review

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Inspiring tomorrow

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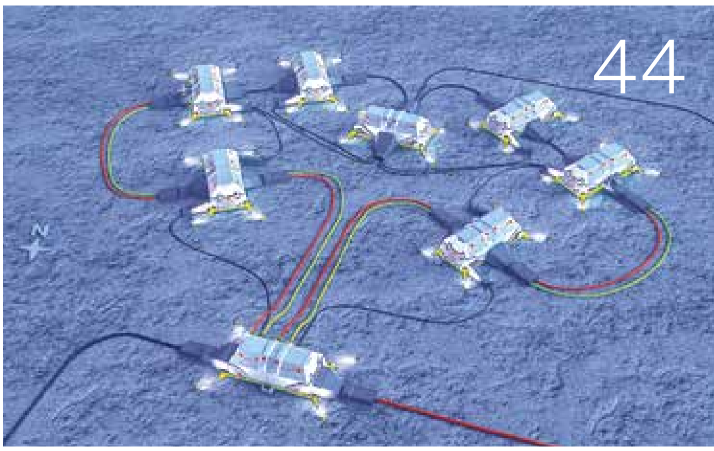

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OmniCore™ robot controller

The theme of this innovation-focused issue is "inspiring tomorrow" because innovation isn't just about coming up with a new or good idea; it requires vision, flexibility, resilience, follow-through, incessant iteration and, perhaps most importantly, a clear and dedicated focus on solving real problems and creating real opportunities. ABB's customer and research experiences provide many of those details so you can be inspired. As always, your feedback is welcome.

abb.com/abbreview

EDITORIAL

Inspiring tomorrow

Dear Reader,

There is saying that if you teach a man to use a hammer, he will treat every problem as if it were a nail. This is even more true of a machine. Classical mass production relies on highly repetitive actions and creates highly uniform products. In the broader world, many problems and requirements are not uniform but variable or even arbitrary. Mass production has often relied on making parameters and requirements artificially uniform (reduced choice for customers), and manual labor has persisted where this uniformity could not be achieved.

In the context of the Fourth Industrial Revolution, production processes rely increasingly on devices and systems that can recognize a very broad range of situations and problems autonomously – and also adapt to them autonomously (or failing that, alert a human). This issue of ABB Review is dedicated to products, services and solutions that lead, enable or illustrate this transition.

Enjoy your reading.

Bazmi Husain
Chief Technology Officer

Innovation highlights 2020

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ABB continues to push the boundaries of what's possible, and then take that further by making it predictably reliable, secure, and cost-effective. From racetracks to factories and shipyards, what's possible is always in the process of becoming what's necessary and doable.

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AI AND ROBOTICS: A FORMULA FOR FLEXIBLE FACTORIES

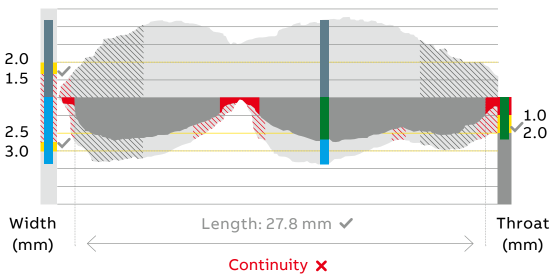
The combination of artificial intelligence (AI) and robotics can substantially improve the flexibility of factory automation by replacing rigid applications with learning capabilities. This powerful mixture of technologies enables the expansion of robot functionalities, thus improving productivity, making work safer and accelerating production. ABB's range of applications in this area includes the use of AI to enable robots to sense and respond to their environment, inspect and analyze defects, and optimize processes autonomously.

For instance, robots equipped with vision sensors can use AI to identify objects regardless of their position, while machine learning algorithms make it possible for robots to determine the best path and gripper positions for picking objects.

AI also enables robots to inspect and analyze a wide range of objects – welding seams are a case in point (graphic) – to detect defects and quality issues. This is achieved through a combination of vision sensors and supervised learning – essentially training by examples.

And when it comes to autonomous process optimization, there's nothing else like the ABB Ability™ Connected Atomizer, the first connected, sensor-equipped, robotic paint atomizer to allow for real-time smart diagnostics and paint quality optimization. By monitoring the condition of key variables such as acceleration, pressure, vibration and temperature, the atomizer reduces internal waste during color changes by 75 percent and reduces compressed air consumption by 20 percent.

ABB is also applying AI algorithms to the analysis of presses and robot behavior in press and stamping lines to minimize equipment waiting times. Using a holistic approach, a control algorithm identifies bottlenecks and manages the start and stop times of robots and presses, thus making lines more stable and predictable. •



ROBOTS: FOCUSING ON FINAL AUTOMOTIVE ASSEMBLY LINES

Automobile production plants are often pictured as highly automated, with lines of robots busily welding bodies. But not all aspects of vehicle production are as technologically advanced. Final assembly is a case in point. Here, the complexity of processes such as cabling, seat installation and cockpit insertion demands dexterous manipulation.

Nevertheless, engineers at ABB are developing techniques that will allow robots to perform a number of initial duties in this area. Probably the most difficult aspect of this challenge is the fact that during final assembly, vehicle bodies are constantly moving linearly. To deal with this, an associated robot is guided by a combination of visual and force control sensors in real time, rather than moving according to a programmed trajectory.

To complete an assembly task in this unstable environment, the first step is that the robot must synchronize with the assembly line's linear movement. This is done by conventional conveyor tracking or by automatic guided vehicle (AGV) tracking technology. AGV tracking, which can also be used in conventional conveyors, is based on real-time vision tracking of high-range, two-dimensional bar codes known as AprilTags. An AprilTag is typically mounted on the AGV-equipped device that is transporting a vehicle while the tracking camera is fixed either in the floor or in the robot foot, when the robot is mounted on a linear axis.

Once a robot has been synchronized with a target vehicle's movement, it starts performing an assembly task while continuously tracking natural features of the target assembly area with an ABB-developed functionality known as Real-Time On-Board Vision that is installed on its gripper. The input from this vision system is combined with continuous feedback data supplied by a force control sensor installed between the robot's wrist and gripper.

The combination of real time on-board vision guidance and force-controlled manipulation (sensor fusion) is the key to successfully performing a given assembly process. Pilot application cases are now in progress in coordination with a major automobile manufacturer. For instance, cockpit assembly is currently underway in German and Chinese plants. Experience gained in these and other facilities is potentially highly applicable to other automotive assembly applications, as well as to other manufacturing environments characterized by continuously moving targets. •

ABB EXPANDS AZIPOD® POWER RANGE FOR FERRIES AND ROPAX VESSELS

Since its launch in 1990, Azipod electric propulsion has become the industry standard for a wide range of vessels, from small craft to icebreakers. In response to customer requests, ABB has filled the gap between the low- and high-power Azipod propulsors with the launch of a new series available in the 7.5 to 14.5 MW range. In addition to ferry and RoPax (roll-on/roll-off passenger) vessels, this power range is also relevant for larger offshore construction vessels, midsize cruise ships and shuttle tankers. With this addition, the Azipod propulsion family now flexibly covers the power range of 1 to 22 MW.

At the core of the new midpower range are ABB's latest fourth-generation permanent-magnet motors, which draw on proven Azipod propulsion technologies but which have been refined to increase power and maximize efficiency. The design simplicity of the propulsion system provides increased robustness and reliability and makes maintenance easy.

Additionally, this "M" series of Azipod propulsion is tailored to provide operating benefits for ferry and RoPax owners and operators. For example, the new series is designed for low onboard height, which allows the Azipod system to be located under the car deck of RoPax vessels so no deck space is taken up and vehicle movement is unhindered.

Based on the straightforward, robust and easy-to-maintain design principles that have seen Azipod propulsion selected across 25 vessel types over close to three decades, the latest midpower series comes to market at a time when ferry and RoPax ship owners face increased pressure to improve energy efficiency and cut emissions. •

OMNICORE™ ROBOT CONTROLLER NOMINATED FOR THE IERA INNOVATION AWARD

ABB's OmniCore™, a new generation of robot controllers designed for the flexible factories of the future, has been shortlisted for the 2019 Invention and Entrepreneurship in Robotics and Automation (IERA) award. Considered one of the most important competitions in the robotics industry, IERA recognizes companies and inventors who turn innovative ideas into market-changing products. The award is presented by the International Federation of Robotics (IFR) and the IEEE Robotics and Automation Society.

ABB's robot controllers are already recognized for their best-in-class path accuracy and cycle times. In developing OmniCore, ABB built on these characteristics while creating a new controller that significantly increases manufacturing flexibility yet is future proofed for developments in the digital manufacturing age.

Thanks to its high level of flexibility, OmniCore gives customers the ability to produce an increasingly diverse mix of products in smaller lots while maintaining productivity.

Featuring "Power-on and Connect" and ABB Ability™, OmniCore can be connected to advanced services that increase performance and reliability, while offering easy connections to a variety of fieldbus protocols, as well as vision and force control systems for complete solutions. OmniCore includes cyber security enforcements to prevent data loss, thereby closing the loop between connectivity, data and control. It also includes SafeMove2, an ABB software solution that transforms industrial robots into collaborative robots capable of safely working alongside humans while remaining productive.

Despite all these advanced features, OmniCore is simple and intuitive to use and is accessed through a newly designed FlexPendant human-machine interface with a simple touch screen for visual programming. •

SUBSEA ELECTRIFICATION SYSTEM ENABLES THE OIL AND GAS INDUSTRY TO TAKE THE DEEP-WATER PLUNGE

In 2013, ABB and its joint industrial partners, Equinor, Total and Chevron, began an expansive project to design and test a complete subsea electrification solution for the oil and gas industry. To enable operations at remote locations in ultra-deep waters, ABB developed modular equipment – components and assemblies – that integrate to form a subsea electrification system.[1] The system consists of variable speed drives (VSDs) switchgear and a protection and control system for the transmission, distribution and conversion of power to subsea pumps and gas compressors at a peak capacity of 100 MW to water depths up to 3,000 meters; and with transmission distances up to 600 km with lifetime requirements for up to 30 years. Topside area is freed, power supply demands and greenhouse gas emissions are reduced.

Adopting a pragmatic step-wise approach to equipment design, ABB successfully ran simulations, laboratory and field tests to ensure every component, sub-assembly and assembly met qualifications according to Technical Readiness Level (TRL) stages defined in DNV RP-A203 and API 17F Standard for Subsea Production Control Systems.

Satisfied with individual device results, shallow water tests (SWT) were conducted: a prototype of a medium-voltage VSD, was operated in a protected harbor test site for over 1,000 hours[2], with impeccable results.

In June 2019, a second SWT was run – this time for 3,000 hours – of a prototype of the entire electrification system: two VSDs in parallel configuration with switchgear and controls. Results of this test and all previous qualification accomplishments ensure system reliability under harsh subsea conditions. This successful SWT test, completed in November 2019, lets the oil and gas industry know that this electrification solution is ready-for-use in the remote subsea environment. •

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Footnotes

1) Stimulated your interest? There is more to read in this issue about the system, its design and qualification on p.44, "ABB's subsea technology is powering the seabed for a new energy future".

2) Please refer to "Setting a course for subsea power conversion facilities" for an in-depth article about the technology, design and functionality of the subsea variable speed drive (VSD) on p.50.

ULTRAFAST HIGH-CURRENT DC BREAKER BASED ON POWER ELECTRONICS

DC distribution systems often need very fast fault protection that simultaneously provides protection selectivity, high survivability and reconfigurability after a fault. ABB has now developed a power-electronics-enabled solid-state DC circuit breaker (SS DCCB) with extremely low conduction losses, high power density and ultrafast reaction time that meets these protection challenges. The high-current SS DCCBs are rated for nominal currents of 1,000 A to 5,000 A, at an operational voltage of 1,000 V DC, and can interrupt a prospective short-circuit current of several hundreds of kA, up to 1,000 times faster than electromechanical circuit breakers.

ABB's SS DCCB is based on the parallel connection of silicon reverse-blocking integrated gate-commutated thyristors (RB-IGCTs) that were developed in-house by ABB. The solid-state breaker can be cooled with water for high power density or, alternatively, with advanced two-phase cooling, which delivers the simplicity of air cooling with a performance close to that of liquid cooling and ensures low installation and maintenance costs and long asset life. Power losses are 70 percent lower than comparable power-electronics solutions.

With all-electric ships becoming more popular, DC onboard power distribution is attracting a lot of attention thanks to its ability to handle large power flows in a confined space with high system efficiency and low life cycle cost. The SS DCCB is perfect for such marine applications and it is there that the device will be used initially. This is the first ABB breaker that is ready to be integrated straight into any DC ship distribution system. A modular architecture, simplified hardware and digital interfaces ensure maximum flexibility.

The new breaker is ideal for numerous other areas too, such as DC microgrids, battery energy storage systems, data centers, electric vehicle charging infrastructure, etc. First commercial application is planned for this year. •

ANOMALY DETECTION APP HELPS ROBOTS REDUCE DOWNTIME

Everyone knows what an anomaly is… right? Well, if all the buttons on your shirt match except for one, that's pretty obvious. But when it comes to separating real alarms from false alarms generated by factory robots, things can get tricky.

A branch of machine learning, anomaly detection focuses on detecting and identifying discrepancies that significantly deviate from the majority of other observations in large data sets or data streams. Such discrepancies, if repeatedly detected and localized, can provide an early warning of malfunctions or confirmation of an event that may require human attention.

By using an historical approach to a huge amount of data, ABB software engineers have developed a statistical path to understanding the event distributions for individual robots in factory environments and obtaining robot status information in real time while each robot is in operation. The approach is designed to show anomaly scores in robot fleet dashboards, generate event alarms automatically, be proactive and predictive in executing maintenance activities, reduce downtime, avoid micro stops and, ultimately, maximize overall equipment effectiveness (OEE).

The idea is to create a tool that customers can use to manage physical parameters' data as well as robot-generated alarms and events on an aggregated basis with a view to obtaining robot status updates, together with score trend graphs that might indicate future issues and a way to quickly identify the root causes of problems.

The tool will be offered by ABB as a machine learning-based application and it will be part of the latest generation of ABB Ability™ Connected Services. •

EC TITANIUM INTEGRATED INTELLIGENT MOTOR AND DRIVE

As its name suggests, ABB's new EC Titanium integrated intelligent motor and drive combines both motor and variable-speed drive (VSD) into one easy-to-install package. The EC Titanium is aimed at 1 to 10 hp applications and incorporates the latest advances in motors and drives into a highly efficient, compact and connected solution.

A ferrite-magnet-assisted synchronous reluctance (FASR) motor design was chosen as low losses mean these motors can cost-effectively reach an efficiency class of IE5. An easy-to-install design and high power density (twice that of induction motors) are further benefits.

An integrated VSD allows customers to match drive speed to process requirements and operate equipment at its most energy-efficient point, thus extending lifetime, saving energy and making conformity to efficiency regulations easier. There is a high total system efficiency at full load. At partial load, where many customers operate, efficiency can be 16 percent better than with an equivalent induction motor.

Other benefits for pump and fan applications include reduced inventory requirements as different flow rates are available from the same package. Further, integrated products lower costs through part reduction and simplified purchasing and assembly. The EC Titanium offers customers multiple connectivity options (hard-wired, RS485 or Bluetooth). Moreover, the drive acts as a sensor for the motor/drive package and a Smart Sensor for Motors can be added to measure additional performance parameters. Once connected, data can be sent to the ABB Ability™ platform where software with advanced algorithms analyze the information and detect anomalies for condition monitoring and predictive maintenance. •

3RD GENERATION PICK-AND-PACK SOFTWARE CUTS COMMISSIONING TIMES FROM DAYS TO HOURS

How can manufacturers respond efficiently to demands for mass customization and shorter product life cycles? Increasingly, the answer is digital twin technology, which allows customers to test out configurations on virtual production lines before physical lines are modified or built.

With this in mind, ABB Robotics has launched the third generation of its PickMaster® software for robotic picking and packing applications.

The software is the market leader for easy configuration of complex robotic actions and has set the industry benchmark for simplifying robot integration in vision-guided random flow picking, packing, and material handling for more than 18 years.

Equipped with digital twin technology for the first time, the software shortens commissioning times from days to hours and cuts change-over periods from hours to minutes. It offers greater flexibility and improved visualization of the cooperation of multiple robots, thus achieving optimized flow results without product losses or incomplete packages in flow-wrapping, tray loading, case and carton packing and handling applications.

As the software enables the offline programming of picking and packing tasks, users can create, simulate and test a complete robot installation in a virtual environment without interfering with their actual production lines. Using digital twin technology, the picking process can be optimized in the virtual world in real time while the real process acts accordingly. This not only helps customers mitigate costly and time-consuming risks, but also shortens the time to market for new products, as product lines can be installed faster and ramped up to full speed without surprises during commissioning.

PickMaster® also offers a modern operator interface for the factory floor, giving operators and plant managers full insight and control of production results. Compliant with the PackML industry standard, it integrates seamlessly with other packaging machinery as well as with production and factory planning systems.

PickMaster® is available in a multitude of configurations and can work seamlessly with all ABB robots, as well as with a range of virtual and physical machines. It is best suited for factories and production lines where higher output, faster response times and quick changeovers are vital. •

A200-H – THE NEW BENCHMARK IN SINGLE-STAGE TURBOCHARGING

ABB’s flagship single-stage turbocharger generation, the A100-H, currently leads the single-stage turbocharging field with pressure ratios up to 5.8, an efficiency of up to 66 percent and brake mean effective pressure (bmep) of up to 22 bar. For higher bmep, ABB’s Power2® two-stage system fits the bill. For an application with a bmep of between 22 and 24 bar, two-stage turbocharging is potentially too complex.

To fill this gap between single- and two-stage turbocharging, ABB has developed the single-stage A200-H, with a pressure ratio up to 6.5 and a peak turbocharger efficiency in excess of 69 percent. The A200-H enables single-stage turbocharging on high-speed gas engines with a bmep of approximately 24 bar while increasing engine efficiency compared to the A100-H.

The A200-H turbine has been matched to the compressor to obtain the highest possible turbocharger efficiency while meeting the mechanical requirements. Further, with a view to future peak-shaving applications with many start-stop cycles, housing stress has been minimized.[1]

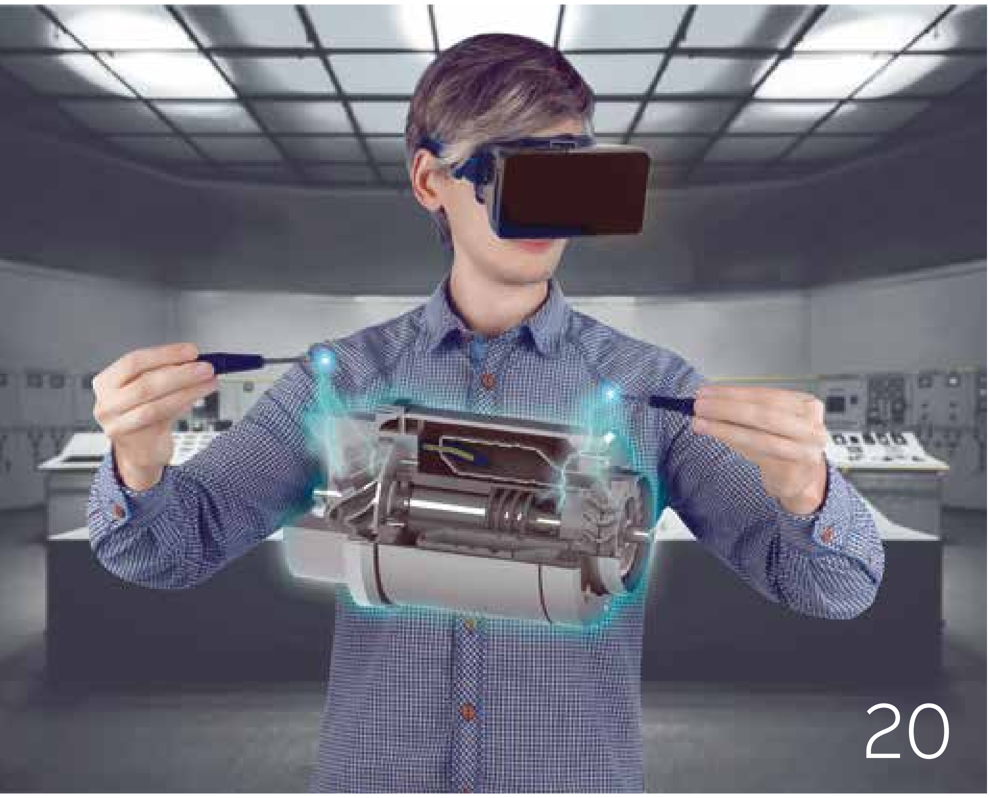
For the first time, the customer can choose between two bearing concepts: a patented bearing module design that supports ABB’s plain bearings or newly developed and highly efficient ball bearings, which, at part load, have a power loss of around 15 percent that of the plain bearing option. These new bearings reduce time-to-full-load by 15 percent.

Monitoring of turbocharger speed and temperature, start-stop cycles, ambient conditions and other parameters will be introduced using turbocharger-integrated sensors or by accessing genset data. These rich data sources enable an exposure-based component life assessment and can, for example, enable rotors to exceed the runtime predefined by more rigid conventional approaches. •

Footnotes

1) For more information on the A200-H turbocharger, please also see “A200-H – the new benchmark in single-stage turbocharging” on pages 56-61 of this issue of ABB Review.

Digital future



More than any technologies of the past, digital tools transform entire economies and cultures. Those effects, and how they feed back into the use of those tools, requires new, innovative ways of thinking about how companies operate overall. ABB has inspiring thinking on that topic.

20 The future of industry: digital transformation
24 Rethinking innovation for the Fourth Industrial Revolution
30 OPC UA and TSN: enabling Industry 4.0 for end devices
36 Stepping up value in AI industrial projects with co-innovation


ABB

DIGITAL FUTURE

The future of industry: digital transformation

Industry stands at the cusp of unprecedented change. Digital society will bring with it fundamental changes in the way industry is organized, in customer-supplier relationships, and even in the way employees are educated.

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Industries are under pressure to fulfill demands for higher productivity and ever shorter product life cycles. At the same time they must follow the trend towards mass customization as well as meeting increasingly exacting environmental protection and compliance standards. They must also deliver ongoing performance gains in digital functionality such as communication, data analysis and presentation. All this is causing upheavals in global value chains as well as profound structural changes in industries. To remain competitive in such a disruptive environment and be able to offer highly customized products in the smallest lot sizes in a cost-effective and sustainable manner, industries need an ecosystem powered by highly connected, data-intensive digital solutions and services: Industries need a digital transformation.

Digital technology improves connectivity, compatibility and collaboration, making the manufacturing and process industry more flexible, productive and efficient than ever. Industry's digital transformation – along with all of its many forms, including the Fourth Industrial Revolution, the Industrial Internet of Things, Industry 4.0, China 2025 and so on – will not only optimize individual manufacturing or process steps, it will also revolutionize global value chains and ecosystems. ABB is a leading provider of solutions in these areas, many of them offered under the brand ABB Ability™.

A prerequisite for the digital transformation is the connectivity of assets such as tools, machines, materials and employees along the value chain →01. This creates a link between the real, physical world and the connected, digital world. But none of this would be possible without standardized communication protocols and data formats as well as hardware interfaces. ABB is represented in leading standards development organizations worldwide.

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Digital technology improves connectivity, compatibility and collaboration, making industries more flexible, productive and efficient than ever.

When assets understand the meaning of information because they use the same terminology, they also understand messages they exchange between themselves and can respond accordingly. This creates the conditions needed for them to interact autonomously and perform the required tasks. Using advanced methods such as industrial artificial intelligence is one of the research and development areas ABB focuses on as part of its efforts to autonomize industries.

The digital twin, a digital copy of a physical asset, is one element of the digital transformation. It enables industries to dramatically shorten the time required for development, production and testing and cut prototype and production ramp-up costs. Having consistent data along

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Title picture.
ABB's dual-armed Yumi robot has taken robot-human collaboration to new heights.

01

the entire asset lifecycle is a prerequisite for the successful use of digital twin technology. The asset itself can be a product, system or factory. A digital twin can be used to improve the details of a product or optimize specific areas along the value chain.

Data integrity and cyber security measures ensure that data processed along the value chain remains complete and unaltered. This is the only way to glean the desired process optimization information from the data.

The idea is to make work easier for people in today's operations, not to make them redundant. On the contrary, autonomous systems perform dull, dangerous or exhausting tasks and make decisions in areas where human intervention is not required. Decisions are only truly autonomous when these systems are able to make the right decisions in situations they have not been taught (programmed) to handle →02.

Automation can create high-quality jobs for people. However, in order to be better prepared for the jobs of tomorrow, even well-equipped countries must re-think their education and training concepts according to a study ABB commissioned. ABB is already preparing for the future by creating "digital workplace environments" and providing employees with intensive training courses in digital automation tools. ABB is also active in university education. For example, the company established the "Jürgen Dormann Foundation for Engineering Education" in 2007. The foundation awards scholarships to electrical engineering students around the world who demonstrate excellent academic performance and require financial resources to continue their studies. The ABB Research Award in Honor of Hubertus von Grünberg was established in 2016. It offers recipients a $300,000 research grant and is presented every three years.

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The digital twin enables industries to dramatically shorten the time required for development, production and testing.

Beyond interoperability between the various elements and rising autonomy, the digital transformation also seeks to achieve a higher degree of sustainability. Digital technologies can help reduce the climate burden. ABB created its "Mission to Zero" slogan to promote climate protection and has already achieved significant results. ABB currently generates over half of its revenues with eco-friendly products and systems; and the trend is rising. Building automation

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01 Humans and machines are working together, in ever closer collaboration. Virtual reality tools support decisions and facilitate access to information in applications as diverse as field maintenance and product design.

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02 By scanning the QR code of this ACS880 drive, this field technician gains instant access to a wealth of data.

products in the private and commercial sectors facilitate energy optimization and convenient control of electrical equipment. Energy savings of up to 30 percent can be achieved thanks to the digital transformation.

ABB has consolidated many digital transformation solutions for industries under the brand ABB Ability™ and is constantly expanding its range of products and services that build on a state-of-the-art platform. The portfolio currently comprises around 200 solutions that can be specifically tailored to customer needs in the company's Customer Experience Centers.

Ready for the transformation
The digital transformation of industries comes in many different forms. The term itself is the lowest common denominator for the wide range of transformations currently taking place. The digital transformation encompasses initiatives and concepts such as the Fourth Industrial Revolution, the Industrial Internet of Things, Industry 4.0, the Industrial Internet Consortium, China 2025 and many others. Communication on the individual initiatives and concepts should always be paired with information on how they are embedded in the digital transformation. •

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ABB is already preparing for the future by creating "digital workplace environments".

02

DIGITAL FUTURE

Rethinking innovation for the Fourth Industrial Revolution

How can innovation processes be transformed to make the best possible use of the Fourth Industrial Revolution's potential? How can companies identify domain- or technology-specific issues that can be replicated across sites or domains with the objective of revolutionizing whole industries? The author of a new book on tomorrow's technologies and business strategies explains.

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With the advent of the Fourth Industrial Revolution and the increasing speed at which products and entire markets are changing, operational excellence has become more business critical for all organizations than ever before. In a world in which development and deployment are a continuous process, development models and practices based on update-and-maintenance cycles of months or even years have become inadequate. Hence, the Fourth Industrial Revolution demands a paradigm shift in terms of bringing new products, technologies and solutions to market in such a way as to enable them to keep pace with expectations.

Companies need to identify domain- or technology-specific issues that can be replicated across sites or domains.

In this context, an important buzzword is solution development. Many business leaders enthusiastically announce that they plan to digitize their plants or transform their organizations from product companies into solution providers. But why all the hype? Isn't that what engineering is all about? When it comes to keeping pace with or even staying ahead of the expectations curve, the real challenge is not solution development, but problem identification. To put it bluntly: a business must define the problem before it can propose a solution. And in the context of the Fourth Industrial Revolution, that means figuring out how new technologies may be able to offer competitive advantages over traditional ones →01. This is the road to identifying value for plant operators and new revenue streams for industrial product and service suppliers.

But that's easier said than done. What may sound like exciting new productivity stimulating digital strategies when announced at board meetings can quickly turn into run-of-the-mill responses when translated into concrete assignments. By the end of the day, what's actually delivered is standard solutions that ignite only a few horsepower worth of pull for existing products and services under the umbrella of digital solutions. Furthermore, many such assignments end up being applicable to only very specific areas and are not scalable.

Photo fig. 02: ©istockphoto.com/Traimak_Ivan

02

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01 Wilhelm Wiese is the author of a new book that focuses on the Fourth Industrial Revolution. This article is based on a section of that book. ISBN 978-1-6871-4652-6, by Wilhelm Wiese, 2019.

—
02 Industrial processes require finding correlations among hundreds of variables. A new analytics module developed by ABB uses Big Data to uncover suspicious patterns in order to accurately predict unwanted events.

Pseudo digital solutions of this ilk can indeed be good for business and can indeed make plant operators happy, but they neither unleash step changes in productivity to improve the bottom line nor do they create new revenue streams for solution providers that can significantly improve the top line. To take a meaningful slice of the predicted multi-billion-dollar potential of the Fourth Industrial Revolution, companies need to challenge current technologies. Therefore, they need to start from the shop floor to identify domain- or technology-specific issues that can be replicated across sites or domains with the objective of revolutionizing whole industries →02.

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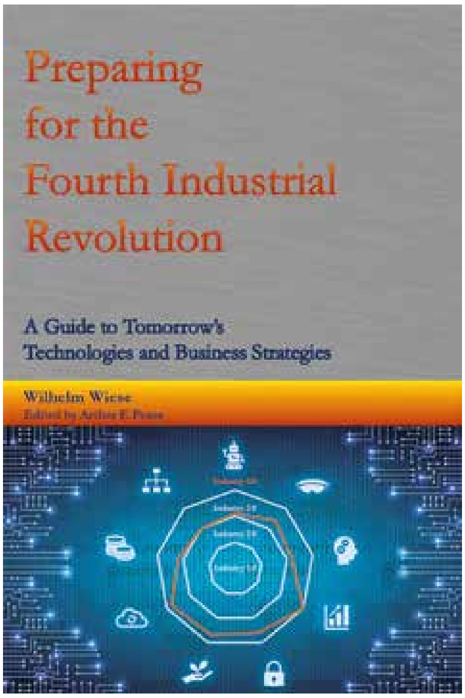
Intrinsically ill-defined or tricky, wicked problems are far from being something to shun. Indeed, they can hold vast promise.

Hence, any solution development must start by identifying the problem statement and the value of a solution. Only after completion of the second step, should an organization initiate the innovation process and evaluate in what ways



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new Fourth Industrial Revolution technologies can be disruptive and add value for its customers' businesses.

The vast promise of wicked problems

Where should this overall process begin? A good starting point is the core of today's very popular design thinking process. A five-phase description of this process is described by Plattner, Meinel and Leifer as: "(re)defining the problem, need finding and benchmarking, ideating, building, testing." [1] The process may also be thought of as a system of overlapping spaces rather than a sequence of orderly steps: inspiration, ideation, and project implementation may loop back through each other more than once as a team refines its ideas and explores new directions.

Design thinking is especially useful when addressing what Horst Rittel and Melvin Webber referred to as "wicked problems," which are problems that are ill-defined or tricky [2]. Far from being something to shun, such problems can hold vast promise. Indeed, the real danger lies in limiting our thinking to well-defined problems because these tend to cause us to come up with solutions that are based on standard rules or current technical knowledge.

	Known to self	Not known to self
Known to others	Shared	Blind spot
Not known to others	Hidden	Unknown

03a

	Known to solution provider	Not known to solution provider
Known to industry	Incremental Low business potential Low risk	Low hanging fruits High business potential Low risk
Not known to industry	Hypothetic Low business potential High risk	Wicked High business potential High risk

03b

To create a picture of what wicked problems are in terms of decision-making processes in the context of the Fourth Industrial Revolution, it is helpful to adapt the Johari window →03a [3].

Originally created by psychologists to support self-help groups, the Johari window can help guide users to the identification of heretofore hidden problems, and thus put them on the road to the identification of novel solutions. As →03b indicates, the window can be subdivided into four key solution areas, the first of which is incremental solutions. For example, if a problem is known to you as well as to others in an industry, then you can expect that it will probably be solved soon with today's technologies or with some incremental changes.

> Potentially the fuel of the Fourth Industrial Revolution, solutions to wicked problems stand the highest chances of being hugely successful.

The second area is low hanging fruits. Here, problem statements are known to industry experts such as plant operators, who are aware of an improvement opportunity, but a solution provider does not yet know about it. This area can be addressed in customer workshops, often called co-creation workshops, where solution providers start understanding the challenges faced by plant operators and can bring in their technical experts to come up with a solution. The resulting exchange of information is designed to crystalize into well-defined problem statements that have a good chance of providing solutions that can, in turn, be replicated and scaled up.

The third area is hypothetical problem statements. Here, risks are high because the solution provider might have to invest a lot of money in development with no certainty of success since the solution is not considered to be critical or does not add enough value.

Finally, we come to the fourth area: wicked problems. These are – potentially – the fuel of the Fourth Industrial Revolution. Here, the level of risk is obviously high because the innovation process is complex, and some ideas are sure to fail; but solving wicked problems will be disruptive, which means that the resulting solutions stand the highest chances of being hugely successful.

— 03 Originally created by psychologists to support self-help groups, the Johari window can help managers identify hidden problems and thus reach novel solutions.

03a The Johari window can be subdivided into four key solution areas.

03b The Johari window applied as problem statement map.

— 04 A typical batch reactor.

04

How ABB licked a wicked problem
Recently, ABB addressed a wicked problem in collaboration with a key customer in the chemical industry [4]. The problem was that the customer's plant operator was occasionally faced with unexpected foaming in their batch reactions →04. In the chemical and pharmaceutical industries, the term "batch process" refers to the execution of several production steps to generate a final product according to a stringent recipe. The foaming caused product impurities so serious that a batch that required seventeen hours to produce had to be discharged and recycled. In addition, this resulted in many unproductive hours to clean tanks and pipes.

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Disruptive changes in solution development open the door to the implementation of new Fourth Industrial Revolution technologies.

Batch processes target products that follow a high-quality standard. Nevertheless, given the number of variables involved, no two batches are identical. Factors such as the quality of input materials, batch size, temperature, humidity and other environmental factors can interact to create anomalous circumstances. What's more, managing the production process itself often includes hundreds of process variables with complex interrelations.

Given these factors, detailed batch monitoring is an essential part of understanding and managing this highly dynamic process. But in this case, although the customer had a vast amount of data available, it was not equipped to link the data from more than 100 process variables from several hundred batches with other production data such as raw material specifications, power consumption and process variable measurements.

Working closely with the customer, ABB deployed experts who applied Big Data analytics to determine the root cause of the problem. Their work uncovered suspicious patterns, such as power consumption peaks as well as steam flow anomalies. Finally, they co-invented a prediction concept capable of producing highly accurate early warnings circa 30 minutes before foaming is likely to occur.

Throughout this collaboration the team used ABB's BatchInsight →05, a product that combines techniques from business intelligence, classic data analysis and machine learning to support process experts in holistically analyzing batch processes.

Concretely, what does this example tell us? Clearly, it illustrates that disruptive changes in solution development open the door to the implementation of new Fourth Industrial Revolution technologies that can play a major role in identifying wicked, ill-defined problems. This process can then be followed, for example, by an artificial intelligence-based root cause analysis to derive solutions nobody has thought of before. All that's needed in order to start digging deeper into data and technology is an initial hunch!

But even hunches need a trigger. So, a good starting point is to begin visiting your plants and asking whether there are any productivity or quality issues that managers have not been able to explain. That's where you'll hear plenty of hunches. From there, one can apply various interrogative techniques, such as an Ishikawa diagram [5] to explore cause-and-effect relationships. The key factor in applying this iterative interrogative technique for analyzing wicked problems is to not look for their root cause. The technique is applied to define the scope of the data that is needed in order to collect and to determine which technology should be applied to find a cause-and-effect relationship that is not detectable with the data and knowledge about this data that's in people's heads. This boils down to a three-step →06 approach.

The first step is about scoping, where the target is to find data that might correlate but which was not considered in this context before. In the second step, the latest technology, such as machine learning or artificial intelligence, is applied to the data to obtain new insights about possible root causes. The third step is about developing a solution. And here's where things really get exciting. Solution development for wicked problems typically begins with several proof-of-concept studies based on building models or digital twins. These are essential because the outcome of machine learning algorithms is associated with a given level of probability that needs to be proven before an implementation in a real industrial process can be performed.

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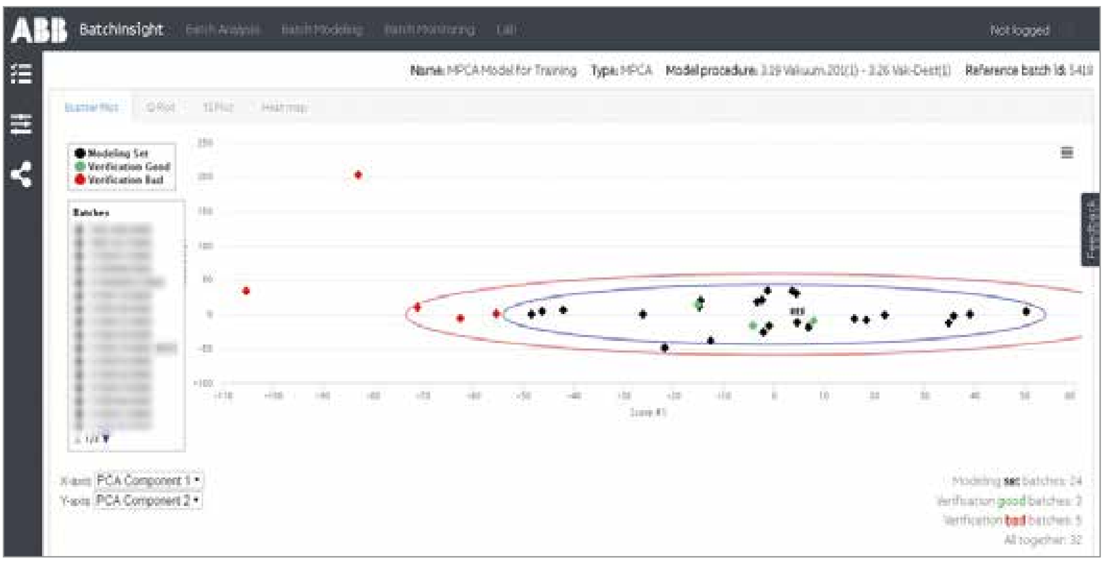
Solution development for wicked problems typically begins with proof-of-concept studies based on building models or digital twins.

Can any plant operator, system provider or device manufacturer do this alone? Probably not. But an excellent problem-solving model is to break this process down in three steps: Why-What-How →07, with the latter distinguishing between how problems are solved in a traditional way and how they should be solved in a collaborative manner to be disruptive.

Solving wicked problems through co-invention

Starting from the 'Why', a deep understanding of the customer's needs, goals and differentiators



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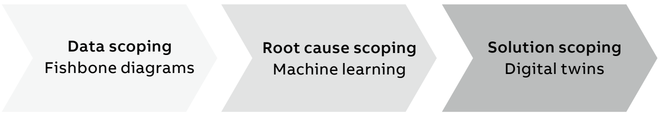

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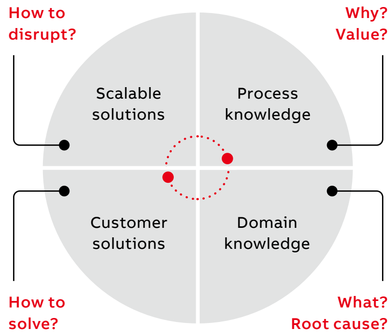

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05 The BatchInsight data analytics module combines techniques from business intelligence, classic data analysis and machine learning to support process experts in holistically analyzing batch processes.

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06 Solution process for wicked problems.

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07 Co-invention is the key to successfully solving wicked problems.

should be the foundation of the common solution process. Without this, one runs the risk of merely implementing technical fixes and partial solutions rather than the solution itself. In other word, the team needs to understand the target plant's production processes, value chain and how this impacts plant productivity and the features of the produced products.

Only after developing a clearly defined problem statement is it time to apply domain knowledge and the latest technologies such as Big Data analytics or machine learning to identify the root cause of the problem and thereby "What" needs to be changed.

The third step is to address "How," which is the core of the paradigm shift from collaboration to co-invention. This is essential because the objective is not to apply an immediate fix for one specific plant or operation area, but of applying Fourth Industrial revolution technologies such as artificial intelligence and autonomous system concepts to making a disruptive change to plant productivity or the features of the produced products that can be replicated in all of the customer's plants or even scaled up for a whole industry.

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Co-invention to solve wicked problems will unleash the potential of new technologies and accelerate industries to new levels of productivity.

All in all, developing solutions for today's wicked problems offers a high probability of unleashing the potential of many new Fourth Industrial Revolution technologies. Furthermore, the application of solutions to industrial environments will continuously prove and improve machine learning capabilities. Finally, this process will rely on the ability to pre-evaluate solutions, which will require the creation of ever more digital twins. These will, in turn, generate the data that will be the foundation for and accelerate the development of tomorrow's autonomous systems. In other words, co-invention to solve wicked problem statements will unleash the potential of new technologies and thereby accelerate industries to a level of productivity that is hardly imaginable with today's technology. •

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DIGITAL FUTURE

OPC UA and TSN: enabling Industry 4.0 for end devices

OPC UA and IEEE TSN are game-changing fundamental elements of Industry 4.0 that can revolutionize industrial automation capabilities, from the field device up to enterprise level. How well do the ubiquitous, and sometimes resource-constrained, devices of today’s automation landscape cope with these new technologies?

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Title picture. OPC UA and TSN promise to change the face of industrial data collection and processing, such as in this photovoltaic-panel manufacturing plant.

ABB sees Industry 4.0 playing a vital role in the future of industrial automation. Two important elements of Industry 4.0 are OPC UA and IEEE TSN.

OPC UA (open platform connectivity and unified architecture) is the next generation of OPC. OPC UA removes many of the shortcomings of OPC and is a more flexible and secure way to handle data. OPC (OLE for process control, where OLE stands for object linking and embedding) goes back to a software interface standard that allows Windows programs to communicate with any compatible industrial hardware device. OPC works in a server/client mode. The beauty of OPC is that it is an open standard, which means that a hardware manufacturer need only provide an OPC server for their device and it can then easily communicate with any other OPC client. The problem of vendor-specific protocols, interfaces, etc. is then solved in one fell swoop. OPC UA can better cope with the volume and complexity of today's data world – a challenge that could not have been foreseen by the developers of OPC.

IEEE TSN (time-sensitive networking) is a set of IEEE standards that provides deterministic networking for OPC UA at lower levels. TSN and OPC UA combined have the potential to not only replace, but also outperform [1] existing fieldbuses. Nowadays, both these technologies claim to be available on the market, at different levels of readiness.

Enabling end devices with OPC UA and TSN can be challenging when those devices are resource-constrained. ABB recently investigated the performance of typical end devices when faced with OPC UA and TSN implementation. In the project, several software and hardware platforms were evaluated to develop three proof-of-concept implementations for different ABB product prototypes. These devices were enabled with OPC UA, then Extended Automation System 800xA and TSN system integration were compared. The question was: "Is the Industry 4.0 concept capable of leveraging deterministic networking and enhanced data access with TSN and OPC UA, and can these new mechanisms be integrated into products to provide broader capabilities and better performance?"

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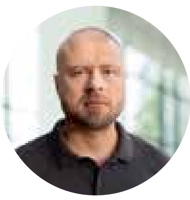
OPC is a software interface standard that allows Windows programs to communicate with any compatible industrial hardware device.

New concepts in industrial automation
Nowadays, the world of industrial automation faces new concepts, such as data analytics, cloud access, edge computing, etc. These concepts have information at their heart: its acquisition, retrieval, representation, processing and distribution.

Process-relevant data originating on devices, on a factory production line, for example, may need to be preprocessed, filtered and communicated to the cloud for management presentation and analytics. Currently, raw production data is often retrieved by fieldbus technologies, which use proprietary specifications both for the data semantics and transport. To access the process data, one needs gateways specific to the particular fieldbus to bridge data and



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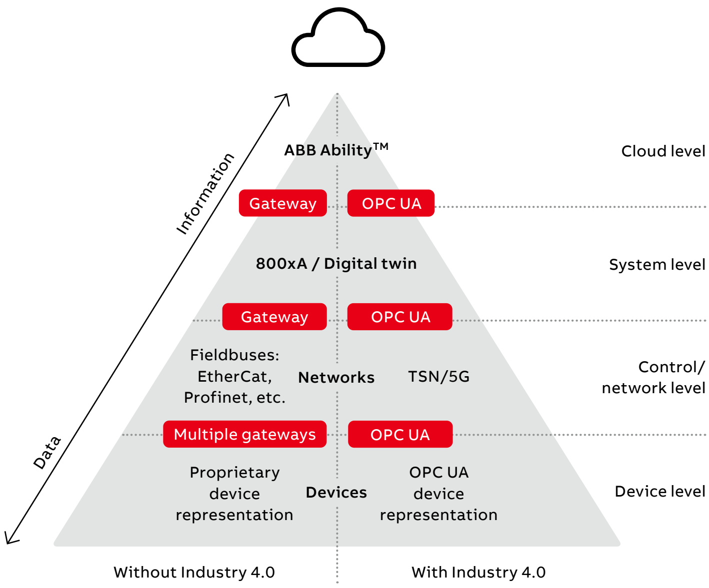

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transport formats. However, OPC UA can unify the information models for all system devices to provide enhanced and transparent data access, using TSN as transport means →01. Such an arrangement also provides powerful semantics to represent device business logic and the transparent client-server communication that can connect the factory floor to the cloud.

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Another positive aspect of OPC UA and TSN is the shift from a proprietary and custom world to a unified and standard one.

Apart from vendor-specific interfaces and protocols, other challenges can arise at the production line level. For instance, demanding applications, such as motion control tasks, need high performance and determinism in the data transport between devices. The fieldbus technologies that were designed decades ago struggle to meet today's requirements. TSN can outperform [1] the existing fieldbuses and allow for future growth in high-performance data transport.

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01 Automation pyramid with and without Industry 4.0.

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02 OPC UA and TSN can unify information models and provide a data transport that is deterministic.

In summary, the requirement to not just unify enhanced information models but also to provide deterministic data transport poses a serious challenge for existing system architectures. Industry 4.0 suggests this challenge be addressed using IoT mechanisms, such as OPC UA and IEEE TSN. While TSN can provide the low-level data transport, OPC UA can serve as an IoT enabler for higher-level applications. A combination of these two technologies can provide two features vital for the future of industrial automation: a fast and robust data transport, and a client-server combination for elaborate device semantics →02.

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A combination of these two technologies can provide a fast and robust data transport, and a client-server combination for elaborate device semantics.

Another positive aspect of the adoption of OPC UA and TSN is the shift from a proprietary and custom world to a unified and standard one. An evident advantage here is the unification of the software, interfaces and access models across product ranges. Furthermore, OPC UA and TSN enable the unification of development expertise between businesses, which may eliminate the existence of duplicate or redundant expertise in a bundle of various narrow fields.

Not all plain sailing

Though OPC UA and TSN may bring new capabilities and improve performance, open questions remain:

- Is the market ready to move from the proprietary (but known) in favor of standard and open (but new)?
- How to ensure a smooth evolution of the technology into the new paradigm?
- Are there any pilot solutions enabled with TSN and OPC UA? And what technologies and strategies are needed to fit OPC UA and TSN into a system?

When deciding in favor of adopting Industry 4.0, a system builder should first answer several questions. For instance, “does the system really need all the capabilities and features of OPC UA and TSN?” Not every application requires deterministic networking or low communication latency. Thus, the scope of TSN adoption will, most likely, vary: Cloud-level interaction typically would not require TSN and, in some cases, neither would field sensors. Similarly, not all end devices need elaborate semantics and uniform accessibility of data.

The second of the three questions listed above concerns integration of OPC UA and TSN into existing system design and management tools: What mechanisms should be used and how should they be unified? These are not trivial questions, given the diversity of multivendor systems and the respective tooling.

Once the decision to support OPC UA and TSN is made, the most pressing questions could be summarized as follows:

- Where does the system require new technology and to what extent?
- How would OPC UA and TSN fit into the system architecture and how should they be configured?

It is important to consider that each system starts (or finishes) at the end device. These ubiquitous devices often have limited resources. Historically, OPC UA was not used in devices with computing power, memory, or power supply that was constrained. Furthermore, full TSN support requires specific hardware to provide real-time capabilities. How much enhancement would the end device need to support the new technologies? What exactly has to happen to prepare end devices for Industry 4.0 and the IIoT? Enabling such resource-constrained devices with OPC UA and TSN can be the most challenging implementation aspect of all.

OPC UA and TSN enablement for ABB end devices

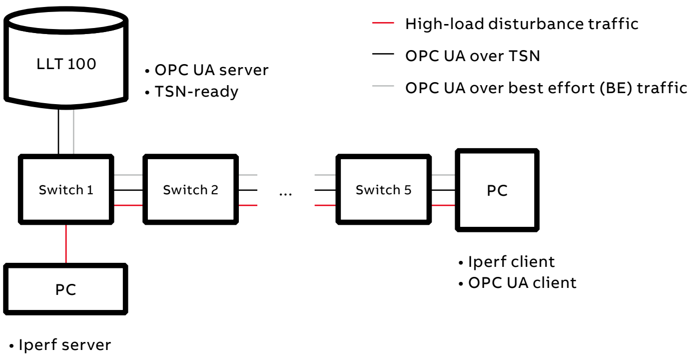
In ABB, a cross-competency team enabled OPC UA for three end devices: an ABB FCB400 Coriolis mass flowmeter, an ABB LLT100 laser level transmitter and an ABB UMC universal motor controller. The detailed description of the OPC UA enablement will be covered in detail in a later article.

During the OPC UA evaluation, the team tackled the TSN enablement for the three prototypes, using third-party infrastructure equipment. The test setup uses several TSN switches (from TTTech), two industrial PCs and the ABB end-device prototypes →03. The test setup is configured using the prototype software, combining the legacy command-line tools with new technologies such as NETCONF (Network Configuration Protocol) and YANG, a data modeling language.

With time-aware shaping (TAS) of traffic , TSN switching infrastructure can offer real-time data exchange, with up to microsecond precision.

However, resource-constrained end devices often cannot match the data transmission times to the microsecond-granular forwarding windows on the TSN switches. To evaluate the consequences under such circumstances, this scenario was tackled in the first steps of the TSN evaluation.

The assessment focused on the application requirements, such as the duration of the control cycles (1 to 5 ms) and the quantity of data exchanged (typically, a read-write operation on several variables). The first phase of the project evaluated the latency and jitter of the OPC UA traffic in scenarios with different traffic loads. The application synchronization and system integration for TSN will be the focus of the second phase of the project, which will be reported in a future article.



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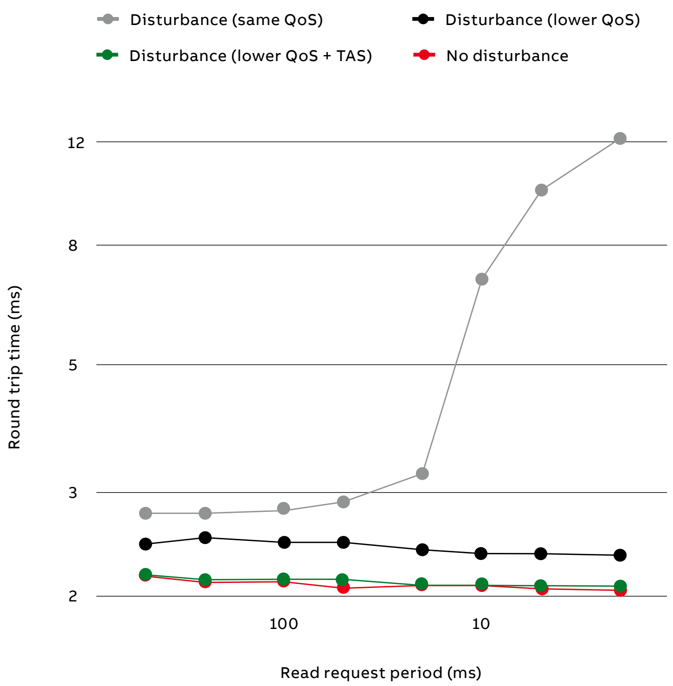

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Results and spin-offs

The TSN enablement evaluation showed that the latency of the OPC UA data exchange can be significantly reduced and bound to a narrower spread. →04 shows the difference in latency for OPC UA read requests to and from the embedded OPC UA server (in this case, the LLT100) in a network where 95 percent of the throughput is consumed by disturbing traffic and with particular reference to the quality of service (QoS). It indicates that even just the introduction of QoS reduces latency despite the high-throughput disturbance traffic. QoS in TSN switches can distinguish messages based on eight priority levels to ensure that important messages are sent first. With TSN mechanisms such as time-aware traffic shaping, OPC UA latency further shortens and becomes more stable. Clearly, even basic TSN support on the end device software improves the determinism in data access, using TSN-ready infrastructure.

The TSN evaluation showed the latency of the OPC UA data exchange can be significantly reduced.

The software concepts developed within the project will evolve in the second phase of TSN adoption, which will focus on automated end device integration in TSN-enabled systems.

The IIoT Device project enabled new device prototypes with OPC UA. Indeed, product development has already started for some of the target devices. Another bonus is that the research project has made available tools and best practices for OPC UA enablement. For instance, an automated code generator that translates the development artifacts (such as device description files) into C-based code ready to be compiled and loaded onto the device for use with an OPC UA server. Another example is the Device Integration (DI) model guidelines that help developers from different areas to represent the device business logic in a standard and functional manner.

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03 TSN evaluation test setup. The high-throughput disturbance traffic was generated using Iperf-2.0.5, a widely used network testing tool.

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04 OPC UA read request latency with disturbing traffic in TSN networks.

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05 Industry 4.0 will play a vital role in the future of industrial automation. ABB is helping efforts on both OPC UA and TSN that will harmonize and standardize Industry 4.0.

A game-changer for industrial automation
TSN-ready switches that deliver the expected determinism in networking are already available on the market. OPC UA client-server software is also available as a product that is ready for integration. The OPC UA PubSub extension, which is more relevant for high-performance applications, is expected soon. According to the OPC Foundation [2], "PubSub enables further adoption of OPC UA at the deepest levels of the shop-floor where controllers, sensors and embedded devices typically require optimized, low-power, and low-latency communications on local networks."

ABB end devices can already be enabled with basic TSN support today. Full TSN support, including hardware, can be provided in the foreseeable future. The full system integration of TSN is still largely an open question: Switch vendors do not aim at solutions for full system integration, but rather add-on modules for network configuration. Automation vendors and system integrators such as ABB hold the know-how for the automation systems, own engineering tools and possess the relevant expertise to decide on the scale of TSN application and integration →05. Therefore, automation vendors, network equipment manufacturers and system integrators continue the joint work to create standard integration mechanisms for TSN that can be adopted throughout the industry.

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ABB representatives are actively driving the respective standardization efforts on both OPC UA and TSN.

To grow into a widely adopted technology paradigm, the basic elements of Industry 4.0 needs to be harmonized and standardized. ABB representatives are actively driving the respective standardization efforts on both OPC UA and TSN. The standardization community is drawing in more and more actors with new considerations that, in turn, bring new features that need to be harmonized with the previously defined ones. Unification at such a scale requires considerable effort. Progress, however, is evident and becomes more and more prominent. •

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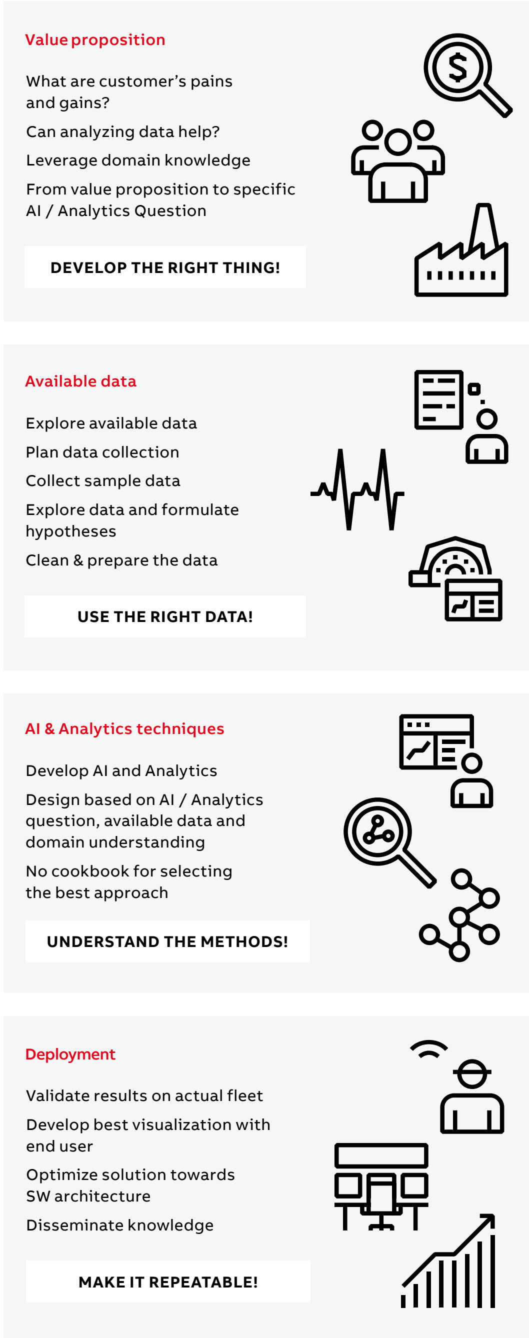
DIGITAL FUTURE

Stepping up value in AI industrial projects with co-innovation

ABB developed a four-step co-innovation approach for analytics and artificial intelligence projects. Leveraging engineering domain knowledge and data science expertise, the approach allows ABB, partners and customers to create advanced analytics and artificial intelligence solutions together.



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01 ABB's 4-step co-innovation approach for advanced analytics and artificial intelligence.

Advanced analytics and artificial intelligence (AI) applications are gaining traction in industrial automation, thereby enabling higher levels of autonomy [1-2]. Nevertheless, AI is complicated, and combining it with automation does not in and of itself generate higher value to a project: Additional value requires focus, high-level skills and enough reliable data. When advanced analytics and AI are applied to relevant well-defined opportunities, considerable additional value can be unlocked as an integral part of an end-to-end solution. The right set of data science expertise, clear domain understanding and engineering knowledge working in concert can ensure this value. Collaborative research and development, where knowledge and expertise are shared and leveraged can underpin this process. With the right experts and experience available, ABB has developed a standardized co-innovation approach to orchestrate this essential collaboration.

Advanced analytics and AI, applied to well-defined opportunities, unlock value as an integral part of an end-to-end solution.

Loosely based on the CRISP-DM approach [3], ABB's new four-step systematic approach has been adapted to run co-innovation projects in advanced analytics, machine learning and AI with partners and customers. While this approach is described as a four-step approach, it is, in practice, an iterative process as knowledge and understanding generated during the collaboration leads to further ideation. ABB's experts have, over the past few years, implemented this process with customers across a gamut of industries, eg, chemicals, automotive and utilities, to focus, use and generate quality data to deepen value of advanced analytics and AI projects [4-5].

Four steps to value: co-innovation
The co-innovation scheme defines processes and objectives in well-structured steps so that automation providers and customers can know where they are and where they want to be at any given time during a project →01.

- Co-innovation step 1: identification and value proposition articulation
- Co-innovation step 2: data inspection and collection
- Co-innovation step 3: AI and analytics modelling
- Co-innovation step 4: deployment

Step 1: Beginning with the identification phase, face-to-face workshops with customers and ABB stakeholders identify "pain points", or problems and issues, relevant stakeholders and then develop a value proposition – the promise of a value or perceived value to be communicated, delivered and acknowledged. The industrial AI problem is thus formulated.

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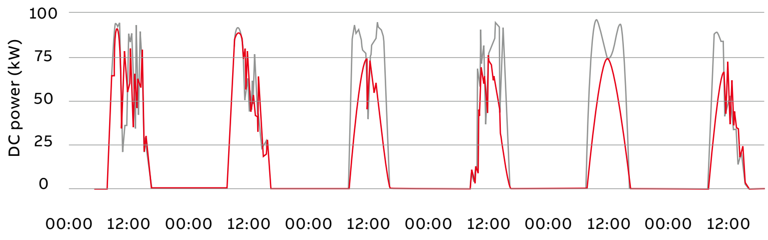
Step 2: Access to the right data with the right quality is paramount to the success of advanced analytics and AI development projects. Data inspection and collection ensures these needs are met.

First, domain and data scientists identify the data needed to address the industrial AI problem through day-long workshops or interviews, thereby facilitating knowledge-sharing.

Second, the suitability of data already available is assessed. Missing data is identified. The experts also consider how fusing heterogeneous data from a variety of sources (eg, signal data, alarm and event data, business data) might also support the realization of the value proposition.



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If data quality or quantity is insufficient, a data collection campaign can be planned, additional sensors installed, or data from a non-obvious source can be substituted for missing data [6].

Step 3: ABB's AI modelling experts begin this phase by exploring the data and preparing it for modelling. Remaining data quality issues are detected and treated [7], correlations are identified, features are designed and hypotheses are generated. Lessons learned from this phase are used to fine-tune the industrial AI problem.

The 'Train-Validate-Tune Test Cycle' is initiated next. Here, the data scientist designs and trains data-driven models, corroborates the model on a validation data set (or in cross-validation) and refines the model hyper parameters or re-engineers features as needed. These approaches vary from purely data driven, such as neural networks, to models based predominantly on the laws of physics, and include everything in between. Hybrid approaches are developed to leverage the strengths and mitigate the weaknesses of each individual model. By combining domain and data science expertise, the design of the model is guided: from properly defining model inputs, outputs and structure to selecting the appropriate modeling approach and defining a cost function that accurately quantifies the performance of the model.

Upon validation, the model is tested on a new data set, one that the algorithms have not been trained on. Furthermore, model interpretation tools are used to investigate the reasoning within black box models like random forests or artificial neural networks.

Mock-up user interfaces, based on real data and predictions, are created early on, thereby boosting modeling and workflow evaluation. And, by continuously sharing results and knowledge with stakeholders and customers during this phase, ABB receives crucial feedback to improve the model.

Step 4: During the deployment phase, the data pipelines and machine learning workflows from the AI modeling phase are operationalized. An in-place system is required for retraining the machine learning models (eg, retraining on request, scheduled or based on some event). A software system is used for running the scoring of the machine learning model and making the output available to the user.

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ABB implemented the four-step approach with customers across a gamut of industries, eg, chemicals, automotive, and utilities.

Together with the customer, ABB decides how to deploy the AI solution, eg, as a web dashboard, integrated in existing software on-site or perhaps as a virtual assistant.

Use case: performance monitoring in a solar power plant

ABB's four-step research and development approach has been successfully deployed to create an advanced analytics solution for industrial automation in utility and process industries, among others.

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02 The algorithm correctly distinguishes a failed tracker (red) from a normally operating system (gray).

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03 ABB's e-mesh™ digital solution will incorporate the final co-innovation AI solution as an additional software solution on top of the base solution to monitor, optimize and improve the performance of distributed energy resources.

In one case, ABB's co-innovation approach helped domain and data science experts from the power grids and electrification businesses and research and development teams in Poland, China, Sweden, Switzerland and Germany deliver an innovative customer advanced analytics solution to monitor the performance of photovoltaic plants. The four-step solution for a solar plant is given below.

Step 1: Condition monitoring systems can increase uptime and yield, and ultimately decrease the life-cycle costs of a solar production plant. However, the distributed and modular nature of solar plants presents challenges. The remoteness of such plants and their typical unmanned operational set-up compounds these challenges. As a result, operators require very accurate and cost-effective monitoring systems that relay the current performance and health of a plant and pinpoint the root cause of any potential problem.

Step 2: The costs associated with installing, configuring and maintaining an independent condition monitoring system, with tailored high-end sensors, cabling and communication requirements, would quickly and adversely impact the value derived from any monitoring system. However, as a provider of advanced industrial digital technologies, ABB was also acutely aware that solar plants already use significant acquisition and storage systems, eg, SCADA systems, remote terminal units, inverters and maintenance management systems. Drawing on domain knowledge of photovoltaics, power electronics, automation and condition monitoring applications ABB evaluated the usefulness of this data relative to the value proposition to properly formulate the analytics task.

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ABB's co-innovation approach helped customer expert teams deliver an advanced analytics solution to monitor the performance of photovoltaic plants.

Step 3: Seizing on comprehensive domain knowledge and strong analytics fundamentals, ABB scientists designed and implemented advanced methods to solve the analytics task: inputs, outputs and cost functions of data-driven models for components within a plant were properly formulated. The resulting system is able to extract meaningful actionable insights from the data →02, eg, degradation rates, fault diagnosis and root cause analysis.

Step 4: A holistic solution was developed by contemplating all analytics steps from data ingestion, through data cleaning to model preparation and deployment. By considering the user experience throughout the process, ABB could increase comprehension and transparency. Currently the development is included as an application aspect of e-mesh™ Analytics Suite, and will be an application that runs on ABB Ability™ e-mesh™ Monitor digital solution →03, which builds on the cloud-based digital platform that aggregates data from distributed energy assets. The novel solution is easy-to-deploy and scalable, while providing a single location to obtain business insights from multiple assets.

Use case: predictive maintenance for standard rotating equipment
ABB also applied the co-innovation method to develop a solution for performing predictive maintenance of rotating equipment in a process plant →04 [8-9].

In this case, customer stakeholders, including plant managers, operators and reliability engineers collaborated with ABB data scientists, rotating equipment asset experts and design-thinking practitioners to create a value proposition to enable predictive maintenance for rotating equipment. There are typically numerous low voltage motors and pumps present in such a plant. Equipment breakdown for this type of equipment and consequent unscheduled maintenance activities are much costlier than a planned maintenance activity. Due to the number of such devices, it is not feasible to manually record data and analyze the health state of each device so, they are usually run to failure, thereby resulting in high overall asset replacement costs.

Step 1: The final value proposition was formulated: 'Safeguard operations against unscheduled breakdown of standard pumps within the next two weeks'. This was translated into an analytics task: Predict if a pump will fail within the next two weeks and, if yes, why will it fail.

—

Together with customer stakeholders, ABB developed a solution for performing predictive maintenance of rotating equipment in a process plant.

Step 2: The data inspection yielded the result that the data, which was already collected, was insufficient for the analytics purpose. Condition monitoring systems were only deployed to large, higher-value pumps. And yet, lower-cost devices

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04 Applying the four step co-innovation approach to condition monitoring and predictive maintenance capabilities of rotating machines allows customers to operate their plants more efficiently.

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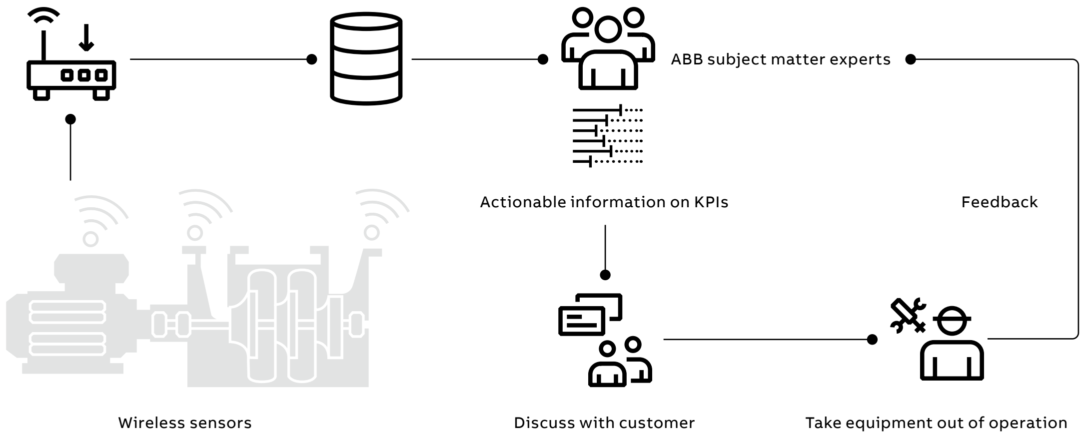
05 The AI solution for standard rotating equipment allows operators to predict pump failures within the next two weeks.



05

can also significantly impact maintenance costs. These devices were not monitored to the same extent. The customer identified, with the support of ABB, a pilot plant to install ABB's wireless sensing technology to generate the required data. ABB set up a suitable data collection infrastructure so that ABB's data scientists could also access the data.

—
Data scientists and domain experts, customers and stakeholders working together and sharing knowledge adds value to the automation process.

Step 3: ABB's data scientists and asset experts analyzed the incoming data and could identify indications of potential faults →05. Cases in which symptoms of faults were identified were immediately shared with the customer who was able to investigate and confirm the detected problems. With data samples from healthy systems and confirmed failure cases, ABB's data scientists were able to train a deep learning model that satisfactorily predicts if a pump would fail within the next two weeks.

Step 4: The research work on predictive maintenance for standard pumps will become part of the ABB asset performance portfolio: a value-added service offering in which ABB's asset experts and customer maintenance managers monitor equipment that is supported by ABB's artificial intelligence algorithms [9].

Be part of the co-innovation process

Relying on their novel 4-step framework to support collaborative research and development, ABB could efficiently develop tailored industrial AI solutions for multiple clients. Data scientists and domain experts, customers and stakeholders working together and sharing knowledge adds substantial value to this endeavor. ABB invites its customers and partners to collaborate with their data scientists and domain experts to experience this illuminating process for themselves and to adapt it to their specific project needs. •

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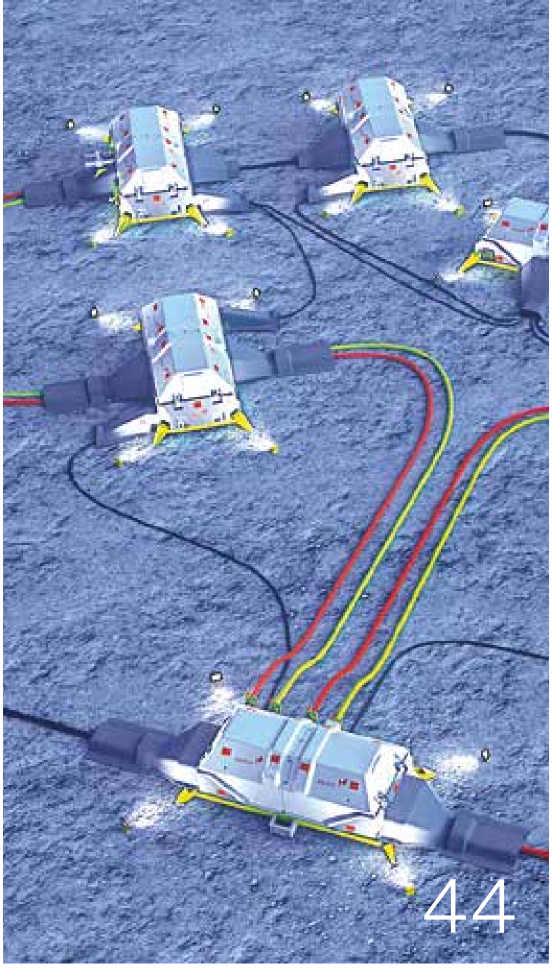
Extreme performance

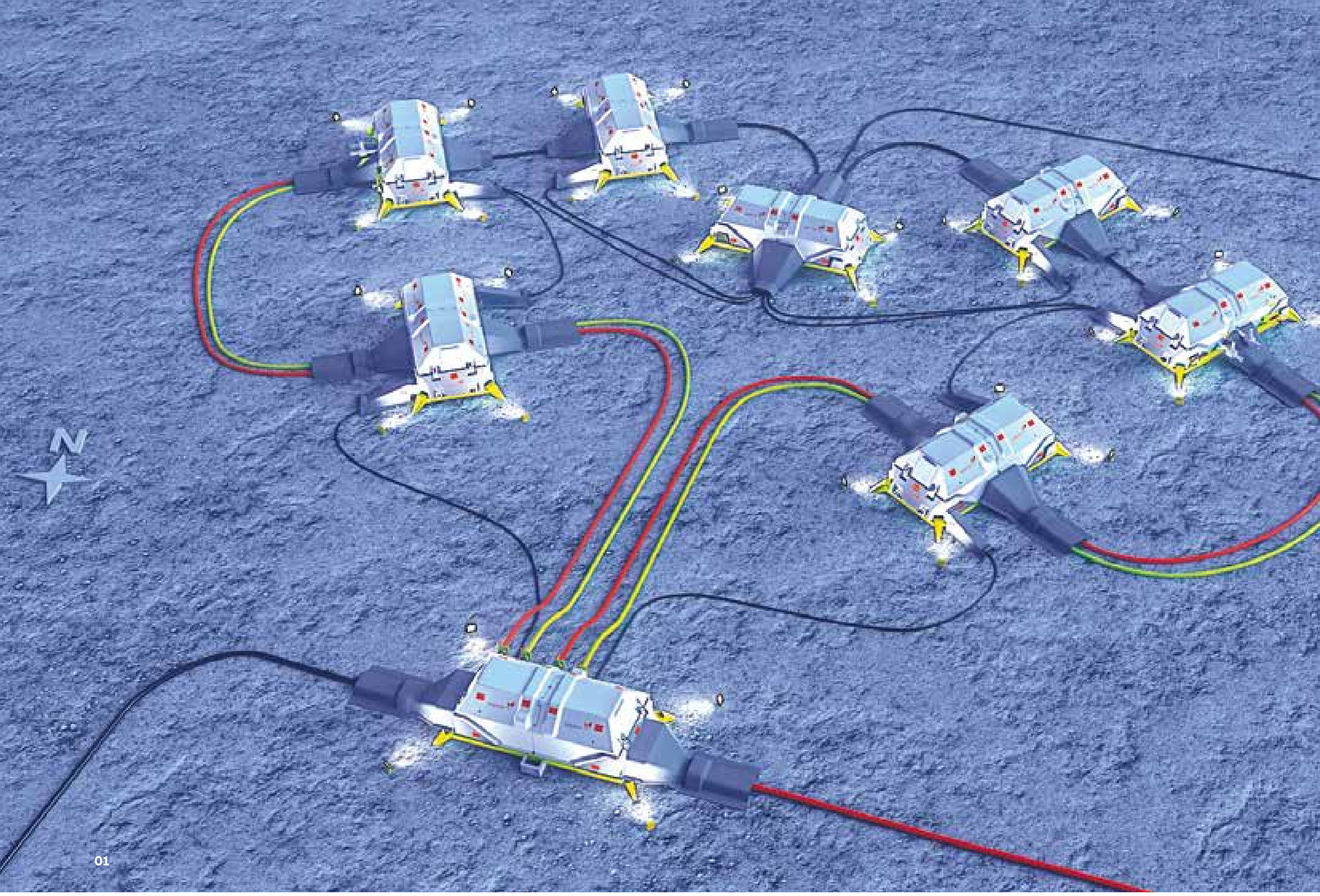


Innovating at the bottom of the ocean is about as dangerous and difficult as it gets, which makes it quite literally a test bed for technologies that enable remote operation and oversight. Lessons learned there can be applied in other places, too.

44 ABB's subsea technology is powering the seabed for a new energy future

50 Setting a course for subsea power conversion

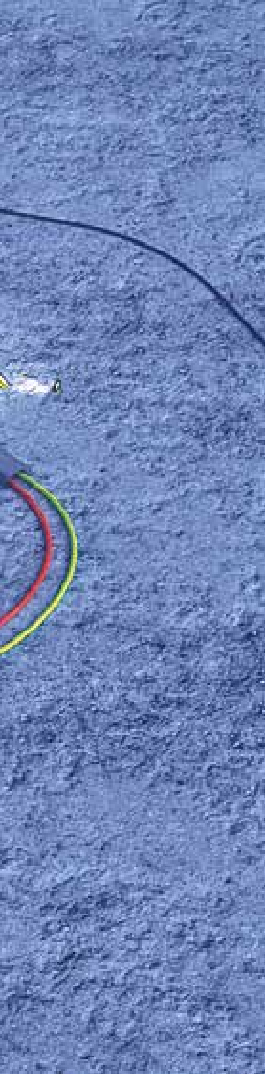
56 A200-H – the new benchmark in single-stage turbocharging


01

EXTREME PERFORMANCE

ABB's subsea technology is powering the seabed for a new energy future

The new ultra-reliable modular design and qualification of ABB's unique electrification system means that production in remote deep waters is more possible now than ever before. The flawless real-world test results show that the system is ready to enter the depths and that a complete subsea production factory is on the horizon.



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01 Artist's rendition of a subsea power and boosting layout from an Equinor case study.

The world's demand for energy in the form of fossil fuels persists even as the availability and accessibility of mature oil and gas fields diminishes [1]. To meet this demand, international oil and gas operators are moving into ever more challenging and remote environments, into ultra-deep waters [2]. While previously too formidable and expensive to consider, the development of new smart, reliable and cost-efficient technologies can support the oil and gas industry's ability to produce in the remote subsea environment and remain profitable. Advances in subsea electrification solutions for power transmission, distribution and conversion could one day allow an entire oil and gas production facility to be located on the seafloor, thereby enabling upstream companies to explore and exploit deeper, scarcer and more remote reservoirs →01. But before this can occur, industry requires highly reliable equipment that is virtually maintenance-free because the costs of retrieving equipment from the seafloor for repair would be prohibitive.

It is with this vision that ABB initiated a US$ 100 million Joint Industrial project (JIP) with Equinor (formerly Statoil), Total and Chevron with support from the Research Council of Norway in 2013 [3]. Relying on their preeminent position as the world's electrification and automation leader, ABB has completed the development of an electrification system for transmission, distribution and conversion of power, to subsea pumps and gas compressors, at a peak capacity of 100 MW, to water depths up to 3,000 meters, with transmission distances up to 600 km; and with little or no maintenance for up to a lifetime of 30 years – a major step toward achieving a subsea factory.

The downside of topside installations
Nowadays, offshore hydrocarbon production facilities typically rely on power generated locally by gas turbines located topside, from a fixed or floating platform (or more commonly from multiple platforms) or from ships. For subsea purposes, power is transported to equipment via multiple cables located close to power consumers, such as pumps and compressors, on the seabed: so-called long step out solutions. Topside installations require continual maintenance, complicated logistics and support; and rely on power generation that emit excesses of greenhouse gases – a costly endeavor.

The ability to distribute, transmit and convert power, subsea, over great distances at depth reliably, would be a game-changer for the oil and gas industry. By installing such electrification systems close to the load, space and weight are reduced on topside facilities, response time to wellheads is lowered, power supply demands are reduced and greenhouse gas emissions are mitigated. ABB has therefore brought its technical expertise to this expansive project, the completion of which is key to the future realization of an entire seafloor factory.

—
Subsea electrification solutions could one day allow an oil and gas production facility to be located on the seafloor.

Rigorous design eases subsea electrification
ABB has used a ground-breaking design approach to develop a flexible, modular electrification solution based on their tried-and-trusted technologies:
- Subsea variable speed drive (VSD)
- Subsea medium voltage (MV) switchgear
- Subsea control and low voltage (LV) distribution

ABB drew on their expertise and experience in subsea power, having introduced the world's first subsea transformer in 1999, to develop equipment that is versatile, robust, powerful and reliable. A deep understanding of the electrical and thermal properties of the equipment, as components, sub-assemblies and assemblies under extreme stress conditions has been essential for the success of this project.

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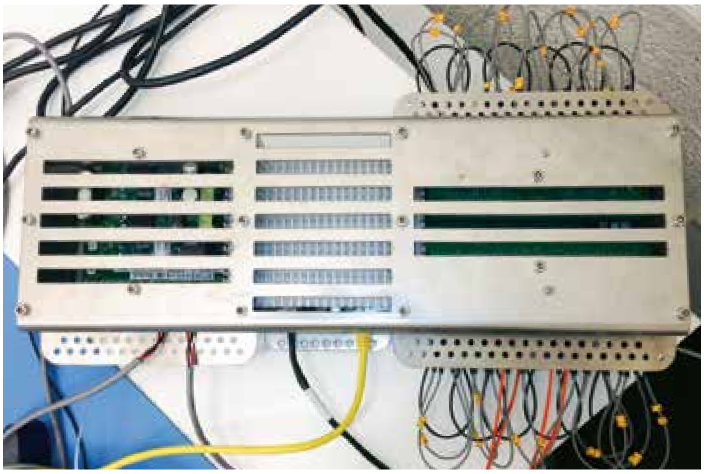

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02b

Considering these demands, ABB implemented a rigorous qualification scheme and relied on the recommendations and Technical Readiness Level (TRL) stages defined in DNV RP-A203 for components, equipment and assemblies in hydrocarbon exploration and exploitation offshore. Requirements for topside systems and equipment, API 17F Standard for Subsea Production Control Systems, including thermal, vibration and pressure tests as well as accelerated lifetime testing and Equinor's own requirements: TR3025 (eg, system design margins and equipment immunity levels) were deployed. This systematic project and design approach, along with deep-interaction with field experts from the JIP partners, allowed design changes to be identified and improvements made early on, thereby securing reliability within specified limits for successful risk management. In this way, the oil and gas industry will have the confidence they depend on that all developed technology is ready-for-use in the most challenging ultra-deep environment.

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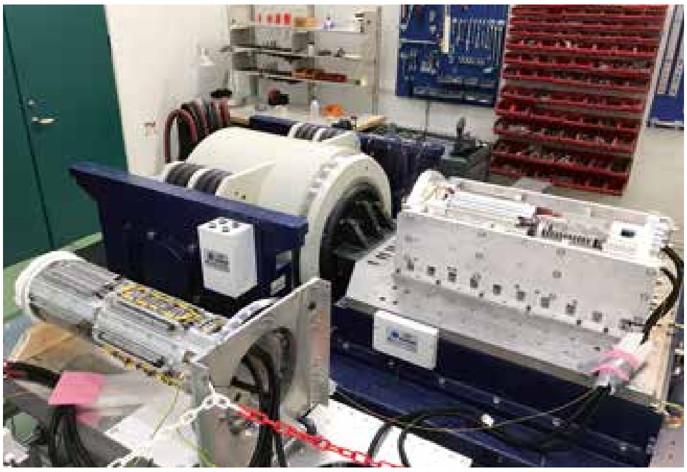
ABB's system delivers power over a distance of 600 km to seabed power consumers on the seafloor at peak water depths of 3,000 m.

Qualification is king: the subsea electronic module

The subsea control and protection system is the brains of the overall subsea power solution and consists of main assemblies for power distribution, conversion, auxiliary supply and control of electric power supply. The new system must deliver power over a distance of up to 600 km to seabed power consumers placed on the seafloor at peak water depths of 3,000 m – something which has never been done before.

This gargantuan challenge was addressed by adopting a pragmatic, step-wise approach to the design of all equipment and systems, including the control system, from concept phase to system testing phase →02-03. Procedures were created to learn the behaviors and limits of materials, parts, components, devices, sub-assemblies and assemblies. Simulations, laboratory and field examinations enabled cyclical design modifications to be made following tests and re-tests →02. For instance, control devices were tested in hard to access environments to replicate remote subsea conditions. At times, under the harshest of environmental test conditions intermittent test deviations were recorded that disappeared once these conditions ceased. To capture the conditions that led to the perturbations, experts collected device data during testing and performed root causal analysis afterward. By relying on this ability to learn through design/test iterations, ABB could correct even elusive design problems and meet all qualifications for components, sub-assemblies and assemblies. This process led to the qualification of the assembled Subsea Electronics Module (SEM) prior to near-real-world field testing →03.



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02 The control components were designed, tested, modified and re-tested. Two stages are shown:

02a An early design stage is shown.

02b The final qualification test of the controller. Product design was invaluable for the development of the final prototype and product.

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03 The final SEM PEC prototype, shown here on its mounting chassis, fulfilled environmental requirements designed by the oil industry in the standards API17F, ISO 13628-6 and Statoil standard TR1233v7.

VSD design and qualification
Drives are at the heart of the subsea power solution; these devices control the speed and torque of subsea motors for seawater injection, boosting and compression applications on the seabed. Hence, VSDs were constructed to be modular, compact, robust and ultra-reliable – maintenance-free for up to 30 years[1].

The drive converts power to a variable output voltage ranging from 2.3 kV to 7.2 kV or more. The operating frequency range is limited to 200 Hz, except for high-speed compressor loads below 5 MVA. An output filter is integrated into the VSD to ensure that the power quality and voltage transients remain within motor and cable tolerances.

An integrated drive transformer is powered by the subsea switchgear at the rated supply voltage (11-33 kV), with either a standard supply frequency of 50/60 Hz or an impressive low frequency of LFAC $16\frac{2}{3}$ Hz. This allows power to be transmitted by one cable over remarkably long distances, up to 600 km.

ABB's VSD modular design can be scaled to operate a range of subsea motors with apparent powers up to 18 MVA. So, even the largest seabed compressor can be powered by two drive units in parallel configuration →04.

The VSDs (and MV switchgear) are enclosed in oil-filled, pressure-compensated tanks; the oil acts to insulate and cool the power components.

Based on a robust cell-topology with power semiconductors and built-in redundancies within the control and power circuits, the design facilitates minimal maintenance. If a power cell fails, the failure is prevented from migrating to neighboring cells; the drive continues to run, even with the loss of one or two cells per phase. Reliability is further enhanced by incorporating a fault management system that is in itself redundant on several levels.

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Learning through design/test iterations, ABB could correct even elusive design problems.

Performing flawlessly during a 345 bars pressure test for over 3,000 hours in Equinor's research and development facility in Trondheim, the main drive components and sub-assemblies – including optical fibers and connectors – demonstrated their readiness for real subsea operations at high pressure.

Subsea switchgear design and qualification
ABB's medium voltage subsea switchgear is used to distribute power to the VSD and other power consumers located on the seabed.

The newly designed switchgear can support up to six feeders including an incoming breaker, or tie breaker to support two switchgears →05. The incomer of the switchgear connects to the secondary of a subsea step-down transformer, or directly to one subsea power cable from topside or shore. The feeders connect to the subsea power consumers (drives for seabed pumps and subsea compressors). With a rated phase-to-phase voltage of 36 kV and main bus bar current of 1,600 A, this modular and scalable design accommodates a range of system cases and configurations →05. The switchgear is integrated with two auxiliary step-down transformers used to power the redundant auxiliary power distribution system as separate retrievable units. Low-voltage miniature circuit breakers enable de-energizing of the system and independent retrieval of the connected auxiliary load, and provides protection from faults in the auxiliary system, and external power input for system status updates.

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Footnote

1) See "Setting a course for automated subsea power distribution and conversion facilities" for an in-depth article on p. 50.

04

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Based on the widely-used ABB vacuum breaker technologies, the oil-immersed components were tested under cyclic and static pressure and completed IEC/IEEE-type test programs. Qualification of the breakers also included make-and-break tests at 16⅔ Hz supply at rated short-circuit current and maximum asymmetry. Several breaker modules were manufactured and, together with relevant electrical and optical control interfaces, subjected to tests, eg, electrical-type tests, mechanical endurance and vibration tests for operation and transport cases, among others.

In an initial phase, four different designs of the 1-amospheric circuit breaker poles of different construction materials and designs were thoroughly investigated. The successful four-feeder breaker module design was then prototyped and tested by ABB in Ratingen, Germany.

Shallow water field tests say it all

Seizing on the success of laboratory testing, ABB and their JIP partners implemented critical field tests, so-called shallow water tests (SWT). In December 2017 a major milestone was reached when ABB successfully completed the first SWT of a full-scale prototype of a MV VSD, in ABB's test site in Vaasa, Finland. The drive was operated over 1,000 hours, during a "power in the loop" test – in a back-to-back configuration with the grid. In this way only a few hundred kilowatts of losses were supplied by the grid. Significantly, the electronic and power components performed thermally in a superior manner during all environmental stress conditions encountered.

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The 3,000 hour SWT of the entire electrification solution and TRL 4 assessment set the stage for the commercial launch.

In June 2019, ABB initiated a critical 3,000 hours SWT of a prototype of the entire electrification solution →06, consisting of two VSDs in parallel configuration →06a,b with switchgear →06c,d and controls. The triumphant completion of this test and TRL 4 assessment by ABB and their JIP partners sets the stage for the forthcoming commercial launch of this remarkable modular electrification system.

From protected harbor to full launch

With a VSD capable of running a load of up to 9 MVA and supporting a load up to 18 MVA, in parallel configuration, this ultra-reliable, flexible and scalable solution covers most subsea power needs industry might desire. Moreover, the power source can now originate from any topside installation or, more importantly, from shore.

With this first-of-its-kind solution, ABB has more than met the rigorous test requirements and qualifications that the oil and gas industry demands. ABB's novel design and test procedures; and collaboration with JIP partners have been central to the success of this achievement and provide confidence that ABB's electrification solution is ready to take the deep-water plunge. •

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04 Two subsea power drives in parallel configuration are shown.

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05 The modular switchgear is shown with a four-feeder configuration. ABB's switchgear with LFAC 16 2/3 Hz power distribution enables very long step-out distances.

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06 The equipment used for the shallow water tests completed in 2019 is shown along with subsea lifts.

06a The switchgear prototype "MVDU" used in June 2019 for the SWT.

06b The subsea lift of MVDU in Vaasa harbor.

06c One of the VSD prototypes used in June 2019 for the SWT.

06d The subsea lift of a VSD prototype used in Vaasa harbor.


06a


06b


06c


06d

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EXTREME PERFORMANCE

Setting a course for subsea power conversion

01

Working with industry partners, ABB has developed a subsea power system for the oil and gas industry that is more advanced than probably any other system of its kind. Outfitted with a pressure-compensated variable speed drive, the system is now about to complete its equipment qualification process – a step toward subsea facilities with integrated drives for pumps and compressors.

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01 Prototype subsea variable speed drives ready for deployment for a shallow water test near Vaasa, Finland.

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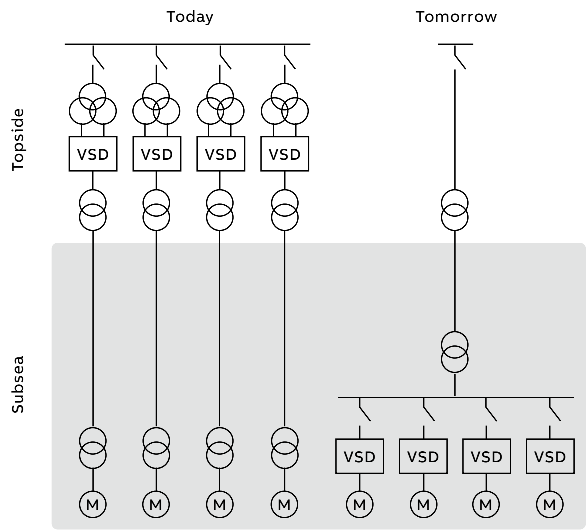
As the oil and gas industry seeks to exploit offshore resources with ever-increasing efficiency, a tantalizing idea has surfaced: What if all the electrical equipment needed for driving and controlling subsea pumping and compression equipment could be located on the sea floor in the immediate proximity of gas compression and oil pumping stations?

Traditionally, such power systems have been stationed onshore or on topside facilities at sea. But if located on the sea floor, they would save space and weight at topside facilities, vastly reduce cable costs, cut response time to variables at wellheads, and considerably reduce the cost of the power supply, while improving reliability and dramatically reducing maintenance costs.[1]

—
What if all the electrical equipment needed for driving and controlling subsea pumping and compression equipment could be located on the sea floor?

In view of these advantages, ABB, Equinor, Total and Chevron are now concluding a joint industry project (JIP) that developed and tested subsea power distribution and conversion technologies. During the first part of the project a full-scale prototype variable speed drive (VSD) converter was built and tested in late 2017 for 1,000 hours in shallow waters →01. An ABB industry analysis indicates that this was the very first time a medium voltage drive was operated at 9 to 12 MVA for an extended period while submerged in a seawater environment.

A second test was recently completed. It was based on the use of a second drive characterized by a refined and improved design. Both drive



02

units were operated in parallel connection to reach higher power levels but with the addition in this case of subsea switchgear and controls to test the full subsea power system.

Breakthrough technology
ABB's variable speed drives are the heart of the subsea project. These 50-ton behemoths drive nearby electric motors for pumps and gas compressors. Modular in design, the VSDs can operate a wide range of subsea motors, ranging in power from 0.5 to 18 MVA, with voltages from 2.0 kV to 7.2 kV and the capability to drive conventional speed pumps and wet gas compressors rated at 50 – 120Hz, as well as high-speed gas compressors at up to 18,000 rpm directly at step-out distances from a few km to over 600 km.

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A subsea VSD system can control multiple nearby compressors and pumps with a single step-out power cable of fixed frequency to the station.

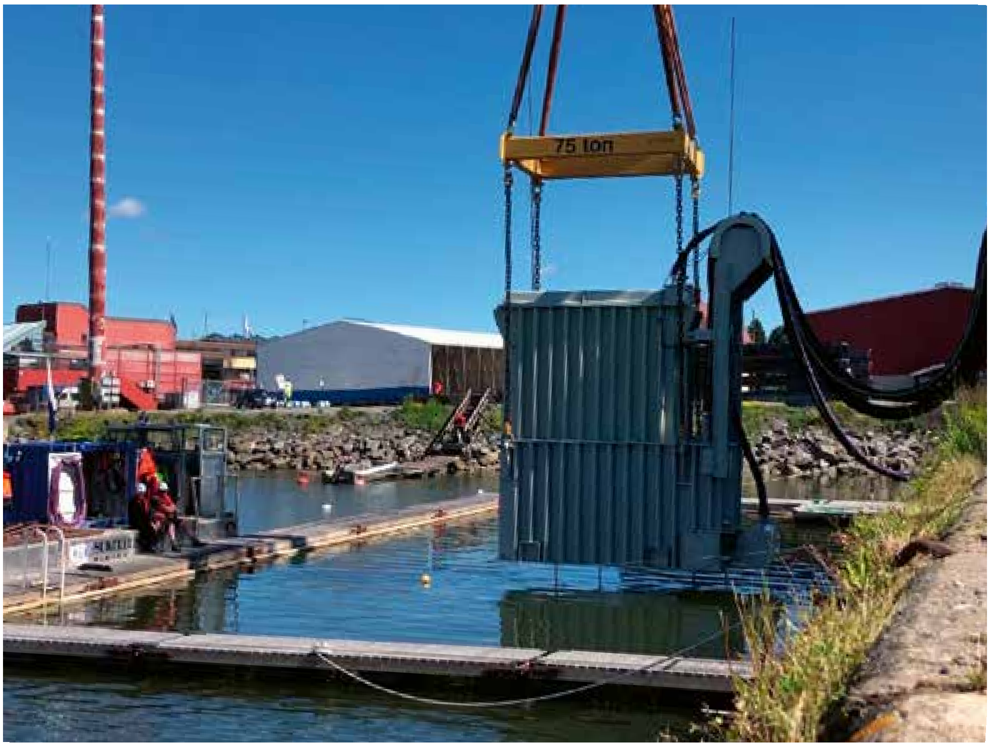
All of the VSD's modules are designed to operate down to depths of 10,000 ft / 3,000 m or more and have been qualified according to API17F and SEPS 1002. One such qualification test included the operation of a power module with all its electronics and power components fully functional in a pressure vessel at 345 bar. The cell converted power up to 1,000 A for 3,000 hours in this high-pressure environment. This was one of the key steps for reaching technology readiness level (TRL) 4 – a milestone that opens the door to allowing oil & gas operators to employ the equipment in production fields.

The tank for the entire VSD utilizes a pressure-compensated design, which effectively removes limits as to the depth of deployment. Pressure compensation is achieved by submerging the drive hardware, including the drive transformer, in a dielectric liquid that also acts as a coolant. The drives' electric power components, including capacitors, semiconductors and control electronics, are designed with enhanced safety margins, redundant hardware, and pressure resistance, and their materials are chosen for compatibility with the dielectric liquid to achieve a highly reliable overall design. Guiding development of this system was a design philosophy that built on but also expanded on ABB's subsea transformer technology. These robust, maintenance-free and exceptionally reliable transformers have been successfully deployed since 1999. Finally, ABB's new VSDs are outfitted with a controller as well as a communication interface to topside. These two units are housed in a subsea replaceable electronic module.

Deep dive
In 2019 two VSDs were deployed in shallow water in a harbor in Vaasa, Finland for testing. As part of a full subsea power system, both converter units operated in parallel in order to demonstrate the highest needed powers.

During the shallow water test, the drives were operated for more than 3,000 hours (about 125 days) at a 22 kV input and 6.9 – 7.2 kV output voltage at different power levels. This confirmed that all components of the VSD system work properly together. In addition, the VSDs' built-in redundancy system has demonstrated itself to enable fault-tolerance as intended by continuing to operate after intentionally disconnecting (and later reconnecting) some of the internal modules through topside commands.

Why subsea conversion sets the pace
As suggested earlier, the subsea concept offers many advantages over conventional topside solutions. As →02 illustrates, the latter require every motor to have its own cable, which may be many kilometers in length. Furthermore, in addition to locating the VSD on the topside, such solutions require a step-up and a subsea step-down transformer to manage cable losses [1].



03

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02 Current and near future solutions for the configuration of key electrical components in subsea environments. When VSDs are placed subsea the result is a massive reduction in the need for motor cables.

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03 Traditionally located onshore or on topside facilities at sea, VSDs may soon operate on the sea floor. Two subsea VSDs were deployed in shallow water in a harbor in Vaasa, Finland. After the lift of the second prototype to water, the equipment operated for a test duration of over 3000 h flawlessly.

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Footnote

1) See "ABB's technology is powering the seabed for a new energy future" on p. 44.

On the other hand, a subsea VSD system can control multiple nearby compressors and pumps with a single step-out power cable of fixed frequency to the station. Several such concepts have been shown by oil majors, including the "subsea garden concept" [2] exemplified on page 44.

From the word go, it was therefore obvious to engineers that subsea deployment was the way to go →03. The only question was, what technologies would make it possible?

Despite the novel environment the VSDs would be exposed to and the need for virtually flawless reliability, it quickly became clear that not everything had to be developed from scratch. To largely remove limits to the depth of VSD deployment, project engineers knew that the device would have to be filled with a dielectric liquid similar to what's used in any standard transformer, thus providing internal pressure transmission, cooling, and electrical insulation [3]. In this situation the tank enclosure can follow similar design rules as a classical transformer tank and does not need to have the capability to withstand as much pressure as some other systems. Instead, an ABB subsea bellow compensator system is used to ensure that internal and external pressure always remain nearly identical.

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It was essential to ensure that the thermal architecture of the entire tank would ensure cooling even at maximum depth with the utmost reliability.

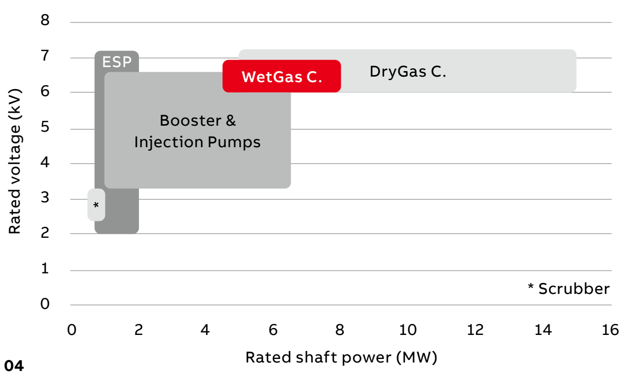
So far, so good! But what proved to be particularly challenging was adapting the electrical and mechanical components of a VSD, such as capacitors, semiconductors, local electronics and wiring to withstand the full environmental pressure at deep deployment locations. Furthermore, it was essential to ensure that all components would be chemically compatible with the dielectric liquid and that the thermal architecture of the entire tank would ensure cooling even at maximum depth with the utmost reliability. These were the key novel aspects that were successfully addressed by the current project.

They were extremely significant achievements because earlier efforts to create a subsea VSD technology required prohibitively heavy massive steel vessels to withstand the water pressure, resulting in difficulties with cooling despite the cold-water surroundings [4].

Naturally, ensuring that all components remain within specified temperature parameters is essential for system reliability and safety. With this in mind, project engineers came up with a passive cooling concept that quite simply employs the interface between the tank walls and the sea water to dissipate losses and thus relies exclusively on natural convection. In short, not a single moving part – always a potential cause of failure – is needed.

Since no single VSD fixed design could cover everything, a modular cell-based drive topology was optimal.

The passive cooling system's performance was analyzed in the full system during the shallow water test. Results demonstrated that the system's temperature distribution inside the tank followed design expectations, meaning that temperature-critical components could be kept in a low temperature environment for maximum reliability even at higher power levels. In fact, the subsea converter places the electronics modules in a near ideal thermal environment. Its oil cooling keeps temperatures constant and low. This approach has been proven to be effective and works with perfect reliability at any sea water temperature, pressure and salinity, as the properties of water in these conditions are well established [5].



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A modular answer to power demands
Another major engineering challenge that confronted project engineers was the very large range of power and voltage demands →04 that VSDs will have to cope with, primarily with regard to booster and injection pumps, wet, and dry gas compressors, as well as smaller power applications, such as submersible and scrubber pumps.

Working with key industry partners, the project's engineers determined a basis of design for variable speed-driven subsea equipment that includes the following key electrical specifications:
- 2.0–7.2 kV output voltage
- 0.3–15 MW motor shaft power
- 0–200 Hz, and for drives < 5 MVA to 300 Hz fundamental output frequency
- 11–33 kV input voltage
- 30-year mission endurance
- Sea water environment at 3,000 m, 0–20 °C water temperatures

Given the breadth of these specifications, it became obvious that since no single VSD fixed design could cover everything, a modular system would be the answer and that, more specifically, a cell-based drive topology would be optimal. The topology chosen for the project comprises a basic power module (PM), referred to as a cell. Each cell's voltage, as well as the number of connected cells, determines a VSD's output voltage to a motor. The cell size, which is directly related to its current rating, is also the converter current rating.

In the first two built units, the cells were designed for a rating of 1,000 A. In order to optimize reliability, a careful trade-off between cell nominal voltage and cell count is necessary for a given output voltage class; a higher cell voltage would lower the cell count and complexity but also reduce the ability to have redundant cells. The trade-off also considers the complexity of the drive transformer.

The cell itself consists of two half-bridges of insulated-gate bipolar transistors (IGBTs), and an assembly of capacitor units for the DC link. The IGBT gate drivers are powered directly from the DC link, thus avoiding high voltage insulated control power supplies. Communication to the cell is by optical fiber from a control-and-measurement unit inside the tank.

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04 Target applications for the subsea VSD and their typical power range and motor voltages.

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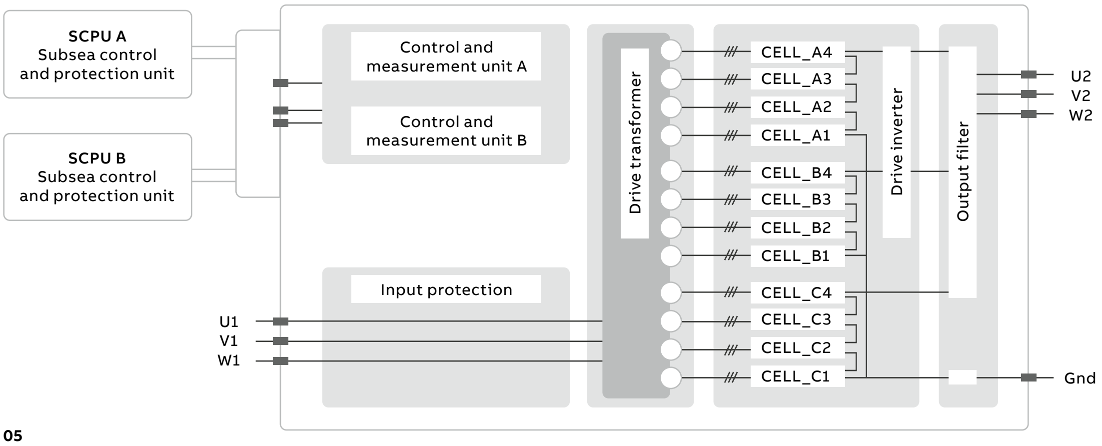
05 Main building blocks, configuration, and single line schematic of a prototype subsea power converter.



05

Each cell is equipped with mechanical devices (disconnectors, bypass) designed to separate it from the main power circuit. This results in a fault-tolerant drive that can remain in operation even if the cell itself fails. The level of redundancy can be selected based on the number of cells installed in a VSD unit in excess of the minimum required for achieving the output voltage. The cell is thus not only a key building block of the subsea converter but also a complete functional subunit and thus a highly meaningful unit for qualification together with all of its subcomponents.

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The cell is not only a key building block of the subsea converter but also a complete functional subunit.

As indicated in →05, the inverter with its assembly of cells supplied by the drive transformer, is complemented by an output filter and an input protection unit designed to limit transients to levels acceptable to connectors, cables, and motor, while guarding against dynamic overvoltages on internal components, respectively. These three units have an inherent built-in flexibility, so that project-specific adjustments are engineered to work without need for requalification, since only identical internal subcomponents are rearranged. Thanks to this approach, the entire power voltage range can be achieved for a given project by simply selecting the right number of qualified units and assembling them as a drive. For higher output currents, two complete converter units, each designed for direct parallel connection, can reach powers of up to 18 MVA.

All in all, shallow water testing confirmed that ABB's subsea VSD and all its components, including redundancy and passive cooling operated properly together up to a level of 1,000 A. The system has thus achieved its goal: technology readiness level 4 and is ready for deployment on the sea floor. •

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01

EXTREME PERFORMANCE

A200-H – the new benchmark in single-stage turbocharging

To fill the gap between ABB's A100-H single-stage turbocharger and Power2® two-stage turbocharger, ABB has developed the A200-H. With a pressure ratio of up to 6.5 and peak efficiency over 69 percent, the A200-H enables single-stage turbocharging on high-speed gas engines with a brake mean effective pressure of 24 bar.

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01 Filling the gap between single-stage and two-stage turbochargers, the A200-H brings brand-new capabilities to a wide range of applications such as marine power plants.

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02 Pressure ratio requirements for lean-burn, high-speed gas engines.

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Driven by demand for decentralized, flexible, cost-effective and environmentally friendly power generation, lean-burn, high-speed gas engines have become a mainstay of the modern power generation landscape. Over the last 20 years, an increase in brake mean effective pressure (bmep) of approximately 1 bar every three years has been observed in these engines, while electrical efficiencies have increased significantly over the same period. This evolution has, in turn, driven the need for turbocharger pressure ratio and efficiency improvements.

With its current single-stage turbocharger generation, the A100-H, ABB defined the state-of-the-art limit for single-stage turbocharging with pressure ratios up to 5.8 and a turbocharger efficiency of up to 66 percent [1]. The A100-H accommodates lean-burn gas engines with a bmep of up to 22 bar. For higher bmep, advanced two-stage turbocharging was successfully introduced to the gas-engine-based power generation market about 10 years ago and has shown convincing operation results ever since. ABB's Power2® two-stage system, for example, offers excessive pressure ratio reserves and efficiencies of over 73 percent – at the cost of additional complexity, weight and expense over single-stage solutions. For gas engines that operate at a bmep of between 22 and 24 bar, two-stage turbocharging is potentially too complex a solution and full utilization of the potential of Power2 requires a bmep level of over 24 bar.

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To fill the gap between single- and two-stage turbocharging, ABB has developed the new A200-H.

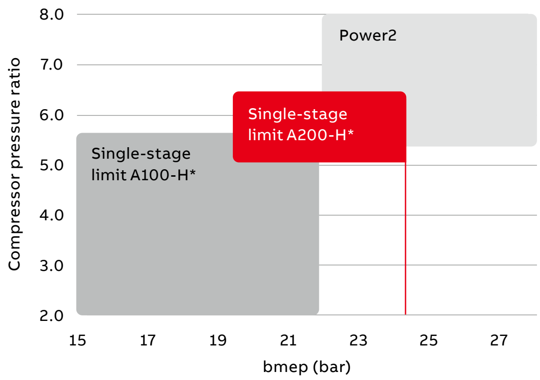
To fill this gap between single- and two-stage turbocharging and thus enable high-speed gas engine manufacturers to continue development work aimed at increasing power density or supporting high-altitude applications, ABB has developed the new A200-H, with a pressure ratio up to 6.5 and a peak turbocharger efficiency in excess of 69 percent →01, 02. The A200-H enables single-stage turbocharging on high-speed gas engines with a bmep of approximately 24 bar while at the same time increasing engine efficiency compared to the A100-H.

Turbocharger efficiency

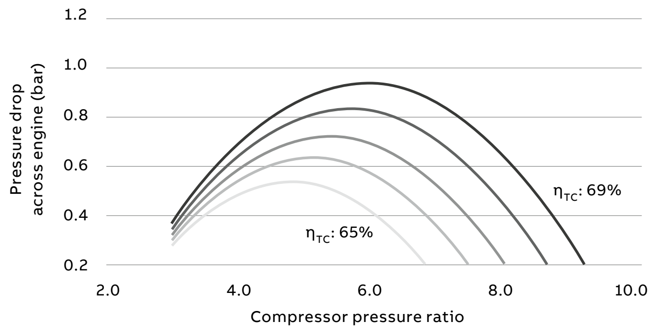
→03 shows that a higher pressure ratio requires a higher turbocharging efficiency to keep the pressure drop across the engine (pressure in the receiver minus pressure before the turbine) constant. It was as a result of these engine requirements that the development targets for A200-H evolved: increased pressure ratio capabilities and at the same time higher turbocharging efficiency compared to the current A100-H turbocharger series.

Compressor-stage concept

The turbocharger specific flow rate had to be optimized for the requirements of a high pressure ratio and high efficiency level. Freedom was given



02 *Base turbocharger matching: 500 m / 30° C (additional reserves for altitude required)



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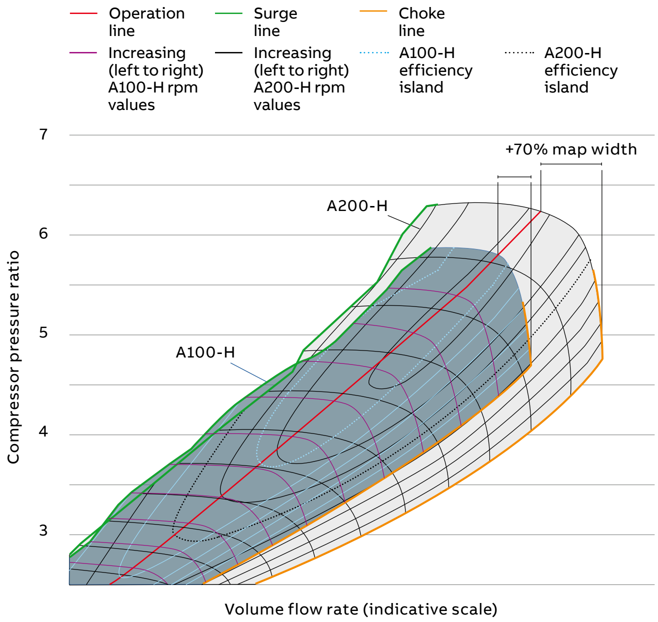


04

to make some dimensions larger than those on the A100-H. Nevertheless, the single-stage configuration still offers simplicity and compactness compared to a two-stage turbocharging solution. The use of a compressor stage with an aluminum alloy impeller allows advantage to be taken of efficient manufacturing processes that enable the required high quality standards. With regard to the challenging thermodynamic target, the aluminum alloy impeller should offer exchange intervals of 40,000 running hours (which may be exceeded by exploiting a digital solution, see below).

Compressor map optimization

→04 shows that the achievable pressure ratio for nominal engine operation is well above 6 for the A200-H. Stable operation of the engine requires a sufficient margin for the operation line in relation to the compressor surge line. Therefore, the compressor map is not only optimized to match the efficiency requirements but is also optimized with respect to the compressor map width. A special focus was the operation range, with pressure ratios up to 6.5 made possible by applying up-to-date map width enhancement technology [2]. An improvement of 70 percent in map width could be achieved compared with the A100-H reference stage.

In keeping with the proven concept for ABB turbochargers, adjustment to the required volume flow will be possible through a range of compressor wheel trims.

Compressor mechanical qualification

The compressor stage is mechanically designed to withstand the excitation of eigenmodes in the operating range. Finite element (FE) analyses coupled with ABB's in-depth knowledge of blade vibration behavior allowed targeted design measures to be taken to either reduce potentially critical resonance amplitudes or to make excitations disappear. The result is a robust design in terms of high cycle fatigue but with a minimum number of qualification loops. The FE analyses also allowed the targeted placement of strain gauges during the qualification procedure →05.

—

The single-stage configuration still offers simplicity and compactness compared to a two-stage turbocharging solution.

Turbine stage

A new turbine stage has been developed to cover the high compressor pressure ratios of up to 6.5 with a high turbine efficiency. The turbine has been matched to the compressor to get the highest possible turbocharger efficiency while meeting the mechanical requirements. All the turbine components – gas inlet, nozzle ring, turbine wheel and diffusor – were designed according to the necessary flow range and pressure ratios. 3D computational fluid dynamics (CFD) was extensively used to ensure high performance and mechanical integrity for the high speeds involved was ensured by FE analysis. The necessary component lifetime and recommended exchange intervals for gas engine applications can be met despite the high speeds.

In combination with the high-pressure compressor, a turbocharger efficiency of over 69 percent could be reached in a technology demonstrator →06.

Housing design

A drop-in design for the air and gas connections was given up in order to focus on the required high performance level. With this new degree of freedom, the air and gas connections were repositioned and extended. An advantage of this reconfiguration is better accessibility of the turbocharger's connecting points and, consequently, considerably easier handling during assembly and service.

—
03 Pressure difference across cylinder as a function of turbocharging efficiency and pressure ratio.

—
04 A200-H compressor extended map width at assumed full load operation points. In the efficiency islands, the engine will perform best.

—
05 High cycle fatigue test with strain gauge measurements.

With a view to future peak-shaving applications, housing stress optimization had to be taken into account at an early design stage. Advanced FE tools were used to, for example, model an improved turbine casing for engine starts that quickly lead to high gas inlet temperatures and to ensure a high number of start-stop cycles can be accommodated.

—
With a view to future peak-shaving applications, housing stress optimization had to be taken into account at an early design stage.

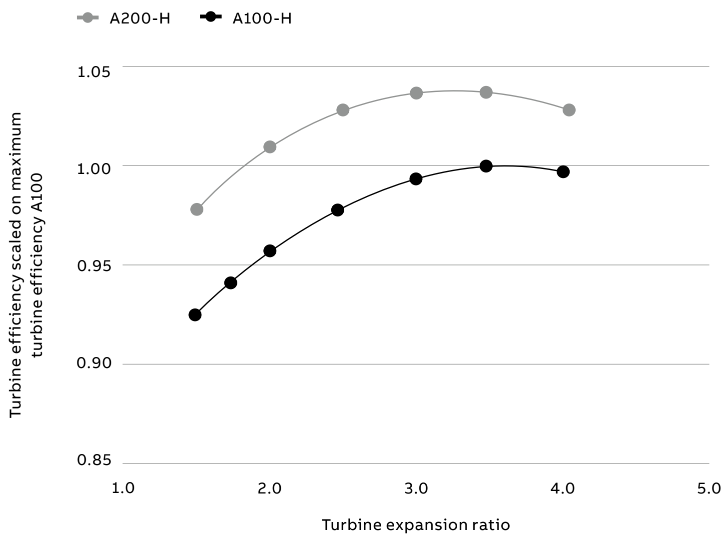
Further, experience with the A100-H generation revealed that mounting larger turbochargers on the engine console would be easier either with hydraulic fastening or with clamping nuts. Hence, the new A200-H turbochargers offer both options →07.

Shaft and bearing system

As with today's radial turbochargers, the use of plain bearings, supported by a squeeze oil damper in the bearing flanges, is the most reasonable option in terms of cost and operational reliability for the new A200-H turbocharger generation. To ensure easy assembly with as few parts as possible, the thrust main and auxiliary bearings are positioned on the compressor side.

The A200-H series lets customers, for the first time, choose between two bearing concepts for the same turbocharger. The A200-H includes a patented bearing module design that supports ABB's plain bearings as well as newly developed and highly efficient ball bearings →08. At part load, power loss for the ball-bearing option is around 15 percent that of the plain bearing option, which makes it the perfect choice for customers with highly transient operation modes. Transient thermodynamic simulations based on a popular 2 MW gas engine and different propulsion concepts demonstrated a time-to-full-load decrease of about 15 percent (hot start and cold start) just by exchanging the bearing system for ball bearings.

05



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The digital capabilities of the A200-H offer more flexibility regarding the assessment of turbocharger maintenance needs.

Both bearing designs are directly connected to the standard engine oil circuit. No additional measures are necessary for the ball-bearing option, but oil consumption as well as heat dissipation into the oil is halved compared to the same turbocharger equipped with plain bearings. The single-module ball-bearing design makes the upgrade from plain bearings easy.

07

Lower lifecycle costs with digital capabilities
Rotor lifetime depends on turbocharger speed and temperature as well as on the number of load cycles. In the past, certain ambient conditions – with defined deviations – and an operation profile were assumed and a conservative approach to the allowable operational parameter values taken. However, cyclic operation – for peak shaving, for instance – is now on the increase. This regime subjects engines and turbochargers to a much higher number of start-stop cycles than in the past. Not only the mechanical load cycles but also the severe temperature fluctuations have a major wear impact.

The digital capabilities of the new A200-H series now offer more flexibility regarding the assessment of turbocharger maintenance needs and the release of operation limits beyond today's recommendations. Monitoring of turbocharger speed and temperatures, start-stop cycles, ambient conditions and other parameters will be introduced with turbocharger-integrated sensors or with access to data from the genset system. The access to installation-specific operation data enables an exposure-based component life assessment, ie, a review of rotor component lifetime consumption and a check of hot static parts that is based on operation history.

An online analysis of collected data allows an assessment of the shaft and rotor components with every inspection, eg, after each 20,000 running hours interval for natural gas applications. If the analysis of operation data permits it, the customer will get a “good to go” for the next inspection interval with full warranty. At the 40,000-hour inspection, customers can opt to receive an extension of the recommended exchange interval beyond the 40,000 hours dictated by the rigid and conventional approach that exists without continuous digital support. Assuming a full engine lifetime of 120,000 running hours, with one major overhaul during that period, the potential extension of the rotor exchange interval will allow the operator to run the turbocharger with only two rotors over the engine lifetime – ie, to exchange the rotor only once, thus reducing cost.

08

06 Turbocharger efficiency: A200-H versus A100-H.

07 A240-H turbocharger with clamping nuts.

08 Testing of bearing module design with an early prototype on ABB's test bench.

For hot static parts under cyclic thermomechanical fatigue (TMF) load, the acquisition of operating data and the correlation with wear and tear behavior of the parts gives new insights and expands the existing experience base significantly. A new analysis algorithm and the latest optimization tools in the design process will allow further TMF-optimized designs of casings and other parts that are prone to severe thermomechanical loads. Future peak-shaving applications will benefit from the new digital offerings with further extended application limits and considerably reduced lifecycle costs.

High-speed engine customers are eager to explore the full potential of the new series and the first A240-H prototypes will soon be ready to test.

Having the digital solutions for A200-H on board offers even more opportunities and added value for A200-H turbocharger operators. Maintenance scheduling, performance trend monitoring, fleet management and timely upgrade advice are some examples of new offerings that will be introduced step by step with the new series.

Timeline and application range

ABB's next-generation A200-H turbocharger series sets an innovative benchmark in single-stage, high-pressure turbocharging. The A200-H responds to the requirements of high-speed engine builders and operators for increased power density, higher system efficiency and reduced specific lifecycle costs. A200-H turbochargers offer compressor pressure ratios up to 6.5 and turbocharger efficiencies of over 69 percent.

New compressor and turbine stages have been developed to ensure an outstanding performance level, mechanical reliability and a suitable component lifetime in demanding full-load operation. The turbocharger design meets challenging requirements – eg, those regarding cyclic operation, efficiency loss minimization, containment safety and rotor dynamics.

The A200-H's digital capabilities offer more flexibility in the assessment of turbocharger maintenance needs and the lifetime assessment of components. Installation and operation-specific data facilitate an exposure-based assessment and potential for reducing lifecycle costs significantly. High-speed engine customers are eager to explore the full potential of the new series and the first A240-H prototypes were tested in late 2019. Three smaller turbochargers, A238-H, A234-H and A231-H, will follow to complete the new turbocharger series. Start-up of production of these turbocharger types is planned for 2021/2022. •

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BUZZWORD DEMYSTIFIER

Additive manufacturing

Turning data into three-dimensional physical objects to produce mass-customized products and characteristics.

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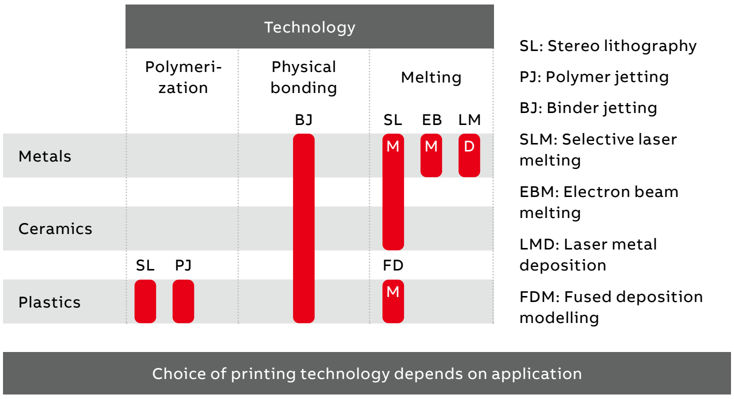
Additive manufacturing, also known as 3D printing, is a process in which a digital model is sliced by the printer's software into 2-dimensional layers and then turned into a set of instructions in machine language for the printer to execute, essentially turning data into a three-dimensional physical object by adding material one layer at a time. Compared with traditional subtractive (drilling or machining) or formative (injection molding) manufacturing technologies, 3D printing is a fundamentally different way of producing parts.

3D printing allows easy fabrication of complex shapes, many of which cannot be produced by any other manufacturing method. The technology also makes it possible to engineer customized product characteristics, such as optimized heat conductance or resistance, high strength or stiffness and even biocompatibility. Furthermore, materials can be filled with metal, ceramics, wood or graphene particles, or reinforced with carbon fibers. This results in parts with unique properties suitable for specific applications.

Low costs, rapid growth

The cost of a 3D printed part depends on the amount and type of material used (plastics, ceramics, metals), the printing process (polymerization, physical bonding, melting), the printing time, and the time required for post-processing →01. Other than these factors, the only cost associated with modifying an existing design is the time required to alter its digital 3D model. Thus, every item can be customized to meet specific customer needs without impacting the item's manufacturing costs.

On the other hand, since unit price decreases only slightly at higher quantities, 3D printing cannot compete with traditional manufacturing processes when it comes to very large production runs →02. Economies of scale therefore do not really apply. Nevertheless, considering recent developments in the automation of 3D printing and the fact that some materials are becoming commoditized, the break-even point is steadily shifting to higher production runs.



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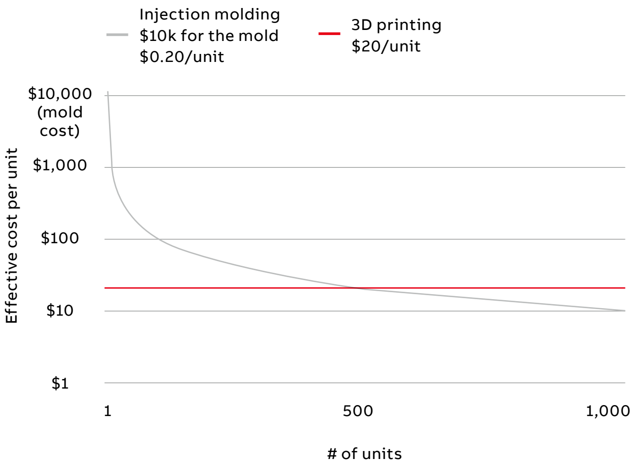

02

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01 Although 3D printing is a relatively new technology, many advanced processes covering a wide range of materials are already available.

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02 3D printing is particularly cost competitive when prototypes or small batches are required.

Other factors that can be expected to impact 3D printing and reduce its costs are the development of fully integrated workflows and operations, and the application of artificial intelligence to generative designs, process optimization, quality prediction, and auto-correction during printing – factors that are likely to open the door to new business models.

—

Recent developments in the automation of 3D printing are shifting the break-even point to higher production runs.

Looking ahead

Spurred by faster printers, decreasing material costs, and demand for increasingly individualized products, adoption of 3D printing has already reached critical mass and is now becoming an accepted production technology. For example, the U.S. hearing aid industry converted to 99 percent additive manufacturing in less than 500 days in 2015.

Wohler's Associates [1] expects that the global 3D printing industry is set to exceed $15 billion in revenue this year (2020), $24 billion by 2022, and $36 billion by 2024. •

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Reference

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