PUMPED STORAGE - GRID REQUIREMENTS FOR BEHAVIOR OF LARGE MOTOR-GENERATORS AND CONFIRMATION OF COMPLIANCE THROUGH SIMULATION

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Keywords: pumped storage, pump turbine, variable speed, transient simulation, wind integration.

ABSTRACT

The role of Pumped Storage Power Plants has been changing from the pure storage function into dynamic grid support within the last several years. This is also one of the reasons, why more and more new pumped storage schemes are planned with the variable speed technology.

However, the experiences with the technology used at wind turbines show that especially the configuration consisting of Double Fed Induction Machine (DFIM) and AC rotor excitation may lead to destabilization of the grid during electrical fault scenarios. Therefore, new grid codes have been developed recently, which often define different rules that are applicable also on large hydro motor generators.

Recent project related investigation showed that the grid requirements for the Fault Ride Through (FRT) scenarios have direct and significant impact on the sizing of the frequency converter for the DFIM solution. The goal of the grid requirements is to achieve a similar behavior as in the case with standard synchronous machines (SM).

In this paper, a comparison of the synchronous fixed speed configuration with the variable speed DFIM options is carried out using a simulation model consisting of the hydraulic, generator and electrical part including transmission lines. Investigated scenarios included the main electrical fault cases specified in the European grid codes as well as customer requirements. Another option for a variable speed technology, a Synchronous Machine with Full Inverter on the stator side (SMFI), will be mentioned. As a summary the impact of the grid requirements on the sizing and design of the individual variable speed solutions (DFIM and SMFI) and the fault behavior will be discussed.

INTRODUCTION

Dynamic grid support is defined as providing fast, reliable and flexible response on deviation from nominal grid condition. Typical grid quality measures are voltage and frequency. Conventional hydro power plants are excellent providers of support functions and hydro pumped storage power plants even more so especially due to their feature of feeding and consuming power to and from the grid. Constant speed reversible pump turbines however are not capable of varying the power consumption dynamically, as in the pump mode the power is fixed by the given hydraulic boundary condition of the plant and the size of the turbine. Thus, other solutions are becoming more often applied to mitigate the increasing demand of power regulation also in pump mode (consuming power) [1]. Figure 1 shows the comparison of the different pumped storage solutions.

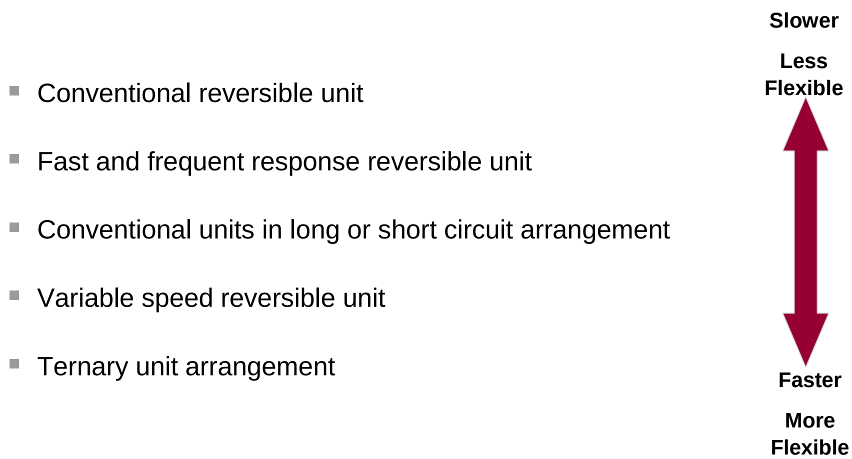


Figure 1: Possible unit configurations depending on regulation responsiveness and grid needs.

Short circuit operation between two reversible units or - for utmost flexibility like wide power ranges and super fast mode switch times - short circuit between the two hydraulic machines (pump and turbine) coupled on one shaft in so-called ternary sets are being built.

Variable speed pump turbine solutions have become attractive recently since the technical development of the required power electronics has moved this equipment into a commercially more competitive range. Changing the speed moves the power consumption control from the hydraulic system to the electrical system. The pump characteristic changes with changing the speed, i.e. more/less power consumption when increasing/decreasing the speed. Limits are given by hydraulic behaviour like instability and cavitation as well as costs/benefit considerations of the electrical equipment. Further positive effects on the operational behavior of variable speed pump turbines compared to conventional reversible solution are: better part load efficiency in turbine mode and smoother operation in turbine mode at very low part load. It has to be noted that the civil design of the power house or cavern respectively has to consider the additional space requirement for the electrical equipment compared to constant speed reversible units.

Most of the variable speed hydro power plants are currently equipped with DFIM, which have during grid faults a different behavior compared to standard synchronous hydro generators. Therefore it is becoming more common in Europe that the customers, resp. Transmission System Operators (TSO) require a simulative demonstration of the DFIM behavior and capabilities, as well as of appropriate control strategy. In the case of the Frades II project the requirements are specified by the TSO REN as shown in Figure 2. The main challenge is the provision of reactive current at a nominal value during specified voltage drops within 30 ms after the voltage drop.

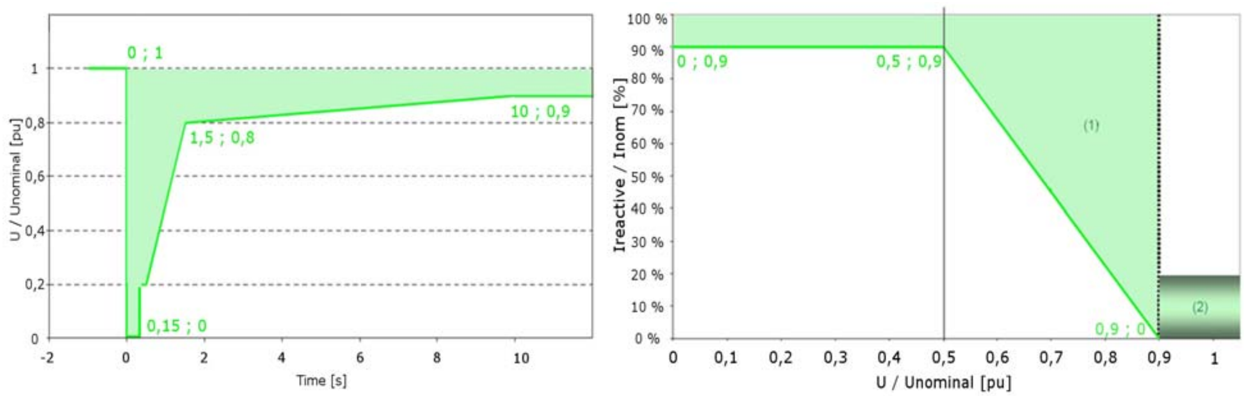


Figure 2: Requirements on reactive current supply during Low Voltage Ride Trough (LVRT).

MODELING OF THE HYDROELECTRIC POWER PLANT

The dynamic behavior of DFIM has been compared with the dynamic behavior of synchronous machine using the simulation software SIMSEN developed by the Ecole Polytechnique Fédérale de Lausanne, EPFL, for the modeling, simulation and analysis of electrical power networks, adjustable speed drives and hydraulic systems. It is possible to simulate the dynamic behavior 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 [2] 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 modeling of the elementary pipe is extended to all standard hydraulic components such as pipes, valves, surge tanks and Francis, Pelton and Kaplan turbines, etc. [3]. 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 4th order procedure. The modeling of the electrical grid can account for detailed grid topology including all production sources and consumers loads [4] or can be extended to a whole independent system operator grid [5] using aggregated models of the different production sources.

Figure 3 presents the SIMSEN simulation model of the pumped storage project of Frades II. It takes into account the waterways, the pump turbines, the motor-generators and the connection to the grid. The model of the DFIM includes the modelling of the two level Voltage Source Inverter (VSI) and the related control structure for pump and turbine operation mode.

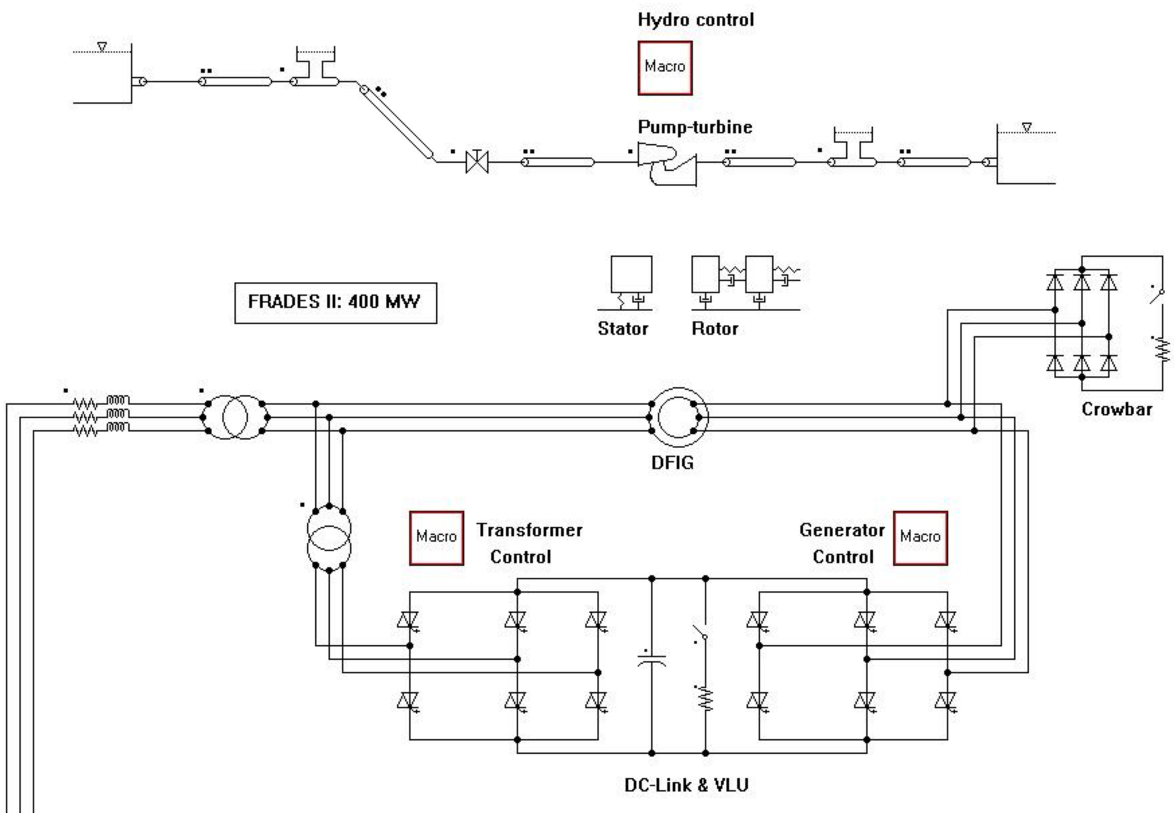


Figure 3: SIMSEN simulation model of the Frades II pumped storage power plant for the DFIM configuration.

DOUBLY FED INDUCTION MACHINE WITH VARIABLE SPEED

The basic configuration of a DFIM driven by a pump turbine is shown in Figure 4. 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 [6]. 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.

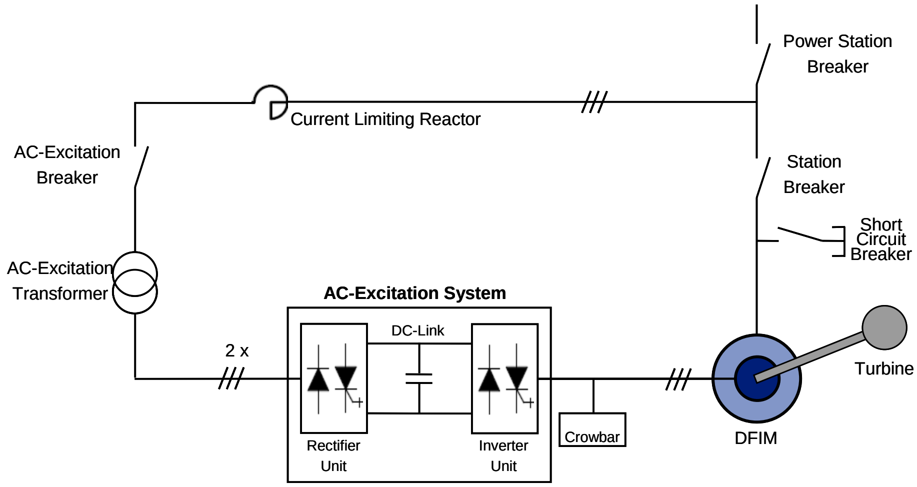


Figure 4: Configuration of a DFIM driven by pump turbine connected to a power grid

The steady operating range of the DFIM, as shown in Figure 5, is defined by thermal limits, i.e. max. currents both in the stator and rotor windings. However, the maximum speed deviation (slip) is determined by the maximum voltage amplitude of the 1st harmonics (slip frequency) in the rotor winding, which is limited by the DC link voltage of the frequency converter. There is an app. linear dependency between the rotor slip and the rotor voltage main harmonic component. On the other hand the DC link voltage together with the cabling and filter design determine the maximum peak voltages in the rotor winding, being thus decisive for the insulation design.

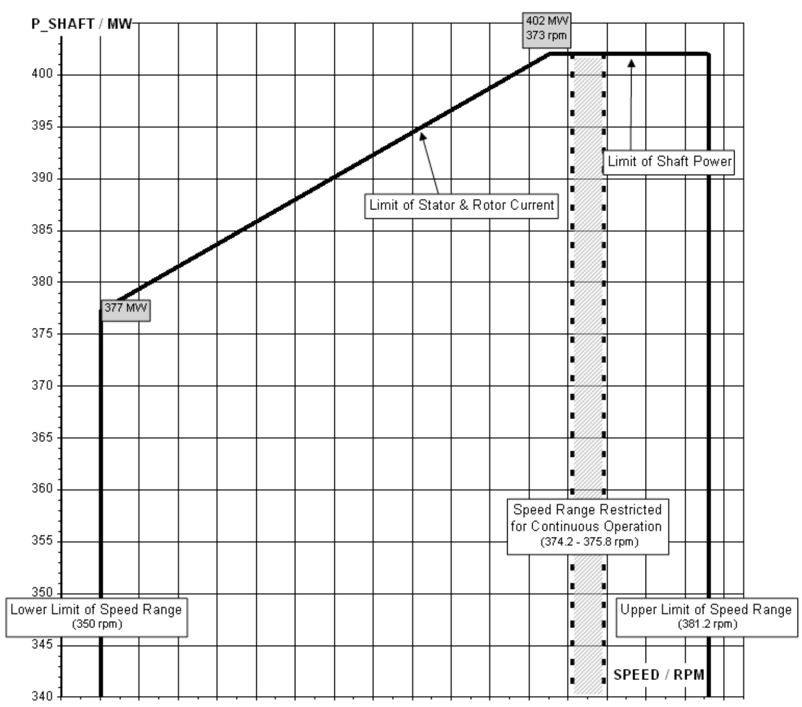


Figure 5: DFIM operating range - Frades II

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 6. 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.

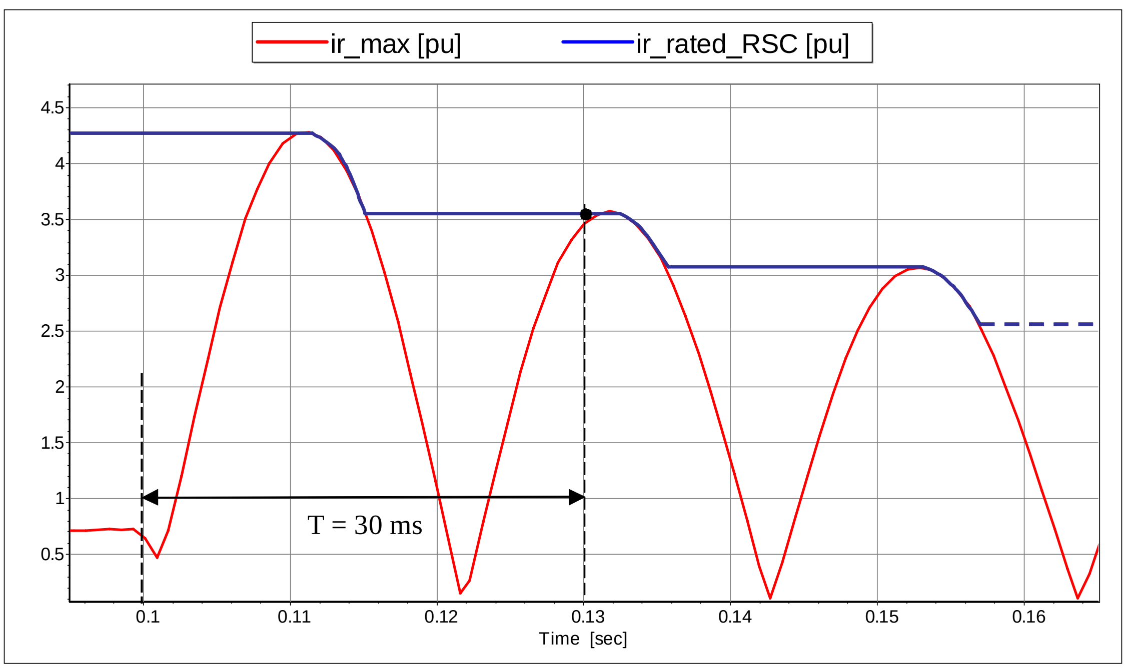


Figure 6: DFIM rotor currents (red) during a short circuit and resulting RSC rated current (blue).

As it can be seen from the short description above, the TSO requirements are decisive for the unit design having an 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:

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

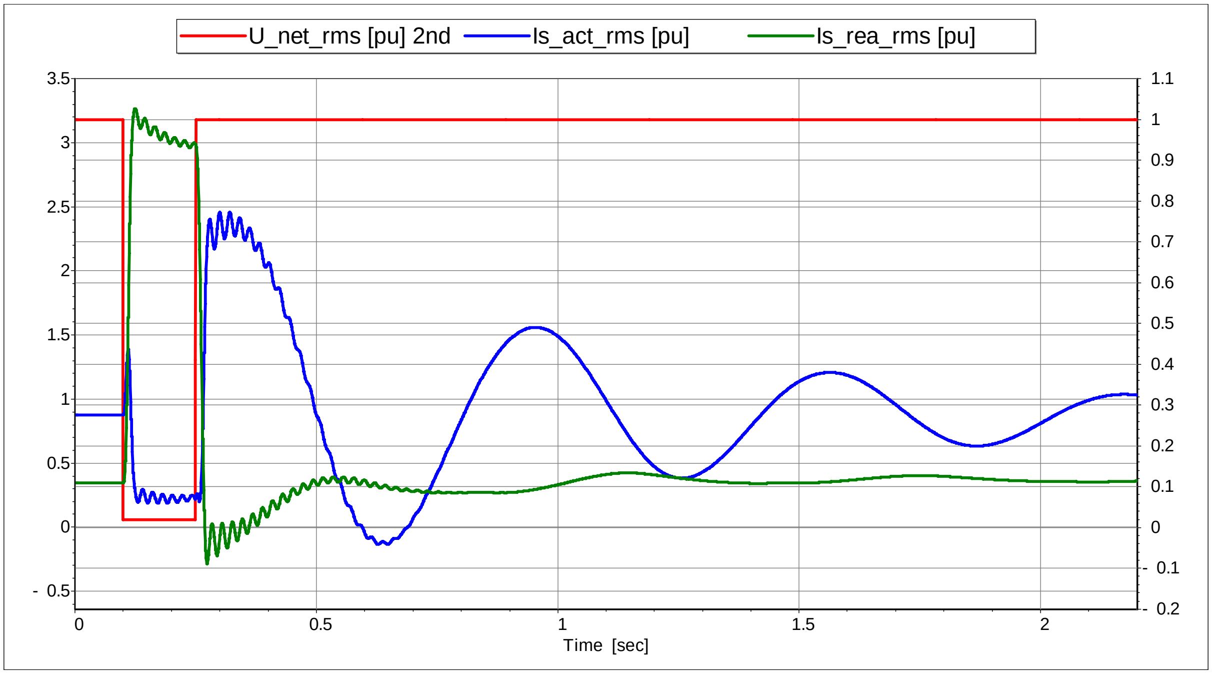
Frequency converter rating [MVA]:

	Grid side converter	Rotor side converter
Steady operation	48	45
Fault ride through	48	64

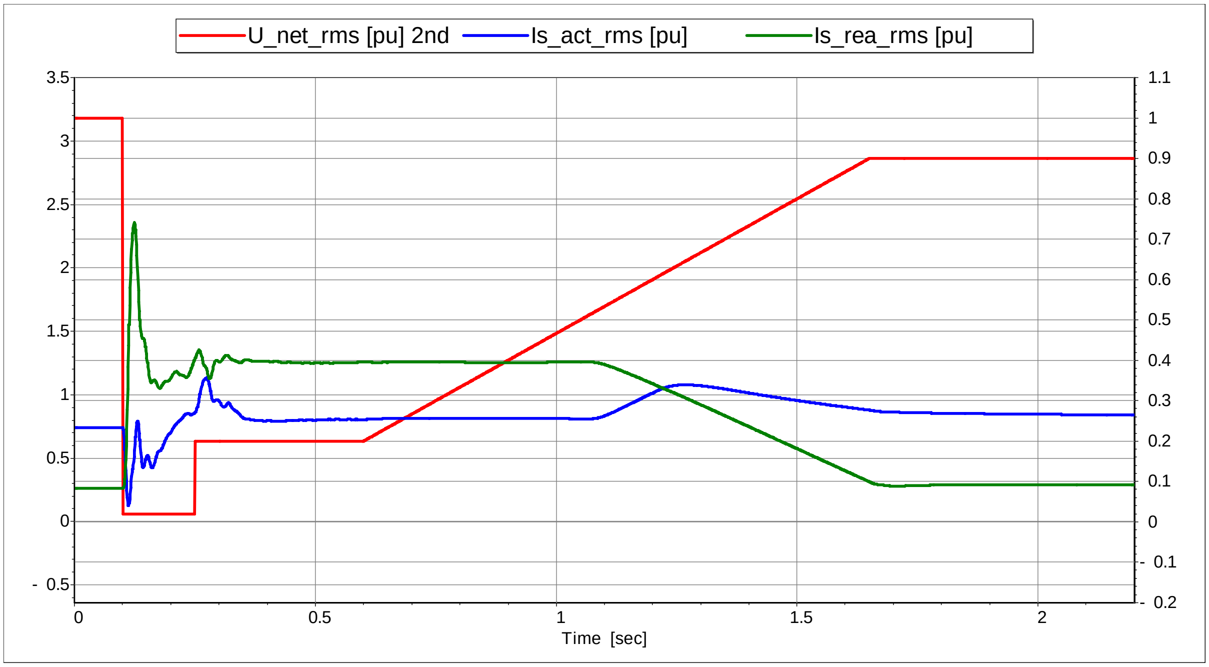
With this design for the Frades II project the unit behavior had to be investigated and guaranteed not only for symmetrical faults, but also for 1 and 2 phase to ground faults, as well as phase to phase faults without ground connection.

SYNCHRONOUS MACHINE WITH FIXED SPEED

The Frades II generators have been offered, next to the variable speed solution, also as a fixed speed option. Comparing both solutions regarding grid fault behavior it has to be mentioned that most of the grid codes at present distinguish between fixed speed and variable speed (doubly fed induction machine) units. The LVRT requirement on variable speed units is much harder and especially the duration of the voltage drop could not be withstood by the synchronous generators in any case, as they would go out of the synchronous operation. On the other hand, the synchronous generators provide the required reactive currents without any special measures during a voltage drop, thus supporting the voltage recovery. A comparison of the unit behavior for both solutions during a voltage drop is shown in Figure 7.



a) Synchronous generator with line 3ph short circuit



b) DFIM with LVRT

Figure 7: Grid fault simulation results: Grid voltage (red, 2nd axis), stator active current (blue) and stator reactive current (green).

SYNCHRONOUS MACHINE WITH FULL FREQUENCY CONVERTER AND VARIABLE SPEED

As a general consideration the solution with full frequency converter and synchronous generator has to be mentioned. With this solution the converter has to be dimensioned for rated power transmission. The concept can be applied to both new and existing power units as shown in Figure 8.

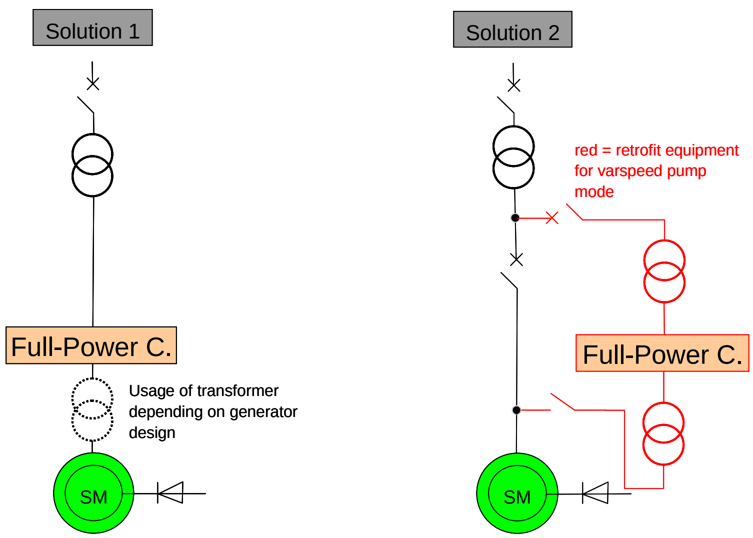


Figure 8: SMFI-topology in new power units (left) and existing power units (right)

In case of a grid fault the compliance with the grid code requirements is achieved only by the grid side converter thus decoupling the generator behavior from the grid fault. Because of the grid connection via a converter the maximum short circuit current is limited to ~ 1 p.u. .

CONCLUSIONS

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

LVRT specifications as well as the reactive power requirements similar to the REN standard (Portugal) are standard in other European countries as well [7], [8].

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 [9], [10].

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