Direct Drive Synchronous Machine Models for Stability Assessment of Wind Farms

Sebastian Achilles and Markus Pöller

***Abstract*— The increasing size of wind farms requires power system stability analysis including dynamic wind generator models. For turbines above 1MW, doubly-fed induction machines are the most widely used concept. However, especially in Germany, direct-drive wind generators based on converter-driven synchronous generator concepts have reached considerable market penetration. This paper presents converter driven synchronous generator models of various order that can be used for simulating transients and dynamics in a very wide time range.**

***Index Terms*—Transmission networks, variable speed wind turbines, direct drive synchronous machines, off-shore wind power generation, power system stability**

I. INTRODUCTION

WORLDWIDE , the total installed wind power capacity as well as the average rated power per wind mill is constantly increasing. In many European countries, particularly in Denmark, Germany, and Spain, wind-power experienced a rapid growth during the past years and contributes nowadays considerably to the overall electricity production.

As a result, there is a strong need for transmission system operators to carry out power system stability analysis of the whole system including dynamic models of on- and off-shore wind farms, so that all interactions between conventional power plants and wind power generators can be assessed.

For this purpose, standard models are needed that can be used for simulating complete power systems with hundreds of generators. For these applications the model complexity must be chosen in a way that model accuracy is sufficient with regard to the response to wind fluctuations and faults in the electrical network but the calculation time for simulating large systems remains in an acceptable range.

Nowadays, for units above 1MW, variable speed concepts are usually applied that are either based on doubly-fed induction machines (e.g. GE Wind-Power, Vestas, RE Power, Nordex, NEG-Micon) or converter-driven synchronous machines (e.g. ENERCON, Pfleiderer).

Some of the largest units currently available and therefore especially suited for off-shore applications are built on the direct drive synchronous machine concept. This paper presents an approach for standard variable speed wind generator models based on this concept. It includes models of all components, generator and converter (diode or PWM), typical approaches for the control circuits and aerodynamics of the turbine.

The focus of the presented models is on power system stability analysis. However, some of the presented models can also be used for flicker analysis, harmonics studies and electromagnetic transients simulations.

All models have been implemented and tested in the power system analysis program DIgSILENT *PowerFactory* [11].

II. CONVERTER DRIVEN SYNCHRONOUS GENERATORS

Figure 1 shows the principal arrangement of a direct drive synchronous generator. Rotor and generator shafts are mounted to the same shaft without gear-box. The generator is a high-pole synchronous generator designed for low speed. It can either be an electrically excited synchronous generator or a permanent magnet machine.

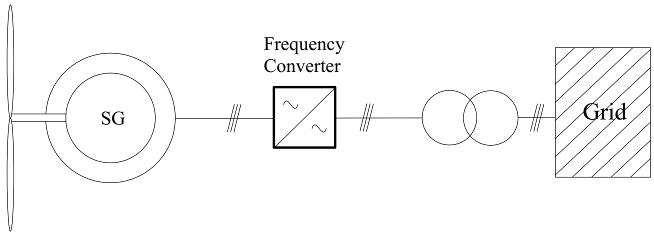

Fig. 1. Direct-drive synchronous generator

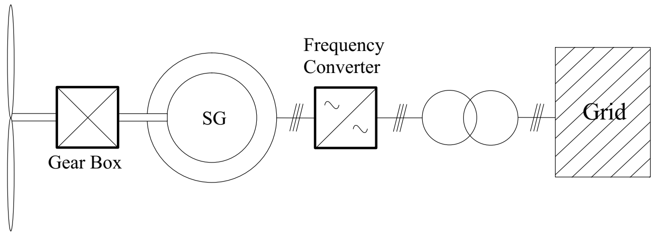

Fig. 2. Converter-driven synchronous generator with gear-box

Synchronous machines of direct-drive wind generators tend to be very large due to the high number of poles. Figure 2 shows a compromise between a direct drive concept and a design with gear box. Here, a robust, single-stage gear box with low ratio is used allowing for a lower number of poles and hence a smaller generator than in a pure direct drive wind generator. Electrically, this concept behaves analogously to the direct drive concept of figure 1.

Permanent magnet machines have usually a higher efficiency and are more compact than electrically excited machines. However, they are still considerably more expensive and require more advanced rectifiers because they don't allow for reactive power or voltage control.

The most common concept for direct drive wind-generators is the ”Enercon”-concept using a salient pole, electrically excited synchronous generator [3].

For allowing variable speed operation, the synchronous generator must be connected to the grid through a frequency converter. There is an almost infinite number of possibilities realizing frequency converters and most of them have already been used for wind power applications in the past. The concept having nowadays the widest spread is shown in figure 3. The generator is connected to an intermediate DC-circuit by a diode rectifier. The grid-side connection is realized by a self commutated pulse-width modulated (PWM)-converter that imposes a pulse-width modulated voltage to the AC-terminal. The PWM-converter is connected to the network through a filter, symbolized by the L-C circuit in figure 3. The level of harmonics in the voltage at the connection point is extremely low.

The control concept for the inverter of figure 3 consists of fast current controllers that regulate AC currents in an AC-voltage oriented

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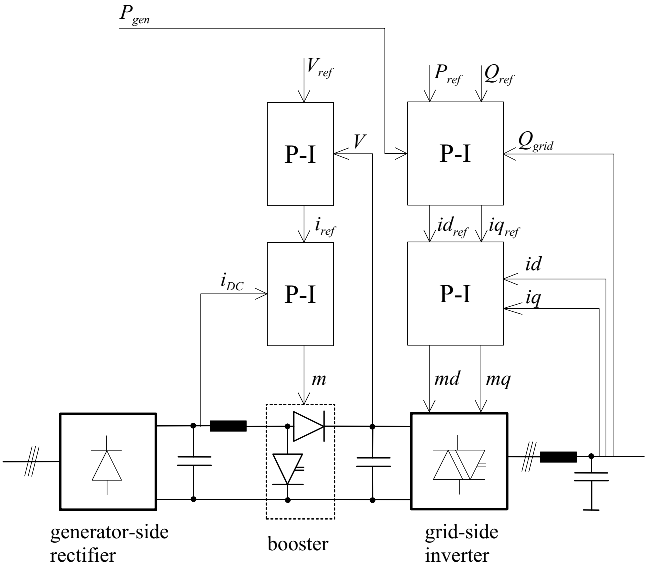

Fig. 3. Frequency-converter with generator-side diode-rectifier and grid-side PWM-converter

reference frame (d-axis: active current, q-axis: reactive current). This fast current control loops can be found in almost all grid connected PWM-inverters.

In a slower control loop, active and reactive power are controlled. The power reference is usually defined by a speed-power characteristic that drives the wind-generator automatically in the operating point of highest efficiency (Maximum Power Tracking strategy).

But controlling active power is just one of several possibilities for realizing the outer, d-axis control loop. Controlling torque instead of power is another alternative. In many designs, generator speed instead of power or torque defines the active (d-axis) current reference.

The DC-booster stabilizes the voltage at the DC-terminal of the inverter. The controller is realized by a fast current controller set by an outer voltage control loop.

Figure 4 shows another frequency converter concept that is very common, especially for permanent magnet generators. Here, both converters, the generator-side and the grid-side converter are realized by self-commutated PWM converters.

The grid-side control can be realized in exactly the same way as in the concept according to figure 3, including all options with regard to torque or speed control.

The generator-side rectifier regulates DC-voltage through the d-axis current and AC-voltage through the q-axis current controller.

In case of electrically excited generators having AVRs, reactive power could be controlled instead of AC-voltage.

III. ELECTRICAL COMPONENT MODELING

A. Synchronous Generator

Synchronous machine models for power system analysis are usually based on the assumption that the magnetic flux distribution in the rotor is sinusoidal (e.g. [10]). With this assumption, the flux can entirely be described by a vector.

The resulting synchronous machine model, also named the "Park"-model can best be described in a rotor-oriented d-q-reference frame.

Figures 5 and 6 show the d-axis and q-axis equivalent circuit diagrams of the synchronous generator model of seventh order. The model considers stator windings, the excitation winding in the d-axis and damper windings in the d- and q-axis. The inductances associated to damper windings can either represent real windings or just model eddy current losses in the rotor. Hence, the described model can be used for synchronous generators with or without damper windings.

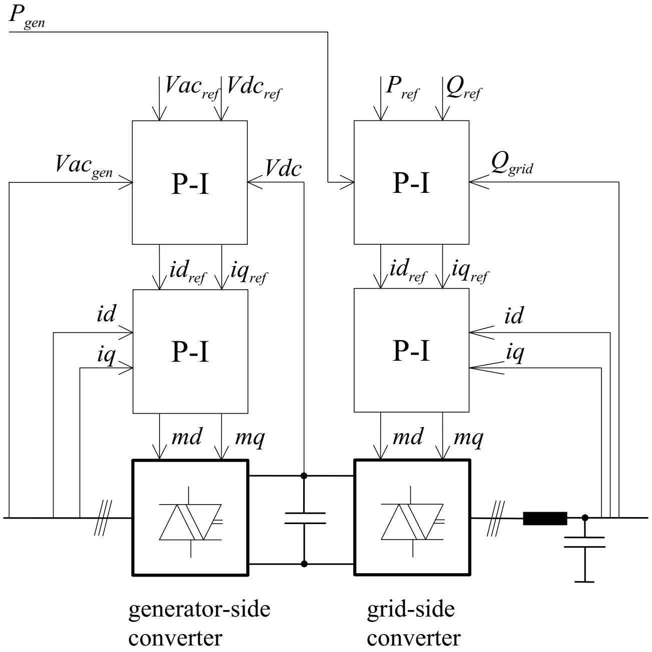

Fig. 4. Frequency-converter with two PWM-converters and intermediate DC-voltage circuit

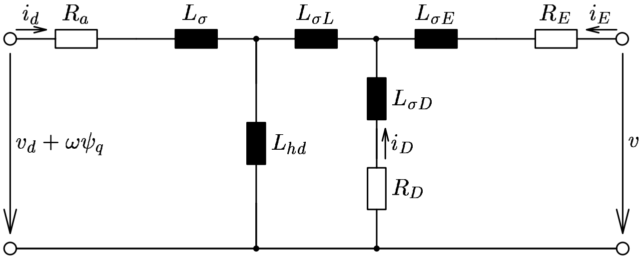

Fig. 5. d-axis synchronous machine model

According to the equivalent circuits of figures 5 and 6 the stator-voltage equations can be expressed as follows:

$$\begin{aligned} v_d &= R_a i_d + \dot{\psi}_d - \omega\psi_q \\ v_q &= R_a i_q + \dot{\psi}_q + \omega\psi_d \end{aligned} \tag{1}$$

The rotor-voltage equations are:

$$\begin{aligned} v_E &= R_E i_E + \dot{\psi}_E \\ 0 &= R_D i_D + \dot{\psi}_D \\ 0 &= R_Q i_Q + \dot{\psi}_Q \end{aligned} \tag{2}$$

The synchronous machine model is completed by the mechanical equation:

$$\begin{aligned} J\dot{\omega}_g &= M_t + M_e \\ \dot{\vartheta}_g &= \omega_g \end{aligned} \tag{3}$$

There is the following relationship between the mechanical variables ω_m and δ_m and the corresponding electrical values that are used in (1):

$$\begin{aligned} \omega &= p\omega_g \\ \vartheta &= p\vartheta_g \end{aligned}$$

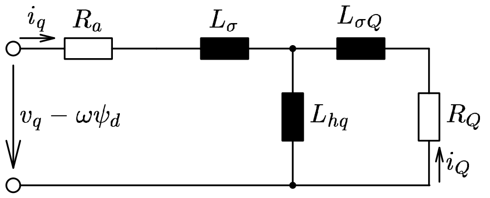

Fig. 6. q-axis synchronous machine model

with p being the number of pole-pairs.

The electrical torque can be calculated by:

$$M_e = \frac{3}{2}p(\psi_d i_q - \psi_q i_d) \tag{4}$$

For completing the synchronous machine model the flux linkage equations are required.

Stator flux linkage:

$$\begin{aligned} \psi_d &= (L_{hd} + L_\sigma)i_d + L_{hd}i_E + L_{hd}i_D \\ \psi_q &= (L_{hq} + L_\sigma)i_q + L_{hq}i_Q \end{aligned} \tag{5}$$

Rotor flux linkage:

$$\begin{aligned} \psi_E &= L_{hd}i_d + (L_{hd} + L_{\sigma L} + L_{\sigma E})i_E + (L_{hd} + L_{\sigma L})i_D \\ \psi_D &= L_{hd}i_d + (L_{hd} + L_{\sigma L})i_E + (L_{hd} + L_{\sigma L} + L_{\sigma D})i_D \\ \psi_Q &= L_{hq}i_q + (L_{hq} + L_{\sigma Q})i_Q \end{aligned} \tag{6}$$

Automatic voltage regulators (AVR) of electrically excited machines can be considered by connecting the AVR-model to v_E.

Permanent magnet generators can be modeled with the above equations by keeping the excitation current i_E to a constant value.

This synchronous machine model of seventh order is able to represent rotor and stator transients correctly. In stability studies however, transient phenomena of the electrical network are usually not considered [10]. Applying the principle of neglecting stator transients to the synchronous machine model reduces stator equations to arithmetic equations:

$$\begin{aligned} v_d &= R_a i_d - \omega\psi_q \\ v_q &= R_a i_q + \omega\psi_d \end{aligned} \tag{7}$$

Equation (7) allows expressing the electrical torque (4) by voltages and currents only:

$$M_e = \frac{3}{2}\frac{p}{\omega}\left(v_q i_q + v_d i_q - R_a(i_d^2 + i_q^2)\right) = \frac{1}{\omega_g}(P_e - P_v) \tag{8}$$

Hence, in the fifth-order-model, the electrical torque is equal to the electrical power (minus stator losses) devided by the mechanical speed.

B. PWM Converter

Grid-side converters are usually realized by self commutated pulse-width modulated circuits (see Figure 7). The circuit is built from six valves with turn-off capability and six antiparallel diodes. Valves with turn-off capability are typically realized with bipolar transistors or IGBTs (insulated gate bi-polar transistors) because they allow for higher switching frequencies than classical GTOs.

In older wind generators, line commutated, thyristor-converters were sometimes used, but due to their high level of harmonics and the lack of reactive power control capabilities there are not used in modern designs.

Depending on the application, the circuit according to Figure 7 is actually modeled using switches according to Figure 8 for representing the valves.

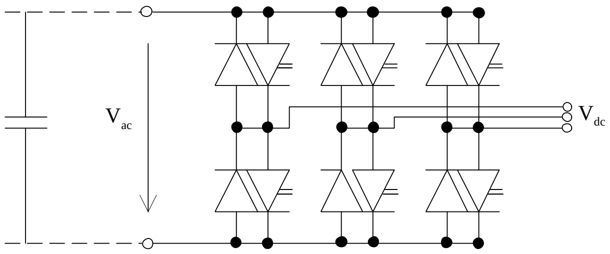

Fig. 7. PWM-converter circuit

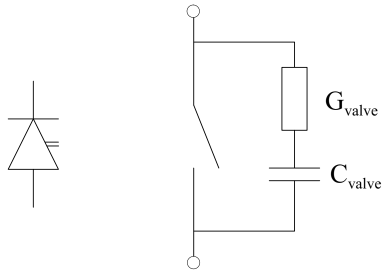

Fig. 8. Valve representation by equivalent switches

However, since switching frequencies are usually in a kHz-range, such a detailed model requires very small simulation time steps why calculation time gets very large.

For applications, in which the control behaviour of PWM-converters is in the center of interest (e.g. power system stability), a fundamental frequency model should be used.

Assuming an ideal DC-voltage and an ideal PWM modulation (infinite modulation frequency), the fundamental frequency line to line AC voltage (RMS value) and the DC voltage can be related to each other as follows:

$$|V_{ac}| = \frac{\sqrt{3}}{2\sqrt{2}} m V_{dc} \tag{9}$$

The AC-voltage phase angle is defined by the PWM converter.

The pulse-width modulation index m is the control variable of the PWM converter. Equation (9) is valid for $0 <= m < 1$. For values larger than 1 the converter starts saturating and the level of low order harmonics starts increasing. The complete characteristic of the PWM converter, including the saturated range is shown in Fig. 9. Because of the mentioned increase of low-order harmonics, the saturated are of a PWM-converter is usually not used or just up to $m = 1.1...1.2$.

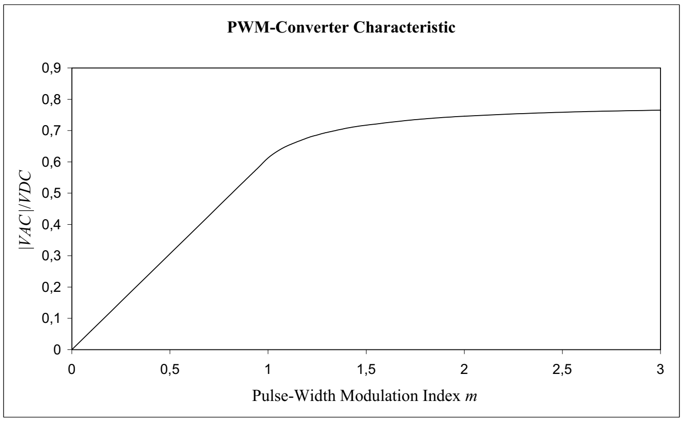

Fig. 9. PWM Converter fundamental frequency characteristic

The converter model is completed by the power conservation equation:

$$V_{dc}I_{dc} + \sqrt{3}\text{Re}\left(\underline{V}_{ac}\underline{I}_{ac}^{*}\right) = 0 \tag{10}$$

This equation assumes a loss-less converter. Because the switching frequency of PWM converters is usually very high (typically several hundreds Hz), switching losses are the predominant type of losses. Since the average switching losses are basically proportional to V_{DC}^2, switching losses can be considered by a resistance between the two DC-poles in a fundamental frequency model.

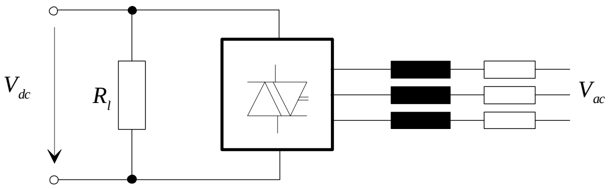

Fig. 10. PWM-converter model including losses

The model according to figure 10 represents switching losses by the equivalent resistance R_l. Load losses can be considered by copper losses of the coupling-reactance.

C. Diode Rectifier

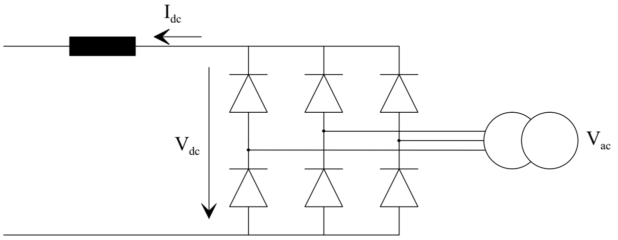

Fig. 11. Diode Rectifier

The diode-rectifier-circuit is shown in Figure 11. As in case of the PWM-converter, a fundamental frequency model is used for stability applications. The fundamental frequency model represents AC-fundamental frequency and the DC-average values of voltages and currents. At fundamental frequency, a diode rectifier can be represented according to the equivalent circuit of Figure 12. DC-voltage drops due to commutation, which are proportional to the dc-current, are represented by the equivalent resistance Z_c.

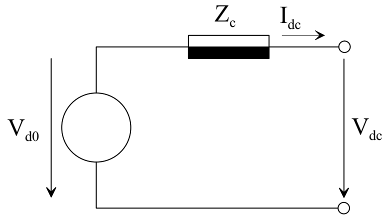

Fig. 12. Equivalent circuit of the fundamental frequency diode rectifier model

The source voltage V_{d0} and the equivalent resistance Z_c are:

$$V_{d0} = \frac{3\sqrt{2}}{\pi}V_{ac} \tag{11}$$

$$Z_c = \frac{3}{\pi}\omega L \tag{12}$$

The commutation angle can be calculated using

$$V_{dc} = V_{d0}\frac{1+\cos\mu}{2} \tag{13}$$

For the AC-side, the following approximate equations can be used:

$$\begin{aligned} P_{ac} &= P_{dc} \\ cos\varphi &= \frac{1+cos\mu}{2} \end{aligned} \tag{14}$$

D. DC-booster

The average values of voltage and current pulse streams generated by the dc-booster (see Figure 3) are as follows:

$$\begin{aligned} V_2 &= mV_1 \\ V_2I_2 &= V_1I_1 \end{aligned} \tag{15}$$

The control variable is the pulse-width modulation index m. The circuit shown in Figure 3 can realize values of $1 < m < 2$.

IV. POWER ELECTRONICS CONTROLLERS

A. Grid-Side Converter

The grid-side converter (see Figures 3 and 4) operates in a stator-voltage oriented reference frame. Hence, d-axis represents the active and q-axis the reactive current component.

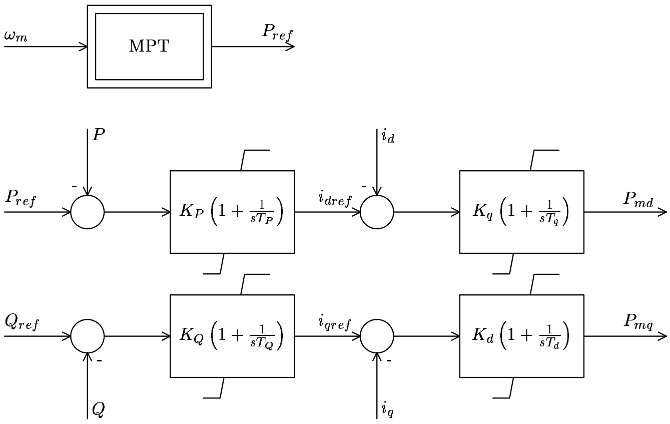

Fig. 13. Grid-side current controller

A very fast inner control loop regulates the d- and q-axis current components of the grid-side PWM-converter. Current references are defined by a slower outer control-loop regulating active- and reactive power.

The objective of the MPT-characteristic defining the active power reference is to drive the generator into the optimum speed-power operation point (optimum $c_p(\lambda)$) at any time.

As mentioned before, there are possible options for the active power regulation shown in figure 13. In many designs, the active-current reference is given by a speed controller, instead of the power controller. In this case, a speed reference is calculated from the actual electrical power using the inverse of the MPT-characteristic.

B. Generator-Side Converter

At the generator-side converter AC-voltage (optional: reactive power) and DC-voltage of the intermediate DC-circuit is regulated.

As before, the controller is equipped with fast current controllers. The current reference values are here defined by voltage regulators as indicated in figure 14.

C. Booster Controller

The DC-booster of Figure 3 regulates the DC-voltage at the DC-side of the grid-side PWM-controller. The concept is analogous to the PWM-converter control concept. An inner loop regulates DC-current and an outer voltage-controller loop defines the current reference.

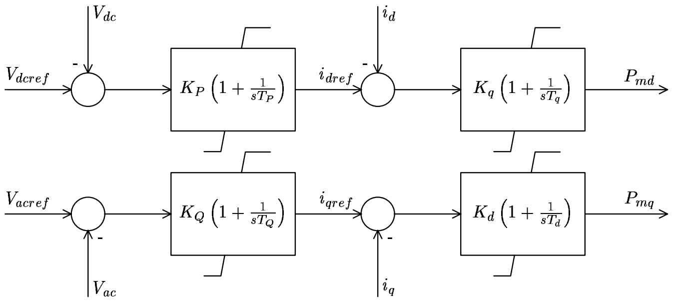

Fig. 14. Generator-side PWM converter controller

D. *Reactive Power Control*

Reactive power control is possible through the q-axis component of the grid-side converter. Variable speed wind power generators can be operated at a constant power factor, which is the standard operation mode today. Alternatively, an AC-voltage controller defining the d-axis current reference can be used in Fig. 13 instead of the reactive power controller, or secondary voltage control can be supported by adjusting the Q-reference (e.g. [4]).

V. TURBINE

Equation (16) shows the aerodynamic equation of a wind turbine that relates mechanical power to wind speed and mechanical speed of the turbine (e.g. [5]):

$$P_t = c_p(\lambda,\beta)\frac{\rho}{2}\pi R^2 v_w^3 \tag{16}$$

with:
P_t: Mechanical power of the wind turbine
ρ: Air density
R: Rotor radius
λ: Tip speed ratio
β: Blade pitch angle
c_p: Power coefficient as a function λ and β
v_w: Wind speed

The tip speed ratio λ is defined by:

$$\lambda = \frac{\omega_t R}{v_w} \tag{17}$$

with ω_t being the rotational speed of the wind turbine.

According to (16) the aerodynamic behaviour is modeled by a steady state equation and therefore, dynamic stall effects cannot be reflected by this model. An approximate method for including dynamic stall effects is described in [6].

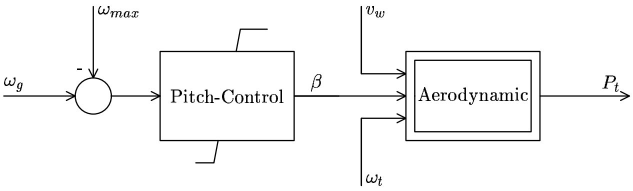

Fig. 15. Generic wind turbine model

In case of rotor frequencies below ω_{max}, active power is regulated according to the maximum power tracking (MPT) characteristic that defines the maximum power depending on the shaft speed as power reference of the power controller. When the maximum shaft speed is exceeded, the active power setpoint remains constant and the pitch angle control system (see Fig. 16) starts acting driving the shaft speed back to the maximum permitted value.

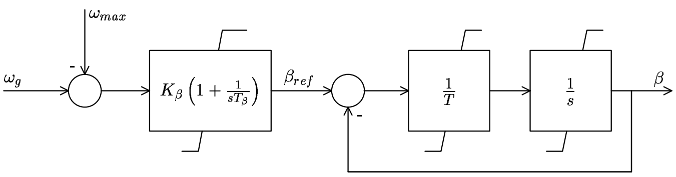

Fig. 16. Generic model of the pitch-control system

A. *Wind Fluctuations*

Wind fluctuations can either be modeled by deterministic models, where the wave-form of a gust or a wind-speed ramp is defined and injected into the input v_w of the turbine model.

Alternatively, stochastic wind-speed models can be used that generate stochastic signals representing wind-turbulence. A turbulence model including rotational sampling- and tower-shadow effects was presented in [6] and is briefly described in [8].

B. *Torsional Oscillations*

When the simulated applications are limited to the impact of wind fluctuations, it is usually sufficient to consider just a single-mass shaft model because shaft oscillations of variable speed wind generators are not reflected to the electrical grid due to the fast active power control [5].

In stability analysis however, when the system response to heavy disturbances is analyzed, the shaft must be approximated by at least a two mass model. One mass represents the turbine inertia, the other mass is equivalent to the generator inertia.

The equations describing the mechanical coupling of turbine and generator through the gear box by a two-mass model can be expressed as follows (see e.g. [9]):

$$J_t\frac{d\tilde{\omega}_t}{dt} = M_t - M_m \tag{18}$$

$$J_g\frac{d\omega_g}{dt} = M_m + M_{el} \tag{19}$$

$$\frac{d\Theta_{tg}}{dt} = \tilde{\omega}_t - \omega_g \tag{20}$$

$$M_m = K_{tg}\Theta_{tg} + D_{tg}(\tilde{\omega}_t - \omega_g) \tag{21}$$

In these equations turbine inertia, turbine torque and turbine frequency $\tilde{\omega}_t$ are related to the generator nominal frequency. The turbine torque is related to the turbine power (see Fig. 15) by:

$$M_t = \frac{P_t}{\tilde{\omega}_t}$$

The electrical torque is defined by (4) and (8).

C. *Protection*

In case of heavy disturbances, direct drive synchronous machines quickly disconnect from the system by blocking the PWM converter. Usually, the following protection criteria a supervised:

- Under- and overvoltage
- Overcurrent
- Overspeed

With regard to under-voltage tripping, the tendency is more and more to enable wind generators to stay on the network as long as possible, even for deep voltage dips ("voltage ride-through"). With the grid-side converter, reactive current support can be provided during voltage dips for lifting the voltage at the generator terminals in case of faults near to the connection point.

VI. SIMPLIFIED MODEL FOR TRANSIENT STABILITY ANALYSIS

For investigating transient stability phenomena, large system models have to be studied considering the interaction of all generators in the system. For reducing calculation time, simplified models of direct drive synchronous generators should be used.

In stability analysis, the model should represent correctly:

- Electrical output at the connection point (P and Q depending on voltage and angle).
- Generator and turbine acceleration.

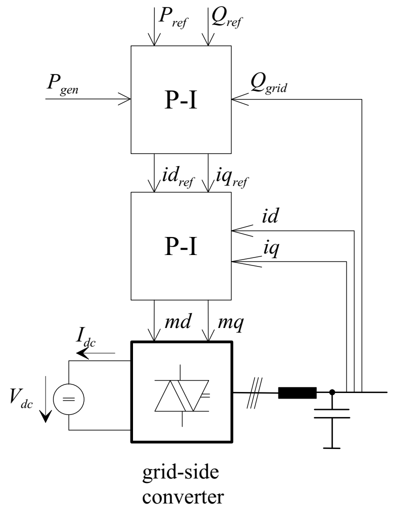

Fig. 17. Simplified model for converter driven synchronous generator

A simplified model can be derived under the assumption that the DC-voltage is constant. This assumption can be justified by the large capacitance in the DC-circuit and by the DC-voltage controllers, which can be found in both concepts, the concept according to figure 3 and figure 4.

With this assumption, only the grid-side converter needs to be represented fed by a DC-voltage source (see Figure 17).

Considering converter losses by a constant value (assumption of constant dc-voltage), the electrical torque can be calculated by (8) using:

$$P_e = V_{dc} I_{dc} - P_l \tag{22}$$

The model can further be simplified by neglecting the time constants of the fast current-controllers. Generally, this is a valid assumption for stability analysis because the current controllers act in sub-cycle timeframes. However, the current-source representation can cause problems in case of faults close to the converter:

Assuming an ideal, three phase fault at the connection point, active and reactive currents cannot be defined independent from each other, but they result from the impedance seen from the converter. In reality, the pulse-width modulation indices would limit and the converter behaves basically like a voltage source. With the current source approach, numerical problems have to be expected because no solution exists to this problem.

Except for faults near to the converter, the current source model provides results with sufficient accuracy. But due to the mentioned problems, the current source approach is not recommended. However, for being able to select reasonable step sizes, an A-stable integration algorithm with variable step size should be used when working with the detailed fundamental frequency PWM-coverter model.

VII. CASE STUDIES

All models presented in the previous sections were implemented and tested using the commercially available power system analysis package DIgSILENT *PowerFactory* [11].

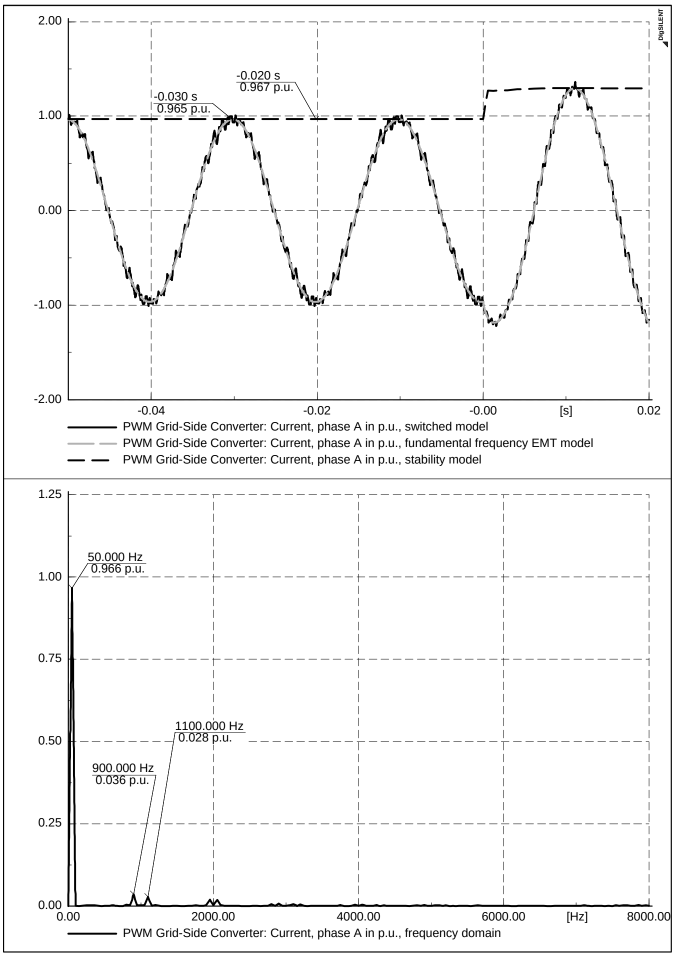

Fig. 18. Benchmark of different PWM-converter models

In order to present results of the wind generator models relevant to power system stability analysis, close fault simulations were performed.

No real data were used for parameterizing the models because of confidentiality agreements with various manufacturers. Instead, typical parameters have been used for all components. In all cases, 5MW turbines were assumed, which are not yet available but should be available for off-shore applications in the near future.

A. PWM converter model

In a first example, the different models of the grid-side PWM-converter and the AC-network are benchmarked. The three different models are:

- Switched PWM-converter model according to the circuit of figure 7 and an EMT[1] -like representation of the AC network
- Fundamental frequency PWM-converter model and an EMT-like representation of the AC network
- Fundamental frequency PWM-converter model and a steady state AC-network model (”stability model”).

All models are directly supported by *PowerFactory*. The network model (steady state or EMT-representation) can be selected when initializing a simulation run. The PWM-converter model (switched or fundamental frequency) can be specified with one parameter.

Figure 18 compares the AC-current of one phase calculated by the three different models. The depicted currents are in p.u. Instantaneous

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[1] **E**lectro**m**agnetic **T**ransients, a network model using differential equations for all AC-network elements

currents are rated to the nominal peak-value, currents of the steady state network model are rated to the nominal RMS-value.

The labels depicted in figure 18 show that the current of both fundamental frequency models match very well. The spectrum obtained by an FFT of the current allows comparing the fundamental frequency component of the switched model with the fundamental frequency models, which match extremely well.

B. Wind generator with grid-side PWM converter and generator-side diode rectifier.

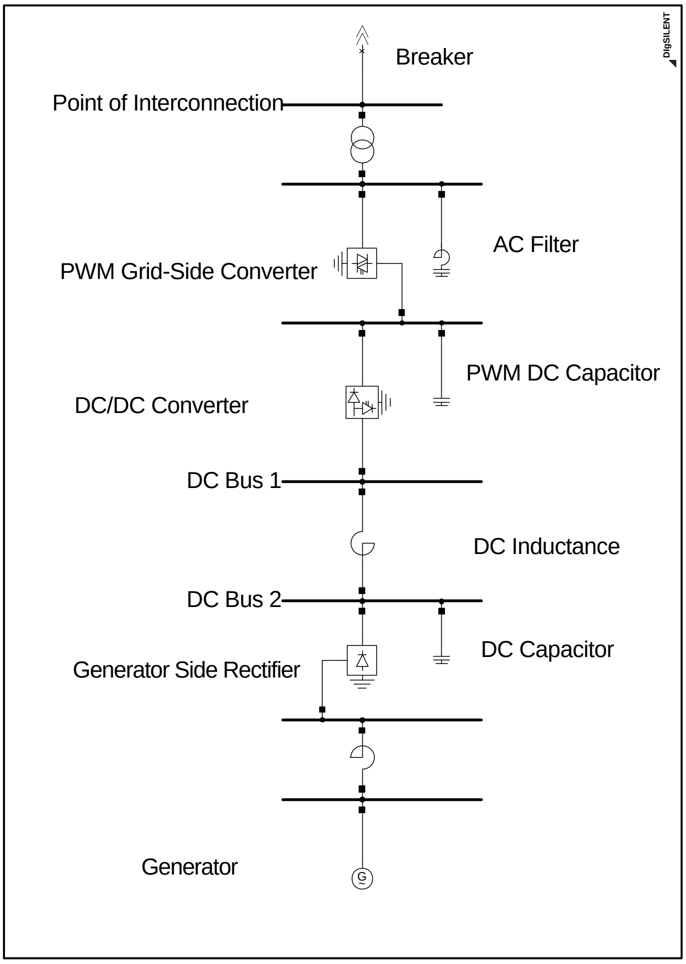

Fig. 19. Electrical representation of a wind generator with a grid-side PWM converter and a generator-side diode rectifier.

The electrical representation of the wind generator according to the concept of figure 3 is presented in figure 19. The PWM Grid-Side Converter model includes a series inductance on the AC side. The controllers applied in the model have the structure depicted in figure 3.

For validating the models under most severe disturbances, voltage-dip ride-through capability was assumed even if this is not (yet) provided by most commercial wind-generators of this design. The response of the system to a voltage sag of 80% at the connection point is presented in figures 20 and 21. The active and reactive power of the grid side converter recovers quickly. Speed and power of the generator are also presented (see figure 21). The small dips in the converter and generator power are associated to the changes in the active power reference generated by the Maximum Power Tracking as a result of the generator speed.

The results of both models match well. The fast generator power fluctuations that can be observed in the results of the EMT model are due to the fact that the connected diode rectifier is represented by a switched model. However, the speed-results from both models match very well.

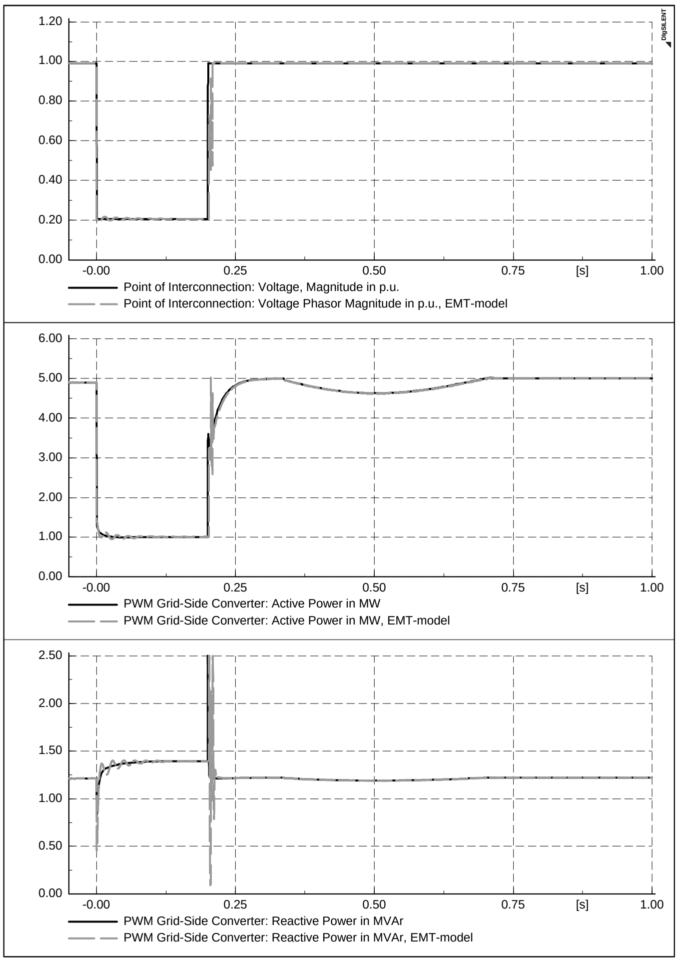

Fig. 20. Voltage sag simulation of the "Diode-Rectifier, PWM-Inverter"-concept

C. Wind generator with two PWM converters and intermediate DC circuit

The same voltage sag of 80% was simulated for a wind-generator according to the concept of figure 4. All controllers were tuned in a similar way as in the previous cases.

The results of a voltage sag of 80% are presented in figures 22 and 23. Because both rectifier and inverter is modeled by fundamental frequency models, also in the EMT-representation, the active power of the generator looks much smoother and is much closer to the stability-result than in the previous section.

D. Simplified model of converter driven synchronous wind generators for transient stability simulations

According to section VI, a simplified model was represented. The electrical model of the generator and the DC circuit dynamics are neglected. However, the mechanical behavior of the generator (shaft, aerodynamics and blade angle control) is represented and allows for consideration of wind turbulences [8].

Figure 24 presents the results of the simulation of a voltage sag of 80% in the connection point with the simplified model. The resulting curves are compared against the results obtained with the detailed model of the concept according to figure 3. The results match very well. The behavior of the active and reactive power at the point of

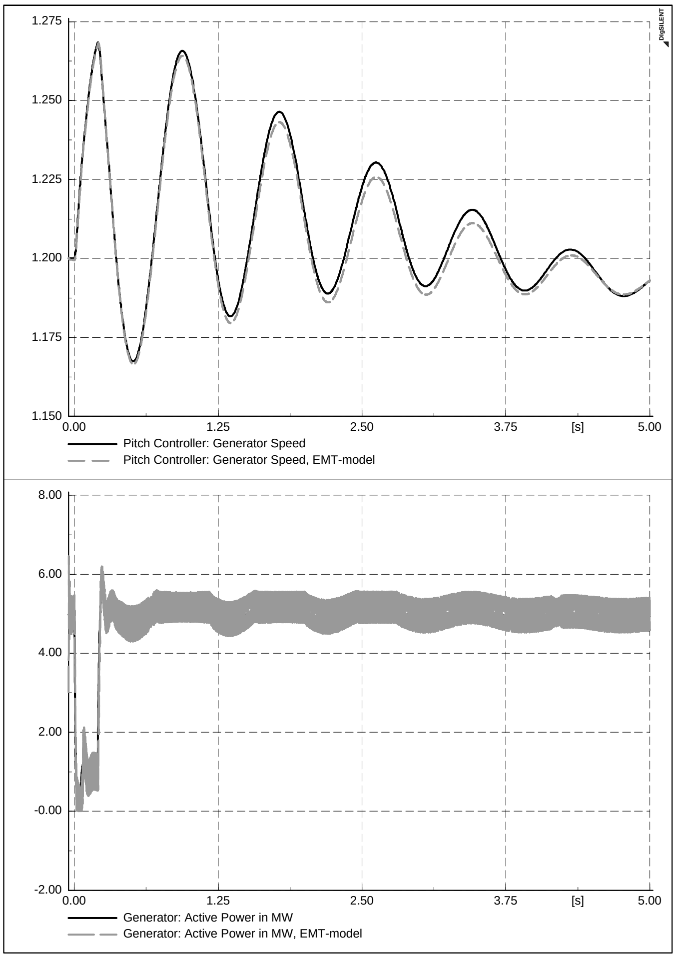

Fig. 21. Voltage sag simulation of the "Diode-Rectifier, PWM-Inverter"-concept

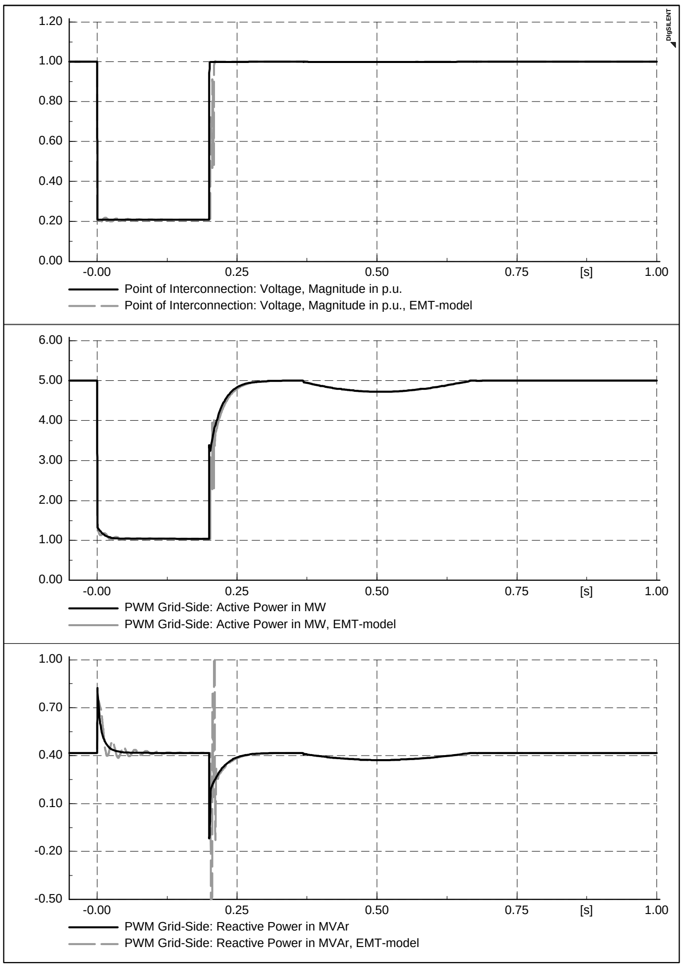

Fig. 22. Voltage sag simulation of the wind generator concept with two PWM converters

connection are mainly driven by the PWM control characteristics. The simplified calculation of the generator speed is perfectly adequate.

VIII. CONCLUSIONS

The modeling of converter driven synchronous machines commonly applied to wind generation applications was treated in this paper. The required representation of the different components particularly for power system stability assessment was carefully described. Detailed representation of these wind generator concepts was implemented and simulation results were presented. A simplified model is also proposed for large-scale power system analysis. The simulation results of this model are compared to those obtained with the detailed models for severe system disturbances. The proposed simplified model provides adequate accuracy for transient and dynamic stability analysis and is efficient with regard to calculation time.

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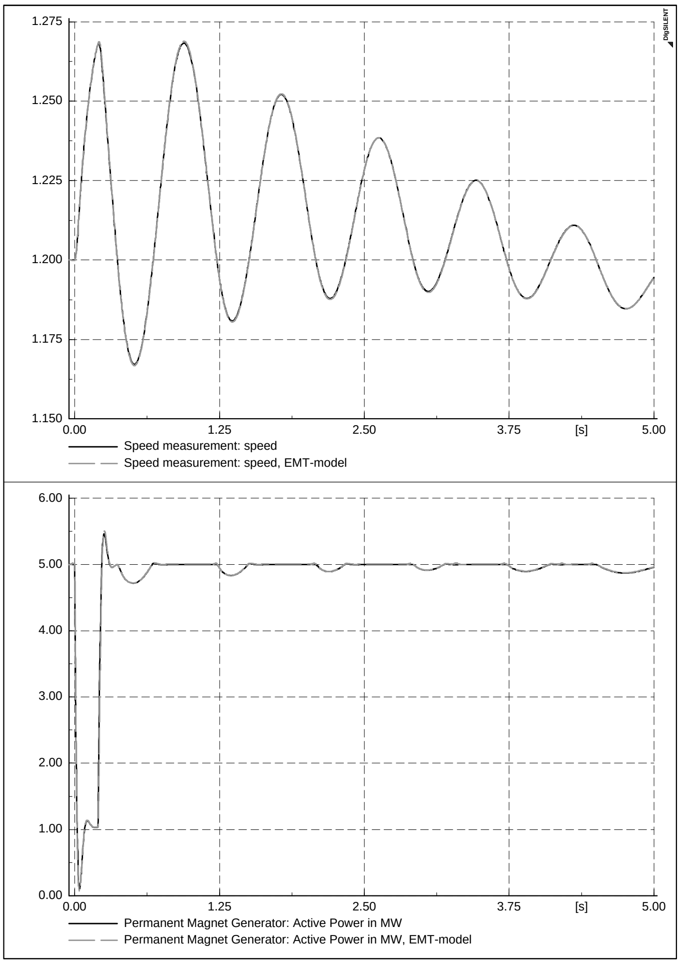

Fig. 23. Voltage sag simulation of the wind generator concept with two PWM converters

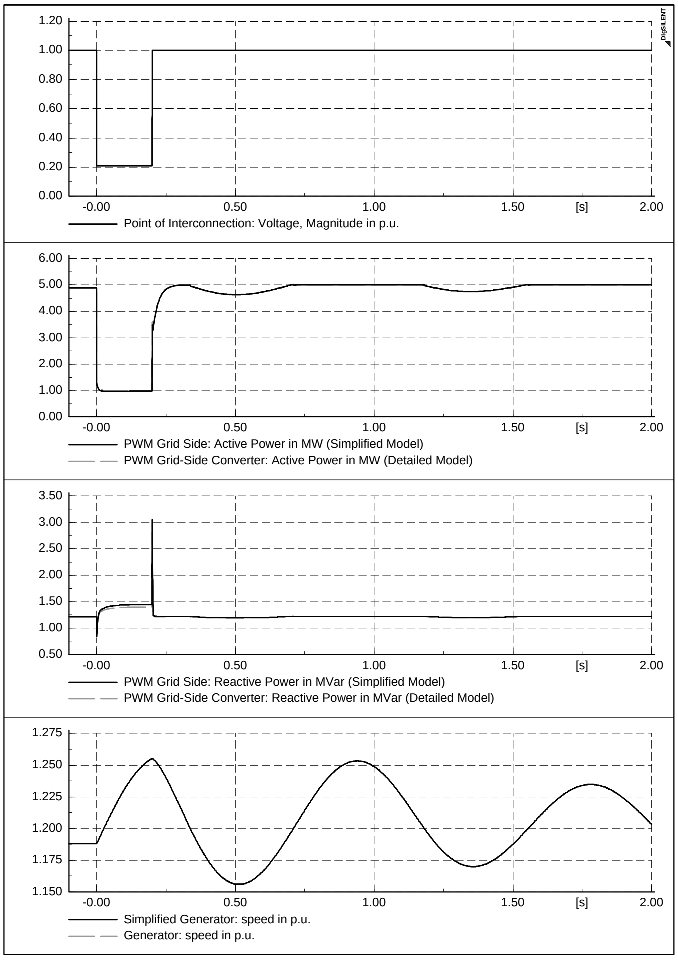

Fig. 24. Comparison of detailed and simplified stability models

BIOGRAPHIES

Sebastian Achilles received the Electrical Engineer degree from the University of La Plata, Argentina and the MS degree in Electric Power Eng. from the Rensselaer Polytechnic Institute in Troy, NY in 1996 and 2000 respectively. He worked on power systems consulting activities for ABB T&D Systems (Spain), GE Power Systems Energy Consulting (NY, USA) and for the Instituto de Investigaciones Tecnologicas de Redes y Equipos Electricos (Argentina). He currently works in the Consulting Department of DIGSILENT GmbH carrying out training and consulting activities on several topics including integration of wind generation to power systems, power system stability, network planning, test and modeling of generator controls and insulation coordination

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