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A NEW FACILITY FOR DYNAMIC TURBOMACHINERY AND WIND-TUNNEL TESTING

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ABSTRACT

Due to high levels of efficiencies reached over the recent years, incremental improvements in turbomachinery development tend to become smaller in terms of efficiency and power density. New concepts, however, like the geared turbo fan design for aircraft engines leading to a new, faster rotating generation of low-pressure turbines, still enable manufactures and operators to realize significant improvements.

For ground-based turbomachinery modes of operation change from continuous load to intermittent and dynamically changing off-design operation and high load gradients in order to cover residual loads due to fluctuating generation by renewable energy resources. For ongoing turbomachinery development, test facilities need to adapt to these new challenges.

Thus, the Leibniz University Hannover has set up a new research alliance “Dynamics of Energy Conversion”, including a completely new test facility for different turbomachinery applications. The new facility is currently under construction and will be commissioned in July 2019.

It includes up to eight rotating test rigs as well as several open and closed loop cascade wind-tunnel applications. A compressor station provides compressed air to the test rigs and wind tunnels. It can deliver high load gradients up to 30% design load per minute. Aerodynamic parameters such as Mach number and Reynolds number can be adjusted independently.

NOMENCLATURE

D_C	casing diameter
D_H	hub diameter
H	height
k	reduced frequency
L	length
Ma	Mach number
N	rotational speed
P	power
P_{el}	electrical Power
P_{tot}	total pressure
P_{in}	rig inlet pressure
P_{out}	rig outlet pressure
Q_m	mass flow rate
Re	Reynolds number
T	temperature
T_{in}	inlet temperature
T_{out}	outlet temperature
u	velocity of the flow
π	pressure ratio
LCWT	Linear Cascade Wind Tunnel
AWT	Aeroacoustic Wind Tunnel
AT	Axial Turbine
HSAC	High Speed Axial Compressor

INTRODUCTION

The constantly increasing level of electrical power generated by wind turbines and photovoltaic systems is leading to a massive change in the electrical supply system. Figure 1 shows the power generation for daily loads of three typical days in Germany predicted for the year 2022. While renewable energies can temporarily provide large portions of the required power, conventional power plants are required to ensure that enough power is produced, especially during winter term. On these days, the required power from conventional sources reaches nearly 100% of the overall produced power. During summer, a massive and quick change between electrical power produced by renewable energies and conventional power plants has to happen. For the year 2020, load gradients of up to 15 GW/h are expected by Pleitgen et al. (2004).

While long term differences between seasons of the year already have a clear impact on the transformation of the energy supply systems, additional “high-frequency fluctuation” due to not or falsely predicted power generation by wind turbines lead to the challenging problem of extremely short times of response for power plants to handle the residual load. Fig. 2 shows the difference between the actual and the predicted power generation of the 160 MW offshore wind farm Horns Rev 1 (EURELECTRIC 2011).

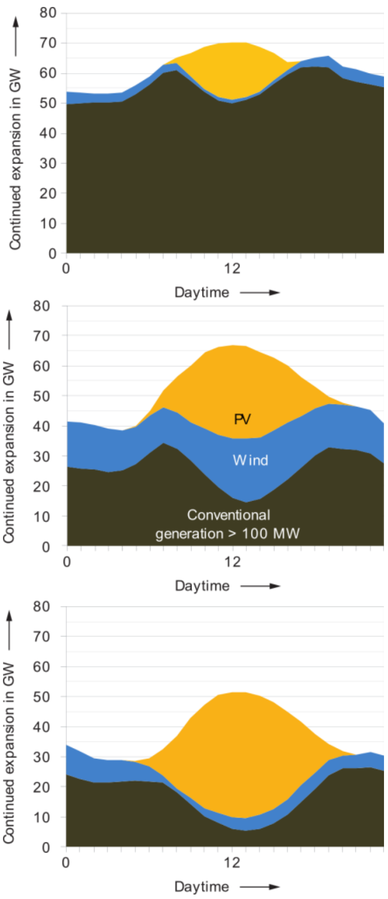

Figure 1: Prognosis for power generation and power supply for the Germany in 2022; top: on Mondays in February, middle: on a Friday in mid may, bottom: on a Saturday at end of May; adapted from Wiese et al. (2013)

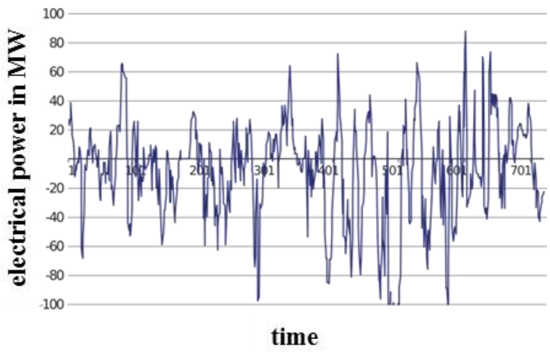

Figure 2: Hourly difference of predicted and actual power of the 160 MW offshore wind farm Horns Rev 1 (EURELECTRIC 2011)

The spread of the underlying time scales of the fluctuations shown in Fig.1 and Fig.2 ranges from a few seconds to weeks and months.

Future energy systems must be optimized for intermittent operation in general and high gradients in generation as well. Pumped-storage hydro power plants can deliver that technical aspect, but will not be able to close the gap due to geological, ecological, and economic reasons.

Thus, the focus on future energy research will be on the development of a reliable chemical-thermal-electrical energy conversion processes with a high, dynamic load range. This energy conversion is typically done by turbomachines that must be adapted to new boundary conditions.

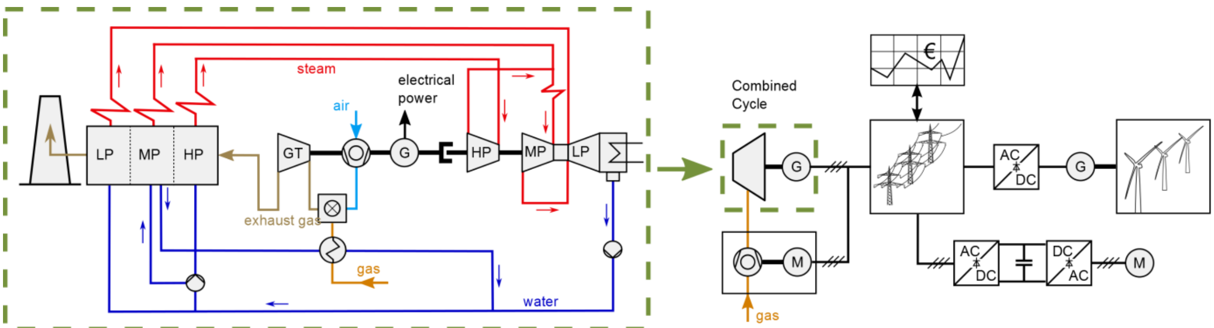

Figure 3: Interrelations between components within the electrical energy supply system by means of a combined cycle power plant

CONCEPT FOR TEST INFRASTRUCTURE

Large components for power plants or other energy converting processes are normally designed in small series or even as unique pieces. High manufacturing costs limit the availability of full or reduced scale prototype systems of steam generators, turbines, or generators in general. This means, that the design processes for these components need to be both very accurate and fast. Existing methods are widely validated for single parts conversion processes and, in terms of design purpose, for steady component operation. In order to meet the future requirements, these design methods must be capable of predicting the dynamic operation as well as dynamic interaction between the components of the conversion process (i.e. steam generator-turbine-electrical generator). Efficiency as a first order design criteria is replaced by reduction of emissions and capability for dynamic operation. In the end, all this must lead to a system, which can still be profitably operated.

Figure 3 illustrates the interaction between different components within the energy conversion process. Thus, the research alliance "Dynamics of Energy Conversion" is divided into 5 subject areas:

1. Dynamics of chemical-thermal energy conversion
2. Dynamics of thermal-mechanical energy conversion
3. Dynamics of mechanical-electrical energy conversion
4. Dynamic coupling of energy conversion processes
5. Energy markets

Multi-disciplinary groups of researchers of the Leibniz University of Hannover are working in one or more areas of those mentioned above.

DYNAMICS OF THERMAL-CHEMICAL ENERGY CONVERSION

This paper focuses on the test infrastructure required for the second subject area "Dynamics of thermal-mechanical energy conversion" with special regard to the energy conversion done by turbomachines. For gas and steam turbines, higher flexibility means high efficiencies in part load operation and secure operation at even lower min-load levels. In order to react to intermittent generation by renewable energy systems, high load gradients of more than 20% of the design load per minute will be required.

At part load operation, highly unsteady, three-dimensional flow pattern will establish within the flow path of turbomachines. State-of-the-art design methods cannot predict this flow pattern correctly. Binner and Seume (2014) investigated the flow characteristics at low load high-pressure steam turbines, showing that unsteady flow effects can occur which lead to possible thermal or structural damage of the turbine.

Furthermore, the efficiency level during part load operation of turbines has to be increased. These can either be done by passive mechanisms (e.g. end-wall contouring) or by applying active flow control (Vorreiter et al. 2012).

As a third subject, start-stop operation of gas turbines leads to an increasing number of overall load cycles. Thus, low-cycle fatigue mechanisms become more important. During the start-phase of a turbine or a compressor, besides cyclic thermal fatigue, critical states of operation have to be passed in terms of natural frequencies of the components (forced response excitation of blades or vanes, flutter in worst case). Design tools need to predict frequencies as well as vibration amplitudes correctly, including fluid-structure interaction. Under certain operating conditions, acoustic resonance can occur and has also been part of the investigations (Hellmich and Seume 2009).

AERODYNAMIC REQUIREMENTS FOR THE NEW TEST FACILITY

A trade-off between the resources required to simulate real engine characteristics and available size of the facility, as well as budget is always required in an investigation of the aerodynamic, aeroelastic and aeroacoustic effects in turbomachines. For fundamental research and near-engine design testing, the aerodynamic, aeroacoustic and aeroelastic scaling is based on

- Mach number Ma,
- Reynolds number Re and the
- reduced frequency *k*.

Often, the scaling is also limited by geometric constrains or increasing rotational speed. To meet most of the criteria listed above, the Leibniz University successfully applied for funding for a new research building called "Dynamics of Energy Conversion" (DEW). The new test facility will include already existing test rigs and the capacity to incorporate new test rigs as well.

The typical scaling of the existing test rigs is represented by the multistage axial air turbine of the Institute of Turbomachinery and Fluid Dynamics. The maximum blade tip diameter is $D_C = 0.5$ m, the hub diameter is no smaller than $D_H = 0.27$ m. A blade chord length of $l = 0.07$ m at exit flow angles between $0° < \beta < 40°$ is assumed. These data lead to scaling parameters according to Tab.1.

Table 1: Attainable scaling parameters for the axial turbine test rig with supply of the new compressor station

Mach Number Ma	0…1
Chord-based Reynolds Number Re	10.000 … 1.000.000
Reduced frequency *k*	0.1 … 0.7

Figure 4 shows the associated Mach-Reynolds-number-operating map of the new compressor station and typical operating points of steam and gas turbines. As the latter are enclosed by the compressor station's operating map the new facility allows for investigations of turbomachinery components at real life conditions in terms of combinations of the aerodynamic similarity parameters Mach and Reynolds number.

For radial as well as axial turbine and compressor tests, several different power trains will be available, covering loads up to 3 MW and rotational speeds up to 30.000 rpm. For up to 10.000 rpm, the electrical motor or generator is directly coupled to the test rig. In the case of higher rotational speed, planetary gear boxes are installed in between. All engines are designed for positive and negative rotational direction and can either drive or brake the connected rig. For emergency reasons, brake engines are also equipped with a large electrical brake resistor and an additional pneumatic brake, in case the frequency converter fails catastrophically.

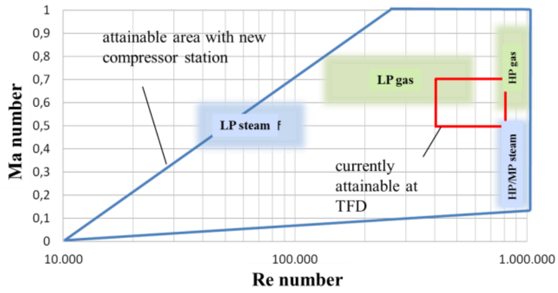

Figure 4: Comparison of Ma number and Re number for typical axial turbines and

Table 2: Aerodynamic inlet boundary conditions for "Open-Loop-Operation"

	Pressure (bara)	**Temperature (°C)**	**mass flow (kg/h)**
wind tunnels	1…2	60…100	80.000
turbines	1…4	60…200	80.000
compressors	use of piping system and coolers, inlet air can be throttled to 0.3 bara		

Table 3: Aerodynamic inlet boundary conditions for "Closed-Loop-Operation"

	Pressure (bara)	**Temperature (°C)**	**mass flow (kg/h)**
wind tunnels	1…8	60…100	92.000
turbines	1…8	60…200	92.000
compressors	use of piping system and coolers, inlet air can be throttled to 0.3 bara		

As types of turbomachinery test stands aside from compressors need an external primary media supply. Thus, a compressor station supplying the test rigs is required for conducting tests. For the new facility, the requirements to such a compressor station are given below. Tab. 2 and 3 shows the aerodynamic boundary conditions for operating the existing rigs as well as planned test rigs at the new facility. Compressed air is chosen as primary test media. A twin-row two-stage compressor design has been selected, as it provides the best fit to the required specifications. The compressor station can operate in either an "Open-Loop" or "Closed-Loop" configuration and consists of two roots blowers and two screw compressors, delivered by AERZEN. Compared to radial or axial turbo-compressors, roots blower and screw compressors do not suffer from any instabilities within their operating behavior, which can be shown in an almost rectangular profiled operating map. Furthermore, due to their functional principle, those machines can also handle partial vacuum at inlet.

With regard to closed-loop operation, the maximum pressure ratio for all test rigs is limited to $\Pi = 4$. To achieve low Reynolds numbers at high Mach numbers the system is designed for a minimum absolute static pressure of 0.3 bar. A complex evacuating system and an additional compressor has been designed for over pressure operation to achieve this. Due to the highly advanced cooling system in combination with a complex valve control system of the compressor station, Ma number and Re number can be adjusted independently from each other. This makes it possibly to reach real engine flow parameters within a wide range of operation. During closed loop operation, the humidity level of the enclosed air can be reduced to almost dry air.

The maximum electrical power consumption of the compressor station and its ancillary units is 6.5 MW. For cooling of the compressed air, the same amount of cooling capacity is required. As there are several other heat sources (e.g. gas burner test rigs) within the research building and neighbored facilities, a total of 12MW cooling capacity is installed as a double circuit cooling system, providing cooling water at two different temperature levels to the test rigs. The overall mass flow rate is determined by five cascaded high precision ultrasonic metering devices, allowing measurements for high mass flow rates as well as very small flow rates. Due to their functional principles, these devices can operate very robustly and with nearly no pressure loss. Further information of the compressor station can be found at deBuhr et al. (2018).

In order to improve the quality and reproducibility of experimental investigations, very strong specifications for flow conditioning at the inlet section of the test cells have been set.
With regard to the increasing interest in small scale effects, the homogeneity of the flow parameters is of great importance and will fulfill the specifications given in Tab. 4.

Table 4: Homogeneity of inflow parameters

P_{tot}	± 0.1% of avg; max. 400Pa
T_{tot}	± 0.1% of avg
qm	± 0.02 kg/s
Air quality	dry air, filtered, oil-free

Custom-build settling chambers designed by AERZEN are installed upstream of the inlet section of the test rigs if needed. By changing mechanical grids inside of the chamber, the turbulence level at test rig inlet can be adjusted.

Since the same experimental setup is commonly investigated over a long period of time, there are also strong requirements for stability and reproducibility from one day to another, as given in Tab. 5.

Table 5: Reproducibility of inflow parameters

P_{tot}	± 100 Pa
T_{tot}	± 0.3 K
qm	± 0.02 kg/s

STRUCTURAL, HEALTH AND SAFTY AND SECONDARY SUPPLY SYSTEM REQUIREMENTS

During the design phase of the new research building several additional boundary conditions had to be considered, in order to ensure a constantly safe and stable operation. Overall test concepts will change over the lifetime of the research building as often as technical specification of particular applications do. The building structure must ensure the safety of the staff, even at dynamic, aerodynamically unstable operation of the test item itself. This leads to high efforts in terms of staff protection, as the maximum power transformation taking place at most of the existing and planned test rigs can reach the power level of the supplying compressor station. Thus, the most important functional characteristics of the building structure are:

- modular, flexible layout
- provide supporting structures for compressors and associated piping
- burst protection in case of failure
- noise protection of working staff
- control and communication system
- power supply / energy absorption of test rigs
- room for secondary supply systems (oil, sealing air,…)
- water cooling of test rig components
- venting of the test environment
- cooling of the test environment

In order to attain all those functional requirements, the building is divided into a strong foundation with an overall housing structure on one hand and modular test cells on the other hand. Figure 5 shows the basic layout of the research building. The inside of the building consists of a large compressor hall, 14 separate test cells, 11 of them connected to the compressor station and several rooms for rig supply systems.

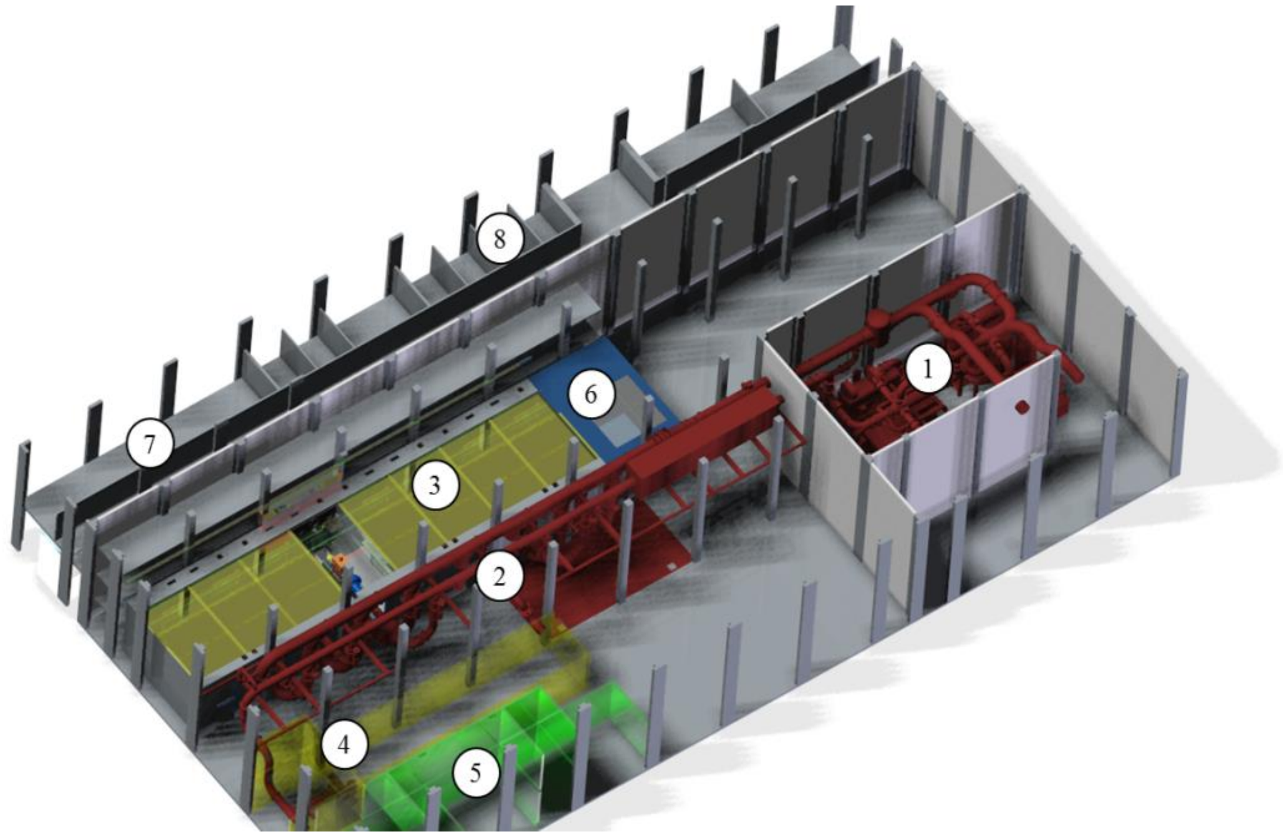

Figure 5: General layout of the new research building; (1) compressor station; (2) primary piping system between compressor station and test rigs; (3) turbomachinery and power plant test cells; (4) linear and annular cascade wind tunnels, aeroacoustic wind tunnel; (5) gas engines; (6) test rig supply; (7) master control room; (8) staff offices

There are four different types of test cells:

- eight test cells for turbomachinery test rigs, providing strong burst protection and connected to the compressor station
- one test cell for open loop linear cascade wind tunnel investigations
- one test cell for closed loop annular cascade and aeroacoustic wind tunnel investigations
- four test cells equipped with a hot gas exhaust system for combustion investigations.

While the compressor hall serves as a large, noise protected cell for the main compressor station, its electrical drives, its water-air-coolers, in-line damping systems and systems for evacuation of the piping system, the rig supply rooms are designed for rig-related secondary systems. These are mainly large frequency converters as well as a complex oil supply and sealing air system for all test rigs.The following description focuses on turbomachinery test rigs, run by the Institute of Turbomachinery and Fluid Dynamics.

TURBOMACHINERY TEST CELLS

Currently, the (non-parallel) operation of two multi-stage axial turbines, a multi-stage high-speed axial compressor, a high-speed axial diffusor rig and a centrifugal compressor are included. In addition, a linear cascade wind tunnel and an aeroacoustic wind tunnel with annular cascades will be part of the DEW research building.

The design of eight turbomachinery standardized test cells follows the above mentioned criteria. With regard to high rotational speeds of the rigs, the test cells are made of highly reinforced concrete walls and have an base area of 5 m x 10 m and a height of H =7 m. The test cells are covered be removable, reinforced concrete top panels, which can be removed by an overhead crane, providing excellent access for heavy-duty goods from above of the opened cell. The inner side of the walls is equipped with a noise damping system as well as the technical installations needed to supply the rig, such as connecting points for cooling water, pneumatic tooling as well as measurement and instrumentation systems. Each cell comes with its own electrical sub-distribution components, independent from the adjacent test cells. Furthermore, each cell is supplied by an air venting system and an electronic controlled air-cooler, keeping air quality high and air temperature at a constant level of T_{cell} = 297 +/-1K.

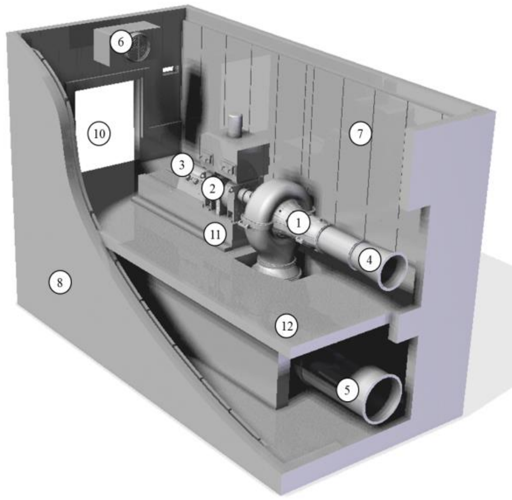

Figure 6: Layout of the Multi-stage axial turbine test cell; (1) Axial Turbine; (2) el. Generator; emergency brake; (4) inlet section; (5) outlet section; (6) air condition; (7) noise damping elements; (8) reinforced wall; (9) door; (10) vibration-isolated clamping plate

Fig. 6 shows a three-dimensional model of the overall layout of the planned axial turbine test cell.

The test rig is mounted on a vibration-isolated clamping plate at a total high of H = 2.5 m. The clamping plate can take all structural and aerodynamic loads of the rig and the adjacent inlet and outlet piping. Thus, the test rig is free of external vibration and external forces.

WIND TUNNEL TEST CELLS

Within the research building, there are also two wind tunnel test cells under construction. One of those has been designed for an open loop vertical linear cascade for turbine or compressor profile investigations. The test cell is equipped with highly effective noise protection and noise damping systems, as the air is discharged to the environment.

The other wind tunnel test cell has been adapted to closed loop annular cascades and aeroacoustic investigations. Both test cells have a direct connection to the main compressor station. Thus, the full capacity of compressed air as given in Tab 3 and 4 is available.

AUTOMIZATION

During rig operation, there is limited or no access to the test cells. This means, that the tests will be run with the help of a highly automated control system. This system is designed as a SPS-based modular grid of self-controlled sub-systems, such as oil-supply or the main compressor station. The control system sends out requests at all subsystems defined by the user and displays the feedback of the subsystems. After all required systems have been started and work within their required parameters, the control system can run a fully automated test sequence, including the control of measuring devices installed on the test rig. Since there is a high level of interaction between the sub-systems as well as the user requests, the control system will be responsible for the secure operation of all technical components.

SUMMARY

The new research buildling “Dynamics of Energy Conversion” will provide a unique, highly flexible state-of-the-art test facility for turbo-machinery and wind tunnel testing. It focuses on the investigation of dynamic effects in terms of unsteady aerodynamics, aeroelasticity and aero-acoustics, as well as on the interaction between different components within energy conversion processes.

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