Model-based Converter Control for the Emulation of a Wind Turbine Drive Train

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Keywords

Converter Control, EESM, Virtual Synchronous Generator (VSG), Wind Energy

Abstract

Failures in wind turbines are often attribute to faults in the power electronics. To investigate the fault mechanisms, a test bench was set up in which entire converters up to a power of 10 MW can be tested under changing climatic conditions and electrical loads. In order to generate realistic loads, one of the converters has to behave like a drive train of a wind turbine. Except from a few differences, the test bench which is used here and has a total power of 300 kW, is a scaled copy of the 10 MW test bench. This small test bench is used to perform preliminary developments of control concepts and test scenarios that can later be transferred to the large test bench. It consists mainly of two back-to-back converters and three transformers. The goal of this work is to force the behaviour of a drive train of a wind turbine on one of the converters. The second converter should be able to perform a generator current control, as is common in wind turbines. This paper shows the implementation of a wind rotor model, the connection with the existing generator model and the implementation of a speed-dependent generator load curve on the side of the device under test (DUT). The results demonstrate the functionality of the overall test bench. For this purpose, different curves of calculated and measured values such as wind speed, pitch angle, rotor speed, phase current and voltage under different conditions are shown. In summary, it can be shown that one of the converters behaves indeed like a drive train of a wind turbine and that realistic scenarios can be created based on measured wind speed curves.

Introduction

To gain a better understanding of the causes of malfunctions in the power electronics of wind turbine converters [1], a test bench was set up in which entire converters can be tested under electrical load and climatic conditions. In addition to the 10 MW test bench, another test bench with a rated power of 300 kW has been built. The basic structure of the two test benches is identical, however there are also some differences. The 300 kW test bench is used to develop and test different scenarios before they are transferred to the large-scale test bench. The focus of these scenarios is to simulate the electrical loads as realistically as possible. Therefore, this test bench does not have its own climate room. Furthermore, the smaller test bench does not have any converters working in parallel, as it is the case in the 10 MW test bench due to its high power. Fig. 1 shows the entire test bench, which consists of a total of three transformers and two full converters. The transformer T1 has an apparent power of only 40 kVA and is

Fig. 1: Photo of the test bench

responsible for compensating the losses of the converters and transformers during the tests. The transformers T2 and T3 with a rated apparent power of 270 kVA have adjustable output voltages, so that different devices under test (DUTs) can be connected. At this time, the two converters (load unit and DUT) are of the same type. The DUT should perform a generator current control as used in wind turbines and the load unit should emulate the drive train of a wind turbine. A full converter is used as load unit, so that the power is driven in a loop keeping the losses low.

System topology

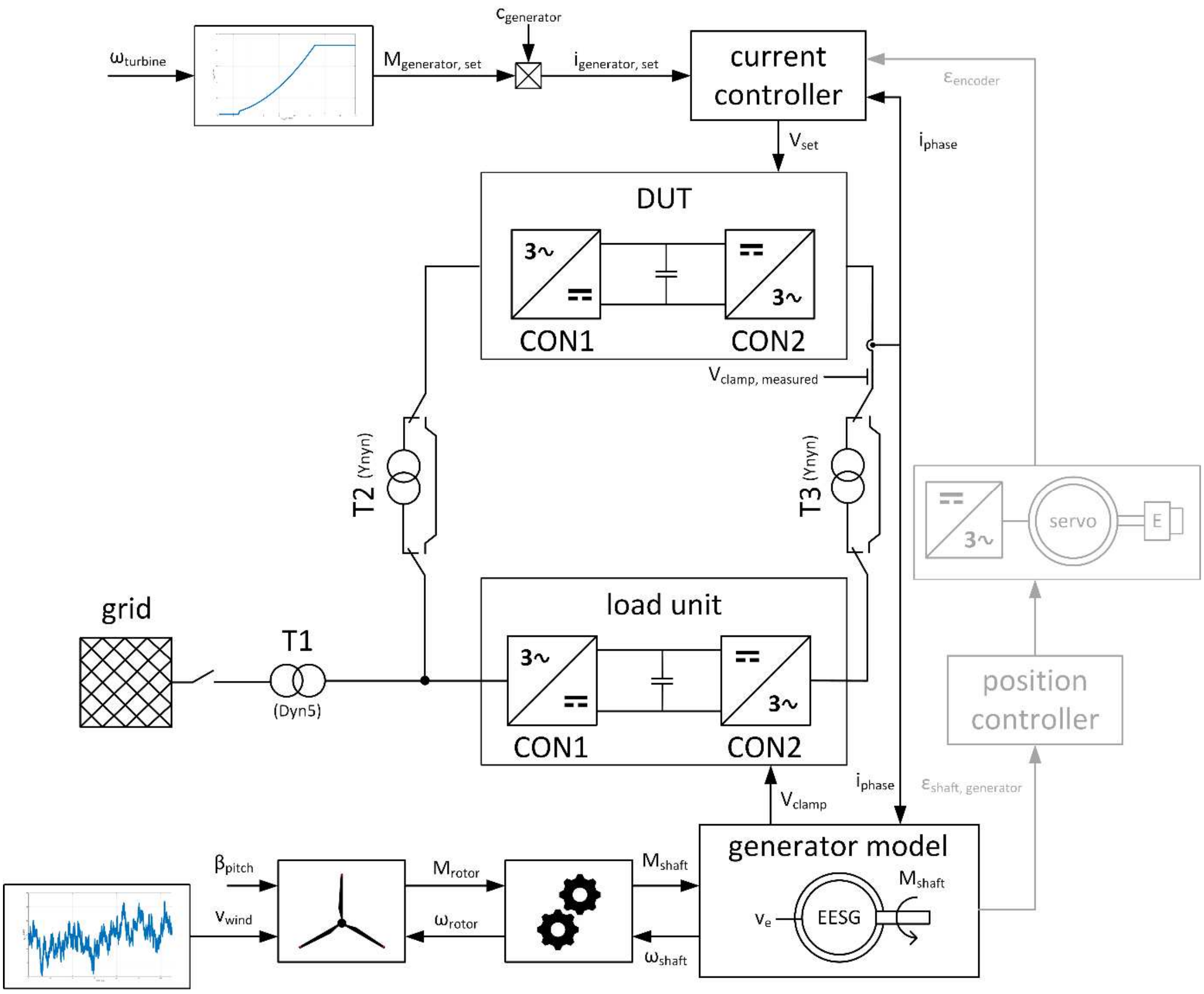

Fig. 2: System topology

Fig. 2 shows the topology of the entire system. The grid-side converters (CON1) are responsible for controlling the DC-link voltages of the load unit and the DUT. The power flow direction is arbitrary, so that the power can be driven in a loop. For this purpose, a current control is implemented on the DUT side, which receives a negative setpoint from a speed-dependent characteristic curve. The current ensures a load on the load unit and, thus, also on the generator model. The load unit is model-based controlled and gets its voltage setpoints from a synchronous generator model. The clamping voltage is influenced by the speed, the load and the excitation of the generator. The generator is part of a drive train, so that the speed depends on the current operating state of the system. The input variable is a wind profile, which generates a driving torque on the wind rotor depending on the current speed and pitch angle.

Generator model

For the model-based control of the converter, the model of an electrically excited synchronous machine according to [2] is used. This model receives three input variables, the currents i_{phase} transferred into the rotating coordinate system, the excitation voltage $\mathrm{V_e}$ and a mechanical torque $\mathrm{M_{shaft}}$, which is applied to the shaft. This is used to calculate the clamping voltages of the generator $\mathrm{V_{clamp}}$, also as d/q values, as well as the rotational speed. For the transformation of the currents and voltages into the rotating reference frame and the back transformation, the shaft angle is used. This model works with normalised values, so that the measured phase currents and the voltage setpoints must be normalised or denormalised. For the calculation on a PLC, the model has also been discretised. In order to simplify the discretisation, the reactance operators $\mathrm{x_d(s)}$ and $\mathrm{x_q(s)}$ were previously transformed into the controllable canonical form, resulting in a structure of simple integrators and coefficients that are easier to discretise. The parameters used for this model are taken from a data sheet of an electrically excited synchronous machine with damper windings and the parameters from Tab. 1.

Parameter	**Value**
Apparent power	9.375 MVA
Rated speed	$500\ \mathrm{min}^{-1}$
Rated torque	143.24 kNm

Tab. 1: Parameters of the synchronous generator

Wind rotor model

The emulation of the wind rotor is based on a characteristic set of curves of aerodynamic power coefficients C_P. This characteristic set of curves is described by the following equations with the coefficients from Tab 2. [3]:

$$\frac{1}{\lambda(i)} = \frac{1}{\lambda + 0.08 \cdot \beta} + \frac{0.035}{\beta^3 + 1} \tag{1}$$

$$C_P(\beta, \lambda) = C1 \cdot (C2 - C3 \cdot \beta(i) - C4 \cdot \beta(i)^x - C5) \cdot e^{-C6} \tag{2}$$

With the parameters:

C1	C2	C3	C4	C5	C6	x
0.6	$116/\lambda(i)$	0.4	0.001	5	$20/\lambda(i)$	2

Tab. 2: Parameters for analytic C_P curves

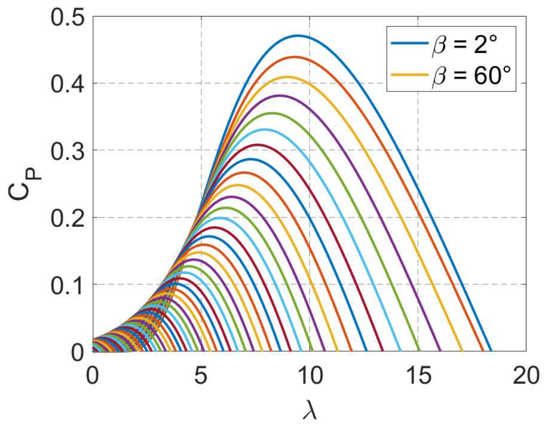

Fig. 3: Generated C_P curves

For a pitch angle β in each case, equations (1) and (2) are used to generate a characteristic curve that is dependent on the tip speed ratio $\lambda = \omega_{rotor} \cdot r_{rotor}/v_{wind}$. The working range in which the pitch angle β can be set is fixed here at 2° to 60°. Thus, at the smallest pitch angle, the highest C_P value of 0.4706 is obtained. Fig. 3 shows the generated C_P-curves. To calculate the torque that the wind generates at the rotor, it is necessary to have the current power that can theoretically be taken from the wind (Eq. 3) and the rotor speed ω_{rotor} .

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A_{rotor} \cdot v_{wind}^3 \tag{3}$$

The torque of the wind rotor is calculated as follows:

$$M_{rotor} = P_{wind} \cdot C_P(\beta, \lambda)/\omega_{rotor} \tag{4}$$

The rotor area A_{rotor} is chosen so that the power at the nominal point $(\lambda_{opt}, \beta_{min}, v_{wind_{nom}})$ is equal to the active power of the generator model of 7.5 MW. To ensure that the calculated torque does not approach infinity, the speed in equation 4 must not become too small. A gear ratio factor of 0.046 ensures that the speed is increased towards the generator and that at the same time the torque is reduced. Since the generator model works with normalised quantities, the mechanical torque must be divided by the rated torque of the generator of 143.24 kNm between the gearbox and the connection. The moment of inertia of the entire drive train in relation to the generator shaft was set to $8.207 \cdot 10^5\ kgm^2$.

Wind profile

The wind speed can be specified either as a changeable constant or from a lookup table. The wind speed must also not fall below a minimum of 3 m/s so that the turbine does not come to a standstill. The wind field in Fig. 4 was generated with the software "TurbSim". It is possible to set different requirements for the wind speed profile. These include the norm-dependent turbulence intensity, the step size of the data points or the mean wind speed. Here the mean wind speed has been set to 11.64 m/s, which is below the rated wind speed of the turbine of 14 m/s. Since this wind field is to be used cyclically, the first data point and the last data point must have approximately the same values. Due to the changeable constant wind speed, the entire wind field can be shifted up or down. This enables changing the operating point of the system between partial load and full load.

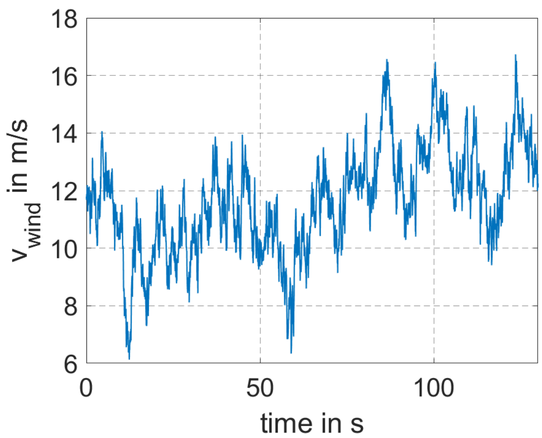

Fig. 4: Windfield generated with TurbSim (Configuration: IEC 61400-1 Ed. 3 (2010), step size: 0.05 s)

Generator load curve

The electrical load on the generator of a wind turbine in the partial load range is usually dependent on the speed. This means that the generator current increases with increasing shaft speed or wind speed. With a constant pitch angle, the speed of the wind rotor should be controlled in such a way that it increases proportionally with the wind speed in order to always remain at the optimal tip speed ratio [4]. However, since the power that can be extracted from the wind increases with v_{wind}^3 (Eq. 3), the electromagnetic torque of the generator and thus the current must increase with ω^2 (Eq. 4). Therefore, the generator curve for the partial load range is quadratic. If the speed falls below the cut-in speed, the target torque is set to zero. Once the rated speed is reached, the wind turbine is in the full load range; here the target torque remains constant at its nominal value. Fig. 5 shows the generator curve generated.

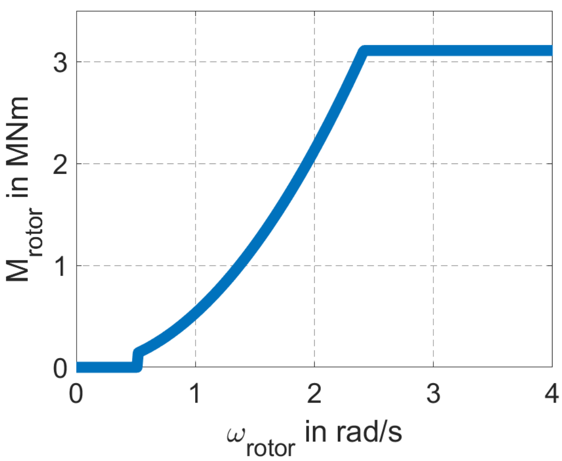

Fig. 5: Generator load curve

Control strategies

Speed control

In this case, the wind rotor is started by a PI controller, which acts on the mechanical torque M_{shaft} via a first-order delay element. This has the advantage that the turbine is already at nominal speed when the rotor model is switched on. Furthermore, this speed control can be used, for example, to test the current control without the electromagnetic torque becoming greater than the driving torque and thereby slowing down the generator too much. The PI controller was designed according to the symmetrical optimum. Once the rated speed is reached, the torque of the wind rotor can be connected as M_{shaft} and the pitch control can be activated. The speed is stabilised indirectly in the partial load range via the electromagnetic torque of the generator. In the full load range, the pitch control must ensure that the turbine rotates on average at the rated speed.

Clamp voltage control

With decreasing speed and increasing electrical load, the clamping voltage of the generator decreases if the excitation voltage is kept constant [5]. The excitation voltage must be controlled so that the electrical power does not additionally decrease due to a lower clamp voltage. For this purpose, the magnitude of the voltage pointer of the clamping voltage is formed from the d and q components by $|V| = \sqrt{\underline{V}_d^2 + \underline{V}_q^2}$ and regulated to one. By regulating the clamping voltage, the generator can be loaded electrically higher, as this causes an increase of the excitation current and thus a shift of the operating point into the stable range of the V-curves of the synchronous generator. If the generator is temporarily accelerated, e.g. by an increasing wind speed, the clamp voltage can also be regulated to its nominal value by reducing the excitation voltage.

Simulation model

Compared to the concept shown in Fig. 2, the tasks of the load unit and the DUT are swapped. This means that the primary and secondary sides of the transformers T2 and T3 are reversed and the model-based control is implemented on the side of the DUT. The hardware of the interesting part of the test bench was modelled using the PLECS blockset, with all the control or actuation built in

Matlab/Simulink. Fig. 6 shows the section from the DC-link of the load unit via the transformer T3 to the DC-link of the DUT.

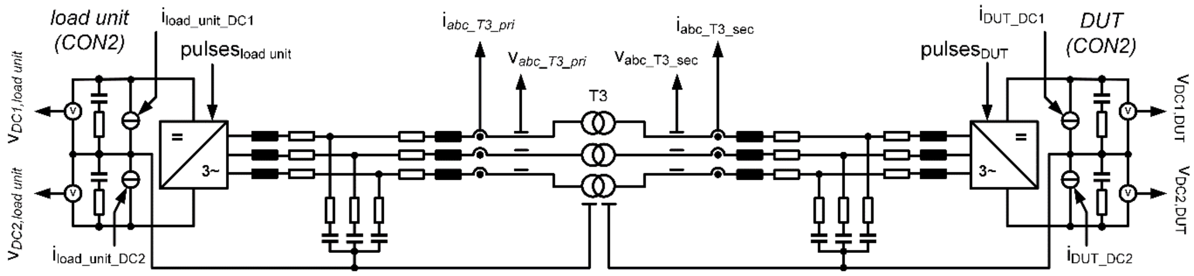

Fig. 6: Simplified PLECS model of the test bench hardware

To simplify the simulation model, the DC-link voltages are controlled by PI controllers acting on controlled current sources. This produces a larger voltage ripple of the DC-link voltages under load, as in the real system. The parameters of the LCL filters and the transformer T3 are partly read from the datasheet, measured or calculated.

Operation of the test bench

Before the actual model-based control and generator current control can be operated, the following steps must be completed:

- Pre-charge of T1 and T2
- Passive charging of the DC-links (load unit and DUT)
- Active boost control of the DC-link voltages

Once this state has been reached, the start-up of the drive train on the DUT side can begin. For this purpose, the drive train is accelerated up to the rated speed by a speed controller, as described above. Meanwhile, the excitation voltage of the generator is intentionally set low (0.02 p.u.) to avoid a high inrush current of the transformer T3 when activating the PWM. After the PWM has been activated, the excitation voltage can be increased to its no-load value (1 p.u.). The control of the excitation voltage and the torque calculation from the rotor model are started as soon as the clamping voltage has reached its nominal value. The torque applied by the wind rotor model now drives the generator. On the load unit side, the current control can now be activated and, shortly afterwards, the current setpoint from the generator curve. The current control is automatically shut down as soon as the measured frequency falls below 40 Hz, as the transformers would heat up too much at these low frequencies. Contrary to the system topology in Fig. 2, the generator angle is not yet transmitted to the DUT with the servo and the encoder. Instead, the pole wheel angle is estimated as a function of the current and the target current is divided accordingly in the d- and q-axes.

Results

Wind speed as step function

In order to illustrate the operation of the overall system, a step change in wind speed is first assumed. This case is not realistic, but it shows that the calculation of the rotor torque and the control of the pitch angle are working correctly. The falling wind speed causes a decreasing torque, which the wind rotor can deliver to the generator. This causes the speed to drop significantly at first. Fig. 7 shows how the speed controller reduces the pitch angle to the smallest value so that the rotor speed in Fig. 8 is stabilised.

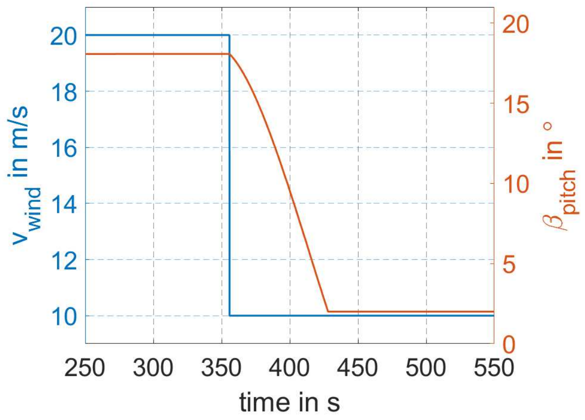

Fig. 7: Reaction of the pitch angle to a wind speed drop

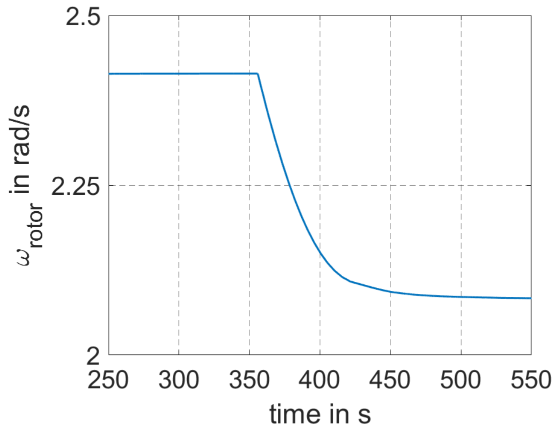

Fig. 8: Reaction of the rotor speed to a wind speed drop

Of course, the electromagnetic torque in this case must not be greater than the available driving rotor torque. Fig. 10 shows that the calculated clamp voltage drops briefly due to the speed drop, but rises again to its nominal value by regulating the excitation voltage. However, there are deviations in the measured voltage, which can be justified by the fact that the frequency of the controlled voltage is further away from the resonance point of the LCL filters. As a result, the damping by the LCL filters is higher. Fig. 9 shows the curve of the set current and the measured current. The characteristic curve-based current control reduces the current setpoint depending on the speed so that the generator speed stabilises at an operating point below the rated speed.

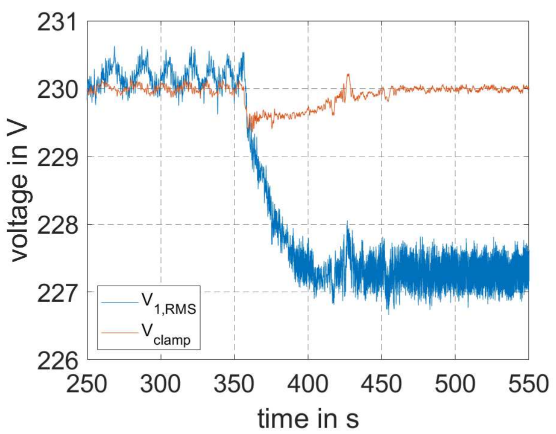

Fig. 9: Changing clamp voltage due to wind speed drop

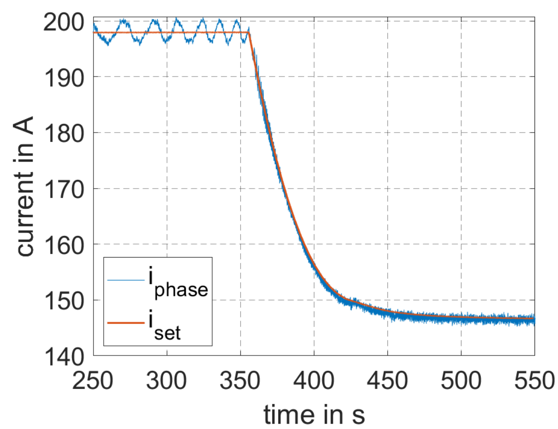

Fig. 10: Reduction of the current set value due to decreasing speed

In order to show the functioning of the frequency-dependent current control in this form, an offset of 5 Hz is subtracted from the input of the generator curve calculated by the PLL. This is necessary because the frequency must not fall below 40 Hz in total, but a reduction of the setpoint current is to be shown. In a real system without a transformer between the generator and the inverter, the frequency may be significantly lower.

Windfield

To investigate how the entire test bench reacts to a continuously changing wind speed, the wind field shown in Fig. 4 is now used instead of a step change in wind speed.

Simulation

The starting speed of the generator is below the rated speed (Fig. 11 and 12), so that the pitch angle is 0° at the beginning. The generator is accelerated by the average wind speed in the range between 600 s and 650 s, which is above the rated wind speed of 14 m/s. The pitch angle increases with increasing speed. As the speed increases, the pitch angle increases more and more to stop the acceleration. This is repeated cyclically as the wind profile is run through. Due to the very large inertia of the wind rotor, the speed in Fig. 12 is out of phase with the wind speed.

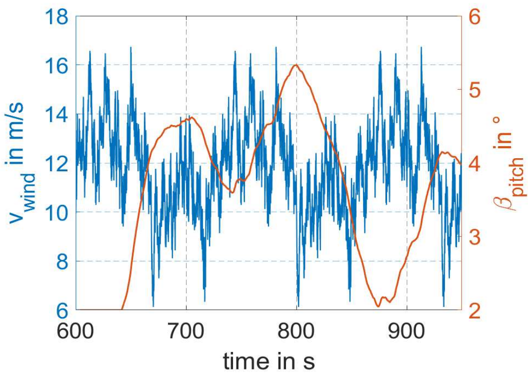

Fig. 11: Simulated wind speed and pitch angle

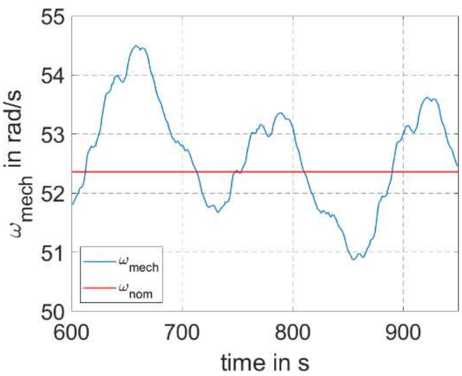

Fig. 12: Simulated mechanical generator speed

The phase voltage measured in the PLECS model is shown in Fig. 13. It can be noticed that this increases accordingly to the other curves with increasing speed. On the one hand, this means that the increase in clamping voltage due to the speed is higher than the reduction due to the higher current and, on the other hand, that the regulation of the excitation voltage is not fast enough to keep the voltage constant. The phase current curve in Fig. 14 also follows the generator speed.

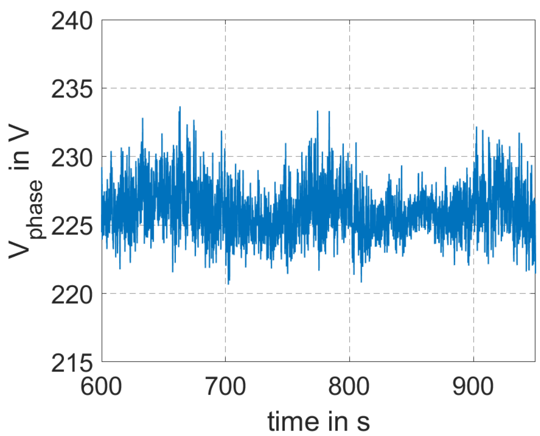

Fig. 13: Simulated phase voltage

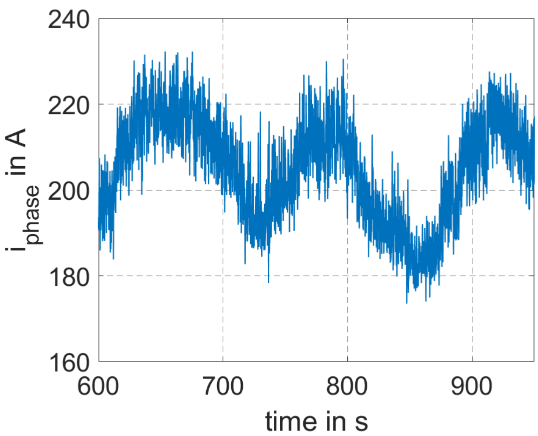

Fig. 14: Simulated phase current (RMS)

Test bench

The same measurement is now performed on the test bench. The wind field is accordingly stored on the PLC, where the rotor and generator model are also calculated. The frequency-dependent generator curve is stored in the PLC of the load unit.

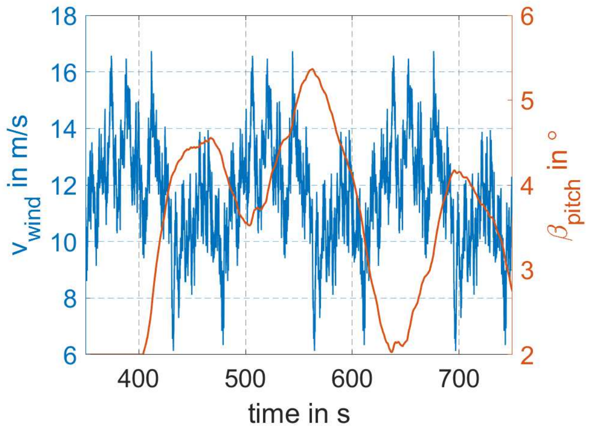

Fig. 15: Wind speed and pitch angle course

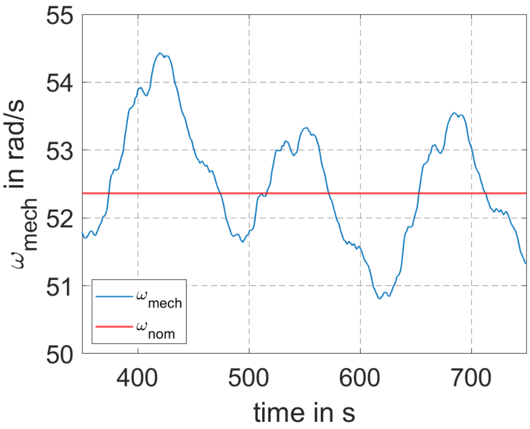

Fig. 16: Generator speed

Essentially, the curves correspond to the results from the simulation. There are differences especially in the measured currents and voltages in Fig. 17 and 18. These do not look as noisy on the test bench and are slightly offset, which is due to the damping properties of real components such as line inductance or deviating component parameters.

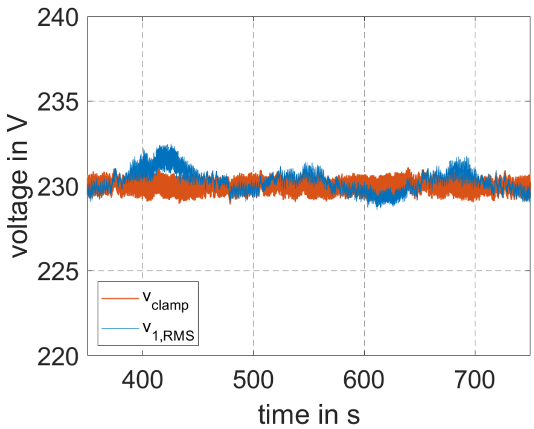

Fig. 17: Calculated and measured generator clamp voltage

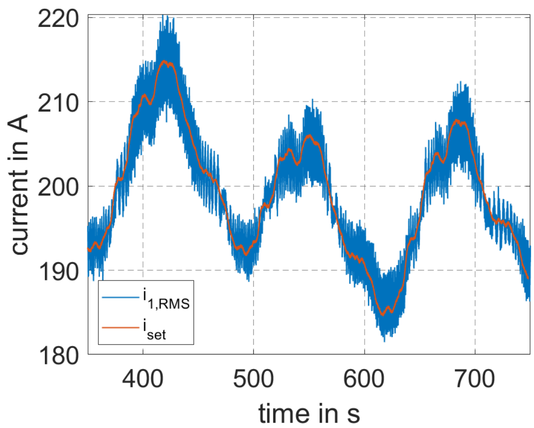

Fig. 18: Measured phase current and its set value

Conclusion

In this work, the model of a generator was extended by a rotor model with gearbox so that it represents a simple drive train of a wind turbine. First of all, it could be shown in simulation how a created wind profile affects the drive train. In the process, controllers were designed that enable simulating the partial-load and full load operation of a wind turbine. Parts of the simulation model could be used directly to generate a programme code for the PLCs of the test bench, which greatly simplifies commissioning and modifications. The results of the simulation and the measurements on the test bench show almost identical curves. The implementation of a frequency-dependent current control and operation in the partial load range were also successfully tested, whereby the setpoint current was separated into an active and a reactive component depending on the magnitude in order to emulate the increase in the pole wheel angle. For a real field-oriented control, the transmission of the shaft angle with the servo from Fig. 2 is still missing. The transfer of the shaft angle from the generator model to the DUT is part of current work.

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