Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

ASSESSMENT OF RISKS RELATED TO HYDRAULIC TRANSIENTS IN THE CONTEXT OF HYDRO TURBINE UPRATING USING CO-SIMULATION

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Abstract—Uprating generating units is a cost-effective way for hydropower utilities to increase their power output to meet with the growing electrical demands worldwide. This procedure however has drawbacks, including possible safety risks related to hydraulic transients in the water passages. This paper presents an approach based on co-simulation to accurately assess these risks, considering the interactions between generating units and their control systems.

Keywords-hydro turbines; uprating; hydraulic transients; co-simulation; control systems

I. INTRODUCTION

Global electricity demands have increased steadily in recent years. This trend is expected to accelerate because of industry decarbonation, transports electrification, data centers proliferation, and artificial intelligence development [1]. Renewable energy sources, such as hydropower, are especially sought after in this context.

The uprating of generating units is an interesting option for hydropower utilities to meet with this growing demand. The process involves the replacement of a turbine runner that has reached the end of its useful life with a modern, optimized design. The original water passages are kept mostly unmodified. This provides a significant power output increase in a cost-effective way and relatively short time frame. In contrast, new hydro projects require massive investments and usually take more than a decade to be commissioned.

Such increase in power is achieved in part through better runner efficiency, but mostly through a significant increase in water flow rate through the turbine. The water passages in hydropower plants are subject to phenomena known as hydraulic transients during maneuvers such as unit load ramping, load rejections or grid frequency deviation [2]. The increase in flow rate due to uprating will lead to higher pressure oscillations amplitude inside the passages during these events, according to hydraulic transient theory [3]. It is therefore essential in an uprating project to validate that the original passages can withstand these oscillations, for obvious safety reasons.

Hydraulic transient simulations can be used to predict the pressure waves travelling through the water passages for any prescribed turbine guide vane opening scenario. This works well for maneuvers such as startups and load rejections where the vane opening follows a trajectory that is roughly predetermined. However, this approach cannot account for the bidirectional interaction between a generating unit and its speed governor, which controls the vane opening during a grid frequency deviation.

This paper proposes a co-simulation approach based on the Functional Mock-up Interface (FMI) standard [4] to include this interaction in the analysis. A global model of an entire power plant was built by coupling two sub-models developed in two different software packages. This so-called co-simulation model was used to confirm that the proposed new runner design was safe regarding hydraulic transients.

II. PROBLEM DESCRIPTION

The study was conducted in the context of an ongoing uprating project at a Hydro-Québec power plant. The plant comprises a low number of generating units equipped with medium head Francis turbines. All turbines will be replaced in the upcoming years. The new runner design will lead to an approximately 20% increase of the water flow rate.

The plant was originally built with a surge tank to dampen the pressure waves created in the water passages during transient events. Pressure is converted to gravitational potential energy as the tank water level rises, lowering mechanical stresses on the walls of the passages. Because the surge tank was dimensioned for the original turbine design, the increase in flow rate and pressure waves amplitude due to uprating could potentially cause it to overflow or even be destroyed under certain circumstances.

Moreover, specific exploitation requirements for this power plant include the ability to operate on an isolated electrical grid, disconnected from Hydro-Québec's main grid. The frequency stability of an isolated grid is significantly lower than that of a large grid. Any perturbation will thus result in a larger and faster frequency deviation which must be corrected quickly to prevent the grid from collapsing. The speed governors automatically manage this by modifying the generating units operating conditions to re-establish power equilibrium on the grid.

This creates pressure waves whose amplitude is correlated with the rate at which the correction is applied. Preliminary studies suggested that modifying the mechanical configuration of the speed governor to reduce the maximum guide vane opening rate could mitigate the oscillations to some extent. However, reducing this rate too much will hinder the generating unit's ability to stabilize the electrical frequency in the case of a production loss elsewhere on the grid. A configuration that allows for both safety (prevention of surge tank overflow or destruction) and operational needs (frequency stabilization) must be found.

A load rejection occurring shortly after a sudden production loss at another nearby facility operating on the same isolated grid was identified as the worst-case scenario. Detailed analyses were required to confirm that even in this extreme situation, the power plant remained safe to operate. For this purpose, developing a full model of the plant, including the control systems, was necessary.

III. Methodology

The SIMSEN software [5] was chosen to model the turbine characteristics and the water passages. While it offers basic control systems modelling capabilities, those are not well suited to represent the complex control logic of real generating unit speed governors. These were instead modelled using the Simulink® software [6]. The two models were coupled using the FMI standard, allowing to solve both simultaneously and factor in the interactions between all components.

A. *Generating Units and Water Passages*

The SIMSEN model includes the upstream and downstream reservoirs, the surge tank, the pipes, and all the power plant's generating units, which are of identical design. A simplified representation with a single unit is shown in Figure 1. The exact plant layout is not shown for confidentiality reasons.

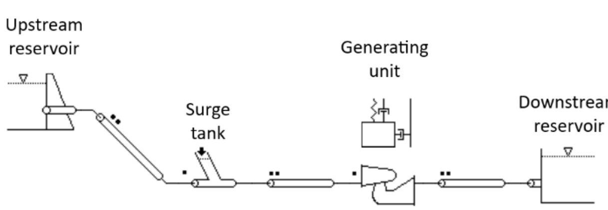

Figure 1. Simplified SIMSEN model block diagram with one generating unit

The software uses a 1-D approach to predict the local, instantaneous flow rate and hydraulic head (or pressure) in the entire system. It also calculates the main quantity of interest for the present analysis, that is the surge tank level.

The dynamics of the turbines are determined by their characteristic curves, which were derived from the hill chart provided by the manufacturer. They define the steady-state relationship between the local flow rate and hydraulic head, the guide vane opening y, the rotational speed ω, and the mechanical torque T_{mech} of each turbine. Additionally, the rotational acceleration $\dot{\omega}$ and torque T_{mech} are related by the equation of motion, also known as swing equation,

$$J\dot{\omega} = T_{mech} - T_{elec}, \tag{1}$$

which is solved for the speed ω by SIMSEN. In Eq. (1), J is the unit's axial moment of inertia.

When synchronized to the grid, the frequency of the electrical cycle produced by a generating unit is directly proportional to its rotational speed. The strong coupling between the grid and each unit allows to consider a system with a single degree of freedom, representing both the electrical frequency of the grid and the speed, or frequency, of the units. This unique frequency can be determined from a global swing equation considering the total inertia and torques for all connected units. When disconnected from the grid, the speed of a generating unit is determined only by its own inertia and swing equation.

In SIMSEN, the effect of the grid on each unit is modelled using the electromagnetic torque T_{elec} imparted on the generator. This torque is specified as

$$T_{elec} = \delta_{sync}[-(1-\delta_{dev})T_{mech} - \delta_{dev}T_{dev}], \tag{2}$$

where δ_{sync} is 0 when the unit is off the grid and 1 when the unit is synchronized to the grid, and δ_{dev} is 0 before a frequency deviation event and 1 afterward. The formulation of Eq. (2) allows to model three distinct situations:

- $T_{elec} = 0$, when the unit is off the grid.
- $T_{elec} = -T_{mech}$, when the unit is synchronized to a stable grid. This ensures zero net torque and constant rotational speed.
- $T_{elec} = -T_{dev}$, when the unit is synchronized to a perturbed grid following a frequency deviation event.

The electromagnetic torque following a frequency deviation, T_{dev}, will be discussed in the following section.

From the co-simulation perspective, the SIMSEN model can be seen as a black box with inputs $(y, \delta_{sync}, \delta_{dev}, T_{dev})$, and outputs (ω, T_{mech}). It should be noted that all variables are unit-specific, except for δ_{dev}.

B. *Control Systems and Frequency Deviation*

The Simulink® model includes a separate speed governor model for each generating unit. All governor models are identical but can be operated individually. Each governor can be started or stopped independently and have a different power setpoint from the others. The electrical power generated by each unit is computed as

$$P_{elec} = \eta P_{mech} = \eta T_{mech} \omega, \tag{3}$$

where $\eta < 1$ represents the efficiency of the machine. The electronics of the governor compare ω and P_{elec} to their respective setpoints and feeds the resulting errors to an algorithm that generates a control signal for the mechanical components. This algorithm includes non-standard PID controllers with resettable and limited integrators, switches, filters, deadbands, etc. The relevant elements of the actual speed governor block diagram were directly implemented in the model.

The mechanical components are a series of hydraulic valves operating on pressurized oil, starting with a solenoid valve acting as the interface with the electronics, leading to the servomotors that ultimately control the guide vane opening y. The dynamics of these valves is governed by nonlinear laws which are determined by electronic configuration as well as mechanical design. These laws are implemented in the model.

The Simulink® model also includes the necessary elements to model a grid frequency deviation event through the T_{dev} term in Eq. (2), which is defined as

$$T_{dev} = T_{mech,0} + \frac{\Delta P_{loss}}{\omega_0}. \tag{4}$$

In Eq. (4), $T_{mech,0}$ and ω_0 are the mechanical torque and rotational speed right before the event, respectively, while ΔP_{loss} represents the sudden electrical power offset due to a production loss ($\Delta P_{loss} > 0$) or a load loss ($\Delta P_{loss} < 0$). A production loss will increase the resistive torque applied on the generator, resulting in the deceleration of the unit. A load loss will have the opposite effect.

The Boolean flags δ_{sync} and δ_{dev} are defined inside Simulink® to create the desired simulation scenario. From the co-simulation perspective, the Simulink® model is a black box with inputs (ω, T_{mech}) and outputs $(y, \delta_{sync}, \delta_{dev}, T_{dev})$. Again, all variables are unit-specific, except for δ_{dev}.

C. FMI Bidirectional Coupling

Bidirectional coupling is achieved using the FMI standard, which allows to exchange the relevant signals between the two models during the solution process. Each model advances its local solution using frozen values received from the other model at the beginning of the time step. The master-slave architecture was retained for this analysis, with Simulink® as the master and SIMSEN as the slave.

Special "external inputs" and "external outputs" blocks are used inside the SIMSEN model to define which signals must be exchanged. The model can then be exported as a standalone Functional Mock-up Unit (FMU), which is an archive containing the model structure, parameters and initial conditions, as well as binary interfaces for the exchanged signals.

The FMU file must be imported inside the Simulink® model by specifying its path in an "FMU" block. This automatically creates a subsystem with input and output ports corresponding to the exchanged signals as defined in the SIMSEN model. This subsystem is shown in Figure 2. It can be used as another other typical block or subsystem available in Simulink®.

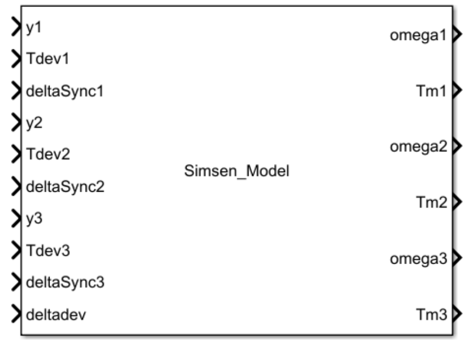

Figure 2. SIMSEN model imported as an FMU inside the Simulink® model

After making the appropriate signal connections, the co-simulation can then be launched using the standard "Run" button inside Simulink®. Both models are configured to use a Runge-Kutta explicit integration method of order 4. A sensitivity analysis was conducted on the time-step size. A value of 0.005 seconds was retained as it offered a good compromise between calculation performance and accuracy. Numerical instability, which is a known issue of the co-simulation method used in the present work [7], were found not to be a concern.

D. Simulated Scenario

The gross hydraulic head is set to its maximum possible value for the plant. The simulation is initialized with all units synchronized on a steady-state isolated grid, each generating 57% of their rated power P_r. This corresponds to the lower limit of the turbines operational range, ensuring the largest possible guide vane movement in reaction to a sudden production loss.

Regarding the surge tank level, the worst-case scenario corresponds to the simultaneous load rejection on all units shortly after a sudden production loss in another plant operating on the same grid. If the load rejection occurs at the worst moment after the initial production loss, the hydraulic transients generated by both events will be in phase. Resonance will occur, amplifying the oscillations inside the water passages, including the surge tank. The exact delay which will cause the strongest resonance depends on the natural frequency of the water column, which is implicitly considered in SIMSEN because the passages are explicitly modelled.

The initial production loss in another plant, totalling $\Delta P_{loss,total}$, is triggered at the 10 seconds mark of the simulation. The value of $\Delta P_{loss,total}$ was selected using trial and error so that the frequency drops as close as possible to 80% of its nominal value without going under, in which case emergency protections would trip the units. Tripping the units at this moment would prevent the resonance described above to occur, causing a less critical scenario. Letting the frequency drop as much as possible without immediately tripping the units creates the largest initial transient and thus the worst initial conditions for the second event.

To reduce modelling complexity, two assumptions are made regarding the grid frequency:

- The inertia of all units from other plants connected to the isolated grid is neglected.
- Only the units explicitly modelled in SIMSEN, i.e. those concerned by the uprating project, will contribute to stabilize the frequency after the deviation.

Both assumptions are conservative as they will cause the co-simulation model to overestimate the frequency deviation and the amplitude of the hydraulic transients. Additionally, the second assumption, combined with the fact that all units are identical and initially operating at the same power, allows to distribute the production loss evenly between them. The electromagnetic torque applied to each unit after the event is thus calculated using $\Delta P_{loss} = \Delta P_{loss,total}\,/3$ in Eq. (4). This approach ensures that the rotational speed computed by SIMSEN using Eq. (1) independently for each unit will be the same, without having to explicitly constrain it inside the model.

Some time after this first event, the second event is generated by simulating a protection relay trip, which triggers a load rejection on all units. An approximate linear approach can be used to determine the natural frequency of the water passages, and so the worst delay between the two events. However, the modelled phenomena are slightly nonlinear, and the exact worst delay could somewhat differ. For this reason, a parameter sweep is conducted to find the delay leading to the worst possible outcome where the level reached in the surge tank is the highest.

IV. Results and Discussion

Simulations of the production loss scenario were carried out for two different mechanical configurations of the speed governor to study the effect of the guide vanes maximum displacement rate. They are hereby referred to as “standard” and “slow” configurations, with the latter having a maximum rate 5 times slower than that of the former. The total production $\Delta P_{loss,total}$ was respectively set to $1.08P_r$ and $0.91P_r$ for the standard and slow cases. The loss required to reach 80% of the nominal speed for the slow case is lower because the speed governor is less effective in correcting the frequency decline.

The simulated rotational speed, guide vane opening, and surge tank level are plotted for the standard configuration in Figure 3. Values are normalized using the nominal speed, maximum vane opening and maximum surge tank level. Results for various delays between the two events are represented by the many lines on each plot. The thick lines correspond to the worst case where the surge tank level reaches the highest value. The delay was incremented by 1 second between each simulation; only a subset is presented to prevent cluttering the figure. Only the results for a single generating unit are shown since the simulated signals for all units are identical.

Immediately following the initial production loss at the 10 seconds mark, the grid frequency (or units rotational speed) starts dropping rapidly. In reaction, the speed governors command the servomotors to rapidly open the guide vanes, reaching the maximum rate determined by their mechanical configuration. This causes an increase in turbine water flow rate. The resulting water deficit upstream of the units is momentarily compensated by the surge tank, decreasing its level.

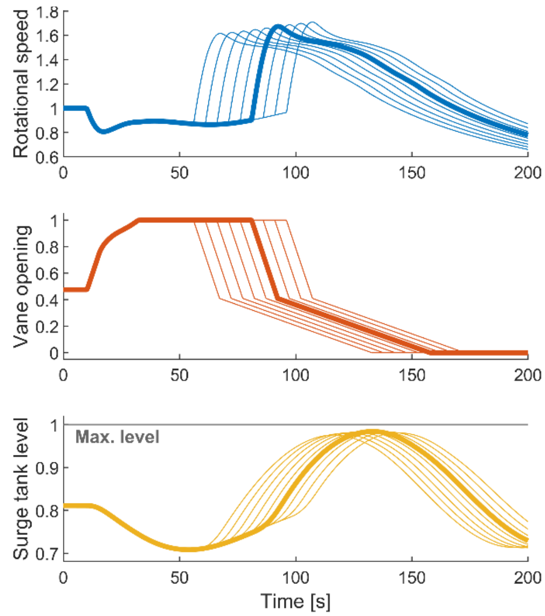

Figure 3. Simulated speed, vane opening, and surge tank level (standard config.)

The increase in turbine flow rate translates to an increase in generated power that contributes to reestablish the grid equilibrium. The frequency decline is slowed down and ultimately reverted.

As the frequency starts rising back, the frequency error is reduced, and the control algorithm gradually reduces the guide vanes opening rate. In the simulated scenario, the production loss is large enough for the units to reach their maximum guide vane opening and maximum power before being able to stabilize the grid entirely.

Eventually, the load is simultaneously rejected on all units. This event can be identified by the discontinuity in the speed signal, after which it starts increasing sharply. Afterward, the grid frequency and units’ speed are no longer linked. The speed governor automatically switches to quick shutdown mode and starts closing the guide vanes to bring back the units to a complete stop as quickly as their mechanical configuration allows. This rapidly restricts the water flow rate that can pass through the turbines. The resulting excess upstream water is accumulated in the surge tank, increasing its level until a peak value is reached. Results show that even in the worst case, this peak value never exceeds the maximum tank level.

A comparison between the standard and slow configurations is presented in Figure 4. Only the worst cases causing the highest predicted surge tank level are shown for each configuration. The worst delay between the two events was identified independently and is different for each configuration. The predicted peak levels are very similar for both cases, although the initial production loss is lower for the slow configuration ($0.91P_r$) when compared to the standard one ($1.08P_r$).

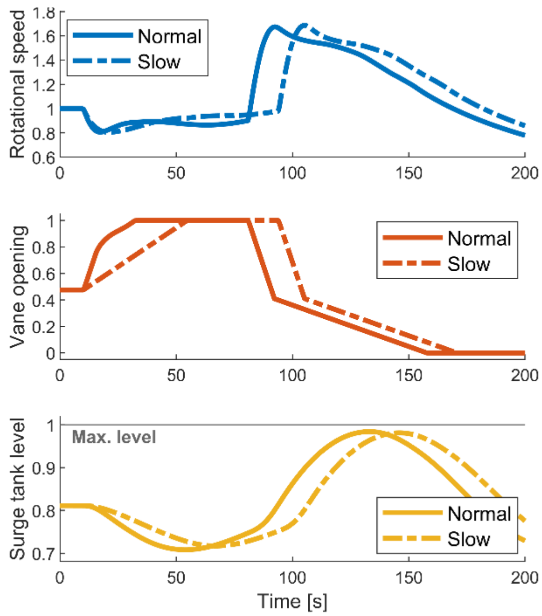

Figure 4. Simulated speed, vane opening, and surge tank level (comparaison between standard and slow config.)

This suggests that the normal configuration is safer than the slow one as it can withstand an event of larger amplitude with essentially the same impact on the surge tank level. This important conclusion contradicts the preliminary studies which suggested that reducing the maximum guide vane opening rate should help reducing pressure oscillations and peak surge tank level. According to the current analysis, the slow configuration delays the moment where the peak is reached but has minimal effect on its amplitude. This finding was only made possible by considering the full interaction between the hydraulic transients and the control systems using co-simulation.

In any case, the simulated level gets close to the limit, but the reader should be reminded that two conservative modelling assumptions were made. The predicted levels are thus probably overestimated, and the real margin of safety is expected to be higher than the plots suggest. This will need to be confirmed with further study.

V. Conclusion and Future Work

A co-simulation approach to assess risks related to hydraulic transients in the context of hydro power uprating project was proposed. The approach allows to consider the bidirectional interaction between generating units and their speed governors by coupling a SIMSEN model of the units with a Simulink® model of the control systems.

It was successfully applied to confirm that an actual turbine uprating project at Hydro-Québec was safe regarding a potential surge tank overflow and destruction risk while operating on an isolated electrical grid. Two conservative assumptions were made by neglecting both the inertia and the control systems of units from other power plants operating on the same grid. Removing the former would require to explicitly model the global swing equation of the entire grid, while removing the latter would require to explicitly model all units synchronized to the isolated grid.

For the sake of brevity, other related work was not presented in this paper. For example, a new power plant algorithm controlling the dispatch of unit startups to minimize surge tank level oscillations was also designed. The algorithm was implemented alongside the speed governors inside the Simulink® model and the co-simulation approach allowed to validate that it was performing as expected.

Integrating control systems in hydraulic transient analyses allows for more realistic simulations, offering new insights that are especially precious in an uprating context, where margins of safety are inherently reduced compared to the original design. The methodology will be refined through its application to future projects as Hydro-Québec is further increasing its electricity production capacity.

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