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Performing hydraulic modeling

Using Simcenter Flomaster to understand
a hydro-pumped storage scheme

Executive summary

The objective of every hydropower plant is to streamline safe, reliable and cost-efficient operations of large turbine generators. Early understanding of the dynamic hydraulic behavior of a hydro-pumped storage scheme will assist engineers in selecting and sizing critical plant components and result in lower lifecycle costs and more reliable system operation.

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I Introduction

JS Pump and Fluid System Consultants, specialists in hydraulic design and modeling complex fluid networks and advanced control systems, provide flow assurance services for a range of industries. With more than 25 years of experience with Simcenter™ Flomaster™ software, JS Pump and Fluid System Consultants are now focusing on hydraulic modeling and optimizing hydro-pumped storage schemes. Simcenter Flomaster is part of the Xcelerator portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software.

The challenge

Design engineers need to model the dynamic behavior of pump-turbine configuration and waterways, which are essential elements of the proposed Burdekin Hydro Pumped Storage Scheme. This white paper demonstrates how design engineers can use Simcenter Flomaster to gain an early understanding of critical hydraulic design parameters such as:

- Hydraulic transients during turbine load rejection and pump trip, potentially causing high-pressure loading in items such as draft tubes and penstocks
- Operating mode changes from turbine-to-pump and pump-to-turbine mode, possibly resulting in excessive out-of-envelope pump-turbine operation
- Energy storage modeling to quantify the overall energy generation and round-trip efficiency expected for the projected pumped storage scheme

The hydro-pumped storage principle

In recent years, Australia has experienced significant increase in power generation from wind and solar energy sources. These sources are the fastest growing forms of renewable energy generation of intermittent nature that will require some form of backup power when they're not available. Hydro-pumped storage is a well-proven concept of energy storage. To achieve this, design engineers are currently investigating several schemes around Australia.

A hydro-pumped storage scheme is a special form of conventional hydropower where a water turbine generates electricity when water is released from the upper to the lower reservoir. By changing rotational direction, the turbine will become a pump and replenish the upper reservoir, storing energy when there is an excess of it, such as during off peak periods.

A Francis pump-turbine is located at the heart of a hydro-pumped storage plant. Design engineers can operate these pumps in both directions of rotation at reasonable efficiencies in pump and turbine modes.

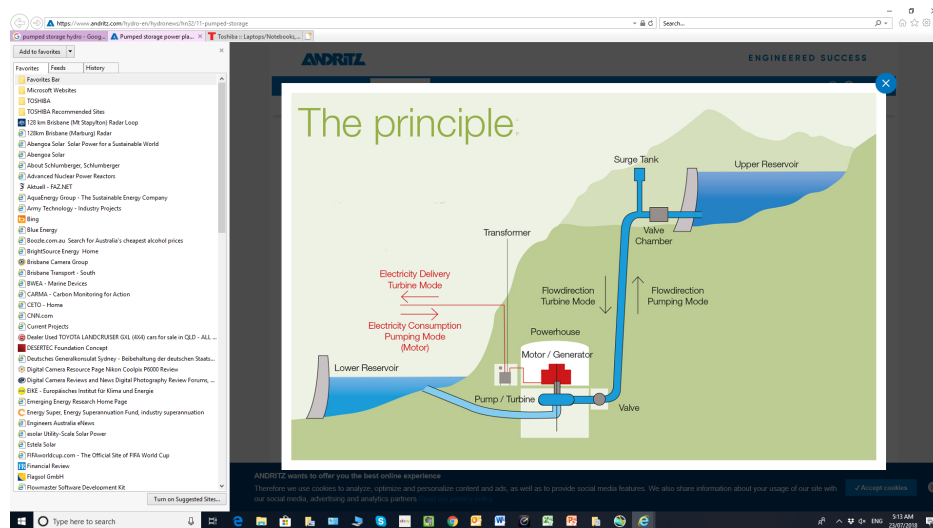


Figure 1. A typical hydro-pumped storage arrangement. (illustration courtesy of Andritz Group)

The penstock connects the pump-turbine with the upper reservoir while the draft tube connects to the lower reservoir. Operating mode changes and plant malfunctions may cause transients that result in pressure surges and pump or turbine overspeed. It is important to know early in the development process what mitigating measures engineers need to ensure plant integrity at a reasonable capital cost.

Hydraulic modeling of the waterway and pump-turbine dynamics will provide indicative design parameters, such as the penstock pressure rating and maximum generator motor speed. Both require careful consideration early on.

The Burdekin Hydro Pumped Storage Scheme

Burdekin Falls Dam was commissioned in 1983 as a large capacity irrigation water storage dam of 1,900,000,000 cubic meters (m³) in volume, the largest water storage of its kind in Australia.

The 300 megawatts (MW) Burdekin Hydro Pumped Storage Scheme located at the Burdekin Falls Dam was originally proposed in 1996 to support the electricity transmission network in North Queensland, Australia. The facility was supposed to be designed as a reversible pump-turbine configuration.

Three penstock and pump-turbine systems with a nominal capacity of 100MW will be made to connect to the existing Burdekin Falls Dam, the upper reservoir and a lower reservoir that has a yet to be constructed. The pump-turbines will operate in parallel to enable a wide flow and power output range that would otherwise not be possible from a single pump-turbine of 300MW. Designers are going to include a common surge chamber early in the design process to reduce surge pressures resulting from turbine load rejection and pump trip. They did not consider variable pump-turbine speed control for this scheme.

Although the upper reservoir of the capacity will be limited to about 90,000,000m³ for economic reasons. The typical static head range for the scheme ranges from 55 meters (m) to 80m with an average static head of about 67m.

Since the main purpose of the Burdekin Hydro Pump Storage Scheme is to generate and store electricity, the scheme could also enable the controlled release of irrigation water of up to 1,000,000,000m³ per year. However, due to limited complexity, this study only addresses the pump storage aspect of the scheme.

The Francis pump-turbine concept

The proposed Francis pump-turbine is a hydraulic machine built to match site conditions and enable economical operation for the project. A typical cross-section of a Francis pump-turbine is shown below to identify the main system components.

The flow controlling guide vanes (GVs) are located between the runner and the spiral casing.

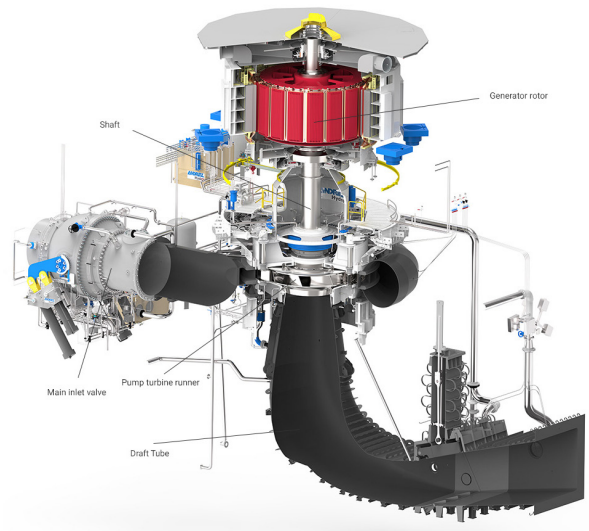


Figure 2. A typical Francis pump-turbine arrangement. (illustration courtesy of Andritz Group)

The hydraulic model development

Using the graphical functionality of Simcenter Flomaster software enables design engineers to create a hydraulic model that closely resembles the hydraulic waterways of the scheme. This helps designers find their way around the model and identify critical system components and nodes.

The hydraulic performance of system components was based on work by the British Hydromechanics Research Association led by D.S. Miller and published as Internal Flow Systems (3rd Edition). The correlations used in Simcenter Flomaster are based on Miller's book and have become an integral part of the Simcenter Flomaster database.

The convention for pump operation is flow rate and shaft rotation in positive direction (+), while turbine operating parameters are shown as negative direction (-). The complete hydraulic model of the Burdekin Hydro Pumped Storage Scheme is shown in figure 13 below.

The Francis pump-turbine hydraulic model

The Francis pump-turbine hydraulic model created using Simcenter Flomaster is comprised of four separate components. The central component is a mixed-flow Francis pump-turbine that runs in reverse when it is in turbine mode. Three-quadrant performance curves define the hydraulic response for the pump and turbine. The functionality of this component allows for the change of logic state, initiating transient events such as turbine load rejection and pump trip.

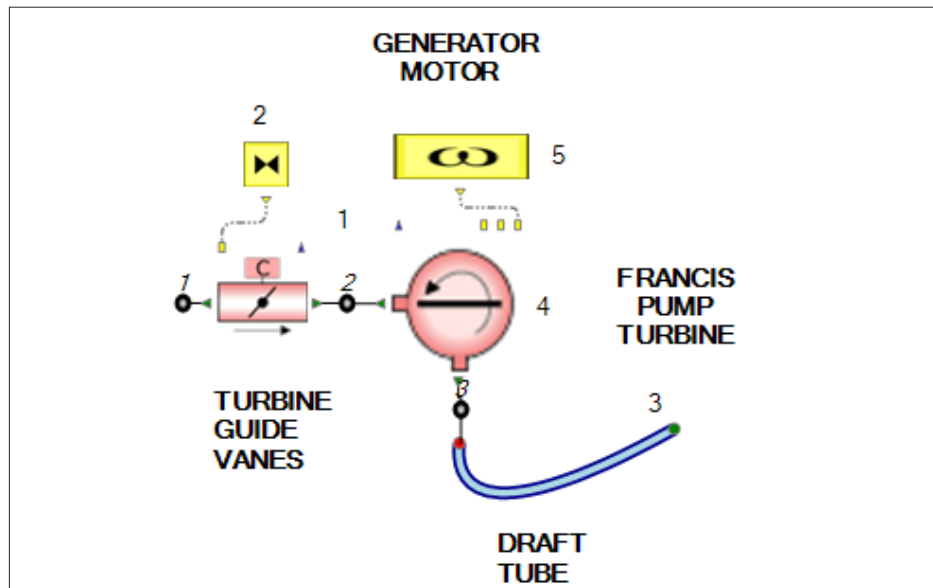


Figure 3. A Francis pump-turbine hydraulic model.

The flow controlling guide vanes (GVs) are typically an integral part of the turbine. While a more sophisticated Francis turbine model is under development, a work-around solution shown above illustrates where designers placed the GV's at the inlet side of the turbine. Due to this simplification, true spiral casing pressure cannot be shown. However, designers can assume that penstock pressure just upstream of the GV's will be similar to spiral casing pressure.

The generator motor model allows designers to set steady-state pump and turbine shaft speeds as well the direction of rotation. This enables the primary mode selection for turbine or pump operation.

The draft tube forms an integral part of the Francis pump-turbine to guide and accelerate or decelerate the high-velocity flow entering or exiting the runner. While designers created the draft tube for progressive cross-sectional contraction/expansion, they applied a pipe of constant diameter for simplicity.

The Francis pump-turbine performance

The Francis turbine performance is expressed in a turbine hill chart and pump performance is shown as pump curves. The graphs below combines turbine and pump performance in three-quadrant performance curves that are normalized for pump efficiency point. These performance curves originate from earlier physical pump-turbine model testing. The blue curves illustrate pump performance, while the green curves represent turbine performance with shaft rotation in reverse.

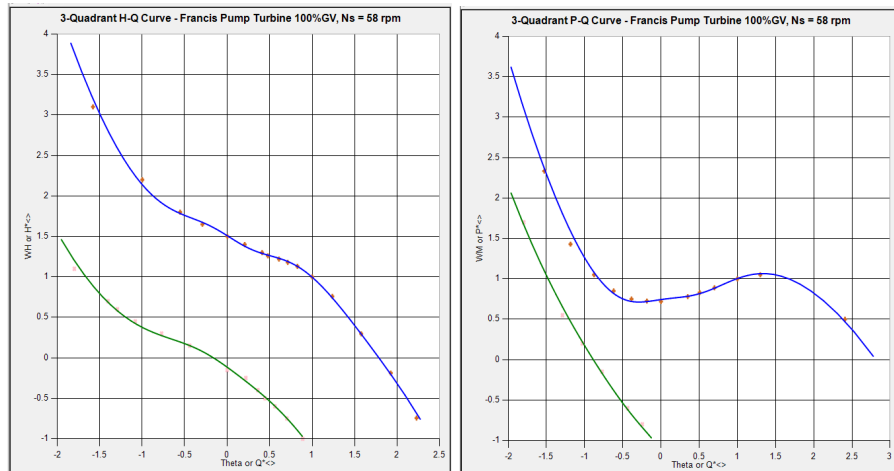


Figure 4. Three-quadrant pump-turbine performance curves.

The turbine load rejection simulations

Design engineers investigated principal cases of transient hydraulic operation, including the 100 percent turbine load rejection and the 100 percent capacity pump trip. Both transient operations are arrested by fast-acting turbine GVs. However, fast GV closure while reducing turbine and pump overspeed will lead to an increase in penstock pressure (water hammer) that designers must optimize for every installation. Also, the magnitude of inertia of mass provided by the generator motor unit will have a significant impact on the acceleration of pump-turbine speed and may require further optimization.

In a worst-case scenario, oil hydraulic power to the GVs may be lost during turbine load rejection or pump trip. In such an event, the pump-turbine speed will accelerate until it reaches runaway speed, resulting in the highest strain on the equipment and must be mitigated as much as economically feasible.

Various graphs below demonstrate the dynamic system response resulting from a 100 percent turbine load rejection event followed by linear GV closing in 15 seconds (s).

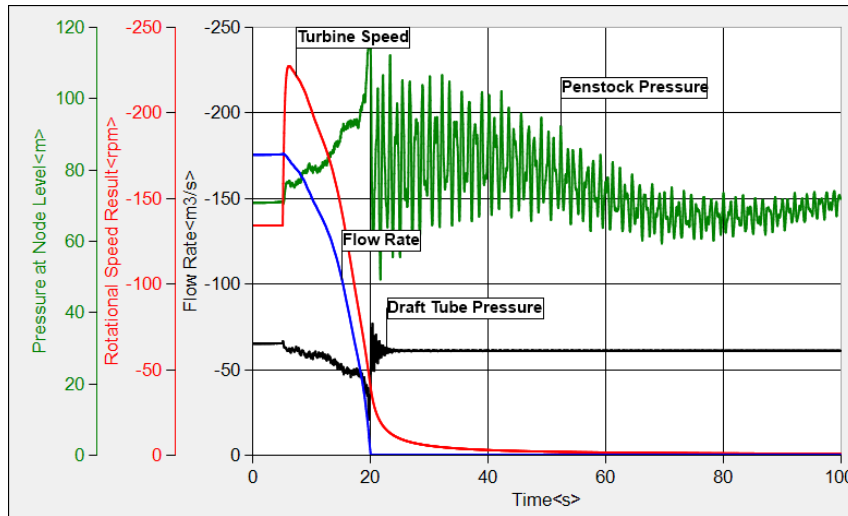


Figure 5. Turbine load rejection and GV close in 15s (turbine graphs).

Figure 5 shows a sharp increase in turbine speed before the GV closure comes into effect. Further optimization such as increasing generator inertia would be desirable to limit shaft speed rise.

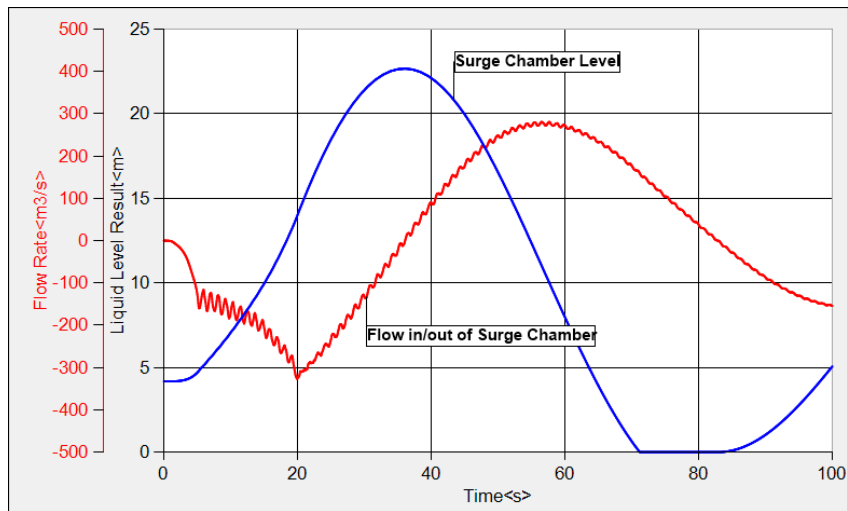


Figure 6. Turbine load rejection with GV close in 15s (surge chamber).

Figure 6 shows the surge chamber water level and indicates that following down surge, the surge chamber will run out of water. Designers can rectify this situation by lowering the surge chamber floor while avoiding air entering the penstock.

The pump trip simulations

Like the turbine load rejection, a pump trip will initiate GV closure in 15s. For comparison, designers can also see the runaway state where the GVs stay open following a pump trip.

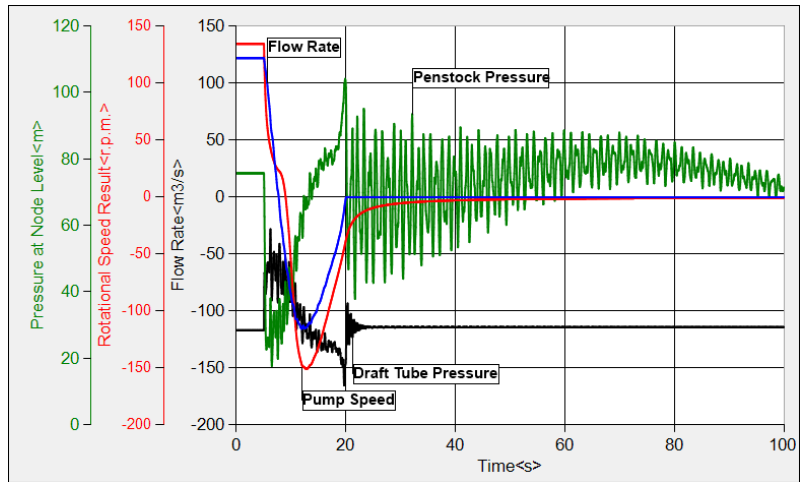


Figure 7. Pump trip and GV close in 15s.

From figure 7, you can see that following a pump trip, the penstock pressure surge is marginally lower than the pressure surge resulting from turbine load rejection shown in figure 5.

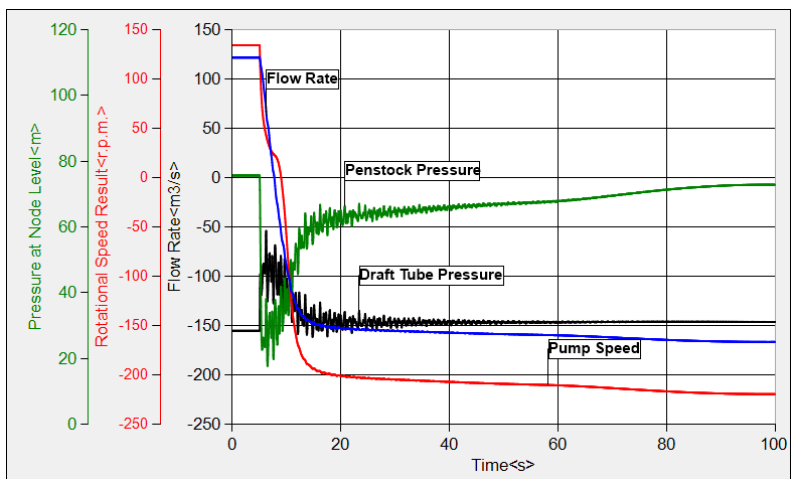


Figure 8. Pump trip with GV not closing (pump runaway).

The pump runaway event shown in figure 8 (same for turbine runaway, not shown) for this type of pump-turbine creates a significantly lower pressure surge than the event with GV closure in figure 7. However, designers can regain control of an uncontrolled runaway operation by slowly closing the turbine inlet valve (not shown in this demonstration).

The turbine pump mode change simulations

The principal operating mode changes come from turbine-to-pump mode and pump-to-turbine mode. Although a turbine and pump can be decelerated by hydraulic means, the start of a pump is limited by the electrical load that can be safely drawn from the transmission network. In general, a turbine can be started much faster than a pump.

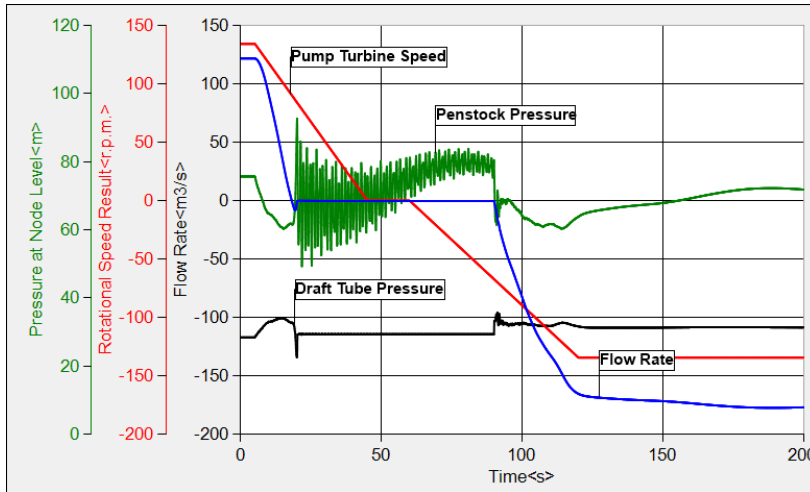


Figure 9. Operating mode change: pump-to-turbine.

Figure 9 demonstrates a pump-to-turbine mode change in about 200s. You can see the pump shut down period modeled as a slow and linear decline in operating speed. It is required to further optimize pump speed deceleration and turbine speed acceleration when the electrical network capabilities are better understood.

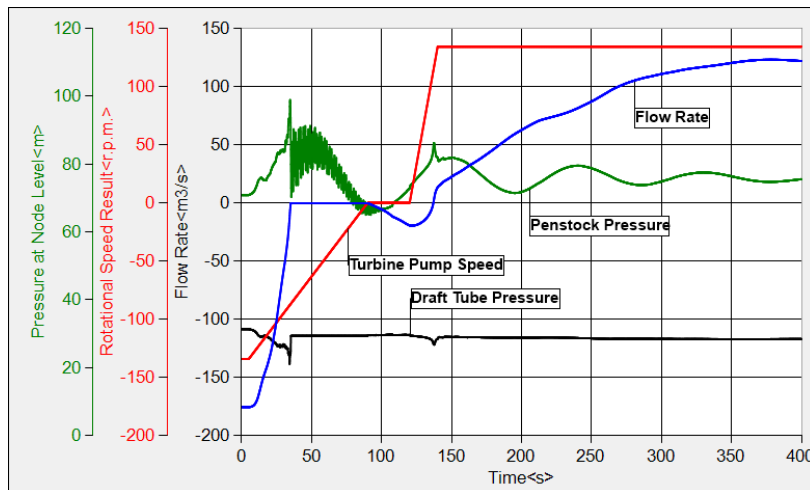


Figure 10. Operating mode change: turbine-to-pump.

The turbine shutdown shown in figure 10 is assisted by GV closure in 15s. Engineers may be required to complete further modeling of longer GV closure times to optimize this operation.

The dynamic storage simulations

The upper reservoir has a large capacity and therefore is not materially affected by the exchange of water volumes. The lower reservoir experiences a significant level variation that affects pump and turbine performance. The operating regime as currently modeled allows for 14 hours of pumping followed by 10 hours of turbinning with both modes operating at maximum capacity.

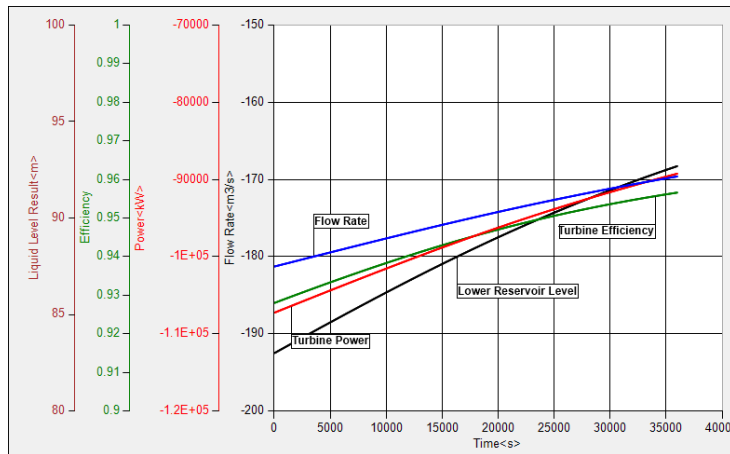


Figure 11. Power generation mode (turbine operation).

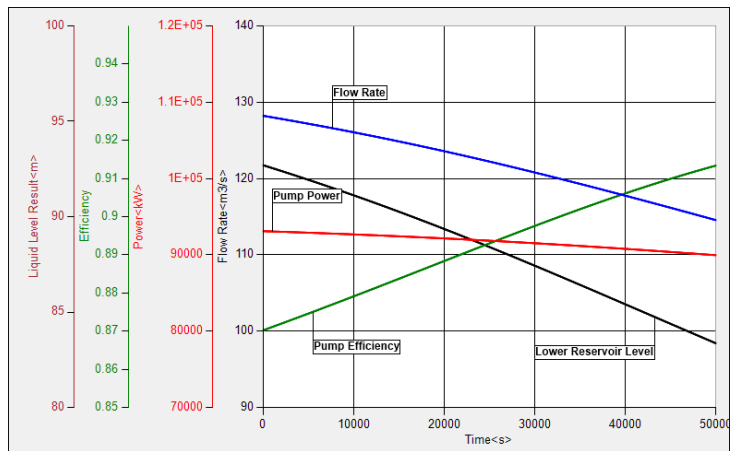


Figure 12. Energy storage mode (pump operation).

Figure 11 and figure 12 indicate the average level in the lower reservoir to be about 88m. At this level, the turbine power is 97MW while the pump power is 92MW. The average flow rates show 175 cubic meters per second (m³/s) for the turbine and 122m³/s for the pump. The turbine efficiency at this level is 94.5 percent while the pump efficiency is 89.5 percent.

It is estimated from these results that the average hydraulic round-trip efficiency and the product of turbine efficiency and pump efficiency are 86.4 percent. Engineers also need to consider further losses such as generator motor and transformer efficiencies arriving at a relatively high practical round-trip efficiency of about 83 percent.

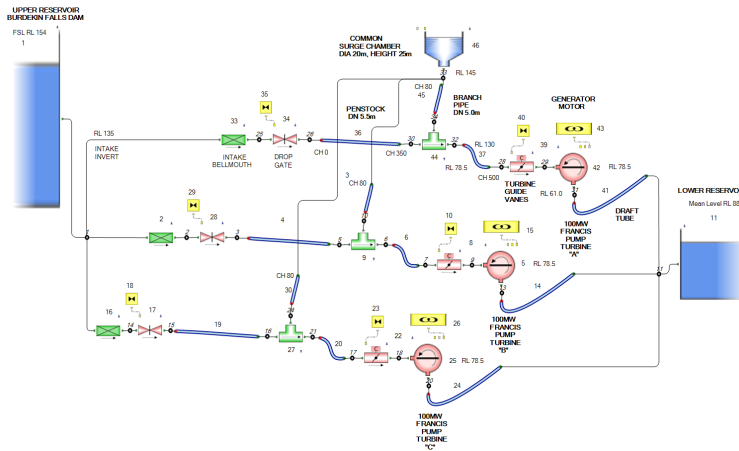


Figure 13. 300MW Burdekin Hydro Pumped Storage Scheme - complete hydraulic model.

Conclusion

Using Simcenter Flomaster helped design engineers enable the preliminary hydraulic analysis of the Burdekin Hydro Pumped Storage Scheme. Based on the given pump and turbine performance, the team identified a practical round trip efficiency of about 83 percent.

The maximum penstock surge pressure indicated at 116m in figure 5 aided designers in the initial selection of the penstock pressure rating. They also indicated the maximum draft tube pressure of 59m in figure 8.

Although surge chamber capacity is considered adequate, engineers will need to lower the chamber floor to prevent it from running empty (shown in figure 6) following maximum down surge.

Engineers can further analyze hydraulic optimization by increasing the generator motor inertia and adjusting the GV closing time as the rapid speed rise and fall shown in figure 5 and figure 6 indicates some scope for improvement.

The Francis pump-turbine work-around solution applied in this study is considered adequate for this early stage modeling. A more sophisticated Francis turbine model is expected to become available at a later stage.

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