# system test benches with variable test environment

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Automation by innovation.

# Contents

## Pitch systems in wind turbine installations: Functionality, safety and testing approaches

# Pitch drives and the need for system testing to obtain TÜV certificates

The pitch system controls the angle of attack of the rotor blades of the wind turbine installation and thus affects the angle of the wind hitting the blade edge. This regulates the torque acting on the rotor and consequently affects the amount of energy extracted from the wind.

In the control loop, the systems acts as a central actuator that governs the generator power output as well as the rotor speed, limiting the rotational speed and preventing overspeed—and the damage it could potentially cause.

In critical operating situations such as sudden load changes, the pitch system performs what is known as a "safe feathering run (SFR)". This involves moving the rotor blades towards the feathered position, sometimes relying on individual profiles, in order to decelerate the rotor safely until it comes to a standstill.

Because it has this safety-relevant function, the pitch servocontroller requires an exceptional degree of reliability. In addition, the availability of the pitch servocontroller in normal operation must be as high as possible because every unplanned stop causes additional mechanical loads as well as yield losses. Electrical pitch systems typically consist of three independent axes. Each axis includes a pitch servocontroller, a motor, a gear unit, a motor encoder, a blade-mounted encoder as well

as an energy storage system that ensures continued normal operation in case of grid fluctuations (FRT[1]) or a grid fault. The system may also include a Center Box.

Pitch servocontrollers differ from standard servocontrollers because they must fulfill particularly high demands on ruggedness and functionality even under extreme environmental conditions. In recent years, functional safety in particular—i.e. the ability to perform safety-relevant functions with the required degree of reliability—has drastically gained in importance. The certified safety functions of KEBA's PitchOne make it possible, for example, to realize a wind turbine installation's safety run according to the highest performance level (PLe).
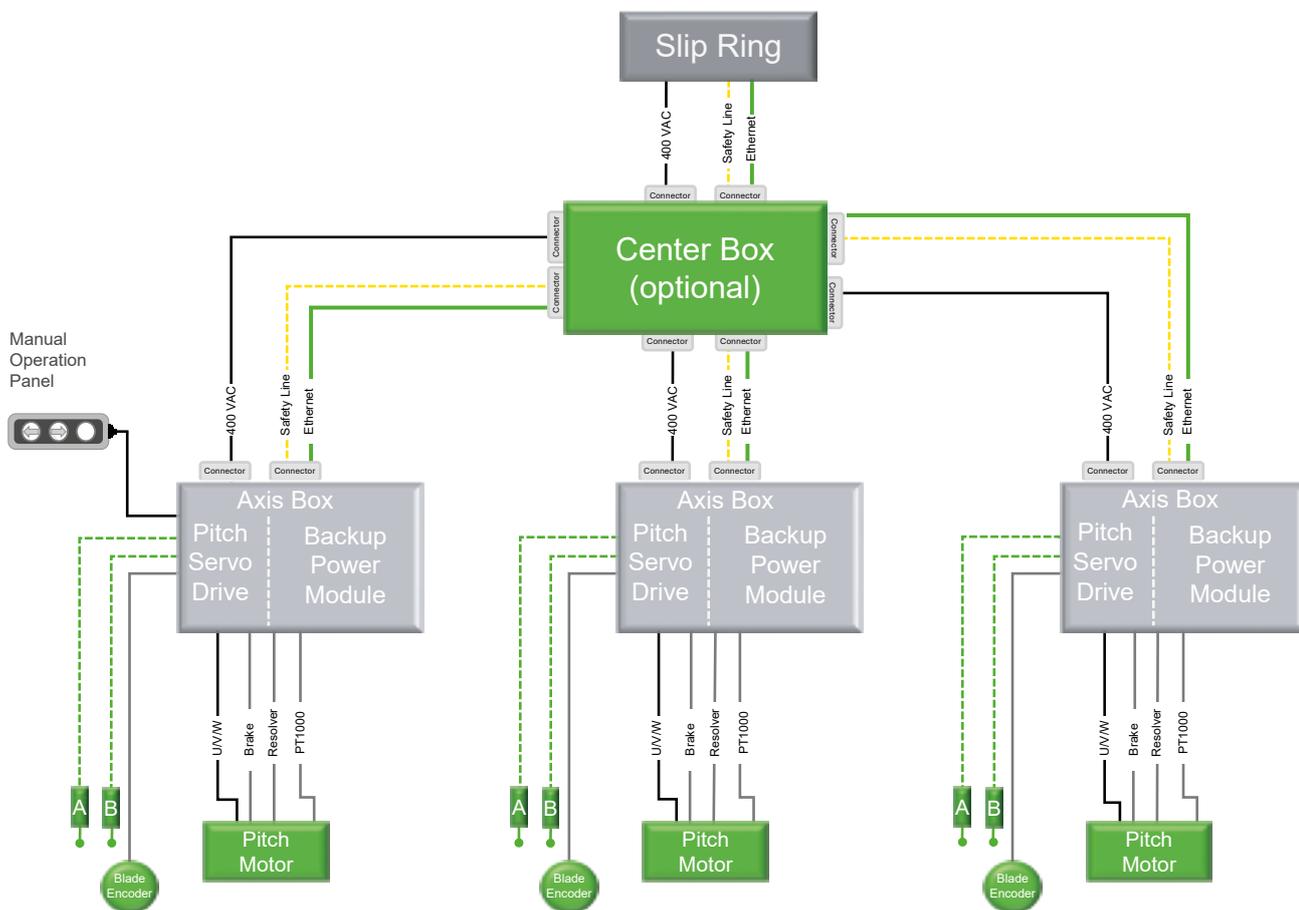
Schematic of a pitch system in a wind turbine installation

[1] "The terms low-voltage ride through (LVRT), under-voltage ride through (UVRT) and fault ride through (FRT) describe a minimum tolerance of electrical generating units in power grids with regard to transient voltage drops. If the voltage drops, a generating unit must not disconnect from the grid immediately; it needs to keep running for a certain amount of time. Transient voltage drops can be caused, for example, by grid faults such as short circuits, ground faults, or lightning strikes. The purpose of the FRT capability of decentralized generating units is to prevent a widespread loss of power generation caused by a domino effect of many small generating units in the event of faults in the transmission network."
https://de.wikipedia.org/wiki/Low-Voltage_Ride_Through

# How is the pitch system tested?

The safety-relevant functions of the pitch servocontroller are developed through a TÜV-certified process and verified through comprehensive testing. A range of test procedures is applied at different levels of the V model:

**1**

## Module and white box testing

Individual software modules are tested offline or directly on the target processor. White box testing is a suitable module testing approach where testing is performed in the known source code.

**2**

## Integration testing

These tests verify the interoperability of the various software modules by testing the module interfaces.
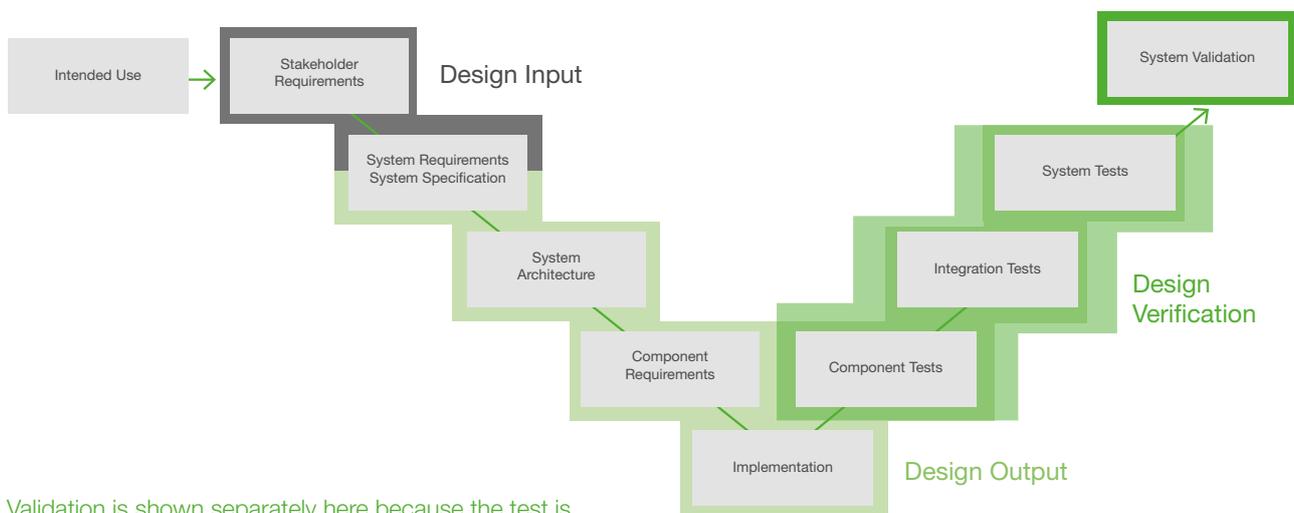
**3**

## System testing

The productive software and hardware of the pitch servocontroller are tested in the typical system environment with support from additional external components.

Finally, the test examines at the V model's top level, the validation level, whether the developed system is suitable for the intended use case.

# Verification level in the V model



| | | | |
| --- | --- | --- | --- |

Intended Use → Stakeholder Requirements — Design Input

System Requirements System Specification

System Architecture

Component Requirements

Implementation — Design Output

Component Tests

Integration Tests

System Tests

System Validation

Design Verification

Validation is shown separately here because the test is not performed based on specified requirements, but rather to ascertain whether the product is suitable for the relevant purpose.

## Preferred method HIL testing

In addition to the testing performed in tandem with development, it is also necessary to quickly analyze faults that occur in the field. Because wind turbine installations are installed around the world, direct field testing can be costly in terms of travel time and expenses. What is more, because the pitch system is installed in the rotating hub, it is anyway impossible to access it while the wind energy plant is running. A fixed installation of measuring equipment would be required in order to record or transmit data to an operator.

Both scenarios would involve prolonged downtime of the wind energy plant and consequently yield losses for the owner. In consequence, acceptance testing and fault analysis are predominantly performed on test benches. This white paper compares various test methods and demonstrates why HIL is the preferred test method.

# 3 reasons for performing software tests

## 1

### Safety relevance & functional safety

The essential functions of the pitch servocontroller are relevant for safety, which means that very high reliability and functional safety are required. The TÜV-certified process implies that comprehensive software testing is required in order to demonstrate compliance with high safety standards (e.g. performance level PLe).

**TÜV certified**

## 2

### Complexity & integration of multiple components

In addition to module and integration testing, system testing is also required in order to ensure that all interfaces and functions operate together correctly.

## 3

### Practical test conditions & field analyses

Since analyzing errors in the field is very difficult, it is necessary to conduct comprehensive test bench testing (white box, integration and system testing) in tandem with development.

## Test bench challenges

# Space, costs & safety risks in pitch system simulation

A physical test bench typically includes all components used in the pitch system in order to make testing as realistic as possible. In addition, load machines for simulating load torques, an adjustable grid voltage supply and, if applicable, a variable ambient temperature are needed in order to mimic the ambient conditions for the pitch system.

A test bench setup of this type requires a lot of space, produces noise and heat during operation, and involves moving parts and dangerous voltages that create a high potential for health hazards to the operating personnel, which must then be mitigated through complex safety precautions. The procurement costs for a physical test bench are often significant.

Since it is usually the case that every wind energy plant manufacturer has their own pitch system design, the test bench must use manufacturer-specific components connected to the servocontroller in order to create test conditions that correspond to the conditions at the wind energy plant. In this context, the cost increase is directly proportional to the number of possible variations. Test bench set-up time needs to be factored in, and the components also require storage space.

It may be necessary to perform tests under extreme conditions, which can severely stress or even destroy the devices. These tests can give rise to costs for new hardware or may even create safety hazards for the operating personnel.

Another aspect of test bench testing is operator costs. Manual tests that require multiple repetitions create labor costs for each test run. Keeping test records is another cost-relevant factor. If tests are conducted manually, there is also a risk that the test procedure is not identical each time. This can lead to discrepant results, and test personnel may need to be trained in new testing procedures.

### Drawbacks of physical test benches

// High space requirements
// High procurement and operating costs
// Safety risks
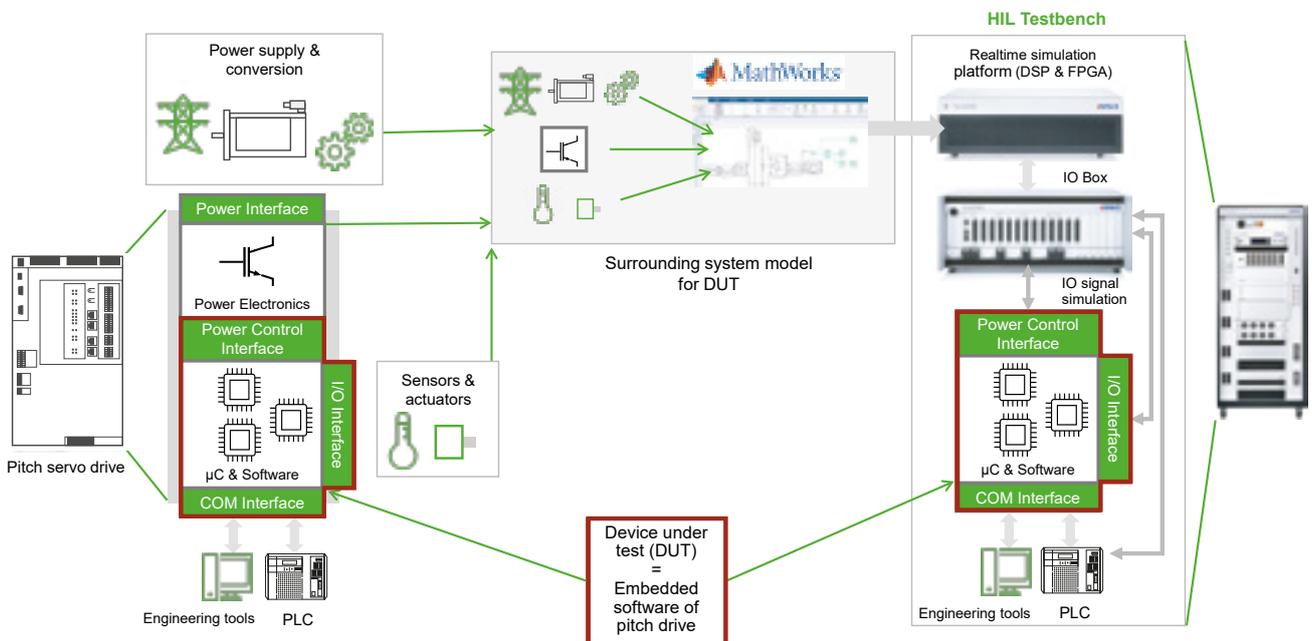// Complexity due to large variety of the devices

### If test automation is lacking
// Manual effort and potential inconsistency
   of results
// Significant record-keeping effort

## KEBA hardware-in-the-loop (HIL) test system

# Comparison of physical and HIL test benches



The figure shows the components of a physical test bench on the left. On the right is the set-up for an HIL test bench. The PitchOne components that are omitted (power electronics, sensors & actuators) as well as the external components (power supply & conversion) are simulated in the model.

Based on the conditions described above, KEBA has decided on the following concept:

In order to achieve maximum flexibility regarding the servocontroller environment, a surrounding system model simulates all components used in the pitch system and connected to the servocontroller. This model runs on an HIL[2] simulator from dSpace. The simulation hardware for the real-time simulation of the models on FPGAs[3] or digital signal processors is an off-the-shelf product. The connection of the servocontroller electronics to the simulator hardware is via a specific adapter that transmits the various control and measurement signals from the DUT via a cable harness to the connection panel of the simulator hardware.

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[2] "Hardware-in-the-loop (HIL) simulation is a technique for validating your control algorithm that will run on a specific target controller by creating a virtual real-time environment that represents the physical system." https://de.mathworks.com/discovery/hardware-in-the-loop-hil.html

[3] "A field programmable gate array (FPGA) is a versatile type of integrated circuit, which, unlike traditional logic devices such as application-specific integrated circuits (ASICs), is designed to be programmable  (and often reprogrammable)... " https://www.ibm.com/de-de/think/topics/field-programmable-gate-arrays

The DUT runs without any dangerous movements or voltages. All input and output variables of the servocontroller electronics are connected to the HIL simulator at the extra-low voltage level. This prevents hardware damage as well as hazards for the operating personnel when critical operating points are approached.

The simulation thus permits performing tests that, in physical test benches, would require monitoring (overtemperature creates a fire hazard, danger from rotating parts at overspeed, etc.) or would even be impossible to test because the necessary conditions for the test cannot be consistently generated or repeated.

Thanks to the design at extra-low signal level, the test bench requires significantly less space[4] and involves fewer hardware expenses. This concept requires the components that are omitted – such as the grid, the input rectifier, the DC link, the brake chopper, the motor power stage and the energy storage power stage – to be built into the simulation model.

## Benefits of the HIL test system at a glance

These benefits make the HIL test system a safe, flexible, and cost-efficient alternative to conventional test bench methods.

// Flexibility

// Safety and protection

// Testing of extreme scenarios

// Cost efficiency and reduced space requirements

// Real-time simulation with standard hardware

[4] The KEBA engine test bench, for example, requires approx. 50 sqm, while the HIL test bench is built into a mobile 19-inch switch cabinet.

# Simulation architecture and test bench set-up

The simulation model consists of four model components (EPSS processor model, EPSS FPGA model, XSG FPGA model, XSG processor model) with a modular structure; each of these models runs with a different sampling time. All simulation values that require very fast computation have been implemented in FPGAs. The other model components run in processor simulations. The necessary data is shared among all simulations.

All of the modeling was done using Matlab Simulink, an established system modeling software with an extensive library of standard blocks. The code generation for the real-time platform is done in combination with the ConfigurationDesk tool from dSpace. This allows us to achieve a flexible and efficient implementation.

// XSG FPGA model: The PWM capturing of the motor output stage, the motor model, the mechanical system with gear unit, as well as the blade encoders and motor encoders are computed in an FPGA with pre-engineered dSpace/Xilinx FPGA models. The use of standard libraries minimizes the implementation effort. An interface enables the data exchange of selected actual values and parameters with the model components of the processor platform. This FPGA works at a clock cycle of 8 ns.

// XSG processor model: This processor model contains the parameter and signal interfaces with the dSpace/Xilinx FPGA and also simulates the field bus. It runs at a sampling time of 1 ms.

// EPSS processor model: Computes the grid simulation, the internal rectifier as well as the energy storage simulation in a model with a 50 µs cycle time. The modeling of the power electronics is performed in Matlab Simulink using the Simscape Electrical libraries, permitting the realization of a reliable model at a high level of abstraction.

// EPSS FPGA model: The DC link, the energy storage power stage (DC/DC transformer), the brake chopper as well as the energy storage current are computed in an FPGA working at a clock cycle of 2.5 µs. The FPGA sub-model of the power electronics was also implemented on the basis of Simscape Electrical libraries.

An essential benefit of this HIL simulation approach is the ability to use run-time parameter configuration for the adjustment of different pitch system variants. Alternative compiled models can be integrated into the test bench quickly so that tests can be performed under variable ambient conditions and for various system configurations with minimal effort in terms of time, costs, and labor.

## Selective axis simulation and interface integration

In the context of an innovative HIL simulation concept, cost savings are realized by providing a full set of model signals only to axis 1 (SUT) of the three symmetrical axes of the pitch system. The primary purpose of the other two axes is to generate the data transmitted during operation via safe cross communication (SCC). Accordingly, the axes are provided with selected signals to a limited extent only, so that the system receives the necessary enable signals for normal operation and at the same time simulates faults that can be triggered by unexpected measuring values from neighboring axes.

For the additional servocontroller axes, a modified firmware is implemented that offers advanced simulation options, such as the simulation of grid and DC link conditions. The generated values are transmitted to axis 1 via SCC.

The communication with the axes and with the HIL simulator is via an Ethernet parameter interface that can be controlled from an operator's PC. These interfaces can be used to download various model variants and firmware images, modify parameters, and read measured values in real time.
In addition, PitchOne is able to access the PROFIsafe/PROFINET interface from inside the simulation model. This makes it possible to transmit commands and read actual values in order to write values in time with the simulation as well as to log processes.

The use of these integrated interfaces ensures that all test-relevant data can be reliably and efficiently collected and processed—a crucial factor for the validation and optimization of safety-critical systems used in the industrial sector.

## Performing manual tests and parameter control

The developed set-up can already be used to realize manual tests. Our proprietary KeStudio DriveManager tool is used for the parametric actuation of the servocontroller, while a built-in scope logs the history of the actual values. At the same time, the Controldesk tool from dSpace can be used for the parametric operation of the HIL simulator, which also supports the documentation of the actual-value history. This combination of manual control and synchronous data logging forms the basis for reproducible test scenarios and initial verifications in the simulation environment.
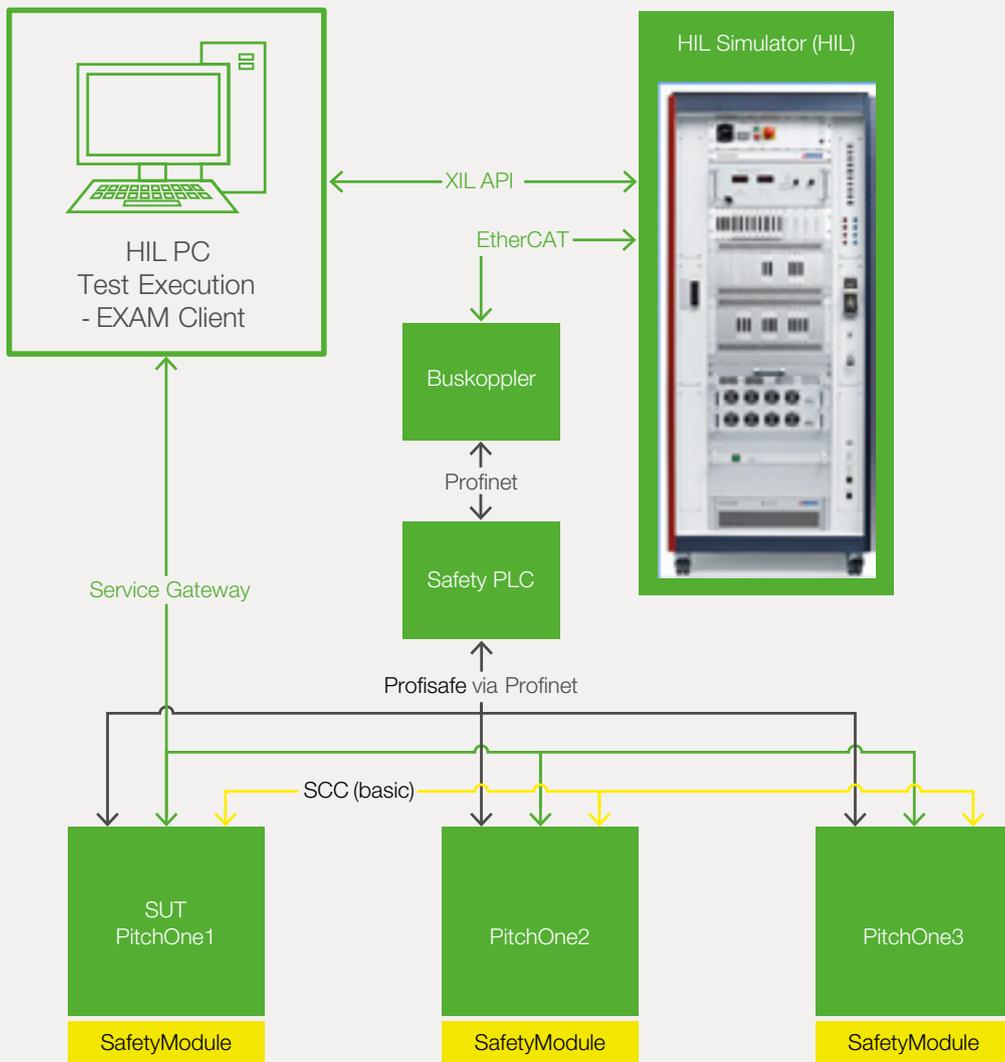


Communication interfaces of the servocontrollers

## Optimized software verification through automated HIL test campaigns—would you dare?

The test bench is primarily designed for system testing with a focus on verifying the software functionality of the servocontroller. All software tests are performed as regression tests for each new major release of the device software. The test scope increases with each new software version because additional functionality needs to be tested. This creates an enormous testing workload, in particular due to the frequent repetition of the same tests.

The time required for a firmware release test campaign is currently about one week of full-time effort, corresponding to 7 × 24 h = 168 hours of pure machine running time, not taking into account the additional work required to evaluate the tests. If these test were conducted manually, provided this was even possible in view of the timing requirements, the required time would multiply significantly. Even with a conservative estimate using a factor of 4, the labor input would increase to about 672 hours (corresponding to 84 man-weeks). Without comprehensive test automation, such a scenario would quickly become uneconomical and would delay the software release cycles considerably.

In order to enable testing at a consistent quality and with less labor input, a test automation environment has been developed for the HIL test bench. This environment supports the parametric actuation of all parameters made available via the servocontroller service interface (ComLib) and the XIL API[5] of the simulator interface. The automation is based on

Python scripts that are generated using EXAM-TA, a test automation software widely used in the automotive industry.

EXAM-TA uses a central server that stores the test project data in a database, allowing the test implementation and the execution of the code to run in parallel on separate PCs. This achieves high test bench utilization and permits the efficient distribution of the implementation workload for new tests. In addition, this architecture ensures a clear separation between test case implementers and testers. A system of finely adjustable access rights tied to role assignments in test projects (e.g. tester, test case implementer, library developer, administrator) minimizes the potential for damage caused by user error.

## Summary

This test automation concept not only ensures the consistent quality of the software but also significantly reduces the labor input and the release times—a crucial advantage in the competitive development of safety-critical systems.
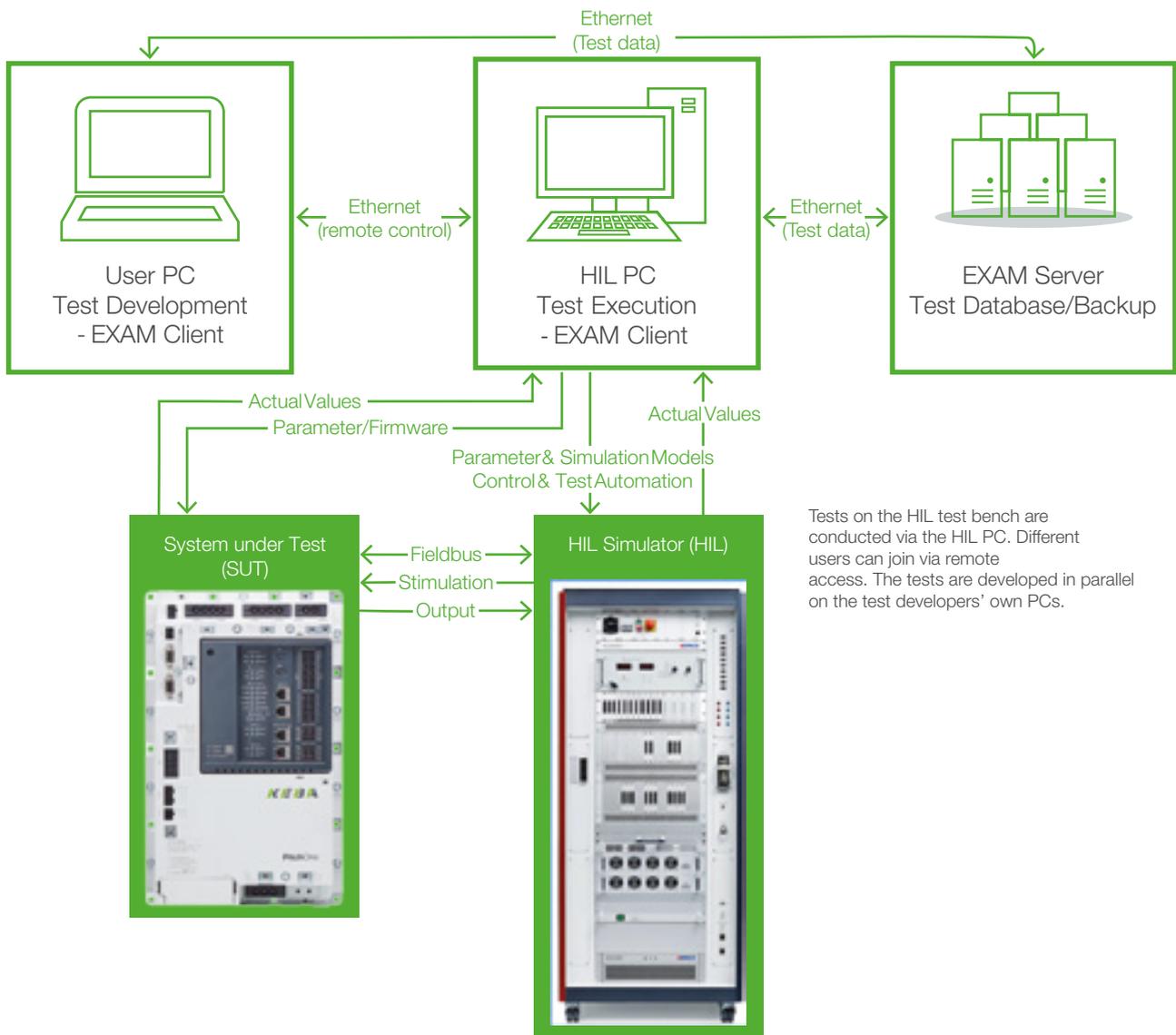
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[5] "ASAM XIL is an API standard enabling communication between test automation tools and test benches."  https://www.asam.net/standards/detail/xil/

# Test automation and reproducibility as key to greater efficiency

In modern test environments, test protocols are generated directly by specialized test automation software—an approach that saves a considerable amount of manual work. These protocols are stored in a central database on a server, facilitating the sharing of test results among multiple users and optimizing collaboration.

Functional safety cannot be certified unless tests are reproducible at any time at a consistent quality. A dedicated test automation tool guarantees the consistency of the test procedures while the version management of the test database makes it possible to reproduce old test project versions.

As the parameter interface of the PitchOne servocontroller is already fully integrated into the test automation and the use of Python makes it easy to quickly include other third-party interfaces, the circle of users of this software at KEBA is constantly growing. Consequently, an increasing number of diverse test procedures such as smoke tests and hardware acceptance tests are being realized on additional test benches (e.g. physical test benches, engine test benches). This flexible and scalable solution is making a significant contribution to the optimization of test processes and to greater efficiency in the development of safety-critical systems.



Ethernet (Test data)

Ethernet (remote control)

Ethernet (Test data)

User PC
Test Development
- EXAM Client

HIL PC
Test Execution
- EXAM Client

EXAM Server
Test Database/Backup

Actual Values

Parameter/Firmware

Parameter & Simulation Models
Control & Test Automation

Actual Values

System under Test (SUT)

HIL Simulator (HIL)

Fieldbus

Stimulation

Output

Tests on the HIL test bench are conducted via the HIL PC. Different users can join via remote access. The tests are developed in parallel on the test developers' own PCs.

## Customer HILs and test interchangeability

In order to achieve greater testing depth and improved software quality, the test bench was not implemented exclusively at KEBA; copies were also provided to customers of the new servocontroller. Since all customers use the same tool chain, tests can be exchanged seamlessly between the customer test projects and KEBA and can be duplicated independently of each other. This makes it possible to reproduce and analyze test cases anywhere in order to demonstrate certain behaviors. In addition, it provides the flexibility to increase the test bench capacity as needed.

## Limits and focus of the HIL model

The HIL model reflects only a subset of the real system and is not able to fully simulate all environmental factors[6]. It focuses exclusively on those areas of behavior that are considered relevant for PitchOne software testing. KEBA's PitchOne HIL is used exclusively for the verification of software on the target hardware. The comprehensive testing of the device hardware requires the use of a complete system; for this reason, supplemental physical test benches have been set up to test, for example, the performance limits and thermal limits of the hardware. The HIL model, by contrast, is used primarily to test the extensive configuration options of the device software.

PitchOne

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[6] "A simulated environment is always only based on the available knowledge, collected measuring values and experience values that are transformed into simplified mathematical formulas and then reappear as models in the HiL simulator. Because of this, and in spite of the progress made regarding simulated environments, the HiL simulator can replace testing in the real world only within a limited scope." https://de.wikipedia.org/wiki/Hardware_in_the_Loop#Luft-_und_Raumfahrt

**Outlook. Progress. Opportunities.**

# Great potential for expansion

The current simulation mode was specially developed for the software testing of PitchOne based on KEBA specifications. It does, however, come with great potential to be expanded to include additional aspects of customer systems and increase simulation accuracy. For example, the behavior of the wind turbine installation control system as well as the connected components can be defined in greater detail. The simulated blade loads can thus be modified to match actual load data from the field, and the grid fault simulation could be expanded to include FRT scenarios, the behavior of the main generator, as well as certification-relevant scenarios.

In the area of test automation, too, there remains significant potential for expanding further test set-ups with KEBA products. As the service interface of all KEBA servocontrollers can be addressed via ComLib, additional test environments can in future be integrated automatically. Moreover, even today all KEBA control systems can be included in the test automation via EXAM. These expansion options provide a flexible, scalable test infrastructure that satisfies growing customer demands.

# Conclusion

### How can the verification of safety-critical pitch systems in wind turbine installations be made more efficient, cost-effective and safe?

KEBA's HIL test system offers an ultramodern solution through the precise, real-time simulation of real system conditions for the DUT, achieving a drastic reduction of time and effort compared to conventional test bench testing. The use of simulation models for the environment not only increases personnel safety—it also makes it possible to automate test campaigns in EXAM that can run without monitoring. This results in fast, reproducible test results, reduced costs and accelerated certification.

This concept thus provides immediate answers to the most pressing questions asked by developers and system owners: How can we test complex, safety-critical systems without having to resort to numerous expensive, time-consuming and hazard-prone physical test benches? And how can we conduct fault analysis in existing systems in a cost-effective and safe manner?
The answer lies in the smart combination of modern simulation technology with an automated test environment—a crucial competitive edge in the wind turbine installation sector.

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# next success story!

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Our team is looking forward to hearing from and to turn your vision into reality.

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