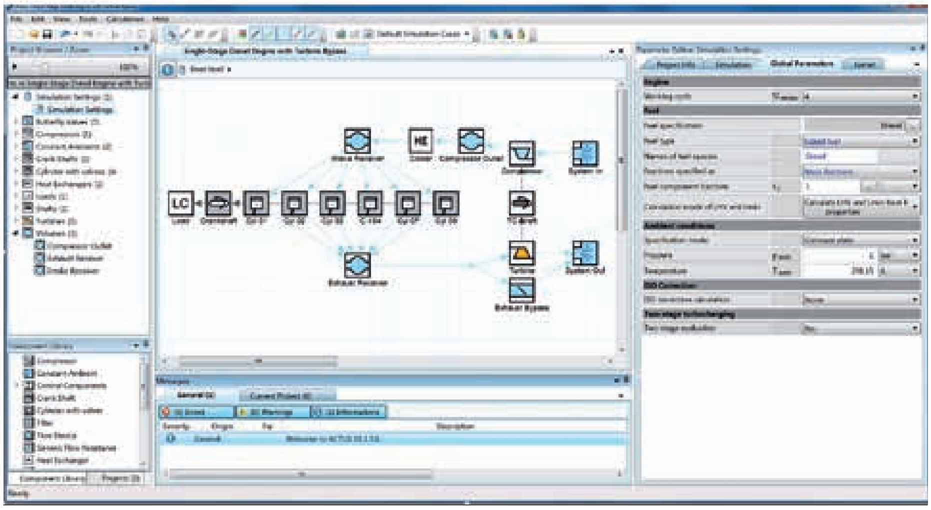
Turbo boost

ACTUS is ABB's new simulation software for large turbocharged combustion engines

THOMAS BÖHME, ROMAN MÖLLER, HERVÉ MARTIN – The performance of turbocharged combustion engines depends heavily on the performance of the turbocharging system itself. The interplay between the engine and the turbocharging system is complex and simulation is an essential tool for understanding this interaction and how best to match the engine components. Today, most engine manufacturers perform simulations to optimize their engine systems' designs. The vast majority of manufacturers rely on commercial simulation tools, which are sometimes supplemented by in-house developments for specific tasks. While today's commercially available tools are usually of very high quality and offer an extremely wide range of functionality, ABB continues to rely on in-house simulation software for its engine simulation needs. The use of in-house software allows ABB to fully customize the simulation to suit the specific needs the company has as a manufacturer of turbochargers for large-bore combustion engines. These needs range from selection of optimal turbocharger specifications in sales to research applications for test benches, turbocharger product development and the development of turbocharging concepts.

1 ACTUS user interface graphical editor showing a model of a simple six-cylinder, single-stage turbocharged engine with a turbine bypass valve.



The simulation of turbocharged engine systems has a long tradition in ABB. The first digital computations were performed in the 1960s with the introduction of the first digital computers [1,2]. These computational tools were continuously improved and extended. In the early 1980s, the existing calculation methods were combined into a single simulation platform called SiSy (Simulation System) that has been continuously extended since then [3].

After more than 20 years of development of SiSy, it became increasingly difficult to further extend the software due to its monolithic software design, so the decision was made to replace the software with a new simulation tool based on a modern, modular software design. The new simulation tool was named ACTUS (advanced computation of turbocharging systems). The software consists of two parts: a modern user interface with a graphical topology editor for setting up the simulations and a simulation kernel for performing the calculations.

Graphical user interface

In the graphical user interface, the engine is built by combining components from a library of distinct elements such as pipes, valves, compressors, cylinders, shafts, etc. and defining their possible interaction through fluid, mechanical, heat, or signal connections → 1. Once the topology is defined, the parameters of each component are specified in the parameter editor (on the right of the figure). A special simulation case editor allows multiple consecutive simulations to be set up – to simulate multiple engine load points in one simulation run, for example. The user interface also gives convenient access to a broad database of detailed performance data for all ABB turbochargers available since the 1970s.

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Simulation kernel

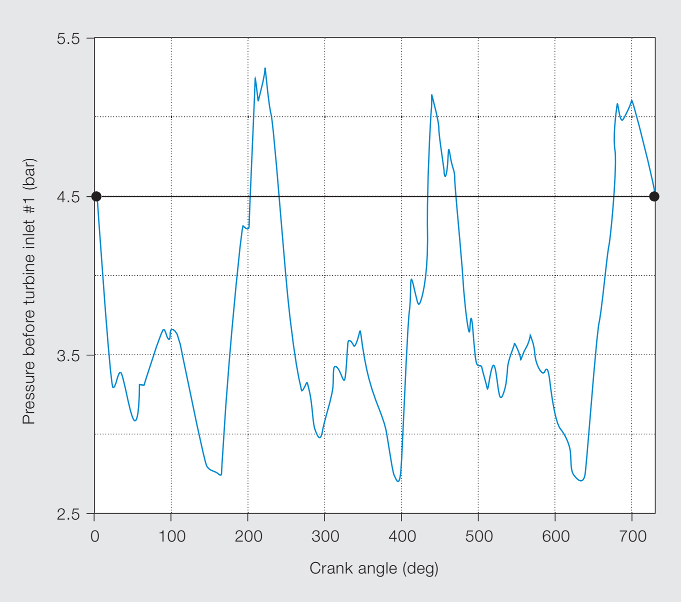
The second part of ACTUS, the simulation kernel, solves the model equations for the system and computes the results. The primary focus of the simulation is to predict the most relevant aspects of the whole engine system rather than focusing on specific, detailed aspects. While nowadays it would be possible to simulate the gas exchange of an engine cylinder with three-dimensional computational fluid dynamics, such a level of detail would not be suitable for a system level computation: The resulting computational time would be prohibitive for use in optimization and, even more importantly, such a calculation would require detailed knowledge of all geometries of the engine, which is typically not available to ABB.

Therefore, the models used in ACTUS are simplified models derived from physical first principles. The system simulation of a turbocharged engine system requires a large number of such simplified models from a range of different disciplines. This includes mechanical models for the crankshaft, and turbocharger shafts and bearings; thermal models for heat transfer; chemical models for emissions; and thermodynamic models for gas properties as well as for compression, expansion, fluid flow and storage.

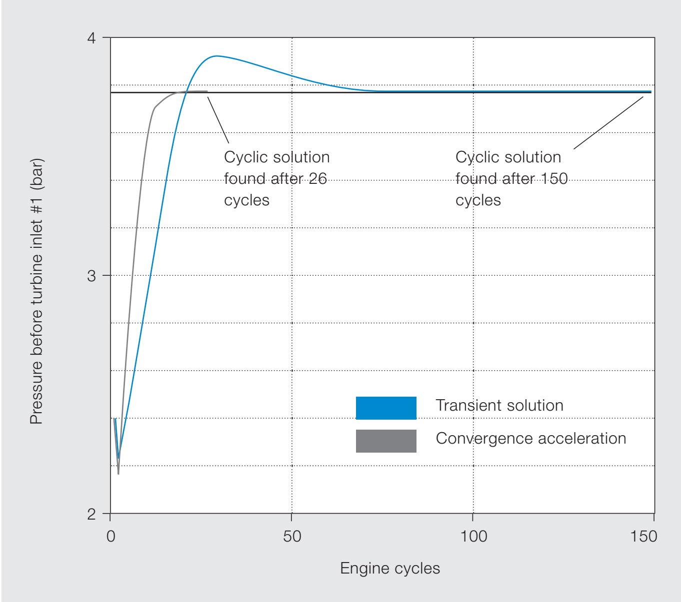
For complex processes, such as the cylinder combustion, the physical first-principle models are commonly complemented by empirical model extensions. These have been derived from the literature or from research collaborations, or have been developed internally within ABB.

Title picture
Only simulation software that has been developed in-house can hope to tackle the immense complexities of engine turbochargers.

2 Pressure before turbine inlet #1 over one engine cycle for a steady engine operation point (at full load)



3 Benefit of convergence acceleration: Instead of requiring 150 calculation cycles in transient mode, the solution is found after 26.



The sales department use ACTUS to select optimal turbocharger specifications for a particular engine – a task most customers rely on ABB to do.

ACTUS convergence acceleration

As most large-bore engine systems run under a constant load for long periods, the constant-load operating points are those of greatest interest for design optimization. Due to the inherently unsteady nature of the combustion engine process, a constant engine load point is not a steady state but rather a situation that exhibits periodicity, as can be seen, for example, from the pressure trajectory near a turbine inlet over one engine cycle → 2.

The solution is periodic when all dynamic states within the system match the initial state after the cycle completion. The most common approach used to determine such a periodic solution is to run a transient simulation long enough for all initial disturbances to decay. Due to the high rotational inertias of the turbocharger and crankshafts, typically more than 100 engine cycles are needed to obtain the cyclic solution → 3. In order to speed up such simulations, ACTUS employs an optimization method, called convergence acceleration, that significantly reduces the number of cycles needed to obtain the cyclic solution. This allows steady-state operating conditions for typical engines to be calculated on a standard PC in a matter of seconds.

ACTUS Match

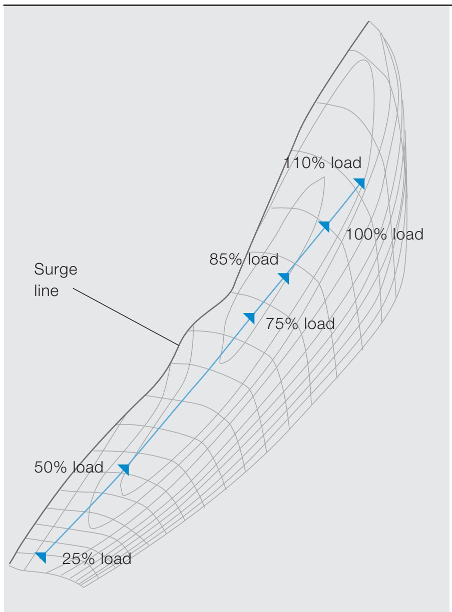
This convergence acceleration is coupled with a unique feature called ACTUS Match. ACTUS Match allows the calculation of the set of simulation input values that will result in a certain desired set of simulation output values. This is useful as system design applications often need to determine a system configuration that yields a desired result. For example, a common task in turbocharger matching is to determine the turbine size such that the engine will operate with an air-to-fuel ratio defined by the engine manufacturer and a given load. From a simulation standpoint, this is a nontrivial task as the resulting air-to-fuel ratio is typically not an input to the simulation, but rather a result depending on the charge air pressure, which in turn depends on the effective turbine area (size).

Here, ACTUS Match allows the required turbine to be determined while, at the same time, taking into account the amount of fuel required to accommodate the desired engine load. ACTUS Match performs this task directly and with only slightly more overhead than a single standard simulation. Most simulation tools require the use of an external optimization process for such applications, which results in significantly increased run times and complexity for the user. This high computational performance allows ACTUS to be used in a very efficient manner for design studies and optimizations.

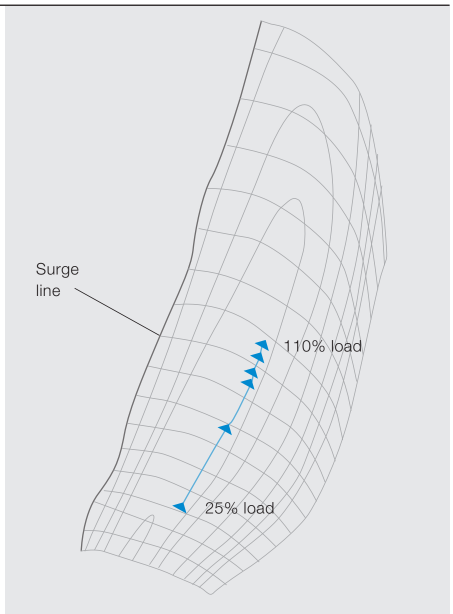
Sales application

ACTUS was introduced in 2012 and is now widely used within ABB. The soft-

4 Typical operating lines for a two-stage turbocharged engine compressor for a power plant application



4a Low-pressure compressor



4b High-pressure compressor

ware has more than 30 users in sales and research departments and at ABB locations worldwide.

A typical use within the sales department is for the selection of an optimal turbocharger specification for a particular engine (in fact, most customers rely upon ABB for this). Starting with key engine data and, if available, measurements from previous similar engines, a simulation model of the engine is constructed. The model is then used to determine the most suitable turbocharger.

For complex engine systems, such as a two-stage turbocharged engine with a turbocharger bypass as a control element, this becomes a complex task. Typically, the engine manufacturer will first define the desired operating conditions for the engine. ABB's task is then to select a compressor and turbine configuration such that the turbocharging efficiency and, thus, the engine efficiency, is maximized. At the same time, the design has to satisfy a series of other constraints such as a given control reserve for the bypass, a minimal distance from the compressor surge line, maximum admissible rotational speeds of the turbocharger and maximum allowable turbine inlet temperatures.

Here, the ACTUS Match feature significantly reduces the throughput time required for the specifications from hours to minutes → 4.

Research applications

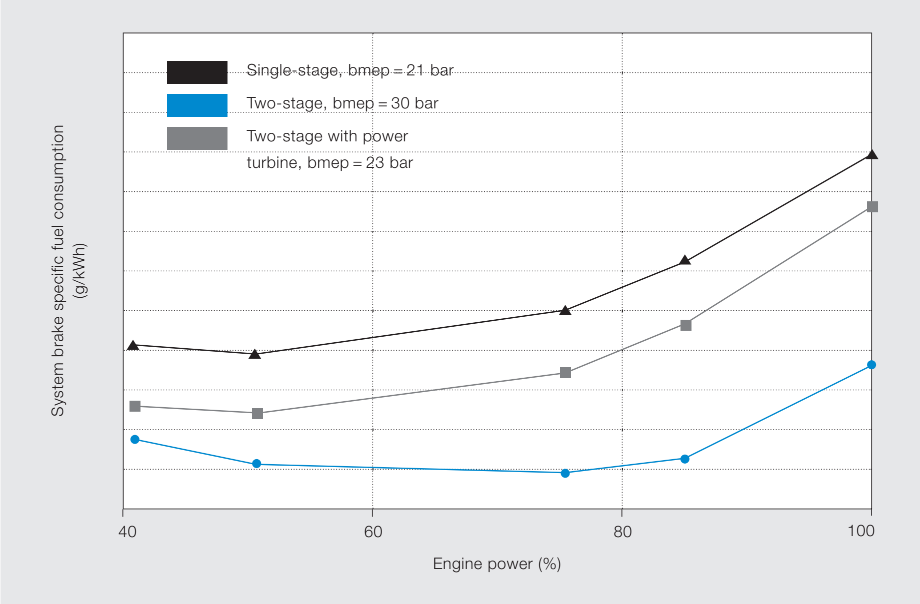
In the turbocharging engineering division, ACTUS is used to investigate new turbocharging concepts and their impact on the combustion engine. A number of these studies were presented at the 27th CIMAC World Congress in 2013 [4,5,6].

One current trend in turbocharging is toward two-stage turbocharging. This allows significantly higher pressure ratios to be used. While the benefits of two-stage turbocharging are well understood for four-stroke combustion engines and several engine manufacturers already offer engines with two-stage turbocharging, the potential for large two-stroke engines is currently not fully understood. In order to gain such understanding, simulation studies were performed showing the potential for total fuel savings at different load conditions [4] → 5.

In the reference case (top curve), the engine is turbocharged by a single-stage turbocharger and a brake mean effective pressure of 21 bar, as is common today. The study shows that by using two-stage turbocharging and either increasing the brake mean effective pressure or employing a power turbine or waste heat recovery system, the overall fuel consumption of the system can be reduced significantly. It should be noted that these results are a prediction based purely on simulation models that have been utilized for the purpose of exploring the potential of future turbocharging

ACTUS is also used within product development to predict design parameters for the next generation of turbochargers.

5 System fuel consumption comparison for different two-stroke engine turbocharging topologies



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options, well before any experimental results would be available.

In addition to the applications described above, ACTUS is also used within product development to predict design parameters for the next generation of turbochargers. ACTUS also features a mode in which turbocharger performance can be evaluated based on measurement data and compared with expected values. Recently, ACTUS was extended so that it can be used to determine the specifications for new two-stage turbocharger test benches at ABB sites. Due to the complexity of two-stage operations, the specification methods previously used were no longer suitable.

Turbocharging the future

The detailed understanding of the turbocharging process and its continuous improvement have always been strengths of ABB. Part of that understanding has been derived from the long-standing tradition of system level simulations of large-bore combustion engines. ABB's new ACTUS simulation tool builds upon that tradition and provides a modern and sound basis for future simulation needs.

As an in-house simulation tool, ACTUS allows very efficient system-level simulations and is highly customized to ABB's specific needs as a turbocharger developer and manufacturer. This allows ABB to continue to support customers in determining the optimal turbocharging solution for their engines and to shape new turbocharging concepts and solutions that enable ABB's customers to further improve engine performance and to comply with future emission legislation.

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References
[1] E. Meier, "Zweistufige Aufladung," Brown Boveri Mitteilungen, vol. 52, no. 3, pp. 171-179, 1965.
[2] M. Ryti, "Computing the gas-exchange process of pressure charged internal combustion engines," Proc. Inst. Mech. Engrs., vol. Vol. 182, pp. part 3L, Paper 11, 1967-68.
[3] E. Codan et al., "Das Programmpaket von ABB Turbo Systems AG für das Design und die Optimierung von Aufladesystemen," in Motorprozesssimulation und Aufladung, Berlin, 2005.
[4] P. Schürmann et al., "Contribution of turbocharging solutions towards improved fuel efficiency of two-stroke low-speed engines," in CIMAC Congress 2013, Shanghai, 2013.
[5] C. Christen and D. Brand, "IMO Tier 3: Gas & Dual Fuel Engines as Clean & Efficient Solutions," in CIMAC Congress 2013, Shanghai, 2013.
[6] M. Kahi et al., "Second Generation of Two-Stage Turbocharging Power2 Systems for Medium-Speed Gas & Diesel Engines," in CIMAC Congress, Shanghai, 2013.