# Studies about the Low Voltage Ride Through Capabilities of Variable-Speed Motor-Generators of Pumped Storage Hydro Power Plants

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***Abstract*** – **In order to fulfil the new challenges within power grids arising from an increasing utilization of renewable energy resources, there is an upcoming demand for pumped storage hydro power plants. Thereby, a full flexibility of active and reactive power production in generating mode as well as power consumption in pumping mode in conjunction with the best available efficiency of both electric and hydraulic devices gains in significance. Nowadays, the utilization of variable-speed pump-turbine units with either synchronous or doubly-fed asynchronous motor-generators can be applied for these tasks. Since these variable-speed units have a very different behaviour in comparison to fixed-speed synchronous machines, more detailed analyses should to be carried out in the design phase of such units. In order to achieve accurate data about steady-state as well as transient behaviour, simulation models of both mentioned arrangements are developed.**

***Keywords*** – **Power generation, Grid code, Synchronous machine, Asynchronous machine, Doubly-fed induction machine**

## I. Introduction

A central part of transmission system operators responsibility is to ensure system security with a high level of reliability and quality [1]. The system behaviour in disturbed operating conditions depends upon the response of power generating facilities to deviations from nominal values of voltage and frequency. With a growing utilization of power generation units fed by renewable energy resources additionally to existing power generation units, general requirements for all power generation units have to be defined in more detail. These specifications defined in so called Grid Codes cover both fixed-speed and variable-speed power generators. In order to fully comply with those new regulations, there are novel challenges regarding capabilities and performances in particular for motor-generator units of hydro-electric power plants.

In hydro-electric power plants, pump-turbines are optimized for operating points defined by speed, head and discharge [2]. At fixed-speed operation, only limited deviations of these operating conditions are allowed. On the other hand at variable-speed operation, the allowable variation of these operating conditions is enlarged. Consequently, such variable-speed pump-turbine units offer greater flexibility and higher efficiency in both operating modes [2]–[4].

For such variable-speed pump-turbine units, there exist two main types of motor-generator units, the synchronous machine with either an electrical or a permanent magnet excitation and the doubly-fed asynchronous induction machine [2]–[6]. Both types of motor-generators as depicted in Fig. 1 and Fig. 2 offer several advantages with generating as well as pumping mode [6]:

- Increased efficiency and extended operation range in both generating and pumping modes.
- Optimized adaptation to the hydraulic system in particular with partial-load and pump-turbine operation.
- Possibility of active power control in pumping mode.
- Possibility of an active injection of reactive power.
- Improved network stability due to separated control of active and reactive power.
- Increased dynamic performance for operating stability purposes.

Due to the variable-speed operation mode, both types of motor-generators have to be equipped with power electronic rectifier units, too. Nowadays, back-to-back voltage source inverters (VSI) with pulse width modulation (PWM) are utilized, depending on the power range with two- or three-level arrangements using IGBT or IGCT modules [3]–[7].

With regard to the above mentioned view points, the paper presents both arrangements of motor-generators and in particular modelling of the utilized three-level PWM converters in order to represent the switching behaviour of the two back-to-back connected parts. The main focus of the simulations carried out

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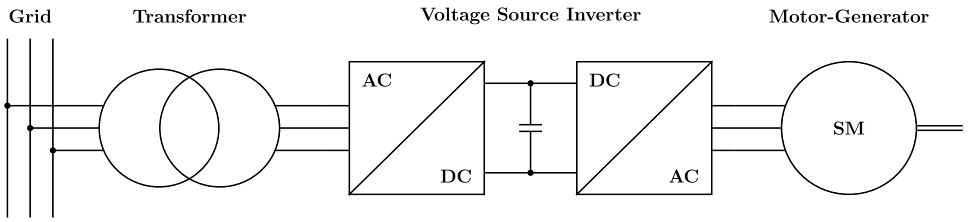

Fig. 1: Synchronous motor-generator (SM) of variable-speed pump-turbine units

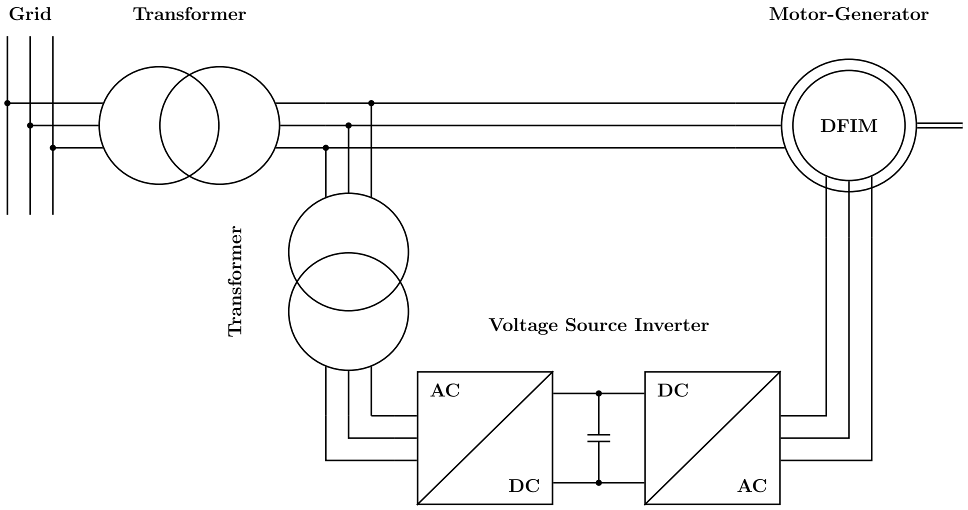

Fig. 2: Doubly-fed induction motor-generator (DFIM) of variable-speed pump-turbine units

lies on studies about steady-state and transient analyses in particular related to grid asymmetries and grid faults. With the latter, the low voltage ride through (LVRT) behaviour is one of the most important tasks [8], [9].

## II. Overview of the Arrangements

As mentioned above, variable-speed pump-turbine units within hydro power plants can be equipped with either synchronous or doubly-fed induction motor-generators. Fig. 1 and Fig. 2 depict typical arrangements of such units.

Thereby, synchronous motor-generators require a back-to-back PWM-VSI connected to stator and grid carrying the full scale power. On the other hand, such units have an extended speed range in comparison to doubly-fed induction machines. Additionally, an essential viewpoint has to be given to the necessity of safety strategies within field weakening region and with disturbances such as load shedding.

Contrarily, doubly-fed induction motor-generators have a direct connection between stator and grid as well as a back-to-back PWM-VSI connected to rotor and stator. This inverter carries only a fraction of the full scale power depending on the desired speed range. Due to the direct connection of stator and grid, these devices are more effected by grid disturbances and failures. In particular grid unsymmetries additionally influence the hydraulic devices due to additional harmonics within the electromagnetic torque.

In order to take into account for critical failure situations, additional devices not depicted above such as a DC-link chopper with upper and lower threshold in dependence on the DC-link voltage and a crowbar on the machine side are inevitable.

## III. Modelling of the Inverter

Under steady-state conditions, rotor speed as well as active and reactive power are predefined by the control strategies of grid and pump-turbine [8], [10], [11]. On the other hand, the range of switching frequencies of a large scaled VSI utilizing IGCT modules is always much greater than the power grid frequency. Consequently, the influence of the switching cycles of the inverter is negligible when studying steady-state and transient effects with those synchronous and asynchronous motor-generators [3], [4]. Moreover with the design phase of such arrangements, many parameters in particular with the control of the inverter are not specified in detail.

Thus, the non-continuous behaviour of the utilized three level converters as depicted in Fig. 3 is replaced by a continuous model representing the back-to-back connection to the two three-phase systems with almost different frequencies, voltages and currents as depicted in Fig. 4. The terminal voltages and the current flow of the two converters connected back-to-back are obtained by introducing appropriate modulation sequences for both voltages and currents according to the time dependent signals defined by the control algorithms of grid and machine side models [12].

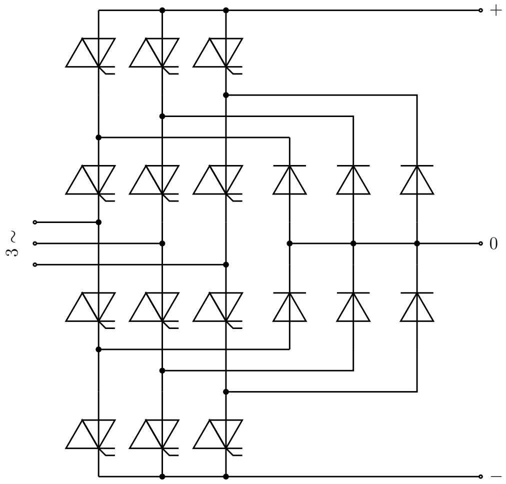

Fig. 3: Three level converter with IGCT modules

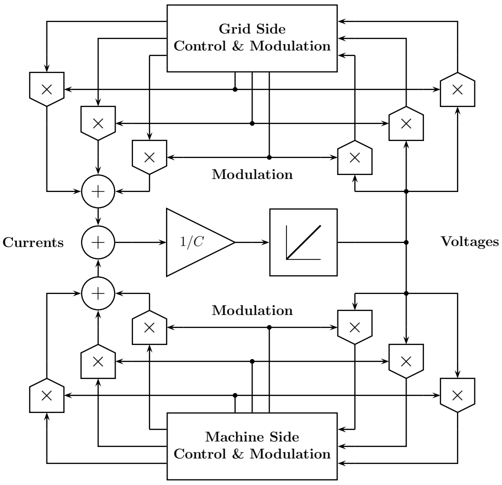

Fig. 4: Model of the three level voltage source inverter utilized with variable-speed motor-generators

As the output voltage can vary between $\pm U_{DC}/2$ only, introducing a time-dependent modulation ratio

$$m_i(t) = \frac{\sqrt{3}\, u_i(t)}{U_{DC}} \quad , \quad -1 \leq m_i(t) \leq 1 \quad , \tag{1}$$

for the respective phase values represents the fundamental component of the output voltages. On the other hand, the current occurring within each inverter phase can be modelled with the same modulation ratio. Thus, the invariance of the power consumption is preserved.

The time-dependent modulation ratios with almost different fundamental frequencies on both sides of the inverter are obtained from the control algorithms on each of the back-to-back connected inverter systems by using the respective two-axes projections of voltage and current space vectors. Consequently, effects induced by the DC-link capacitors are fully included with our simulations.

The introduction of this pseudocontinous inverter model avoids effects arising from switching cycles of the back-to-back connected converters. Therefore, the simulation time is considerably reduced without any lack of taking account for transient effects arising from grid disturbances or load cycles [4], [6], [12]. But for an accurate inclusion of delays caused by the original switching cycles, a time-delay of 1/6 of the switching cycle period has to be introduced with the simulation model [4], [6].

## IV. SIMULATION APPROACH

### A. *Control strategies*

In order to describe both types of motor-generators with the same simulation approaches, the well-known two-axes theory of induction machines with various coordinate systems as

- $\alpha\beta$ stator fixed reference frame,
- $dq$ rotor fixed reference frame,
- $xy$ linkage flux oriented reference frame,

and their respective transformations

$$\underline{F}_{dq} = \underline{F}_{\alpha\beta}\ \mathrm{e}^{-\jmath\gamma} \quad , \quad \underline{F}_{xy} = \underline{F}_{\alpha\beta}\ \mathrm{e}^{-\jmath\delta} \tag{2}$$

as shown in Fig. 5 are used with all simulations [13]. Thereby, phase values and space vector of stator quantities are related as

$$\underline{F}_{\alpha\beta} = \frac{2}{3}\left(F_a + F_b\ \mathrm{e}^{\jmath 2\pi/3} + F_c\ \mathrm{e}^{\jmath 4\pi/3}\right) \quad , \tag{3}$$

$$F_a = \mathrm{Re}\big(\underline{F}_{\alpha\beta}\big) \quad , \tag{4a}$$

$$F_b = \mathrm{Re}\big(\underline{F}_{\alpha\beta}\ \mathrm{e}^{-\jmath 2\pi/3}\big) \quad , \tag{4b}$$

$$F_c = \mathrm{Re}\big(\underline{F}_{\alpha\beta}\ \mathrm{e}^{-\jmath 4\pi/3}\big) \quad , \tag{4c}$$

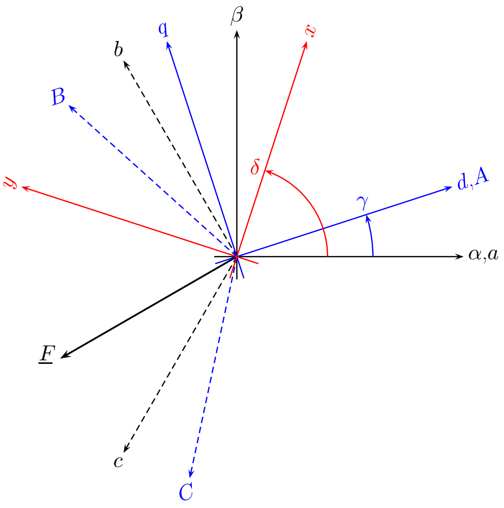

Fig. 5: Two-axes theory, coordinate systems

as well as phase values and space vector of rotor quantities

$$\underline{F}_{dq} = \frac{2}{3}\left(F_A + F_B\ \mathrm{e}^{\jmath 2\pi/3} + F_C\ \mathrm{e}^{\jmath 4\pi/3}\right)\ , \tag{5}$$

$$F_A = \mathrm{Re}\big(\underline{F}_{dq}\big)\ , \tag{6a}$$

$$F_B = \mathrm{Re}\big(\underline{F}_{dq}\ \mathrm{e}^{-\jmath 2\pi/3}\big)\ , \tag{6b}$$

$$F_C = \mathrm{Re}\big(\underline{F}_{dq}\ \mathrm{e}^{-\jmath 4\pi/3}\big)\ , \tag{6c}$$

respectively.

Active power of the stator

$$P(t) = \frac{3}{2}\ \mathrm{Re}\big(\underline{I}^*_{\alpha\beta}\,\underline{U}_{\alpha\beta}\big) = \frac{3}{2}\left(I_\alpha\,U_\alpha + I_\beta\,U_\beta\right) \tag{7a}$$

$$= \frac{3}{2}\ \mathrm{Re}\big(\underline{I}^*_{dq}\,\underline{U}_{dq}\big) = \frac{3}{2}\left(I_d\,U_d + I_q\,U_q\right) \tag{7b}$$

$$= \frac{3}{2}\ \mathrm{Re}\big(\underline{I}^*_{xy}\,\underline{U}_{xy}\big) = \frac{3}{2}\left(I_x\,U_x + I_y\,U_y\right) \tag{7c}$$

and reactive power of the stator

$$Q(t) = \frac{3}{2}\ \mathrm{Im}\big(\underline{I}^*_{\alpha\beta}\,\underline{U}_{\alpha\beta}\big) = \frac{3}{2}\left(I_\alpha\,U_\beta - I_\beta\,U_\alpha\right) \tag{8a}$$

$$= \frac{3}{2}\ \mathrm{Im}\big(\underline{I}^*_{dq}\,\underline{U}_{dq}\big) = \frac{3}{2}\left(I_d\,U_q - I_q\,U_d\right) \tag{8b}$$

$$= \frac{3}{2}\ \mathrm{Im}\big(\underline{I}^*_{xy}\,\underline{U}_{xy}\big) = \frac{3}{2}\left(I_x\,U_y - I_y\,U_x\right) \tag{8c}$$

will describe power flow with both types of motor-generators. Based on the introduced reference frames, both power components are independently described by respective voltage and current space vectors.

Following the suggestions with [14], [15], the synchronous machine will be modelled within the *dq* rotor fixed reference frame while the doubly-fed asynchronous machine will be modelled within the *xy* reference frame adjusted to a vanishing $x$-component of the stator voltage. The latter approach significantly simplifies the cross-coupling of the components of stator and rotor currents with the control algorithm.

### B. Low voltage ride through cycles

Detailed investigations of LVRT behaviour and capabilities according to various grid code requirements are carried out in detail. Fig. 6 depicts typical low voltage ride through cycles as defined by various Grid Codes. In order to comply with this requirements, a fast acting voltage control has to provide typically a reactive current in dependence on the voltage drop as depicted in Fig. 7. Thereby, the active power range is reduced according to pre-defined current limits.

According to the LVRT-B cycle depicted above, the behaviour of both a permanent magnet synchronous (PMSM) and a doubly-fed induction machine (DFIM) are shown in the following.

Fig. 8, Fig. 9 and Fig. 10, Fig. 11 show active and reactive powers as well as voltages and currents within the *dq* reference frame obtained with a PMSM with an apparent power of 35 MVA, respectively.

On the other hand, Fig. 12, Fig. 13, Fig. 14 show active and reactive powers obtained with a DFIM with

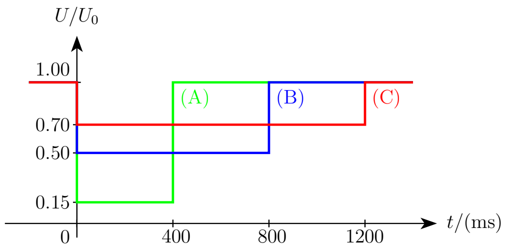

Fig. 6: Typical low voltage ride through cycles

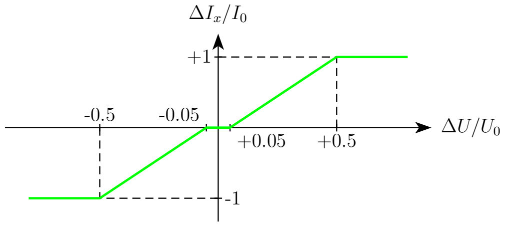

Fig. 7: Typical reactive current support during grid faults

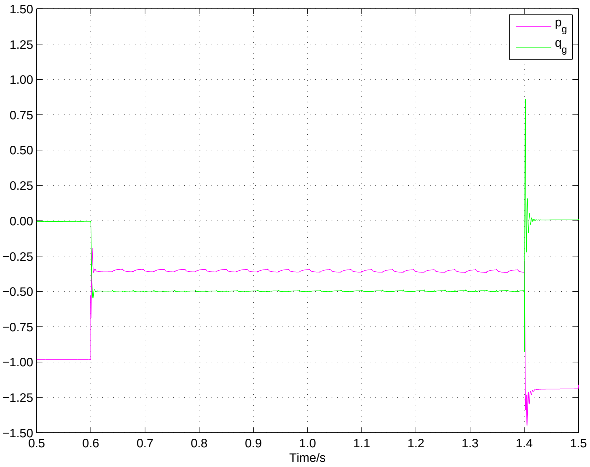

Fig. 8: Active and reactive power during a LVRT-B cycle on the grid side, PMSM

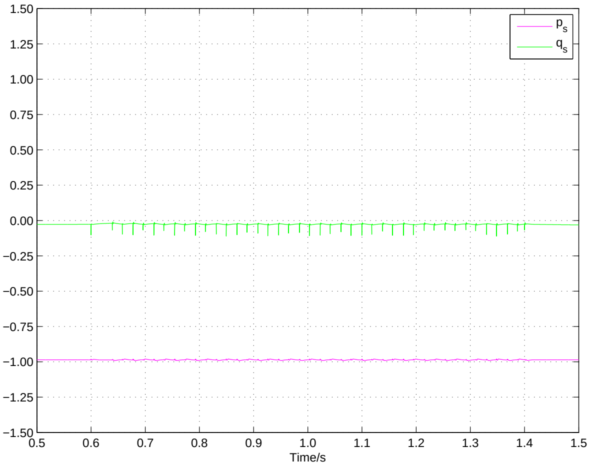

Fig. 9: Active and reactive power during a LVRT-B cycle on the machine side, PMSM

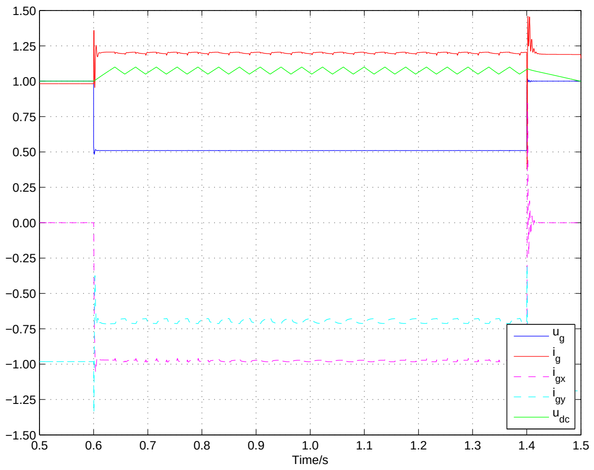

Fig. 10: Voltages and currents during a LVRT-B cycle on the grid side, PMSM

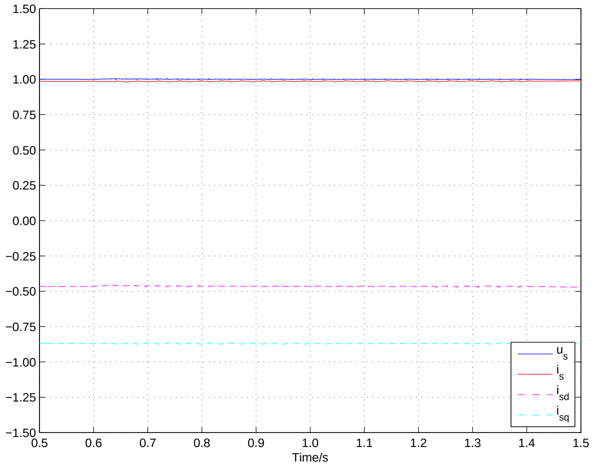

Fig. 11: Voltages and currents during a LVRT-B cycle on the machine side, PMSM

an apparent power of 350 MVA. Accordingly, Fig. 15, Fig. 16, Fig. 17 show voltages and currents within the $xy$ reference frame.

Obviously, both arrangements can fulfil the requirements of the Grid Code successfully. Thereby, the LVRT operational behaviour of the PMSM is covered mainly by the converter while the machine operates regularly. On the other hand, there are very high current peaks with the DFIM which can only be compensated by using the crowbar. Consequently, the LVRT operational behaviour now shows rather slowly decreasing oscillations according to very long time constants of the machine in the range of $(6 \ldots 8)$ s.

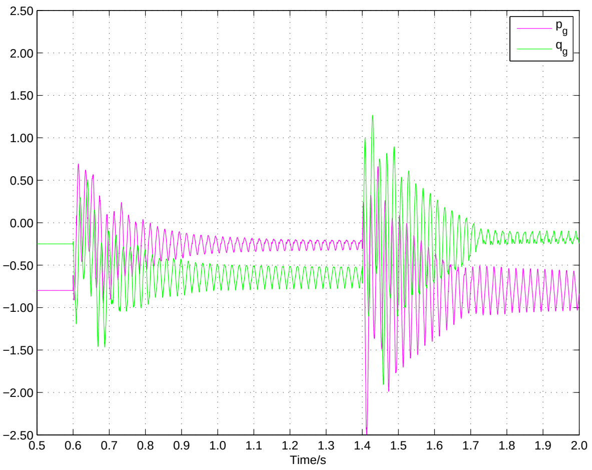

Fig. 12: Active and reactive power during a LVRT-B cycle on the grid side, DFIM

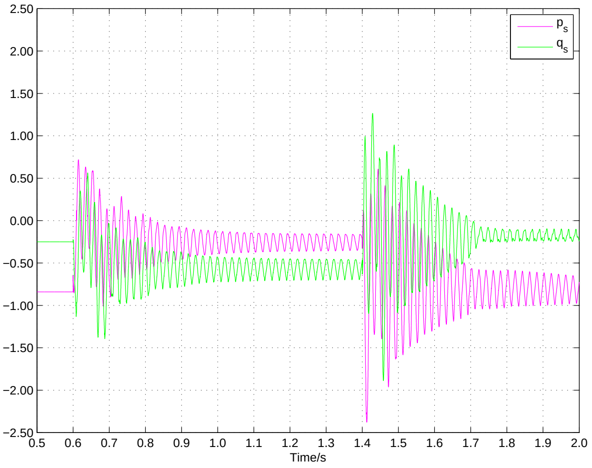

Fig. 13: Active and reactive power during a LVRT-B cycle on the stator side, DFIM

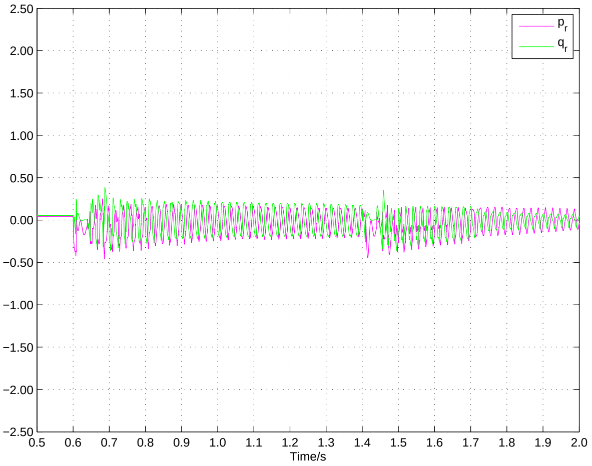

Fig. 14: Active and reactive power during a LVRT-B cycle on the rotor side, DFIM

## V. CONCLUSION

The utilization of variable-speed pump-turbine units such as synchronous or doubly-fed induction motor-generators with hydro power plants allows for new challenges within the electric energy markets. An application of these units in the range from 30 MVA up to 500 MVA requires powerful design and simulation methods in order to reliably predict both steady-state as well as transient operational behaviour. In addition to the above presented results, advantages and drawbacks of both types of motor-generators as well as

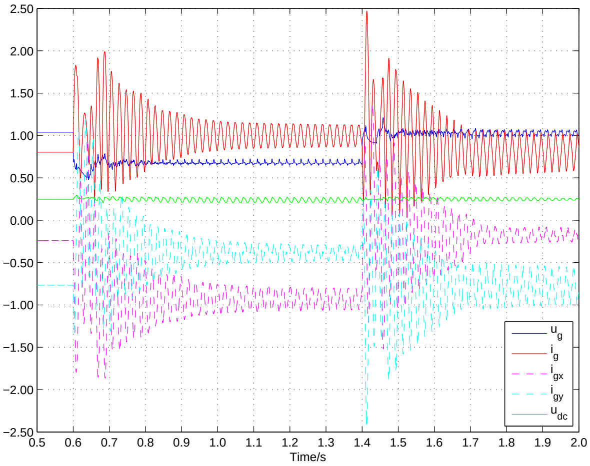

Fig. 15: Voltages and currents during a LVRT-B cycle on the grid side, DFIM

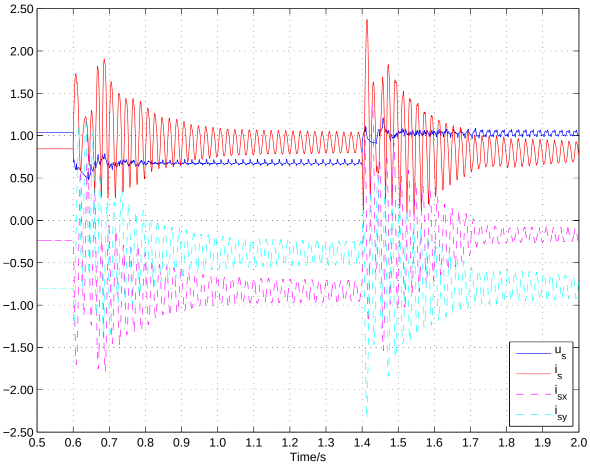

Fig. 16: Voltages and currents during a LVRT-B cycle on the stator side, DFIM

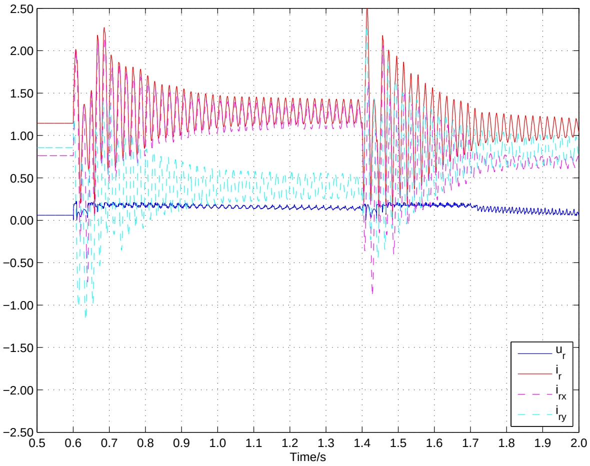

Fig. 17: Voltages and currents during a LVRT-B cycle on the rotor side, DFIM

the influence of various control strategies are very important tasks which are further analyzed. Moreover, detailed simulations about start-up and synchronization as discussed in [16] are necessary for a successful design of the complete electrical system.

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