioning run showed that the back pressure curve was less than required and so 7% of the holes were blocked up in an even pattern over the gate surface.

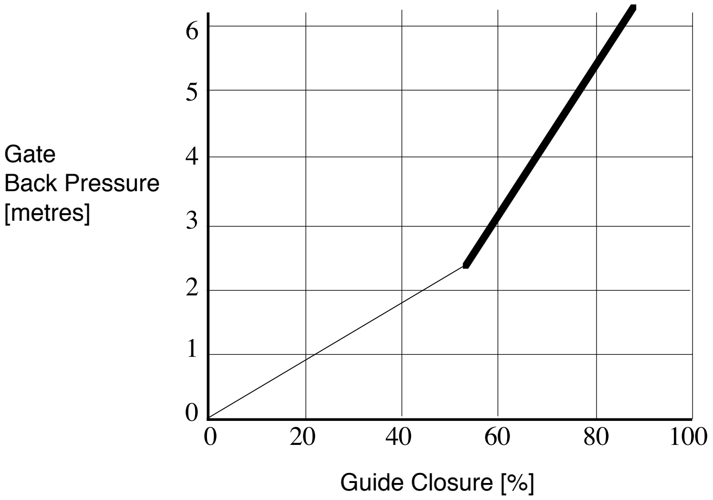


Fig.7 Gate Back Pressure Curve

With the turbine operating at full power (61.5 MW) the turbulence downstream of the gate is significantly less than with the old runners under normal operation.

When the gate is partially raised at reduced outputs the water jet is free to pass unimpeded through the gap between the lower edge of the gate and upper edge of the baffle blocks. The resulting downstream turbulence, while greater than with the gate fully down, is still no worse than that from the old runners.

The setdown in water level during the gate tests was measured and found to be approximately 50 mm.

9 Costs

The total cost of the re-runnering and machine overhaul, including the draft tube gate, was $13.9 M. The cost for the gates was $3.4 M. This included the design, redesign, laboratory tests, design reviews, construction, installation, commissioning, and supervision of the work.

The need to install the gates at night and the more complex gate that resulted from the model testing, increased the costs significantly.

An expenditure of $3,400,000 has allowed the turbines to generate an additional in 34 MW without the risk of excessive cavitation. 34 MW of peaking power from, for instance, a gas turbine, would cost at least $600/kW. The gate project has thus provided 34 MW of peaking power for $100/kW with no environmental impact.

10 Summary

The design of the gates achieved the following:

- A gate that dissipates 2.2 MW of hydraulic energy without significant vibration or downstream turbulence.
- The interaction of the adjustable gate and the fixed baffle blocks to produce satisfactory back pressure response without any significant downstream turbulence.
- An overall design that avoided the need for massive and expensive reinforcing of the draft tube area.
- A PLC based control system that monitors the turbine back pressure and controls the raising and lowering of the gate to provide the pressure required at high outputs while allowing efficient operation at lower flows. This is fully automatic, requiring no operator intervention.
- The arrangement of the gate and hoisting equipment which complies with the existing powerhouse constraints.
- Provision of easy access for maintenance and stoplog installation.
- Provision in the design for underwater installation and position adjustments so that the gates could be installed without the need for a construction cofferdam and without undue disruption to generation.

The installation of a porous draft tube gate has allowed new turbine runners to operate at maximum output without any risk of cavitation while allowing operation without any loss of efficiency at lower outputs. The gate has reduced the extent of the tailrace turbulence.