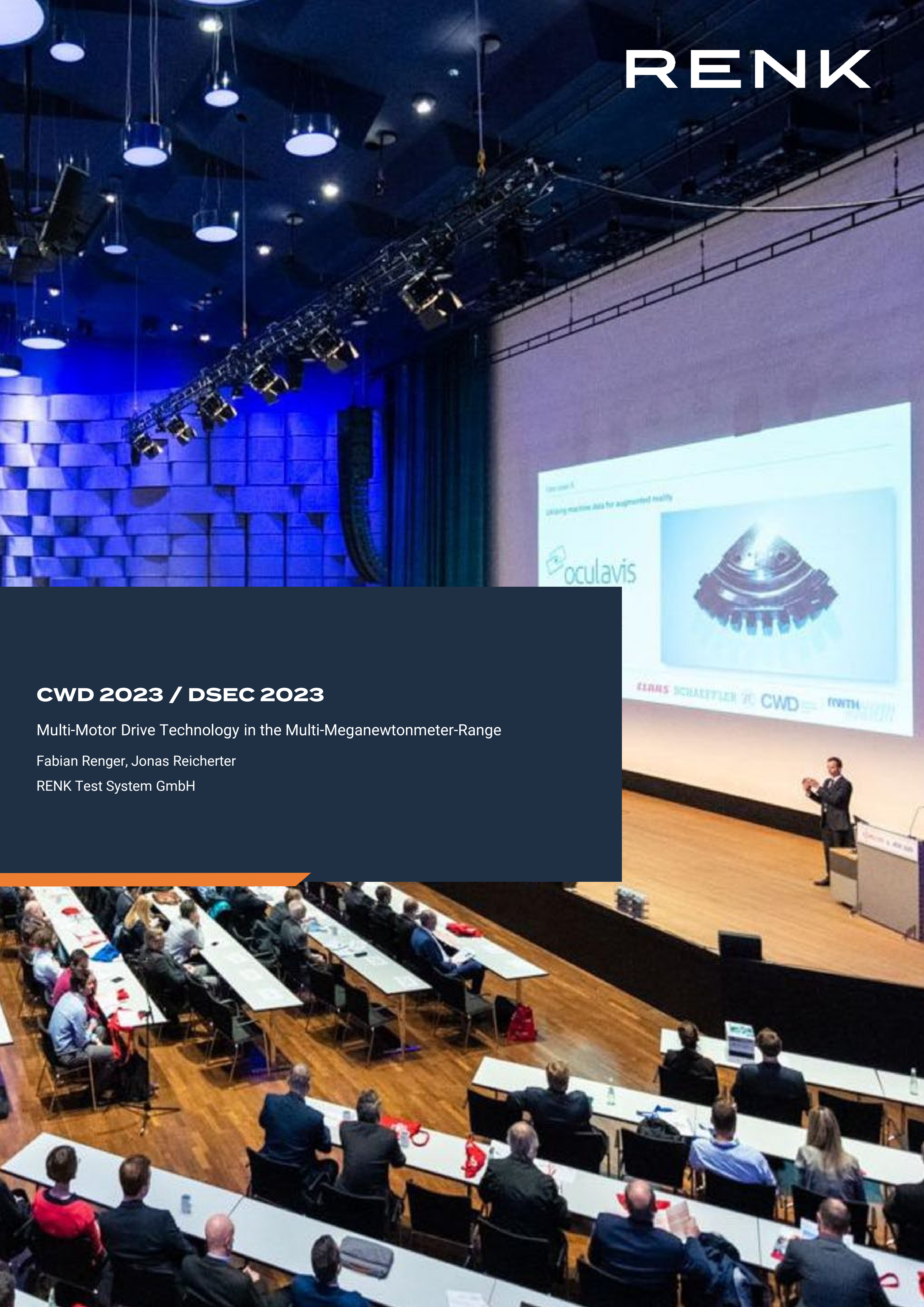

CWD 2023 / DSEC 2023

Multi-Motor Drive Technology in the Multi-Meganewtonmeter-Range

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Drivetrains: Performance and Efficiency

Multi-Motor Drive Technology in the Multi-Meganewtonmeter-Range

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Keywords: Wind Power, Test Stand, Multi Motor, Meganewtonmeter

Abstract: RENK has been successfully manufacturing multi-motor drives and generators for a wide variety of industrial applications for many years. Based on this, RENK Test System GmbH (RTS) is now developing a 35 MW drive with a maximum torque of 43 MNm for a wind turbine test stand.

The concept of the multi-motor drive is used for applications with extreme torques and maximum operational readiness required. The arrangement of several electric motors to a single compact drive enables a resulting torque that is otherwise only possible with high-risk and high-cost special solutions in motor design, such as direct drives. However, the arrangement of a number of standard motors in combination with proven RENK gear technology results in a system of highest reliability and lowest costs.

This paper will focus on the various applications this drive technology is already in use, as well as the challenges running a test bench with it. Such as backlashing and control dynamics. Another focus within this paper will be the virtual commissioning of the test rig with our digital twin technology.

1. Introduction

The idea of using a motor-gearbox-combination as a drive system or powertrain for industrial applications is as old as the electric motor itself. However, this combination has its limitations, when high torques or high speeds are required as this drives the complexity and costs of the gearbox and or the electric motor, respectively generator.

Figure 61: Motor-Gearbox-Drive-System for a 7.5 MW (left) and 15 MW (right) Wind Power Nacelle Test Rig

As we have the requirement of having high power density, while creating 43 MNm of torque for a wind power nacelle test bench, we came up with the idea to use multiple motors and a common gearbox. Using multiple motors to distribute the load to several smaller entities is not a new concept and is for example used in tunnel boring machines. This and the optimum combination of gearbox ratio and number of motors was also shown by Hans-Georg Herzog from the Technical University of Munich and our colleague Thomas Stöckl in [STÖ22].

2. State of the art at RENK

Also for the RENK Group, it is a very common approach to combine multiple electric motors with a gearbox to fulfill extreme customer requirements. In marine and industrial applications, we have at the moment two products, which are utilizing this approach:

1) Integrated Front-end Power System – IFPS® for marine applications
2) Compact Planetary Electric Drive – COPE® for industrial applications

Both solutions have their specific requirements and therefore solutions. The following two chapters will give a short overview on those requirements and how they are fulfilled. This will then lead to the requirements of the wind power nacelle test rig and how we intend to master those.

2.1 IFPS®

Large vessels for transporting goods and materials from continent to continent usually have a 2-stroke engine and mostly three 4-stroke diesel-gensets. These gensets are used to provide electrical energy to the vessel for subsystems, such as lighting and communication. The gensets need their own foundation and need continuous maintenance and service. Plus, they have a negative influence on the CO_2 emission balance of the ship. However, the EEDI phase three is mandatory for ships starting in 2025, meaning a reduction of greenhouse gas emissions by 30% compared to 2013.

On some vessels, shaft generators are used, which are directly connected to the main engine. Also, a combination of one gearbox plus one AC generator connected to the main shaft is a common solution. All solutions have their pros and cons, with one con being heavy and allocating a lot of space, which reduces the space to carry goods and materials.

Figure 62: IFPS® with two generators mounted on a two stroke diesel engine

Compared to the already existing solutions, the following requirements need to be fulfilled by the product:

- Low weight
- Low space requirements
- Easy and low-cost maintenance
- Redundant
- Adoptable to different engines and nominal speeds

The input shaft is on the one end connected to the crankshaft of the engine and on the other end to a flexible coupling. This coupling transfer the torque from the engine shaft to the input gear of the IFPS®. The coupling is necessary to decouple (torsional) vibrations from the input gear. Up to four generators, with a total power of max. 2.5 MW, are then driven by the common gear and a pinion for each generator.

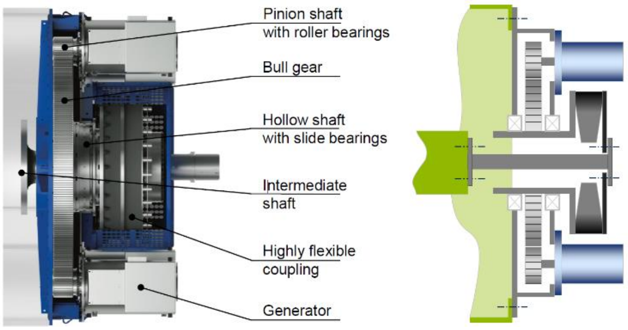

Figure 63: Mechanical layout of IFPS®

All generators feed the produced electrical energy into discrete converters, which are commonly connected to a DC bus, which feeds the electrical energy to the vessel grid via an active frontend.

A common problem with combining multiple motor arrangements with a gearbox is the danger of uneven load distribution. In this case, we control the load of the single motors via the frequency converters within their voltage barriers. Meaning that we control the torque of each motor individually, to align them to each other.

2.2 COPE®

To process minerals and other hard materials, large mills are used. Vertical roller mills are usually driven by one electric motor and a gearbox with a combination of bevel gear and a planetary gear set. This proven solution is used since the 1950s.

Figure 64: KPBV mill gearbox with bevel gear and planetary gear set

With the constantly increasing size of vertical rollers mills, also the torque rating of these mills is increasing. The bottleneck of the gearboxes is the bevel gear and the limitation of transferrable torque through this gear contact. Additionally, if the large electric motor is damaged, the complete cement mill must be shut down. Compared to the already existing solution, the following requirements need to be fulfilled by a product:

- Same space requirements for the drive system, especially in height
- Redundant drive system, to avoid long downtimes due to failures of the motor or the drive system

- Increased torque capability of up to 5 MNm
- Compensation of hard torque impulses
- Working under high vibrational conditions
- Same or better durability

Also here, a multi-motor-drive solution was utilized. The motors can be driven by converters or direct online (DOL). The control module is rather simple as the drive system only ramps up to the nominal point of operation and stays in this load state during operation. Dynamic operation is not required.

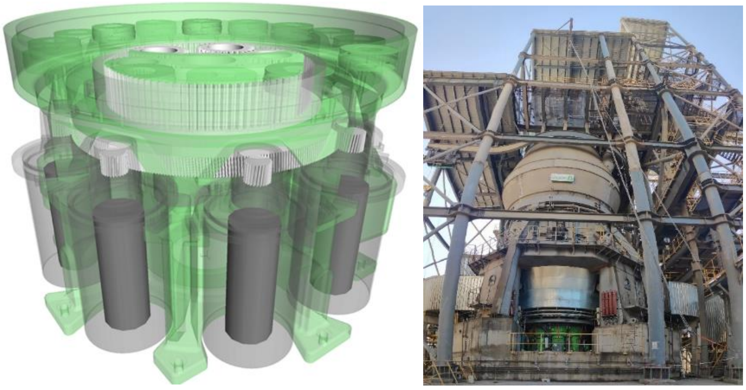

Figure 65: COPE® 3D Model (left) and installed under the roller mill (right, green part)

3. Multi-Motor-Drive for Wind Power Test Bench

3.1 Introduction

In 2017, South Korea announced its “3020 Plan”, which set the target of 20 % renewable energy production by 2030. This plan was affective as of 2018. In 2019, we established a connection to Gyeongnam Technopark (GNTP) in Changwon-Si, Korea. GNTP is a public research institute and plans to enhance the technical capability of South Korea on the topic of renewable energy production, especially wind power. The overall target is to build a test bench, to test wind power nacelles with turbines with a nominal power of up to 20 MW. This means to build a test bench drive system with a torque of 43 MNm, which was never done before.

During a pre-investment design study, our colleagues from RENK Korea investigated the possibility to design and build such a test rig, with the possibility to upgrade the drive power, while keeping the costs as low as possible. The result of the study was to design the drive system as a multi-motor drive.

When the multi-motor drive is used as a test rig drive, the requirements are different from those for the use in a ship or as a mill drive unit. The drive must simulate the conditions in the field as realistically as possible on the test rig. This can be turbulent wind conditions resulting in dynamic load conditions. Likewise, it is also important to simulate the resonant frequency of the real drive train of the wind turbine with rotor on a test rig without rotor [FGW18]. Another challenge is the simulation of emergency stop processes, as well as LVRT tests with DFIG systems, where dynamic torque changes occur [RÖD21].

Depending on the test, this results in highly dynamic requirements for the drive as well as sign changes for the torque.

3.1.1 Drive train dynamics

The control bandwidth is the decisive criterion for the dynamic control of drive trains. This results from the torque actuating times of the drive and the transmission of torque via the drive train. The transmission of torque is limited by the first resonance point of the drive train.

If we compare the setup with direct drive and with multi-motor drive with regard to the natural frequency of the mechanical part of the system, the following result is obtained.

Boundary conditions

The application is investigated on a system test rig for wind nacelles. The setup consists of a drive (multi-motor drive/direct drive), coupling, wind load application unit (LAU), adapter and nacelle.

The parameters for coupling, LAU, adapter and nacelle are the same in both studies. For the nacelle, the parameters of the IEA 15 MW reference turbine were used [IEA20]. The parameters of the remaining components result from the design concepts of RENK for a test bench drive torque of 30 MNm.

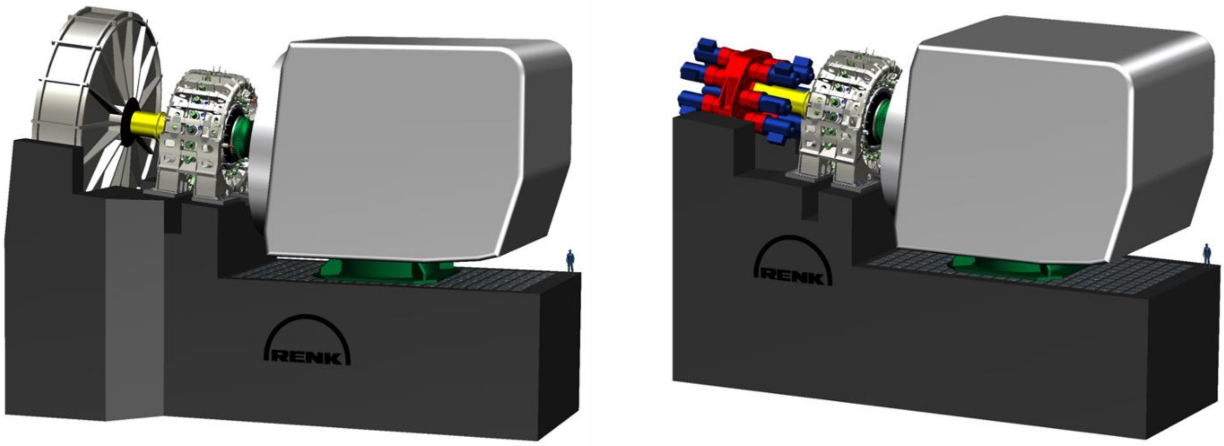

Figure 66: Wind Power Nacelle Test Rig with Direct Drive and Multi-Motor Drive

Result

With the multi-motor drive, the first natural frequency is at 9.5 Hz, with the direct drive it is at 12.5 Hz.

Since the mechanical natural frequency of the drive train with multi-motor drive is lower than with direct drive, this results in a reduced bandwidth and thus lower dynamics, if the same control approach is used. To compensate this disadvantage, a state space controller is used, since conventional controllers are not able to control in the range of the resonance point.

The problem of the resonance point can be controlled by state feedback. The state variables themselves or suitable linear combinations of the states are processed in the controller. In this specific case, the state space controller is designed in such a way that, in addition to the controlled variable, the motor speed, the state variables nacelle speed and nacelle torque are also fed back.

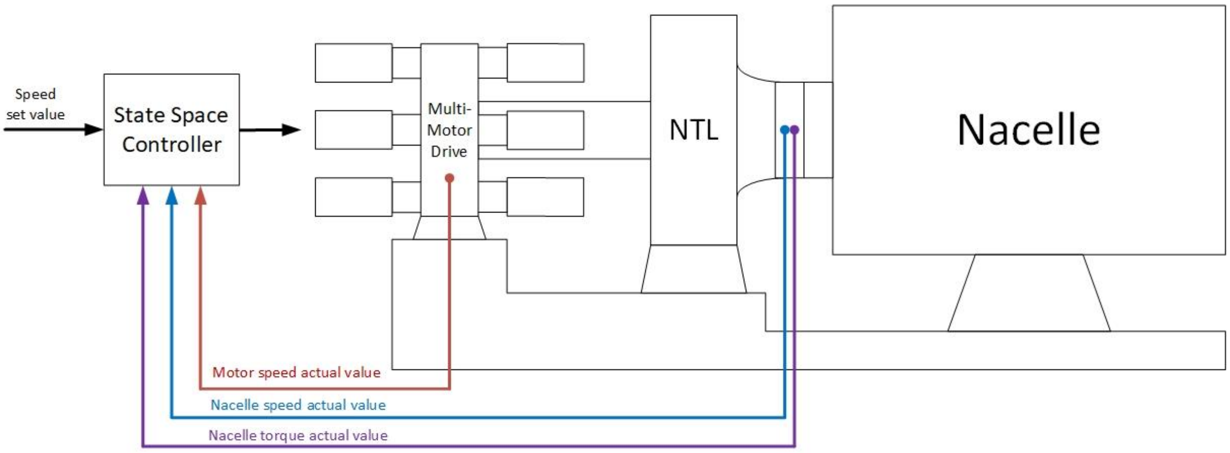

Figure 67: State Space Controller Structure

For the design of the control system, the basic approach of Schröder [SCH09] was applied and followed in a modified form. The desired dynamics of the system are selected using the pole placement method and the controller parameters are determined by comparing coefficients. In the present problem, the dynamics of the system are sufficiently fast and do not require acceleration by the controller. For this reason, the actuating energy is to be used for damping, which makes the control very robust. The damping effect of the controller makes it possible to go closer to the resonance point of the system, which results in an increase in bandwidth.

This control approach is already known at RENK and has already been successfully used in practice for automotive and railway test rigs.

3.1.2 Passing through the gear backlash

Another, and probably the most serious difference between a direct-drive powertrain and a geared solution, such as the multi-motor drive, is gear backlash.

If the sign of the torque changes, one tooth flank changes to the other in the gear unit. As a result, the angular difference from load to motor is no longer proportional to the torque. When a torque set point is applied, this causes the gears in backlash to accelerate and strike the opposite tooth flank after the backlash has been passed. This leads to disturbing torque overshoots.

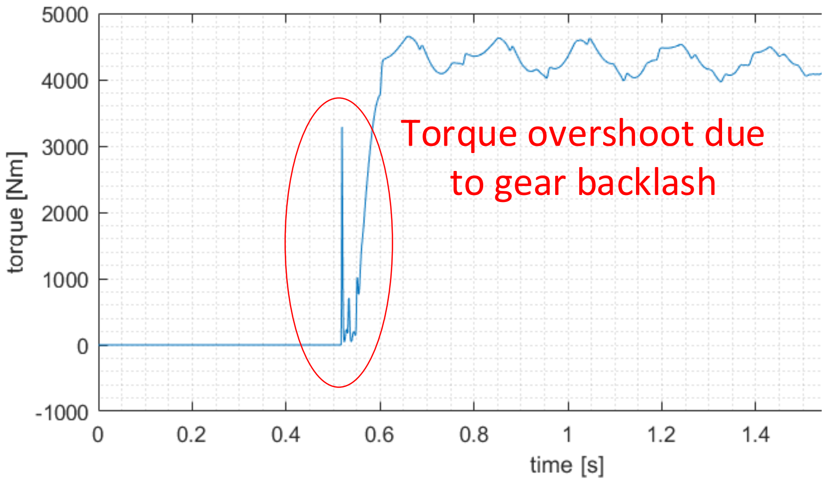

Figure 68: Torque overshoot

In order to minimize this effect, it is therefore primarily necessary to avoid this acceleration in the gear backlash. As described earlier in the chapter on state space control, both the motor speed and the load speed are fed back as measured variables. This opens up the possibility of limiting the differential speed from drive to load while the backlash is being traversed. To do this, it is necessary to detect when the system is in gear backlash. This is done with the help of the torque at the load, if the torque exceeds a defined threshold value or a lower torque is present for a certain duration, the system is not in gear backlash and the differential speed limitation is deactivated.

Two operating situations were considered to assess the effectiveness of the measure. Acceleration from zero speed to rated speed with full motor torque and braking from rated speed to zero speed (see Figure 69: below). The torque is applied immediately in the air gap in each case. The simulated operating situation is classified as more extreme than the test scenarios to be expected on the test rig.

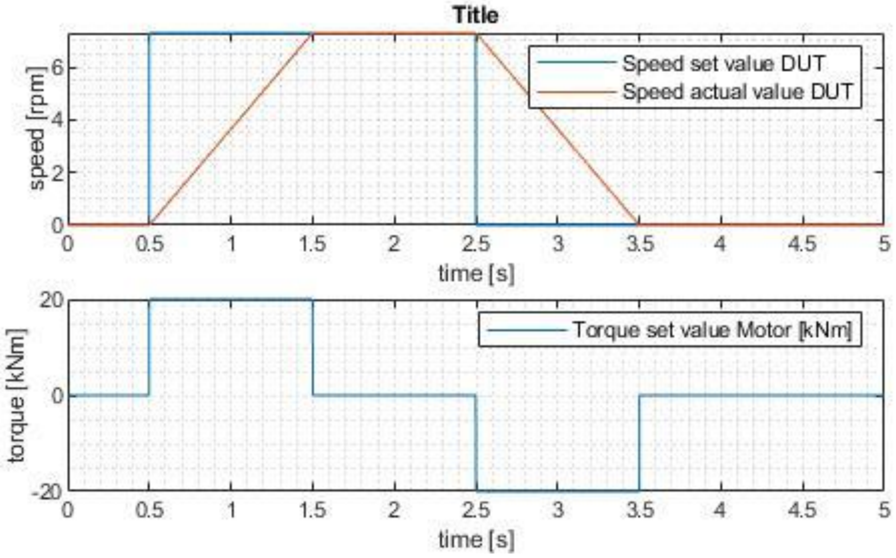

Figure 69: Examined operation point

Differential speed limitation	Disturbing torque overshoots measured on motor shaft* [Nm]	
	Acceleration 0 to nominal speed with full motor torque	Deceleration nominal speed to 0 with full motor torque
Not active	3300	4500
Active	720	580

Table 5: Disturbing torque overshoot comparison

* The torque signal between the motor shaft and the sun gear 1 shows the most significant effect of the gear backlash in percentage terms. Therefore, this point in the drive train was selected for investigation.

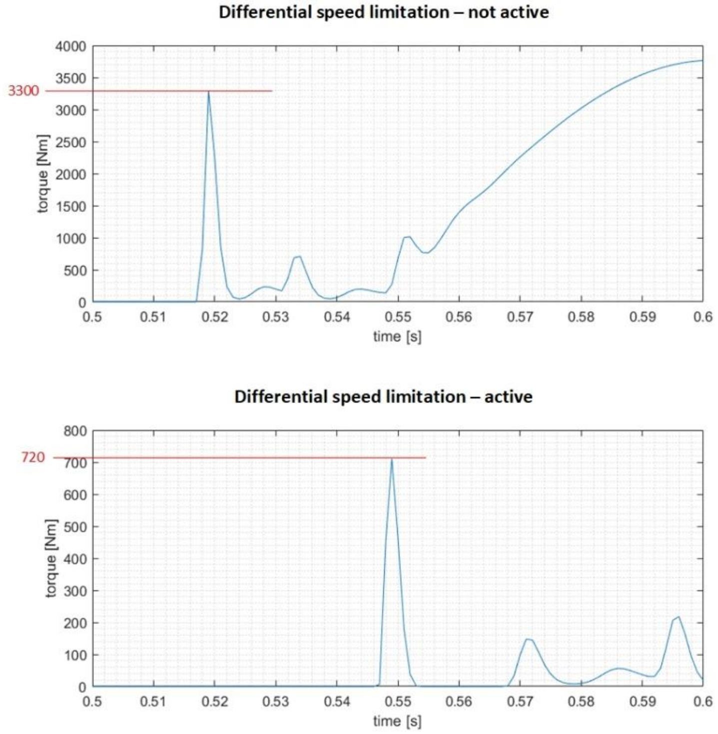

Figure 70: Comparison of torque overshoot with and without differential speed limitation

Figure 70: shows the comparison of the torque overshoot with and without differential speed limitation. It can be seen that a time shift of 0.03 - 0.04 s occurs in the two trajectories. The reason for this is that the speed limitation in the gear backlash restricts the dynamics in this range. However, this only affects the range close to zero torque, since this function is deactivated in the remaining operating range.

The differential speed limitation can reduce the torque overshoot caused by the gear backlash by more than 78 %.

3.1.3 Virtual commissioning of the drive system with digital twin technology

Even though the state space controller and the differential speed limitation has already been tested in practice, the application on the system test stand for wind nacelles is different. The drive converters used here are medium-voltage converters compared to the low-voltage converters of the other applications. The software and the control of the converter are different here. Furthermore, the sensor technology in terms of bandwidth and quantization also plays a decisive role for the function of the dynamic control. The sensor technology has not yet been used in this form in practice.

These circumstances make it necessary to test the application intensively in the simulation. Furthermore, the commissioning time on the real machine should also be as short as possible with the lowest risk of unplanned expenses.

The approach is that first in different simulation environments alone, such as finite element method, multibody simulation and MATLAB/Simulink the system is developed, optimized and tested.

From this, an abstracted model in MATLAB/Simulink is derived, that contains the most important properties of the detailed models from a controller point of view. For example, only the first resonance point is relevant for the control and not those of higher frequencies, thus the degrees of freedom of the model can be reduced accordingly.

In a next step, this abstracted model is directly integrated into the automation system of the test bench via a target language compiler. This can be done automatically from MATLAB/Simulink to RDDS (RENK Dynamic Data System – test bench automation system).

After this step, the model of the test bench and the automation system are together in one software environment on the same hardware. With this configuration, it is possible to test the entire automation application of the test bench. In particular, status machines and the previously described control algorithms, such as state space controller and differential speed limitation are the focus here.

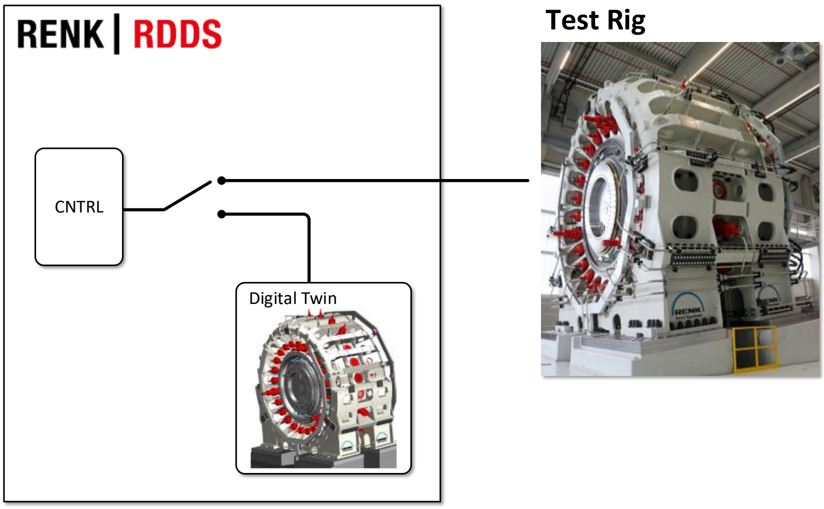

Figure 71: Virtual commissioning with digital twin in RDDS

After commissioning is completed, the system is handed over to the user. This approach offers the possibility for the user of the test bench, to virtually check his test campaigns as well as target values in advance, with the aim of optimizing the test bench utilization and minimizing risks (pre-simulation tool).

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