Assessment of hydro unit grid code compliance by means of numerical simulations

C. Nicolet
Power Vision Engineering sàrl
Chemin des Champs-Courbes 1
CH-1024 Ecublens
Switzerland

B. Kawkabani
Electrical Machinery Group
EPFL, Ecole polytechnique fédérale de Lausanne
CH-1015 Lausanne
Switzerland

J.-L. Drommi
EDF-CIH,
Electricité de France,
Centre d'Ingénierie Hydraulique
38042 Grenoble
France

T. Singainy
P. Grillot
EDF-CIH,
Electricité de France,
Centre d'Ingénierie Hydraulique,
73370 Le Bourget-du-Lac
France

Abstract

This paper presents the results of a study conducted for an existing pumped storage hydroelectric power plant with 4x230MW, to assess the grid code compliance of the hydro units using detailed numerical simulation models. Therefore, the hydroelectric power plant was modelled using the simulation software SIMSEN, taking into account: the upper reservoir, the penstocks and pressurized pipes, the Francis reversible pump-turbines, the surge tanks, the galleries, the rotating inertia, the synchronous motor-generators, the transformers and the control systems including turbine governor and voltage regulator. The power network model was adapted according to the specifications of the Grid Code edited by the French Transmission System Operator, RTE, Gestionnaire du Réseau de Transport d'Electricité. After a careful validation of the model against on site measurements, the model was used to simulate 7 of the most critical load cases of the RTE Grid Code such as: low voltage ride through (LVRT), short-circuits, load shedding, primary and secondary control for voltage and frequency stability. The paper presents the comparison between simulation results obtained with fully detailed hydroelectric model with those obtained with the electrical model only, evidencing the contribution of turbine governor to system stability during electrical faults. These results enabled to define the level of complexity of the simulation model required for the different load cases investigated. In case of non-compliance with the specifications, this approach also offers the possibility to improve the control performances of the hydro unit, considering the impact on system stability and on the power plant integrity.

1. Introduction

Due to deregulated market and the increasing penetration of new renewable energies, the contribution of hydroelectric power plants to power network stability becomes of major interest, [6], [13]. Indeed, hydroelectric power plants feature high flexibility, extended operating range, quick time response, and therefore are capable to provide primary, secondary and tertiary control services, [3], [5]. The Grid Codes edited by the local Transmission System Operators, TSO, define the requirements related to generation unit stability during electrical faults and to primary and secondary control performances required to contribute to frequency and voltage control. If the control services can be fairly evaluated by on-site measurements, the stability of the units during electrical faults has to be evaluated by means of numerical simulations.

Usually, numerical simulation of electrical fault is performed assuming constant generating torque, or simplified models of the generation process. For design purposes, these simplifications are relevant, because extreme design values usually occur in the first instants following an electrical fault. However, as far as the system stability and related damping is concerned, depending of the system configuration, it may require several seconds to recover constant output power consecutively to a major electrical fault. For hydroelectric units featuring stabilisation time above typically 3 s, a significant contribution from the hydraulic system and associated control to the system stability can be expected. For such systems, it make sense to perform fully coupled hydroelectric numerical simulations comprising hydraulic system, turbine and related governor, rotating inertias, generator and voltage regulator and connection to the electrical grid.

This paper presents the results of a study of an existing pumped storage power plant, which grid code compliance was assessed by means of numerical simulations, using electrical, hydraulic and hydroelectric simulation models. The comparison of the results obtained for different load cases with the different models points out the relevance of full hydroelectric simulation for some of the load cases.

2. Grid Code compliance requirements

2.1. General context in France

Since the deregulation of French electrical market and the birth of French TSO named RTE, "Gestionnaire du Réseau de Transport d'Electricité", several rules and requirements have been implemented to contractualize the responsibilities of French power producers regarding grid support. These requirements include performance guaranties described in several forms of the RTE technical documents. Some performances can be assessed on line, such as actual voltage or frequency control capacity; other requirements are for power producers to demonstrate through simulation results that the transient behavior of the units remain stable.

For frequency control, RTE requirements are very similar to other TSO and states as follow:

- **for primary control:** 2.5% of max power to be delivered within maximum 30s;
- **for secondary control:** 9% of max power to be delivered within 133s;
- **for tertiary control:** to be put on line within 15minutes.

2.2. Requirements from RTE

RTE edited Grid Code requirements to connect a new or upgraded power plant to the French power network, see [10]. In case of upgrade, Grid Code requirements shall apply if power output is increased by 10% or more. Among the different requirements, the grid code specify the contribution of the new power plant to the power network stability. These requirements depend on the fuel source, power level and voltage level at the connecting point. Table 1 presents the list of the 22 forms to be provided to RTE to demonstrate the compliance of the new power plant to the Grid Code requirements. The forms 1 to 10 have to be provided prior to the first connection of one unit to the power network. The forms 1 to 4 are of information type while the forms 5 to 10 have to be evaluated by numerical simulations. The forms 11 to 22 have to be evaluated by on-site measurements, if forms 1 to 10 were conform. Each RTE form defines:

- the simulation model or operating configuration to be considered;
- the initial conditions of the tests and associate parameters;
- the assessment method;
- the compliance criteria to be fulfilled.

The forms 5 to 10 are evaluated by numerical simulations as they are difficult to setup in reality, and also as they are inducing unwanted perturbations on the power network and may also lead to severe loading of the equipment; see for example Form 9 related to short-circuit at full power. Each RTE requirement regarding transient behaviour of the units has a precise goal:

- Form n°6 : Voltage stability in case of small voltage disturbances. The aim is to confirm that, whatever the grid topology, generating units remain stable (see case study § 5.1);
- Form n°7: Unit stability during grid topology switching. The goal is to confirm that the generating units keep stable during network power line switching (case not presented in this paper);
- Form n°8: Unit stability during grid short-circuit. The goal is to assess the risks of loss of synchronism, risk of tripping of generating units during and after a short-circuit fault that is normally cleared by grid protection. (see case study § 5.2);
- Form n°9: Low Voltage Ride Through. The aim is to assess any risk of tripping or loss of synchronism of generating sets during a voltage deep whose shape is described at Figure 16 (see case study § 5.3);
- Form n°10: Voltage stability during large frequency transient. The goal is to check that generating unit stator voltage remains perfectly controlled during large grid frequency deviation ($\Delta f = \pm 200$mHz – case not presented in this paper).

Regarding the Forms 11 to 22, even if the final evaluation will be based on the in-situ tests, it is very useful to evaluate the compliance for some of the forms also by means of numerical simulation first, to anticipate some difficulties on site. In case the compliance is not reached, the numerical simulation enables to select appropriate solutions prior the tests, to guarantee the success of the measurement campaign.

Therefore, such approach has been undertaken by EDF-CIH, in collaboration with EPFL and Power Vision Engineering Sàrl, to perform the evaluation of grid code compliance of one existing pumped storage power plant, for the Forms 6 to 10, 14 and 15. Table 1 summarizes the forms that have been simulated, and those which part of the results are presented in the present paper. The simulations results could ultimately lead to upgrade option choices, either to remain below the 10% output power increases threshold, or should the results be satisfactory, undertake a rehabilitation beyond 10% output power increase.

Table 1 List of forms to be delivered for a new power plant, or power plant with a power upgrade of 10% to demonstrate its compliance to RTE, the French Transmission System Operator (TSO), requirements (Grid Code Compliance Assessment).

Form N°	Description	Conformity assessment	SIMSEN model used	Simulated/ Presented
1-4	Data and certifications	Data	None	NO/NO
5	Constructive capacity in reactive power	Simulation	None	NO/NO
6	**Voltage stability in case of small perturbation**	**Simulation**	**Electrical**	**YES/YES**
7	Stability in case of load transfer from 4 transmission lines to 3 transmission lines	Simulation	Electrical and hydroelectric	YES/NO
8	**Stability in case of short-circuit**	**Simulation**	**Electrical and hydroelectric**	**YES/YES**
9	**Stability in case of low voltage at power network**	**Simulation**	**Electrical and hydroelectric**	**YES/YES**
10	Voltage stability in case of frequency deviation	Simulation	Electrical and hydroelectric	YES/NO
11-13	Data exchange, grid connection and power quality	In situ tests	None	NO/NO
14	**Frequency primary control capacity**	**In situ tests**	**Hydraulic**	**YES/YES**
15	**Frequency secondary control capacity**	**In situ tests**	**Hydraulic**	**YES/YES**
16	Frequency secondary control capacity	In situ tests	None	NO/NO
17-19	Primary and secondary voltage control	In situ tests	None	NO/NO
20-22	Power reduction capacity, isolated grid operation, fast restart capability	In situ tests	None	NO/NO

3. Case study description

To select the case study, EDF-CIH chose a Pumped Storage Power Plant built in the 80 s, where a pump-turbine upgrade would be meaningful. The simulations undertaken in collaboration with EPFL and Power Vision Engineering Sàrl, were aimed at identifying any potential issue to fulfill the Grid Code requirements in order to choose a relevant upgrade option. The layout of the pumped storage power plant of interest is presented in Figure 1. The power plant comprises upper reservoir, two penstocks, 4 reversible Francis pump-turbine units of about 230 MW each operated under medium head of approximately 400 m, downstream surge tanks and tailrace tunnel to connect downstream reservoir. The pump-turbines are connected to fixed speed synchronous motor-generators linked to 400 kV large electrical power system through transformers.

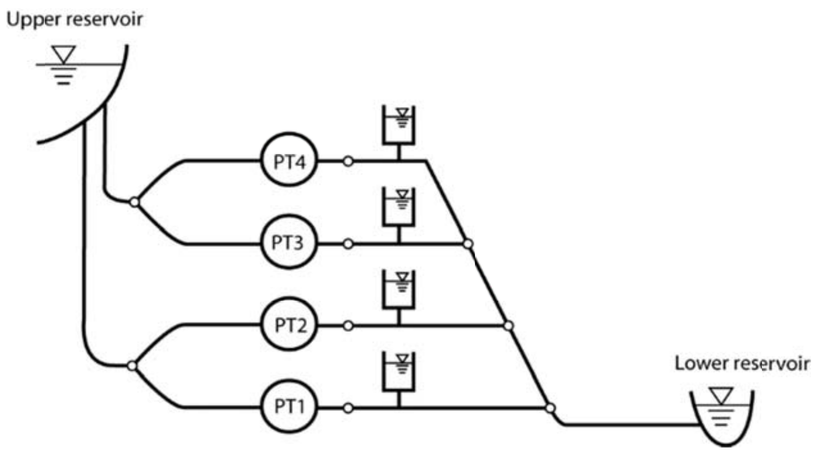

Figure 1 Scheme of the power plant layout.

4. Case study modeling and validation

The pumped storage power plant of interest was modeled using the simulation software SIMSEN developed by the EPFL for the simulation of the dynamic behavior of hydroelectric power plants, [11], [7], [8]. Three models were setup:

- **An electrical simulation model:** including motor-generator, the related voltage regulator, the shaft line rotating inertia transformer, transmission lines and connection to an infinite power network;
- **A hydraulic model:** including the upper and lower reservoirs, the waterways, the surge tanks, pump-turbines and related turbine governor, the rotating inertia;
- **A hydroelectric model:** combining the electrical and hydraulic models.

Depending of the nature of the Form requirements, either electrical or hydraulic models have been considered. In addition, for some load cases, the full hydroelectric model was also considered and the simulation results compared with the first model. The modeling of the electrical and hydraulic parts of the SIMSEN models are presented below.

4.1. Hydraulic system modeling

Figure 2 presents the SIMSEN model of the hydraulic part of the pumped storage power plant. The model includes: the penstocks, the repartitors, the pump-turbines modelled with 4 quadrant characteristics [y,N11,Q11,T11], the downstream surge tanks, the collectors and tailrace tunnel. The model also includes the unit total inertia and the turbine governor of PID type. The modeling of hydraulic components in SIMSEN is briefly presented in Appendix 1.

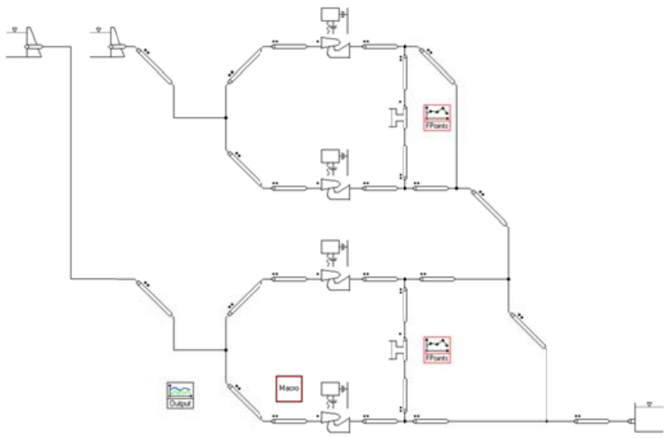

Figure 2 SIMSEN model of the hydraulic system of the pumped storage power plant.

4.2. Electrical system modeling

The motor-generator is connected to an infinite network through a high voltage overhead transmission line as presented in Figure 3. The model of the synchronous machine of laminated rotor type takes into account transient and sub-transient characteristic quantities, see Canay [1], [2]. The saturation effect of the magnetizing reactance xad in the direct-axis is taken into account using a nonlinear characteristic curve. The study is performed for two extreme values of the reactance Xcc of the transmission line: a = 0.05 p.u and b = 0.3 p.u. The rotor of the synchronous machine is supplied by a static excitation system. The voltage regulator is a PID controller represented by different blocks.

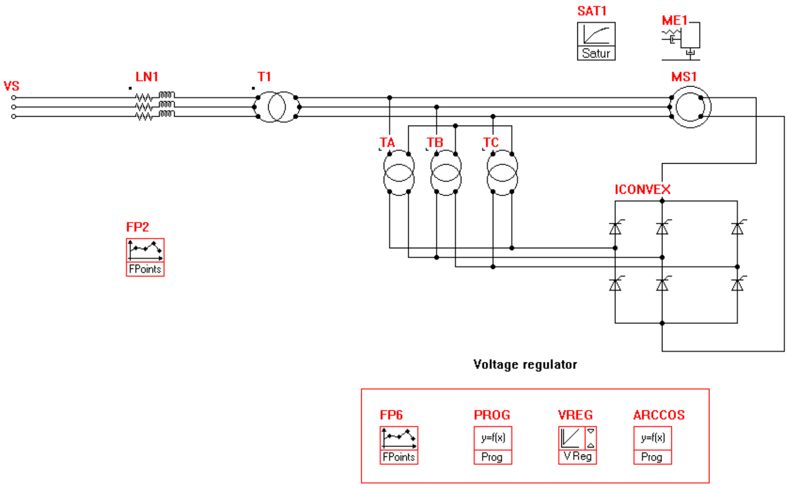

Figure 3 SIMSEN model of the electrical system of one unit of the pumped storage power plant.

4.3. Simulation Model Validation

The hydraulic model of the pumped storage power plant was validated by the comparison of simulation results of emergency shutdown in turbine mode and pumping mode with on-site measurements. The turbine governor model was then validated by the comparison of the simulation results of one unit in case of grid disconnection, re-synchronization, and re-loading of the unit. For the simulation, the re-synchronization phase was simplified, assuming the grid reconnection was successful. The simulation results of the pump-turbine unit obtained for this sequence is presented in Figure 4, while the comparison between measurements and simulations are presented in Figure 5 to Figure 7 respectively for the guide vane opening, rotational speed and the spiral case pressure. The comparison shows very good agreement and demonstrate that pumped-storage model, including the turbine governor is representative of the dynamic behavior of the power plant also when subjected to speed and power controls.

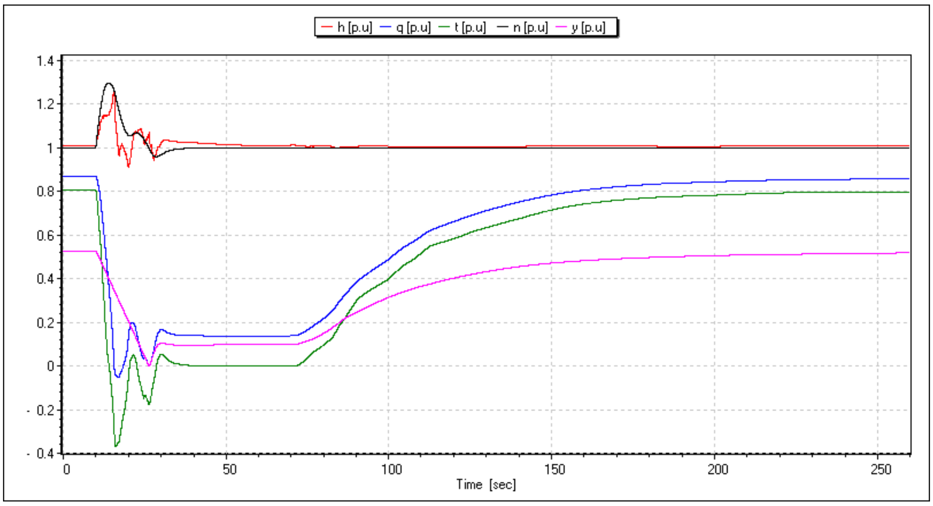

Figure 4 Simulation results of pump-turbine transient behavior in case of unit grid disconnection, resynchronization and loading.

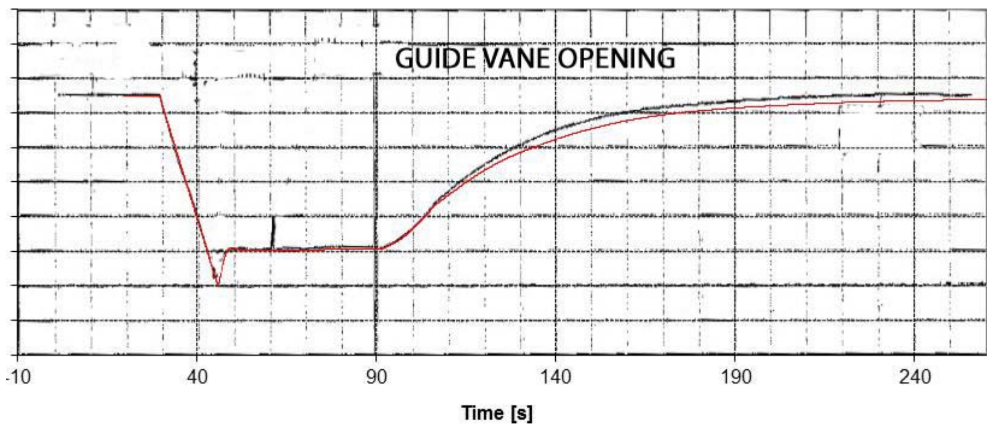

Figure 5 Comparison of simulation results and measurements of the pump-turbine guide vane opening in case of unit grid disconnection, resynchronization and loading.

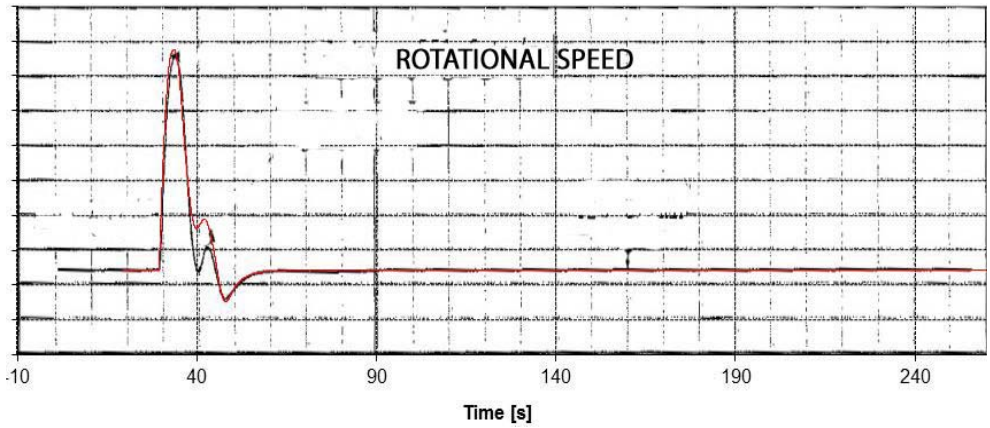

Figure 6 Comparison of simulation results and measurements of the pump-turbine rotational speed in case of unit grid disconnection, resynchronization and loading.

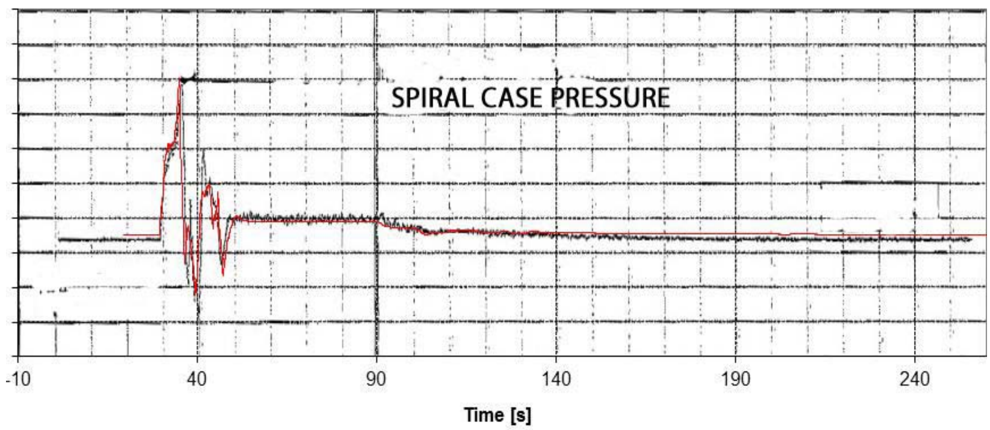

Figure 7 Comparison of simulation results and measurements of the pump-turbine spiral case pressure in case of unit grid disconnection, resynchronization and loading.

5. Grid code compliance assessment by numerical simulation

As indicated in the Table 1, the load cases presented in this paper are the following:

- Form 6: voltage stability in case of small disturbances;
- Form 8: stability in case of short-circuits;
- Form 9: stability in case of low voltage at the power network;
- Form 13: frequency primary control capacity;
- Form 14: frequency secondary control capacity.

The simulation results obtained for the abovementioned forms are presented in the sub-chapters below.

5.1. Form 6: Voltage stability in case of small disturbances

Figure 8 presents the electrical configuration to be considered to assess the compliance with the requirements of the Form 6 in case of voltage small disturbances.

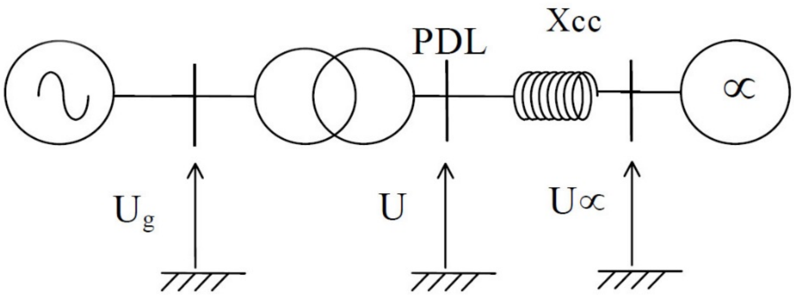

Figure 8 Layout of the electrical model to be considered for the simulation of the form 6 of RTE Grid Code (source RTE [10]) related to voltage stability.

The synchronous machine has the following initial conditions: rated voltage, rated active power and reactive power nil. The load case consists in a voltage setpoint step change of 2% applied on the voltage regulator. The resulting terminal stator voltage and the active power at the delivery point are represented respectively in Figure 9 and Figure 10. One can notice that the synchronous machine remains stable, and the stabilization time of the active power with a value of +/-1% of the final value, is less than 10 seconds, result which is in accordance with RTE Grid Code.

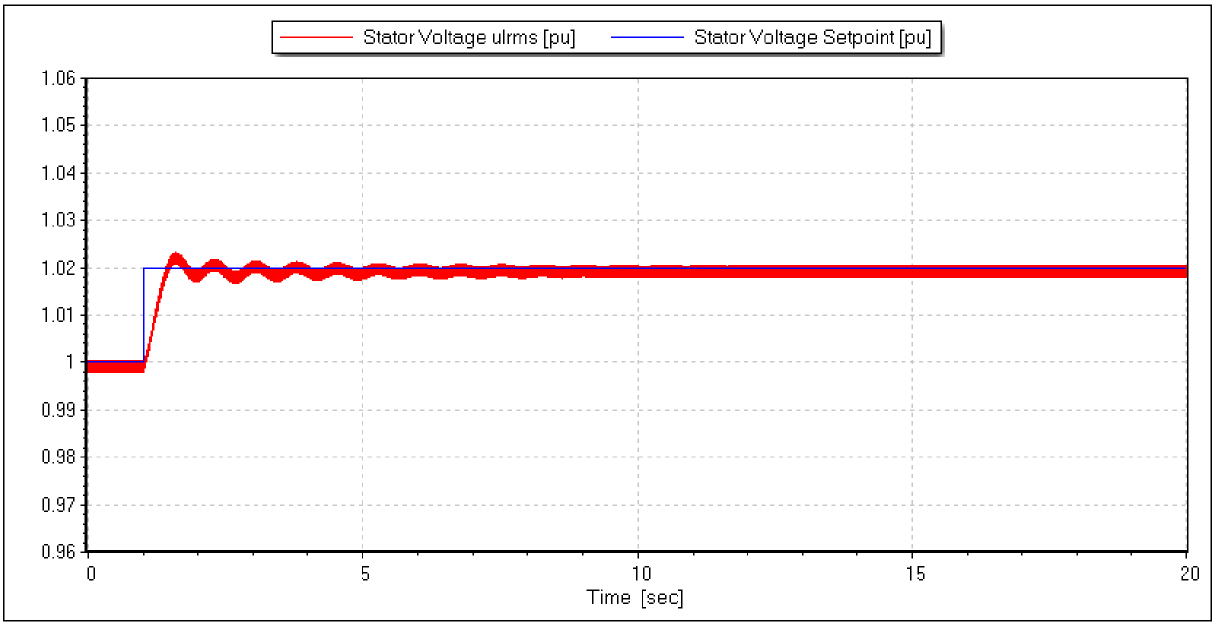

Figure 9 Simulation results of synchronous machine terminal stator voltage resulting from a voltage setpoint step change of 2% with Xcc=0.3 pu (form 6 b).

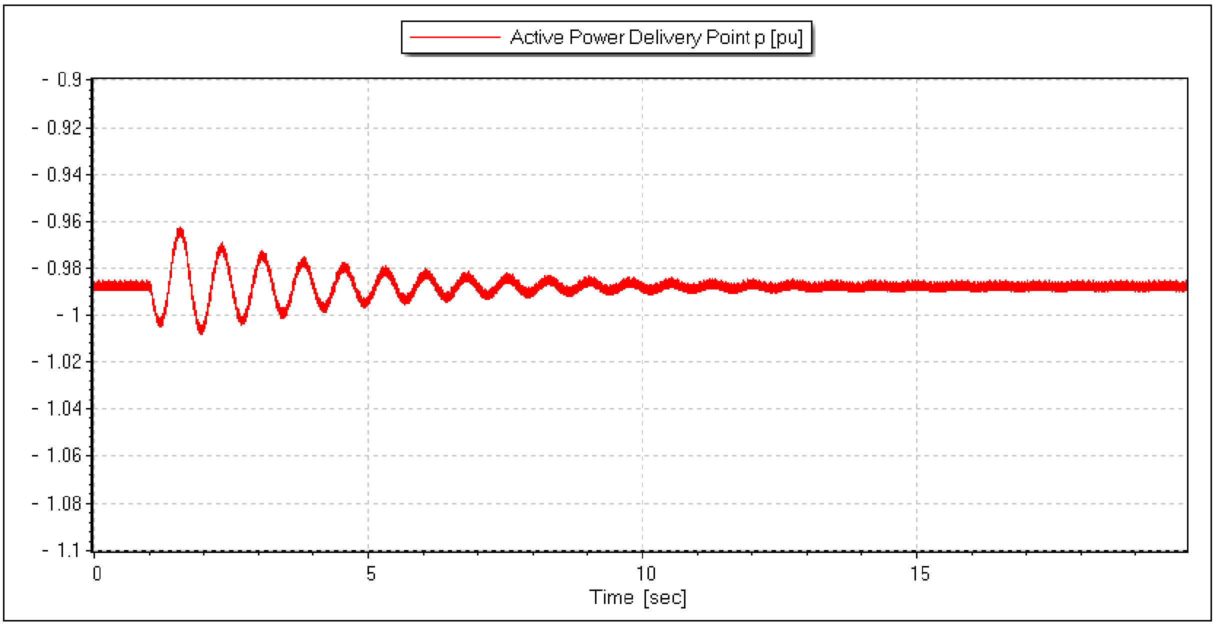

Figure 10 Simulation results of synchronous machine terminal active power resulting from a voltage setpoint step change of 2% with Xcc=0.3 pu (form 6 b).

5.2. Form 8: Stability in case of short-circuit

Figure 11 presents the electrical configuration to be considered to assess the compliance with the requirements of the Form 8 in case of short-circuit.

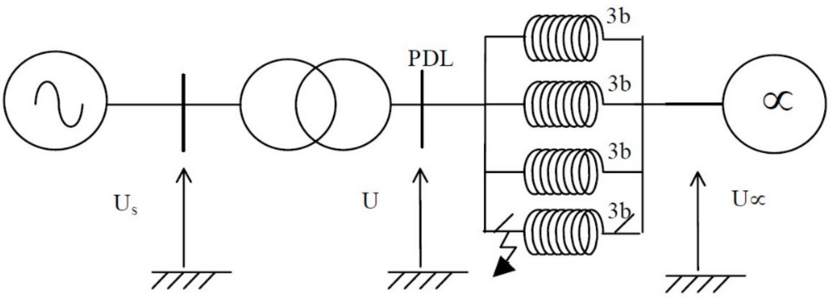

Figure 11 Layout of the electrical model to be considered for the simulation of the form 8 of RTE Grid Code (source RTE [10]) related to short-circuit.

The synchronous machine is operated with the following initial conditions: rated voltage, rated active power and reactive power nil. On the 4th transmission line with impedance value of 3b= 0.9 p.u, a three-phase short-circuit of duration 85 ms and fault clearance is simulated, considering both electric and hydroelectric models. The comparison of simulation results obtained with hydroelectric and electric models for the voltage at the delivery point (PDL), for the active power and for the synchronous machine rotational speed are presented respectively in Figure 12 to Figure 14. The simulation results of the pump-turbine transient behavior obtained with hydroelectric model are given in Figure 15.

The comparison of the simulation results points out, that the frequency deviations induced by the three-phase short-circuit lead to a reaction of the turbine speed governor contributing to the damping of the active power oscillations consecutive to the electrical fault. For this load case, the simulation results obtained with the electrical and hydroelectric models fulfill the RTE Grid Code requirements for the stabilization of the active power, which should be within +/-5% in less than 10 s. However, one can also notice the important contribution of the turbine governor for the active power and rotational speed stabilization, which stabilization time is reduced from 9.5 s to 6.7 s thus giving more confidence and robustness to the simulation results.

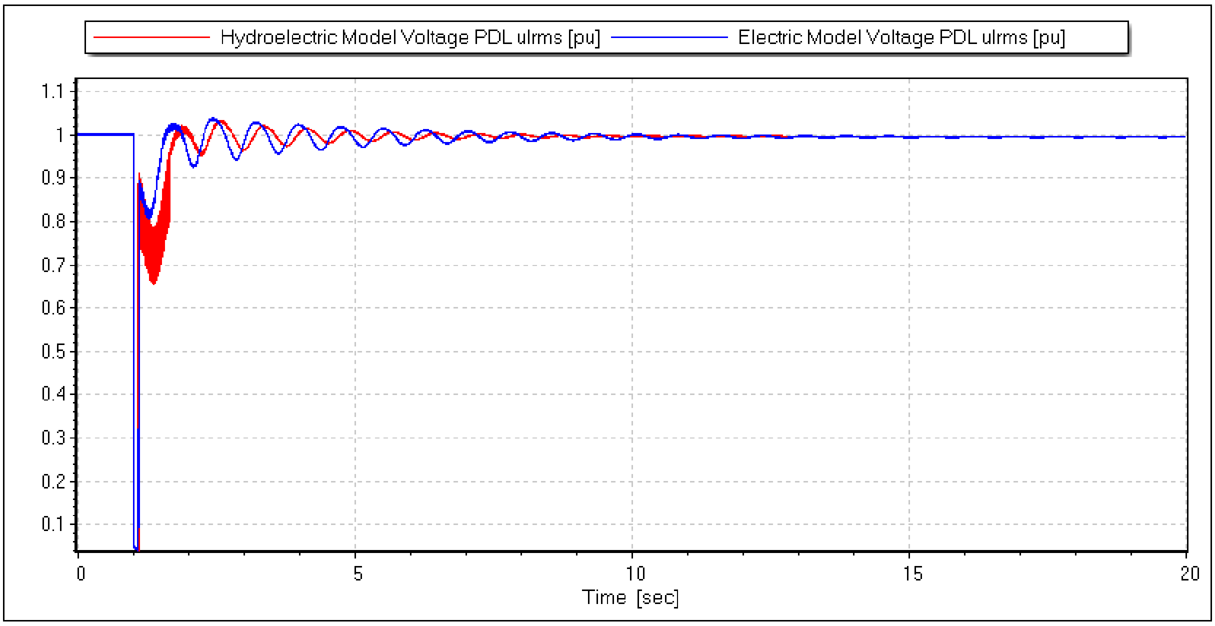

Figure 12 Comparison of simulation results of the voltage at the delivery point (PDL) obtained with hydroelectric model and electric model in case of short-circuit of duration 85ms and fault clearance (form 8).

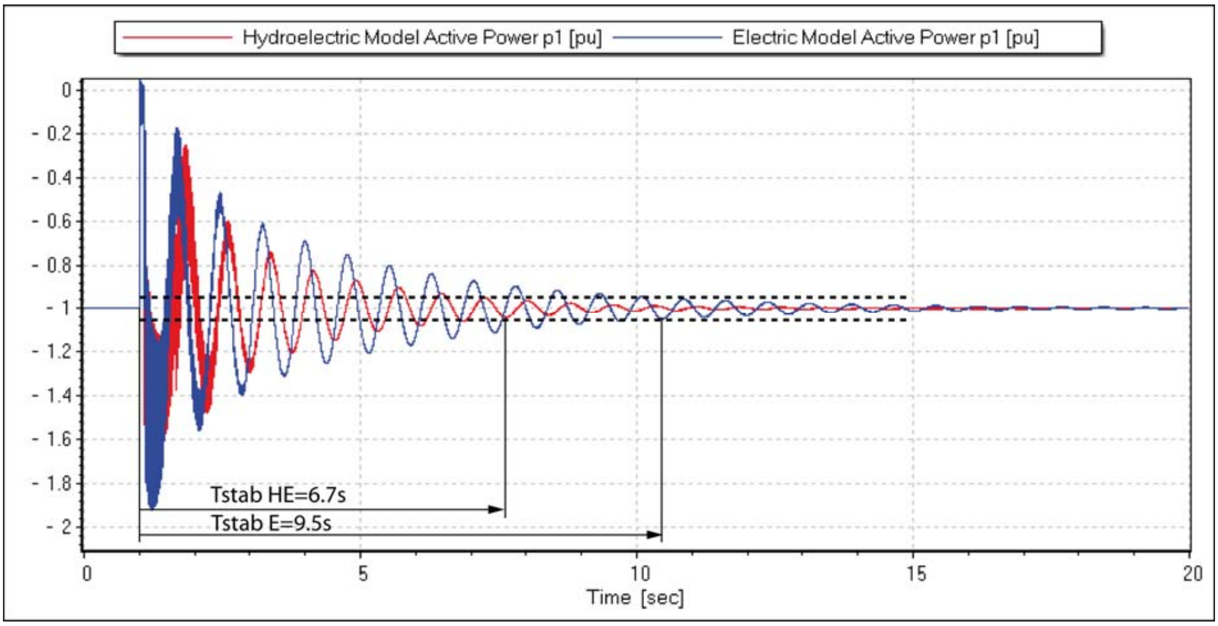

Figure 13 Comparison of simulation results of the active power at the delivery point (PDL) obtained with hydroelectric model and electric model in case of short-circuit of duration 85ms and fault clearance (form 8).

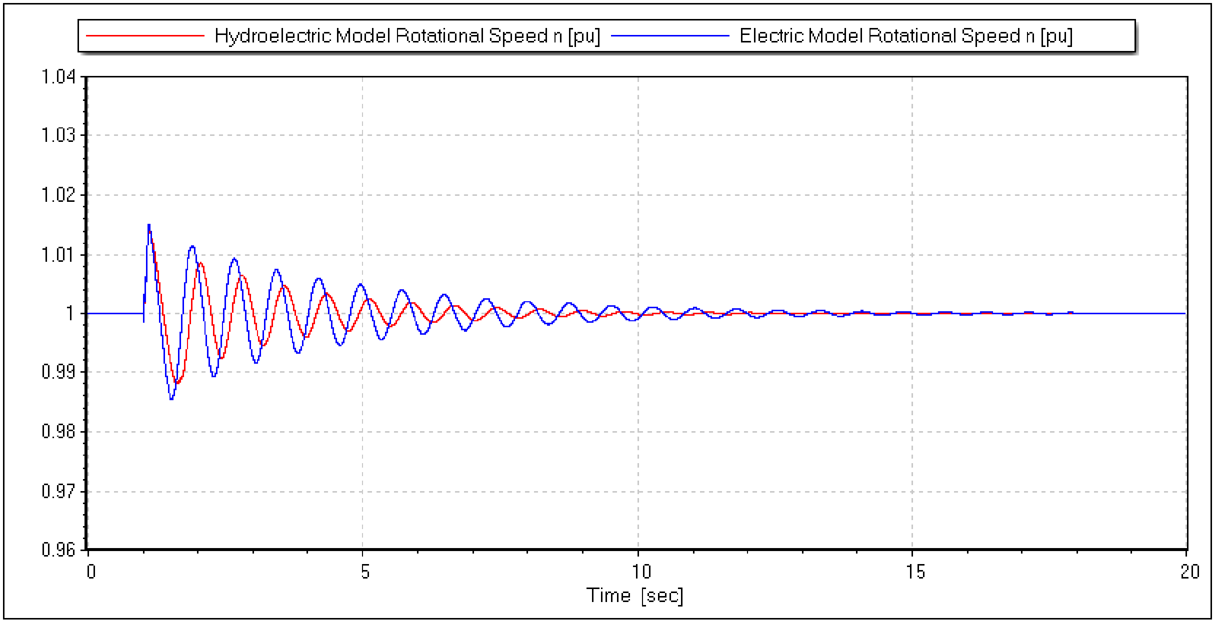

Figure 14 Comparison of simulation results of the synchronous machine rotational speed obtained with hydroelectric model and electric model in case of short-circuit of duration 85ms and fault clearance (form 8).

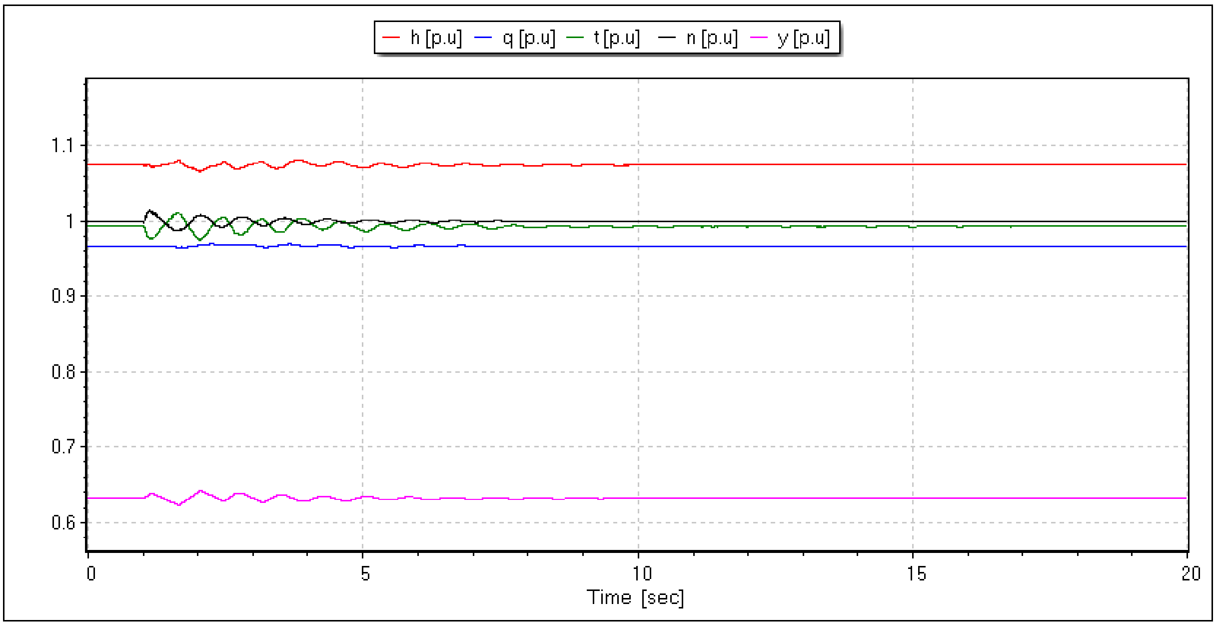

Figure 15 Simulation results of the pump-turbine transient behavior obtained with hydroelectric model in case of short-circuit of duration 85ms and fault clearance (form 8).

5.3. Form 9: Stability in case of low voltage at the power network

Figure 16 presents the low voltage profile to be imposed at the power network, see case 1, considering no transmission lines, to assess the compliance with the requirements of the Form 9 in case of low voltage at the power network. The zero voltage duration is of 150 ms, while the voltage increases then to 0.5 pu and remains constant for 550 ms, and finally returns to its original value in 800 ms. For the study, 12 different low voltage profiles fitting in the general pattern have been simulated. In this paper only the results of the cases 1 and 2 are presented.

Figure 17 presents the simulation results obtained with electrical and hydroelectric models for the case of voltage profile case 1, when the unit is operated at rated power. It could be noticed that for both models the unit disconnects from the power network, even if in the case of the hydroelectric model, the rotational speed is brought back to synchronism by the turbine governor but only after 10 s. Figure 18 presents the pump-turbine transient behavior resulting from the low voltage case 1, and it could be noticed that the turbine cannot react faster as the guide vane are closing with the maximum possible rate corresponding to the closing rate in emergency shutdown conditions. These simulation results do not take into account the generator and unit protection system, which in this case would have triggered an emergency shutdown of the unit due to over-frequency.

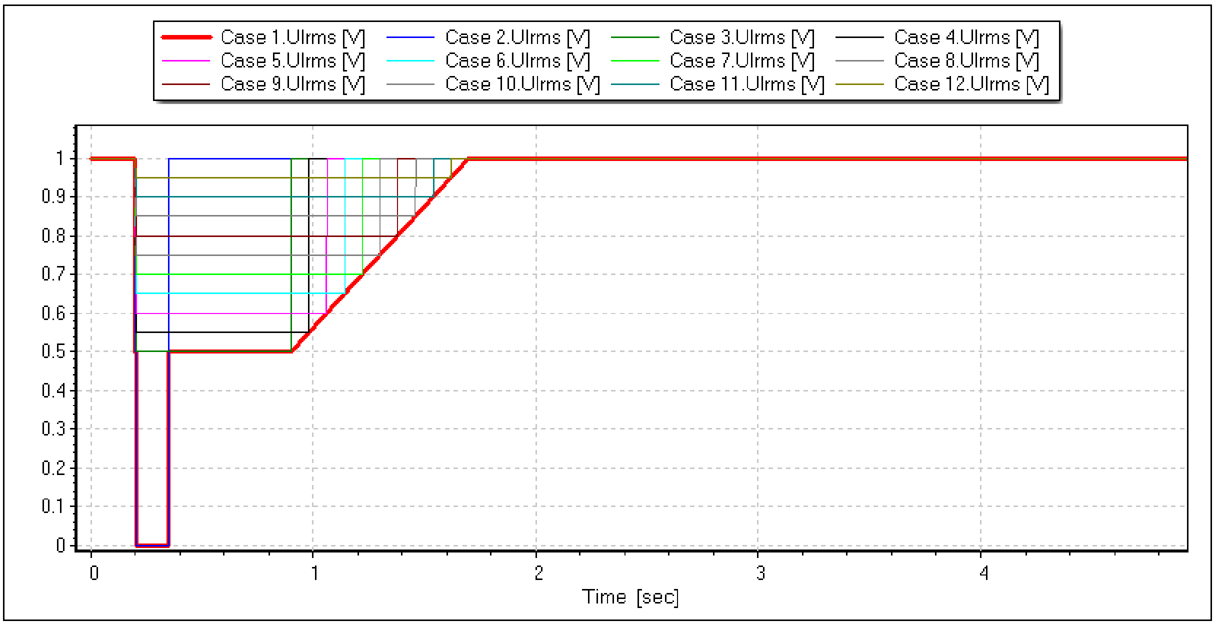

Figure 16 Twelve different voltage profiles considered at the infinite grid for the simulation of the form 9 of RTE Grid Code (source RTE [10]) related to Low Voltage Ride Through (LVRT).

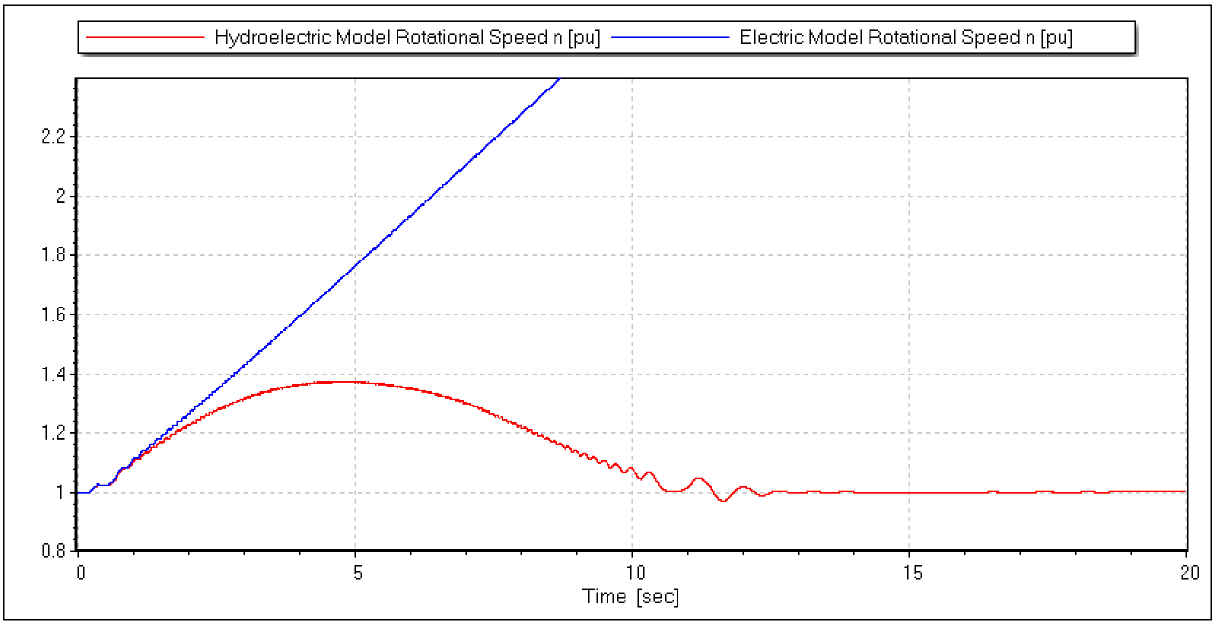

Figure 17 Comparison of the simulation results of the rotational speed of the unit obtained with hydroelectric and electrical models and resulting from low voltage profile at the power network of the form 9 of RTE Grid Code considering profile of case 1 of Figure 16.

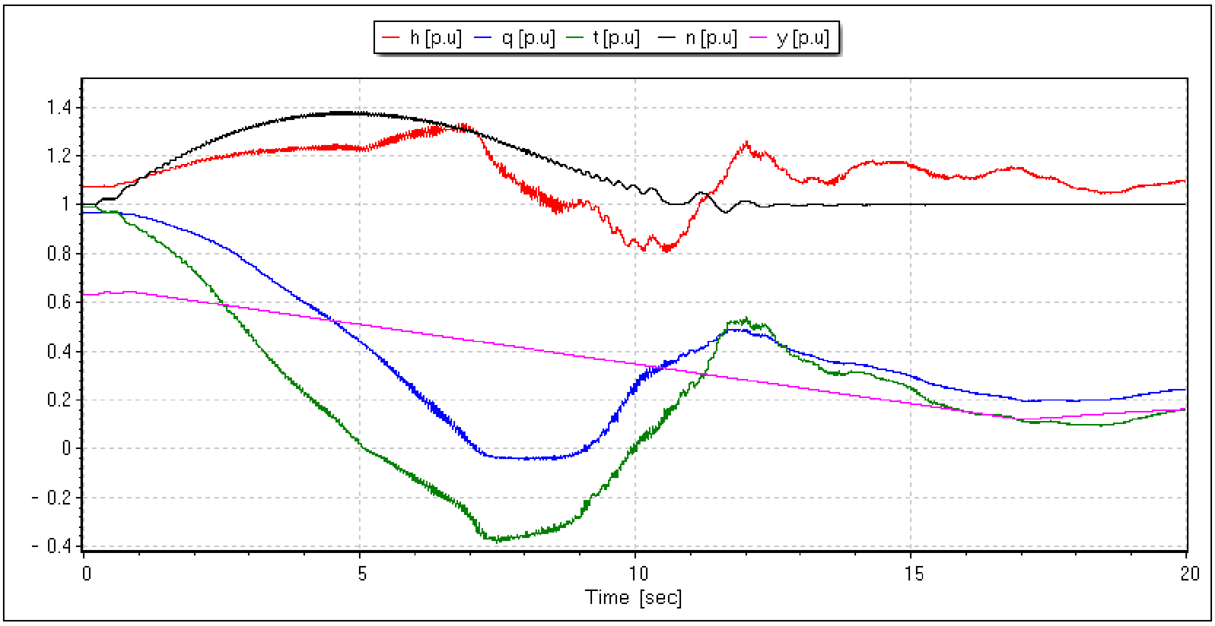

Figure 18 Pump-turbine transient behavior obtained with hydroelectric model and resulting from low voltage profile at the power network of the form 9 of RTE Grid Code considering profile of case 1 of Figure 16.

Figure 19 presents the voltage profile of the case 2, while Figure 20 and Figure 21 show respectively the comparison of the pump-turbine rotational speed and output power obtained with the electrical and hydroelectric models. For this load case, it could be noticed that even if the turbine governor contributes to the system stability, the difference between both results are small. For both simulation models the unit successfully complies with the grid code requirements as the unit remains in normal operation after the voltage drop.

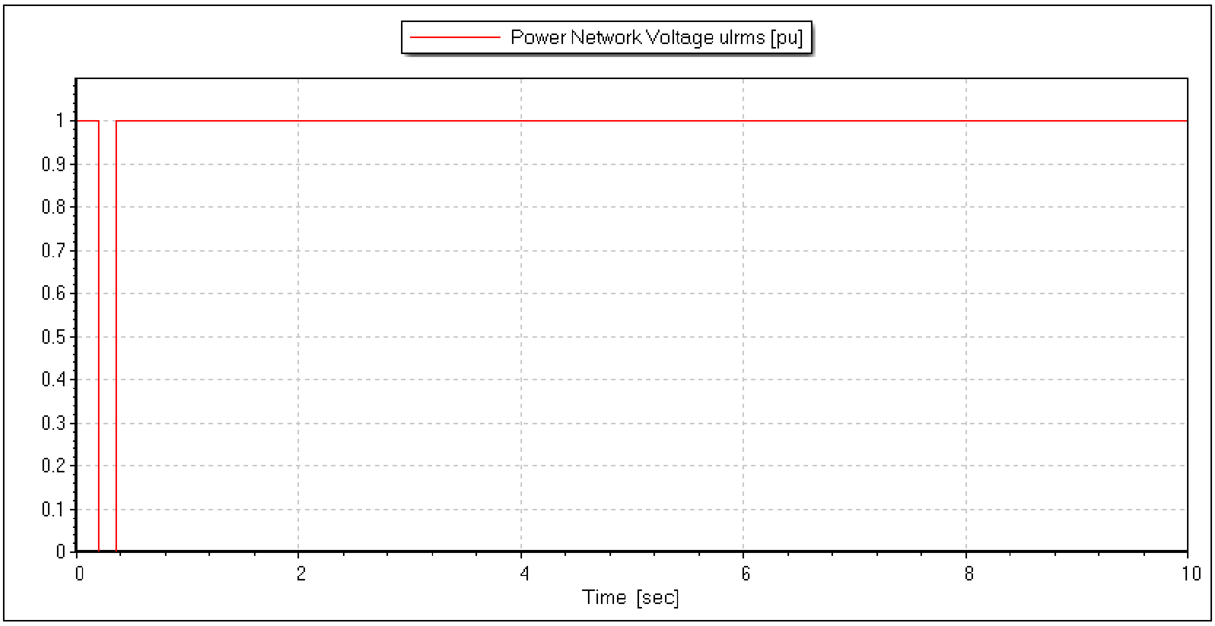

Figure 19 Low voltage profile at the power network of the form 9 of RTE Grid Code considered for the case 2 of Figure 16.

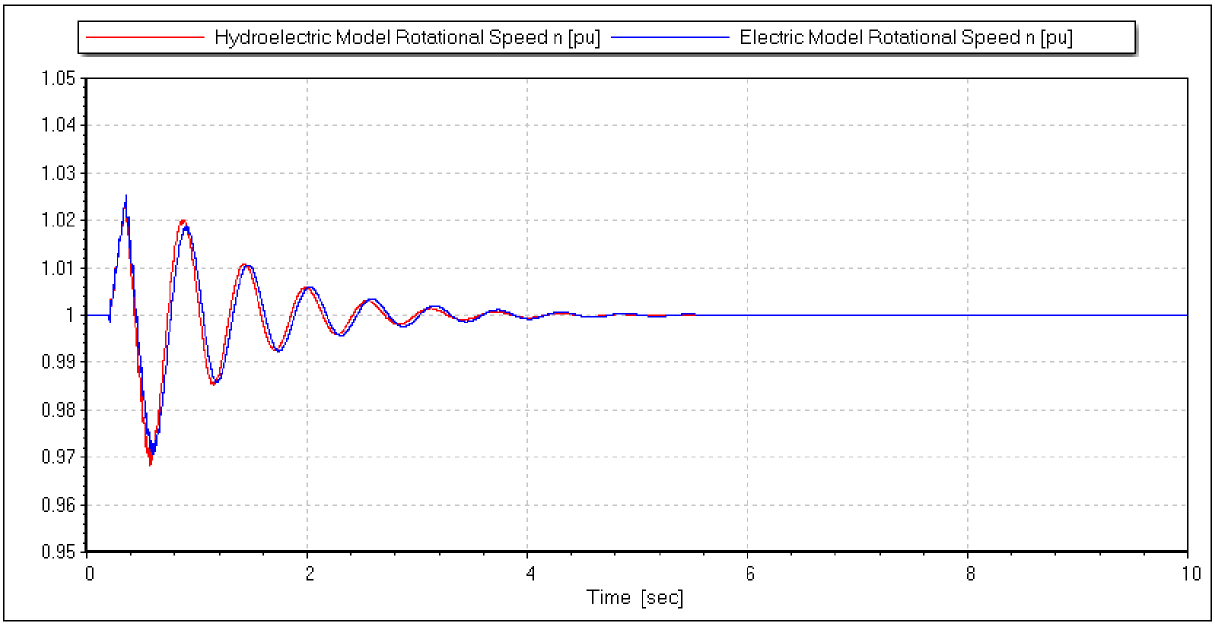

Figure 20 Comparison of the simulation results of the rotational speed of the unit obtained with hydroelectric and electrical models and resulting from low voltage profile at the power network of the form 9 of RTE Grid Code considering profile of case 2 of Figure 16.

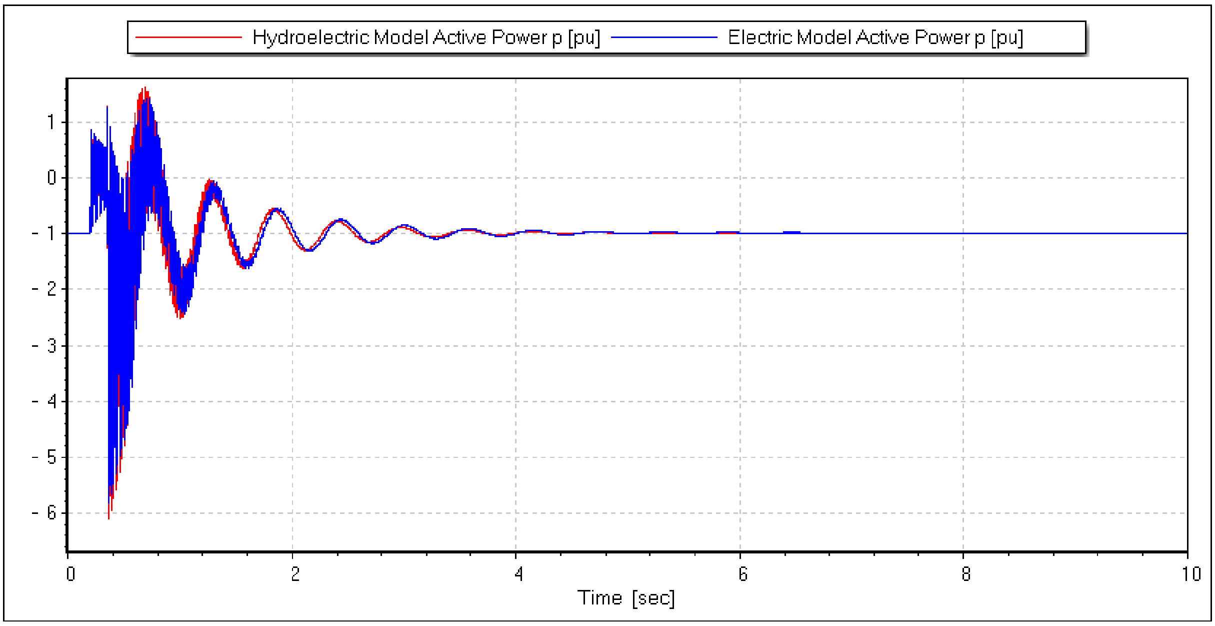

Figure 21 Comparison of the simulation results of the active power of the unit obtained with hydroelectric and electrical models and resulting from low voltage profile at the power network of the form 9 of RTE Grid Code considering profile of case 2 of Figure 16.

5.4. Form 14: frequency primary control capacity

The form 14 evaluates the capability of the unit to provide frequency primary control, i.e. the capacity of the unit to reduce or increase output power respectively in case of power network frequency increase or decrease, within 30 s, and then to maintain this power variation for at least 15 minutes. The frequency primary control capacity of a generating unit is given by the "permanent speed droop" of the unit Bp which is defined as follow:

$$Bp = \frac{\Delta f / f_{ref}}{\Delta P / P_{ref}}$$

Where Δf: frequency deviation [Hz]
f_{ref}: power network reference frequency [Hz], 50 Hz in Europe
ΔP: power variation induced by the frequency variation Δf [MW]
P_{ref}: reference power of the unit [MW]

Figure 22 shows the typical test to be performed on site to assess the primary control capability for RTE. It consists in introducing a fictive frequency deviation from external signal, and then measuring the power response, and checking that the primary control power ΔP corresponding to the unit permanent speed droop Bp is delivered in less than 30 s, and also that 50% of this power variation was already achieved after 15 s for units of minimal nominal power of 40 MW. During the test, different frequency deviations, positive and negative and ranging from 15 mHz to 200 mHz have to be tested, and also for different initial conditions of active power.

This test was performed by means of numerical simulation with the hydraulic model, and the simulation results of one of the 7 load cases to be performed is presented in Figure 23. It could be noticed that, with the present setting of the turbine governor, the primary control requirements are not fulfilled. The unit is capable to provide the regulating power, but not in the expected time.

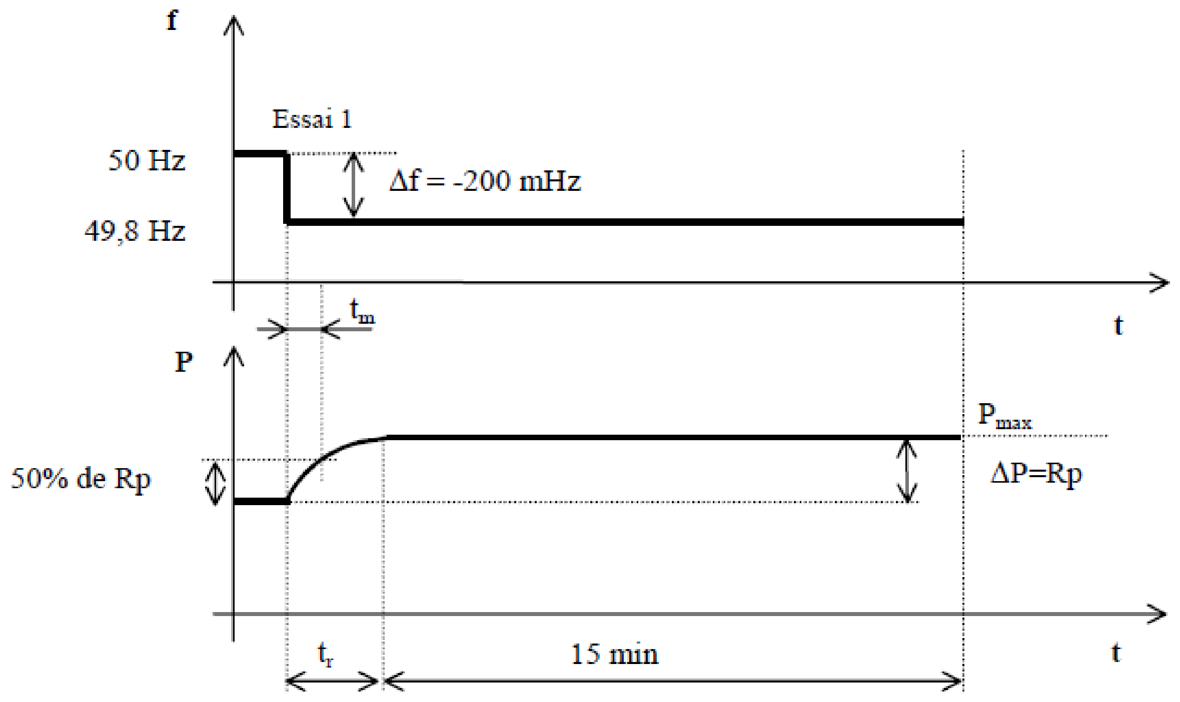

Figure 22 Power time response requirements of the form 14 of RTE Grid Code (source RTE [10]) for frequency primary control.

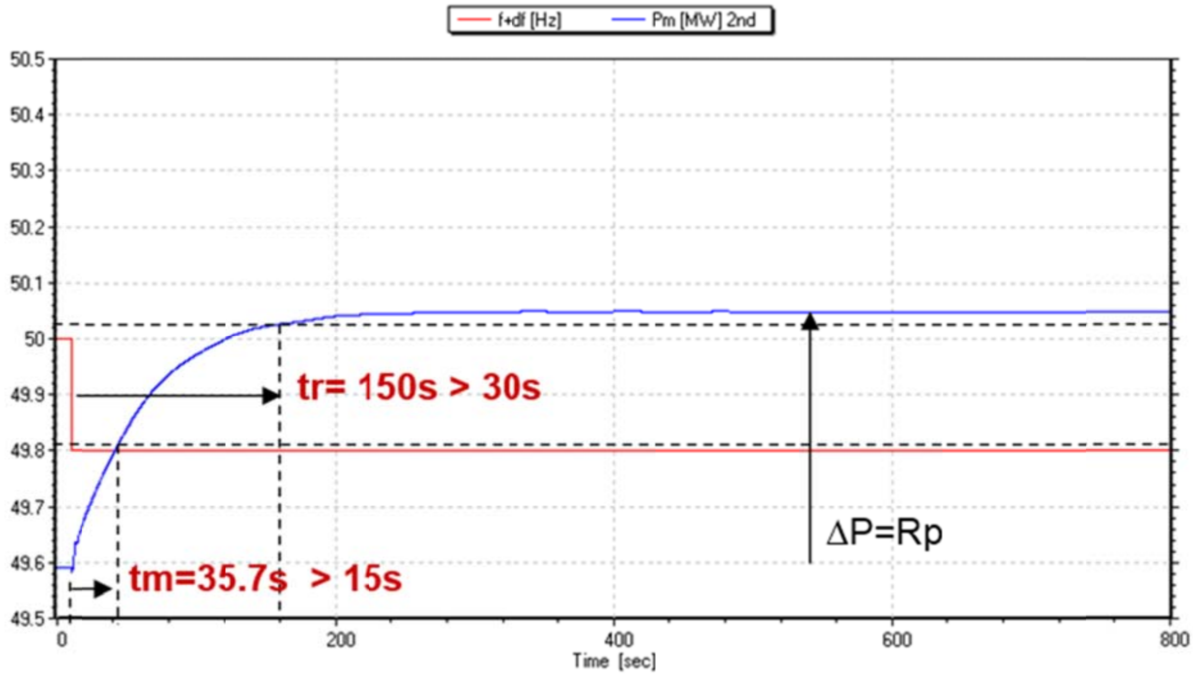

Figure 23 Simulation results of the active power time evolution resulting from primary control test case of form 14 with frequency drop of Δf =-200 mHz.

5.5. Form 15: frequency secondary control capacity

The form 15 evaluates the capability of the unit to provide frequency secondary control, i.e. the capacity of the unit to reduce or increase output power according to a power setpoint change, within 800s, and then in 133s. The new power setpoint should be maintained for at least 15minutes. During the test to be performed in-situ, it is requested that the power output signal remains within minimum and maximum boundary limits, and also that the general behavior is not oscillating.

Figure 24 and Figure 25 present the simulation results for two tests of power setpoint increase respectively in 800s and in 133s. It could be noticed that for the variation of power setpoint in 800s, the output power of the unit remains within the limits, while for the ramp in 133s, the power output is below the minimum limit over 80% of the ramp duration. With the present turbine governor setting, the unit fulfills the 800s ramping capability, while the ramping capability in 133s is not fulfilled.

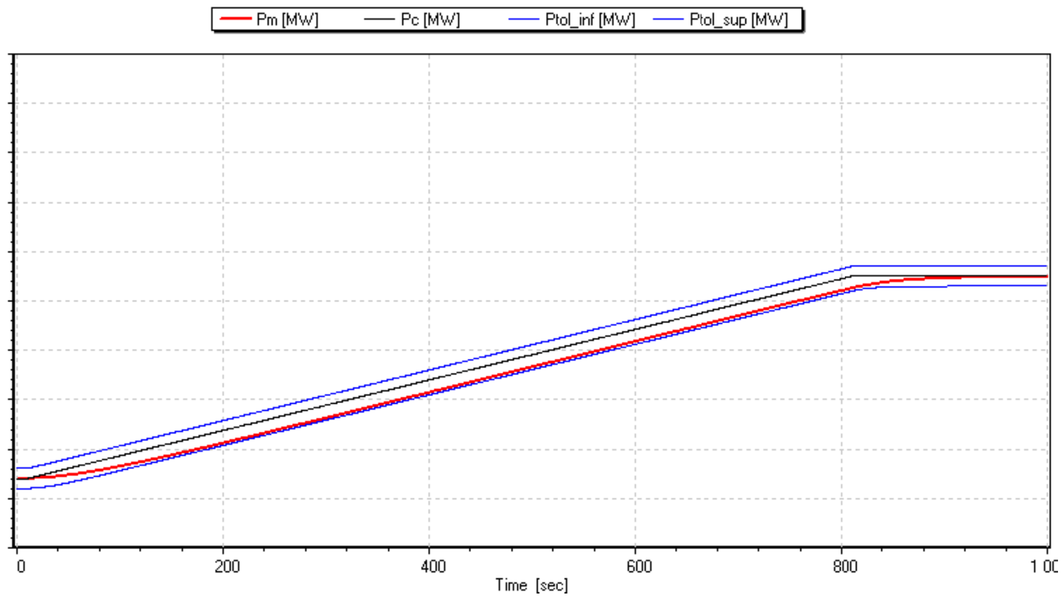

Figure 24 Simulation results of the active power time evolution resulting from secondary control test case of form 15 with active power setpoint ramp of 800s.

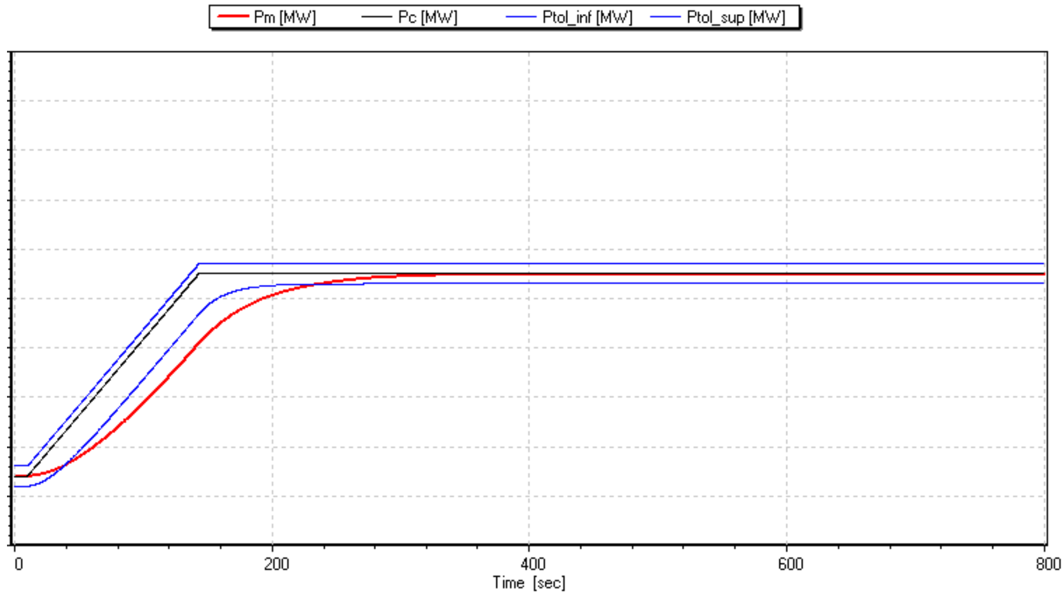

Figure 25 Simulation results of the active power time evolution resulting from secondary control test case of form 15 with active power setpoint ramp of 133s.

6. Recommandations for grid code compliance assessment by numerical simulation

Table 2 summarizes the simulation model which are recommended for the different forms of the RTE Grid Code, and provides comments on the results obtained on the present study.

Table 2 Recommendations about the simulation model to be considered for the different forms requested by the RTE Grid Code.

Form N°	Description	Conformity assessment	Simulation model used	Recommended simulation model for the present study	Comments
5	Constructive capacity in reactive power	Simulation	None	None	Active and reactive allowed operating domain to be determined according to manufacturer data and equipment parameters.
6	Voltage stability in case of small perturbation	Simulation	Electrical and Hydroelectric	**Electrical**	Induces very small frequency deviations with very limited turbine governor contribution.
7	Stability in case of load transfer from 4 transmission lines to 3 transmission lines	Simulation	Electrical and Hydroelectric	**Hydroelectric**	**The turbine governor improves the active power and rotational speed stabilization, but the compliance criteria are fulfilled with both models.**
8	Stability in case of short-circuit	Simulation	Electrical and Hydroelectric	**Hydroelectric**	**The turbine governor improves significantly the active power and rotational speed stabilization, and the compliance criteria are fulfilled with both models**
9	Stability in case of low voltage at power network	Simulation	Electrical and Hydroelectric	**Hydroelectric**	**The turbine governor improves the active power and rotational speed stabilization, but the compliance criteria are fulfilled only for cases 2 to 12 with both models, while case 1 is not fulfilled with both models also.**
10	Voltage stability in case of frequency deviation	Simulation	Electrical and Hydroelectric	**Electrical**	Induces very small frequency deviations with very limited turbine governor contribution.
14	Frequency primary control capacity	In situ tests	Hydraulic	**Hydraulic**	The frequency primary control is ensured by the turbine governor only.
15	Frequency secondary control capacity	In situ tests	Hydraulic	**Hydraulic**	The frequency secondary control is ensured by the turbine governor only.
16	Frequency secondary control capacity	In situ tests	None	None	Simulation not relevant.
17-19	Primary and secondary voltage control	In situ tests	None	None	As for forms 6 and 10, electrical model is expected to be sufficient
20-22	Power reduction capacity, isolated grid operation, fast restart capability	In situ tests	None	None	Not investigated, but hydroelectric model is expected for form 21 related to isolated grid.

The following comments can be formulated from the Table 2 :

- Forms 6 to 10 have to be evaluated by means of simulations; the results obtained for the present test case shows that the forms 6 and 10 related to voltage stability do not require hydroelectric simulations, because the frequency deviations induced by the perturbations remains small, and as a consequence, the turbine and related governor do not contribute significantly to system stabilization;
- For forms 7 and 9, the frequency deviations induced by either load transfer from 4 to 3 lines, or the low voltage ride through, LVRT, induces frequency deviations so that the turbine and related governor contributes significantly to the system stabilization, and thus results obtained with hydroelectric model feature shorter stabilization than with electrical model only; but for the present case study, the compliance criteria are fulfilled with both models;
- For the form 8, related to short-circuit, the stabilization time was considerably improved from 9.5 s, which is hardly compliant with the criteria of 10 s, down to 6.7 s by considering the hydroelectric model instead of the electrical model alone; the stability is improved because the frequency deviations obtained during the short-circuit are significant enough to induce a reaction of the turbine governor which contributes to system stabilization**, thus, it is highly recommended to use the hydroelectric model in such cases in order to avoid the underestimation of the system damping;**
- The hydroelectric model is recommended for the transmission line load transfer, the short-circuit, and the low voltage ride through, i.e. the forms 7, 8 and 9; but one can notice that electrical model results are always pessimist, therefore, if the results obtained with the electrical model are not compliant, it is worth to perform hydroelectric simulation as higher damping will be achieved through the turbine and related governor;
- In the present test case, no Power System Stabilizer, PSS, was used, its use will certainly contribute to the active power stabilization and can improve the situation with respect to the stabilization time;
- In the present study the main contribution of the turbine and related governor was obtained from the speed control loop, featuring higher gain, and therefore higher contribution than the power control loop; thus, the conclusions obtained here can be different for a different turbine governor; but the trend of improving the system stability with the hydraulic system will probably remain;
- For the forms 14 and 15, related to frequency primary and secondary control, only hydraulic model was considered as active power response time depends almost exclusively on the turbine governor performances.

7. Conclusions

This paper presents the grid code compliance assessment of a pumped storage power plant by means of numerical simulations considering electrical, hydraulic or hydroelectric models. The simulation results obtained for the present test case have shown that:

- For existing power plant, it is very important to validate the simulation model including the control parts, by comparison with on-site measurements, in order to reduce as much as possible the uncertainty on the system parameters, control structure and associated parameters;
- For voltage stability load cases, electrical models are sufficient;
- For frequency primary and secondary control performances, hydraulic models are sufficient;
- However, hydroelectric models have to be considered for load cases such as short-circuits, low voltage ride through, and transmission line load transfer;
- The low voltage ride through requirements cannot be fulfilled if the overall pattern (case 1 of Figure 16) of voltage is considered; this load case appears to be problematic, as the only solution to improve this situation would be an increase of the total inertia of the unit, to limit frequency deviation during the low voltage phase, and hopefully avoid loss of synchronism and over speed of the unit, as the fastest guide vane closure was already achieved during the simulation of this load case;
- Contribution of Power System Stabilizer, PSS, was not evaluated here;
- The hydraulic turbine and related governor improves the system stability and associated stabilization time; this is mainly due to the speed control loop which gain is higher than the power control loop; thus, improvements are obtained only for load cases leading to significant speed deviations;
- Different turbine governor may lead to different results, but in general hydraulic system will contribute to improve the system stability; as a result, if grid code requirement is not fulfilled with an electrical model, it is strongly recommended to perform hydroelectric simulations.

For the present test case, and according to RTE requirements, only the forms related to electrical faults have to be evaluated by means of numerical simulations. However, some of the forms to be evaluated by on-site measurements can be anticipated by numerical simulations, and in case identify early potential problems, and allow for possible solution evaluation.

Regarding investment choices, too simple simulation model may lead to under optimized solution since the present case study demonstrates that some grid code performances are hardly achieved with the electrical model alone, while the complete hydroelectric model provides robust and unquestionable results. According to the results obtained for the present pumped storage, the owner can envisage quite an extensive power plant upgrade with a certain confidence, as the frequency primary and secondary control can be improved by optimizing the turbine governor parameters.

8. Acknowledgements

The authors would like to thank gratefully EDF-CIH for the authorization to publish the main results of the present study.

9. Nomenclature

A:	pipe cross section [m^2]	n:	per unit rotational speed $n=N/N_R$ [pu]
D_{ref}:	machine reference diameter [m]	p:	static pressure [Pa]
H:	net head [m]	q:	per unit discharge $q=Q/Q_R$ [pu]
Q:	discharge [m^3/s]	p:	pressure [Pa]
N:	rotational speed [rpm]	t:	time [s]
P:	power [W]	t:	per unit torque $t=T/T_R$ [pu]
T:	Torque [Nm]	u:	per unit voltage [pu]
a:	pipe wave speed [m/s]	y:	turbine guide vane opening [-]
h:	piezometric head $h=z+p/(\rho g)$ [m]	Z:	elevation above a datum [m]
h:	per unit head $h=H/H_R$ [pu]	$_R$:	subscript for rated
g:	gravity [m/s^2]		

References:

[1] **Canay, I. M.,** "Extended synchronous machine model for calculation of transient processes and stability", Electric machines and Electromechanics, vol. 1, pp. 137-150, 1977.

[2] **Canay, I. M.,** "Physical significance of sub-subtransient quantities in dynamic behaviour of synchronous machines", Electric Power Applications, IEE Proceedings B, (Volume:135 , Issue: 6), pp. 334-340, Nov. 1988.

[3] **Fisher, R. K., et al.,** "A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe", Louisville, USA, Hydrovision 2012.

[4] **Jaeger, R. C.**, "Fluid transients in hydro-electric engineering practice ".Glasgow: Blackie, 1977.

[5] **Koritarov, V.,** "Modeling and Analysis of Value of Pumped Storage Hydro", NHA Annual Conference 2013, Washington, DC, USA. http://www.dis.anl.gov/psh

[6] **Martins, N., et al.,** "The integration of large amounts of renewable energy in the Portuguese Power System", SHF : «Pumped storage Powerplants», Lyon, nov. 2011.

[7] **Nicolet, C.,** "Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems", Thesis EPFL n° 3751, 2007, (http://library.epfl.ch/theses/?nr=3751).

[8] **Nicolet, C., Greiveldinger, B., Hérou, J.-J., Kawkabani, B., Allenbach, P., Simond, J.-J., Avellan, F., "**High Order Modeling of Hydraulic Power Plant in Islanded Power Network", IEEE Transactions on Power Systems, Vol. 22, Number 4, November 2007, pp.: 1870-1881.

[9] **Paynter, H. M.,** "Surge and water hammer problems". Transaction of ASCE, vol. 146, p 962-1009, 1953.

[10] **RTE**, Gestionnaire du réseau de transport d'électricité, Référentiel Technique, 1.2.2009, pp. 1-502.

[11] **Sapin, A.,** "Logiciel modulaire pour la simulation et l'étude des systèmes d'entraînement et des réseaux électriques", Thesis EPFL n° 1346, 1995, (http://library.epfl.ch/theses/?nr=1346).

[12] **Souza, O.H., Jr., Barbieri, N., Santos, A.H.M.,** "Study of hydraulic transients in hydropower plants through simulation of nonlinear model of penstock and hydraulic turbine model", IEEE Transactions on Power Systems, vol. 14, issue 4, pp. 1269 – 1272, 1999.

[13] **U.S. Energy Information Administration,** "International Energy Outlook (IEO) 2013", DOE/EIA-0484 (2013), July 2013. http://205.254.135.7/forecasts/ieo/pdf/0484(2013).pdf

[14] **Wylie, E. B. & Streeter, V.L.,** "Fluid transients in systems". Prentice Hall, Englewood Cliffs, N.J, 1993.

The Authors

Christophe Nicolet graduated from the Ecole polytechnique fédérale de Lausanne, EPFL, in Switzerland, and received his Master degree in Mechanical Engineering in 2001. He obtained his PhD in 2007 from the same institution in the Laboratory for Hydraulic Machines. Since, he is managing director and principal consultant of Power Vision Engineering Sàrl in Ecublens, Switzerland, a company active in the field of optimization of hydropower transients and operation. He is also external lecturer at EPFL in the field of “Transient Flow in Systems”.

Basile Kawkabani received his master degree in 1978 from SUPELEC, Ecole Supérieure d’Electricité in Paris France, and his PhD degree in 1984 in Electrical Engineering from the Ecole polytechnique fédérale de Lausanne, EPFL, in Switzerland. From 1992 to 2010, he was lecturer and research associate at the EPFL Electrical Machinery Laboratory. He is currently a senior scientist in STI Scientists Group (Electrical Machinery - EPFL), and senior member of the IEEE. His interests include modeling of power systems, power system stability and control.

Thierry Singainy graduated from ENSEM (Ecole Nationale Superieure d'Electricité et de Mécanique) in Nancy; he was awarded as electrical engineer in 2011. He has been working with Electricité de France since 2011. He drafts the detailed design documents for the electromechanical equipment and supervises the generator renovation or reconstruction work for projects that he is in charge of, as well as supervising the contractors.

Jean-Louis Drommi graduated from Institut National Polytechnique de Grenoble; he was awarded as electrical engineer in 1986 and received an advanced study diploma in automation. He has been working with Electricité de France since 1987 at several technical positions both in hydro and nuclear field. He now leads a team of electrical engineer at the Hydro Engineering Center in Grenoble France.

Patrick Grillot graduated from Institut National Polytechnique de Grenoble; he was awarded as hydraulic engineer in 1990. He has been working with Electricité de France since 1990 as design and commissioning engineer for many hydro project. He now leads a team of hydraulic and mechanical engineers at the Hydro Engineering Center in Le Bourget du Lac France.

10. ANNEXE 1: Modeling of the Hydraulic machinery and systems in SIMSEN

By assuming uniform pressure and velocity distributions in the cross section and neglecting the convective terms, the one-dimensional momentum and continuity balances for an elementary pipe filled with water of length *dx*, cross section *A* and wave speed *a*, see Figure 26, yields to the following set of hyperbolic partial differential equations [14]:

$$\begin{cases} \frac{\partial h}{\partial t} + \frac{a^2}{gA} \cdot \frac{\partial Q}{\partial x} = 0 \\ \frac{\partial h}{\partial x} + \frac{1}{gA} \cdot \frac{\partial Q}{\partial t} + \frac{\lambda |Q|}{2gDA^2} \cdot Q = 0 \end{cases} \quad (1)$$

The system (1) is solved using the Finite Difference Method with a 1st order center scheme discretization in space and a scheme of Lax for the discharge variable. This approach leads to a system of ordinary differential equations that can be represented as a T-shaped equivalent scheme [4], [9], [12] as presented in Figure 27. The RLC parameters of this equivalent scheme are given by:

$$R = \frac{\lambda \cdot |\overline{Q}| \cdot dx}{2 \cdot g \cdot D \cdot A^2} \qquad L = \frac{dx}{g \cdot A} \qquad C = \frac{g \cdot A \cdot dx}{a^2} \quad (2)$$

Where λ is the local loss coefficient. The hydraulic resistance R, the hydraulic inductance L, and the hydraulic capacitance C correspond respectively to energy losses, inertia and storage effects.

The model of a pipe of length *L* is made of a series of n_b elements based on the equivalent scheme of Figure 27. The system of equations relative to this model is set-up using Kirchoff laws. The model of the pipe, as well as the models of valve, surge tank, hydraulic turbines, etc, are implemented in the EPFL software SIMSEN developed for the simulation of the dynamic behavior of hydroelectric power plants, [7], [11]. The time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4th order procedure.

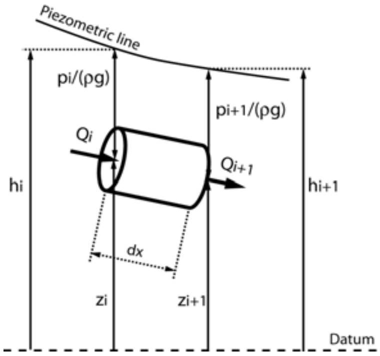

Figure 26 Elementary hydraulic pipe of length dx.

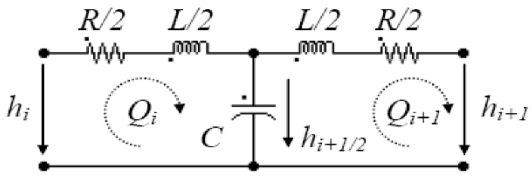

Figure 27 Equivalent circuit of an elementary pipe of length dx.

The modeling approach based on equivalent schemes of hydraulic components is extended to all the standard hydraulic components such as valve, surge tanks, air vessels, cavitation development, Francis pump-turbines, Pelton turbines, Kaplan turbines, pump, etc, see [7]. The hydraulic machines are modelled with 4 quadrants characteristics defined by speed factor N_{11}, the discharge factor Q_{11}, and the torque factor T_{11} defined as follows:

$$N_{11} = \frac{N \cdot D_{ref}}{\sqrt{H}} \qquad Q_{11} = \frac{Q}{D_{ref}^{\ 2} \cdot \sqrt{H}} \qquad T_{11} = \frac{T}{D_{ref}^{\ 3} \cdot H} \quad (3)$$