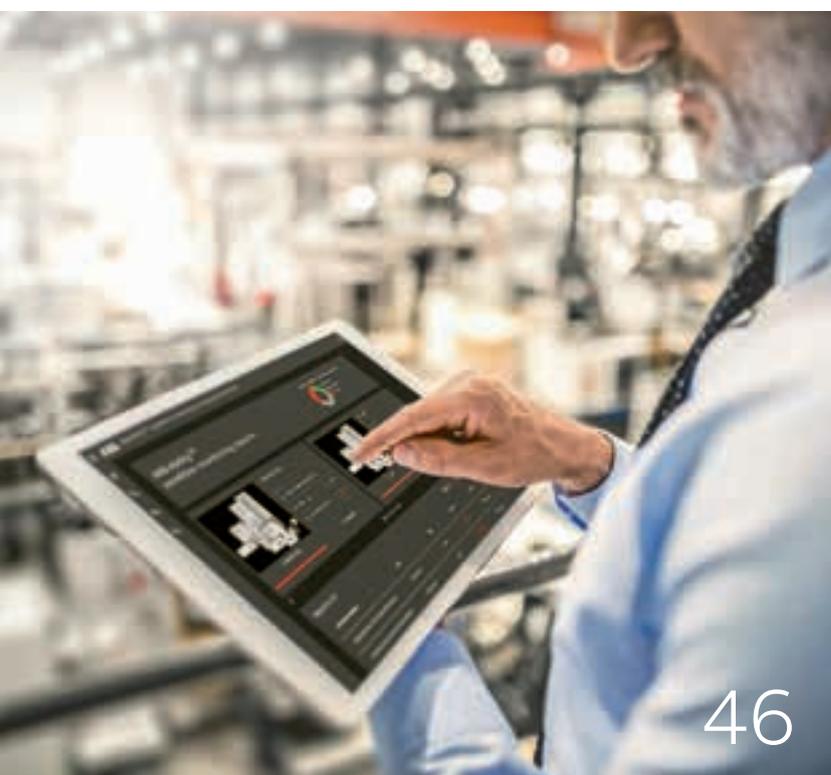


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Machines with intelligence



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The Tmax XT digital breaker

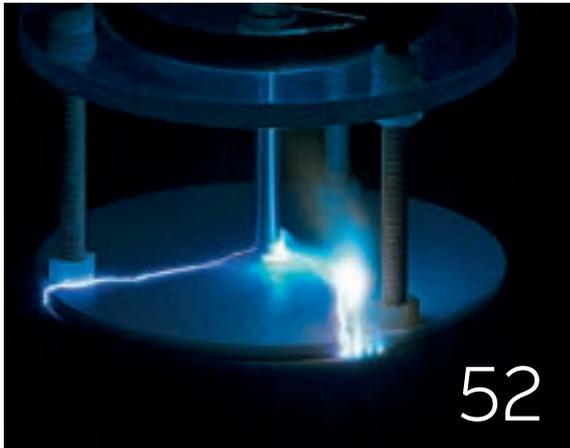
Puffer-type load break switch





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Machines with intelligence

Intelligent machines are a lot like intelligent people. They don't know everything but possess the ability to learn, apply insights instead of merely provide answers, and aren't innately smart but can understand and adapt. This issue of ABB Review focuses on how these technologies are transforming manufacturing and business, thanks to intelligent people and intelligent machines working together.

EDITORIAL

Machines with intelligence



Dear Reader,

There is typically a gap between what is scientifically possible and what is viable in practice. The purpose of engineering is to reduce that gap and transform the fruits of research into tangible benefits that serve people and industries while preserving the natural environment.

The current issue of ABB Review focuses on applying the ever-growing capabilities of artificial intelligence (AI) to industrial processes. AI not only improves the collection, connection and exchange of information, it makes it possible to transform entire manufacturing processes to be more efficient, productive and sustainable.

Among the questions considered in this issue are: whether and how we can we trust AI, how we can improve the way AI systems learn, and how we can use AI to guide both existing systems and to design better ones.

Enjoy your reading,

A handwritten signature in black ink, consisting of stylized initials 'B' and 'R' followed by a horizontal line.

Björn Rosengren
Chief Executive Officer, ABB Group



Machines with intelligence





Smart machines must be reliable, trustworthy, communicative, and able to learn before they can be called intelligent. ABB is helping to lead the way by developing such machines and putting them to work with customers.

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- 14 A formula for accelerating autonomous anomaly detection
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MACHINES WITH INTELLIGENCE

The digital Lighthouse Program: igniting transformation

In 2017, ABB launched the digital Lighthouse Program, an initiative that selected and partially financed the development of innovative digital solutions in collaboration with customers. The program has already resulted in the commercialization of 30 new products.

—
01 The digital Lighthouse Program speeds the introduction of innovative digital solutions to the market.

Digital innovation in a 130-year-old, multi-industrial global corporation is not always easy. Nonetheless, innovation is essential for organizations that want to be leaders in the era of digitalization. One of the key enablers of innovation is the ability to test new ideas, learn from the results and iterate the ones that hold promise.

In 2017, ABB took on the challenge of catalyzing digital innovation. To this end, the company launched the digital Lighthouse Program, which selected and partially financed the development of innovative digital solutions in collaboration with customers. ABB believed the Lighthouse Program could marry good internal ideas with the necessary funding, resources and customer co-innovation to shorten significantly a product's time to market →01.

Two and half years later, at the program's completion, 66 minimum viable products (MVPs) had been deployed with customers and over 40 customer testimonials published. To date, 30 products developed under the Lighthouse Program have been released commercially. But the most important feature of the program is



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the culture of digital innovation fostered within ABB, which means that, in future, far fewer digital innovations will now sit untried and untested on the shelves.

Digital transformation

Digital innovation and transformation are vital for ABB's growth and its ability to deliver higher-order customer value while also securing the company's offerings from race-to-the-bottom

—

The Lighthouse Program invited people with good ideas to champion and defend them within a business framework.

price pressure. If ABB can digitalize and expand its portfolio of integrated digital solutions to meet the needs and expectations of the company's massive installed base of loyal customers, the company will continue to prosper.

But digital transformation is easier said than done.

Digital transformation in large companies is hard for two principal reasons. First, traditional organizations spend most of their R&D budget on

incremental product improvements that slowly but steadily increase market share in well-defined markets. By contrast, digital innovation programs are all about the future. Here, R&D resources work on novel products or in markets that are either nascent or do not yet exist →02, which makes agility, speed-to-market and risk-acceptance essential. Some projects will fail, but those that succeed can be game-changers.

Second, the success of digital innovation is not measured simply by the launch date. Digital products must be treated as fledgling businesses by the marketing or product management teams and nurtured through extensive experimentation. Models that show the most potential should be rapidly scaled up. Those that do not should be quickly abandoned.

ABB's ignition switch

The Lighthouse Program launched in April 2017 and ran until the end of 2019. The primary goals of the program were:

- Accelerate the development and deployment of innovative digital solutions built on the ABB Ability™ Industrial Internet of Things (IIoT) platform.
- Encourage co-development of solutions with customers, engaging them at an early stage.
- Speed up ABB's adoption of leading-edge digital technologies such as artificial intelligence (AI), augmented and virtual reality, digital twins and blockchain.



—
02 Whereas much R&D spending is on improving current products in well-defined markets, digital innovation programs are all about the future.

—
03 An intelligent shipping concept was one result of the Lighthouse Program.



03

The early-stage customer collaboration aspect of the program was very popular.

The Lighthouse Program selected, financed and launched a cohort of around 12 digital innovation projects every six months. Two main criteria for project selection were:

- Each approved project should present a high-risk and high-innovation profile that would not be funded without the Lighthouse Program.
- The relevant ABB entity should be prepared to contribute resources.

The program funded 50 percent of each project, with the remainder paid for by the ABB entity proposing the project. An unexpected benefit of this co-funding model was that it encouraged ABB entities proposing similar projects to pool their efforts to access more funding. Not only was this approach more efficient, but it also meant that customers had access to applications that work with an expanded number of ABB products.

The Lighthouse Program invited people with good ideas to champion and defend them within a business framework. Applicants identified customers willing to co-develop new digital products, explained what customer pain points the products would address, outlined the obstacles

to success and how the program's support funding would overcome them, and highlighted the immediate and long-term revenue potential.

Each digital solution strove to meet two final requirements to be considered successful:

- Deploy an MVP with a customer within nine months of project kick-off.
- Release a public customer testimonial within two months of the deployment.

The first goal drastically shortened the development time to which ABB's R&D teams were accustomed. The goal of deploying a just-good-enough MVP instead of ABB's usual close-to-technically-perfect standard was a powerful accelerant. As one participant noted, "the Lighthouse Program introduced customer co-creation. Historically, ABB has developed products itself, then offered them to customers. Under the program, ABB and customers collaborated from the beginning to develop solutions that directly address customer pain points."

Project proposals received additional consideration if they could demonstrate:

- Cross-business collaboration that ensured sustainable future networking benefits and best-practice sharing.
- The extent to which the project integrated with and enhanced the ABB Ability™ Industrial Internet of Things (IOT) platform.
- How the project would integrate and develop emerging digital technologies such as AI, machine learning and digital twin technologies.



Each funded project was officially kicked off via a virtual meeting organized by the Lighthouse Program team to ensure that the teams were prepared to begin work. A lesson learned early on was that forcing the kick-off too soon led to delays, lost momentum and frustration. In prac-

In all, ABB employees proposed 170 projects to the program, of which 73 were funded.

tice, two months of preparation time between acceptance and kick-off ensured adequate staffing and alignment of resources. On many of the projects, global teams were spread over several continents and multiple time zones.

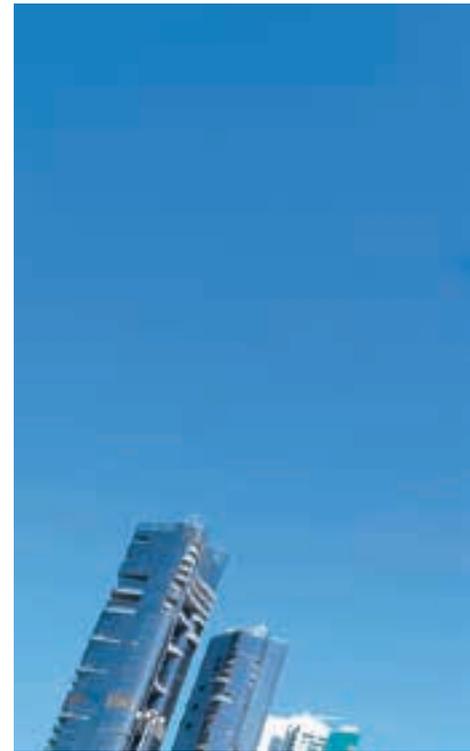
The Lighthouse Program team reviewed the progress of each working team every two months. This schedule allowed them to cross-pollinate best practices across the entire project portfolio. Every second week, teams summarized their achievements and upcoming goals in a sprint report that was aggregated into a widely circulated Lighthouse Program portfolio dashboard.

Interestingly, the early-stage customer collaboration aspect of the Lighthouse Program became one of its most popular features. Initially, development teams came to the program primarily to tap into the internal funding. Soon, however, they began to give equal importance to working with customers early in the product life cycle, which led to better-focused products and shorter time to market.

Digital Lighthouse Program Results

In all, ABB employees proposed 170 projects to the program, of which 73 were funded. All 19 areas of business in ABB were represented, a rare, simultaneous company-wide embrace of change.

Funded projects successfully co-developed and deployed 66 MVPs with customers, 40 of which resulted in public customer testimonials. Over 60 percent of projects trialed new business models, such as subscription pricing. Two



04

projects were the first offerings on the online ABB Ability™ Marketplace, where customers can buy cloud-based digital solutions. Multiple ABB entities were involved in 17 projects, while 19 utilized emerging digital technologies. To date, 30 MVPs have been further productized and are fully released for sale to customers.

Two successful examples

The intelligent shipping concept designed under the Lighthouse Program introduced two remote, intelligent passenger-ferry solutions that use LiDAR, radar, GPS and cloud connectivity, and that can be fitted to virtually any vessel →03. Software predicts where the ferry will be in 30 s and the optimum manner for executing maneuvers is superimposed on actual surrounding conditions, enabling controllers onshore to control the vessel remotely. The solution enables an entirely automated “sense-analyze-act” loop, a significant step toward autonomous operations, with humans remotely on standby in case intervention is required. The co-developing customer was Suomenlinnan Liikenne Oy, with the cooperation of Helsinki’s City Transport and the Finnish Transport Safety Agency (TRAFI).

Detecting harmful methane, ethane and other leaks from pipelines has been challenging and expensive because pipelines often traverse unreachable or inhospitable terrain. ABB Ability™



—
04 Co-developed with customer ULC Robotics, ABB Ability™ Mobile Gas Leak Detection uses drones to check pipelines for leaks.

Mobile Gas Leak Detection, co-developed with customer ULC Robotics, detects leaks with 1,000 times more sensitivity than traditional methods by using drones that fly swiftly along pipelines →04. This protects the environment, infrastructure and workers while safeguarding the pipeline owner's revenue. Cloud connectivity allows secure, quick and efficient distribution of data anywhere in the world. Authorized users can view the progress of drone flights in real-time and review and act on leak reports.

Guiding the way to the future

Was the Lighthouse Program a success? Michael Wade, Professor of Innovation and Strategy at IMD in Lausanne and Director of the Global Center for Digital Business Transformation, followed the Lighthouse Program carefully. His assessment: "The Lighthouse Program has been a breath of fresh air for ABB, in an industry where things happen in years, not months and certainly not weeks. Digital transformation is tough, and the sad reality today is that most efforts in this direction fail. So, ABB's deployment of 66 MVPs within two years, and more importantly, the commercialization to date of 30 of those products is an extremely rare and promising achievement."

The Lighthouse Program succeeded on several fronts: It ignited digital transformation, created an operational template for earlier-stage

co-innovation with customers and demonstrated ABB's commitment to helping customers execute their digital transformations.

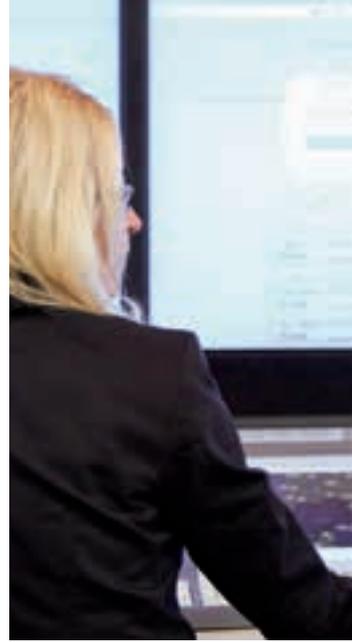
Enabling real collaboration inside large organizations is challenging. The Lighthouse Program succeeded in encouraging teams from different parts of ABB to join forces in a powerful new way. Today, all ABB businesses currently have or are

—
The Lighthouse Program succeeded in encouraging teams from different parts of ABB to join forces in a powerful new way.

creating their own Lighthouse Program-like programs, accelerators or incubators. Crucially, ABB management is actively nurturing these efforts to sustain the change over time and at scale. •

MACHINES WITH INTELLIGENCE

A formula for accelerating autonomous anomaly detection



Machine learning is becoming increasingly important in identifying anomalies and thus improving the level of quality control autonomy in process industries [1], [2]. But training such systems to identify meaningful deviations from normal data is often challenging because of a paucity of real-world examples.

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With a view to overcoming this drawback, Corys and ABB have combined two simulation technologies to create an environment that generates data that is remarkably similar to that produced by specific processes in real industrial plants. This new level of simulation accuracy opens the door to tailor-made, targeted and accelerated anomaly detection capabilities.

Industrial facilities need to run as smoothly as possible. To do so, indications of potential problems, such as anomalous vibrations, temperatures, pressures, and sounds need to be detected, identified, analyzed, and managed in their earliest stages. Anomaly detection, a key form of machine learning, can play a major role here by effectively supporting plant operators as they monitor the health of industrial systems.

Machine learning models, however, are typically trained using historical plant data. But as industrial systems are very robust, there are often not enough examples of real failure cases in the data to train reliable models. Moreover, even if some failure cases did occur, they are often hard to find in the data because they were not labeled as such by the operator, or because they were not noticed when they occurred. Furthermore, this state of affairs can lead to the mistaken identification of anomalous situations as being normal.

Creating an infrastructure for machine learning research

With a view to overcoming these drawbacks, data scientists are using high-fidelity process simulators, such as the Indiss Plus Simulator from Corys [1], to train machine learning models on specific normal and abnormal plant situations, such as, for example, valve failures, in order to correctly label such events.

For instance, Corys and ABB have created an infrastructure for machine learning designed to explore the potential – as well as the data requirements – of different algorithms in a realistic setup. →01 shows the experiment's infrastructure for machine learning research created by Corys and ABB. At the heart of the

—
 A combination of simulation systems generates data that is remarkably similar to data produced in industrial plants.

infrastructure are the simulation tools of the two companies: Corys' process simulation Indiss Plus and ABB's control system simulator 800xA Simulator [3]. Individually, both tools have been proven to be highly accurate in several operator training projects. Now, in a combined configuration, the tools can generate a simulation of the behavior of a process and its associated automation system, such as, for instance, a real plant's control logic, including alarms and safety logic.



different initial process states and automatically performing operator actions. It also starts the data collection that receives data from an 800xA Simulator, making it possible to use ABB's 800xA as a simulated control system in a simulator, with identical operator layout, view and control logic

—
 Simulated datasets were used to train an anomaly detection model that could detect simulated device failures.

A key advantage of Indiss Plus in this setup is that it also opens the door to simulating various plant equipment failures, eg, a valve leakage as shown in →02. The resulting failure data can overcome the issue of not having a sufficient number of failure cases to support machine learning.

To create simulation data sets suitable for the training and validation of a machine learning model, the execution of simulation experiments must be automated. In the present case, an experiment controller was developed as shown in →01. The experiment controller takes in an experiment plan describing when to perform various operator actions like setpoint changes and when to trigger failures within the Indiss Plus process simulation. The experiment controller performs batches of experiments, starting and stopping the process simulation from

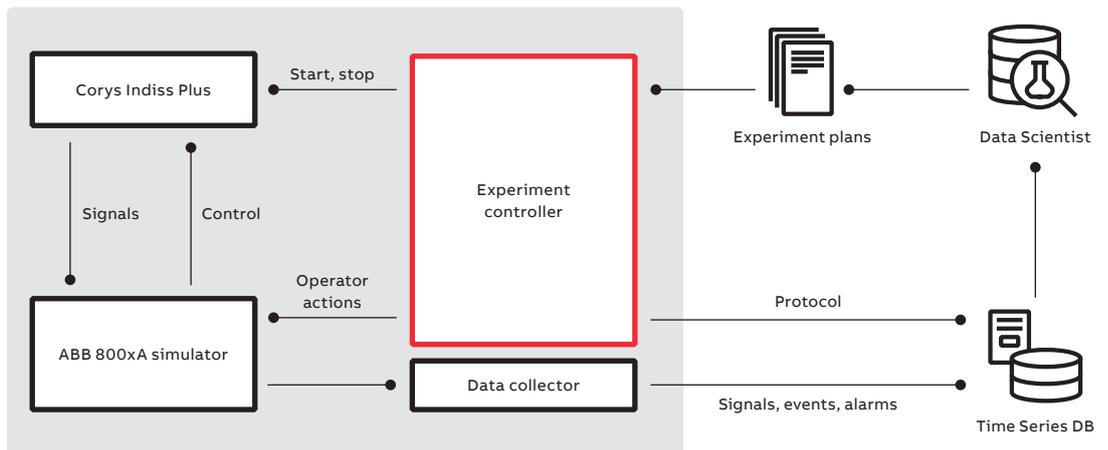
as in the plant. The data and a protocol of the actions performed by the experiment controller are stored in a time-series database and made available to a data scientist for the training of machine learning models.

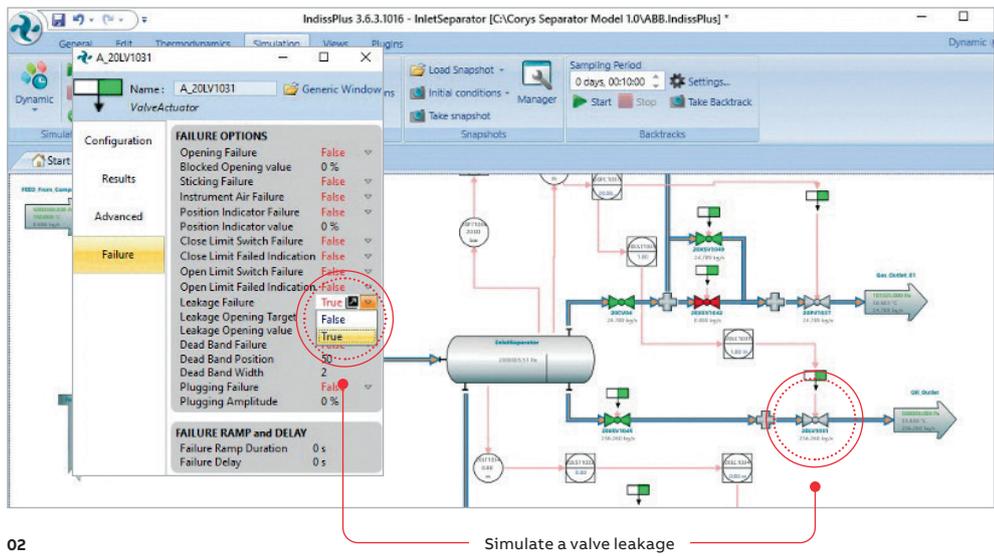
Case study: Developing a machine learning model for anomaly detection

In the study described in this article, simulated datasets were used to train a model for anomaly detection that would be able to detect simulated device failures.

A feasible approach in machine learning for detecting anomalies in signal timeseries is to utilize so-called autoencoders [4]. An autoencoder is composed of two artificial neural networks, the first one learning to compress the data (encoder) and the second one learning how to reconstruct the compressed data (decoder). For the purpose of anomaly detection, the degree of

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 01 Data generation and collection infrastructure.





02

Simulate a valve leakage

error indicated by the reconstructed data is used to measure how abnormal the data is.

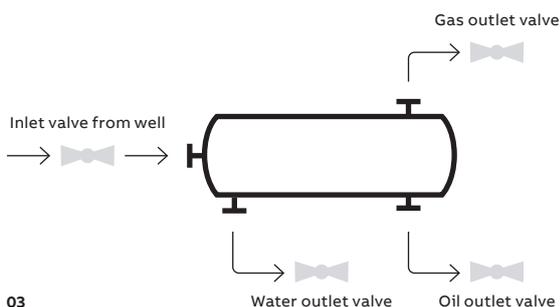
For the purposes of the current study, Indiss Plus from Corys was used (a high-fidelity process simulator). Here, Corys had implemented a high-fidelity simulation model of a three-phase separator process that is typically used in oil production. The core component of this process is a separator vessel that segregates fluids from a well into three outputs: oil, gas, and wastewater. In order for the separator to function properly, it is important to maintain the oil, water, and gas levels in balance. This is performed automatically by the control system by adjusting several valves →03. If a setpoint in one of the levels is changed, the system will adjust the other valves automatically to keep the whole separator in balance.

The above-described simulator was used to train an autoencoder to detect a physical valve failure such as a valve blockage or leakage. Such failures are often difficult to detect by operators, particularly if they are not represented directly in an HMI, which can occur eg, if sensors for detecting

these failures are missing. The idea was to train an autoencoder that learns the signal trends from the three-phase separator process during normal operation, ie, when there are no failures. The trained autoencoder was then applied to try to reconstruct the trends for different simulated device failures.

In the current evaluation the autoencoder was able to detect device failures as anomalies because the signal trends that represent these failures had not previously been seen by the autoencoder during model training. This led to a relatively high reconstruction error. When the error was higher than a predefined threshold, the autoencoder classified this situation as

A simulator was used to train an autoencoder to detect a physical valve failure such as a blockage or leakage.



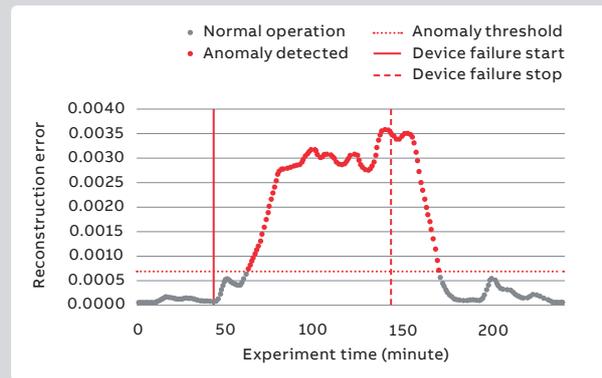
03

anomalous and reported the anomaly to the user. As shown in →04, this anomaly threshold was exceeded exactly at the time of the device failure; but when the failure was removed in Indiss Plus, the reconstruction error from the autoencoder went back to normal. When an anomaly is detected, a subsequent step is to locate its potential root cause. In →04 the root cause was found to be in the oil valve.

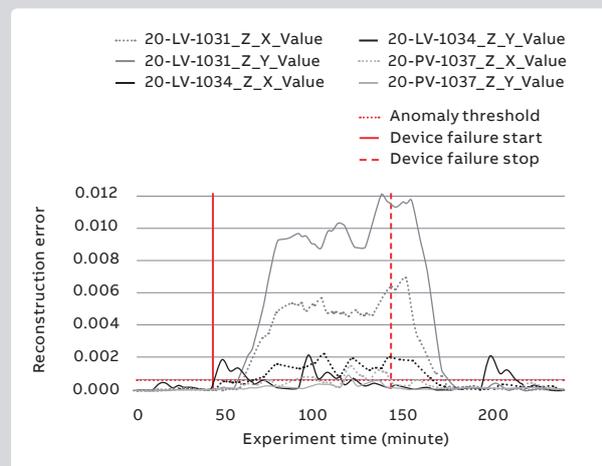
Toward hybrid digital twins

The research described in this article outlines how ABB and Corys have worked together to

RECONSTRUCTION ERROR



SIGNAL-BASED RECONSTRUCTION ERROR



TOTAL CONTRIBUTION OF DIFFERENT SIGNALS TO ANOMALY



localize the anomaly root-cause

localize the anomaly root-cause

create an infrastructure for reproducible machine learning research. The Corys Indiss Plus and ABB 800xA Simulator tools create an environment that produces data that is remarkably similar to that produced by real industrial plants. The key difference is that machine learning scientists have full control of the data generation and can test and evaluate their approach in a sound and comprehensive way. The combination of

Hybrid digital twins hold the promise of becoming a key enabler of future autonomous industrial plants.

high-fidelity simulation based on first-principle models and machine learning enables the creation of plant digital twins composed from different types of models that can be leveraged depending on the different types of functionalities the digital twins should deliver to the various plant stakeholders, ranging from operators to plant managers. Such hybrid digital twins hold the promise of becoming a key enabler of future autonomous industrial plants.

The logical next step in this research will be to test the machine learning infrastructure described in this article in a simulation of an actual customer plant. This will make it possible to investigate the potential benefits of machine learning models that have been pre-trained using simulation models of actual applications. •

04

02 Simulation of a realistic plant equipment failure using Indiss Plus (here: a leakage of the selected valve).

03 Separator vessel in a three-phase separator process.

04 Detection of a device failure (here: valve leakage) with the help of an autoencoder model that was trained with simulated process data.

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 MACHINES WITH INTELLIGENCE

When machines and robots work as one

B&R, a division of the ABB Group and a global leader in industrial automation, has developed Machine-Centric Robotics – a solution that allows machines on the factory floor to communicate with associated robots in real time.



01



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Machine-Centric Robotics will make it easier to operate machines as there will be only one user interface for machine and robot. As a result, for the first time ever, ABB will be able to offer its customers machine controls, including drives, safety systems, HMI, vision, and robots, as a package from a single source – something no other company matches.

Robots are evolving. Increasingly, they are working alongside humans, learning from experience, becoming networked, mobile, and even autonomous. These characteristics are in high demand for many reasons: aging societies, a shortage of skilled workers, and pressure for locally produced and individualized products that are nevertheless affordable and of the highest quality [1].

As manufacturers scramble to satisfy these requirements in a world of work transformed by Covid-19-related health and safety considerations, B&R has jointly developed in collaboration with other ABB departments a solution that allows machines on the factory floor to communicate with associated robots in real time →01.

Instant removal

A practical example of what has been achieved to date is the detection of an imperfection by a B&R vision camera. Here, in less than a millisecond, data regarding the imperfection is converted into a control command for an associated ABB robot,

In less than a millisecond, data regarding imperfections is converted into a control command for an ABB robot.

and the defective workpiece is removed from a production line without any manual intervention and without affecting the speed of the manufacturing process.

Behind the solution, which integrates ABB robots into the B&R control system, is a single architecture that melds the information needed by these



MAPP TECHNOLOGY

is revolutionizing the creation of software for industrial machinery and equipment. Modular preprogrammed (mapp) software components are as easy to use as a smartphone app. Rather than write lines and lines of code to build a user management system, alarm system or motion control sequence from the ground up, developers of machine software simply configure ready-made mapps with a few clicks of a mouse. Complex algorithms are easy to manage. Programmers can focus entirely on machine processes.

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01 Machine-Centric Robotics allows machines on the factory floor to communicate with associated robots in real time.

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02 Modular preprogrammed (mapp) software components are as easy to use as a smartphone app.

two previously separate systems. This eliminates the need for a dedicated robotics controller, a separate control cabinet and specialized personnel for specific robotics languages.

The integration of ABB robots into machine automation solutions is supported by B&R's pre-configured software modules. The modules

—
The integration of ABB robots into machine automation solutions is supported by B&R's pre-configured software modules.

are designed to make robotics applications extremely easy for machine builders to create. For instance, B&R's mapp →02 Robotics software includes standard functions for control and commissioning as well as advanced functions such as feed-forward control, and compressor

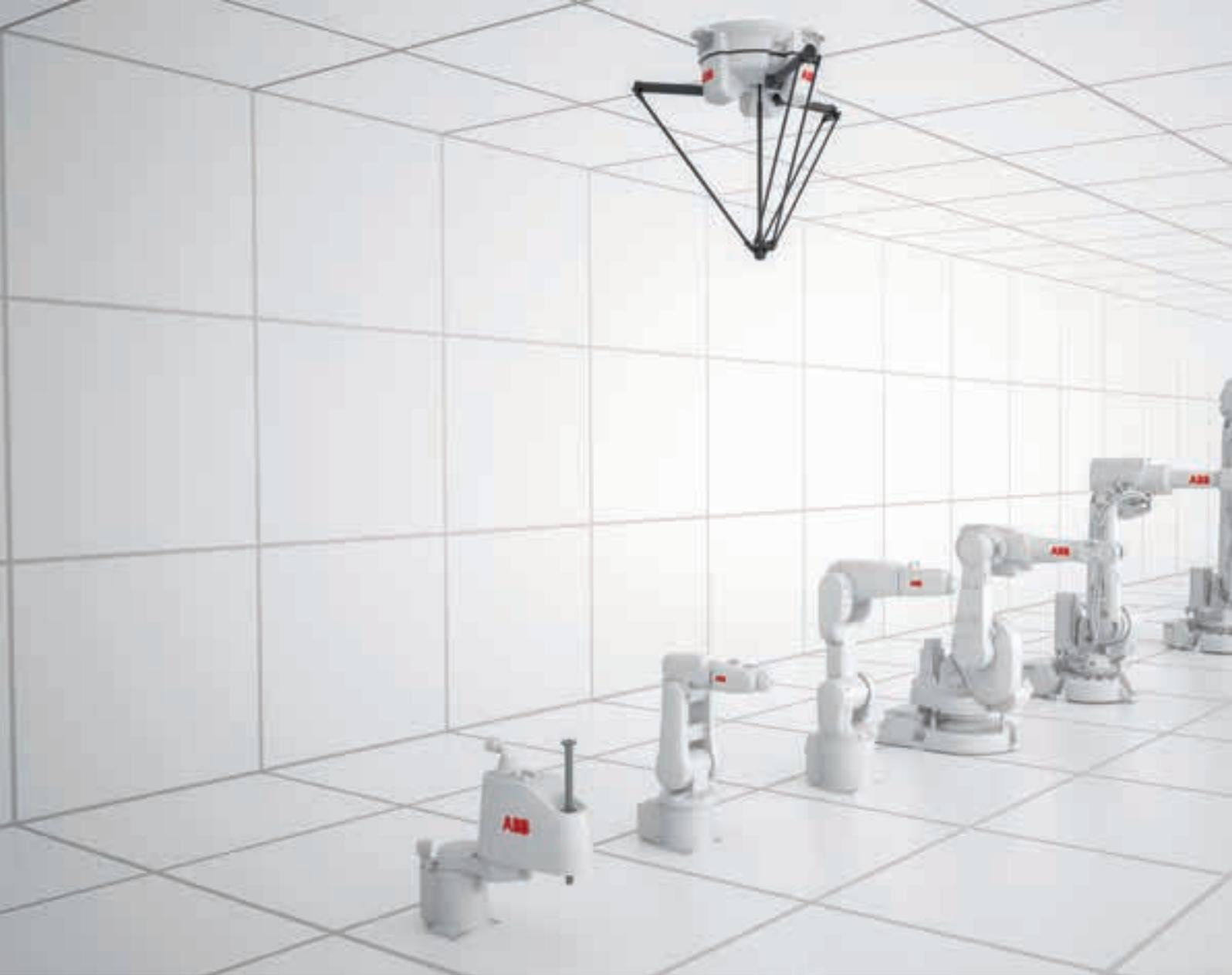
and workspace monitoring. This allows the user to implement complex and highly dynamic applications without having to write new code, thus dramatically reducing development times.

Single source

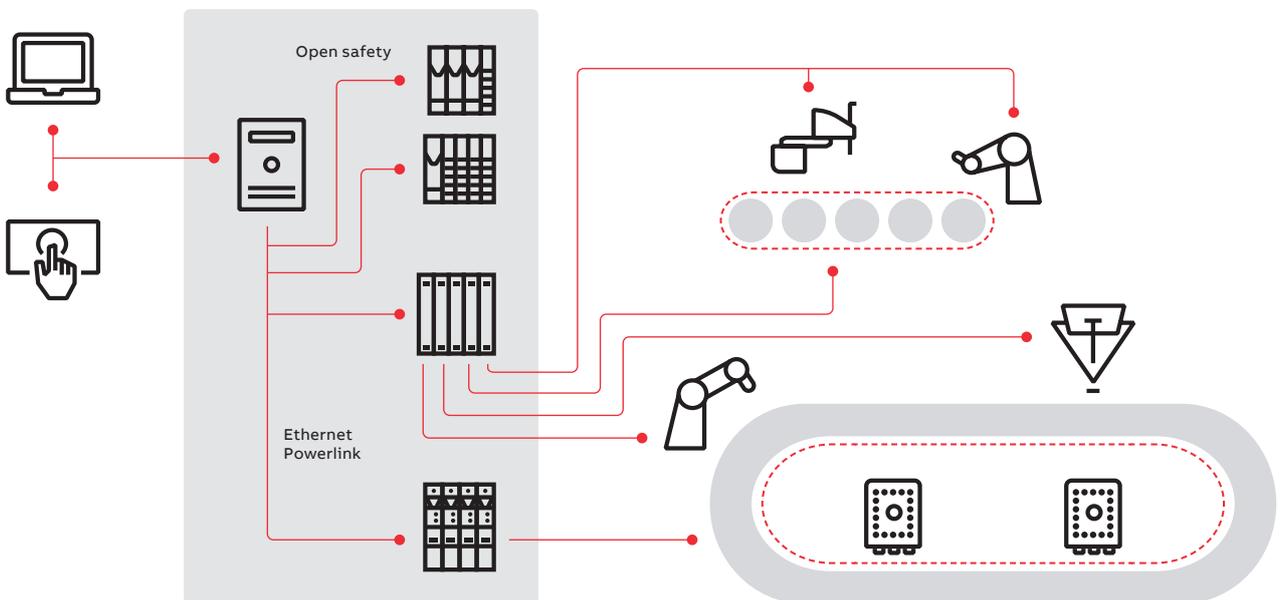
For B&R's customers – primarily those who mass produce machines – these developments are exactly what is needed. The main reason for this is clear: Normally, the task of integrating and programming a robot is resource-intensive, especially for small and mid-sized OEMs, because many machines depend on extremely fast, precisely timed processes. Coordinating these processes in hard real-time with an external device is a daunting if not impossible challenge.

A second reason is that the average PLC programmer is not familiar with the tools and programming languages used to develop robotics applications. And third, dealing with an additional supplier consumes time and resources.

What is more, although this new solution will give OEMs a single source they can turn to for



03



04



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03 B&R customers can choose from an array of articulated arm, SCARA, delta, and palletizer robots in various sizes and payloads.

—
04 Robots are fully integrated in the B&R system.

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[1] T. Okuma, "Editorial," 2018. Available: https://ifr.org/downloads/press2018/Editorial_WR_2019_Industrial_Robots.pdf

Footnote

1) SCARA (Selective Compliance Articulated Robot Arm) is a type of robot that is rigid in the third dimension.

both robotics and machine control, ABB's classic robotics offering will remain the same. That means that robot-centric applications such as automotive welding will remain in the domain of ABB's other robotics divisions.

The distinction between the two areas is straightforward. If an entire process centers around a robot – as is the case with welding – then it is clearly a robotics application. But if a robot plays only a supporting role – like sorting out defects at full production speed – that is what B&R's machine-centric robotics is all about.

Boot camp for robots

Obviously, the associated customers are as different as these applications. Machine-centric robotics is aimed at B&R's traditional audience: machine builders. Robot-centric solutions, on the other hand, are typically used by systems integrators and end users – in short, classic ABB

customers. Add it all up and it is clear that the B&R and ABB teams are now able to address the unique demands of each group's customers.

Both groups will benefit from synergies. Machine builders will be able to choose from a wide range of ABB robots →03, including articulated arm, SCARA¹, delta and palletizer robots in various sizes and with various payloads – characteristics

—
A pilot operation is now in progress and the first round of robots will be available in mid-2021.

that are particularly important for machine applications where a high degree of synchronization with other components is required, as is the case with picking solutions. They will also benefit from direct, comprehensive robotics and machine control system consultation and support. B&R on the other hand, will become the sales channel of choice for machine builders looking for robotics solutions.

In a nutshell, what the B&R and ABB engineering teams have accomplished is to optimize communication between B&R servo drives and the motors in ABB's robots →04. As this process nears completion, the teams are entering an intensive testing phase.

Each robot will undergo six months of fatigue testing boot camp. This phase is designed to guarantee that customers' robots, controllers, and drive system will all work together flawlessly. A pilot operation is now in progress, and the first round of robots will be available in mid-2021. •

 MACHINES WITH INTELLIGENCE

One-stop-shop solution for machine automation and robotics



B&R robotics specialist Sebastian Brandstetter explains how customers benefit from unprecedented precision in synchronization between robotics and machine control.

AR Mr. Brandstetter, what added value can an OEM expect to gain from integrating robots into their machines?

SB I see three main advantages. First, robots make machines more flexible. Second, a robot can often be the simplest way to accomplish certain tasks. Third, robots can do work that would be too hazardous, strenuous or monotonous for human workers.

AR Do many processes still require manual human intervention?

SB The amount of automation in manufacturing has clearly grown dramatically over the past three decades. Yet, there are still plenty of machines and plants where human workers are required for certain steps in the process. Imagine a sheet metal bending machine, for example. You still see workers inserting the sheets into the brake and turning them as needed until all the bends have been made. It's a very demanding job, and one that is increasingly hard to find qualified workers to perform.

AR Which makes it a perfect candidate for robots.

SB Exactly right. But not only that. In addition to inserting the sheets, the robot can also serve as an additional motion control axis in the bending process. Not to mention the fact that a fully

automated bending machine can run 24 hours a day.

AR Could you not build a machine like that with a conventional robotics solution?

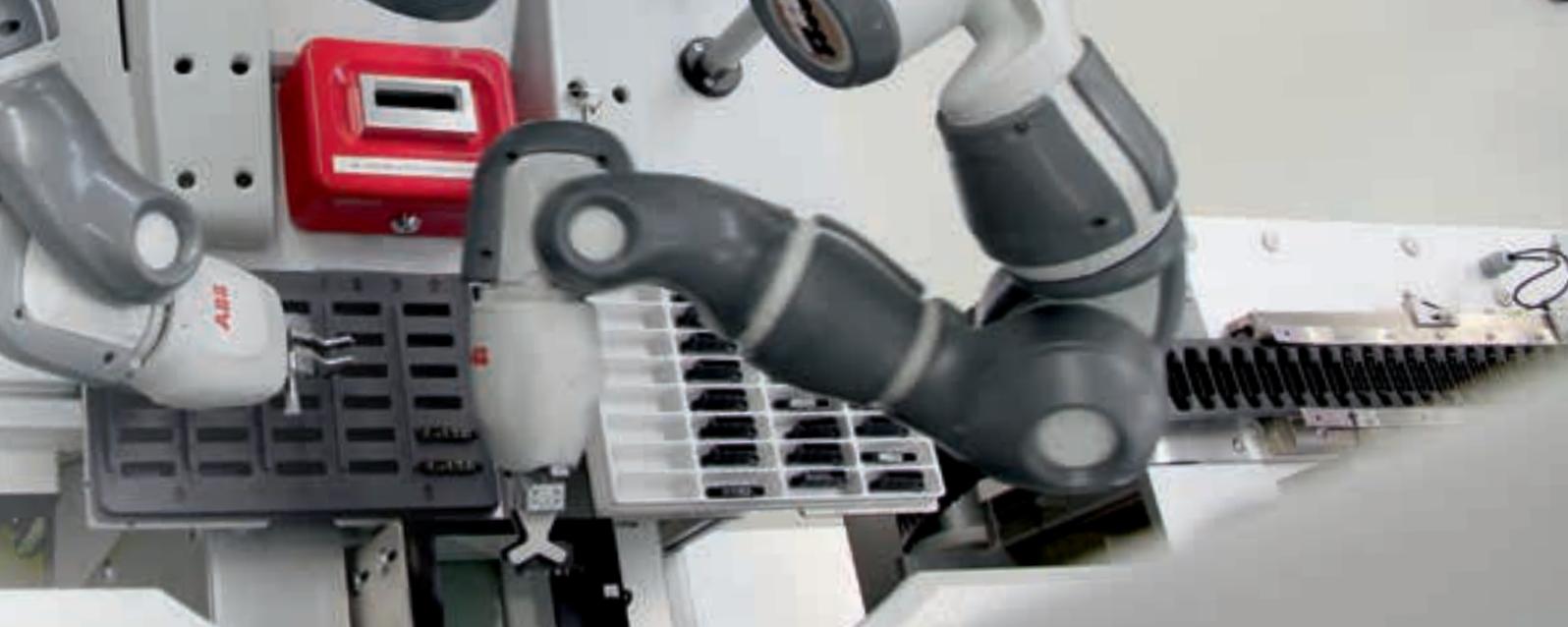
SB It is not that simple. The movements of the bending machine and the movements of the robot are tightly intertwined. To get quality bending results, the axes need to be exchanging

I do think an investment in robotics pays off in many more cases than people expect – including operator safety.

data constantly. The only real way to do that is to have the robotics application as an integral part of the machine – so you have only one controller and only one control application.

AR You mentioned earlier that robots make machines more flexible. Could you explain how they do that?

SB If you look at a typical production machine, it's designed to create a specific product, or even a specific model of a specific product. Sometimes there are complex mechanical systems in place to do things like move products from one level of the machine to the next. If anything about the product changes – its size, its shape or its weight – these systems all need to be adjusted, replaced or even completely redesigned. But a robot does not care about all that. It just quickly recalculates its path and is ready to go.



AR It sounds like robots would make any machine more productive.

SB I would not take it quite that far. But I do think an investment in robotics pays off in many more cases than people expect. That includes cases where operator safety is at stake.

AR How so?

SB Think about something with a lot of fast-moving parts, like a bottling line. Any bottles that are defective or have fallen over need to be removed from the line very quickly. If you want to have a human operator do that, you have to slow the line down to a safe speed so they can open the safety gate. But if you have a robot do it, the machine can continue uninterrupted at full speed.

AR When you add robots, do the machines require more space?

SB Quite the opposite, in fact. Integrated robots actually reduce a machine's footprint by performing manipulations that would otherwise require complex – and therefore large – mechanical

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Machine builders can offer their customers a new breed of machine: one that adapts automatically to new products.

systems. What is more, robots can be installed horizontally or upside down to save space. And for machine builders who combine robotics with an intelligent track system, there is even greater potential for optimization.



**Sebastian
Brandstetter**

Product Manager
Integrated Robotics,
B&R
Eggelsberg, Austria

AR For instance?

SB The shuttles on the track system can each be controlled independently and synchronized to the movement of the robot with microsecond precision. Processing steps can be performed while the shuttles are in motion and adapted for different products without any changes to the hardware. You get more output from a machine that takes up less floorspace.

AR What does that mean for machine builders?

SB They can offer their customers a whole new breed of machine: a machine that adapts automatically to new products – even ones that did not exist when the machine was first built. They can deliver on one of the most pressing consumer expectations: individualized products at mass production prices. •

 MACHINES WITH INTELLIGENCE

Explainable artificial intelligence: the key to trusting machines

How can we learn to trust machines? The key is to advance explainable artificial intelligence (XAI). ABB glances back at pioneering research by leviathan companies and examines current research into this business-essential field.



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Artificial Intelligence (AI) models permeate our daily lives, often without our realization: For instance, Netflix uses a recommender engine to suggest movies to its users. This seemingly simple process uses machine learning (ML) to help the algorithms automate millions of decisions based on the user's activities [1]. Facebook uses its patented process "computer vision contact detection system" to recognize objects as it sorts through images on user accounts for logos and brands so advertisers can target users with ads in sponsored story posts [2]. Beyond entertainment and advertising, big data science and ML is infiltrating mission critical applications like disease detection and



K. Eric Harper
Former ABB employee

AI models are difficult to explain even among data scientists, thereby making acceptance problematic.

diagnosis, loan application decision-making and self-driving cars. These applications can have a crucial impact on our lives. Which movies to view might be frivolous but whether a mortgage is to be issued or not is highly pertinent. Here lies the crux of the problem: these AI models are difficult

to explain even among data scientists, thereby making acceptance problematic. Without the ability to explain the models, or "explainability", it is likely that these models will not be accepted or used. Furthermore, the General Data Protection Regulation (GDPR) calls for greater transparency in data processing and clarity in AI processes, thereby making model explanations essential [3].

Whether humans or machines are involved, a decision rationale would foster an understanding of the motivation behind models and create a sense of urgency; this would increase the likelihood that the resultant recommendations could be accepted and implemented. Without this understanding it is impossible to trust the machines we build. So, ABB researchers delved into the history of explainable AI to illuminate how past lessons can enable future AI expansion.





Rationale for early industrial AI

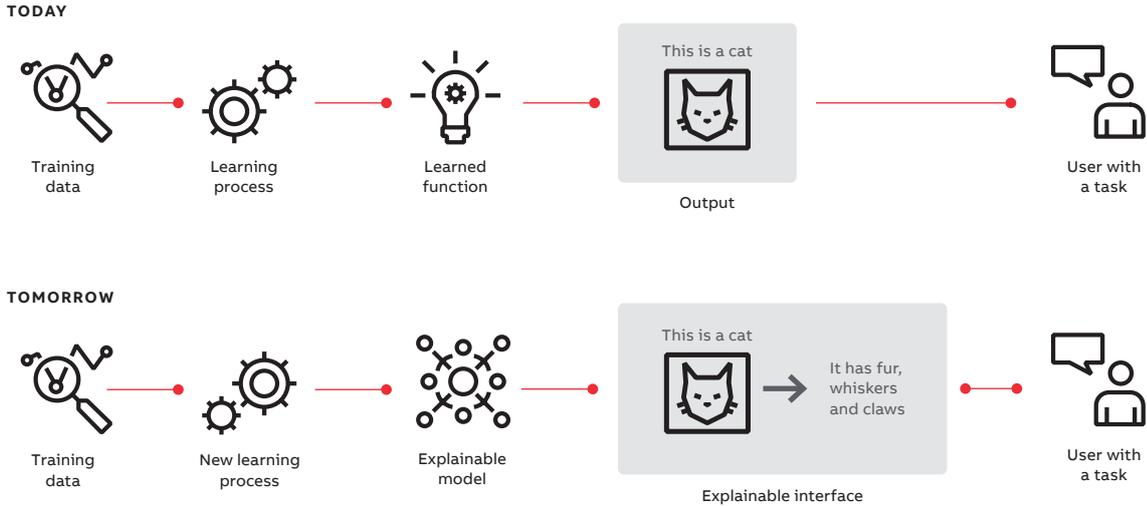
This currently active research area began with the requirement that diagnoses be defensible. In the 1980's the first operation-focused knowledge-based decision support system was invented and commercialized by Westinghouse with Carnegie Mellon University [4]. A contributor to the accomplishments cited in this paper, Eric Harper, was directly involved in GenAID, TurbinAID and ChemAID (Artificial Intelligence Diagnostics) and contributed to intellectual property and software technology advances based on a key patent that focused on an operation system [5] with evidence and best practice to address abnormal conditions. Subsequent Westinghouse patents describe a method and system to exhaustively exercise a knowledge base in order to confirm that expected outcomes result from known inputs of abnormal data [6]. Harper built

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ABB researchers have delved into the history of XAI to illuminate just how to enable future AI expansion.

the tools and techniques for exploring knowledge and tracing support to justify specific actions based on diagnoses. This critical intellectual property is now in the public domain and these findings are still relevant today [7].

Innovations for explaining AI results

Recently, a prominent software consultancy adopted ideas to generate a model based on knowledge representation. Their US patent



01

application suggests that a combination of k-means clustering, principal component analysis, forward or backward chaining, and fuzzy logic would resolve the general problem of explaining AI results in the real world [8]. Utilizing additional methods →01, a credit rating agency that manages credit risks runs models exhaustively with different inputs to successfully show customers how various inputs lead to different outputs, thereby helping customers understand the credit decisions made [9]. In a US patent application, Intel describes a technique to identify discrepancies between observed results from the machine learning training phase, and results obtained during operation [10]. Another Intel patent application describes the influence of neural networks for explainable AI: this process comprehensively traces dependencies and strength of support, between lower and higher neural network layers, back to their input features in a way that looks surprisingly like a forward chaining expert system [11]. Google combines these ideas with their tools and framework [12]; IBM established a similar platform [13].

Explainable AI trends

This resurgent research attention in XAI is classified into distinct categories based on the degree of transparency: graded from complete black box (low transparency) to white box characteristics (high transparency) [14]:

- Opaque systems
- Comprehensible systems
- Interpretable systems

Although there are many benefits to designing and developing XAI models, they can add significant costs. The trade-off is between explanation

and accuracy. This balance and degree of transparency will be driven by business needs and how the application is adopted in the real world.

The logic behind the decisions of ML models is complex and not apparent. Trusting the resultant critical decisions without governance is problematic. This concern was daunting from the beginning: neural networks were available in the 1980's for machine diagnostics but were not implemented. Hence, it is increasingly important to provide XAI in specific domains. In this way, XAI models can be subjected to formal verifica-

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XAI development will be driven by business needs and how models are adopted in the real world.

tion, and this capability is especially important for medical applications where recommendations have life and death consequences.

Another challenge needs to be addressed before ML models can be readily accepted: a bias is exhibited if the training data does not span the complete solution space [15]. Such bias defects might be revealed if tests are performed across a wide range of conditions to benchmark the solution's strengths and weaknesses.

Still, dazzling new insights can be won from XAI models. Today's ML systems are trained through

— 01 Schematic illustrates how to open up “black boxes” with explainable AI today and in the future. This model was developed by FICO [9].

— 02 A practical support for decision-making is shown redrawn from Bellows, et al., [23]. Decision-making relies on calculating confidence (CF), severity (SEV), and importance (IMP).

Footnote

1) Go is an abstract strategy board game for two players.

millions of examples so that data patterns can be recognized that are not obvious to humans. Westinghouse’s earlier dream that engineers would one day pore over the data collected from models like GenAID, apply data science methods and discover new innovations is almost realized. New insights have emerged through use of XAI systems: one can extract distilled knowledge from the machine learning to acquire new perceptions, eg, new strategies for playing Go¹ were developed with ML and are now used by human players.

Nonetheless, opaque decision support is not attractive to businesses. Clearly, a bank must communicate why a credit request was rejected. And, AI models must comply with the law by providing evidence for the decisions generated.

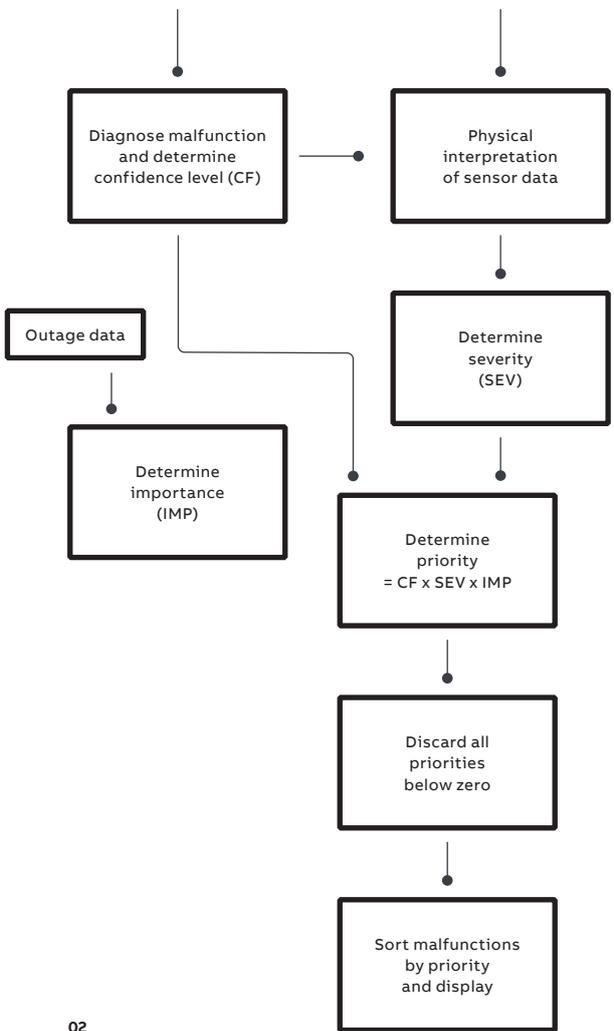
Generalization of these concerns led the European Union to adapt new regulations that

implement a “right to explanation”, whereby a user has the right to ask for the rationale of a relevant algorithmic decision. There is hope that XAI will provide the confidence, trust, fairness and safety that is required for ML models in training and operating modes to win over businesses [16].

Explaining AI models: the current state of affairs

Currently, two approaches are used to make AI models more explainable. First, the model structures are inherently selected with an interpretation goal in mind. Alternatively, complex AI models are reverse-engineered to make them comprehensible. However, designing models with easy-to-understand rationale can compromise accuracy and vice versa, eg, complex Deep Neural

ML systems are trained through millions of examples so that data patterns can be recognized that are not obvious to humans.



Networks (DNN) are accurate but lack interpretability. Algorithms like linear regression or decision tree-based models are much easier to explain but less accurate. Striking a balance between accuracy and interpretability of AI models is currently the focus of intense research [17].

Another XAI research area examines the difference between local and global interpretability [18] →03. The local perspective, from sensitivity analysis (SA) principles, identifies how the model output changes with input or tuning parameter perturbations. Although not producing an explanation of the function value itself, SA can determine the factors and configurations that explain the model results. The global perspective uses two techniques. Layer-Wise Relevance Propagation (LRP) redistributes the prediction function backwards, starting from the output layer of the neural network and back propagating to the input layer. LRP explains the classifier’s decisions by decomposition and can be represented by heatmaps [19]. Data-driven Intrusion Detection System (IDS) is an adversarial approach used to find the minimum modifications (of the input features) required to correctly classify a given set of misclassified samples. The modification magnitude visualizes the most relevant features that explain the reason for the misclassification. Both LRP and IDS were combined by researchers to play Atari games driven by Deep Reinforcement Learning (DRL) [20].

Research in the field of XAI has been extended to enable dataset comparisons. Linguistic Protoform Summaries in tandem with Fuzzy Rules are used to design a system that can compare various datasets [21] numerically and explain

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ABB delivers value to customers by incorporating AI advances to improve predictive maintenance, optimization, and performance.

differences using natural language. So-called, Human Machine teaming is a key factor in XAI research in which usability is an important consideration for model design and use. Here, ML models should allow a user to interactively tune the models based on iterative learning [22].

A practical approach for decision support

Engineering teaches us that any complex problem can be solved by dividing the work into multiple components, building and verifying them independently and integrating them back together for a complete solution. In the 1980's, a Westinghouse system for explainable decision support and asset management invented techniques [23] to prioritize the repair of plant equipment by validating measurements and then fusing current conditions into system diagnosis



and recommendation →02. A major electrical equipment manufacturer continues to use this system for site-based monitoring of power plants and turbo generators, and runs the service in their Power Diagnostics Center [24]. Fundamentally, potential issues can be ranked based on three dimensions:

- CF – confidence level in a diagnosis
- SEV – reciprocal of the time to failure
- IMP – costs caused by failure and to repair maximum damage

These dimensions are calculated for each of the equipment sensors, components and systems that contribute to a malfunction or outage: this combination is used to determine the action priority for each possible malfunction. The rationale for the ranking was explainable to customers: the three dimensions, and diagnosis details were traced back through components and sensor readings. In this way customers could accept the rankings without necessarily delving into the details.

Relevance to ABB

Since computing power was sparse in the 1980's, automated service solutions were tuned to extract the best performance with limited resources. Nowadays, each of these originally construed characteristics can be calculated for even the finest granulation of components and then assembled based on their relationships and dependencies. ABB excels at employing knowledge and processes gleaned from early work for their automated service solutions. Today, ABB relies on a wealth of condition monitoring solutions that indicate confidence levels whenever problematic equipment issues arise →04–06. ABB Ability™ Advanced Digital Services solutions contain features that address the critical issue



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03 Explainable AI makes it possible for users to understand and accept decisions. The ability to discover, to control and to justify are all interconnected.

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04 At ABB, AI has radical potential and so is being applied in many industrial domains. For example, during an industrial analysis at a plant, the engineer tags patterns of interest that can then be used to train a classifier based on RNNs.

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05 By designing explainable AI in ABB sensor diagnoses, plant operators and managers can understand and accept what needs to be done.

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06 Customers benefit from explainable AI without the need to understand all the calculations used to make decisions.



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of time-to-failure. With talented engineers and information scientists available, ABB produces data science solutions for calculating the important dimensions: CF, SEV, and IMP where appropriate. A keen understanding of the overall cost of

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By designing XAI in applications, ABB stands out in the market: This fosters trust – more crucial now than ever.

repair following failure positions ABB to diagnose issues based on data; this has led to new services like ABB Ability™.

As a pioneering leader in the industrial automation domain, ABB delivers value to customers by incorporating AI advances to improve predictive maintenance, optimization, and performance. Nonetheless, plant operators and managers must understand the justification and rationale behind decisions generated by AI models, recommended by operations and service applications, before they will implement potentially costly actions →05. By designing explainable AI in applications, ABB stands out in the market: This fosters trust – more crucial now than ever. When models are explainable, experts and end users can be assured that outcomes are bias-free, safe, legal, ethical and appropriate. •

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MACHINES WITH INTELLIGENCE

Golden batch analytics produce consistent top quality

Batch processes, though agile, are complex, dynamic and nonlinear. ABB Ability™ BatchInsight quickly detects evolving process abnormalities in such processes and isolates the relevant process variables so the operator can reduce off-specification product and energy consumption and increase productivity.

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01 Big data can be harnessed to improve productivity and energy efficiency in the process industries.

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Big data processing architectures like Hadoop or Spark enable new possibilities to analyze and exploit historical data generated by process plants [1,2]. Predictive maintenance, operation support, soft sensing for monitoring and control, and integration of control and enterprise resource planning (ERP) layers are just some of the envisioned applications of such technologies in the process industry sector.

One area in particular where big data can be exploited to make significant improvements is the batch process industry →01. Accordingly, ABB, in collaboration with experienced end users at a pilot customer, has developed ABB Ability™ BatchInsight, an operator support system able to detect and troubleshoot abnormalities in a batch in real time. This online system helps operators to run plants in a smooth and trouble-free way as emerging process issues can be detected at an early stage and corrective actions taken while the batch is running.

The adopted approach uses historical data to learn the expected behavior of the batch process under nominal conditions and builds a statistical “golden batch” model, which is then used as a reference for the batch currently under production. Deviations from this golden batch model generate a warning to the operator.

Application scenario batch analysis

More than 300 batch runs from a period of over two years were sourced from the pilot plant and used to generate a statistical golden batch model reflecting all the possible good batch behaviors →02.



02

 A screenshot of a data table with columns for 'Batch ID', 'Start Time', 'End Time', 'Yield', 'Quality', and 'Status'. Red arrows point to the 'Batch ID' column with the text 'Batch ID used for modeling', to the 'Quality' column with 'used for modeling good batch for verification', and to the 'Status' column with 'Bad batch for verification'. The table contains several rows of data with numerical values and status indicators.

03



Deviation over time (dark green: all variables; light green: a selected variable)

04

Contribution per variable

Contribution of one selected variable over time: currently investigated batch (blue) against a reference batch (grey)

—
02 ABB Ability™
BatchInsight batch
label dialog.

—
03 ABB Ability™
BatchInsight model
editor.

—
04 Contributions to the
deviation per variable
and over time.

As a first step, these batches were labelled as “good” or “bad” – an exercise that is often not as straightforward as it first seems. For example, a batch might have started to go in the wrong direction, but then the operator intervened and made sure that the batch was produced smoothly – ie, in time and with good quality. From the perspective of the plant, this is a good batch, whereas, from the perspective of machine learning, it is a bad batch, because without the operator intervention a production problem would have occurred. To complicate matters, the

ABB Ability™ BatchInsight contains a detailed model of a batch, as defined in ISA88.

operator may also have intervened for a reason that has nothing to do with potential unwanted behavior. During production, it is usually clear to the operators what is going on, but later on it is sometimes much less obvious why the trend curves look the way they do; important operational context can get lost. Modern big data analytical tools depend on such context information. It is crucial to develop a system to record this information and train and motivate operators to use it appropriately.

→02 shows an example of a ABB Ability™ BatchInsight batch label dialog. It can be easily extended with additional label groups. In this example four groups are shown: BatchDuration, Quality, BatchOperation and Shift (“Schicht”) and individual labels. The currently selected label group is marked blue and the labels it contains are shown below. The batch label dialog can be opened from all places where batches are involved. It is also possible to assign labels automatically via scripts. Later on, when the analyst needs to decide which batches are used to build the model, the labels can be of critical assistance.

The model editor is used to select appropriate historical batch runs for the golden batch model →03. In addition, known good batches and known

bad batches can be used for verification to ensure that the model has a sufficient quality level.

Batch alignment

ABB Ability™ BatchInsight contains a detailed model of a batch, as defined in ISA88, a standard addressing batch process control. This model includes timestamps of the start and end of each batch operation and phase. Batch durations differ from one batch to the next. Dynamic time warping (DTW) – a time alignment technique – is used to stretch or compress the datasets to make them comparable without losing or changing the dynamic characteristic of the data.

Alternatively, a computation of similarity between batches can be used to generate a similarity index that can be compared with a reference value. This approach allows a finer and more efficient analysis: because a group (or “cluster”) of batches might exhibit the same types of abnormalities, the diagnosis could be made only for a subset of these batches. Ideally, such clusters would separate good and bad batches.

Dimensionality reduction

While clustering allows batches that are similar to the reference (nominal/healthy) batch to be separated, more details are required in order to diagnose faulty batches. A multiway principal component analysis (MPCA) [3] is, therefore, used to analyze the reasons for the batch failure. This approach focuses on the process variables that statistically explain the detected batch variability. An online implementation of this technique allows early detection of an abnormal evolution of an ongoing batch.

Estimation of batch quality

One key ambition of a batch operation is to ensure that the product target quality is reached. Current industrial practice is to take samples from the batch during its evolution and send them for laboratory analysis. Based on the analysis results, the process operator adjusts the batch process variables and the batch process duration accordingly.

Partial least squares (PLS) regression is a linear dimensionality reduction method that allows the statistical analysis of highly correlated large multivariate datasets. Batch process quality monitoring relies on a variant of PLS – multiway partial least squares (MPLS).

An MPLS model is a regression model that relates the batch quality to the batch process variables, acting, therefore, as an inferential (soft) sensor able to tackle a crucial issue in the process industry: the lack of reliable online quality measurements. In addition, MPLS is able to predict quality measurements hours before they become available from the lab. In some cases, this can shorten waiting times and lead to better asset utilization.

Diagnosing the details

Once ABB Ability™ BatchInsight detects a significant deviation from the golden batch model, the operator's display shows what is different →04. Compared to a single-variate analysis, multivariate analysis techniques can take correlations between variables into account.

Supporting the expert

Batch processes can be complex, even for domain experts: Good/bad batch decisions must be taken, statistically relevant process variables need to be identified and, in the end, fine-tuning is required. Therefore, ABB Ability™ BatchInsight includes novel techniques that support the preparation of the process analysis, including

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ABB Ability™ BatchInsight allows batches that deviate onto a bad trajectory to be dynamically corrected.

automatic identification of relevant variables for the different phases of the batch process and an automatic proposal of batches to use for the MPCA and MPLS models. These techniques act as recommenders and free up the expert



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to investigate core issues using ABB Ability™ BatchInsight's analytics techniques →05.

Online batch monitoring

ABB Ability™ BatchInsight's online alignment algorithms allow batches that deviate onto a bad trajectory to be dynamically corrected and key process variables inside a corridor derived from previous golden batches can be shown →06. In addition, statistical key performance indicators calculated from multivariate analysis can be used to generate alarms. A challenge faced during online monitoring is that it is often unclear how far the process has already progressed.

Feedback from the application partner

Tests were run together with the end user (a batch chemical plant) with historical batch data emulating an online approach (meaning data for the current batch was only available until the current step). The MPCA model was used to detect a foaming problem that occurred in a fraction of the batches. The model was trained only with batches without foaming. In 83 percent of the cases, the system was able to predict a foaming



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05 Because ABB Ability™ BatchInsight does much of the process analysis work, the expert is freed up for core issues.

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06 ABB Ability™ BatchInsight improves the process by dynamically correcting batches that move out of the desired process window.

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In 83 percent of the cases, the system was able to predict a foaming event at least 5 min before it occurred.

much appreciated tool that alerts operators and enables them to react in a timely fashion to an abnormal situation – here, foaming events – by adjusting the correct process variable. Such timely interventions lead to a reduction of off-specification product, energy and wasted production time. •

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event at least 5 minutes before it occurred. Often it predicted the foaming hours before. Although foaming was wrongly predicted in 17 percent of the cases, the predictions are very helpful as the operator can then focus on suspect batches.

Keeping the batch on track

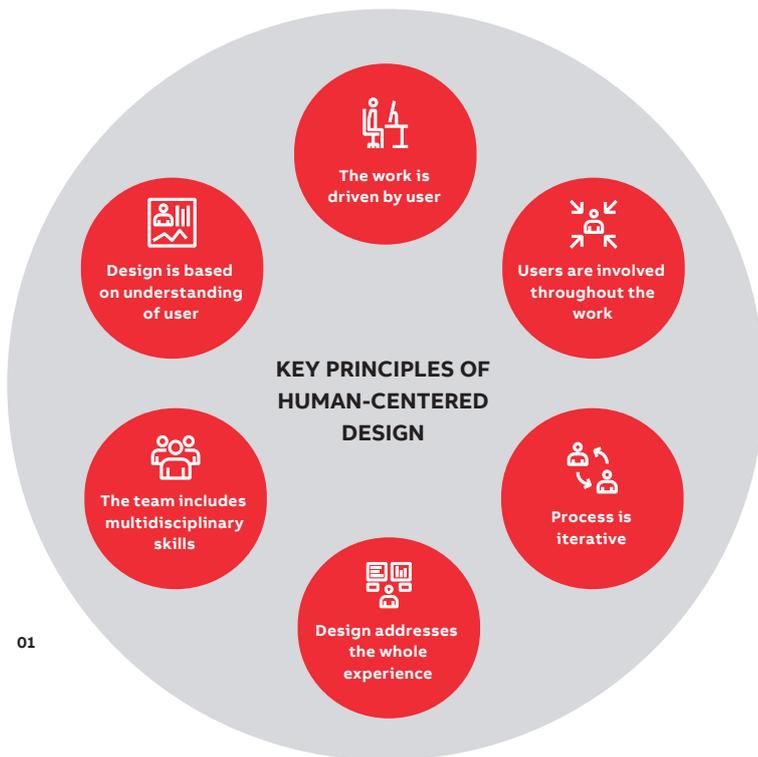
The ABB Ability™ BatchInsight online operator assistant, developed and validated in close collaboration with an application partner, allows the early detection of process abnormalities and the isolation of the process variables explaining them. An operator may be responsible for several batches running in parallel production lines or even have other tasks inside the plant. Here, ABB Ability™ BatchInsight provides a

MACHINES WITH INTELLIGENCE

Humanizing technology

Technology, connectivity, and data processing capabilities are developing and breaking new ground at a dizzying rate. Even so, raw performance is only half the story. The greatest breakthroughs are of little value if humans cannot use them to their potential. At ABB, user experience (UX) and customer experience (CX) are an integral part of the design cycle.





01



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Computers are intended to be an extension of the human brain. The transfer of thoughts, information and commands must be as seamless and effortless as possible. In other words, an interface must be intuitive and natural to use. Users should be able to access and master new tools and functions with as little learning curve as possible.

In the past few years ABB has increased the number of dedicated UX experts across all parts of the company to support and revolutionize digital product design processes. The ambitions and targets are high: By 2025 all ABB digital products will have undergone a redesign with emphasis on alignment and coherence.

Good UX design is not just a method or discipline but also a mindset. Emphasis is placed on “outside-in” thinking – meaning the designer perceives the requirements from the customer’s perspective. This approach is often labeled “design thinking” [1] and involves a holistic, highly-creative and iterative methodology →01.

ABB combines expertise in human-centered design with its long-standing knowledge of the industries it serves. In doing so, ABB advances the capabilities of automation and tackles sustainability challenges – areas that are key for customer effectiveness and profitability in the digitally transformed landscape.

The quality of UX is commonly viewed as a competitive advantage, and will continue to develop

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Emphasis is placed on “outside-in” thinking – meaning the designer perceives the requirements from the customer’s perspective.

as a cross-functional discipline. In 2020, Google announced that UX is about to become an important ranking factor¹ for all websites, while a recent LinkedIn report [2] indicates that UX design is one of the top five in-demand skills.

The focus of product and service creation will be on meaningful features and user-friendly interfaces. The goal is to humanize the technologies ABB delivers to customers and users.

Articles in upcoming issues of ABB Review will present and expand on different aspects of the company’s UX approach and philosophy. •

01 Human-centered design is an ISO standardized process. The essence of it to work in a highly collaborative, holistic and iterative manner, have customer focus in all activities, and to apply multidisciplinary skills.

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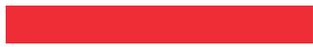
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Footnote

1) Ranking factor describes the criteria applied by a search engine when evaluating web pages in order to compile the rankings of the search results.



Sensors

and

analytics





An old saying goes something like this: The world’s problems look like nails if all you have is a hammer. The analytic and predictive capacity of today’s digital tools only get better with more data but that data needs to be more accurate and diverse. ABB is working with customers to offer something more than hammers.

- 40 From sensors to deep insights
- 46 Advanced digital services for gas analyzers

SENSORS AND ANALYTICS

From sensors to deep insights

ABB Ability™ Smart Sensors and remote monitoring systems boost safety, extend equipment life, and significantly, or even completely, eliminate downtime. They are also opening the door to the Factory of the Future – a concept in which data collected from equipment such as motors, mounted bearings, gearing, variable-speed drives, and pumps is combined and can be accessed and analyzed remotely, providing deep insights into the health of entire processes.

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01 IoT-based wireless sensors allow for permanent monitoring of a vast range of devices and processes.

—
02 The ABB Ability™ Smart Sensor for mechanical products.

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03 ABB's Smart Sensor enables companies to benefit from the IoT.

Smaller, smarter, safer. These are some of the key characteristics that describe the evolution of sensors over the last decade. More recently, however, the value of sensors has been further accentuated by three separate developments: the availability of cloud computing, data analytics, and mobile data transmission [1]. These developments have opened the door to the arrival of IoT-based wireless sensors that allow for permanent monitoring of a vast range of devices and processes at a fraction of the cost of traditional condition monitoring systems →01.

Indeed, smart sensor-based condition monitoring is providing users with the data tools to follow their equipment throughout its entire life cycle and track exactly how such equipment

—
Digitized sensing produces continuous, consistent, high-quality information that supports reliable operation and optimization.

reacts to a user's specific conditions and processes. Users can track, quantify, and eventually predict maintenance intervals, life-expectancy, and replacement schedules.

Representing a quantum shift away from traditional vibration measures, which require physically attaching discrete-point sensors to collect data, long periods between measurements, and potential safety risks to maintenance personnel, the world of digitized sensing produces continuous, consistent, high-quality information that supports reliable operation and optimization, while making it possible to capture any deviations in standards, thus ensuring real-time quality control [2].

A smart sensor is born

An example of the convergence of these trends and capabilities is the ABB Ability™ Smart Sensor

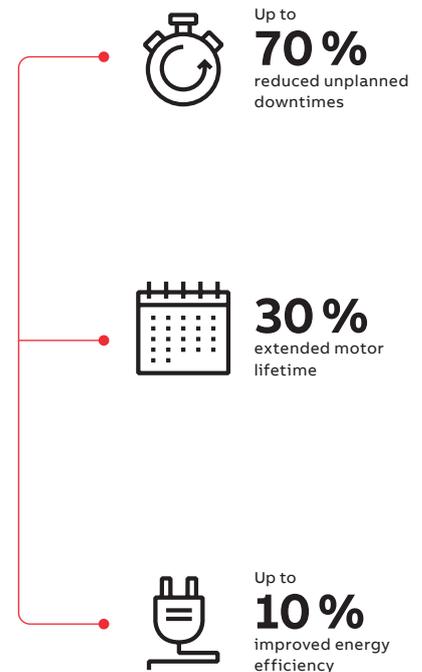


02



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03

for mechanical products →02. Essentially a monitoring solution that provides an indication of a device's overall health, the sensor delivers an indication of whether maintenance is needed. In the course of this process it provides warnings, allowing users to plan maintenance before problems arise, and thus avoiding downtime →03.

Furthermore, thanks to the sensor's ability to monitor equipment remotely, maintenance teams can safely check equipment health without the

KEEPING A HISTORIC CAMPUS OPERATIONAL



04a

The ABB Ability™ Smart Sensor is already paying dividends at the University of Virginia in Charlottesville, US →04a [3]. When the Covid-19 pandemic forced the closing of the University in early 2020, a maintenance team responsible for the campus's McCormick zone relied on over sixty-five ABB Ability™ Smart Sensors for mechanical products to keep critical lab environments stable and equipment performing. The ability to know when there was a problem – without physically being there – also allowed the university maintenance team to operate safely.

The maintenance team is responsible for ensuring that approximately ten buildings on campus maintain comfortable temperatures for students and faculty, and that each research laboratory in the zone maintains the stable environment needed for controlled experiments. Past maintenance practices required nearly daily adjustment of air handling equipment, much of which is impossible to access without shutting down equipment →04b.

Late in 2019, the team learned about ABB Ability™ Smart Sensors for mechanical products and decided to test a number of them on bearings. The sensors, which immediately began providing real-time information regarding the status of equipment, operated so efficiently that more were soon added to critical air handling unit bearings across the facility. This, in



04b

turn, led to the discovery of unidentified problems in equipment that had not previously appeared to require maintenance or replacement. After each correction, the team added a sensor and compared pre- and post-repair results, ultimately determining that post-repair vibration levels were nearly perfect and proving that repairs had been properly performed. Thanks to the quality of the resulting information, the maintenance team's schedules and spare parts inventory management have become increasingly predictable. The team now knows what truly needs attention each day, rather than merely relying on a prescribed maintenance schedule, and has been able to minimize and optimize downtime.

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 04 Over 65 ABB Ability™ Smart Sensors for mechanical products keep critical lab environments stable and equipment performing at the University of Virginia.

04a The University of Virginia was founded in 1819.

04b A Smart Sensor in an HVAC application similar to those at the University of Virginia.

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 05 ABB's new plug and play gateway allows customers to seamlessly connect to ABB Ability™ Smart Sensors in most remote locations using AT&T or Verizon cellular providers.

risk of physical contact – a key feature since it obviates the need for technicians to remove safety guards to access equipment for routine maintenance.

Another big advantage for maintenance teams and operators is that sensor data allows them to focus specifically on those pieces of equipment that actually need attention rather than inspecting every machine – and trying to figure out if a certain level or type of vibration or temperature potentially spells trouble. Rather than calling in experts, the Smart Sensor provides maintenance personnel with the data to make decisions and avoid breakdowns →04.

Wireless options

Operators can choose how often data is collected – say once every 15 minutes or once every 12 hours – depending on the dynamics of a process. And technicians have several wireless options for accessing and collecting the resulting data: through ABB's gateway, through a new Plug & Play gateway →05, or by means of a smart phone app, thus making it possible to monitor conditions on the spot or from a remote location.

Users can check the status of equipment, for instance, at any time with a smartphone via the ABB Ability™ Smart Sensor app →06. The interface includes a red, yellow and green “traffic light” display that provides a quick overview of the condition of every asset that is being monitored.

Factory of the future

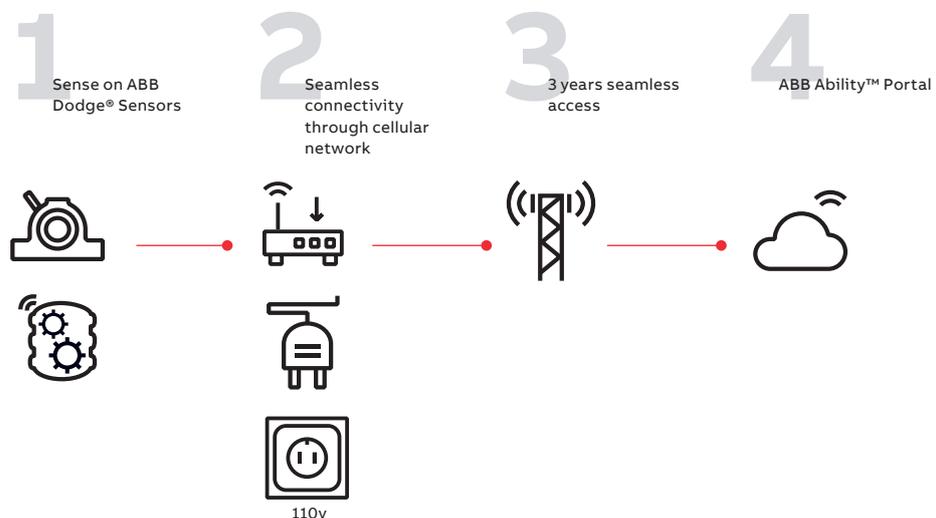
Smart, connected factories are the future of manufacturing. ABB Ability™ connects users to the power of the Industrial Internet of

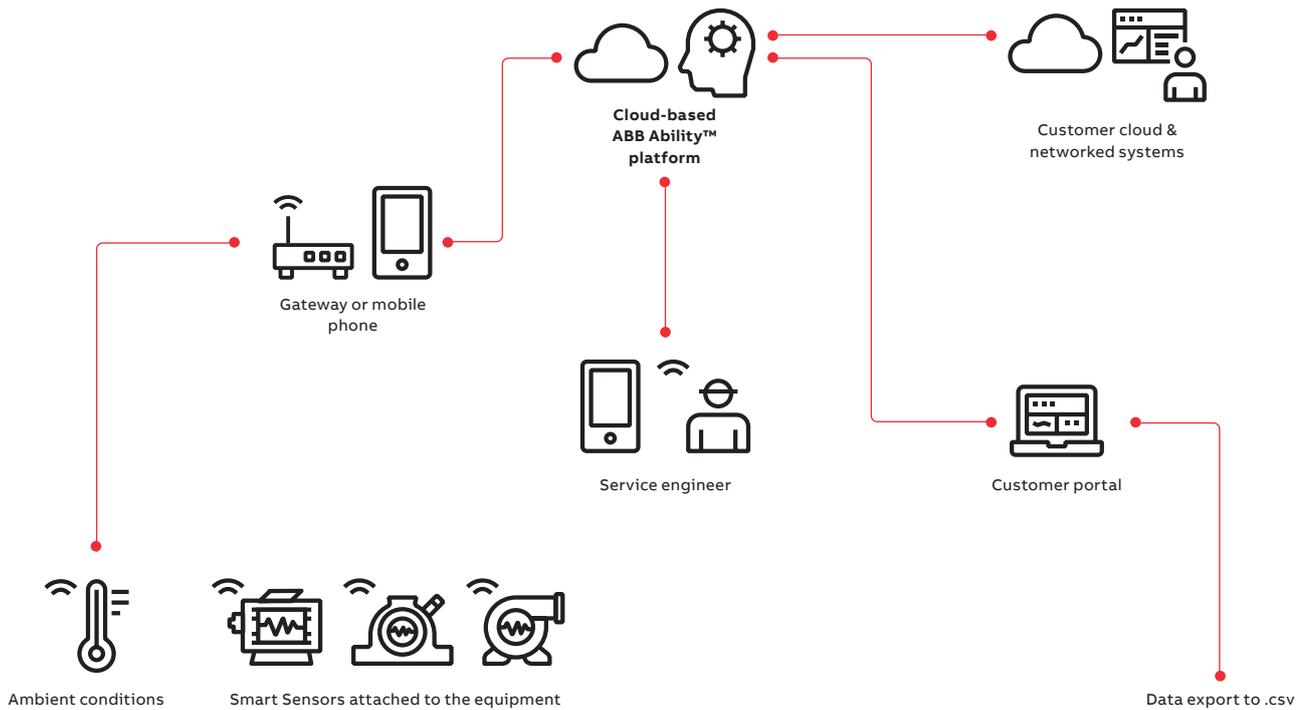
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 Users can check the status of equipment at any time with a smartphone via the ABB Ability™ Smart Sensor app.

Things (IIoT) by combining data collected from equipment such as motors, mounted bearings, gearing, variable-speed drives, and pumps. This data can be accessed and analyzed remotely, providing deep insight into the health of the entire process.

Specifically, data can be transferred to the ABB Ability™ Digital Powertrain monitoring platform. This offering is a suite of digital solutions, including devices, software, and services that combines connectivity and data analytics to make customer operations efficient, predictable, and safe.

Data from multiple sensors can be transmitted by a user's smartphone or the gateway to a secure, cloud-based server, where it can be analyzed by advanced algorithms to identify faults. The data is stored in the ABB Ability™





06

digital portal, from which it can be accessed and graphically displayed for further analysis. Naturally, all of these capabilities are based on the highest level of cybersecurity. Users have the option of setting up a personal identification

Data from multiple sensors can be transmitted by a user’s smartphone or the gateway to a secure, cloud-based server.

number for each sensor and all communications are based on the latest Transport Layer Security (TLS) protocols.

The new plug & play gateway solution, which relies on two of the most popular cellular providers in the U.S., provides seamless connectivity from sensors all the way to the ABB Ability™ digital portal.

All in all, the ABB Ability™ Smart Sensor converts traditional motors, pumps, mounted bearings, and gearings into smart, wirelessly connected devices. It measures key parameters, such as vibrations and temperature-related conditions from the surface of equipment, which can be

used to gain meaningful information regarding condition and performance. This enables users to identify inefficiencies within their systems and reduce risks related to operations and maintenance →07.

Furthermore, thanks to new firmware, the Smart Sensor can be updated to also display features such as velocity RMS, change measurement interval, change accelerometer range, and start/stop detection. These features, all of which are the result of customer feedback, significantly enhance the Smart Sensor’s existing capabilities. •

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06 ABB's condition monitoring solution for motors.

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07 ABB Ability™ Smart Sensors have given GrainCorp the ability to actively monitor its equipment bearings.

07a GrainCorp has worked with ABB and A1 Electric Motors to develop a custom solution based on ABB Ability™ Smart Sensor technology.

07b ABB Ability™ Smart Sensor technology is helping GrainCorp by alerting the company to spikes in the temperature of its cooker bearings.



07a

IMPROVING THE EFFICIENCY OF THE OILSEED INDUSTRY'S REFINING

The ABB Ability™ Smart Sensor is bringing improved efficiency and savings to Australia's oilseed industry. GrainCorp Oilseeds →07a is a regional Australia canola seed crusher and oil refiner with a 20-year track record producing canola oil and a range of oils and meals for domestic and international markets [4].

In response to alignment issues and associated overheating in its main cooker bearings, GrainCorp worked with ABB and its channel partner, A1 Electric Motors, to develop a custom solution based on ABB Ability™ Smart Sensor technology. The system designed for GrainCorp featured bearing sensors, motor sensors and a gateway. This has given GrainCorp the ability to actively monitor its equipment

bearings and assess their condition with a view to preventing failures. Indeed, the implementation has been so successful that GrainCorp is now in talks to integrate the sensors into the ABB Ability™ Digital Powertrain monitoring platform. Consolidation into this complete program would enhance A1 Electric Motors' capability to remotely monitor GrainCorp's assets on its behalf, which is particularly important since site access is strictly limited and traditional condition monitoring activities are restricted to limited periods. All in all, empowering GrainCorp to proactively monitor its primary cooker bearings and motors and to support these steps with expert service has boosted process efficiency and virtually eliminated the potential of system failure →07b.

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07b

SENSORS AND ANALYTICS

Advanced digital services for gas analyzers

With environmental regulations tightening, emissions monitoring equipment must be kept in first-class order. ABB Ability™ digital services for gas analyzers enhance the benefits of preventive maintenance and aid the shift from preventive to predictive maintenance.



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Air pollution regulations are becoming tighter in many countries, with regulatory focus on continuously validated measurements of emissions. Many countries now require 24/7 monitoring of NO_x, carbon monoxide, carbon dioxide, sulfur oxides, hydrochloric acid and hydrogen fluoride. Often, dust, mercury and dioxins must also be

Digital services for gas analyzers can aid the shift from preventive to predictive maintenance.

monitored. Not surprisingly, these tougher regulations bring with them increased compliance overheads for operators: In Europe, for example, measurements must be validated every hour. Three hours without measurements invalidates an entire monitoring day and annual monitoring downtime may not exceed 11 days (97.5 percent availability).

ABB Ability™ digital services for gas analyzers
Unfortunately, just as regulations are becoming stricter, in-house analytics expertise is becoming rarer. This diminishing pool of knowledge can lead to delays in troubleshooting emission-gas

analyzer issues and, thus, endanger emission compliance. A robust approach to maintenance helps counteract this risk.

Until now, ABB gas analyzers have very often been subject to a preventive maintenance strategy in which periodical inspections and service interventions are performed to reduce breakdowns and enhance equipment life →01. This approach guarantees availability and removes the burden of knowledge from customer-supported personnel.

Now, digital services for gas analyzers can help strengthen the benefits of preventive maintenance as well as aid the shift from preventive to predictive maintenance. This ABB Ability™ offering consists of:

- ABB Ability™ Remote Assistance for measurement devices
- ABB Ability™ Condition Monitoring for measurement devices

ABB Ability™ Remote Assistance for measurement devices

ABB Ability™ Remote Assistance for measurement devices is a service aimed at improving the customer experience during technical support. The service enables an authorized ABB service engineer to log in to an on-site industrial-grade

gateway – after the customer has requested intervention from the call center – and connect with the device under investigation to collect all the data required for troubleshooting the problem. Instead of an engineer having the customer step through the device diagnostics over the phone, the engineer can perform the troubleshooting. The customer receives, via mail or phone, a clear overview of progress and a solution or a solution recommendation.

The ABB Remote Assistance industrial-grade gateway has been designed to fulfill stringent cyber security requirements. Gateway usage policies are defined and enforced to prevent malicious access. Only authorized and trained ABB service personnel will be able to access the gateway and device data, and only with the customer's consent. Gateway access can be through a 4G network or via Ethernet. Rigorous security measures, including firewall restrictions, are applied to these networks to ensure cyber security.

Together with ABB's Dynamic QR Code assistance for analyzers – an ABB service product that provides comprehensive diagnostics and a real-time health check of an analytic system without any need for training or remote connectivity [1] – the ABB Ability™ Remote Assistance for measurement devices represents the first layer of digital service products provided for this type of product.

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01 Preventive maintenance is often used to keep the ABB gas analyzers shown here in top working condition. ABB Ability™ digital services for gas analyzers now enhances the effectiveness of preventive maintenance and enables more widespread use of predictive maintenance.



ABB Ability™ Condition Monitoring for measurement devices

A second digital service product that is designed to provide condition data is the ABB Ability™ Condition Monitoring for measurement devices. This service product is, as with the ABB Ability™ Remote Assistance for measurement devices, delivered via an industrial-grade gateway. The gateway is connected to the analyzers on-site

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pre-emptive intervention is crucial for gas analyzers that play a critical role in process control or environmental emission monitoring.

and regularly monitors key tags that reflect their health. Retrieved data is stored in a database and processed to uncover early warning signs of degradation and its possible source. The data and findings are collected in health reports that can be accessed by ABB service engineers or the customer and can be sent via email to authorized personnel →02.

Health checks can be performed at scheduled intervals (daily, weekly, or monthly) to collect real-time measurements and diagnostics. ABB specialists evaluate these parameters against established performance benchmarks to provide service recommendations. Findings can lead to the specific maintenance activities necessary to avoid unexpected stoppages due to excessive deterioration of critical components. Problems can be resolved during a scheduled maintenance visit or plant shutdown before an actual failure happens.

Such pre-emptive intervention is crucial for gas analyzers that play a critical role in process control or environmental emission monitoring, as well as for analyzers in inaccessible locations – eg, in marine, offshore, or mining applications.

Ultimately, the goal of the ABB Ability™ Condition Monitoring for measurement devices is to avoid unplanned downtime and optimize the total cost of ownership.

Standalone solution

The ABB Ability™ Condition Monitoring for measurement devices can work as a standalone on-premise solution without the need for external ABB intervention and the health check report can be analyzed by the customer's maintenance



02

personnel. At any time, customers can contact ABB to discuss maintenance strategies. This approach is ideal for self-maintainers where the customer maintenance personnel can leverage the data provided by the ABB Ability™ Condition Monitoring for measurement devices with the aid of in-house expert resources.

ABB Ability™ Condition Monitoring for measurement devices complements ABB Ability™ Remote Assistance for measurement devices for a complete ABB-connected remote service offering.

Business intelligence engine

At the heart of the ABB Ability™ Condition Monitoring for measurement devices is a business intelligence engine, which captures data from the analyzers, analyzes it and produces an indication of the analyzer's health. This engine is in the

—
 The solution features a fully-fledged management system in compliance with ABB's cyber security norms.

form of a Web service, which makes it easy to accommodate equipment configuration changes. A cloud-based version of the service, available soon, will further increase flexibility.

The solution is conceived as a platform that provides basic services – such as a report generator, data analysis engine, etc. This architecture

simplifies the addition of new analyzers. The data definitions and related analysis software for a specific analyzer type reside outside the platform – in the so-called verification definition files – which speeds the onboarding of new analyzers and simplifies software component maintenance.

Database confidentiality

Data is a critical part of the solution and an ABB custom-made database is used to store it. This database is kept loosely coupled with the rest of the software to ensure data confidentiality and controlled access. Analyzer data is stored in the database along with a timestamp for every data point to ensure the correct data set is retrieved for the creation of historical reports.

The solution features a fully-fledged user management system in compliance with ABB's cyber security norms. Other critical elements of cyber security such as system hardening, data encryption and secure data transmission are also addressed. Important data points are encrypted and stored. The complete solution, along with the hardware, is tested by the Device Security Assurance Center, which is an advanced security lab within ABB.

More than gas analyzers

ABB Ability™ Remote Assistance for measurement devices and ABB Ability™ Condition Monitoring for measurement devices currently support ABB's product line of continuous gas analyzers (CGAs). Support for other product lines, including gas chromatographs and spectrometers is currently under development. The two digital services will be extended to include ABB's digital advanced service offering such as data analytics, and predictive maintenance.

A better view of things

To complement the service portfolio and improve the customer experience, ABB exploits appropriate new technology, for example, augmented reality (AR), which is used to visualize virtual data superimposed on the real world. ABB Ability™ Remote Insights for service, for example, is a collaborative application that improves interaction between remote experts and field personnel by enabling live instruction and guidance that can be overlaid on live video using AR.

Troubleshooting of industrial devices is primarily based on experience and offline manuals. A drawback of the latter is that the engineer must continuously shift his vision between the manual and the device under investigation. Two AR-based approaches have been developed to remedy this situation: The first uses a 3-D computer-aided design (CAD) model of the

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02 Condition monitoring dashboard.

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03 The engineer's AR view.

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04 Flexible remote assistance options allow experts to assist the customer.

device superimposed on the real device, along with step-wise instructions for troubleshooting. The second approach connects a remote expert with the local engineer's AR device via a video call. Thus, the expert sees exactly what the service engineer sees and can guide the engineer remotely →03–04. The expert can annotate the service engineer's view and can send artifacts, such as images and videos, to facilitate troubleshooting. This approach makes best use of the expert's time and allows coverage of many more sites than would be the case were the expert to have to travel to each one.

One application area in which AR is expected to offer major benefits is the repair of emission monitoring equipment on marine vessels. Currently, when a problem occurs, the onboard maintenance engineer must phone ABB service. If the problem cannot be rectified over the phone, then an ABB service technician would either be waiting at the next port or, in extremely urgent cases, be flown directly to the vessel. With

the use of AR, the maintenance engineer can fix the issue with assistance from 3-D CAD models or the expert, who is connected to the engineer's AR equipment as described above.

Expertise and technology

With emission regulations tightening, financial penalties for emission transgressions increasing and experienced in-house analytics experts becoming rarer, it is important that companies bring in the very best external expertise and technology to help them keep their gas analysis equipment in working order. ABB Ability™

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The products enable fast and incisive remote intervention by ABB experts.

Remote Assistance for measurement devices and ABB Ability™ Condition Monitoring for measurement devices are two new digital services for gas analyzers that provide exactly such expertise and technology. With these two products, regular periodical preventive inspection is enhanced and the way is opened to predictive, as well as simpler, maintenance. The products enable fast and incisive remote intervention by ABB experts, thus ensuring that the very best skills are employed in keeping emissions monitoring equipment in top order and providing peace of mind. •

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03



04



Energy for action





Electricity, already arguably the form of energy with the highest penetration across all sectors and geographies, will further grow in dominance due to areas such as transportation. ABB has been a leader in enabling electricity for over a century. The company is pioneering new ways to do it for the next one.



- 52 Virtual High-Voltage Lab
- 58 Energizing private vehicles, public transit systems and ports
- 62 TmaxXT: digital breakers for a digital era
- 68 A new way to make switchboard electrical connections
- 72 Puffer-type load break switch for SF₆-free applications
- 78 Rogowski coil current sensors for arc flash detection



ENERGY FOR ACTION

Virtual High-Voltage Lab

Predicting the dielectric performance of electrical equipment by using electrostatic field computations and experiments can lead to inaccurate results. ABB's simulation tool, Virtual High-Voltage Lab (VHVLab) – built on proprietary ABB knowledge – improves the predictability of dielectric withstand.

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Dielectric dimensioning is a crucial aspect of the development of medium- and high-voltage devices like switchgear, cable accessories and transformers. When introducing a new device to the market, manufacturers are obliged to certify the product by performing a series of dielectric type tests defined by technical standards. A test is successful if the electric insulation of the device can withstand AC and lightning impulse (LI) electric field stresses without breakdown. The prediction of test results is typically supported by electrostatic field computations that

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 The VHVLab simulation tool provides a software framework focused on the prediction of dielectric test results.

are compared with the critical values specified for the given materials such as gases, liquids and solids, and interfaces between them. However, this obvious approach is, in many cases, insufficient because dielectric failures do not have a simple relation to field strengths.

The ABB simulation tool VHVLab provides a software framework focused on the prediction of dielectric test results and is aimed at closing the gap between numerical computations and experiments →01–02. VHVLab's predictions are achieved by combining engineering simulations with empirical knowledge obtained from experiments and first-principle simulations of

microscopic models. This type of software is not available commercially because the simulation procedures integrated into VHVLab are derived from ABB test experience gained in a real HV laboratory. Such a tailored platform is a competitive differentiator to commercial simulation software and allows for faster design loops. The development of VHVLab has been driven by industrial research supported by specialized academic partners.

This article presents a short description of the VHVLab architecture, followed by a collection of case studies originating from the development of an eco-efficient medium-voltage load break switch [1]. Each study deals with a different simulation procedure, covering features such as streamer inception, sharp edges, triple points and surface charging.

VHVLab architecture

The core component of VHVLab, which includes discharge modeling, is connected via predefined interfaces with two external components: the visualizer and the background field solver →03. This open structure enables the integration of any arbitrary external software component. The preferred choices here are an in-house, electrostatic boundary element method (BEM) solver – used in ABB since the 1990s for dielectric simulations [2] – and a customized implementation of ParaView, a well-established, freely accessible scientific visualizer.

The VHVLab core module is implemented as a Java application that includes a graphical user interface to guide the ABB engineer through the discharge evaluation.

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01 VHVLab, a new ABB simulation tool, helps predict dielectric test results. Shown is part of the test laboratory of SINTEF – an independent research organization in Trondheim, Norway, with whom ABB work closely on dielectric performance.





02

The workflow is:

1. Load the initial background field solution, calculated prior to the VHVLab session.
2. Specify the surface roughness and the gas properties: pressure, temperature, gas type, mixture composition, etc. Based on the specified data, the critical stress above which a discharge can be initiated is evaluated by VHVLab.
3. Compute critical spots where discharge inception can occur and select points for further evaluation.
4. Specify parameters for the calculation of inception and discharge paths.
5. Start and monitor computations.
6. Evaluate inception results for all selected and calculated points.

7. Enable visualization of graphs with field characteristics along computed discharge streamlines.
8. Define surface-charge boundary conditions and compute the background field with surface charge. Return then to step 3 until the evaluation has reached a satisfactory degree.

Results are illustrated in the following case studies.

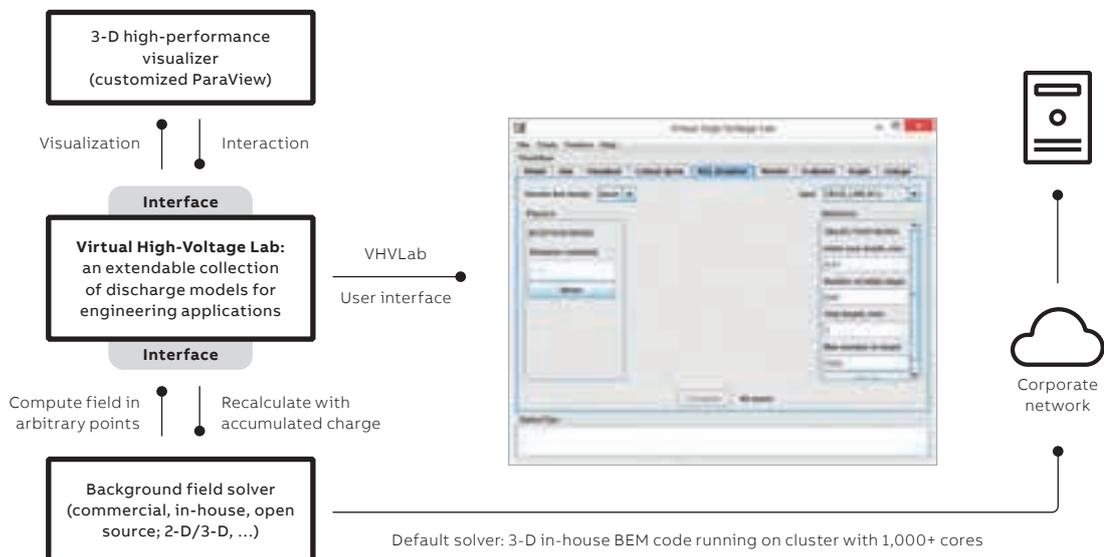
Streamer inception

Inception of a gas discharge in an electric field starts with the appearance of the first free electron from which a Townsend avalanche is initiated. If a critical number of electrons are gen-

Inception starts with the appearance of the first free electron from which a Townsend avalanche is initiated.

erated, a self-propagating streamer head forms. This streamer inception criterion is contingent on the field-dependent effective ionization coefficient, which accounts for impact ionization and electron attachment and detachment. The value of the inception voltage is calculated iteratively by changing the applied voltage and scaling the electric field values along a discharge path until the criteria for inception are met.

One of the first applications of the streamer inception models implemented within the VHVLab framework was for a new air-insulated



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02 Dielectric behavior is a critical aspect of electrical equipment.

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03 Architecture of VHVLab simulation framework.

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04 Evaluation of streamer inception voltage and test results for a ring main unit disconnecter.

04a Electric field strength at 125 kV LI and field lines calculated for critical spots (lighter colors/dots show areas more liable to discharges).

04b Traces of discharge on the surface of a knife shield after LI test.

12 kV switchgear application. A replacement of SF₆ by pressurized air, while keeping the same size of compartments and insulation integrity, was the main design challenge, which could be solved only with intensive support by simulations for shape optimizations. Interestingly, the design that was obtained could also fulfill the requirements of 24 kV switchgear by using ABB’s AirPlus (air mixed with fluorinated ketones) as the insulating gas. For both ratings, VHVLab was able to predict an inception voltage that passed the LI tests. →04 shows an evaluation of streamer inception voltage and test results for a ring main unit disconnecter. A difference of around 10 percent between the measured withstand and simulated inception voltages is typical for prediction of LI test results and is assumed by engineers as a safety margin.

Sharp edges

Field enhancements around sharp edges are well-known sources of LI test failures in medium-voltage switchgear, and recent trends to reduce device sizes – and thus clearances, ie, the shortest distance through the gas between

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Sharp edges and triple points are the most likely locations for electron emission in the presence of a high electric field.

two stressed electrodes – exacerbate the situation. An ABB research project using VHVLab investigated how the sharpness of electrodes influences the withstand voltage [3]. One of

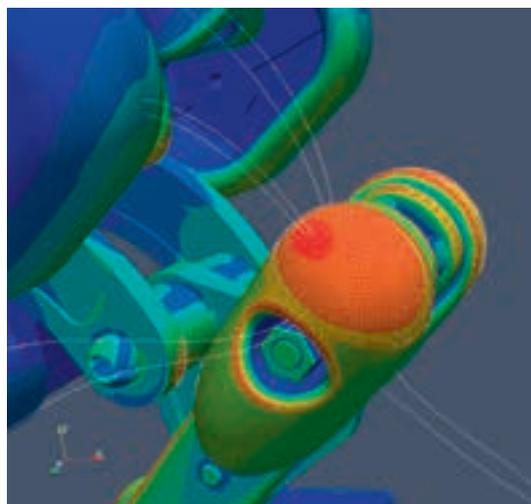
the results clearly shows a relation between the rounding radius of the sharp edge and the experimental withstand voltage, which decreases with the increasing sharpness of the edge →05. Breakdown is a stochastic process and multiple tests deliver a probability distribution that allows a voltage to be estimated at which the probability of breakdown is 2 percent or 50 percent. Furthermore, it was confirmed that the simulation, based on inception criteria, agrees well with experiment. The study was limited in scope to one aspect of sharp edges: short distances, ie, reduced clearances, which are typical in compact switchgear designs; for long distances in air, sharpness does not matter.

→06 shows an application of sharp-edge simulations for a recently designed SF₆-free load break switch. The inception values calculated for critical spots A and B are 75 kV and 68 kV, respectively, and are confirmed by 75 kV LI tests in air: there is no breakdown at spot A, but failures occurred at spots B for this initial design variant.

Triple points

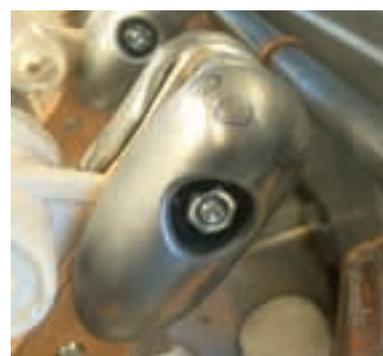
The triple point is the junction in switchgear of metal, solid dielectric and gas, and is the most likely location for electron emission in the presence of a high electric field. The triple point is also a prime location to initiate flashover or breakdown. In the development of the 12 kV switchgear in →04, triple-point problems were encountered during AC dielectric tests on the mechanical bushing, which consists of an insulating shaft mechanically connecting the grounded drive with the rotating disconnecter that operates under high voltage →07a.

To assist ABB in investigating the dielectric performance of such a configuration in air,

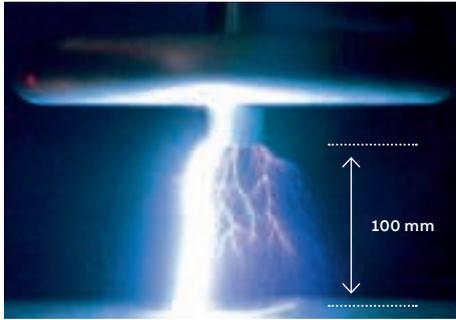


04a

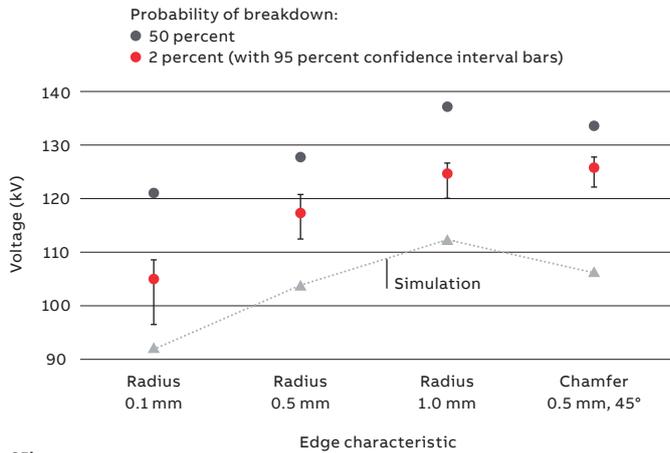
Voltage in kV	Air	AirPlus
Measured	86.7	133.7
Simulated	77.8	120.0



04b



05a



05b

researchers from SINTEF built an experimental setup that enables a flexible choice of triple-point configurations [4] →07b. The relationship between the measured AC withstand voltage (estimated statistically as the average breakdown voltage reduced by two standard deviations) and the electrode separation shown in →07c, is one example of an experimental result for a selected shape of the grounded electrode mounted around the insulating shaft.

The simulation of inception at triple points is not straightforward due to a very specific field distribution existing in the narrow space between the solid dielectric and the electrode. An evaluation of streamer inception criteria can be performed for several variants of discharge path

and using different field strength components for determination of ionization coefficients →07d. Although this type of simulation can properly reproduce the trends observed in experiments, the simulated values of inception voltage differ from those measured. According to the current VHVLab guidelines, engineers can select any of the proposed evaluation variants. These variants all ensure a conservative prediction but the safety margin is not well defined. This situation indicates that breakdowns caused by triple-points require further investigation that focuses not only on inception models, but also on other influences such as surface charging, polarity changes, roughness and trapped particles.

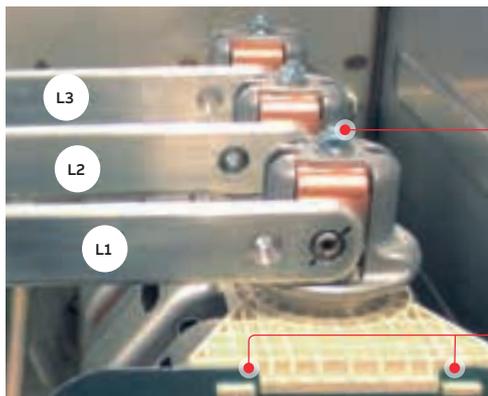
Insulator surfaces and charging

Interaction of discharges with dielectric surfaces – eg, electrodeless streamer inception, discharge creep along surfaces and surface charge accumulation – are of great relevance for practical applications. Over the last decade, ABB has collaborated with academic partners in these areas [5,6].

One example of discharge interaction applicable to engineering simulations integrated into VHVLab involves saturation charge, which can be considered as a boundary condition prescribed

Inception simulation at triple points is hard due to a very specific field distribution between the dielectric and electrode.

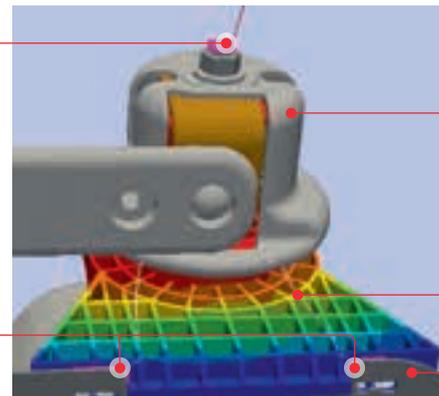
in an electrostatic field computation. Saturation charge is interpreted as the maximum possible surface charge that can be accumulated on a dielectric surface by a discharge. Experiments and first-principle simulations confirmed the



06a

Spot A: edge of the screw; inception value = 75 kV

Spots B: edges of the support plate; inception value = 68 kV



Active electrode

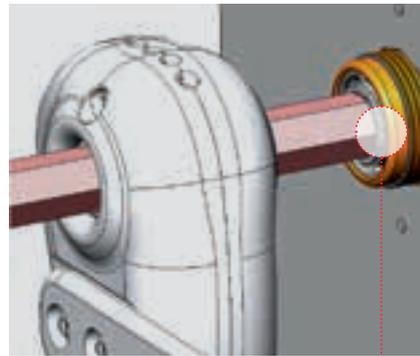
Discharge path length = 60 mm

Grounded electrode

06b

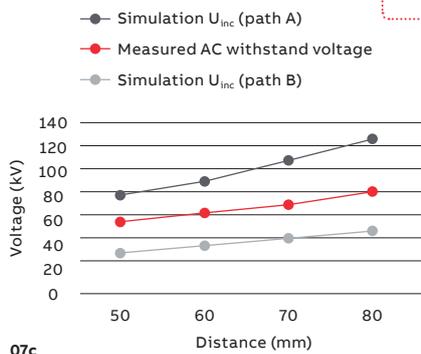
05 Results of sharp-edge experiments and simulations in atmospheric air [5].

05a Test arrangement with a breakdown after applying a positive lightning impulse. The exposed electrode is a cylinder with rounded or chamfered edge.



07a

05b Comparison of measured breakdown/withstand voltages and the simulated inception.



07c

06 Sharp-edge evaluation examples in a compartment of 12 kV gas-insulated switchgear (air, 1.3 bar).

06a There is no breakdown at spot A, but failures did occur at spots B for this initial design.

06b In order to ensure precise simulation, the sharp edges have been rounded with a radius of 0.1 mm, which properly reflects the sharpness of the tested part.

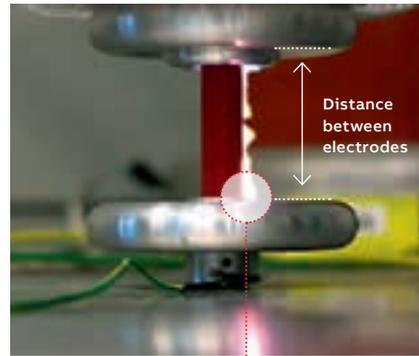
07 Triple-point analysis.

07a Hexagonal mechanical bushing of a 12 kV switchgear with a critical triple point at the grounded, drive side, on the right.

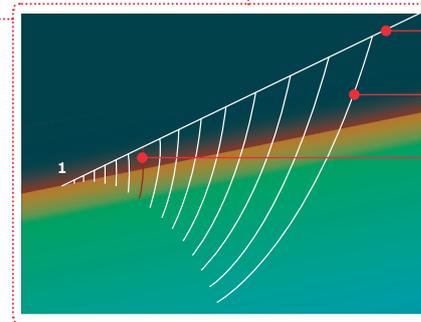
07b Snapshot of a discharge in the experimental setup built at SINTEF for measurement of AC breakdown in atmospheric air.

07c Comparison of the AC experimental withstand voltage (peak value) with two variants of the simulated inception voltage, U_{inc} , as a function of distance between electrodes. Note: The U_{inc} values evaluated for path A must be reduced by an empirical factor of 0.5 for a safe prediction.

07d 3-D color plot of electric field strength and two variants of discharge path evaluated near critical triple point "1" with the maximum field value. The path along the insulator and all field lines are in the same plane, which is perpendicular to both insulator and electrode surfaces. The path along the insulator in the 3D model is perpendicular to the "triple line", which is in this picture the line marked by high (red) stress values.



07b



07d

Path B along insulator
Field lines starting at electrode surface
Path A is along the field line with the lowest inception voltage (dark line)

concept and nature of saturation charge, in particular its ability to suppress subsequent streamer inception and prevent breakdown for LI tests [6]. An implementation included within the VHVLab framework made it possible to compute surface charge effects in devices with highly complex 3-D geometry in a straightforward way. An attractive feature offered by surface charge analysis is a quantitative explanation of why some devices can pass the LI test, although calculations that neglect surface charging predict a breakdown [7].

VHVLab – future developments

VHVLab is a useful simulation framework for medium-voltage switchgear that can be used by nonexperts. Fast and structured design iterations can be achieved as an intrinsic part of the development workflow and dependency on

the availability of labs and physical test variants is reduced. Still, VHVLab does not offer a fully automatic virtual test where a discharge can be simulated and visualized by pushing a button. However, the tool makes a first step in this direction by offering a collection of numerical procedures and empirical rules that allow engineers to evaluate, visualize and understand discharge phenomena. In this context, VHVLab is not only an engineering tool but also a knowledge database into which the experience of researchers and developers has been gathered, providing a foundation for future digital testing. •

Acknowledgment

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ENERGY FOR ACTION

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Energizing private vehicles, public transit and ports

Demand for all forms of electric vehicles is booming. This trend is being propelled by a desire to counteract poor urban air quality, reduce noise, improve quality of life, and, above all, minimize global climate change.

The most visible sector in which this trend is taking shape is personal transportation. For instance, according to BloombergNEF's Electric Vehicle Outlook 2020 [1,2] annual passenger EV sales will reach 26 million by 2030 while electric buses will completely dominate their sector by the late-2020s.

But cars and buses (also trucks) aren't the only kinds of vehicles making the transition to electric power. EVs are also very suitable for applications such as those fulfilled by automated guided vehicles (AGVs).

AGVs have a range of advantages: no driver is needed, allowing personnel to be redeployed to more productive tasks; performance and costs are predictable; vehicles operate 24/7; and overall safety is improved within the automation environment in which they operate.

With so many EV types entering the market, the rush is on to build charging stations – which is

where ABB comes in. ABB has years of experience in developing, installing, commissioning, and maintaining charging infrastructures. In fact,

ABB is the partner of choice for the world's biggest electric vehicle OEMs and nationwide EV charging network operators.

the company is now the partner of choice for the world's biggest electric vehicle OEMs and nationwide EV charging network operators.

This experience has underpinned the decision by major companies and public entities to choose ABB as a partner in the deployment of public transit, private vehicle, and AGV charging – the subjects of the following three examples.

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MILAN: TICKET TO A CLEANER FUTURE

Northern Italy's industrial metropolis, has a roadmap to a green future. The city of over three million plans to trade in all of its 1,200 diesel buses for brand-new all-electric ones by 2030.

—
01 Milan's new all-electric buses can charge overnight in 5 hours at ABB charging stations. The city expects to have 1,200 such buses in service by 2030.

By 2030, Milan's entire range of public transit services, including trolleys and subways, will be 100 percent electric. The city's public transit service (Azienda Trasporti Milanesi or ATM), which operates 158 bus lines covering 1,550 km, estimates that, when fully implemented, conversion of its buses will slash its demand for diesel fuel by 30 million liters per year and cut CO₂ emissions by 75,000 tons per year.

What is more, ATM has stipulated that all of the energy generated for its electrical systems must be guaranteed to come from certified renewable sources and must thus have a zero emissions footprint. Expected to cost upwards of €1.5 billion, the plan to exchange diesel buses for electric ones – and install an associated charging infrastructure – is the result of a commitment made by the city at the Paris Climate Summit.

Initial plans call for three of the city's five bus depots to be converted into electric charging hubs for buses as well as for large fleets of service vehicles. In addition, four new depots will be built. One of the hubs is also being outfitted with 100 kW recharging stations from ABB →01, as well as modular ABB transformer stations and plug-in charging columns, all of which will be managed by algorithms designed to optimize the recharging process while minimizing energy

demand. Substantial amounts of energy will also be saved once an automated and optimized parking system for arriving and departing buses is implemented.

By the end of 2021, the city expects to be operating 167 fully electric buses and 8 terminus stations equipped with 200-kW pantographs, each capable of supplying 35 kWh in eight to 10 minutes – more than enough power to ensure an effortless return trip to the depot, regardless of heating and cooling requirements.

The buses themselves will be powered by nickel-manganese-cobalt (NMC) 240 kWh batteries capable of completing a 180 km zero-emissions route under the most stressful conditions. Buses will be fully recharged in 5 hours each night at their respective depots.

In a report [1] entitled "Elements of success: Urban transportation systems of 24 global cities," McKinsey & Company placed Milan among the world's top ten cities in terms of the quality of its mobility systems. The report analyzed mobility according to availability, accessibility, efficiency, convenience, and sustainability before, during and after trips and in conjunction with customers' opinions.

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FAST EV CHARGING ANYWHERE, ANYTIME

Japan wants to modernize its electric vehicle infrastructure and accelerate its shift toward sustainable mobility. More specifically, it intends to increase the share of EVs and plug-in hybrids on its roads to between 20–30 percent by 2030, from just 1 percent in 2018 [2].

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02 Terra 184 chargers offer customizable features such as cable management systems, screens and credit card payment terminals.

To meet this goal, e-Mobility Power Co., Inc. (eMP), a joint venture between Tokyo Electric Power Company Holdings (TEPCO) and Chubu Electric Power, two of Japan's biggest utility companies, has selected ABB's newly launched Terra 184 electric vehicle chargers. The high-power, compact chargers will be installed at roadside retail locations and other public places across the country to offer users quick and convenient charging options anytime, anywhere. In late 2020 eMP began replacing obsolete chargers with more than 250 Terra 184 units.

With the ability to charge up to two electric vehicles simultaneously, the Terra 184 is part of ABB's product line of DC fast chargers. Designed to produce 180 kW of charging power for one outlet or simultaneously providing 90 kW for two separate outlets, the chargers are capable of handling future EV models equipped with high voltage battery systems and can provide a quick refill of 60-mile range in under 8 minutes of charge.

Terra 184 chargers are based on the CHAdeMO charging standard, the development of which was led by TEPCO, eMP's main shareholder. The

chargers are also based on OCPP, an international standard protocol, which allows them to be remotely controlled and maintained.

Thanks to its conformity with these standards, the Terra 184 can be connected via ABB Ability™ – ABB's unified, cross-industry, digital offering that extends from device to edge to the cloud – for centralized control and fast global service for software updates and maintenance – attributes that are vital for the rapid deployment of EV charging infrastructures. This allows EV charging network operators to develop deep insights and statistics on energy usage at the charger, site, and network levels [3].

With highly customizable features such as cable management systems, screens and credit card payment terminals, the Terra 184 delivers maximum charging convenience for a broad range of EV users →02. Offering a safe, smart, and sustainable charging solution that supports ABB Electrification's Mission to Zero, a vision for a zero-emission reality for all, the Terra 184 is available direct from ABB in Europe and in North America.

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03a



03b

03 Tuas Port, Singapore, automated container terminal project.

03a The terminal's 162 AGVs will be electrified and powered by an ABB charging infrastructure.

03b Each charging station will be integrated into an "eHouse" with supporting electrical infrastructure in a complete e-mobility solution.

A CHARGING INFRASTRUCTURE FOR SINGAPORE'S AUTOMATED CONTAINER TERMINAL

Two of the major trends driving all forms of mobility are the introduction of electric vehicles and the rise of autonomous vehicles.

In Singapore, these trends are set to converge at the Tuas Port, which, by 2040, is slated to feature the world's largest fully automated container terminal. With an annual handling capacity of 65 million TEUs (twenty-foot equivalent units), the terminal will be a major milestone in Singapore's development [4].

Set to enter preliminary service in late 2021, the terminal →03a will phase in a fleet of 162 automated guided vehicles (AGVs) over two years to handle the distribution of heavy shipping containers. Those vehicles will be electrified and powered by the port's DC charging infrastructure, which will be supplied by ABB. In addition, the company has worked closely with the Land Systems arm of ST Engineering to secure a contract with PSA Singapore, the port's operator, to deliver and commission integrated smart charging stations for the facility's AGV fleet.

The contract includes eighteen smart fast-charging stations with built-in fault tolerance and self-diagnostic features. Each station will be integrated into an "eHouse" on a prefabricated skid, outfitted with medium- and low-voltage switchgear, a transformer and 450 kW high-power chargers with associated control and monitoring equipment [5]. This configuration combines EV charging with its supporting electrical infrastructure in a complete e-mobility solution →03b.

Although ABB offers a portfolio of heavy commercial electric vehicle pantograph connection options, at Tuas, such solutions would be impeded by the presence of a container on an AGV. As a result, specially designed and customized side-access, pin-type connectors from Stäubli will be used. Combined Charging System (CCS), an open and universal charging protocol based on international standards, will ensure communication between each electric vehicle and the charging infrastructure.

PSA's fleet management systems will centrally monitor the status of the port's charging stations and AGV battery levels and schedule the AGVs for charging accordingly. Once an AGV arrives at its designated charging station, it will signal that it is ready to commence its charging session.

A breakthrough for ABB, the Singapore port project marks the first time the company's chargers will be used to power a fleet of autonomous vehicles for commercial operation. •

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ENERGY FOR ACTION

Tmax XT: digital breakers for a digital era

Designed for extremely high performance, ease-of-use and connectivity, the new ABB SACE Tmax XT molded-case circuit breaker (MCCB) not only provides intelligent and comprehensive circuit protection but also improves energy management, installation and servicing.



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Early circuit breakers consisted of a simple thermal-magnetic trip unit that sensed current levels and operated a switch in the event of overheating or a short circuit. In the late 1980s, electronic trip units based on current transformers emerged that measured the current rather than just sensing it. An element of control then entered the picture – delayed tripping, for example.

In recent years, the evolution of monitoring needs in the context of an increasingly connected world and the emergence of sophisticated control needs have forced the pace of circuit-breaker development. For example, air-core current sensors have now replaced the old iron-core current transformers, introducing advantages such as increased accuracy across the entire operating range of the trip unit, which is up to 12 times its rated current, in many cases. Modern electronics also make it possible to integrate the measurement of voltage into the breaker without the need for additional voltage transformers, thus saving space and installation time.



01

Functional integration has continued apace, eliminating complexity and doing away with many of the transformers, meters, cables, terminal blocks and ducts that competed for the limited space in the switchboard.

From protection device to data source

The integrated metering capability provided by the last generation of trip units offered the chance to build up an extensive metering architecture without increasing the dimensions or complexity of a distribution system. This advance allows more variables to be measured in more places, at kHz sampling rates. Data can

Modern electronics make it possible to integrate the measurement of voltage into the breaker.

then immediately be digitalized and processed onboard the unit. If the trip unit has a data logger, then the values of currents, voltages and other parameters can be stored, analyzed, visualized or downloaded in different formats to other devices.



—
01 The Tmax XT MCCB range.

Although these devices deliver a certain level of sophistication, the functionality and ease-of-use delivered by the new ABB SACE Tmax XT MCCB changes the circuit breaker game significantly →01.

The ABB SACE Tmax XT MCCB

The Tmax XT range of circuit breakers delivers higher performance, better protection and more precise metering than equivalent units – and covers currents from 160 to 1,600 A. The Tmax XT is equipped with ABB's Ekip Touch protection trip units, which provide preconfigured or customizable digital and analog interfaces. The combination of Tmax XT and Ekip Touch delivers a performance that was traditionally in the realm of the multimeter or network analyzer: voltage, energy, power and harmonics measured with accuracy levels of better than 1 percent; harmonics calculated up to the 50th; and detection thresholds lying under 0.4 percent of the nominal current.

Tmax XT has at its disposal plug-in modules to sense temperature (by means of thermocouples), voltages from a different power line, vibration and pressure. In fact, any 4–20 mA sensor can interface to the Tmax XT. Information obtained by these sensors can be immediately processed by the trip unit – to generate alarms, output a command or trip a breaker – rather than being

sent to a supervision system on a communication bus for remote handling. All these sensors interface via the Ekip Touch trip unit that is installed in the Tmax XT →02.

Commonality across the range

With the world's most precise electronic trip units in the smallest frames, the Tmax XT range builds on the Emax 2, the industry's first smart low-voltage air circuit breaker. In fact,

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The Tmax XT range delivers higher performance, better protection and more precise metering than equivalent units.

the Tmax XT range has the same logic, features and interfaces as the Emax 2. This commonality, which only ABB can provide on the entire circuit-breaker range, delivers significant time savings and enhances installation quality.

A new way to access information

Tmax XT trip units are equipped with a color touch screen display, which – thanks to an internal battery – can be turned on even when



02a



02b

the breaker is de-energized. This availability means that, after a trip, it is possible to navigate through the menu to find the data needed to understand the reason for the trip before reclosing the circuit breaker.

The touch screen utilizes intuitive icons like those found on tablets or cellphones. Complex functionalities are easy to handle – either directly from the touch display or by exploiting the Bluetooth communication capability of the trip unit: Once a cellphone is paired with an Ekip Touch trip unit in a TmaxXT →03, all reading and setting activities can be accomplished via the free Epic cellphone app →04.

Connecting to the TmaxXT

There is much value in the data collected by TmaxXT circuit breakers – especially if data from many breakers in different locations can be gathered, aggregated, compared and analyzed as a whole. To do this, a data transmission means

must be provided. The Ekip Touch trip units that fit into TmaxXT enable the potential of ABB Ability™ Electrical Distribution Control System (EDCS) to be opened up, providing over 10 communication protocols. (ABB EDCS is a cloud-based platform that enables a user to monitor and manage a facility’s electrical distribution via

—
 The Modbus module ensures fast integration of new products into existing systems.

smartphone, tablet, or computer in real time to optimize energy use and costs.) Dedicated modules can be snapped onto the breaker to enable these communication capabilities – for example, for field buses such as Modbus RTU, Profibus DP and DeviceNet.

The Modbus module ensures fast integration of new products into existing systems. At 12 Mbps, Profibus DP is the perfect choice in automation switchboards if a high-speed data exchange rate is required. Solutions for connecting the circuit breakers to Ethernet networks are also available: Modbus TCP/IP communication modules run at up to 100 Mbps and can be used as a Webserver, allowing browser access to the data stored inside the trip unit.



03

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02 Ekip accessories that enhance the power of Tmax XT.

02a Ekip Cartridge, an external accessory that can be installed on a standard 35 mm DIN rail to allow other external accessories to connect to Ekip Touch and Tmax XT.

02b Ekip Signalling 3T, an accessory that connects via Ekip Cartridge to provide three analog inputs for temperature sensors and one analog input for 4–20 mA current loops.

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03 The Tmax XT2 – XT4 can be configured with the Ekip Touch trip unit family. Shown is the Tmax XT5 three-pole trip unit, Ekip Touch.

—
04 Example of an Epic app screen. The app runs on most cellphone operating systems.

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05 The architecture of Ekip Com modules that connect to Tmax XT.

Interfacing to the outside world

The IEC 61850 standard is becoming widespread as a communication protocol for protection and control systems in electrical plants. Circuit breakers need to handle fault conditions very quickly and for this reason, the two types of low-latency communication services described by IEC 61850 are implemented on Tmax XT: MMS (Manufacturing Message Specification) for vertical communication, and GOOSE (Generic Object Oriented Substation Event) for horizontal communication.

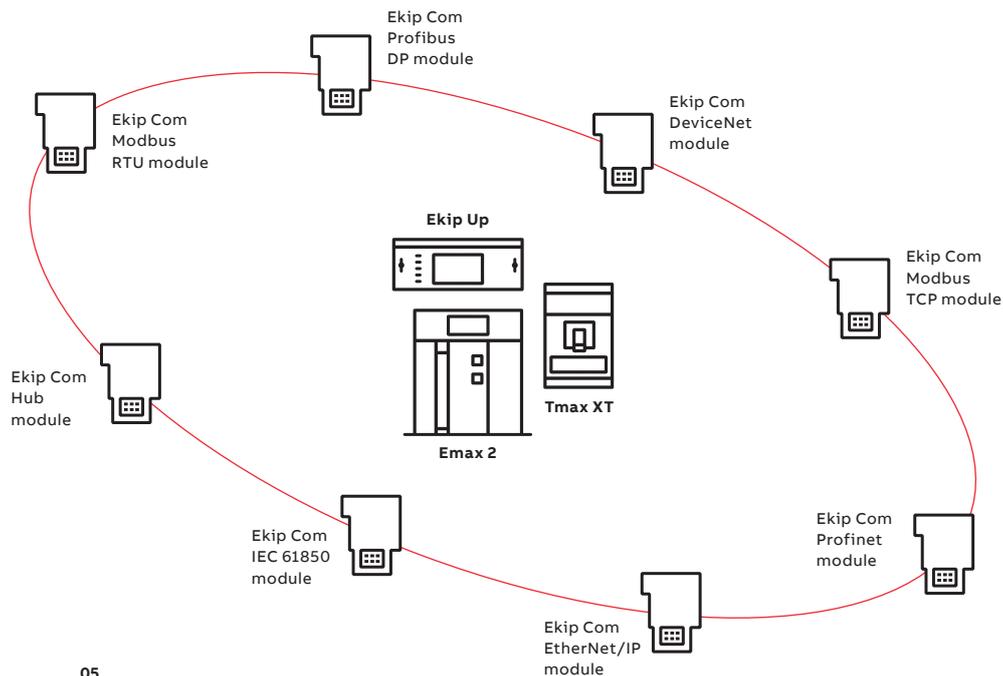
The Tmax XT’s connectivity paves the way to move from a reactive maintenance or repair approach to a predictive approach. Rather than having the breaker trip in the first place, analysis of data from the breaker, or a network of breakers, can help prevent faults from happening in the first place.

The breaker’s connectivity also allows real-time control of plants via remote monitoring and control. When the Ekip trip units are equipped with specific modules →05, control logic can be implemented, networks reconfigured, or generators controlled, to name just a few examples related to smart grids. Finally, by adding an Ekip



04

Com Hub module to a trip unit it is possible to concentrate data from multiple breakers and connect the network to an ABB-managed cloud space.



05



06

Tmax XT for a greener world

Control of power consumption at every level in a plant is a prerequisite for energy efficiency optimization, electricity bill reduction and the avoidance of fines for excess demand. Further, a comparison of similar facilities in different locations can help identify best practices across a company.

A further incentive for careful power control comes from Green Building certification, which is becoming essential in many countries for new residential construction and infrastructure such as hospitals, shopping malls and data centers. Green Mark Platinum certification, denoting the highest level of building energy efficiency, is becoming a common stipulation in construction specifications.

The Tmax XT is ideal for this type of extensive power monitoring. The breaker's built-in connectivity links smartphones, tablets and PCs to data analysis tools on the ABB Ability™ EDCS cloud-computing platform to monitor, optimize, control and predict the condition of the electrical system →06. The extreme precision of the data measured means users have ready access to accurate information, making it easier to monitor resources and identify opportunities for savings. Using the embedded smart power controller can help reduce energy consumption, allow efficient assessment for Green Mark Certification purposes and effectively reduce external auditing costs.

Cyber security

Cloud technology can significantly increase the scalability of architectures, improve the flexibility of interconnection to both new- and previous-generation devices and help to protect

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There are three different modes of cloud operation, each with its own special security considerations.

investments. However, modern distributed systems involve a significant increase in the perimeter of exposure to cyber threats, both intentional and involuntary. ABB Ability™ cloud architecture has been developed together with Microsoft in order to enhance performance and guarantee the highest reliability and security →07. There are three different modes of cloud operation, each with its own special security considerations:

- Device to cloud scenario. In this case, a “whitelist” for unique identification is established and only local commission is permitted. An encrypted communication channel, exploiting the same protocol as banking systems, is used. No commands can be sent from the cloud to the plant.
- “In the cloud” refers to communication between data centers. ABB/client data is stored exclusively in certified data centers with state-of-the-art cyber security standards, relying on Microsoft Azure cloud platform security policy.
- Browser to the cloud scenario. Here, access to data requires first an authentication via ABB single sign-on (SSO) and a specific authorization. Communication runs via an encrypted channel and no commands can be sent from the cloud to the plant.

All these security implementations are designed according to potential threat analysis and are developed according to security guidelines and recurring code review. Furthermore, cyber security is continuously under assessment and validated by penetration tests to verify robustness.

A future-facing intelligent breaker

The Tmax XT family evolved to face and overcome increasingly complex and broad challenges in the world of electrical protection. The breaker's rich selection of features has made it into

—
06 A typical display from the ABB Ability™ EDCS cloud-computing platform.

—
07 The Tmax XT has not only excellent connectivity characteristics but also the highest reliability and security.

an intelligent multifunctional and modular platform that is light years removed from the humble breaker technology of the 1980s. Precise measurement, comprehensive data acquisition, extensive communications, cloud capability and cyber security are just some of the strengths of a product family set to create the future of electrical systems and to give customers the chance to create whole new levels of sophistication in their electrical installations. •

—
The breaker's rich selection of features has made it into an intelligent multifunctional and modular platform.



ENERGY FOR ACTION

A new way to make switchboard electrical connections

The ABB ReliaGear® neXT power panel and ReliaGear® SB fundamentally change how switchboard electrical connections are made. Combined with a modular distribution panel board structure and the ABB SACE® Tmax® XT circuit breakers, the result is faster, more reliable power installations with higher quality.

01

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The majority of electrical connections in industry are made by plug-in or bolted connectors, both of which have their issues. Bolted connections, for instance, are susceptible to loosening over time, which can lead not only to high-resistance effects like heating but also to arcing and short circuits. Because the state of the electrical connections in an installation plays a uniquely critical role in its safety, efficiency, reliability and longevity, ABB has introduced the new ReliaGear plug-in design to ensure optimal connection performance →01.

ReliaGear neXT And ReliaGear SB plug-in connections

ABB's ReliaGear plug-in design represents a significant improvement over the classic bolted-joint method of device installation and connection. The central novel feature of the ReliaGear neXT and ReliaGear SB design is the fixed (vertical) panel board bus and the slots it incorporates →02. Correspondingly, the

connectors on the associated circuit breakers (ie, the line-side connectors) feature a clip with matching geometry that engages the slots in the vertical bus assembly →03. Further, while the forces generated during fault currents can loosen traditional connections, ReliaGear cleverly harnesses these forces to tighten the connection.

ABB has introduced the new ReliaGear plug-in design to ensure optimal connection performance.

ReliaGear plug-in breaker assemblies incorporate the circuit breaker and the line-side connector assembly into a single, factory-assembled item.

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01 ABB's ReliaGear plug-in design simplifies installation work in which electrical connections are made. Shown is the ReliaGear neXT front panel, in the closed position.

—
02 ReliaGear neXT connectors.

—
03 Installation of devices, such as this circuit-breaker, is very straightforward.

There is no strap kit with multiple conductors and no hardware kit, and the line-side connector is pre-assembled in a single unit. With no field assembly required and no complex kit of parts for connection, installation is straightforward and simple.

Mounting

The ReliaGear neXT panel board's modular design is the key to faster installations. A steel mounting bracket, affixed to the circuit breaker, provides a fulcrum on which the circuit breaker is levered into position, engaging the plug-in fingers with the vertical bus. The circuit breaker is then secured in position by easily accessible mounting screws, attached through the steel mounting bracket. There is no torque to check on the electrical connection and no special tools are

required. The line-side connector design helps to ensure proper alignment and supports the clips during installation and removal.

The neXT rail system allows easy and straightforward installation of devices of various widths and lengths due to its equally spaced slots. Any device with back-bracket slots that fit into the openings on the rail and install into the bus stack

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The ReliaGear neXT panel board's modular design is the key to faster installations.

may be positioned there. Conversely, and by design, the largest devices will not engage the slots or vertical bus if the panel cannot accept the device.

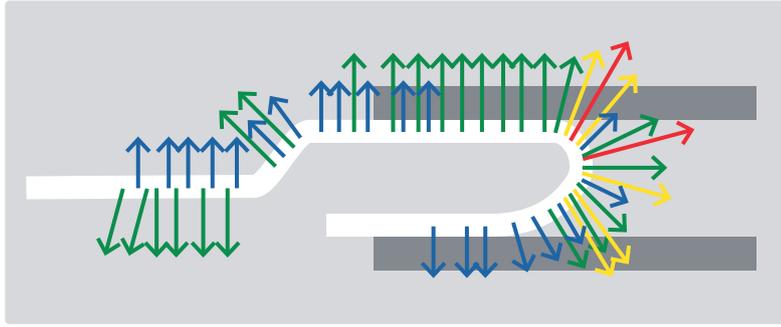
The slots are designed so that the "X" spacing (the number of mounting positions available) can accommodate the various circuit-breaker widths. Each circuit-breaker frame and bus-stack-mounted accessory has specific requirements for X-spaces. The frame also accommodates blank spacers to fill in gaps.



02



03



04

When a device is installed in the rail system, the underlying frame hole will align with the bolt hole at the back bracket, allowing installation of the screws. This efficient design ensures that the devices being installed are positioned correctly and fully engaged.

The ReliaGear neXT and SB system has been thoughtfully designed so that insertion is as easy as possible while helping to achieve contact integrity. Given the plug-in nature of the design, the insertion forces scale with the current-carrying capacity of the device being installed. For low-ampacity breakers, the insertion will be an easy operation requiring minimal hand force and support. For larger-frame circuit breakers, the ReliaGear neXT power panel is designed so that the breaker's weight is supported until final insertion.

Investigation revealed that, on average, installation of a circuit breaker and strap kit, completed by an experienced technician, can take 10 minutes or more to complete and requires the proper torque wrench to ensure a suitable connection. Adding a similar circuit breaker to the ReliaGear neXT panel board took under 30 seconds, left adjacent devices unaffected and required only basic hand tools.

Performance at rated load

The circuit-breaker line-side connector includes a compression spring inside the clip, secured via features in the clip itself, that achieves the required contact pressure during typical operating conditions. As a spring-loaded connection, this joint does not loosen over time; there are no threaded connections to inspect or maintain; and the contact pressure is maintained by the spring. The ReliaGear clip assembly is a patented solution that provides a repeatable and reliable force

to the connection, helping to ensure a secure and robust connection.

When considering the contact area of electrical connections, it is important to take into account the ratio of apparent contact area to true contact area. While common sense might suggest that this ratio is higher with a perfect surface than with a line contact, experimentation and calcu-

—
 Adding a similar circuit breaker to the ReliaGear neXT panel board took under 30 s, using only basic hand tools.

lation reveal the reverse to be true: A ReliaGear neXT clip assembly held by the embedded compression spring increases the ratio from around the 20 percent seen in the traditional approach to over 40 percent →04. Attaining an equivalent contact area using a classic bolt-on style connection requires highly torqued, high-strength fasteners – a particularly vulnerable arrangement in the field.

Performance under short-circuit conditions

The electromagnetic forces generated during fault currents can impact joint resistance on bolt-on connections, thereby impacting thermal performance. Here, the ReliaGear plug-in clip design turns the tables and exploits these forces to create the opposite effect. With ReliaGear, the repulsive forces between the clip and the panel board bus are overcome by the repulsive forces generated in the arms of the clip itself →04.

What might be described as “blow-off” forces are

— 04 Force vector diagram showing repulsive forces within the ReliaGear neXT and SB clip impinging on the vertical bus and creating compressive force during a high-current/short-circuit event. Force magnitude shown increases from blue through green to red. Resultant compressive force creates a stronger connection than during nominal operation.

— 05 IP20 compliance for finger-safe vertical bus stack assembly was determined by testing with a calibrated probe.

harnessed and turned into “blow-on” forces. With this arrangement, the contact force is intensified proportionally with the magnitude of the current, allowing the clip assembly to remain in place during faults and short circuits.

Vibration testing

Vibration is a significant cause of connector failure in the field so the structural and functional integrity of the ReliaGear neXT assembly system was verified by thorough vibration testing. The test was conducted by rigidly mounting a neXT assembly on a vibration table and subjecting the assembly to values that met or exceeded those required by the relevant code: International Code Council – Evaluation Services Acceptance Criteria (156ICC-ES AC156).

Ingress protection (IP)

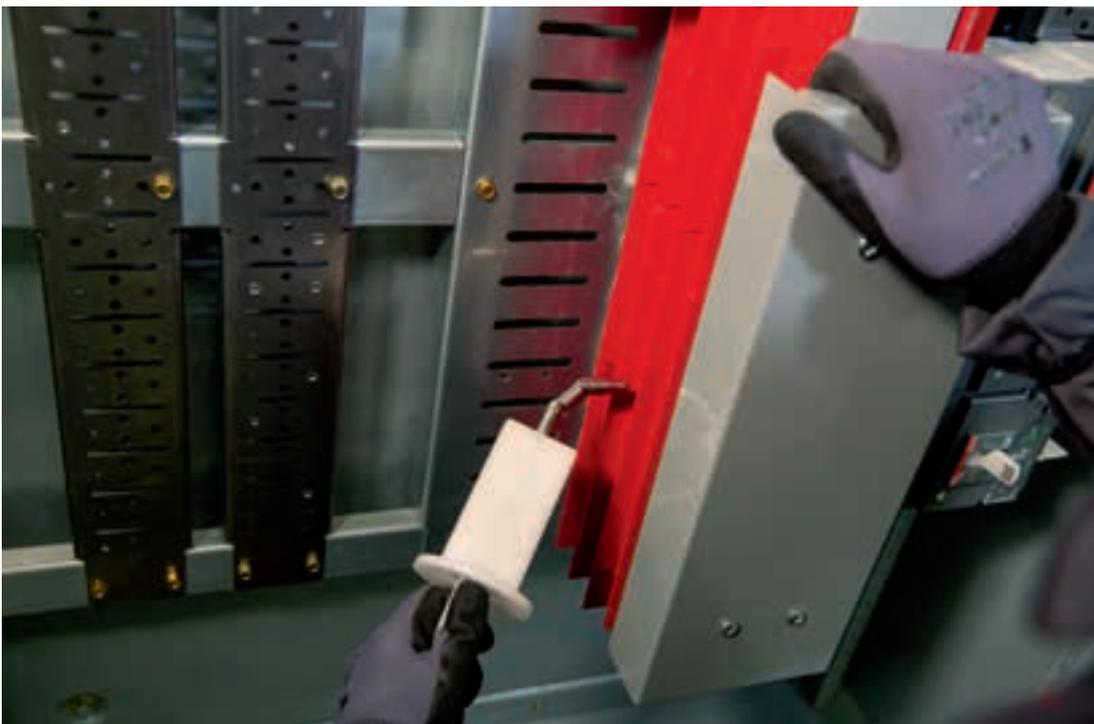
An ingress protection (IP) code, according to the IEC 60529 standard, defines a mechanical housing’s degree of protection against the intrusion of dust, accidental contact and water. The patented IP20 ReliaGear neXT design incorporates a molded-in mechanical barrier that protects certain configurations of the main bus stack against accidental contact of solid objects of sizes larger than 12.5 mm. This complies with an IP20 level of protection, generally recognized as “finger safe.” The design also minimizes the risk of a foreign body contacting the bus system →05.

Safe and reliable connection

Safety and reliability are the most important aspects of any electrical connection scheme. The ReliaGear neXT panel board has been designed and tested to enhance safety and to provide long-term reliability. ReliaGear’s plug-in connections improve on the plug-in connections that have a long history of use in power distribution

— The structural and functional integrity of the ReliaGear neXT assembly system was verified by thorough vibration testing.

and control equipment, providing a better true contact/apparent contact ratio at rated current than bolted equivalents. The design even exploits electromagnetic forces created during fault conditions to improve the electrical connection. In short, the ReliaGear design makes installation safer, easier and faster while ensuring long-term, high-quality performance. •





ENERGY FOR ACTION

Puffer-type load break switch for SF₆-free applications

Vacuum-technology load break switches (LBSs) are used in switchgear filled with environmentally friendly alternatives to the SF₆ insulating gas. These switches have some drawbacks. Refined puffer interrupter technology promises a reliable, cost-effective and easy-to-use LBS alternative.

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Environmental concerns related to the global warming potential of SF₆ are promoting a new generation of gas-insulated switchgear (GIS) based on environmentally friendly insulating gases. In this switchgear, vacuum switching technology is used for the LBS and much research effort has concentrated on the dielectric and thermal challenges [1, 2] this technology poses. Vacuum switches are also costly and require an additional disconnecter switch, which includes a complex drive mechanism.

Refined puffer interrupter technology promises a reliable, cost-effective and easy-to-use LBS alternative →01.

Puffer interrupter technology for eco-efficient insulation gas

The puffer interrupter consists of a compression chamber and an interruption chamber →02. The principle of operation is to “blow out” the arc by



01

using the overpressure generated by compression of the gas by the piston. The compressed gas is released into the arcing zone, where it cools the arc ignited between the contacts. The arc is extinguished at the first current zero (CZ) crossing if the contact distance and cooling achieved is sufficient to withstand the transient recovery voltage (TRV). The TRV arises from magnetic energy trapped in the inductances on the load side of the circuit breaker, where it gives rise to a current that circulates between the capacitances and inductances there. This current can generate a transient overvoltage. The difference between the voltage potential upstream of the breaker and these transient overvoltages gives the TRV.

SF₆ is very suitable as an insulating gas in switches due to its intrinsic capability to both cool the arc and quickly restore the insulation level after the switching event. Replacing SF₆ with eco-efficient alternatives in a puffer interrupter reduces interruption performance both in the thermal and dielectric phases (see following two sections) due to inferior arc-quenching properties and lower dielectric strength of alternative gases.

ABB has designed a puffer interrupter that overcomes these challenges posed by eco-efficient gases. Significantly better interruption performance in SF₆ alternatives is achieved by creating a so-called stagnation-point flow pattern of gas

around the arcing zone. Further, because weak dielectric strength in both cold and hot zones in the LBS may cause restrikes, innovative solutions have been implemented to tailor the flow pattern of the hot gas to prevent arc re-ignition. Although interruption capability is the main challenge, the functionality of a new LBS also has an optimized dielectric and thermal design. Advances made in these respects allow a compact LBS to be created that uses eco-efficient insulation gas alternatives while maintaining the established ratings and footprint of SF₆ GIS.

Thermal interruption

Different topologies of the flow around an interrupter arcing zone are shown in →03. The common flow pattern utilized in SF₆ medium-voltage (MV) puffer interrupters is called “simple flow.” Here, the gas flows straight through the moving contact and nozzle system toward the fixed contact. Experiments with a simple flow puffer interrupter under different gas pressures and loads have indicated that the interruption performance is not sufficient for SF₆-free MV applications [3].

Two alternative designs were explored: Single-flow and double-flow designs, which both feature a “stagnation point” that is found to improve the interruption performance significantly for air compared to the simple flow design →03. A stagnation point is a point in a flow field

—
The principle is to “blow out” the arc using the overpressure generated by compression of the gas by the piston.

where the local velocity of the fluid becomes zero and all the kinetic energy is converted into pressure energy. The stagnation-point type of flow is commonly utilized in high-voltage circuit breakers, but no applications are known for commercial MV LBSs.

During the opening operation in stagnation-point type designs, the piston attached to the moving contact compresses the gas, which results in overpressure in the compression chamber. At the same time, the arcing tulip contact is pulled away from the arcing pin, which consequently generates an arc →04. The arc initiation heats the gas, which partly “clogs” the critical cross-section of the nozzle, resulting in an even higher pressure

01 New puffer interrupters offer advantages over the vacuum circuit breakers (VCBs) used in switchgear like this SafePlus Air CCV (ie, 2 x VCB + 1 x isolator switch) GIS.

02 Schematic drawing of the gas puffer interrupter.

03 Simple flow and two stagnation-point type flows – single flow and double flow.

04 Opening operation of a puffer switch based on double-flow geometry.

The specific arrangement of the flow pattern chosen significantly improves interruption performance.

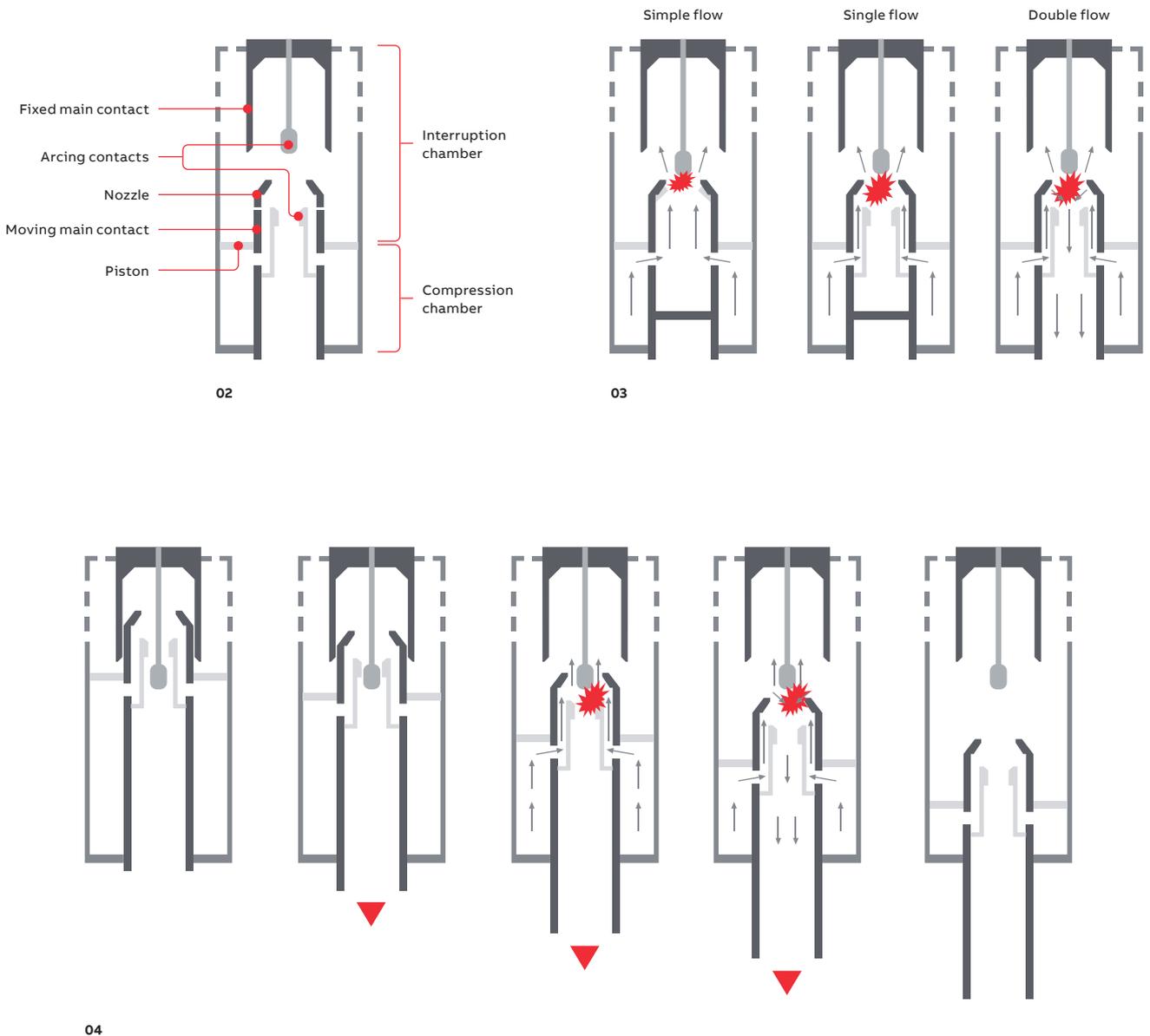
in the compression volume. Eventually, the pressurized gas from the compression volume blasts into the arcing zone and helps to extinguish the arc. The arc extinction should preferably occur at the first CZ crossing, and, therefore, enough gas pressure is needed to blow out the arc at that point. As a part of the new design, customized

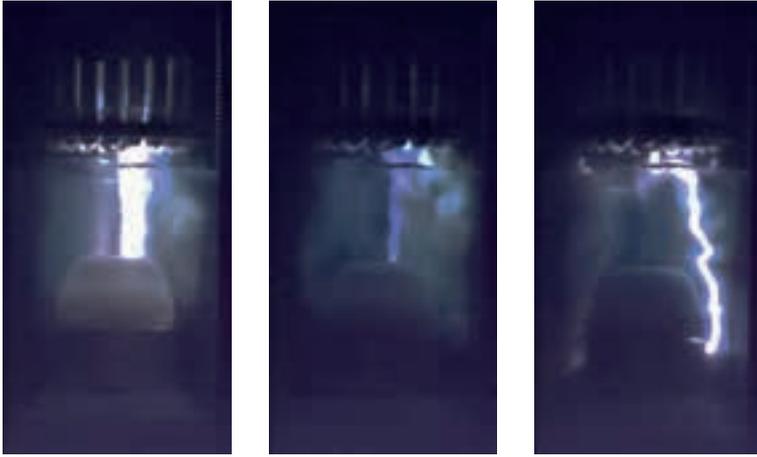
ports are made around the arcing zone. Fresh gas can then enter via these ports to quickly replace the ejected hot gas.

Many parameters of the puffer design influence the gas flow and pressure buildup in the system and lead to different interruption capabilities. In the switching device discussed here, the gas is used as both an arc interrupting and a dielectric medium. The specific arrangement of the flow pattern chosen in the arcing zone significantly improves the interruption performance.

Dielectric restrike

The dielectric phase – around 10 to 100 μs after CZ and characterized by a residual current close





05

to zero – may generate restrikes if a hot gas and metal vapor mixture generated by the burning arc remains around the contacts. This mixture has lower dielectric strength than cold insulation gas and when the TRV increases, restrikes may take place within or away from the original plasma channel. To quantify the robustness of the new switch design in this respect, experiments were conducted at different development stages →05.

In addition to full-scale experiments, computational fluid dynamics (CFD) modeling is another major tuning tool for both root-cause analysis and sensitivity analysis of new switchgear design concepts. →06 illustrates CFD modeling of the cloud of accumulated hot gas around the contacts in the double-flow design for two different arcing times. The ideal situation would be to push this hot gas away from the moving main contact – ie, it is essential to tailor the flow pattern of the hot gas generated during the interruption event in such a way that reignition

in the dielectric phase is prevented. The flow pattern can be controlled by splitting the fixed arcing contact (arc pin) and giving the fixed main contact multiple contact members with pressure-release openings. Further, the gas outlets should be large enough to avoid the flow of hot gas toward the main contact and any change in the contacts should not sacrifice the required cross-section of the main current path →07.

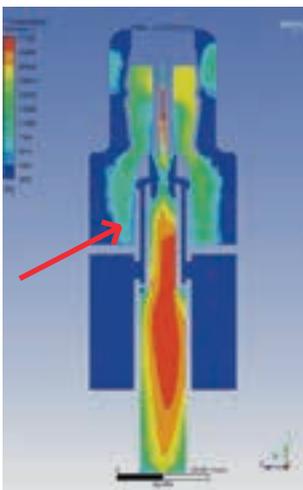
By implementing some openings on the field controllers around the interruption chamber, the hot gas, vapors and exhaust generated during the arcing event are transported away from

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CFD modeling is another tuning tool for both root-cause analysis and sensitivity analysis of new switchgear designs.

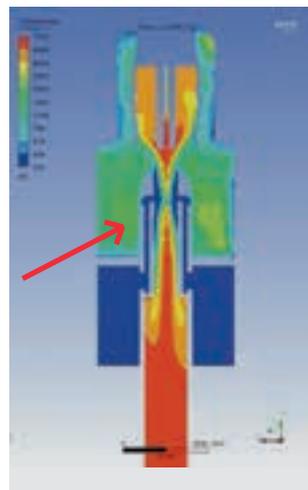
regions with high electrical field stress, which not only assists cooling but also helps to maintain the dielectric strength of the gas at the level needed between phases.

Dielectric design

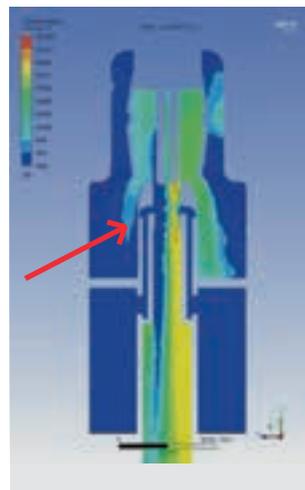
Although the dielectric withstand of air in, say, a ring main unit (RMU) application is almost one third that of SF₆ [3], the footprint of a new air-insulated switching unit should not be greater. Therefore, substantial effort has been made to reduce the electric field stress near compo-



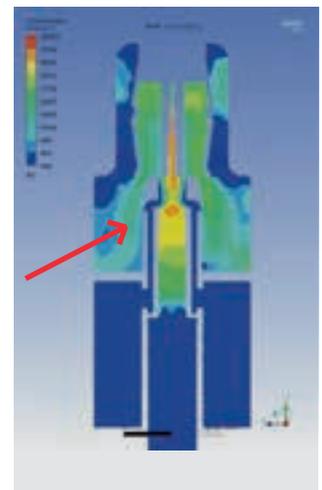
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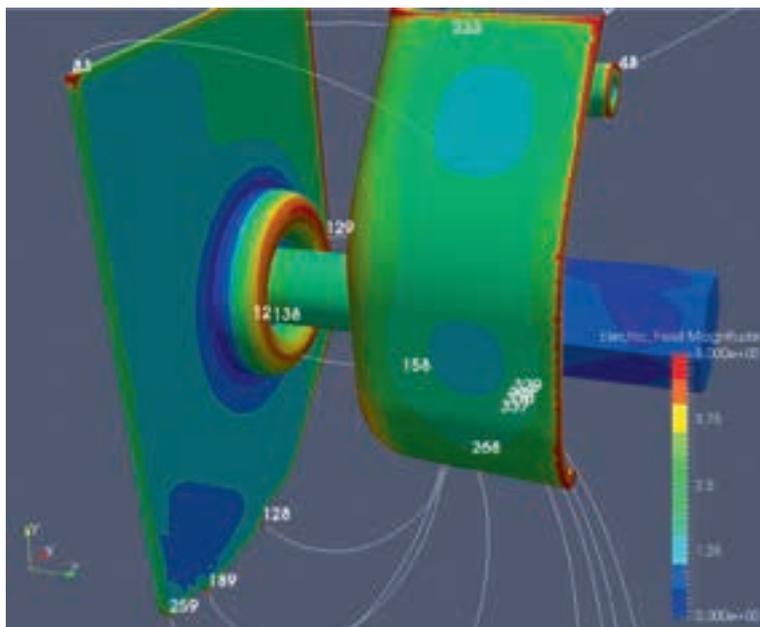
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07a



07b



08

05 A hot cloud from the arc settling around the moving main contact, which resulted in restriking to it. Design changes can push the hot gas away from the moving main contact and prevent the dielectric restriking.

06 Temperature distribution just after CZ crossing. The arrows indicate the gas that is pushed away.

06a Arcing time = 5.25 ms.

06b Arcing time = 13.3 ms.

07 Effect of the outlet at the end of the tube on the accumulated hot gas around the main contact just before the CZ. Double-flow design reduced the accumulated hot gas around the main contact.

07a Double flow.

07b Single flow.

08 Electric field stress at a critical region. The numbers identify the critical points that are used to extract the data, colors show the electric field magnitude.

nents [3]. This action has resulted in very smooth parts that are, in effect, field shields →08. Novel designs have been implemented to overcome high-stress regions at triple points, where conductive solid, insulating solid and insulating gas meet [4]. Finally, the sophisticated design of the puffer interrupter fulfilled all dielectric requirements based on common standards such as IEC 62271-1 [5].

Full-scale testing

Full-scale interruption type tests were conducted on a commercially available ABB SafeRing/ SafePlus Air unit, according to the “active load” test duty classes E3 and C2 of the IEC standard for a rated voltage of 12 kV at a nominal current of 630 A [6].

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[4] A. Blaszczyk et al., “Virtual High-Voltage lab,” *ABB Review*, 2/2021 pp. 52–57.

[5] IEC, “High-voltage switchgear and controlgear – Part 1: Common specifications for alternating current switchgear and controlgear,” IEC 62271-1 ed. 2.0, 2017.

[6] IEC, “High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV,” IEC 62271-103 ed. 1.0, 2011.

A cost-effective and easily operated alternative to a vacuum LBS

Puffer interrupters, which use the gas blast produced by the relative movement of moving and fixed contacts, are widely used in SF₆ switchgear due to their compact size, simple structure and excellent interruption characteristics. In a puffer switch, the interrupting capability depends on the interaction between arc, gas properties, flow pattern, pressure buildup and geometry. The

Novel designs have been implemented to overcome high-stress regions at triple points.

stagnation-point type of flow improves the interruption performance compared to simple flow in non-SF₆ gases. The successful performance of the new interrupter design described here makes it a cost-effective and easily operated alternative to the LBSs using vacuum interrupters and paves the way for the next generation of environmentally friendly RMUs. •



ENERGY FOR ACTION

Rogowski coil current sensors for arc flash detection

ABB's TVOC-2 Arc Guard System™ is an optical arc flash mitigation device with one of the fastest reaction times on the market. Adding the CSU-2 current sensing unit to the TVOC-2 eliminates nuisance trips arising from non-arc-related flashes →01.



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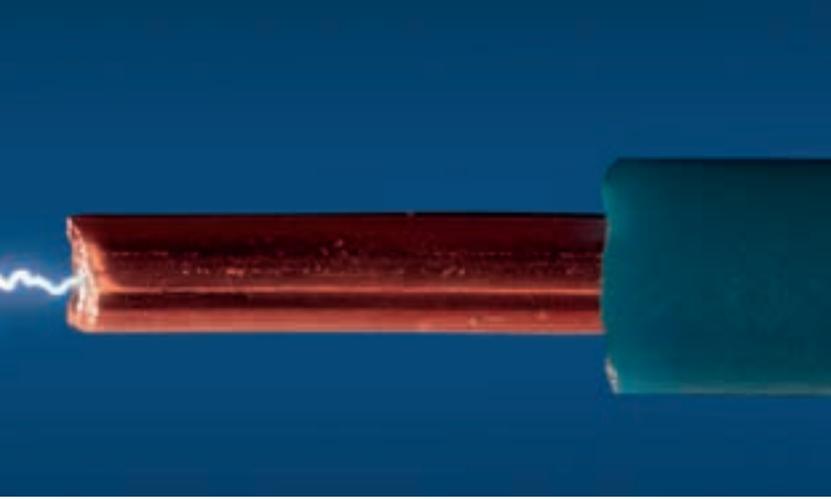
With temperatures of over 10,000 °C, current densities of up to 100 A/cm² and violent pressure waves, an electric arc flash in an electrical enclosure is an extremely dangerous and undesirable event.

Most arcing accidents in electrical equipment are down to human error (eg, when an operator is working on the equipment), faulty connections, or inquisitive animals. Most often, the accident occurs during switchgear maintenance or installation when the cabinet door is open. With the door open, the frontline defense of arc-proofed switchgear design – strong doors – is absent.

Accidents are rare but serious when they occur. Injuries can be severe or even fatal and damage to equipment extensive. Replacing and repairing the damaged equipment can lead to lengthy downtimes.

It is clear, then, that arc flashes are events to be avoided at all costs. If they cannot be avoided, their effects must be minimized. An arc guard system is, therefore, a necessary part of a modern switchgear design.

Much work has been conducted to mitigate the effects of arc flashes and ABB has had effective



01 The ABB CSU-2 current sensing unit.

02 ABB's TVOC-2 Arc Guard System™.

countermeasure products on the market for some decades. ABB's TVOC-2 Arc Guard System™ – the new version of a well-established arc guard system that has been protecting people and electrical equipment from dangerous electrical arcs for over 35 years – is a device that uses optical sensors to detect an electric arc →02. The TVOC-2 interfaces perfectly with ABB Emax 2 circuit breakers, for instance, to provide a fast-response active protection system that limits the damaging effects of internal arcing.

TVOC-2 Arc Guard System

The TVOC-2 Arc Guard System employs optical detectors that sense the light flux associated with the electric arc phenomenon. Upon sensing extraordinary light levels, the TVOC-2 sends a tripping signal to the circuit breaker. Current interruption stops the local power grid from

ABB's TVOC-2 Arc Guard System™ uses optical sensors to detect an electric arc.

feeding further electrical energy into the arc. The reaction time of the detection is less than 1 ms. →03 shows example locations for the optical detectors. Strategic detector positioning will eliminate interference between zones of detection. Sensors are calibrated to have equal light sensitivity and their fish-eye lens design lets them observe a large solid angle, so orientation is not critical.

Electromagnetic interference (EMI) immunity is conferred by the use of fiber-optic cables, which are not only impervious to the EMI that will certainly accompany an arc fault but also

faster at transmitting signals; every microsecond counts during an arcing event.

To avoid false tripping due to camera flashes, nearby welding activity, sunlight, etc., the arc mitigation device can be combined with a current sensing unit and set to activate only when an overcurrent is also registered. This is where the Rogowski sensor comes in.

ABB Rogowski coil current sensors

Over the past few decades, ABB has developed Rogowski coil current sensors for use in electrical equipment such as switchgear. Now, that same technology provides a basis for the new ABB CSU-2 current sensing unit for the TVOC-2. The CSU-2 detects the fast current rise that accompanies faults associated with arc flashes. To eliminate nuisance tripping, the TVOC-2 will only trip the circuit breaker if it "sees" a flash and, at the same time, the CSU-2 current sensing unit detects an overcurrent.

The Rogowski coil is placed around the conductors. The current flowing through the conductors creates a magnetic field in the sensor's winding and thus induces a voltage in the winding. This voltage is proportional to the first derivative of the primary current and is presented as an output on the secondary terminals. The sensor response is linear over the whole measuring range, up to short-circuit currents, which means the sensor covers a much wider range than the current transformer conventionally used.

The Rogowski coil current sensor has several advantages over more traditional approaches.

Benefits of ABB Rogowski coil current sensors

Sensors based on alternative principles, such as the Rogowski sensor, are replacing conventional



02

instruments in switchgear and other electrical installations as part of a strategy to significantly reduce equipment size, increase safety, offer greater rating standardization and provide a wider functionality range.

A variable clamping system for new installations and a split-core solution with an open loop for retrofits make Rogowski coil installation quick, easy, safe and reliable. The current sensor is connected to the CSU-2 by an RJ45 connector. A green indicator light on top of the CSU-2 flags that this connection is secure. The CSU-2 current sensing unit continuously supervises the Rogowski coils' functionality to ensure fast and reliable detection of overcurrent.

One current sensor can be used for nominal currents from 100 A to 4 kA and still measure peak currents of more than 150 kA without saturating. This wide measurement range allows the same current sensor to be used in applications with quite different loads – for example, incoming and outgoing feeders. This aspect of the sensor has further advantages: panel builders can now operate with a smaller inventory and interchangeability of parts is enhanced. Furthermore, the same sensors can be used if a substation were to be upgraded for higher primary currents.

Rogowski coil sensors offer not only significant space savings compared to standard current transformers but also easier handling and

storage, due to their light weight. Also, the absence of a ferromagnetic core means the power losses experienced by conventional solutions are eliminated and, therefore, the sensors exhibit extremely low energy consumption. Lower energy consumption improves both the economic and environmental credentials of the

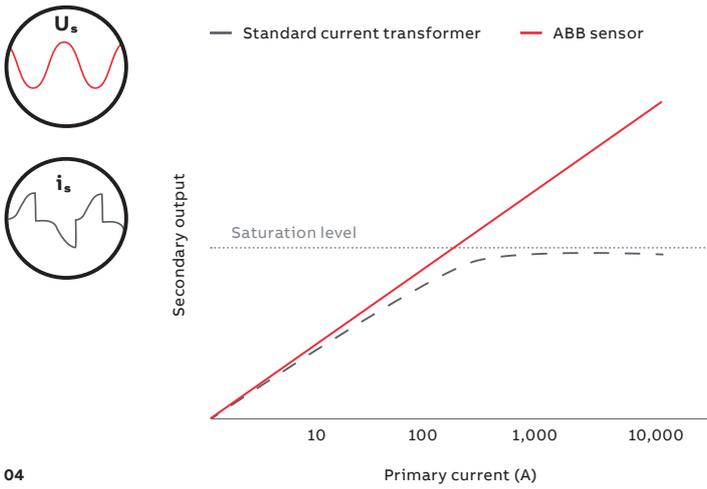
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One current sensor can cover from 100 A to 4 kA and still measure peak currents of over 150 kA without saturating.

solution. Air cores are not susceptible to saturation, a major problem in current transformers with ferromagnetic cores →04–05.

The CSU-2 uses dedicated and factory-calibrated Rogowski coil current sensors in order to ensure fast and safe tripping at low as well as high current levels.

Guarding the future of electrical installations
Arc protection systems are becoming an essential element of electrical cabinet design. Because such systems reduce damage and downtime costs, some insurance companies encourage their use by reducing the cost of cover for sites





04

— 03 Optical detectors are placed strategically for best coverage.

— 04 The sensors' linearity means there is no saturation and no distortion of secondary signal.

— 05 Rogowski coil sensor elements. The sensing coil surrounds the conductor.

05a Medium-voltage version with an openable coil.

05b Medium-voltage version with a fixed coil.

05c Low-voltage version with a small-diameter coil.

05d Low-voltage version with a large-diameter coil.

where they are installed. Protection against arcing events is also becoming enshrined in legislation. For example, the Low Voltage Directive of the European Union stipulates that measures to prevent damage by excessive heat, caused by arc flashes, for example, are to be taken.

The combination of the TVOC-2 Arc Guard System™ and the CSU-2 current sensing unit ensures an electrical installation adequately addresses all aspects relating to arc flashes. The duo ensures

The combination is one of the most effective and reliable arc mitigation products available.

continuous operation, safety and protection. The Rogowski current sensor is easy to install or retrofit and will provide a current measurement with a longer life time and reduced maintenance requirements.

With a design based on ABB's decades of experience in the arc mitigation field, the TVOC-2 and CSU-2 ensure the safety of personnel even when the cabinet door is open and provides all-around, comprehensive arc protection. The combination is one of the most effective and reliable arc mitigation products available. •



05a



05b



05c



05d



BUZZWORD DEMYSTIFIER

Smart materials

Can materials be smart? Can they remember things? The answer is “yes!”



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The term “smart” most likely comes from the fact that such materials are by no means rigid and solid, like conventional materials, but can adapt and change form depending on external stimuli such as temperature or magnetic field. Some even have a “memory” to remember a shape that was trained before. In practice, these materials can be used for actuation, sensing and energy harvesting without any modification of the material itself.

Smart materials offer a wide range of functionality for many applications.

Four classes of smart material are close to, or are already in, industrial application:

- Piezoelectric materials
- Thermal shape memory alloys (SMAs)
- Magnetic shape memory alloys (MSMAs)
- Dielectric elastomers (DEs)

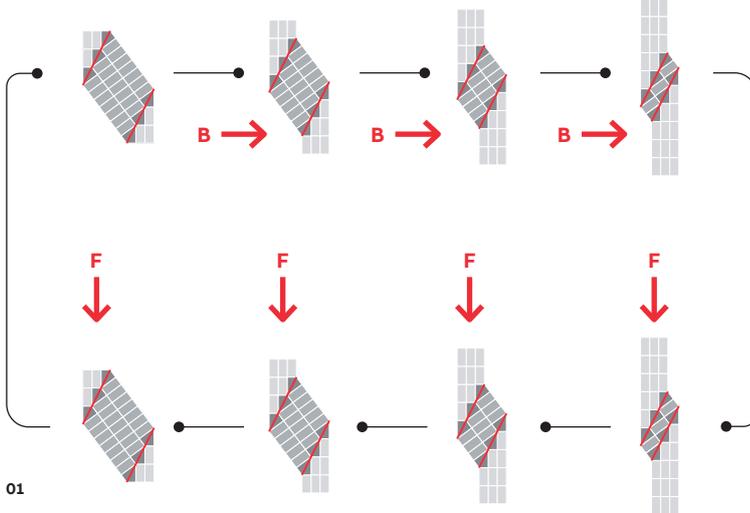
Of these, the piezoelectric materials are the most mature. They are already used in industrial applications, especially in the automotive industry, which might be one reason for their ubiquity. A typical application would be in an injector for common rail engines. As sensors, they are used for force sensors and load cells, for example.

SMAs are also a mature technology. The most prominent applications of this material class are found in medicine (eg, stents). The best-known SMA is a nickel-titanium alloy paper clip that can be deformed drastically, resetting to its initial shape when heated by a candle or put into hot water. This behavior derives from the material's two different crystal structures, which are temperature-dependent. At ambient temperature, the material is in its “cold” crystal structure. The SMA’s “warm” crystal structure must be trained by temperature cycling thousands of times. When, subsequently, mechanically deformed and then heated above the transition temperature at which the crystal re-orient its internal structure, the material “remembers” its trained shape, to which it reverts. The transition temperature for standard materials is around 60 °C.

For industrial SMA actuators, a standard design is a simple wire that can be stretched and is then pulled back when heated (by passing a current, for example). This structural change can exert high forces if a large cross-section is used.

Similar to the SMAs are the MSMAs, which react not only to temperature, but also to magnetic fields. MSMA manufacture is challenging because casting the required monocrystalline ingot is a complex process. Within this ingot, a magnetic polarized and folded magnetic crystal structure will evolve during solidification. The MSMA elements (“sticks”) are cut out of the ingot in a beneficial orientation. The folded, magnetically

B: External magnetic field
F: External force



01 Applying an external magnetic field (B) leads to a proportional deflection of the folded crystal structure. In standard applications, resetting to the original shape is done via an external force (F).

polarized crystal structure within these sticks allows them to deform when an external magnetic field is applied →01.

The combination of thermal and magnetic effects makes MSMA ideal for applications where both a thermal and a magnetic response is required – eg, in a domestic miniature circuit breaker (MCB).

DEs form the last class of smart materials listed above. The rubbery DE material is typically sandwiched between two electrode plates of opposite polarity, as in a standard capacitor. An applied voltage causes the plates to mutually attract, squeezing the elastomer. This basic deformation allows a wide versatility of actuator designs. In sensing mode, any displacement of the DE (configured as a membrane, for example) changes the capacitance, allowing precise deformation measurement. The first industrial products employing this principle will be launched soon.

Smart materials offer a wide range of functionality for many actuation and sensing applications – and all with a very simple design with a low part count compared to alternative solutions. Smart, indeed. •

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Assets and connectivity

Just as we must take care of our bodily health to be able to perform optimally, a company must protect and care for its assets to ensure its productivity. The next issue of ABB Review will look at asset health and how customers know they can rely on the condition of ABB's equipment.