Simulation of Steady-State and Transient Operational Behaviour of Variable-Speed Motor-Generators of Hydro Power Plants

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Abstract – **Renewable energy resources like hydro power plants play a more important role in the upcoming future of power grids. Thereby, a full flexibility of utilizing the grid capabilities in terms 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, this can be done by utilizing variable-speed pump-turbine units with either synchronous or doubly-fed asynchronous motor-generators. In order to achieve accurate data about steady-state as well as transient behaviour, simulation models of both arrangements are developed. In particular, the low voltage ride through capabilities according to various grid code requirements have to be analyzed in detail.**

Index Terms – **Pump-turbine, Power generation, Synchronous machine, Asynchronous machine, Doubly-fed induction machine**

I. Introduction

In hydro-electric power plants, pump-turbines are optimized for operating points defined by speed, head and discharge [1]. 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-turbines offer several advantages for both operating modes [1]–[3].

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 [1]–[5]. Both types of motor-generators offer several advantages with generating as well as pumping mode [5]:

- Increased efficiency and extended operation range in both generating and pumping mode particularly under partial load.
- Possibility of active power control in pumping mode.
- Improved network stability due to better reactive power control.
- 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 [2]–[6].

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 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 [7], [8].

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

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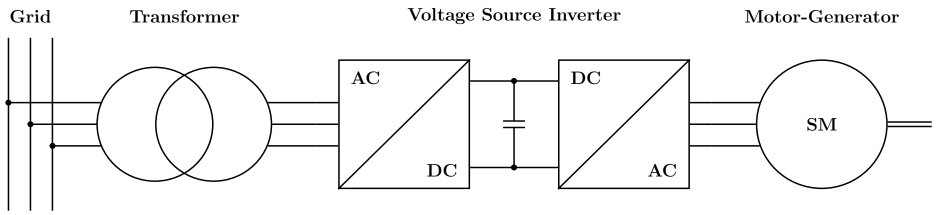

Fig. 1: Synchronous motor-generator (SM) of variable-speed pump-turbine units

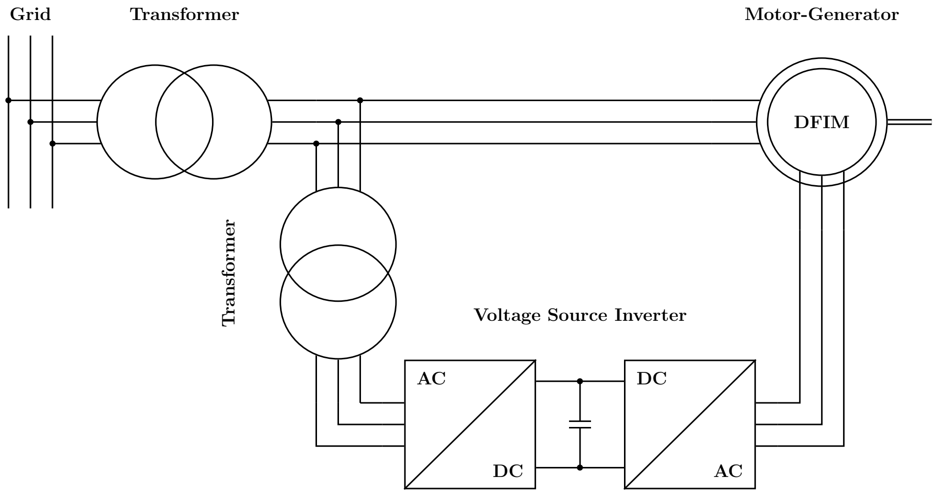

Fig. 2: Doubly-fed induction motor-generator (DFIM) of variable-speed pump-turbine units

carrying the full scale power. 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.

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 fixed reference frame,

and their respective transformations

$$\underline{F}_{dq} = \underline{F}_{\alpha\beta}\ \mathrm{e}^{-\jmath\gamma} \ , \quad \underline{F}_{xy} = \underline{F}_{\alpha\beta}\ \mathrm{e}^{-\jmath\delta} \tag{1}$$

as shown in Fig. 3 are utilized throughout all simulations [9]. Thereby, phase values and space vector of stator quantities are related as

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

$$F_a = \mathrm{Re}\big(\underline{F}_{\alpha\beta}\big) \ , \tag{3a}$$

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

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

as well as phase values and space vector of rotor quantities

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

$$F_A = \mathrm{Re}\big(\underline{F}_{dq}\big) \ , \tag{5a}$$

$$F_B = \mathrm{Re}\big(\underline{F}_{dq}\ \mathrm{e}^{-\jmath 2\pi/3}\big) \ , \tag{5b}$$

$$F_C = \mathrm{Re}\big(\underline{F}_{dq}\ \mathrm{e}^{-\jmath 4\pi/3}\big) \ , \tag{5c}$$

respectively.

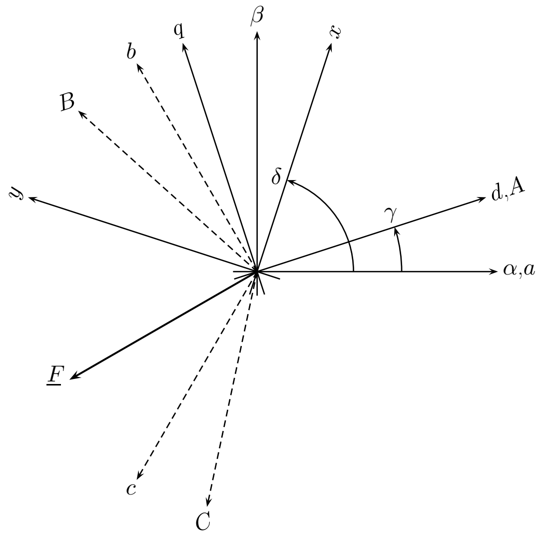

Fig. 3: Two-axes theory, coordinate systems

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 [7], [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 [2], [3].

Thus, the non-continuous behaviour of the utilized three level converters as depicted in Fig. 4 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. 5. 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].

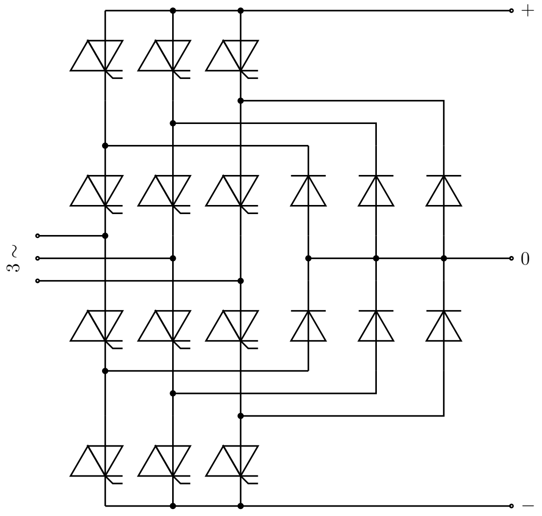

Fig. 4: Three level converter with IGCT modules

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

$$m_i(t) = \frac{2\,u_i(t)}{U_{DC}} \quad , \quad -1 \leq m_i(t) \leq 1 \quad , \tag{6}$$

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 inverter sides 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.

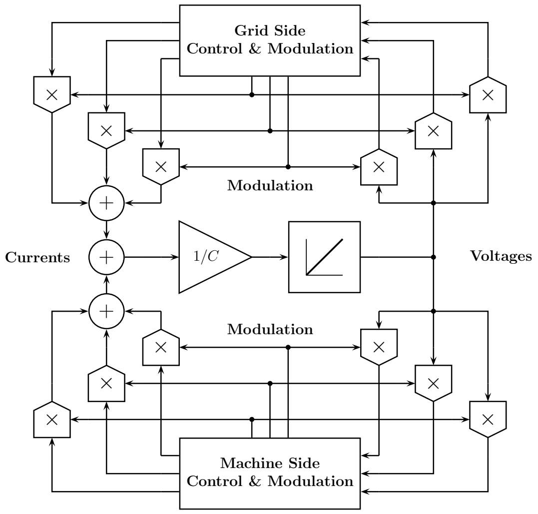

Fig. 5: Model of the three level voltage source inverter utilized with variable-speed motor-generators

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 [3], [5], [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 [3], [5].

IV. Simulation Results

A. Control strategies

Active power of the stator

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

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

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

and reactive power of the stator

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

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

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

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 [13], [14], 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. Preliminary Results

With the intent of the comparison of symmetric and asymmetric grid conditions, Fig. 6 and Fig. 10 depict a simulation of a transitional state with constant active but changing reactive power into an over-excited operational mode in pumping mode. Corresponding, Fig. 7, Fig. 11 and Fig. 8, Fig. 12 show grid voltages and grid currents, respectively. Finally, Fig. 9 and Fig. 13 depict the DC-link voltage versus time.

Obviously, the DC-link voltage control can handle the changing reactive power on the grid side very well with symmetric grid conditions. On the other hand, with an assumed asymmetry of 10% of the grid voltages, the active and reactive power flow cannot be constant due to the asymmetry. Consequently, the DC-link voltage control cannot be as perfect as with symmetric grid conditions, too. The smallest deviations always occur in operational states without any reactive power flow.

V. Conclusion and Outlook

The utilization of variable-speed pump-turbine units with synchronous or doubly-fed induction motor-generators with hydro power plants allow for new challenges within the electric energy markets. An application of such units in the range from 50 MW up to 500 MW requires very 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, detailed investigations of LVRT behaviour and capabilities according to various grid code requirements will be carried out in detail. In particular, a comparison of various control strategies as well as advantages and drawbacks of both types of motor-generators are very important tasks. On the other hand, detailed simulations about start-up and synchronization as discussed in [15] will be necessary for the successful design of the complete electrical system.

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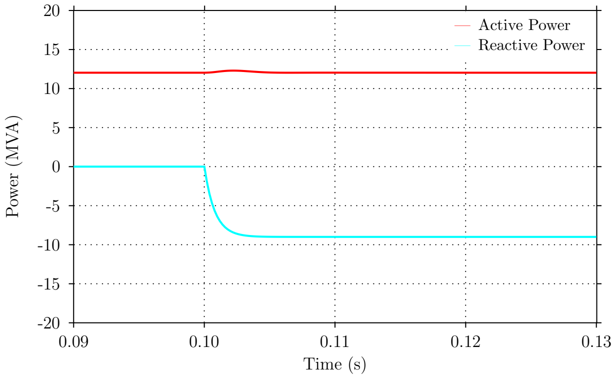

Fig. 6: Active and reactive power, symmetric grid

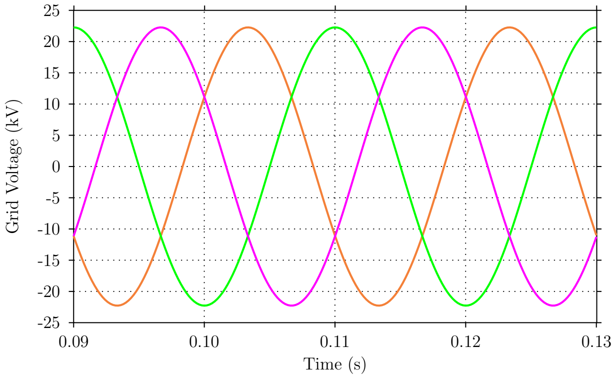

Fig. 7: Grid voltages versus time, symmetric grid

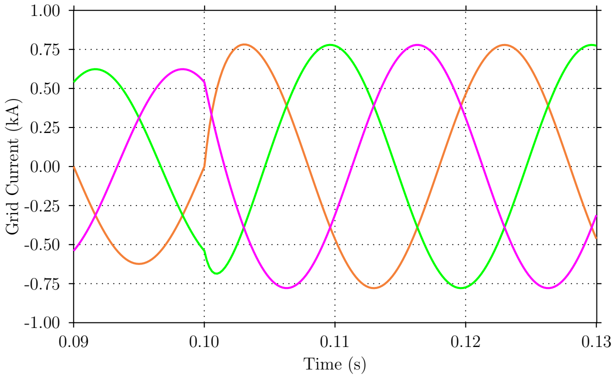

Fig. 8: Grid currents versus time, symmetric grid

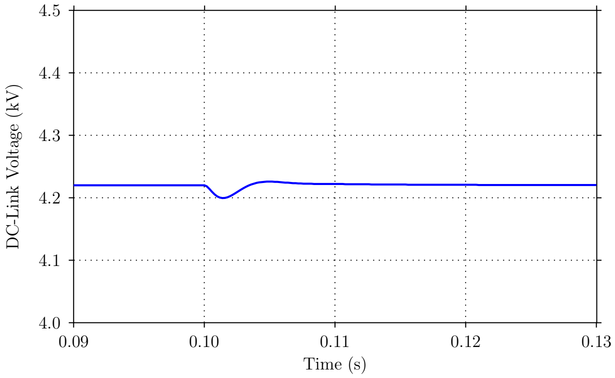

Fig. 9: DC-link voltage versus time, symmetric grid

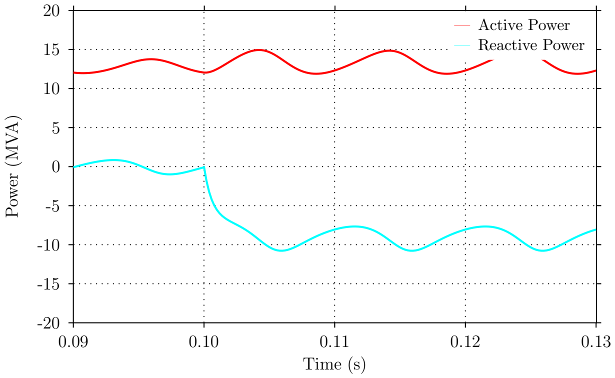

Fig. 10: Active and reactive power, asymmetric grid

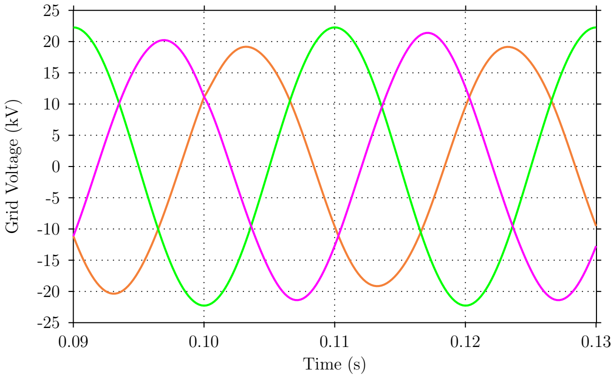

Fig. 11: Grid voltages versus time, asymmetric grid

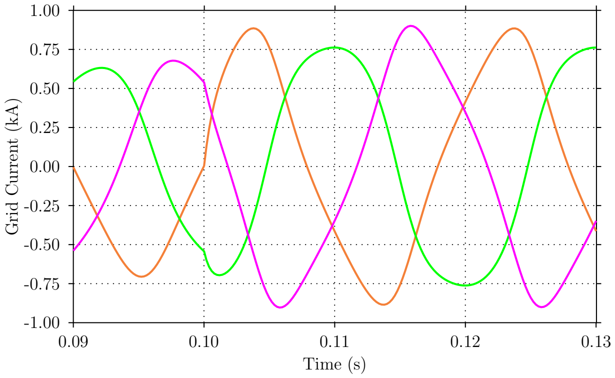

Fig. 12: Grid currents versus time, asymmetric grid

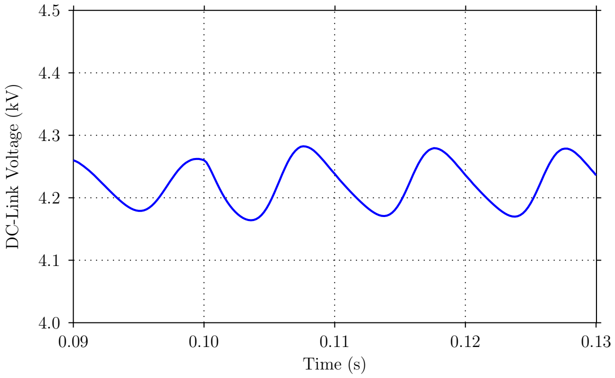

Fig. 13: DC-link voltage versus time, asymmetric grid