Hydroelectric Interactions with Variable Speed and Fixed Speed Machines in Pumping Mode of Operation

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Abstract

This paper presents the modelling, simulation and analysis of a high head 2x200 MW pumped storage power plant considering both variable speed and fixed speed technology with focus on pumping mode of operation. First, the model of the power plant setup with the simulation software SIMSEN is presented. On the hydraulic side, the simulation model takes into account the upper reservoir, the long gallery, the surge tank, the penstock, 2 multi-stages pumps, and the tailrace tunnel connecting to the lower reservoir. On the electrical side, the simulation model takes into account the motors and related control system, the transformers, the transmission lines and the connection to the 230 kV power network. For comparison purposes, the motor is modelled with both fixed speed and variable speed technology. The variable speed motor model comprises a Doubly Fed Asynchronous Motor equipped with a back-to-back VSI (Voltage Source Inverter) cascade. Then, the dynamic behaviour of the power plant is simulated in pumping mode with both technologies and compared in case of: (i) pump start-up, (ii) short-circuit on transmission lines and (iii) standard grid code voltage drop at power network. System stability and possible hydroelectric interactions of the pumped storage power plant are presented and discussed for the 3 above mentioned scenarios.

1 Introduction

The selection of appropriate technology between variable speed and fixed speed machine during feasibility study of new pumped storage scheme is a challenging techno-economic task. Both technologies offer advantages and disadvantages that have to be carefully assessed as they depend strongly on the site characteristic. If some technical aspects such as efficiency, operating range, submergence, equipments volume and related excavation, etc, can be reasonably evaluated, some aspects related to system stability, regulating services and other ancillary benefits are more difficult to address. Moreover, Transmission System Operators, TSO, require demonstrating the capability of new units to withstand typical power network faults and to comply with Grid Codes, [7]. In this context, time domain simulation of the dynamic behaviour of the whole pumped storage power plant including the hydraulic circuit, the electrical installations, the control system and the power network can provide useful insights for decision making.

Variable speed pump-turbine units have become nowadays major partner to increase stability of electrical power networks due to their high level of operating flexibility, see Figure 1. Indeed, variable speed pump-turbine units offer several advantages for both pumping and generating modes, [2], [3], [5], [6], [17], [18] such as: (i) possibility of active power control in pumping mode, (ii) efficiency increase and wide range of operation in generating mode especially under partial load, (iii) network stability improvement by reactive power control, (iv) network stability improvement by instantaneous active power injection in the grid (flywheel effect), and (v) higher head variations can be supported. Extended operating range in pump mode and higher efficiency in turbine mode achievable with variable speed units are illustrated in Figure 1.

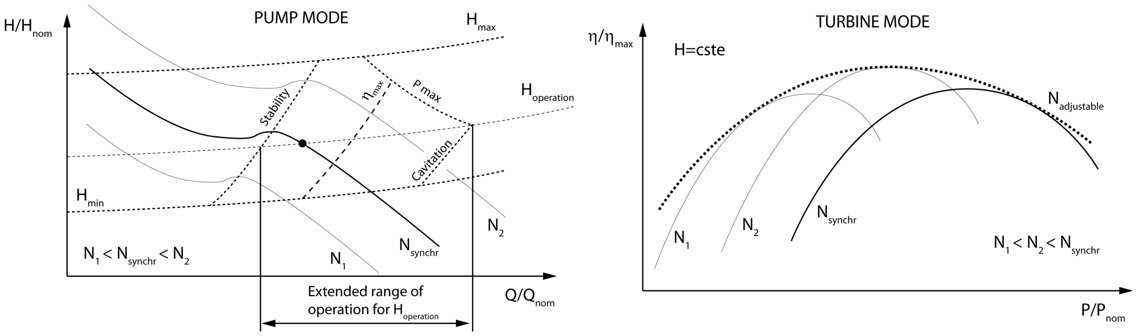

Figure 1 Advantages of variable speed machines compared to fixed speed machines for pump (left) and turbine (right) mode of operation.

This paper presents the modelling, simulation and analysis of a high head pumped storage power plant considering both variable speed and fixed speed technology with focus on pumping mode of operation. The power plant is a conventional hydroelectric power plant equipped with 6 Pelton turbines of 50MW where a new pump power house of 2x200MW to be connected on the same adduction system is under feasibility study. For this project, the variable speed technology is expected to provide additional services compared to traditional fixed speed technology. Therefore, the dynamic behaviour of this power plant has been investigated by means of time domain simulation of the whole hydroelectric power plant. First, the model of the power plant setup with the simulation software SIMSEN is presented. On the hydraulic side, the simulation model takes into account the upper reservoir, the long gallery, the surge tank, the penstock, the 6 Pelton units considered at rest, 2 multi-stages pumps, and the tailrace tunnel connecting to the lower reservoir. On the electrical side, the simulation model takes into account the motors and related control system, the transformers, the transmission lines and the connection to the 230 kV power network. For comparison purposes, the motor is modelled with both fixed speed and variable speed technology. The variable speed motor model comprises a Doubly Fed Asynchronous Motor equipped with a back-to-back VSI (Voltage Source Inverter) cascade. Then, the dynamic behaviour of the power plant is simulated in pumping mode with both technologies and compared in case of: (i) pump start-up, (ii) short-circuit on transmission lines and (iii) standard grid code voltage drop at power network. System stability and possible hydroelectric interactions of the pumped storage power plant are presented and discussed for the 3 above mentioned scenarios.

2 Modeling of the Hydraulic Machinery and Systems

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 2, yields to the following set of hyperbolic partial differential equations [21]:

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

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], [15], [19] as presented in Figure 3. The RLC parameters of this equivalent scheme are given by:

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

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 3. 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, [8], [9], [10], [16]. The time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4th order procedure.

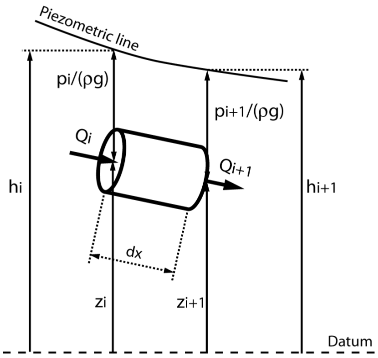

Figure 2 Elementary hydraulic pipe of length dx.

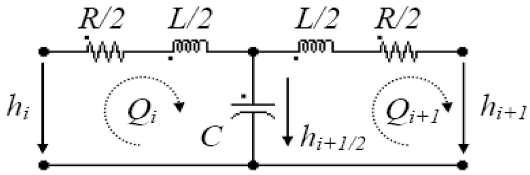

Figure 3 Equivalent circuit of an elementary pipe of length dx.

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 [8].

3 Pumped Storage Power Plant Model

The layout of the pumped storage power plant of interest is presented in Figure 4. The pumped storage is composed of upstream reservoir, a 8km long gallery, a surge tank, a 1250m long penstock, a turbine power house with 6 Pelton turbine of 50MW each and a separated pump power house equipped with two multi-stages pumps of 200MW each. The hydraulic layout of the pumped storage power plant SIMSEN model is presented in Figure 4. This model accounts for detailed water-hammer, mass oscillation phenomena and pump 4 quadrant characteristics [8]. This paper focuses on the transient behavior of the pumped storage in pump mode of operation while Pelton turbines are considered at rest. For the pump power house two technical solutions have been compared:

- fixed speed synchronous motor of 235MVA;
- variable speed (VarSpeed) doubly fed induction motor (DFIM) of 235MVA equipped with a back-to-back VSI (Voltage Source Inverter) cascade.

The electrical layout of the VarSpeed solution is presented in Figure 5 and the system characteristics are summarized in the Table 1.

The model of the synchronous motor is based for the damper winding on 1 equivalent rotor circuit in the direct-axis and 1 equivalent rotor circuit in the quadrature-axis allowing taking into account a sub-transient behavior, see [1]. The synchronous motor is controlled by an ABB Unitrol voltage regulator. The model of the induction machine is based on classical d, q Park equations expressed in a, b, c quantities. This electrical system can be divided into two sections, a transformer section and a machine section, see Figure 5. The transformer section operates as a Static Var Compensator (SVC), its main role being to exchange reactive power with the grid. The reactive power and the capacitors voltage are controlled by acting on the transformer primary side currents through the right-side converter. The main role of the machine section is to control the active power of the machine. The active power and the stator reactive power of the machine are controlled by acting on the rotor currents through the left-side converter. The detailed control structure of the transformer and machine sections are presented in [13] and [14]. For the present investigation, pseudo-continuous model of the VSI is considered for reducing the computational time without loss of accuracy for the motor general behavior, see [11], [12]. The pseudo continuous model consists of modeling the VSI by equivalent voltage sources.

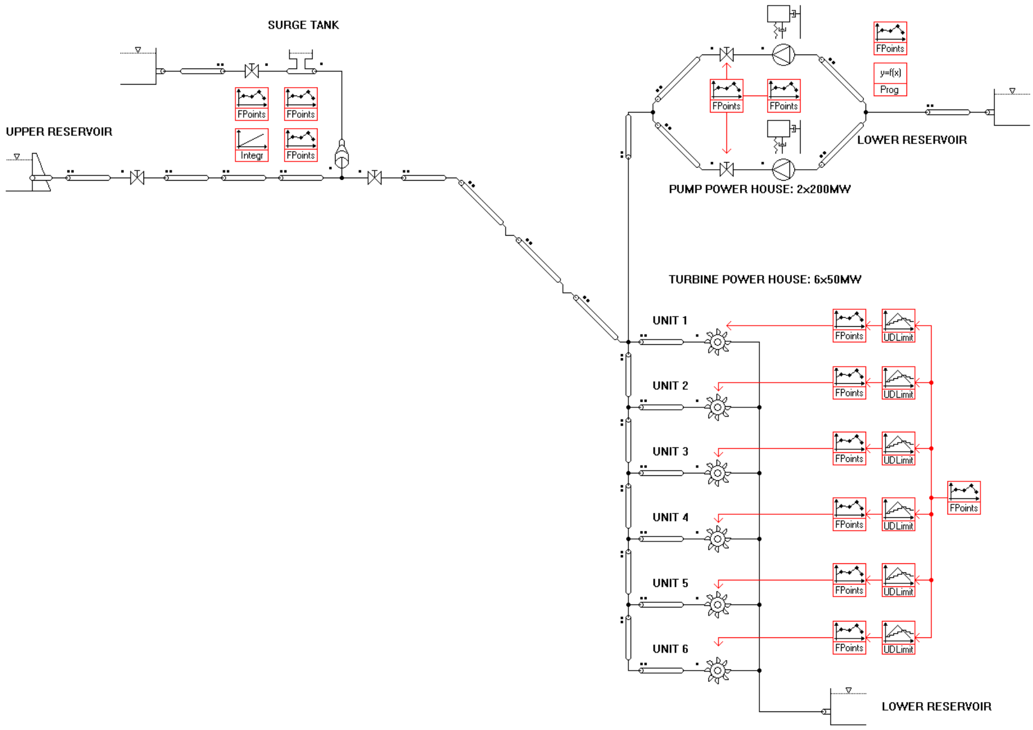

Figure 4 Pumped storage power plant layout and SIMSEN simulation model.

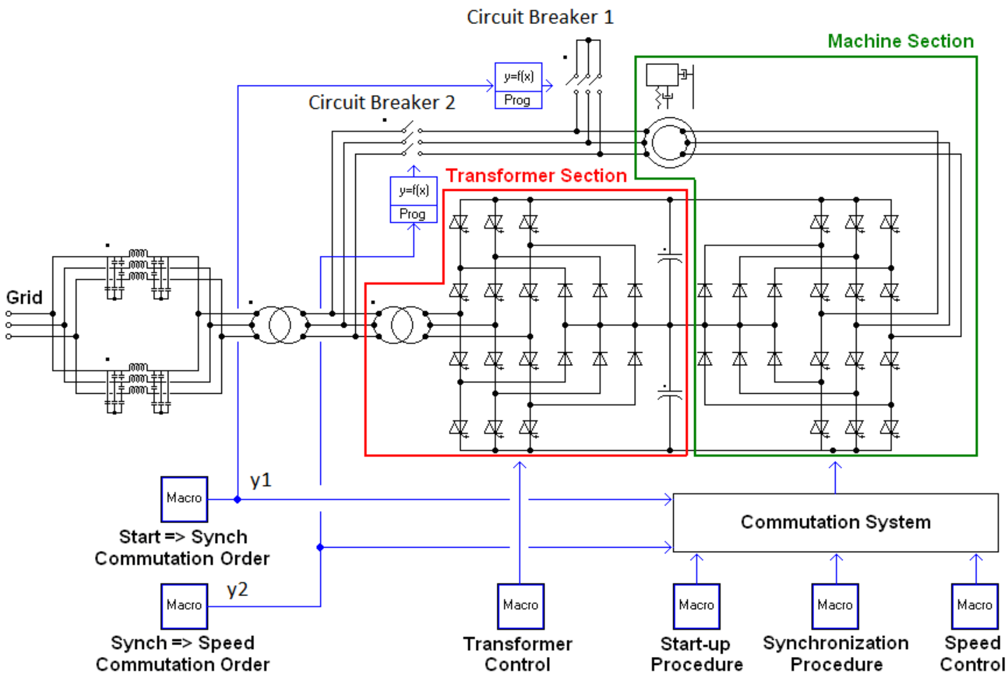

Figure 5 Electrical layout of the Doubly Fed Induction Motor.

Table 1 System characteristics.

Pumps	SM Motor	DFIM Motor	Grid
P_R=200 MW N_R=500 rpm Q_R=20 m^3/s H_R=830 mWC Nb. stages: 3 Nq per stage=33	S_n=235 MVA U_n= 18kV N_n = 500 rpm	S_n=235MVA U_n= 18kV U_{DCn}=6kV N_n = 500 rpm	Un=220kV f=50Hz

4 Pump Start-up, watering and loading

4.1 Pump start-up with variable speed unit

The start-up of large pump equipped with variable speed motor without supplementary equipment can be an issue and its feasibility and related start-up time must be evaluated at early stage of the project. The start-up of asynchronous motor is carried out with the rotor cascade by short circuiting the stator. The pump is dewatered, thus the hydraulic part can be modeled by a resistant torque function of the rotational speed and accounting for pump rotation in air, bearing losses and ventilation losses representing 2.8% of the nominal power at nominal speed. The strategy considered for the start-up is based on a stator flux oriented control, so that it is possible to control the speed and the stator flux by acting on the rotor currents of the machine. This procedure is divided in three phases:

- **phase 1:** the electromagnetic torque is set to nominal value with rotor voltage increasing proportionally to rotational speed until maximum voltage is reached;
- **phase 2:** the stator flux set point is then reduced as it depends on the current in quadrature axis which is defined in order to maximize the electromagnetic torque;
- **phase 3:** the current in quadrature axis is reduced in order to maximize the electromagnetic torque until the minimal speed for synchronization which is defined as 90% of the nominal speed, is reached.

Once the machine has reached the minimal speed required for synchronization, the stator is switched off and the stator voltage can be regulated in order to synchronize the machine with the grid. The synchronization is optimal if stator and grid voltages are equal in amplitude, frequency and phase. When these conditions are achieved the stator is connected to the grid by closing the circuit breaker number 2, see Figure 5. Then the machine switches to speed control and the nominal speed is reached with a ramp set point. The detailed start-up procedure can be found in [14]. The simulation results of the start-up of the doubly fed induction motor are presented in Figure 6. The start-up is achieved in about 260s which is reasonable time.

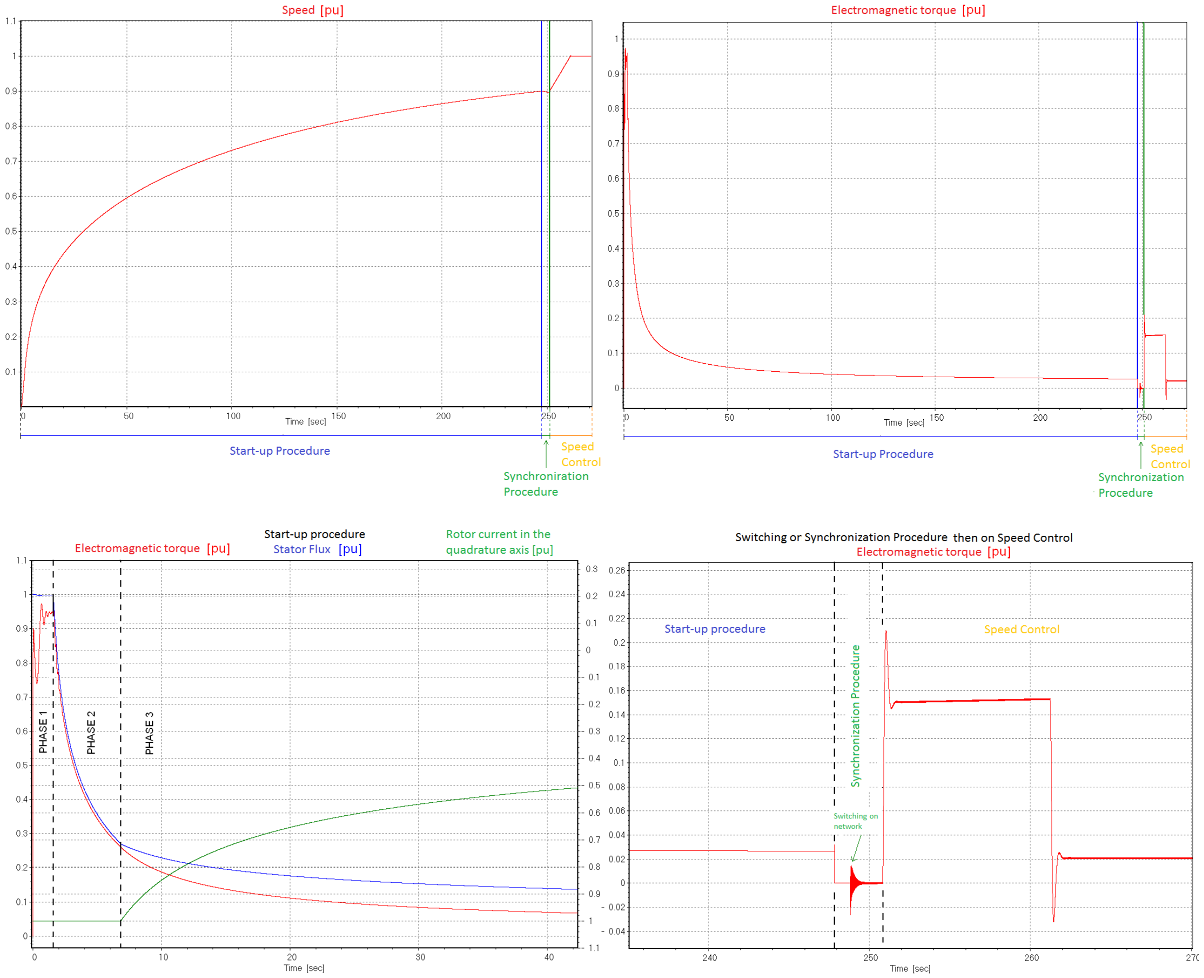

Figure 6 Simulation results of the start-up procedure of the dewatered pump with the doubly fed induction motor.

4.2 Re-watering and loading

Once the machine is connected to the grid, the pump can be re-watered and then the main inlet valve can be opened to reach normal pump operation. This procedure is simulated with VarSpeed and Fixed Speed motor assuming that the first unit is already in normal pump operation. These procedures are described in the following sub-chapters.

4.2.1 VarSpeed transient

Figure 7 presents the simulation results of the re-watering and loading of unit1 equipped with doubly fed induction motor while the unit 2, also equipped with variable speed motor is already in pump operation. This procedure can be decomposed in four phases as follows:

- **phase 0:** the unit 1 is connected to the grid but the pump is dewatered and unit 2 is in pump mode of operation; as the operation of the pump in air cannot be modeled with the steady state 4 quadrant characteristic which corresponds to operation in water, the dewatering is modeled by an external torque in order to compensate the pump torque, so that the input power corresponds to pump operation in air of about 2.8%;
- **phase 1:** the re-watering is simulated by linear variation of the external torque in 10s; thus the input power of unit 1 vary also linearly as the rotational speed is constant; as a consequence, the related variation of pressure in the pump is not modeled;
- **phase 2:** the rotational speed of the unit 1 is modified in order to have the same pressure on both sides of the spherical valve;
- **phase 3:** the main inlet valve of the pump of unit 1 is opened linearly in 20s; the discharge of the pump remains equal to zero, as the pressure at the pump outlet is equal to the pressure in the penstock;
- **phase 4:** the control of unit 1 switches from speed control to output power control; the power set point of the pump is increased linearly to nominal pump power in 25s; the power control results in rotational speed increase of the unit and leads to the increase of the net head and thus of the discharge reaching approximately the nominal value; then the unit 1 is in normal pump operation.

One may notice that the pressure equilibrium enables to suppress the pressure fluctuations in the penstock related to the spherical valve opening. Therefore this procedure contributes to reduce the possible fatigue of the penstock related to pump start-up. Moreover, one can also notice that the unit 2 which is operated also in power control features constant input power during the whole start-up procedure of unit 1.

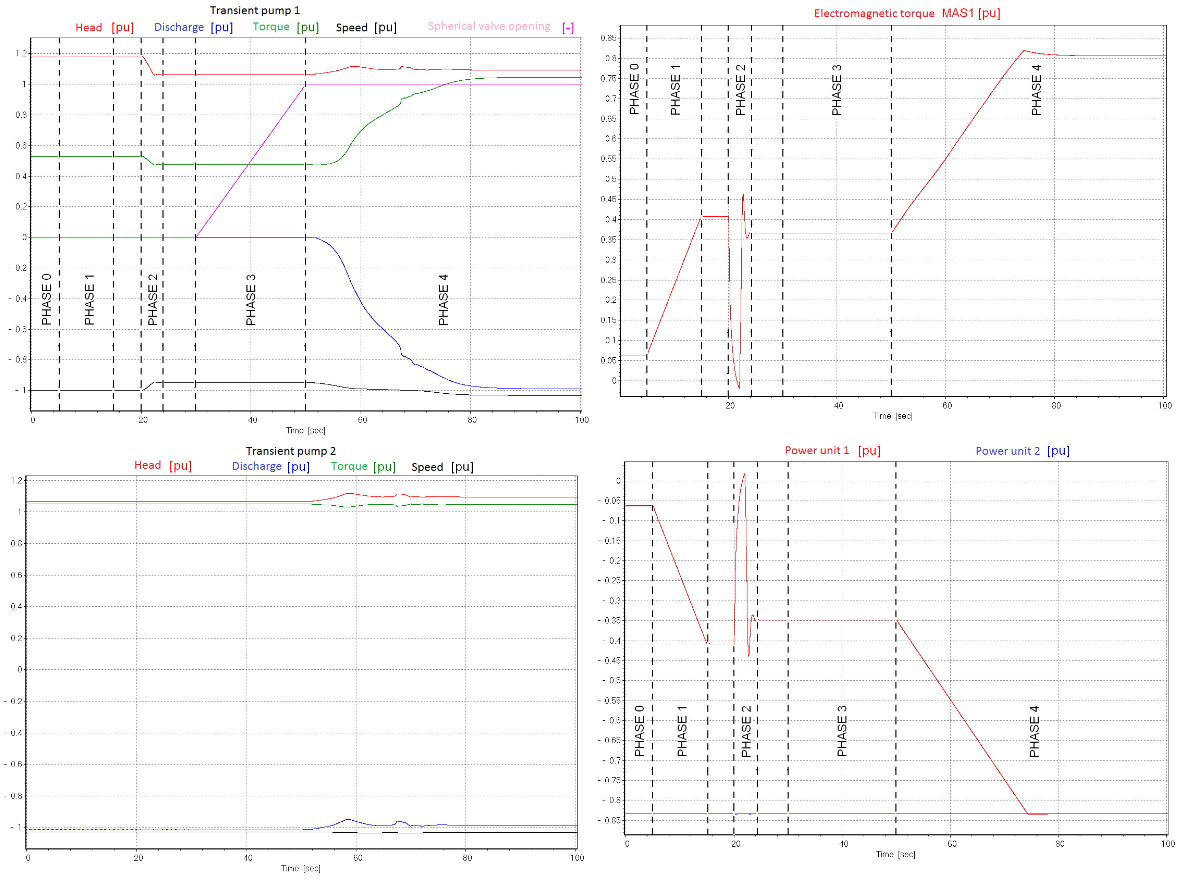

Figure 7 Re-watering of the pump and loading with the doubly fed induction motor.

4.2.2 Fixed speed transient

Figure 8 presents the simulation results of the re-watering and loading of unit 1 equipped with synchronous machine while the unit 2, also equipped with fixed speed motor is already in pump operation. This procedure can be decomposed in two phases as follows:

- **phase 0:** unit 1 is connected to the grid and unit 2 is in normal pump operation; here the operation in air is also modeled with external torque which compensate the pump torque in order to have the input power equal to the operation in air, i.e. 2.8% of the nominal power;
- **phase 1:** the re-watering is simulated by linear variation of the external torque in 10s; thus the input power of unit 1 vary also linearly as the rotational speed is constant; as a consequence, the related variation of pressure in the pump is not modeled;
- **phase 3:** the main inlet valve of unit 1 is opened linearly in 20s; at the beginning of the valve opening the discharge of unit 1 increases rapidly and produces pressure variation at the end of the penstock of about 6%; after valve opening, the unit 1 is in normal pump operation.

One may notice that the pressure fluctuation induced by the valve opening of unit 1 induces also variation of the net head of the unit 2, which experiences also input power fluctuations. These two negative effects, the pressure and the input power fluctuations, can be almost suppressed with the use of variable speed machine.

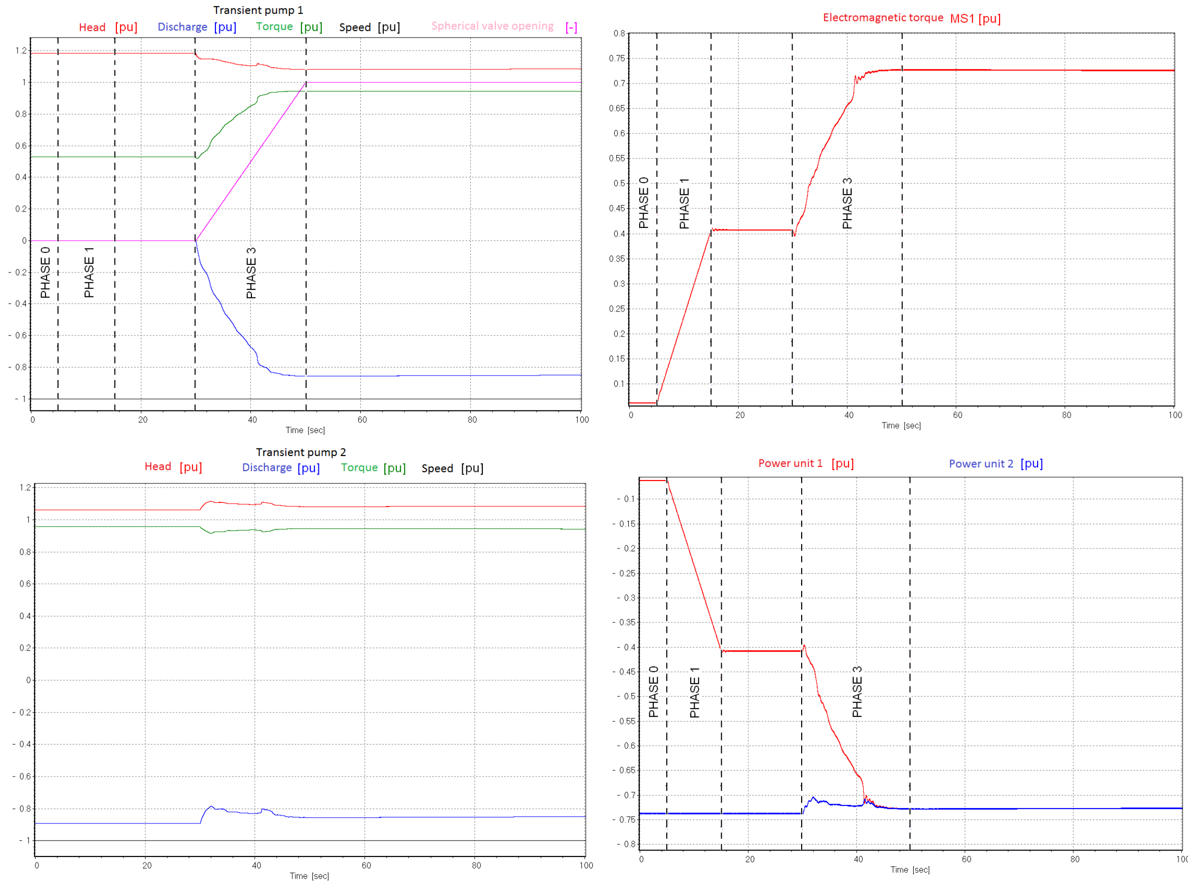

Figure 8 Re-watering of the pump and loading with synchronous motor.

5 Electrical Faults

The dynamic behavior of unit 2 in pump mode of operation is simulated in case of electrical faults on the power network with variable speed and with fixed speed machines. For both simulations the hydraulic part of the model is identical while the electrical part is adapted according to the Figure 9. The variable speed machine, in power control, is connected to the infinite 220kV power network via a main transformer and two electrical lines in parallel modeled with PI models. The fixed speed machine with voltage control is also connected to the infinite 220kV power network via a transformer and two electrical lines in parallel. The voltage regulator is an ABB Unitrol controller.

These two models are used to simulate the following electrical faults:

- short-circuit on the electrical line 2 with a duration 100ms and 250ms before the line 2 and related short-circuit is isolated by opening of circuit breaker DISJ 21 and DISJ22;
- power network voltage drop according to Transmission System Operator, TSO, Swissgrid.

The simulation results of these two electrical faults are described in the next sub-chapters.

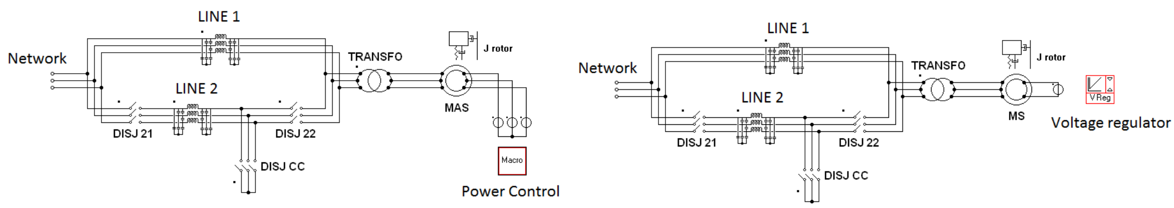

Figure 9 SIMSEN model of electrical part for the simulation of electrical faults with variable speed machine, left, and fixed speed machine, right.

5.1 Short-Circuits

The simulation results with variable speed and fixed speed motor of short-circuit on the electrical line 2 of duration of 100ms and 250ms are respectively compared in Figure 10 and Figure 11. The short-circuit of 100ms, produces strong transient electromagnetic torque characterized by a 50 Hz period of oscillation imposed by the power network. After elimination of the electrical faults by the line 2 disconnection, the unit 2 recovers normal pump operation with both technologies. In case of fixed speed machine, the electromagnetic torque oscillates with low periods which induces rotational speed oscillations and thus discharge oscillations. These oscillations are damped after 5s. In case of variable speed machine, the rotational speed drops to 99% during the short-circuit and then increases slowly to recover nominal speed after 15s. However, the input power recovers nominal value 1s after the electrical fault is eliminated.

In case of 250ms short-circuit, the variable speed machine is rather similar to 100ms results and input active power is also recovered after 1s with a speed drop of about 2%. However, in this case, the fixed speed machine does not recover the synchronism after the fault elimination, and would have to be shutdown.

In this case, the variable speed technology enables to withstand longer duration of short-circuit and thus features better dynamic behavior.

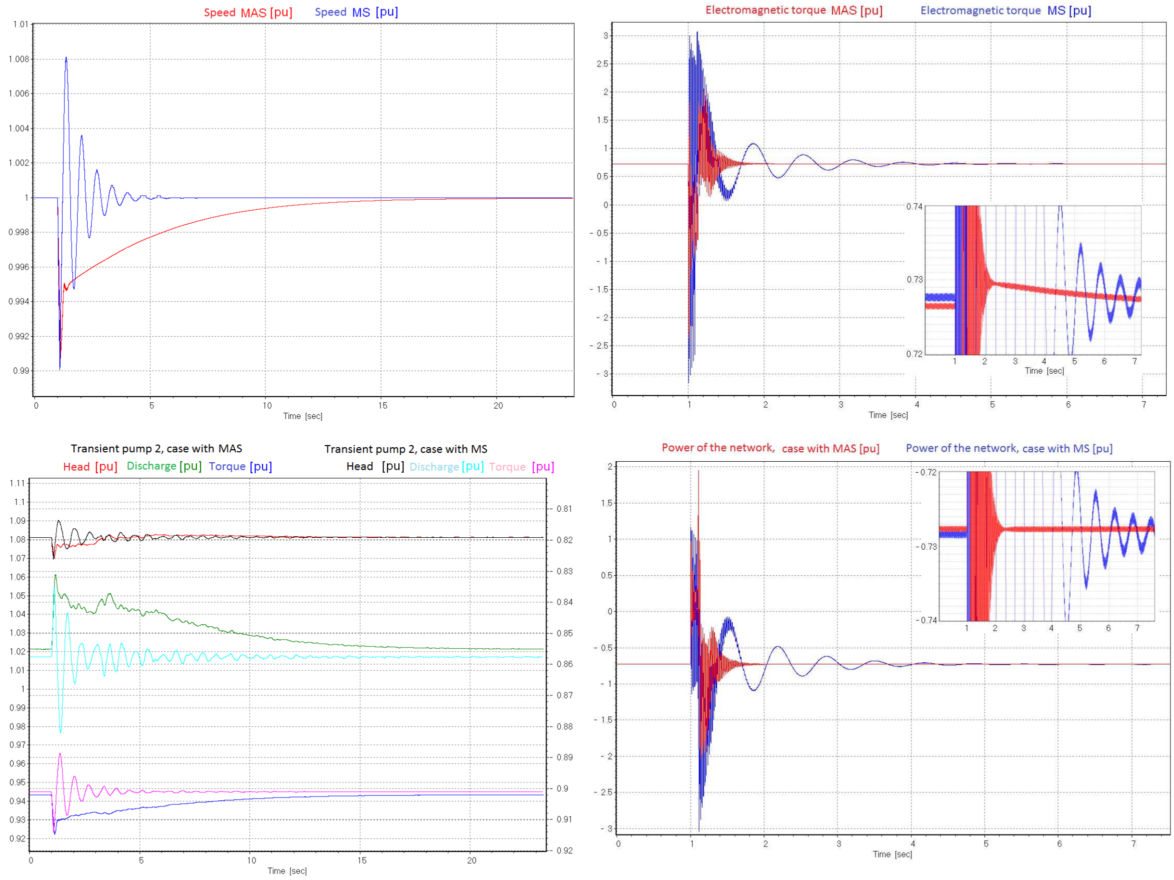

Figure 10 Comparison of the transient behavior of unit 2 in pump mode of operation resulting from short-circuit of 100ms on line 2 with VarSpeed and fixed speed motor.

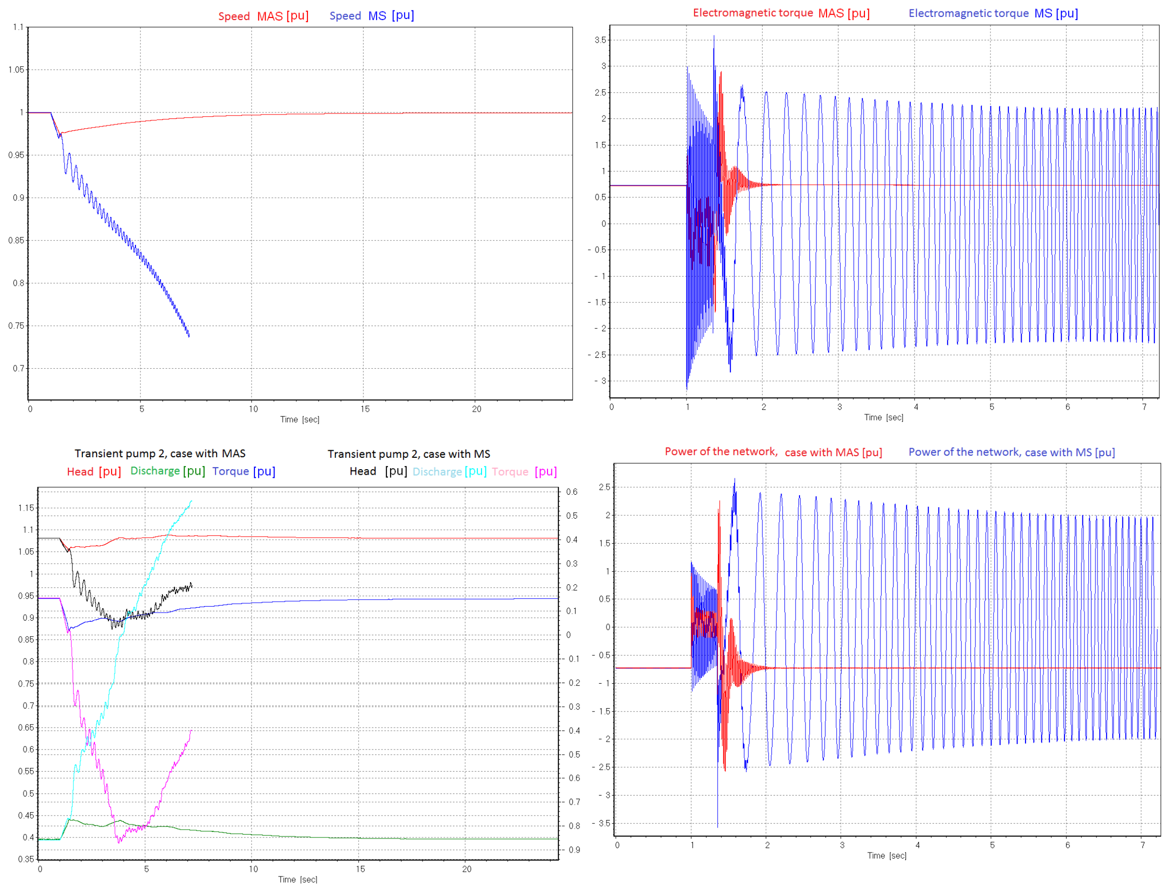

Figure 11 Comparison of the transient behavior of unit 2 in pump mode of operation resulting from short-circuit of 250ms on line 2 with VarSpeed and fixed speed technologies.

5.2 Grid Voltage Drop

Swissgrid, the Swiss TSO, requires that electrical machine remains connected to the grid when the voltage of the power network drops to zero for 150ms and then increases linearly to 90% of the nominal voltage in 1.35s as represented in Figure 12, [20]. Figure 13 presents the comparison of the simulation results of unit 2 in pump mode of operation and experiencing the voltage drop of Figure 12 with VarSpeed and fixed speed. It can be noticed that the VarSpeed machine recovers normal pump operation when the voltage reaches 90% of the nominal value while the fixed speed machine loose the synchronism and must be disconnected from the grid. During the voltage drop, the VarSpeed machine experiences a rotational speed drop of 4%, and thus the pump features large discharge and torque fluctuations. Figure 14 left shows the evolution of the pump net head as function of the discharge during the transient, evidencing the pump unstable characteristic. If the same fault is simulated with an initial rotational speed of 1.03 pu instead of 1 pu, see Figure 14 right, it can be noticed that the pump does not experience anymore unstable behavior related to the pump characteristic. Indeed, in case of high head operation, it is possible to operate the pump with a higher rotational speed in order to increase the margin with pump stability limit as illustrated in Figure 15.

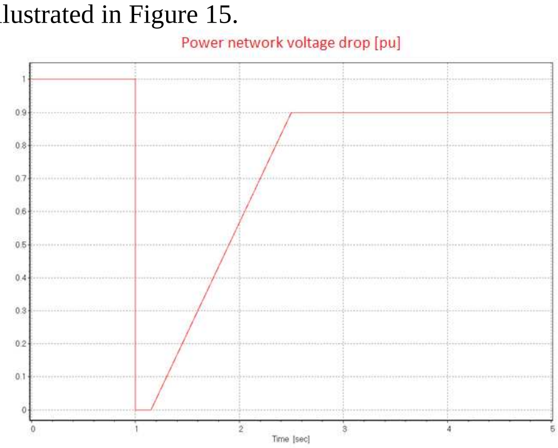

Figure 12 Power network voltage drop defined by Swissgrid.

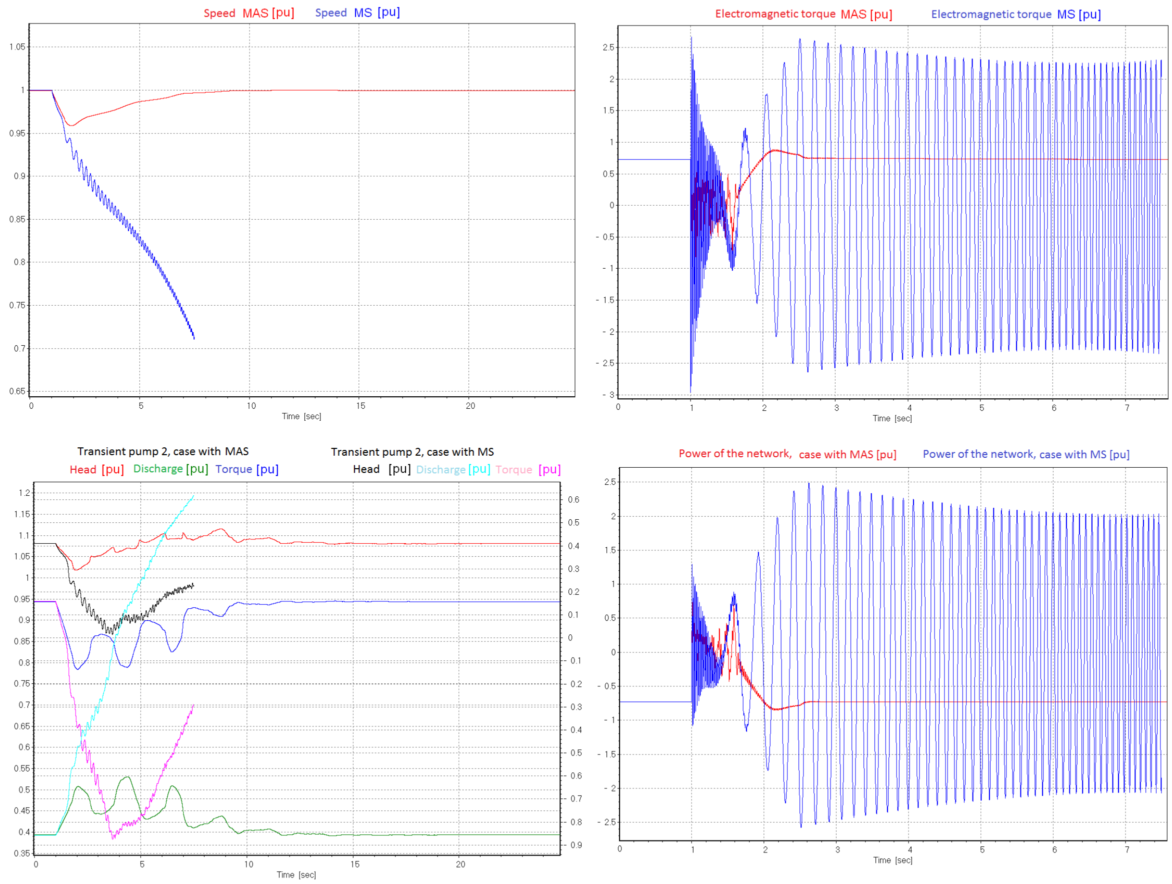

Figure 13 Comparison of the transient behavior of unit 2 in pump mode of operation resulting from power network voltage drop of Figure 12 with VarSpeed and fixed speed motor.

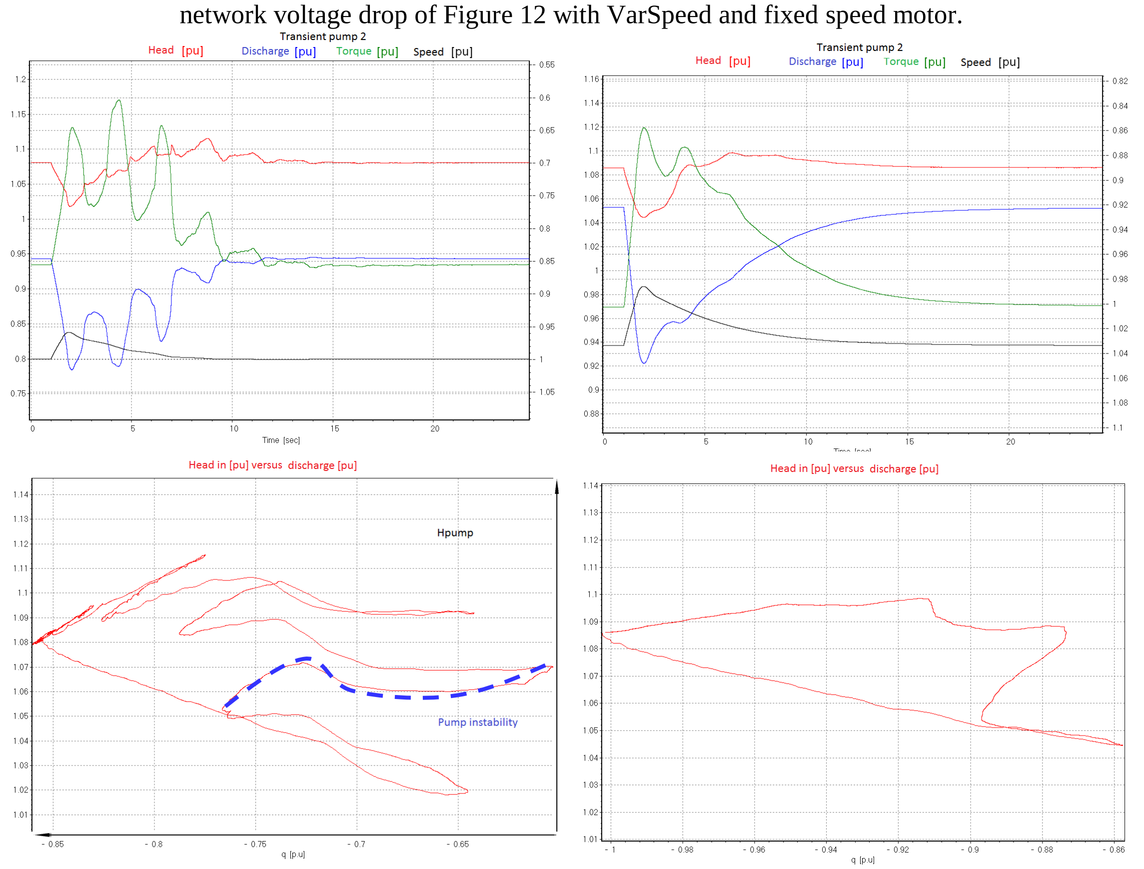

Figure 14 Pump transient behavior in case of voltage drop with VarSpeed machine with initial rotational speed of 1 pu, left and in case of initial rotational speed of 1.03 pu, right.

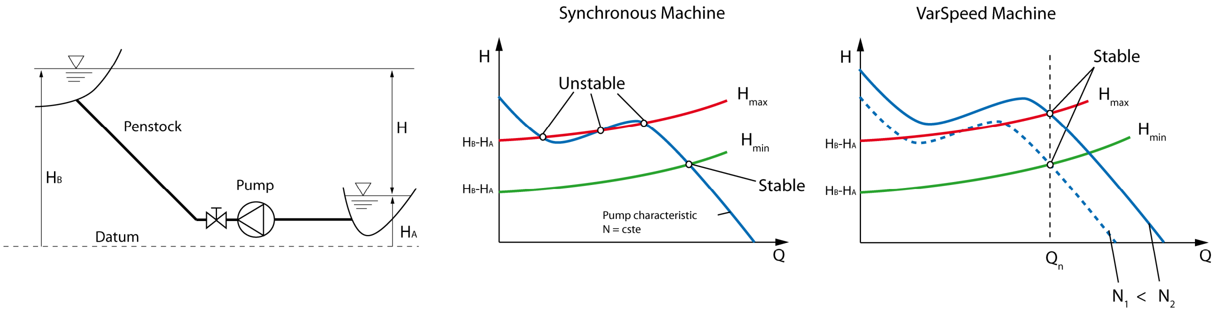

Figure 15 Pump stability with fixed speed machine and VarSpeed machine when the speed is increased for high head operation.

6 Conclusions

The transient behavior of a pumped storage power plant was investigated by means of numerical simulation of the whole hydroelectric power plant modeled from water to wire. The time domain simulation of the dynamic behavior of the power plant in pump mode of operation with both variable speed and fixed speed technology enabled to point out the following conclusions:

- the start-up of the 200MW dewatered pumps can be achieved with VarSpeed technology without supplementary equipment within 260s; this time can probably be reduced if the modulation process is modified from PWM to fixed cycle ratio;
- during the re-watering and the loading, the variable speed technology enables to reduce the pressure fluctuations resulting from the spherical valve opening as the rotational speed can be setup in order to have pressure equilibrium on both side of the valve prior to the opening; moreover, the power control enables to keep the input power of the neighboring units constant during the start-up procedure and thus contributes to power network stability;
- the variable speed motor can sustain longer short-circuit than the fixed speed motor up to 250ms and thus features increased stability performances;
- the variable speed motor complies with the voltage drop criteria defined by the TSO while the synchronous machine would not;
- the variable speed technology also enables to increase the margin with respect to the stability limit especially under high water level operating conditions by increasing the rotational speed and thus avoid unstable behavior of the pump in case of voltage drop.

If some aspects investigated here can be fairly investigated with separated electrical and hydraulic simulation models, some of them featuring strong hydroelectric interactions can only be addressed with a full hydroelectric simulation model. Such kind of simulations can provide key insights at early stage of project to assess and select the most appropriate technology for the electromechanical equipment. Using SIMSEN simulation software for the pumped storage of interest, it was possible to point out that the variable speed technology provides better stability performances than fixed speed machines and that these equipments comply with the TSO requirements. Moreover, it was also shown that this technology enables to reduce pressure fluctuations and improve stability margin during normal operation and faults and thus would reduce penstock solicitations and possible fatigue.

7 Nomenclature

A: pipe cross section [m^2]
A_g: gallery cross section [m^2]
A_{ST}: surge tank cross section [m^2]
D_{ref}: machine reference diameter [m]
H: net head [m]
Q: discharge [m^3/s]
N: rotational speed [rpm]
Nq: specific speed [$rpm \cdot m^{3/4} \cdot s^{-1/2}$]
$$Nq = N \cdot Q^{1/2} / (H / Z_s)^{3/4}$$
P: power [W]
T: Torque [Nm]
a: pipe wave speed [m/s]
h: piezometric head $h=z+p/(\rho g)$ [m]
g: gravity [m/s^2]
p: static pressure [Pa]
l_g: length of the gallery [m]
p: pressure [Pa]
t: time [s]
x: position [m]
y: turbine guide vane opening [-]
Z: elevation above a datum [m]
Z_s: number of stages [-]
ω: rotational pulsation [rd/s]
$_R$: subscript for rated

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