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THE INTEGRATION OF PUMPED STORAGE STATIONS IN THE BRAZILIAN NATIONAL INTEGRATED SYSTEM: ELECTRICAL SYSTEM BEHAVIOUR ANALYSIS

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Abstract. *The increasing share of renewable sources of energy introduces new issues in terms of system operation and equipment design. The insertion of pumped storage stations in an existing electrical system has been previously observed worldwide. In Brazil, the combination of various favourable conditions stimulates the installation of pumped storage stations. In the analysis for the implementation of these stations it is fundamental the correct simulation of the electrical system operating conditions. The unstable behaviour of renewable and non dispatchable sources, the behaviour of pumped storage stations, and their contribution to optimization of power system operating conditions must be well modelled and investigated. Computational simulations are a cheap and accurate tool. The current work presents two real cases of operation simulations of pumped storage stations. One presents grid stability investigations and the other concerns computational simulations of back-to-back operation of a power plant. The first study gives an overview of investigations conducted for a variable speed project Frades II showing what impact requirements have on the unit and converter* *design. The back-to-back start procedure is performed according to the constraints imposed by the rated current on the starting circuit. Current and power during system acceleration are kept under acceptable levels.*

Keywords: *Pumped storage, stability, numerical modelling*

1 INTRODUCTION

The change in the Brazilian energy matrix in recent years, with the increasing share of renewable but not dispatchable sources such as wind power and solar energy, presents a new scenario for the national system operator. Furthermore, it represents new challenges for those responsible for the design and definition of pumped storage stations that certainly will be part of the new Brazilian electrical system.

The insertion of pumped storage stations in an existing electrical system is not new in the world. This has been observed in other systems such as the European and the North American markets. In Germany, for example, over the last two decades, the replacement of nuclear plants by wind and solar sources led to the construction of several pumped storage power plants. Those plants are responsible for energy storage and play an important role in the regulation and stability of the electrical grid. In Brazil, the combination of very favourable conditions for wind and solar power stations and adequate geographical conditions for the installation of pumped storage stations stimulates the process of implementation of these plants. The process tends to be very fast as soon as regulatory issues are solved.

In the initial studies for the implementation of pumped storage stations, one of the most important aspects is the correct simulation of the electrical system operating conditions. The unstable behaviour of renewable and non dispatchable sources, the behaviour of pumped storage stations, and their contribution to optimization of power system operating conditions must be well represented and analysed. Factors such as the system response time to load variations, actual contribution of machines with variable speed, transient conditions during the pump-turbine and turbine-pump passages can only be defined with appropriate computational simulation of the hydraulic and electrical phenomena. The computational simulations must consider accurate models of the hydraulic and electric machines as well as of the electrical system and its main components.

Voith Hydro has long been dedicated to develop these studies internally in order to improve the design of pumped storage stations and their key components. Currently the simulations are performed with the software SIMSEN, developed in partnership with the École Polytechnique Fédérale de Lausanne. In order to perform these studies Voith has a group of specially trained employees.

The current work presents two real cases of operation simulations of pumped storage stations. The first one presents grid stability investigations under pre-defined electrical faults. The second case concerns computational simulations of back-to-back operation of a power plant in China. The main objective of this paper is to introduce key issues in stability analysis and the importance of appropriate numerical modelling for accurate dynamic behaviour prediction and design optimization.

2 STABILITY OF A HYDROELECTRICAL PLANT DURING GRID FAULTS

Due to increased penetration of renewable energies in past years, new rules have been defined for behaviour of the hydroelectrical plants during faults in the electrical grid. These rules are defined in the so called grid codes. Stabilizing behaviour has to be proven by simulation prior to connection of the unit to the grid.

Numerical simulations are a useful tool for dynamic behaviour prediction. Today's simulations make it possible to investigate the dynamic behaviour of a whole hydroelectric power plant from water to wire, including hydraulic circuit, pump turbine, motor-generator, electrical grid and the control system in the hour to microsecond domain.

The model of electrical machines is based on classical d, q Park equations expressed in a, b, c quantities (Canay, 1977) and enables to take into account saturation effects. The model of hydraulic components is based on momentum and continuity equations for a pipe of length dx. The modelling of the elementary pipe is extended to all standard hydraulic components such as pipes, valves, surge tanks and Francis, Pelton and Kaplan turbines (Nicolet, 2007). The equation system is set-up using Kirchoff laws and time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4^{th} order procedure. The modelling of the electrical grid can account for detailed grid topology including all production sources and consumers loads (Nicolet et al., 2008) or can be extended to a whole independent system operator grid (Koutnik et al., 2010) using aggregated models of the different production sources.

2.1 Numerical Modelling and Results

Figure 1 presents the SIMSEN simulation model of the pumped storage project of Frades II. The model takes into account the waterways, the pump turbines, the motor-generators and the connection to the grid. The model of the Double Fed Induction Machine (DFIM) includes the modelling of the Voltage Source Inverter (VSI) and the related control structure for pump and turbine operation mode.

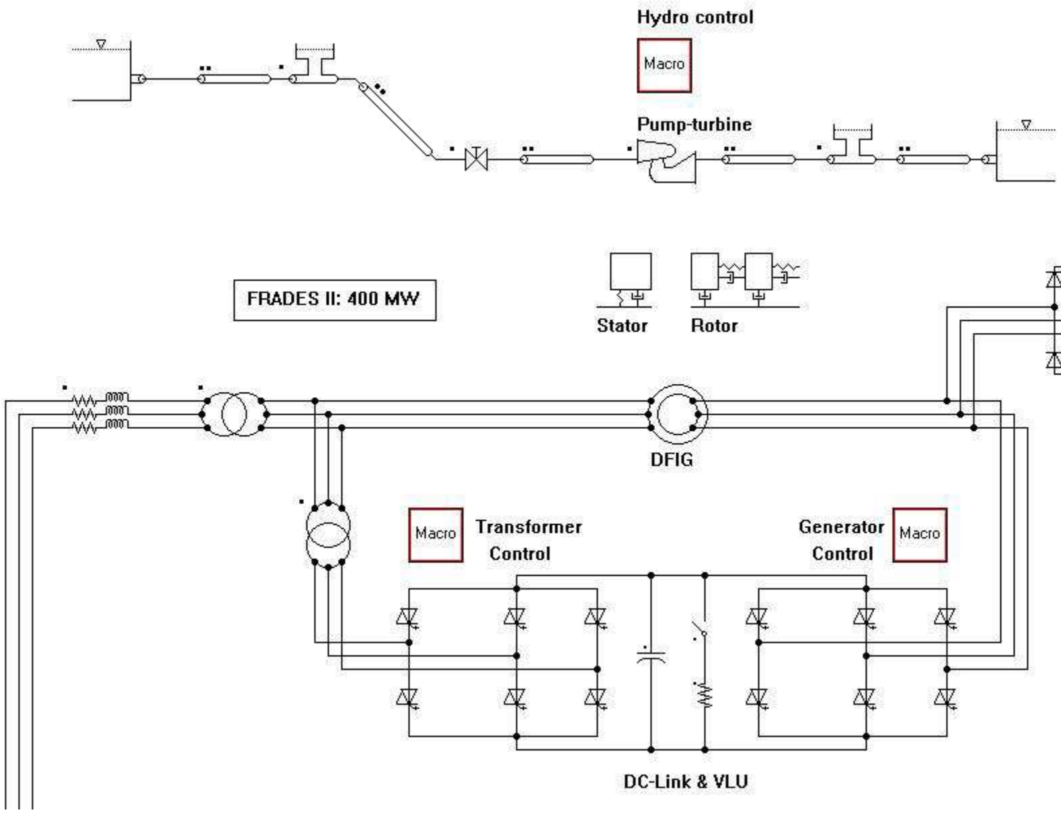

Figure 1: SIMSEN simulation model of the Frades II pumped storage power plant for the DFIM configuration

The generator used in Frades II is of a DFIM type driven by a pump turbine is shown in **Figure** 2. The turbine is directly connected to the DFIM through a mechanical shaft. The wound-rotor induction machine in this configuration is fed from both stator and rotor sides. The stator is directly connected to the grid while the rotor is fed through an AC excitation system.

In order to produce electrical active power at constant voltage and frequency to the utility grid in the operation range from subsynchronous to supersynchronous rotational speed given by the operational constraints of the hydraulic machine, the active power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction (Hodder, 2004). Therefore, the AC excitation system consists of a rotor-side converter (RSC) and grid-side converter (GSC) connected back-to-back by a DC-link capacitor.

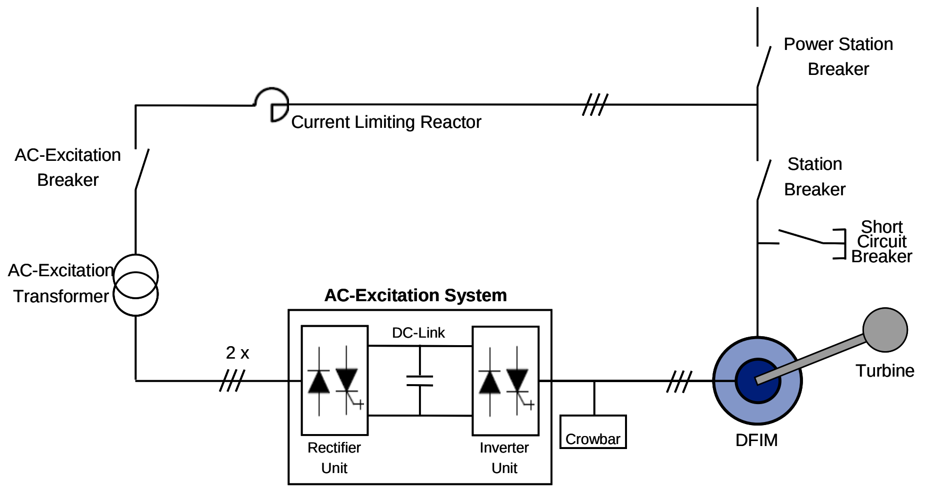

Figure 2: Configuration of a DFIM driven by pump turbine connected to a power grid

In case of a major grid fault, the unit speed will change (increase while in turbine mode of operation and decrease while in pump mode of operation) and must remain within the unit and frequency converter (AC excitation) limits given by the maximum producible rotor voltage of the RSC.

At the same time the stator winding is subject to high over currents, which also induce high currents in the rotor windings - up to 4.5 per unit (p.u.) shown in **Figure** 3. These short circuit currents decline exponentially with the time. The rotor currents are however limited by the semiconductors' capabilities of the RSC, which depend on the semiconductor type. If the rotor current exceeds the semiconductor limit, the frequency converter has to be protected by deactivating the switching of the RSC and if available activating the crowbar (short circuiting of the rotor windings via a resistance).

During such a period, when the frequency converter is in the protected mode, the generator is uncontrolled and behaves like a normal squirrel cage induction machine - starting to draw the reactive power from the grid and thus acting counterproductive against the voltage recovery. As some of the grid codes specify the time, within which the generator has to be in the normal controlled mode, they specify indirectly, which currents have to be handled by the frequency converter. For the Frades II requirements of 30 ms, the resulting rotor currents are much higher than the nominal ones - around 3.5 p.u.. The shorter the time limit, the higher the currents which have to be handled by the RSC.

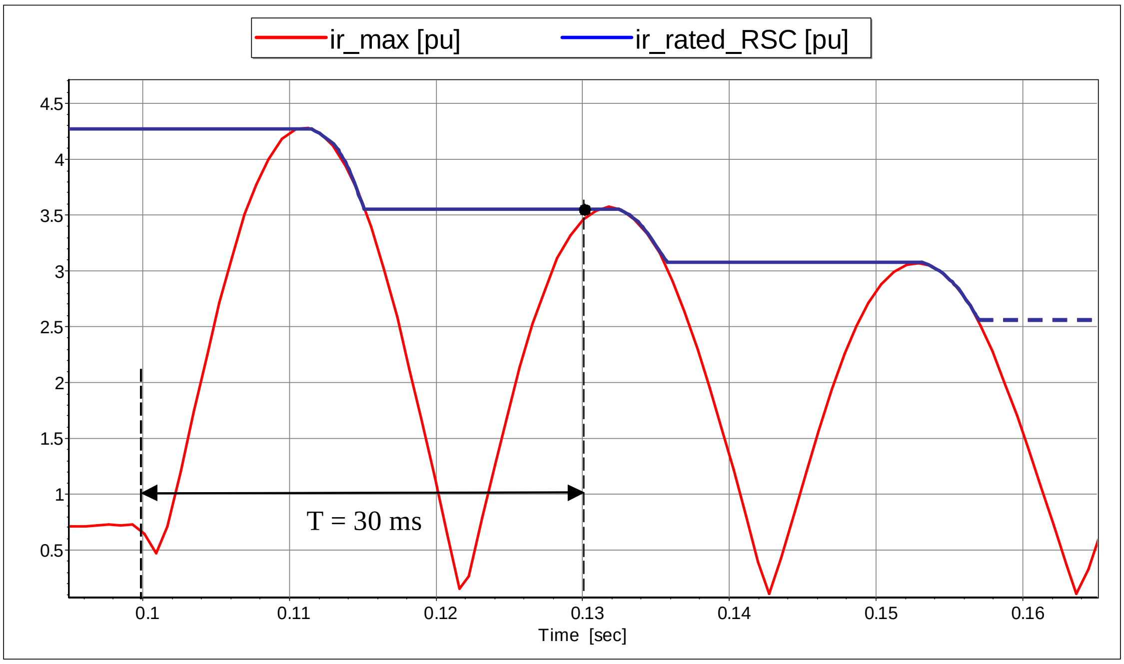

Figure 3: DFIM rotor currents (red) during a short circuit and resulting RSC rated current (blue)

The Transmission System Operators (TSO) requirements are decisive for the unit design, having impact on both generator designs as well as on the frequency converter rating. By increasing the rating of the rotor side converter, it is ensured that the converter can handle the short circuit current without exceeding its thermal limitations. The impact on the Frades II unit design is shown in the table below.

Table 1. Frades II generator nominal data

Steady speed range	350 - 381.2 rpm	Min. speed (LVRT)	340 rpm
Stator voltage	21 kV	Rotor voltage	5.5 kV
Stator current	11.9 kA	Rotor current	7.1 kA
Stator rating	433 MVA	Rotor active power	27.5 MW
Stator power factor	0.93	Rotor power factor	0.61

Table 2. Frequency converter rating [MVA]

	Grid side converter	Rotor side converter
Steady operation	62	45
Fault ride through	62	82

With this design for the Frades II project, the unit behaviour has to be investigated and guaranteed not only for symmetrical faults, but also for 1 and 2 phase to ground faults, and phase to phase faults without ground connection.

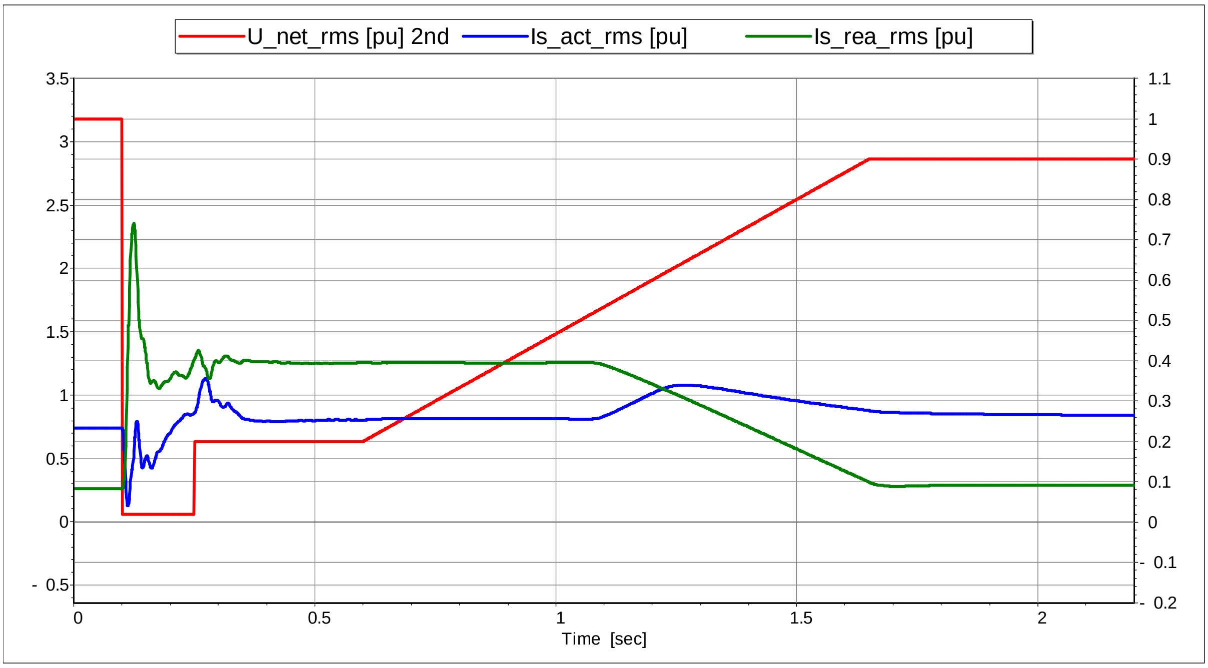

Figure 4: DFIM active and reactive currents during voltage dip (Low Voltage Ride Through - LVRT)

This study gives an overview of investigations conducted for a variable speed project Frades II showing what impact the TSO requirements have on the unit as well as converter design.

Low Voltage Ride Through (LVRT) specifications as well as the reactive power requirements similar to the *Rede Eléctrica Nacional* (REN) standard from Portugal are common in other European countries as well (Berndt and Hermann, 2007), (National Grid Electricity Transmission, 2010).

3 BACK-TO-BACK OPERATION – START UP INTO PUMP MODE OF OPERATION

In order to bring a pump-turbine into the pump operation, several starting methods are possible:

- using pony motor,
- using Starting Frequency Converter (SFC),
- asynchronous start,
- back-to-back start.

As the first three mentioned possibilities require dewatering of the pump-turbine runner in order to reduce the power needed for accelerating the unit, the back-to-back option allows direct startup of the unit into pump mode of operation without dewatering of the unit. The typical power consumption of a pump-turbine at nominal speed in pumping sense of rotation and closed distributor reaches approximately 20% to 60% of the nominal power depending on the hydraulic characteristic of the pump-turbine such as specific speed.

Using back-to-back procedure, some equipment may be saved (for example, blowdown), thus reducing the cost and number of subsystems. Back-to-back procedure may be applied between units within a single power plant (if more units are installed) or even between different power plants. In such a case a special direct connection line between the power plants is necessary.

Power plants with more than two units and common hydraulic circuit may present more complex interactions. Flow dynamics at bifurcations must be taken into account and analysed. Numerical simulations allow these effects investigation.

In some cases, the back-to-back procedure is used as a backup for the pumping start in case that the SFC fails. Usually only single SFC is used for all installed units within power plant.

In order to design all electrical connections including protection system in the power plant even for the back-to-back operation, it is necessary to know the current and voltage values during such operation. This is possible using nowadays simulation tool.

3.1 Numerical Modelling

In order to investigate the behaviour of the system in question during back-to-back start the hydraulic, mechanical and electrical subsystems are modelled in SIMSEN simulation software. The numerical methods are similar to what is described in item 2.1.

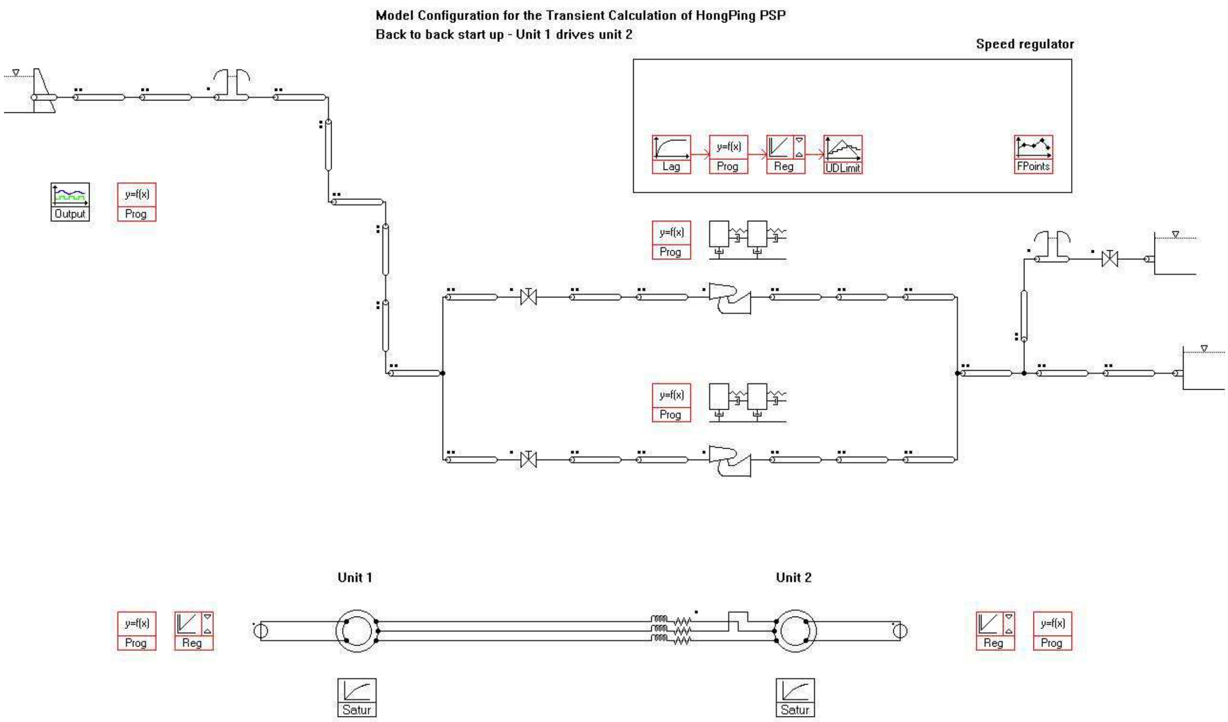

Figure 5: Hydroelectrical structure of unit 1&2 of the Pumped Storage Power Plant (SIMSEN)

The electrical machines stator terminals are connected as shown in the bottom of Fig. 1. Both field circuits are excited during the process from the network or from batteries, if black-start capability is required. The machine in turbine mode acts as a generator feeding the machine in pump/motoring mode. Therefore, back-to-back start enables the machine sets to be brought to rated speed without drawing any power from the grid.

The turbine speed must be properly controlled in order to “drag” the second machine set synchronously. The turbine acceleration process as well as the voltage and frequency increase rate on the electrical side must proceed according to the acceleration of the inertial masses (pump and motor rotors) coupled to the motoring set.

3.2 Start up in Water Results

Initially, units 1 and 2 are in stand still condition before the speed controlled unit 1 (acting in generator mode) is starting up unit 2 (acting in motor mode). The excitation controller PI parameters have been chosen to be T_i=2s and K_p=15. The start-up procedure is initialized at t=5s.

Figures 6 and 7 show the pump and turbine speed. It can be noted that the governor of unit 1 opens the wicket gates increasing the turbine speed. This increase of speed of the turbine is followed by the speed increase of the pump. The speed oscillation is found to be reasonable.

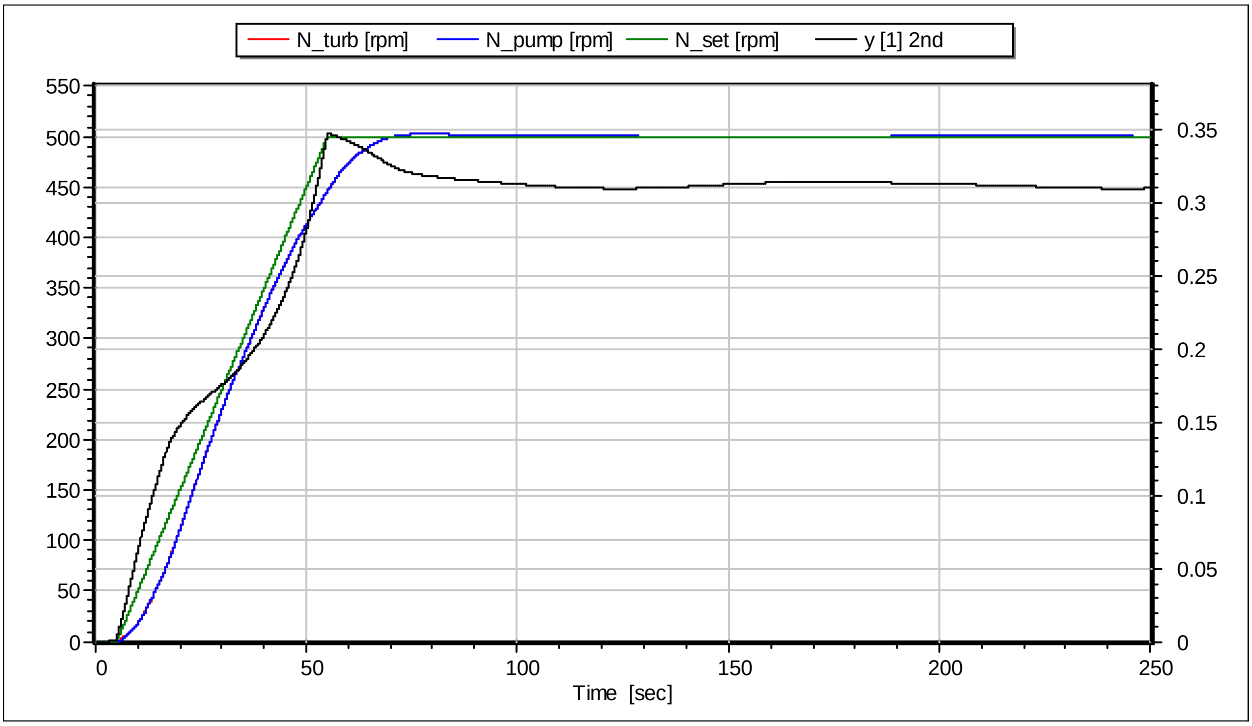

Figure 6: Speed of turbine and pump and turbine wicket gate opening

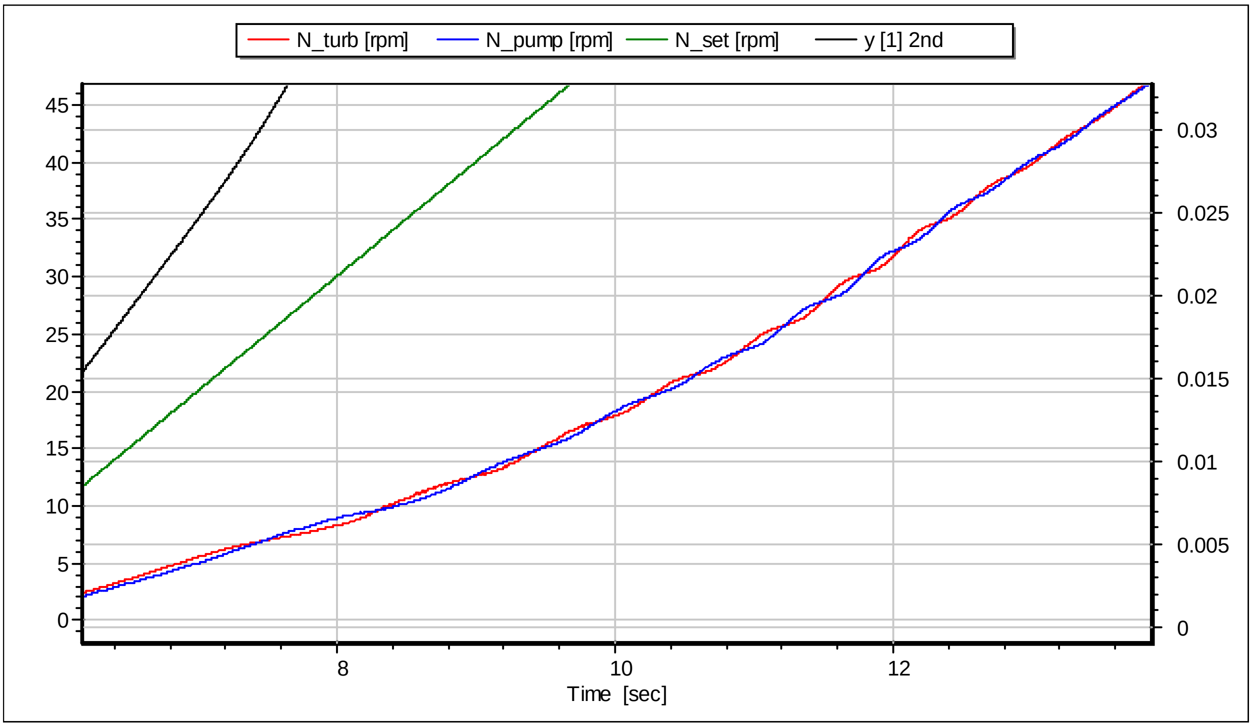

Figure 7: Speed of turbine and pump (area of speed and current oscillation)

Figures 8, 9 and 10 indicate the shaft torque of the turbine and pump, the excitation current and voltage and air gap torque of the generator and motor. The peak values and oscillations of these variables are within acceptable ranges therefore the procedure is stable.

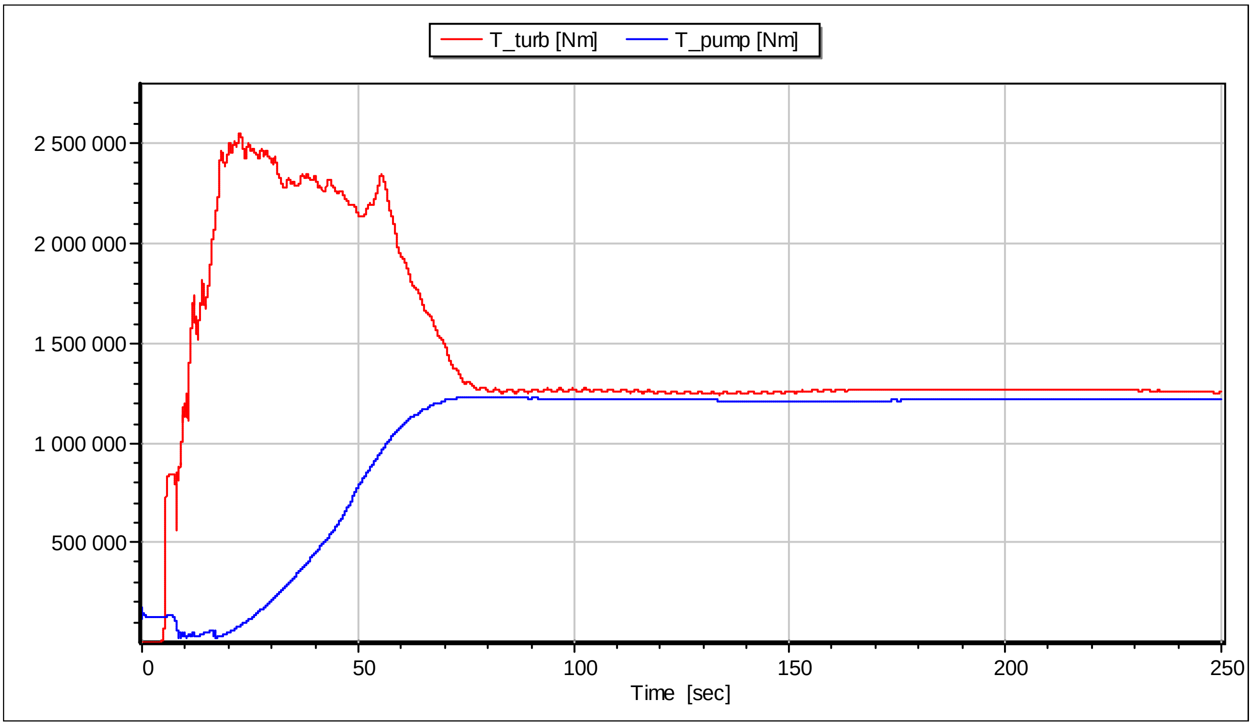

Figure 8: Torque of turbine and pump

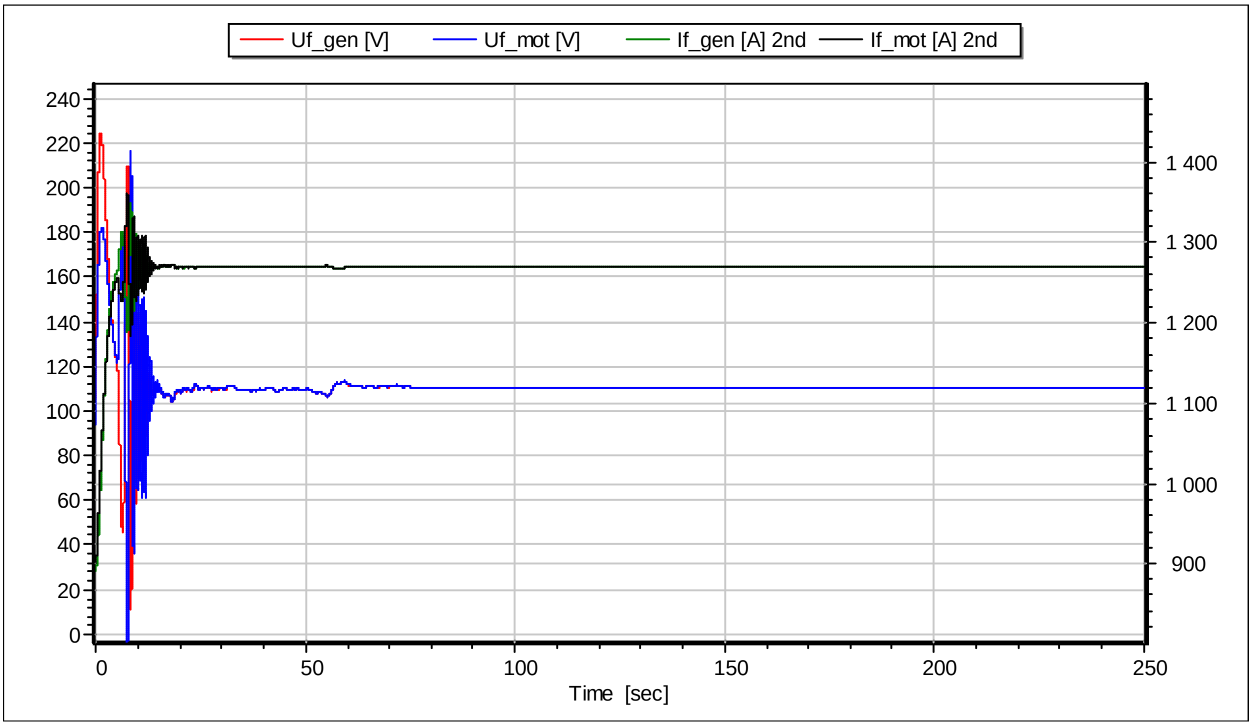

Figure 9: Excitation voltage and field current of generator and motor

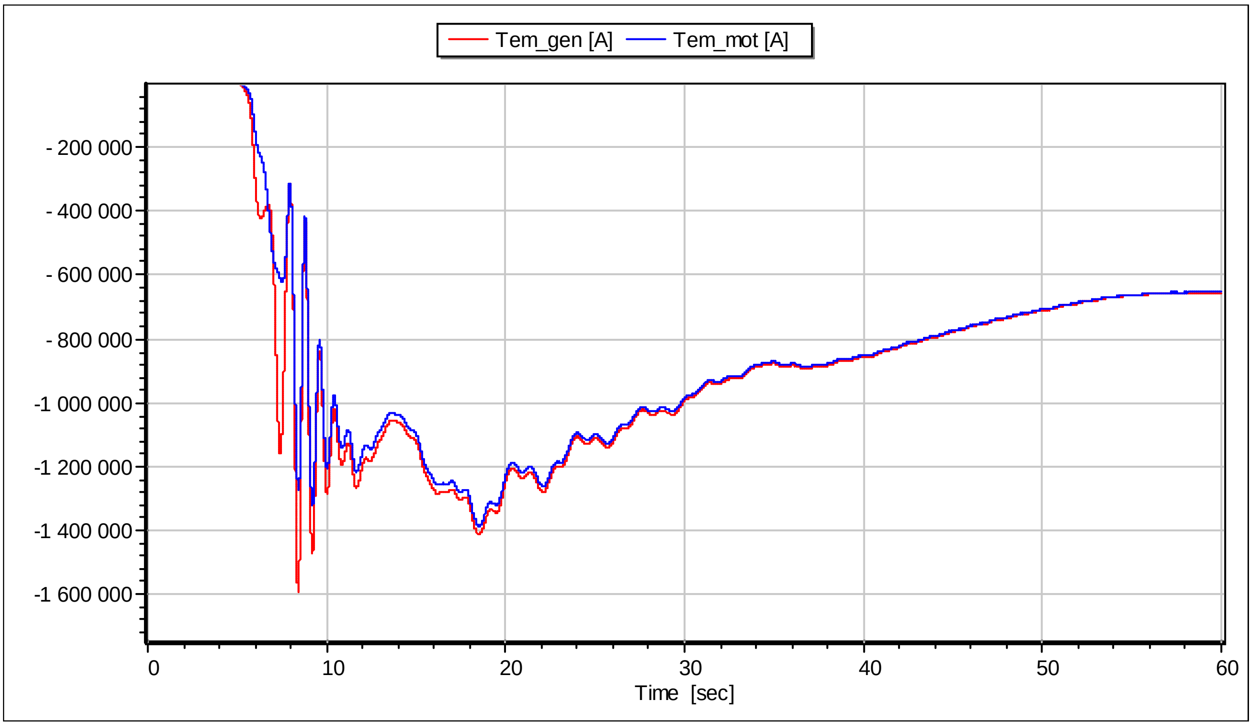

Figure 10: Air gap torque of generator and motor

The back-to-back start procedure can be performed according to the constraints imposed by the rated current on the starting circuit. Current and power during system acceleration could be kept under acceptable levels. The simulation proved that at the pumped storage plant in question start up in water is possible.

4 CONCLUSIONS

The insertion of pumped storage stations in existing electrical systems plays an important role in the regulation and stability of the existing electrical grids. In the initial studies for the implementation of pumped storage stations, the correct simulation of the electrical grid operating conditions and the power plant dynamic behaviour is essential to guarantee appropriate operation of the electrical system. The unstable behaviour of renewable and non dispatchable sources, the behaviour of pumped storage stations, and their contribution to optimization of power system operating conditions must be well represented and analysed. These initial studies and the dynamic conditions achieved in the numerical simulations have direct impact on the hydraulic waterways configuration, power unit's design parameters and power plant time response. This confirms the need to perform appropriate analysis during the feasibility studies and prior to the project development stage.

Due to increased expansion of renewable energies in past years, new rules have been defined for behaviour of the hydroelectrical plants during faults in the electrical grid. The first part of this paper presents numerical simulations of the pumped storage project of Frades II under short circuit and voltage dip. This study gives an overview of investigations conducted for a variable speed project Frades II showing what impact the TSO requirements have on the unit and in the converter design.

In the second part of the current paper, the back-to-back start up procedure in water is analysed for a power plant connected to an electrical grid. The results indicate that the current and power during system acceleration could be kept under acceptable levels. The simulation proved that at the pumped storage plant in question start up in water is possible.

Using the SIMSEN advanced simulation technology approach and in depth knowledge of pump turbine units as well as control system technologies, Voith Hydro can provide the services as described in this paper when designing pumped storage units both with fixed and variable speed units (Koutnik et al., 2008), (Simond et al., 2006).

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