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> Evolution and trends in designs of rotating electrical machines for renewable generation

Fundamental Model of Full-power Converter Variable Speed Hydro Generators: Control and Simulation

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SUMMARY

Speed control of large hydro generators has become feasible due to the development of high-power electronics. Hence, hydro generators can run at the maximum efficiency operating point with respect to the output power and head. The application of speed control in pumped storage hydro generators is especially advantageous.

Iberdrola is converting to variable speed two of the four units of Torrejón pumped storage hydro station (4x32 MW). Torrejón pumped storage hydro station belongs to the Tagus river system. The conversion is aimed at extending the Torrejón head operating range in pumped mode making feasible the storage of up to 210 GWh by connecting the upstream and downstream reservoirs of Torrejón (Valdecañas and Alcántara). The massive development of solar photovoltaic generation in Spain is making the development of energy storage facilities very attractive.

Speed control of hydro generators can be implemented by controlling either a doubly fed induction machine or a synchronous machine connected to the grid through a full-power converter.

In the case of a synchronous machine connected to the grid through a full-power converter, the converter comprises two voltage source converters (the machine side converter and the grid side converter) with pulse width modulation coupled through a DC link capacitor. The stator of a synchronous machine is fed by the machine-side converter that applies a variable frequency three-phase voltage source to the machine. Machine rotor speed is controlled by controlling the frequency of the three-phase voltage source. The grid side converter controls the reactive power supplied to the grid.

The hydro turbine is equipped with a speed governor. A unit controller coordinates the control of the synchronous machine and the hydro turbine.

This paper details a generic model of a full-power converter variable speed hydro generator. The model is aimed at investigating interactions between synchronous machine and turbine controls. The interactions between the synchronous machine and turbine controls will be investigated by time-domain simulation. Time-domain simulations in case of a step-change in the reference power are performed. The time variation of rotor speed, gate, flow, mechanical and electrical power are shown.

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This model described in this paper is a step forward in developing the model required by the system operator and a valuable tool for the conception of the control system and the investigation of the interactions between the machine and turbine controls. Although converter and turbine manufacturers will provide detailed models of their components, such models are not open source. Generic open-source models by representing the fundamental dynamics of the systems [6] have the advantage of making easier the understanding of the unit response and more robust computational performance when incorporated into large power system dynamic simulation models.

The model will comprise

- The model of the synchronous machine, the AC/DC-DC/AC voltage source converters, and the machine and grid side converter controls
- The model of the penstock, the turbine, and the governor
- The unit controller

The machine-side converter is used to control the rotor speed by controlling the electromagnetic torque. Precisely, the q-axis current component controls the electromagnetic torque while keeping the d-axis current component equal to zero.

The grid side converter is controlled in such a way that

- The d-axis current component is used to control the DC-link capacitor voltage
- The q-axis current component is used to control the reactive power supplied to the grid

A nonlinear model of the turbine, including the dynamics of the penstock, will be considered. In addition, the turbine will be equipped with a PI governor.

The inputs to the unit controller are the head and the desired power output. The unit controller provides to the machine side converter the reference rotor speed and the reference electromagnetic torque. The unit controller also provides to the turbine governor the reference rotor speed and the reference gate position. The unit controller determines the reference rotor speed and the reference gate using the hill chart of the turbine.

The interactions between the synchronous machine and turbine controls will be investigated by time-domain simulation. Time-domain simulation in case of a step-change in the reference power is performed. The time variation of rotor speed, gate, flow, mechanical and electrical power are shown.

KEYWORDS

Hydro generator, Variable speed, Full-power converter.

1 INTRODUCTION

Speed control of large hydro generators has become feasible due to the development of high-power electronics. Hence, hydro generators can run at the maximum efficiency operating point with respect to the output power and head. The application of speed control in pumped storage hydro generators is especially advantageous [1].

Speed control of hydro generators can be implemented by controlling either a doubly fed induction machine or a synchronous machine connected to the grid through a full-power converter. Doubly fed induction machines are used in large units like the Limmern pumper storage plant in Switzerland. Synchronous machines connected to the grid through full-power converters are being considered for medium-size units.

In the case of a synchronous machine connected to the grid through a full-power converter the grid, the converter is made up of two voltage source converters (the machine side converter and the grid side converter) with pulse width modulation coupled through a DC link capacitor. The hydro turbine is equipped with a speed governor. A unit controller coordinates the control of the synchronous machine and the hydro turbine [3].

This paper details a generic model of a full-power converter variable speed hydro generator. The model is aimed at investigating interactions between synchronous machine and turbine controls. The interactions between the synchronous machine and turbine controls are investigated by time-domain simulation. Time-domain simulations in case of a step-change in the reference power are performed. The time variation of rotor speed, gate, flow, mechanical and electrical power are shown.

Iberdrola is converting to variable speed two of the four units of Torrejón pumped storage hydro station (4x32 MW). Torrejón pumped storage hydro station belongs to the Tagus river system. The conversion is aimed at extending Torrejón head operating range in pumped mode making feasible the storage of up to 210 GWh by connecting the upstream and downstream reservoirs of Torrejón (Valdecañas and Alcántara). The massive development of solar photovoltaic generation in Spain is making very attractive the development of energy storage facilities.

The grid connection of the new units requires fulfilling the European network code on requirements for grid connection of generators [4] and its Spanish implementation [5]. The network code includes compliance monitoring by system operators. Among other requirements, steady-state and dynamic models should be provided and validated.

This model described in this paper is a step forward in developing the model required by the system operator and a valuable tool for the conception of the control system and the investigation of the interactions between the machine and turbine controls. Although converter and turbine manufacturers will provide detailed models of their components, such models are not open source. Generic open-source models by representing the fundamental dynamics of the systems [6] have the advantage of making easier the understanding of the unit response and more robust computational performance when incorporated into large power system dynamic simulation models.

Generic models of variable speed hydro units based on doubly fed induction machines can be found in the literature [7]. However, generic models of units based on full-power converters are yet not available.

Validation of the proposed model will be addressed in the commissioning test of the Torrejón units. It is expected to report such results in the near future.

The paper is organized as follows. Section 2 contains the notation used throughout the paper. Section 3 details the model. Section 4 discusses the simulation results. Section5 provides the conclusions of the paper.

2 NOTATION

ω_0 : speed base $\omega_0 = 2\pi f_0$.

ω_s : synchronous speed $\omega_s = 1$.

ω_r : rotor speed.

$\mathbf{v}_s = v_{sd} + jv_{sq}$: machine stator voltage.

$\boldsymbol{\psi}_s = \psi_{sd} + j\psi_{sq} = \psi_{sd}$: stator flux.

$\mathbf{i}_s = i_{sd} + ji_{sq}$: stator current.

v_{rd} : machine rotor voltage.

i_{rd} : machine rotor current.

R_s, R_r machine stator and rotor resistance.

L_s, L_r machine stator and rotor leakage inductance.

L_d, L_q : d-axis and q-axis inductances.

L_{md}, L_{mq} : d-axis and q-axis magnetizing inductances.

t_m : mechanical torque.

p_m : mechanical power.

t_e : electromagnetic torque.

$\mathbf{v} = v_d + jv_q$: grid voltage.

$\mathbf{v}_a = v_{ad} + jv_{aq}$: grid side converter voltage.

$\mathbf{i}_a = i_{ad} + ji_{aq}$: grid converter current.

$\boldsymbol{\psi}_a = \psi_{ad} + j\psi_{aq}$: grid side converter flux.

R_a, L_a, resistance and inductance the grid side converter connecting filter.

v_C : DC-link capacitor voltage.

g : governor gate.

q : turbine flow.

q_{NL} : no-load turbine flow.

h : turbine head.

T_W : penstock water time constant.

η : .turbine efficiency.

p_s : power to machine side converter.

p_a : power from the grid side converter.

x_{a1} : state variable of the i_{ad} PI controller (grid side converter).

x_{a2} : state variable of the i_{aq} PI controller (grid side converter).

x_{a3} : state variable of the v_C^2 PI controller (grid side converter).

x_{s1} : state variable of the i_{sd} PI controller (machine side converter).

x_{s2} : state variable of the i_{sq} PI controller (machine side converter).

x_f : state variable of the filter of the governor.

x_r : state variable of the PI controller of the governor.

x_g : state variable of the gate servomotor of the governor

$[\bullet]^*$ set point of $[\bullet]$

3 MODEL

The model comprises

- The unit controller

- The model of the synchronous machine, the AC/DC-DC/AC voltage source converters, and the machine and grid side converter controls
- The model of the penstock, the turbine, and the governor

3.1 Unit controller

The inputs to the unit controller are the head and the desired power output. The unit controller provides to the machine side converter the reference rotor speed and the reference electromagnetic torque. The unit controller also provides to the turbine governor the reference rotor speed and the reference gate position. The unit controller determines the reference rotor speed, the reference gate, and the reference electromagnetic torque using the steady-state characteristic curves of the turbine. Test of scale models of turbines provides several families of steady-state characteristics ([8]-[10]). Manufacturers provide such curves to their customers. Analytical expressions (three-order polynomials) of the curves have been estimated from the experimental curves. As those expressions are expressed in real magnitudes, they have been transformed to per unit magnitudes using an appropriate base system (nominal head, nominal flow, nominal power). Precisely, we have considered efficiency versus rotor speed and gate opening

$$\eta = \eta(\omega_r, g)$$

and gate opening versus head and flow

$$g = g(h, q)$$

Figure 1 shows that the unit controller determines the unit reference values finding the optimal operating point of the turbine from the operating efficiency point.

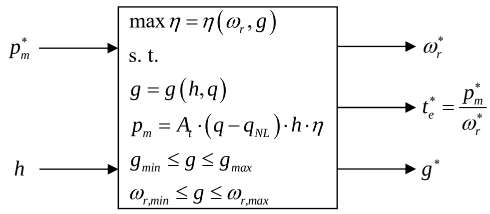

Figure 1: Unit controller.

3.2 Synchronous machine and machine controls

In the case of a synchronous machine connected to the grid through a full-power converter to the grid, the converter is made up of two voltage source converters (the machine side converter and the grid side converter) with pulse width modulation coupled through a DC link capacitor, as shown in Figure 2. The stator of a synchronous machine is fed by the machine-side converter that controls the electromagnetic torque. The grid side converter controls the reactive power supplied to the grid.

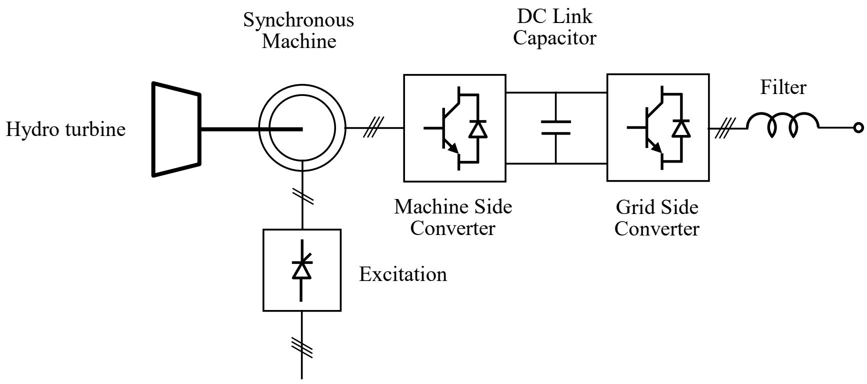

Figure 2: Variable synchronous machine connected to the grid through a full-power converter.

Figure 3 shows the synchronous machine equivalent circuits. Figure 4 depicts the grid side converter equivalent circuit. Figure 5 displays the turbine-synchronous machine rotor and DC link capacitor dynamic models

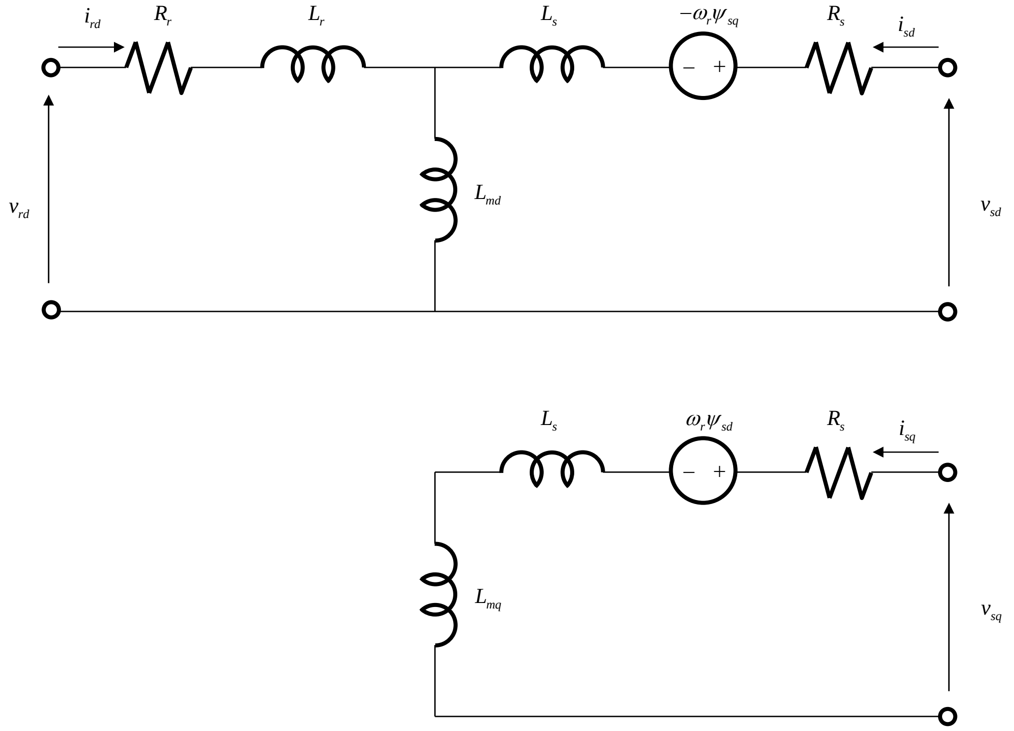

Figure 3: Synchronous machine equivalent circuits.

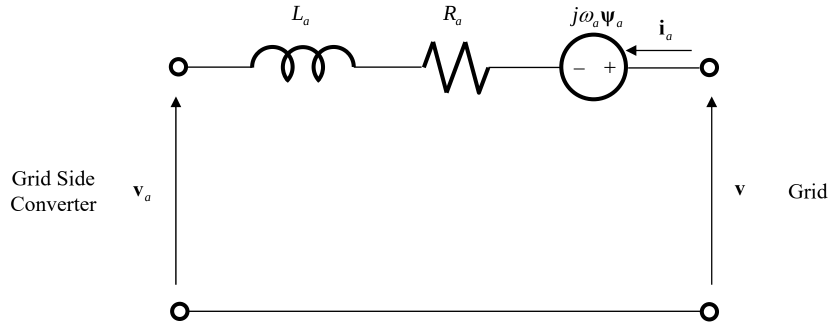

Figure 4: Grid Side Converter equivalent circuit.

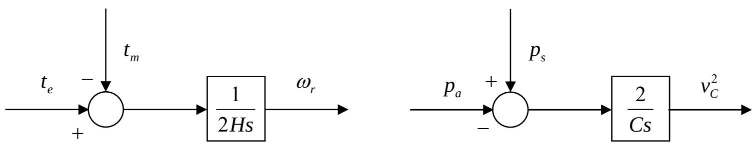

Figure 5: Turbine-synchronous machine rotor and DC link capacitor dynamic models.

The machine side converter controls the electromagnetic torque by controlling the q-axis current component controls the electromagnetic torque while keeping the d-axis current component equal to zero [11]. Figure 6 shows the control of the machine-side converter control scheme.

Figure 7 shows the grid side converter control scheme. The grid side converter is controlled in such a way that [11].

- The d-axis current component is used to control the DC-link capacitor voltage
- The q-axis current component is used to control the reactive power supplied to the grid

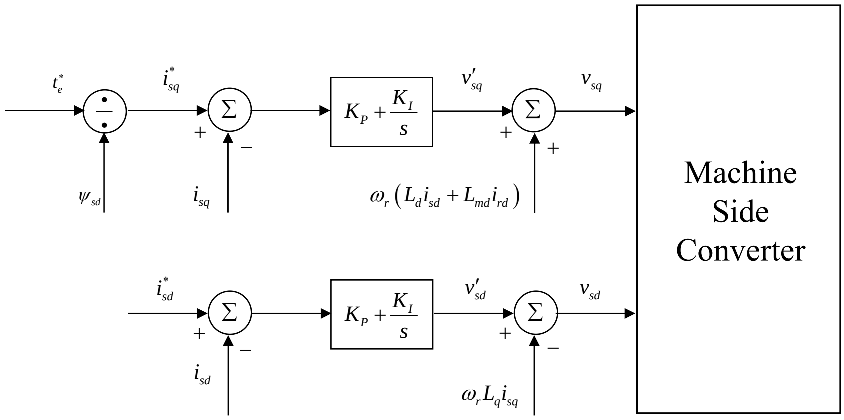

Figure 6: Machine Side Converter controls.

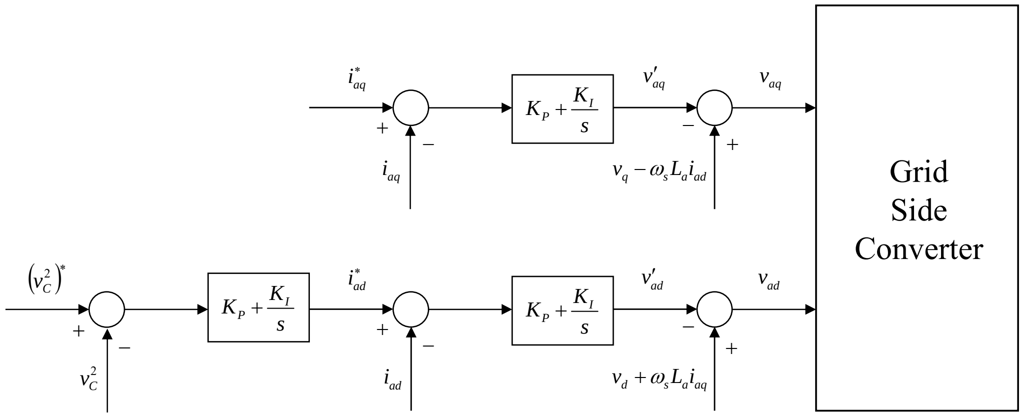

Figure 7: Grid Side Converter controls.

The settings of the converter PI controllers are designed as described in [11]. The input data are the machine and the converter data (resistances and inductances) and the desired bandwidth and damping. The desired bandwidth of the inner and the outer loops is 25 rad/s and 2.5 rad/s, respectively, whereas the desired damping is 70%.

3.3 Penstockocck, turbine, and governor

A nonlinear model of the turbine, including the dynamics of the penstock, is considered. Figure 8 shows the turbine model. In addition, the turbine will be equipped with a PI governor. Figure 9 shows the governor model.

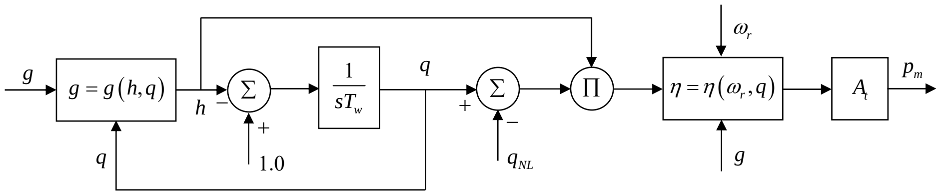

Figure 8: Turbine model.

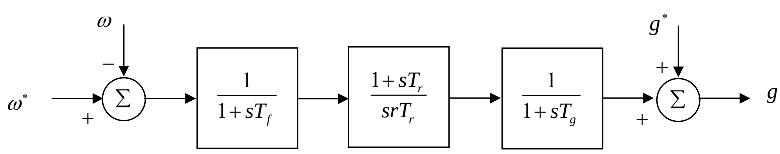

Figure 9: Governor-model.

3.4 Mathematical formulation and implementation

The model is formulated as a set of nonlinear differential and algebraic equations that can be written in compact form as follows

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{z},\mathbf{u})$$
$$\mathbf{0} = \mathbf{g}(\mathbf{x},\mathbf{z},\mathbf{u})$$

where the state variables $\mathbf{x}$, the algebraic variables $\mathbf{z}$, and the input variables $\mathbf{u}$ are

$$\mathbf{x}^T = \left[\psi_{sd}\ \psi_{sq}\ \psi_{ad}\ \psi_{aq}\ x_{a1}\ x_{a2}\ x_{a3}\ v_C^2\ x_{s1}\ x_{s2}\ \omega_r\ x_f\ x_r\ x_g\ q\right]$$
$$\mathbf{z}^T = \left[i_{sd} i_{sq}\ i_{ad}\ i_{aq}\ v_{sd}\ v_{sq}\ v'_{sd} v'_{sq} v_{ad}\ v_{aq}\ v'_{ad}\ v'_{aq}\ i^*_{ad}\ t_e\ t_m\ p_s\ p_a i^*_{sd}\ i^*_{sq}\ g^*\ g\ h\right]$$
$$\mathbf{u}^T = \left[p_m\ v\ v^*_{rd}\ i^*_{aq}\ (v_C)^*\right]$$

The model has been developed and implemented as a Matlab script by the authors. Nonlinear time response is computed using Runge-Kutta 4-5 numerical integration algorithm [12]. All variables are in per unit of the device MVA base. Model data is provided in the appendix.

4 SIMULATION RESULTS

The interactions between the synchronous machine and turbine controls are investigated by time-domain simulation. Time-domain simulation in case a step-change in the reference power has been performed.

Figure 10 shows the electrical and mechanical torques. It can be seen the very fast response of the electrical power as governed by the full-power converter. The response of the mechanical torque is slower. Of course, mechanical torque is identical to the electrical torque at the end of the transient. The mechanical torque exhibits at the beginning of the transient the characteristic inverse response of the hydro turbine. The overshoot of the mechanical torque confirms that the tuning of the PI regulator of the governor must be optimized.

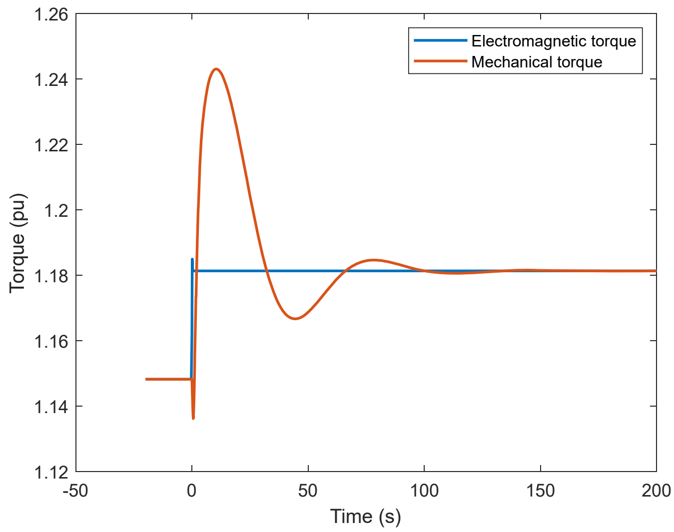

Figure 10: Response to a step of reference power: electrical and mechanical torques.

Figure 11 shows the variables of that describe the behavior of the hydraulic turbine: head, flow, and gate. The head exhibits an upward transient coming back to the original steady-state. Flow and gate increase to increase the mechanical torque.

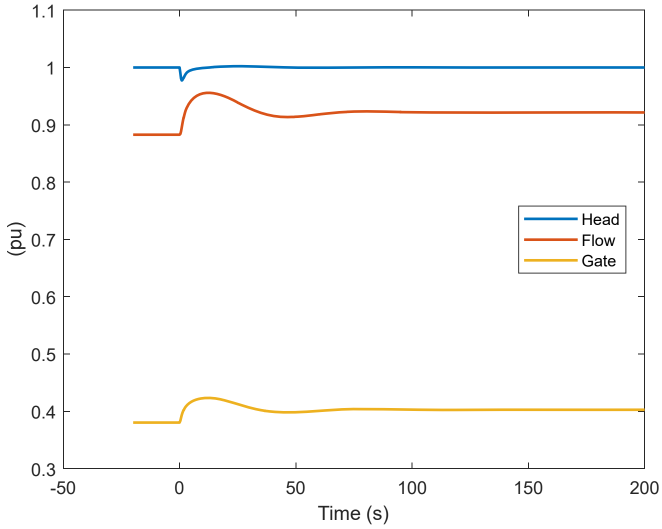

Figure 11: Response to a step of reference power: head, flow and gate.

Figure 12 shows the rotor speed. The rotor speed increases to reach the maximum efficiency corresponding the desired power output. The PI regulator provides a smooth transient response.

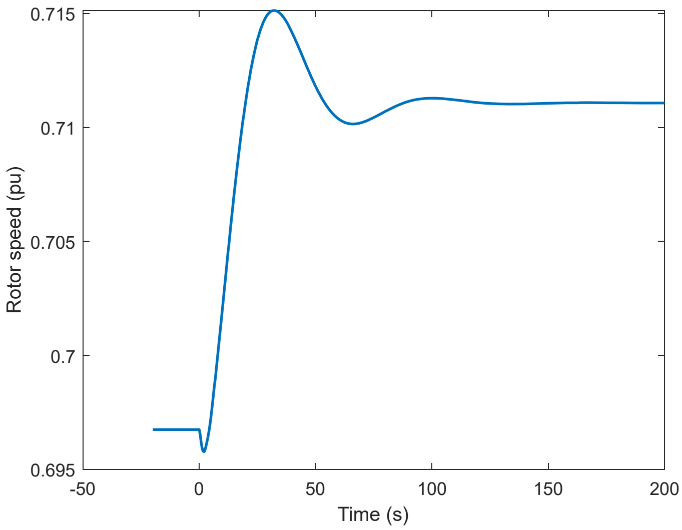

Figure 12: Response to a step of reference power: rotor speed.

5 CONCLUSIONS

This paper has detailed a generic model a full-power converter variable speed hydro generator. The model is aimed at investigating interactions between synchronous machine and turbine controls. The variation of the electrical power turns out to be very fast due to the control of the full-power converter. Turbine variables exhibit smooth and slower response pattern without any adverse interaction with the electrical variables.

This model described in this paper is a step forward in the development of the model required by the system operator and a valuable tool for the conception of the control system and for the investigation of the interactions between the machine and turbine controls. Validation of the proposed model will be addressed in the commissioning test of the Torrejón units. It is expected to report such results in the near future.

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APPENDIX: MODEL DATA

$R_s = R_r = 0.2\,pu$

$L_s = L_r = 0.1\,pu$

$L_{md} = 0.9\,pu$, $L_{mq} = 0.5\,pu$

$R_a = 0.008\,pu$

$L_a = 0.08\,pu$

$C = 0.055\,pu$

$H = 3\,pu$

$T_W = 1s$

$T_f = 0.2s$

$r = 0.6\,pu$

$T_r = 7.8s$

$T_g = 1s$