ABB Research Center United States
Technical Review 2015

Power and productivity
for a better world™

Content

Dr. Le Tang
Vice President and Head of US Corporate Research Center

Dear Friends and Colleagues,

It is my great honor to present to you the 2015 issue of the annual ABB US Corporate Research Center (USCRC) Technology Review.

ABB has a proud history of innovation and providing cutting-edge technology solutions in power and automation to make the world a better place. ABB's commitment to this tradition is reflected in the large and growing investment in R&D.

The world faces unprecedented challenges in climate change, environmental degradation, resource depletion, and terrorism. The ongoing technology advancements in new materials, sensors, and internet of things, digitalization, artificial intelligence, robotics, advanced manufacturing, control, and optimization present us with opportunities to overcome these challenges. In this report, we present to you a sample of the research activities at USCRC. These research topics cover, but are not limited to:

- Next generation power electronics (SiC, GaN) – High efficiency power conversion
- Renewable power – Innovative direct drives for wave energy harvesting and conversion
- Building automation – Intelligent control to reduce energy footprint
- Microgrid – Renewable power integration and resilience
- Stochastic grid operation – Benefits and challenges of multi-stage stochastic optimization
- Cyber-physical security – Protection of critical infrastructure using sensors and data analytics
- 3D robotic vision – Precision painting control on flexible panels of irregular shapes
- Location-aware mobile system – Used for asset management

We believe that an open innovation environment is essential in a world of fast-paced technology transition and increasing technology specialization. We actively participate in government-funded research programs and have achieved very impressive results on the awarded projects. The collaborations with internal and external partners have been essential to our success.

I hope you will find the reading of this report informative and enjoyable.

Le Tang, Ph.D.
Vice President and Head of US Corporate Research Center
ABB Inc.

USCRC Overview

The US Corporate Research Center (USCRC)

The US Corporate Research Center (USCRC), with its main office in Raleigh, NC and a satellite office in Windsor, CT, is one of the local Research Labs in the global ABB Corporate Research community.

USCRC Building on NSCU Centennial Campus, Raleigh, NC

Mechatronics and Sensors Lab, Windsor, CT

Our Mission and Vision

In line with ABB's global mission to drive innovation, the US Corporate Research Center aims to maintain and strengthen the company's position as a technology innovation leader.

USCRC MISSION

To provide leading-edge technologies
and innovative solutions to ABB businesses.

USCRC VISION

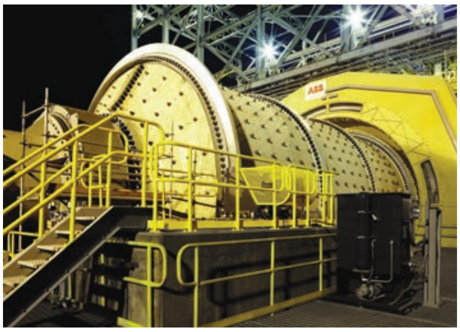
To be a premier Corporate Resarch Center
fostering innovation and advancing
ABB technology for
power and automation industries.

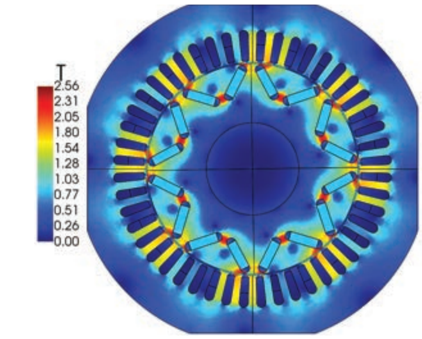
Research Areas

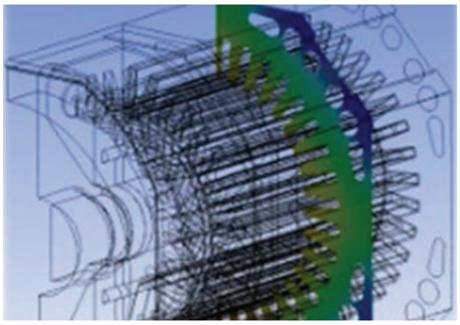
Control
Innovate automation, operation, protection and maintenance solutions for industrial and electrical systems including their associated components

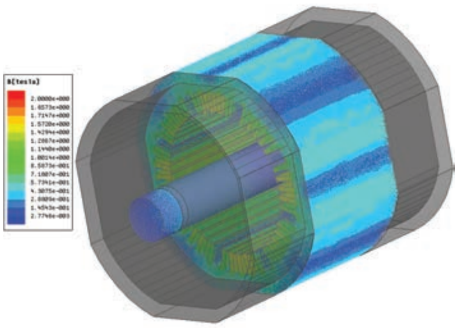
Electromagnetics
Devise novel products and systems using insights into electromagnetics, dielectrics, heat transfer, acoustics and electro-chemistry

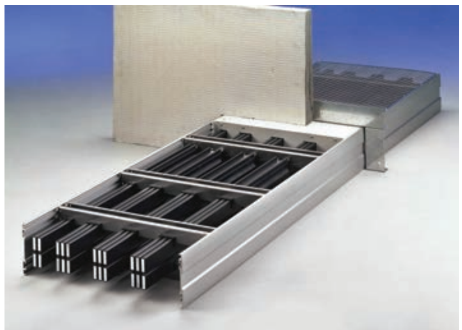
Materials
Investigate novel materials for future products as well as identify/deploy cutting edge manufacturing processes





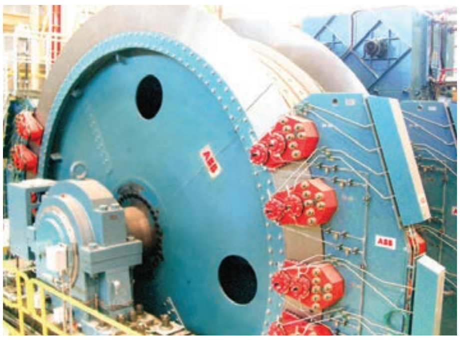






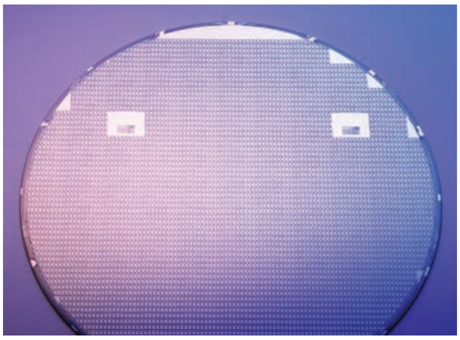
Mechanics

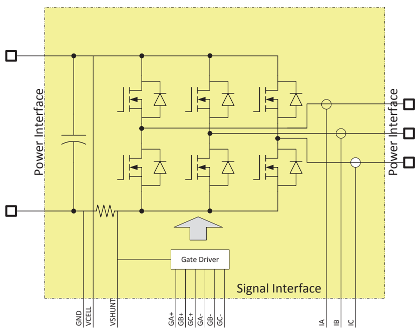
Analysis, design, track manufacturing advances, use, and maintenance of diverse mechanical system (robotics to switchgear)



Power Electronics

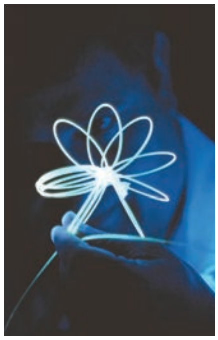
Realize novel power electronic solutions and power semiconductors for diverse applications





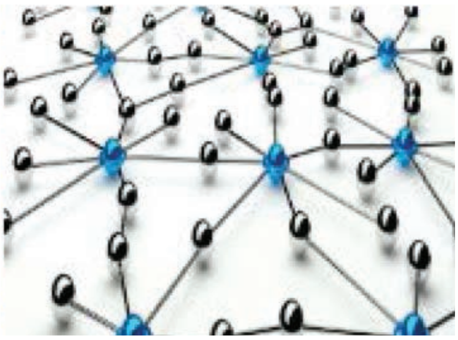
Sensors

Create innovative measurement solutions for electrical and industrial systems, secure competence in electronics for smart and reliable devices



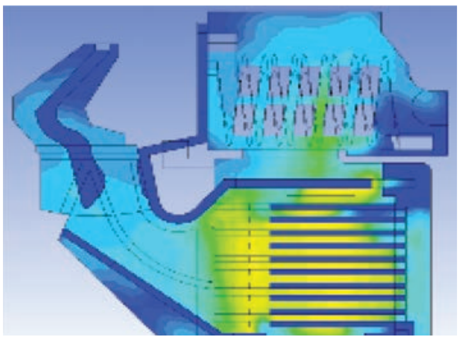
Software

Create sustainable, secure, and user friendly software-based automation solutions, using efficient software engineering methods and architectures



Switching

Devise cutting edge AC and DC interruption technologies for the entire voltage range

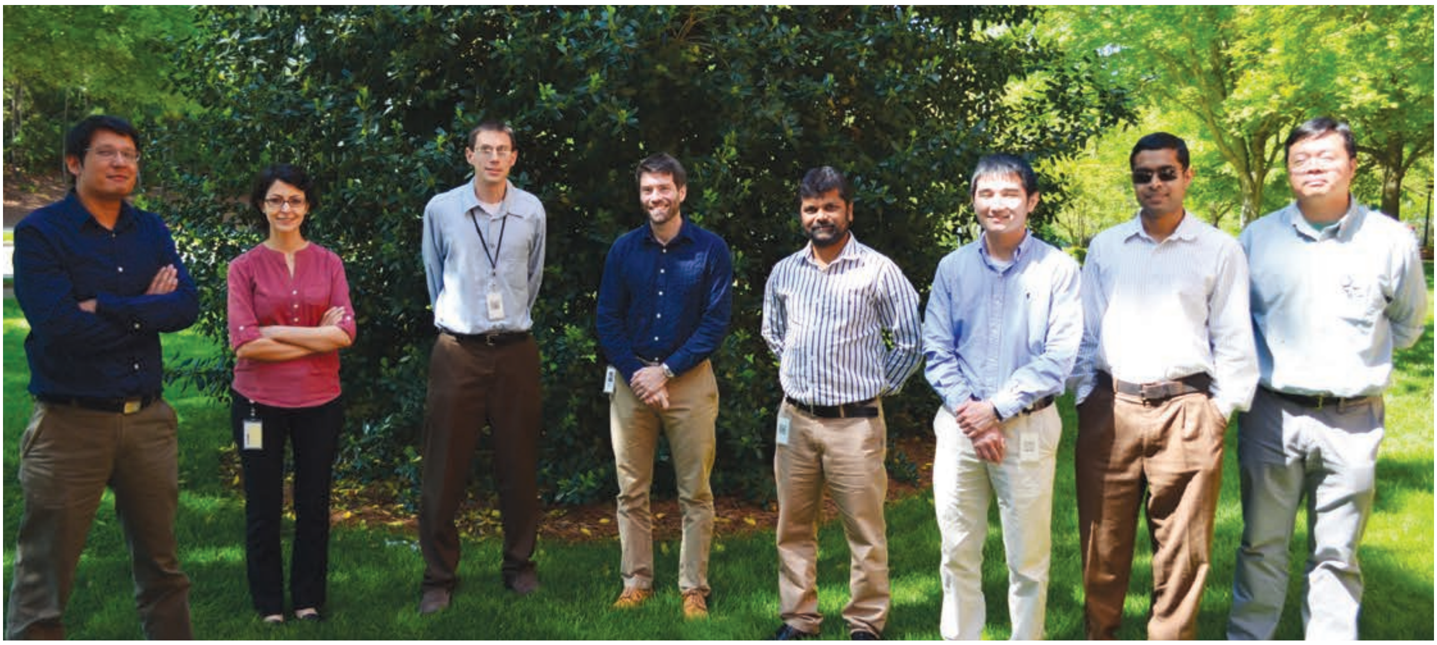


People

Our diverse population of R&D engineers and scientists work hard to develop breakthrough technologies that change the way the world works and the way industries do business.

USCRC Researcher Country of Origin

Bangladesh	India	Pakistan
Canada	Iran	Philippines
Chile	Italy	Romania
China	Mexico	Russia
Egypt	Nepal	South Korea
Germany	Nigeria	United States




Raleigh, NC skyline

Local Community

Raleigh, North Carolina – A great place to live and work

Raleigh is one of the three major cities (Raleigh, Durham, and Chapel Hill) of The Research Triangle, often referred to simply as “The Triangle”. The Triangle is a region in the Piedmont of North Carolina in the United States, home to Duke University, University of North Carolina at Chapel Hill, and North Carolina State University,.

North Carolina is the 10th most populated state in the US, with approximately 10,000,000 people. Its Capital, Raleigh, is the 2nd largest city and home to 452,000, according to the U.S. Census Bureau, 2014.

Raleigh Area in the media

- #1 Mid-Sized American City of the Future (Raleigh, NC), Financial Times / April 2015
- #1 Best Cities for Jobs (Raleigh, NC), Glassdoor | May 2015
- #1 Metro for Science, Technology, Engineering and Math (“STEM”) Leadership (Raleigh-Durham, NC), Business Facilities | August 2015
- #2 Best Large City to Live in (Raleigh, NC), Wallet Hub | August 2015
- #2 City for Business and Careers (Raleigh, NC), Forbes / July 2015
- #2 City Creating the Most Technology Jobs in 2015 (Raleigh-Durham), Forbes | April 2015
- #2 Life Science Cluster (Raleigh-Durham, NC), JLL Life Science Outlook | July 2015
- #3 Community in U.S. for Overall Well-Being (Gallup-Healthways Well-Being Index | April 2015
- #3 Metro for Economic Growth (Raleigh-Durham, NC), Business Facilities | August 2015
- #3 American City to Visit in 2015 (Raleigh, NC), The Huffington Post | February 2015
- #4 Top Digital County (Wake, NC), Government Tech | July 2015

Hub of High Tech Business and R&D

Raleigh is part of the Research Triangle (home to the Research Triangle Park, or RTP), which comprises the cities of Raleigh, Durham and Chapel Hill. It was founded in 1959 by NC leaders in academia, business and government, and it's the largest continuously operating research park in North America.

RTP covers more than 7,000 acres and is home to over 170 research, technology and ag-bio companies, such as Cisco Systems, IBM, GlaxoSmithKline, Fidelity Investments, Biogen Idec and BASF. Its headquarters is located on Davis Drive in Durham, NC, and is only a 25 minute commute from downtown Raleigh.

Home to World Class Universities

North Carolina boasts 51 colleges and universities, some of which include NC State University (NCSU), the home of ABB's US Corporate Research Center, as well as several ranking in the top 100, such as Duke, Wake Forest University and the University of North Carolina at Chapel Hill (UNC). We are proud that Forbes.com has ranked Raleigh in the Top Ten of "America's New Brain Power Cities".

Beaches and Mountains

Centrally located, Raleigh is only a 2 hour ride to our beautiful NC beaches or 3 hours to the mountains. With an average annual temperature of 60 degrees, weekend trips to the mountains or the coast are pleasant most anytime of the year.

Arts and Sports

According to the website, Visit Raleigh.com, greater Raleigh is often dubbed the "Smithsonian of the South", wherein you'll find the NC Museum of Art, NC Museum of Natural Sciences and NC Museum of History.

Raleigh is also home of the Carolina Ballet and the NC Theatre, as well as a variety of cultural art and music venues available at little or no cost.

Sports enthusiasts with enjoy Raleigh's Carolina Hurricanes NHL Hockey Team, the Carolina Mudcats minor-league baseball team, the Durham Bulls minor-league baseball team and Cary's Carolina Rail Hawks pro soccer team.

Investing in the next generation

ABB is a proud $1,000,000 sponsor of Raleigh's Marbles Kids Museum. This unique museum allow children to imagine, discover and learn through interactive exhibits, educational programs and giant-screen IMAX films. Designed specifically for children under the age of 12, it's a place for kids to learn in the midst of extraordinary adventures in play.

Windsor, CT

The Mechatronics and Sensors department functions out of the Windsor, CT office. This location is in close proximity to several leading academic institutions, particularly several with a strong focus on robotics, mechanics and sensors. These include MIT, Harvard, Princeton, Yale, WPI, RPI, UMass, UConn, Boston University, Cornell, and Northeastern.

The Mechatronics and Sensors team is located roughly halfway between Boston and New York, approximately 100 miles from each. This department, which specializes in industrial and service robotics, is close to a large amount of cutting edge robotics research. For example, the Boston Globe reports that Boston and the surrounding area is home to more than 100 robotics companies, such as iRobot, Rethink Robotics, Boston Dynamics, Ki`va Systems, Adept MobileRobotics, and Barrett Technology. It is also close to the New England Robotics Validation and Experimentation (NERVE) Center.

Windsor, CT is also at the center of the Aerospace Component Manufacturer's "Aerospace Alley," a collection of over 50 leading aerospace companies. It is also within a short drive from several other high tech firms such as General Electric, United Technologies, Alstom, Westinghouse, Siemens, Pfizer, General Dynamics – Electric Boat, Xerox, Gerber Scientific, and KAMAN.

Externally Funded Projects

The congruence between the funding areas targeted by various US Government agencies and ABB's R&D strategies continues to be strong. Government funding helps to advance ABB R&D goals, and reduce technical risk. So, securing 3rd party funded projects to supplement internally funded USCRC activities continues to be a key metric.

During the past year, with the assistance of the ABB Washington, DC office, we have held a number of meetings with key members of various agencies, to discuss ABB capabilities and interests. There is increasing interest in software, robotics, materials, and mechanical areas, and we are pursuing opportunities aggressively.

Collaboration Partners

We work with leading universities, national labs, government entities, and other research organizations across the globe to advance state of the art, explore new frontiers, and develop new technologies. That opens many doors for talented researchers to collaborate with us and enrich their professional careers.

At ABB, innovation is our lifeblood: We are always looking for new ways to make our customers more competitive and minimize environmental impact.

That is why we work with the very best talent, in a wide range of engineering disciplines including power and energy systems, power electronics, electromagnetics, materials science, robotics, software, and sensors.

We invest heavily in collaborations with more than 39 leading universities in North America and worldwide to develop long-term disruptive technologies and short-term evolutionary innovations for our existing products and services.

Our Global R&D Lab has 8 research areas, ranging from sensors, software, and control technologies to switching, power electronics, electromagnetics, materials, and robotics. Each research area devotes time and resources to our university collaborators in select areas, and equips them with our latest products and services, to help us create the breakthrough technologies of tomorrow.

Collaboration structure

The collaborations are structured in the following ways:

- Consortia of government, business, and academic partners focused on specific large-scale projects such as FREEDM, CURENT, and PSERC.
- ABB Internship Program: We offer internship opportunities to promising graduate students and senior researchers with projects focusing on industrial applications of power and automation technologies that save energy and improve people's lives.
- We work with distinguished professors who divide their time between ABB and academic institutions, directing commercial projects, guiding PhD students, and shaping educational programs at our partner universities.
- We sponsor technical seminars and guest speakers in relevant disciplines to exchange the latest advancements, share experiences, and identify future collaboration opportunities.
- Structured university partnerships: In several countries ABB top management partners with university management to develop research and education programs with regular workshops and seminars, master's student placements at ABB and more.
- Industrial PhD programs: We fund a number of ABB employees pursuing PhDs in commercially relevant areas.
- ABB technologists offer short courses or teach an industrial course in areas such as software and smart grids.
- We partner with academic institutions, national laboratories, private sector, and customers to advance the state of the art in R&D and demonstration projects.

Internship Program

Every year we carefully select and invite promising graduate and undergraduate students and senior researchers to join us for innovation and technology development. Although the bulk of the program targets graduate students in STEM disciplines, we have hosted undergraduates, post-docs, and visiting scholars in the center. The normal internship cycle typically runs from May to August but fall and spring internships are also popular and extended depending upon the need and availability of funds in particular projects.

Our interns engage in a wide variety of activities from early concept evaluations to prototype implementations to hands-on experiments and anything in between. These internships not only enrich the technical breadth of our interns, they also help sharpen the soft skills required to enter the corporate environments and advance career opportunities.

Collaboration Partners

Universities

- Carnegie Mellon University, Pittsburgh, PA
- Case Western Reserve University, Cleveland, OH
- Clemson University, Clemson, SC
- Georgia Tech, Atlanta, GA
- Michigan State University, East Lansing, MI
- MIT, Cambridge, MA
- North Carolina State University, Raleigh, NC
- Ohio State University, Columbus, OH
- Pennsylvania State University, State College, PA
- South Carolina State University, Columbia, SC
- Texas A&M University, College Station, TX
- Tokyo Marine University of Science and Technology, Tokyo, JP
- University of British Columbia, Vancouver, CA
- University of British Columbia, Vancouver, BC
- University of Connecticut, Mansfield, CT
- University of Delaware, Newark, DE
- University of Florida, Gainesville, FL
- University of Idaho, Moscow, ID
- University of Illinois at Urbana Champaign (UIUC), Urbana, IL
- University of Massachusetts, Amherst, MA
- University of Memphis, Memphis, TN
- University of Nebraska, Lincoln, NE
- University of North Carolina-Charlotte, Charlotte, NC
- University of Notre Dame, South Bend, IN
- University of Texas, Austin, TX
- University of Wisconsin-Madison, Madison, WI
- University of Zurich, Zurich, CH
- Virginia Commonwealth University, Richmond, VA
- Virginia State University, Petersburg, VA
- Virginia Tech University, Blacksburg, VA
- Washington State University, Pullman, WA
- York University, Toronto, ON

Industry

- Ameren, Urbana, IL
- Bonneville Power Administration ,Portland, OR
- Nippon Steel & Sumitomo Metal Corporation, Japan
- Resolute Marine Energy, Inc., Boston, MA

National Labs

- Oak Ridge National Laboratory, Oak Ridge, TN

Consortiums

- CAMAL (Center for Additive Manufacturing and Logistics), Raleigh, NC
- CAPD, Pittsburgh, PA
- CEIC (Carnegie Mellon Electricity Industry Center), Pittsburgh, PA
- CHPPE (Center for High Performance Power Electronics), Columbus, OH
- CPES (Center for Power Electronics Systems) – High Density Integration & Renewable Energy and Nanogrids, Blacksburg, VA
- CURENT (Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks), Knoxville, TN
- FREEDM (Future Renewable Electric Energy Delivery and Management), Raleigh, NC
- GearLab, Columbus, OH
- Industrial Internet Consortium (IIC), Needham, MA
- PowerAmerica, Raleigh, NC
- PSERC (Power Systems Engineering Research Center), Madison, WI
- ROSE-HUB, Charlotte, NC
- Robot Operating System (ROS-Industrial Consortium Americas, San Antonio, TX
- Smart Lighting, Troy, NY
- TWCC, Austin, TX
- WEMPEC (Wisconsin Electric Machines and Power Electronics Consortium), Madison, WI

Professional/Standard Community Involvement

Our researchers work with various business units to develop next and next next generation products, systems, and solutions. They are also involved in professional communities and standard making bodies advancing the state of the art and practice of technology in their respective areas of research. Below is an example list of professional societies and working groups that our researchers are involved in making lasting and broad contributions for the benefit of the industry at large.

Professional Societies

- ASME (American Society of Mechanical Engineers)
- IEEE Power & Energy Society
- IEEE Control System Society
- IEEE Signal Processing Society
- IEEE Electron Devices Society
- IEEE Industry Applications Society (IAS)
- IEEE Power Electronics Society (PELS)
- IEEE Robotics and Automation Society
- IEEE Control Systems Society

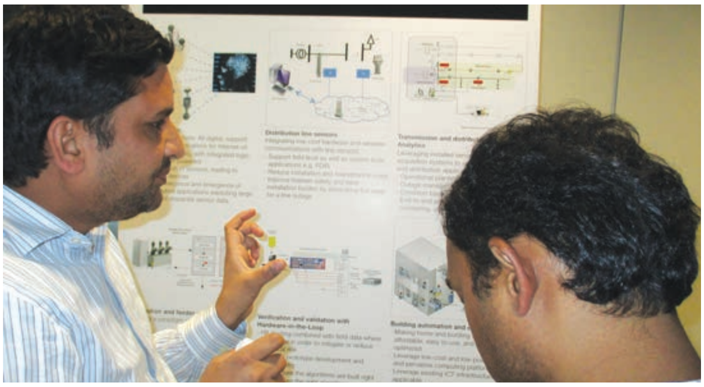
Working Groups, Task Forces, Committees

- IEC TC 57 Power systems management and associated information exchange/ WG 17 Communications Systems for Distributed Energy Resources
- IEEE 2030.7 WG Distribution Resources Integration/Microgrid Controllers TF
- IEEE PES Cyber Security Task Force
- IEEE PES Analytic Methods for Power Systems Committee
- Editor: IEEE Transactions on Sustainable Energy
- IEEE Distribution System State Estimation Working Group
- IEEE PES CAMS Working Group on High Performance Computing for Power Grid Analysis and Operation
- IEEE Task Force on Interfacing Techniques for Simulation Tools
- IEEE Task Force on Cyber Security of Power Systems
- IEEE Task Force on Open Source Software (OSS)
- North American Synchrophasor Initiative WG (NASPI)
- IEEE PES Power System Relaying and Control Committee
- IEEE PES Power System Operations, Planning and Economics Committee
- IEEE PES Transmission and Distribution Committee
- IEEE PES Power System Dynamic Performance Committee
- IEEE PES Power System Communications and Cybersecurity Committee
- IEEE PES Power System Instrumentation and Measurements Committee
- IEEE PES Smart Buildings, Loads and Customer Systems Committee
- IEEE International Conference on CYBER Technology in Automation, Control, and Intelligent Systems Program Committee (CYBER)
- The World Congress on Intelligent Control and Automation (WCICA) Program Committee
- Chair: IEEE Robotics and Automation Society Connecticut Chapter
- IEEE International Conference on Robotics and Biomimetics (ROBIO) Program Committee
- NIST NBD-PWG – Big Data Public Working Group
- NIST CPS-PWG – Cyber Physical Systems Public Working Group

Events

USCRC Open House

"2015 New Research / Meet out Research Scientists" was the theme for our 2015 USCRC Open House. This event is held annually and keeps ABB employees, who work outside of the Research arena, abreast of new research. It featured a Poster Session wherein the actual researchers were on hand to discuss their new projects and advanced innovations. This event kicks off the Fall Season and is fondly received, both for the information, and the complementary Frozen Yogurt Bar.



USCRC represented at International Conferences

This presentation gave an overview of the evolution of industrial robotics, introduced their intelligent components, and described their intelligent functions and applications from a corporate R&D and manufacturing automation point of view.

George Zhang, Sr. Principal Scientist, presents "Industrial Robotic Intelligence and Advanced Applications" at the International Conference on Robotics and Biomimetics.

Offshore Europe 2015

The Offshore Europe Conference is known to be Europe's premier Oil and Gas ("O&G") exploration and production conference. The 2015 event was attended by 56,000 people from over 100 countries.

USCRC's research scientists, Dr. Greg Cole and Greg Rossano, demonstrated the ABB air gap crawler at Offshore Europe 2015 in Aberdeen, Scotland. The ABB air gap crawler is a robot designed to visually inspect the air gap between the stator and rotor of large machines. This enables motors and generators to be inspected without removing the rotor.

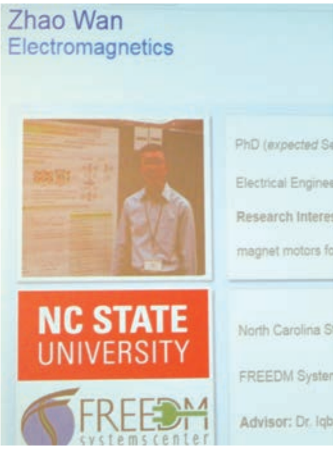
2015 IEEE MIT Undergraduate Research Technical Conference ("URTC")

The 2015 IEEE MIT URTC brings together undergraduates around the world to present, discuss, and develop solutions to advance technology for humanity. The conference was hosted on the MIT campus.

Harald Staab, Sr. Principal Scientist, delivering plenary talk at 2015 MIT URTC.

USCRC Interns present their projects to staff

USCRC hires 30+ Interns each year to work with our staff on its research and project applications. They represent some the finest students from the top Graduate Programs at various Universities across the country and globe (see more details under “Collaboration Partners”). Below are some of our interns presenting their projects to USCRC Staff.



USCRC Holiday Food Bank Drive

ABB Inc. matches the contributions of non-perishable foods donated by all departments, transposing pounds into dollars. USCRC’s contributions weighed in at nearly 400 pounds.

Featured R&D Articles

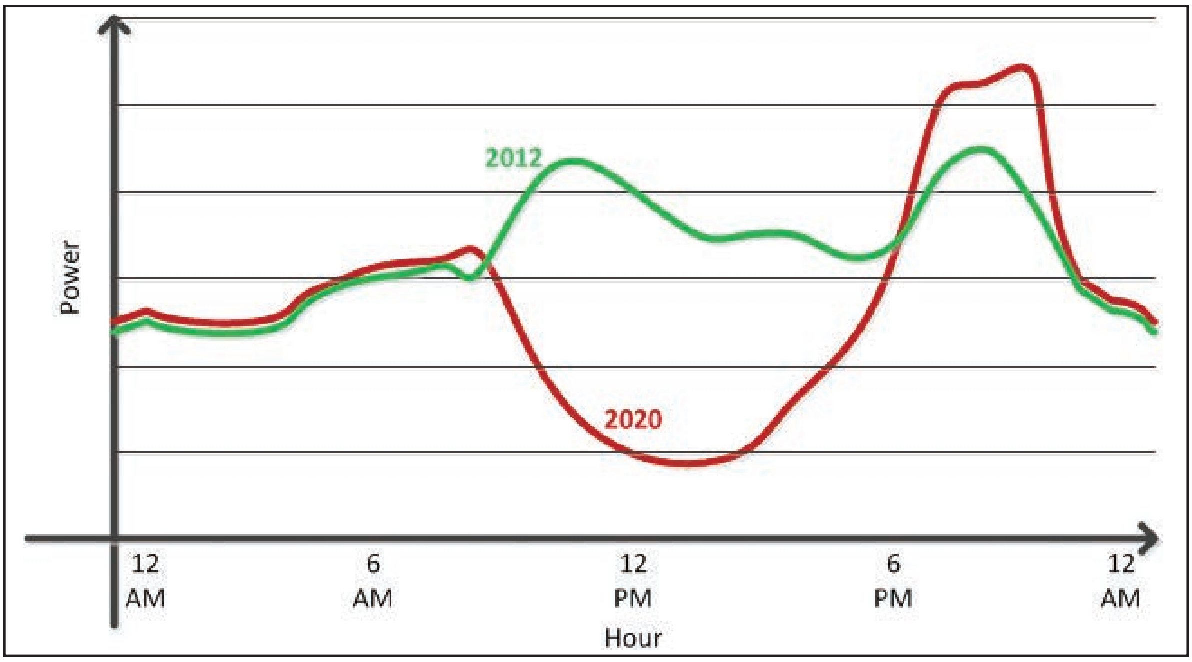


Figure 1: Anticipated 'Duck' Curve Due to Renewable Generation

Flexible Demand Response for the Volatile Grid

Dr. Joseph Carr, Dr. Alex Brissette, Dr. Tao Cui

The Volatile Grid

Managing the volatility of the load power demand has always been a key task for the electric grid. Generator governors with droop control can balance base variations in demand, while fast acting spinning reserve is used to respond to rapid load changes, faults, and lost generation. These mitigation methods have been sufficient to ensure the stability of the grid up to this point.

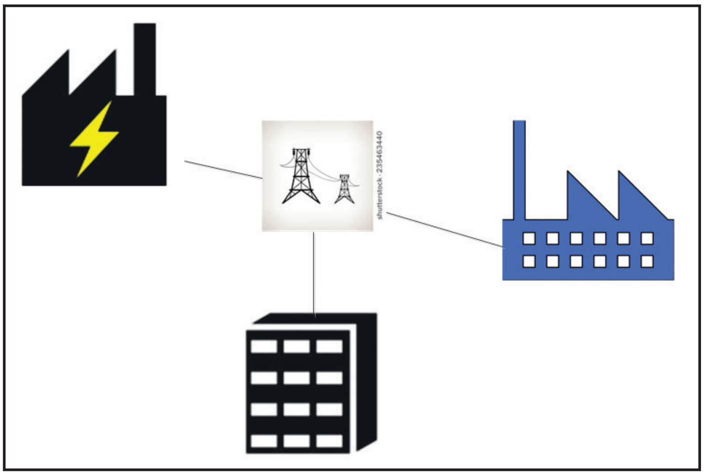
The introduction of variable renewable generation such as wind and solar has exacerbated this volatility, placing new demands on the controllable generators. Examples such as the duck curve shown at the beginning of this article demonstrate that the ramp rates are steeper with renewable generation and the trenches are deeper, which cuts into baseline generation. If one were to zoom to a shorter time scale, one would also see that the short term variations are more frequent and of larger magnitude. The steep ramp rates outpace generator governors, requiring substantial investment in higher cost spinning reserve generators.

A plethora of alternative solutions for mitigating this volatility have been proposed. Many kinds of energy storage have been explored, ranging from large installations of lead acid batteries to cutting edge super capacitors and hydrogen fuel cells. With the advent of fracking, natural gas prices are low enough to balance wind and solar power production for quite some time. Elsewhere in this journal, a method to take advantage of curtailment in a heavy renewable power scenario is described. Finally, direct control of loads has generated increasing interest as a solution for volatility. This article describes approaches to load control through the use of building intelligence and energy management: the so-called Active Building.

Demand Response

Classical demand response systems make use of pre-existing contracts and person-to-person communication to implement their programs. A facility would sign an agreement with the utility to reduce their load by a pre-agreed amount upon request in exchange for a credit for their electric bill. The utility would contact the facility manager over the phone or with email hours or days in advance, and then the facility manager would implement the pre-agreed reductions.

Figure 2: Demand Response in Industrial and Commercial Facilities



These restrictions limited the application of demand response. It was most commonly used for peak load reduction based on day-ahead forecasting, and was implemented only in large loads such as industrial facilities where the scale of the load justified the cost to make the changes. It was not frequently implemented even in large commercial buildings, where individual loads were small and it would require considerable effort to implement a change large enough to impact the grid.

The technologies that enable the Internet of Things have created a new type of demand response: automated demand response (ADR). Using web applications and internet-connected microprocessors, the demand response may now be generated and implemented without the need for human intervention. An open-source automatic demand response protocol, OpenADR, has been developed to facilitate these interactions. Since automatic demand response was released, there has been a dramatic increase in participation in demand response programs. Even individual homes can participate in these programs through aggregators as their thermostats may be connected with OpenADR in order to implement demand response by turning off the HVAC at a commanded time.

This new ADR technology is the basis for a new method of mitigating the volatility of the grid power. Not only can smaller and smaller loads be shed in a cost effective manner, but they can also be commanded in very short time periods. Demand response is no longer constrained to days or even hours of lead time, but may be implemented within seconds of the grid detecting a disturbance. Certain loads, such as lighting, HVAC, or water heating, can respond quickly enough that they can balance even the rapid changes in renewable energy sources. Furthermore, these loads have sufficient tolerance that they can service this balancing function with a minimal impact on the occupants of the building.

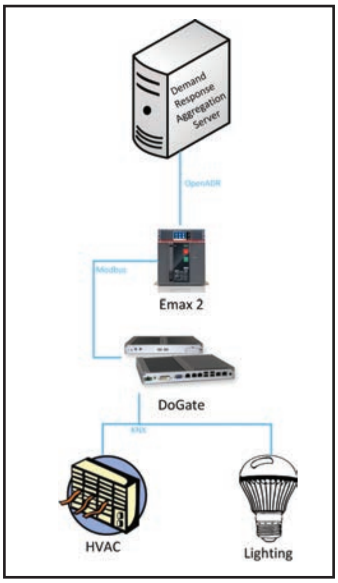


Figure 3: Active Building Architecture

Active Building

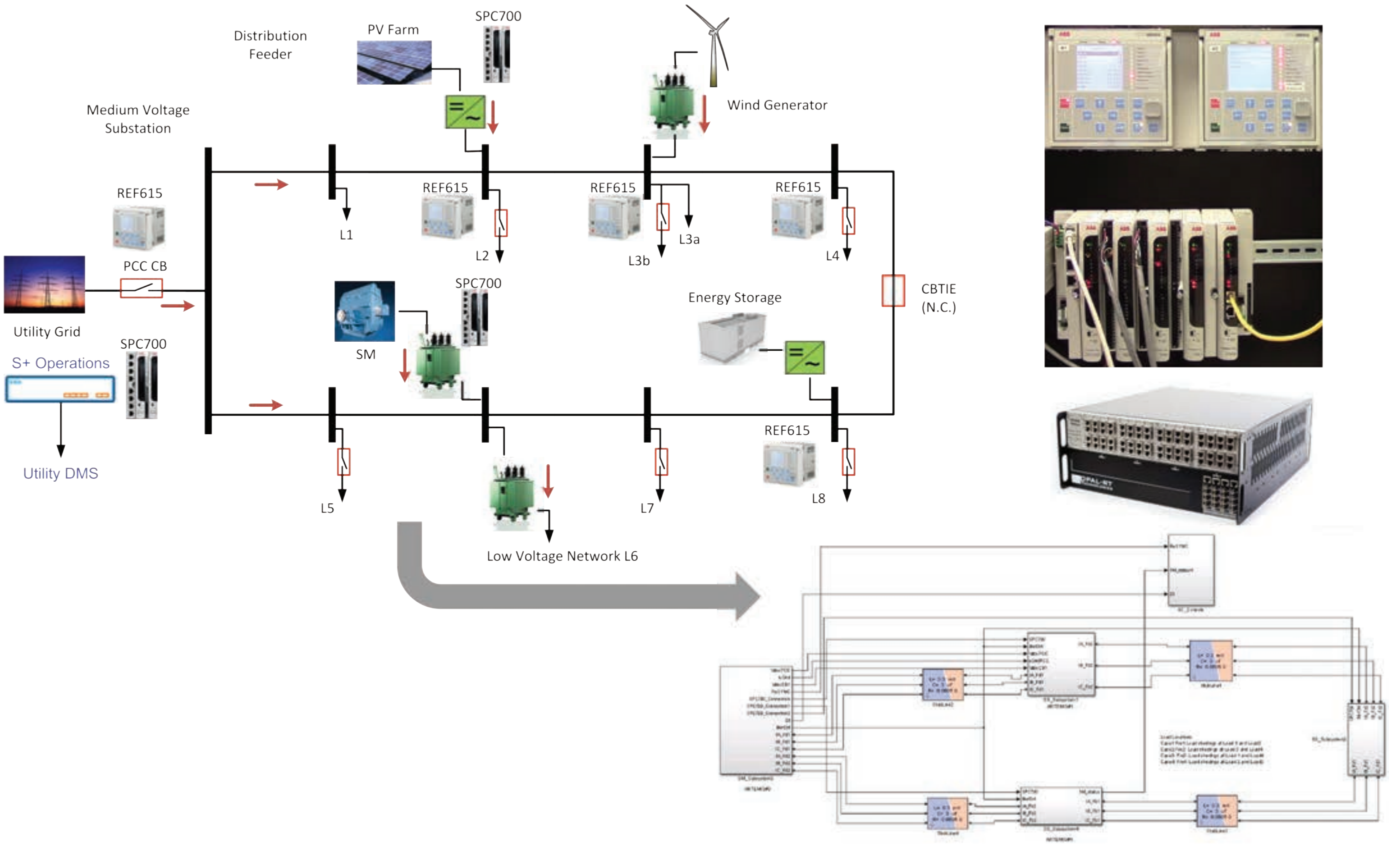
The Active Building project has explored control techniques to implement demand response within the building automation system of large and medium sized commercial buildings. ABB's Emax 2 circuit breaker is fitted with an OpenADR Virtual End Node interface in order to receive automatic demand response signals. The Emax 2 Ekip power management system implements these signals as a change in its power limit. If the building power exceeds the limit, a signal is sent to various loads in order to cause them to disconnect.

Many of these loads, such as HVAC systems and lighting, are already networked in the building automation system The ABB DoGate building automation gateway, then, provides a convenient mechanism to control these loads. It is able to read disconnect signals from the Emax 2 circuit breaker over Modbus. These signals can be processed using the DoGate's gateway function. A change in the signal from the Emax 2 can be mapped to various loads in the building. This can trigger a change in a zone's thermostat settings, the dimming level of lighting, or the temperature setpoint of a water heating unit, among other changes. The gateway function is even able to establish multiple different settings based on the value of the signal received from the Emax 2, enabling a variety of responses depending on the required action. This variety of control can be exploited to find a way to meet the demand response goals while minimizing the discomfort experienced by the building occupants.

Testing in the Active Building product has demonstrated that the OpenADR signals may be received by the Emax 2 product and that the DoGate is able to read changes in the state of the Emax 2 and implement load reductions based on that state change. Various methods are being explored to allocate the load reductions in order to minimize occupant discomfort, and future tests will evaluate the tradeoffs between energy reduction and comfort.

Conclusions

Advances in communications and control technology are poised to take demand from a cause for instability on the grid to a solution for it. Loads like HVAC and water heating have intrinsic energy storage properties that enable them to ride through temporary interruptions as might be required to balance renewables, while loads like lighting are able to operate in a degraded state, here dimming, where they can provide sufficient functionality at a lower power level. With the rise of the Internet of Things, more and more loads may be scheduled in order to smooth out variance on the grid. Dishwasher start times could be coordinated with times of peak power availability, or the HVAC could be turned on to precondition a building in order to fill in load troughs that occur overnight. Experiments at ABB seek to find ways to implement this demand control in a way that provides maximum value to both the utility and to the consumer.



Integrated Microgrid Control and Protection System Designed for Interoperability

Dr. Dmitry Ishchenko, Dr. Alex Brissette, Dr. Anil Kondabathini, Dr. Ravindra Singh and Dr. Zhenyuan Wang

Introduction

Distribution power systems nowadays are most impacted by the integration of distributed energy resources (DER) into the grid, and this trend is only expected to accelerate with the increased deployment of microgrids. Such wide-scale DER integration introduces new challenges related to power system operation, protection, energy management and dispatch. Microgrid technologies are becoming less of a niche and more of a mainstream concept with a high probability of being adopted by the utilities around the globe. These challenges impose new requirements on distribution management systems in general and microgrid automation systems in particular, such as the ability to implement fast remote control functions, deal with modified distribution configurations, and adapt protection systems to changing conditions. Ultimately, this leads to the use of significantly more telecommunication and information technologies. Another critical requirement for further proliferation of DER technologies and microgrids is interoperability, i.e. use of standardized communication interfaces between different systems and components of the microgrid.

Problem Description

Modern microgrids are complex integrated engineering systems that rely heavily on communication technologies to achieve coordinated control. As such, they require detailed modeling of various microgrid components that include a wide range of time constants from minutes and seconds for dispatch to milliseconds for stability and protection related phenomena. Using real-time simulation platforms to validate microgrid controls is essential for the development and testing of several use cases particularly for grid-tied microgrids. It also allows for integration of the microgrid controllers, protection relays and the DER controllers into the simulation for added realism.

The problem of unplanned, controlled islanding due to external faults is of particular importance since it occurs very fast, and it is critical to respond equally quickly to avoid microgrids collapse. It should be noted that unintentional islanding is currently not allowed by the IEEE 1547 Standard [2]; however, the intentional islanding operation is permitted. The operational modes for such schemes are described in IEEE 1547.4, which defines so called "island" systems as those that can include local and/or area electrical power systems. Using IEC

61850 communications to integrate ABB supervisory microgrid controllers with the advanced protection and control functions offered by ABB protection relays allows for complex and complete microgrid control schemes to support the unplanned islanding use case, as well as the more conventional planned islanding case. Resynchronization and reconnection of the microgrid to the area electrical power system can also be performed. The system can implement fast distributed control, which would have been impossible to accomplish with older communications protocols (such as Modbus), or even with local or remote I/O. Additionally, using IEC 61850 communications for microgrid supervisory control helps to reduce the engineering and commissioning time because they eliminate the need for complex I/O wiring.

IEC 61850 Communications

The rapid advancement and success of IEC 61850 technology in the substation automation space allowed for the expanded scope of the standard from the substation to the field device and microgrid levels. The extensions of the original IEC 61850 object models are currently under development by Working Group 17 of IEC Technical Committee 57 with the particular focus on the following aspects [1]:

- Management of the interconnection between the DER units and the power systems to which they connect, including local power systems, switches and circuit breakers, and protection;
- Monitoring and controlling the DER units as producers of electrical energy;
- Monitoring and controlling the individual generators, excitation systems, and inverters/converters;
- Monitoring and controlling energy conversion systems, such as reciprocating engines (e.g. diesel engines), fuel cells, photovoltaic systems, and combined heat and power systems;
- Monitoring and controlling auxiliary systems, such as interval meters, fuel systems, and batteries;
- Monitoring the physical characteristics of equipment, such as temperature, pressure, heat, vibration, flow, emissions, and meteorological information.

The DER object models are based on open-system language, semantics, services, protocols, and architecture, which have been standardized by IEC 61850. These DER object models reuse components of the existing IEC 61850 object models where possible, but also include some extensions to IEC 61850. By extending IEC 61850, WG17 provides the object modeling and services required for information exchange with DER, which include dispersed generation (DG) devices and dispersed storage (DS) devices, as well as with distribution feeder and network equipment, such as power electronics, switchgear, and other components to support automation of power distribution system [3].

Additionally, support of IEC 61850 communications, which have been specified by North American Smart Grid Interoperability Panel (SGIP) as one of the key Smart Grid standards, helps to promote the microgrid controller solution for international utility applications.

The microgrid control logic is implementing using both horizontal (GOOSE) and vertical (MMS) IEC 61850 communications between protection relays and the microgrid controller. Properly organizing GOOSE messaging requires configuring the Data Sets and GOOSE Control Blocks (GCB) on the GOOSE Publisher side and subscribing to the GCB on the Subscriber side. It is recommended to use GOOSE messaging for fast control such as synch-check and load shedding, while the MMS reports can be used for voltage and frequency measurements on the microgrid side.

General Requirements

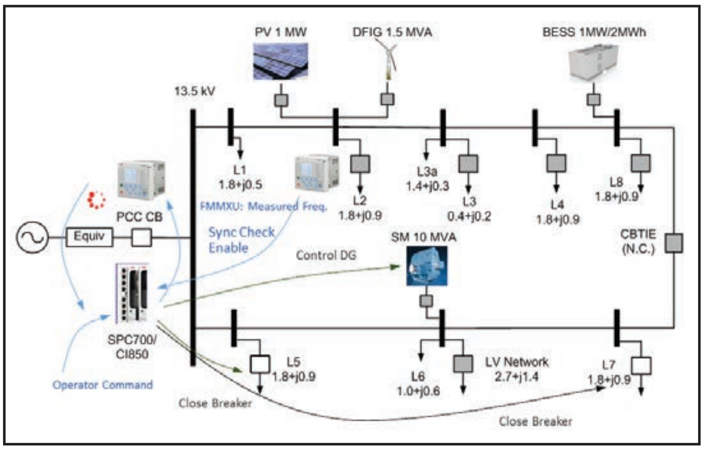
The requirements for planned and unplanned islanding are formulated so as to maintain compliance with IEEE 1547 requirements [2]. In the context of the developed system, planned islanding is defined as an islanding process that is triggered by the operator or a SCADA command, and unplanned islanding is a process whereby the microgrid disconnects from the area electrical power system.

In particular, the microgrid must be able to quickly disconnect from the main grid in case of external faults within the maximum islanding times that are specified in IEEE 1547requirements.

In the integrated protection and control system that has been developed by USCRC, these requirements can be met by utilizing the overcurrent, under/overvoltage and under/overfrequency protection functions of ABB REF615 protection relays, as each of these elements has multiple instances in the current implementation.

Additionally, for the unintentional islanding case, automatic load shedding/restoration control functions are assumed critical for maintaining the stability of the microgrid when the system has limited generation capacity. To prevent system frequency from deviating from the nominal value, a fast load shedding function is required to automatically shed some non-critical loads in order to save the system from blackout. This function can be implemented using the ABB REF615 relay's automatic load shedding functions, which have two stages for load shedding with adjustable thresholds. It is also possible to enable auto-restoration after under-frequency load shedding, which, in the proposed prototype, is supervised by the microgrid controllers.

For reconnecting an islanded microgrid to the main grid, a resynchronization procedure is often required, as the frequency/voltage in the microgrid may drift with respect to the main grid



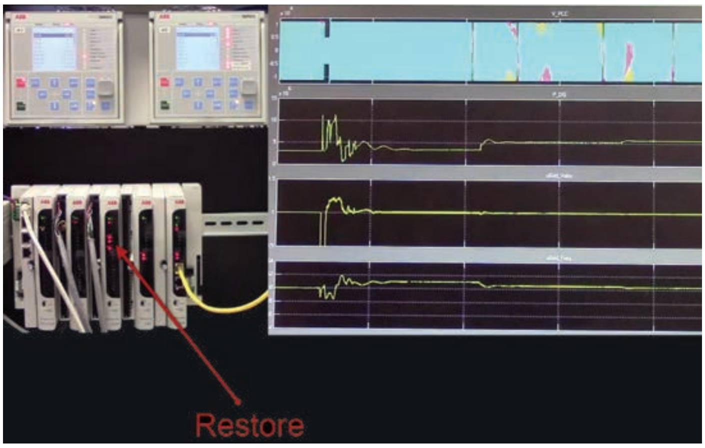


Figure 1: Integrated microgrid protection and control functions for resynchronization. | Figure 2: HIL Simulation results – unplanned islanding and resynchronization.

voltage or frequency. The specific reconnection requirements defined by the IEEE 1547 for microgrids with an aggregate rating of DR units of 1-10 MVA are as follows:

- Frequency difference (Δf, Hz): 0.1 Hz
- Voltage difference (ΔV, %): 3
- Phase angle difference (ΔΘ, °): 10

An algorithm must be implemented to ensure that these requirements and the requirements of IEEE 1547 are met rapidly and at the same time. In the current typical utility practice, a separate synchronization and generator paralleling device, such as the ABB SYNCRHOTACT, may be required to synchronize the generator with the main grid. However, in the developed prototype, IEC 61850 communications are used to collect voltage and frequency measurements on the main grid and microgrid side, and the generator control can be performed by the microgrid controller logic, thus eliminating the need for a separate synchronization device.

Real-time Hardware-in-the-loop Testing

A power system time-domain simulation model has been developed using MATLAB-Simulink/Simscape Power Systems and converted tothe format suitable for use on the OPAL-RT RT-LAB real-time simulation platform. The one line diagram for the microgrid model used for the real-time HIL simulation is shown in Figure 1.

The model includes a number of controllable loads and DER with two physical REF615 relays and microgrid controller integrated with the power systems simulator via IEC 61850 and analog and digital I/O. An integrated microgrid protection and control system has been developed based on ABB Symphony Plus technology, and its operation for various microgrid use cases validated through HIL simulations. Figure 2 shows an example case for unplanned islanding due to an external fault: load shedding is followed by diesel generator ramp-up, load restoration, and finally resynchronization of the microgrid to the area electrical power system.

Conclusions

Even though the microgrid as a concept has existed for many years, until recently there have not been too many standard approaches to implementing communications and control in microgrids in place that specifically target microgrids as such. However, several standards related to DER and their integration can either be directly applicable, or easily extended to also cover the microgrid space.

The common theme and key concept for all of the functional and automation-related standards is interoperability. It is the glue that ties together various system components and enables easy integration and commissioning. Interoperability is provided by the international standards and will be a key enabler for the adoption in the microgrid case as the microgrids become less of a niche and more of a mainstream concept. Real-time hardware-in-the-loop simulation is invaluable for development, validation and testing of the key grid connected microgrid control modes, particularly unplanned islanding, resynchronization and restoration.

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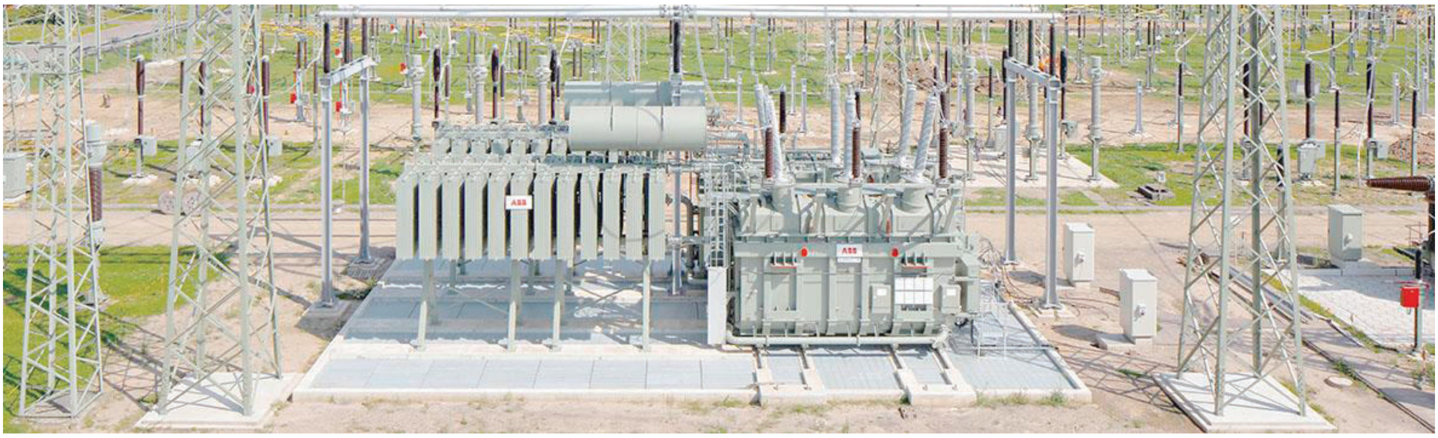


Advancing Transformer Physical Security with Sensors and Analytics

Dr. Mirrasoul J. Mousavi, Mr. James Stoupis, and Dr. George Frimpong

Introduction

According to a recent USA TODAY report, about once every four days, part of the nation's power infrastructure is struck by a cyber or physical attack [1]. A 2013 substation sabotage incident marked the first major intentional attack on the power infrastructure, underscoring the changing physical security requirements.

When such incidents occur, large power transformers (LPT) often become the center of attention for the right reasons. While LPTs make up less than 3% of transformers in the U.S, between 60%-70% of the nation's electricity flows through these transformers in high voltage substations [2]. Additionally, it may take between 5 to 16 months to replace a damaged LPT and restore service. Power transformers in general are among the most critical assets on the power grid due to the lack of availability of spares, customization of design, manufacturing lead times, transportation difficulties, and installation requirements.

Recognizing the national security importance of the power grid infrastructure, NERC developed CIP-014-1 per FERC's order that went into effect in October 2015. This reliability standard requires certain transmission owners to assess the vulnerability of critical substations and implement security plans by August 2016.

The latest patent-pending technology from ABB advances the state of the art in physical security by leveraging vibro-acoustic sensors and just-in-time impact detection and assessment algorithms. An overview of this innovative technology developed in close collaboration with the Transformers business unit is the subject of this article.

Motivation

According to a recent survey conducted by Utility Dive, 80% of utility executives surveyed consider planned sabotage a potential threat to their substations [3]. According to the same survey, utilities have reported over 300 intentional physical attacks on power infrastructure between 2011 and 2014 that resulted in power disturbances. Enhancing substation physical security and in particular that of power transformers through sensors and automation addresses this critical vulnerability factor impacting grid reliability. If the transformer physical integrity is compromised, it needs to be dealt with immediately, at least operationally, to contain the magnitude of the damage and avoid substantial consequential and/or collateral losses as a result of a catastrophic failure. While highly impactful, these incidents are not expected to be frequent and therefore deployment cost is always a non-technical constraint. This motivated the research project to assess feasibility and develop a cost-effective just-in-time impact detection and assessment system for power transformers. The feasibility was proven through a series of field trials and hypothesis testing experiments. The final outcome was a set of solution specifications and a prototype solution based on the signature analysis of vibro-acoustic measured data.

Solution Concept Overview

The solution concept for sensor-based impact detection and assessment is composed of specialty sensors, a Sensor Data Processor (SDP), a Remote Terminal Unit (RTU) for remote communications, and an interface to the control center. The sensors may be wired, wireless, and/or autonomous sensors with power harvesting features requiring no power source for operation. They measure various physical quantities related to motion, sound, light intensity, and other environmental factors. For example, they may measure acceleration along three axes and sound waves. These sensors may be installed stand-alone around the transformer, attached to the transformer tank, or installed inside the tank.

The data from these sensors are gathered by the sensor data processor (SDP) unit. This processor receives the sensor data and may time-stamp them. It further performs preliminary data processing tasks such as filtering and averaging on the raw data. The SDP also runs detection algorithms for local alarming and annunciation. The output from the SDP unit is received by the RTU and communicated over a preferred communications medium to the utility control center interface system. This interface system may receive the data from the RTUs and run more sophisticated algorithms on the data set for damage assessment and detailed integrity check. The final outcome is displayed on the operator dashboard in real-time. In certain implementations and with special attention to operations and cyber security requirements, the output from these sensors can be used to control the closing of cooling system valves in the event of loss of oil detected by other means. The output from these sensors can also be used to open valves to engage redundant cooling system for the transformer, if one is installed.

The sensor-based system is furthermore used as a triggering system for activating other security systems. For example, it can be used to guide substation cameras to take specific shots of the transformer or substation perimeters. Such evidence gathered just-in-time may be used for forensic analysis and in-court proceedings to argue liability. In this case, the SDP unit runs another set of algorithms to determine the onset of an attack and send a trigger signal to the appropriate monitoring and surveillance system for detailed measurement and recording of the event. Conventional monitoring systems are either fixed at particular angles and assets or move slowly and likely to miss the onset of the attack.

A low-cost hardware embodiment of the solution concept was developed and demonstrated in a field test. In its basic form, the solution consists of a minimum of four RMS accelerometers with the detection and assessment logic embedded in a PLC device. These accelerometers are to be strategically placed on the transformer tank wall to cover the impact from all vulnerable areas. The system monitors the transformer tank for any excursions beyond the set limits, in which case it lights up an LED and/or raises a digital flag that can be mapped in a Supervisory Control and Data Acquisition (SCADA) system for automated or semi-automated initiation of control actions. The number of assertions activated as a result of the impact denotes the severity of the impact. An attack that is registered by all accelerometers is considered to be more severe in nature than an attack that triggers an assertion by only one accelerometer.

Proving Feasibility through Field Trials

Three sets of tests were pragmatically conducted at three different locations to assess the technical feasibility and address the research and design questions. The first set of tests conducted at a ballistics laboratory according to UL 752 Ballistic Standards at select levels. The data and images gathered through these trials helped specify sensor and data acquisition requirements for the subsequent field trials. Figure 1 shows an example UL-9 trial with visible shrapnel upon impact on the face plate.

The second set of tests was conducted at a gun club by subjecting a transformer tank to various shots fired from various guns 55 meters away from a water-filled network transformer tank. The vibration and acoustic measurements using various bullets allowed a thorough analysis and characterization of impact signatures including bullet impacts and benign hammer and rock impacts. Figure 2 shows the RMS accelerations corresponding to the bullet, rock, and hammer trials. As seen, there are clear differences in the RMS waveforms that are leveraged to differentiate a bullet impact from a benign impact of a rock thrown at the transformer tank. Interestingly, some hammer strikes start to resemble the bullet trials. This is a desired outcome as it indicates that all blunt attacks can be detected and asserted by the same setup.

The third set of tests was performed on a live transformer to establish baseline vibration and acoustic figures and signatures. These trials used high-fidelity sensors and data acquisition devices and helped validate the hypothesis that RMS measurements were adequate for basic impact detection. However, more detailed analysis would require transient vibro-acoustic measurements. The close proximity of the subject transformer to a rail road -just on the other side of the fence- and an airport location allowed the research team to measure and observe realistic environmental effects and design the detection methodology around robustness to false alarms. Impact of naturally-occurring events such as energization impact of transformer, pumps, and fans were recorded and observed.

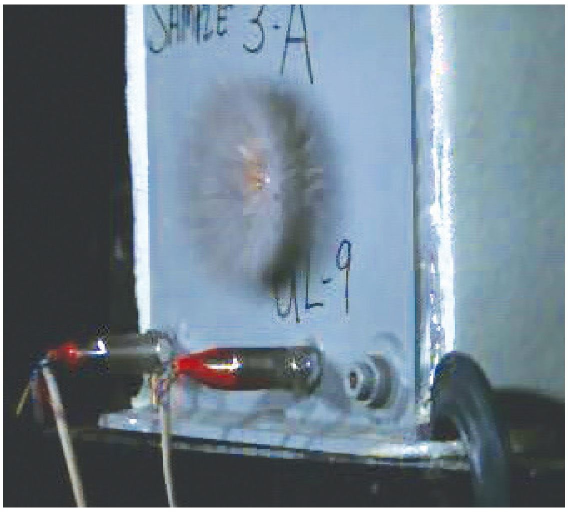
Solution Benefits

There are a number of advantages in enhancing physical security measures with sensors and data analytics. The most important benefits are as follows:

1. The detection is nearly upon impact. This gives crucial time for the operators to decide what to do to mitigate the impact. The main benefit of a quick response is the possibility to save the active parts of the transformer from severe damage and a subsequent prolonged outage.

2. The system is also beneficial in cases where the transformer survives the attack. In this case knowledge of the attempted assault can trigger on-site inspections or justify other investments for hardening the transformer or the substation.

3. The detection is specific to the transformer and therefore more actionable in contrast to general purpose substation security measures such as video monitoring.



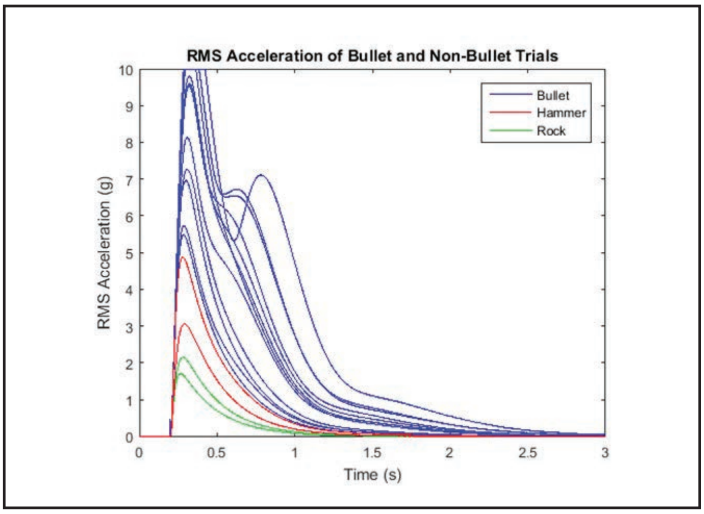


Figure 1: Impact on a test object during a UL-9 trial | Figure 2: RMS acceleration for bullet trials

4. The detection is automatic therefore no active monitoring by an operator is required all the time.

5. The sensor-based system acts as a triggering system for activating other security measures such as surveillance cameras.

Concluding Remarks

The just-in-time impact detection and notification solution is another innovation from ABB to help utility customers achieve and exceed their physical security goals with respect to power transformers and other high-value assets. This solution addresses a key area of physical security for just-in-time detection and assessment of potential or actual impact. The information from this system can be used in automation and control schemes to alarm or alert the operators upon impact and/or prevent further damage e.g. by initiating redundant cooling systems. It is noted that for control applications, certain operational and cyber security requirements must be considered and addressed which are beyond the scope of this article.

Acknowledgment

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Robust Scalar Control for Synchronous Machines

Dr. Sara Ahmed, Dr. Zach Pan and Dr. Hongrae Kim

Robust scalar control for synchronous motors is developed. The new control allows the synchronous machines to run at their best efficiency point and to be stable for the entire operating range. With this developed scalar control, ABB is able to offer LV AC drives that are low-cost, high efficient, and easy to use with both synchronous and induction motors. With increasing demand for higher efficiency motor drive systems, it is expected that the synchronous machine drives using developed scalar control will replace scalar controlled induction motor drives in many applications like HVAC systems.

Introduction

With demands for lower cost and higher efficiency motor drives, engineers are looking for alternative solutions to replace induction motors (IMs) in many applications. One of the promising machine topologies is the synchronous machines with its various types, like synchronous reluctance (SynRM) and interior permanent magnet (IPM). SynRMs for example; are known to be

- Compact - about two frame sizes smaller than a conventional IM motor
- Efficient
- Reliable - no magnet and cool running rotor.

Scalar control is a very simple control method for controlling the speed of an IM. It requires only nameplate motor parameters and no ID run to measure the motor parameters and tune controllers. Therefore, scalar control is widely used for IMs in many applications where cost is the main driver and high dynamic performance is not required.

Combining a synchronous machine with a scalar drive will offer a low-cost, easy to use, and possibly high efficient solution for many applications such as fans and pumps. However, key challenges like stable operation for the entire operating range and running at the best efficiency point must be overcome in order for scalar control to be used for synchronous machines and for synchronous machines to replace IMs in various applications.

USCRC developed robust scalar control for SynRMs and IPMs, which allows them to run at their best efficiency point by a simple perturb and observe method and to be stable for the entire operating range. The developed control does not require more and better sensors than conventional scalar control. In addition, it does not require any hardware modifications to conventional scalar drives. Therefore, it does not add any extra cost to the conventional scalar drives. It is also worth mentioning that it does not have any computational complexity as it require no parameter estimation and no feedback control.

In addition, the developed control is capable of flying restart in scalar control mode. Flying restart is a practical control feature that in case of power disruptions that may result in tripping of the machines; allows the machine to go back to the original speed as soon as power is restored. This feature is commonly used with vector and DTC control. It avoids the need to restart the machine from zero speed, and allows immediate resumption of normal operation.

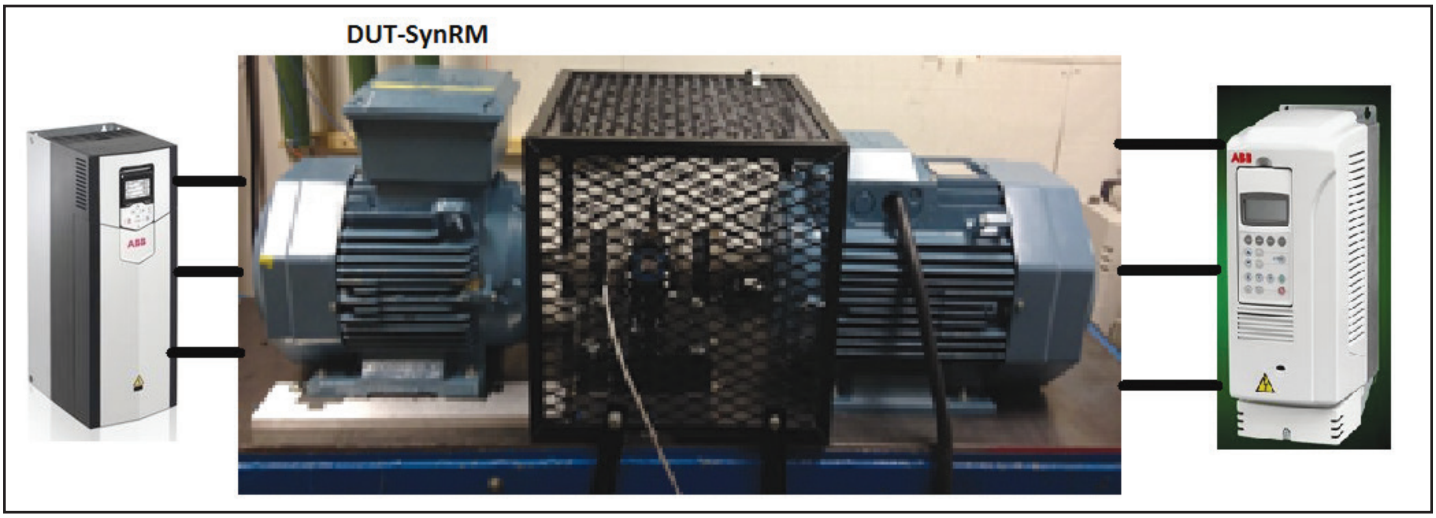

Figure 1: Experimental Setup: SynRM driven by an ABB low voltage (LV) AC drive coupled to an IM

Verification

The developed scalar control was thoroughly verified experimentally under various conditions such as low load, full load, and step loading at rated speed. Figure 1 shows one of the experimental setups used for verification. The setup consists of a SynRM driven by an ABB low voltage (LV) AC drive and an IM driven by another ABB LV AC drive.

It was successfully verified that the SynRM drive system using the developed scalar control is stable for the entire operating range. It also runs at its best efficiency point that is quite comparable to the efficiency that Direct Torque Control (DTC) drives offer as shown in Figure 2.

Summary

This article presented the developed robust scalar control for synchronous motors, which allows them to run at their best efficiency point and to be stable for the entire operating range. The developed control does not require any hardware modifications and therefore, it does not add any additional cost to conventional drives. It was successfully verified depicting efficiency points comparable to current DTC controlled drives. The developed innovative solution is believed to allow ABB to gain more market share mainly in high efficiency demanding applications.

Internal Customer

BU: DMDR, Low Voltage AC Drives

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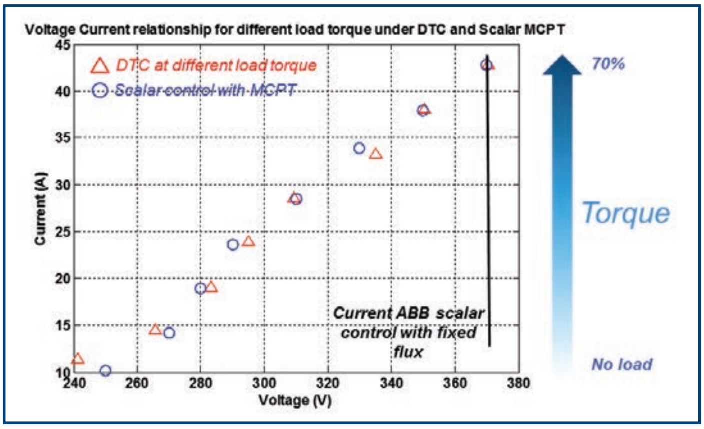
Figure 2: Voltage Current Relationship for different load toque under DTC and developed scalar control



The Renewable Power Challenge to Grid Operation Optimization

Dr. Xiaoming Feng, Dr. Khosrow Moslehi

Growth in Renewable Power

November 4th 2013, Denmark's wind turbines supplied 122% of the country's demand for electric power. October 3rd, 2013, Germany's solar and wind power peaked at 59.1%, with solar contributing 11% at 20.5 gigawatts at its peak. In 2015, Germany's annual renewable power energy production surpassed 180 TWh, more than 30% of the annual gross power consumption of 597 TWh. The trend is global. According to Global Wind Energy Council, at the end of 2015, total global wind power capacity reached 432,419 MW, representing cumulative growth of 17%. Similarly solar power is growing at a neck breaking speed. According to PV Magazine, a record 40 GW Solar Capacity was installed in 2014, and 55 GW predicted in 2015 globally. By 2020, the cumulative installation will reach 540 GW.

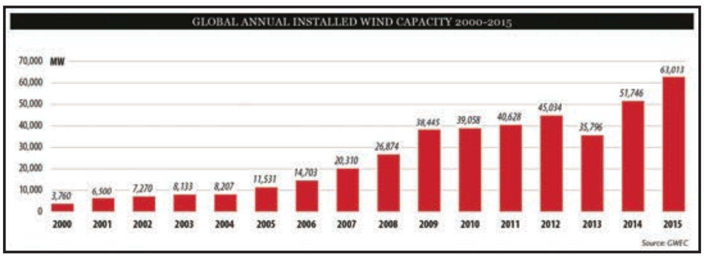


Figure 1: Global Annual Installed Wind Capacity 2000-2015

Non-dispatchability, Uncertainty, and Intermittence of Renewables

Unlike fossil fuel based power or hydro power, renewable powers from wind and photovoltaic sources are non-dispatchable. We have little control over how much power is produced and when it is produced. Renewable power productions can also be very volatile (uncertainty) and sporadic (intermittence). At high level of renewable power penetration, these properties of renewable power can no longer be ignored and must be considered explicitly in power system planning and operation. Traditional deterministic scheduling will not do well under high level of uncertainty, which will become the new norm ushered in by renewable power. To ensure operation feasibility and security, deterministic resource scheduling will likely result in excessive reserve cost, load shedding, and curtailment of renewable power.

While energy storage technology, demand response can help to mitigate some of the renewable uncertainty, energy storage is still very costly and its deployment very limited. An important challenge to power system planners, operators, and researchers is how we can make better planning and operation decisions under such high level of uncertainty.

Optimization under Uncertainty

In deterministic optimization, all the parameters in the problem definition are assumed to be deterministic and known at the time the problem is solved. In optimization under uncertainty (stochastic optimization), we need to

- characterize the underlying stochastic process of the uncertainty parameters
- account for the impact of uncertainty on feasibility of the solution
- define objective function that evaluate the merits of the solution under uncertainty

The uncertainty of a parameter can be modeled by interval values or by discrete probability distributions. It's important that any cross correlations between the stochastic parameters across space and time are also considered. Feasibility constraints can be handled on a deterministic (satisfied under all scenarios) or probabilistic basis (satisfied for most but not all scenarios).

There are two types of decisions to make in optimization under uncertainty: the decisions that are made before uncertainty is resolved (outcome is known) and the decisions that are made after the uncertainty is resolved. If the uncertainty is resolved all at once, we have a two stage stochastic optimization problem (Figure 2), which can be defined as,

$$\min_{x} E(\min_{y_\omega} f(x, y_\omega, \omega),\ s.t.\quad g(x, y_\omega, \omega) \leq 0)$$

Where w is the random variable vector; x is the stage one decision vector; y_w is the stage two decision vector; $f(x, y_w, w)$ is the objective function; and $g(x, y_w, w) \leq 0$ is the constraint vector.

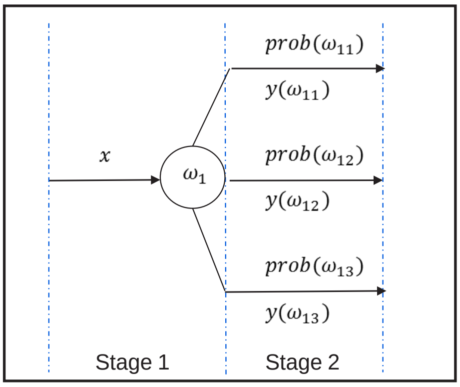


Figure 2: Two stage stochastic optimization illustration

Number of Uncertainty Stages

If the uncertainty is resolved in multiple stages, we have a multi-stage stochastic optimization. In a unit commitment problem, if x represents the commitment decisions, y represents the dispatch decisions, and the subscript represents the decision interval, the two-stage and multi-stage stochastic unit commitment problem can be summarized as the following sequences of decision, observations, and decisions.

Two-stage problem

Decision$(x_1, x_2, \dots, x_T)$, Observation $(\omega_1, \omega_2, \dots, \omega_{T-1},\ \omega_T)$;

Decision$(y_1, y_2, \dots, y_{T-1}, y_T)$.

Multi-stage problem

Decision(x_1), Observation(ω_1) ;

Decision(y_1, x_2), Observation(ω_2) ;

Decision(y_2, x_3), Observation(ω_3) ;

...

Decision(y_{T-1}, x_T), Observation(ω_T) ;

Decision(y_T).

It can be seen that, in multi-stage problems,

- the uncertainty is not assumed to be completely resolved after the first stage decisions;
- the decisions are deferred until more uncertainty is resolved.

One can easily show the following fundamental inequality to hold for all stochastic problems under any conditions.

Theorem: A multi-stage (N>2) stochastic optimization has an optimal solution that is equal or better than that of a two stage stochastic optimization of the same structure.

The proof can be constructed by noticing that the two stage problem is equivalent to the multi stage problem augmented with additional constraints that force the decisions in late stages to be identical to those in earlier stages.

In addition to the benefit attributable to optimality inequality, another benefit of decision deferral is the deferred decisions face smaller uncertainty. The forecast error variance diminishes as forecast lead time reduces to zero.

$$Var(\omega_N | (\omega_0, \omega_1, \dots, \omega_{N-2}\omega_{N-1})) \leq Var(\omega_N | \omega_0))$$

Figure 3 illustrates the error of forecast for hour 24 made at hour 18 is no greater than the error of forecast for hour 24 at hour 6 or 12.

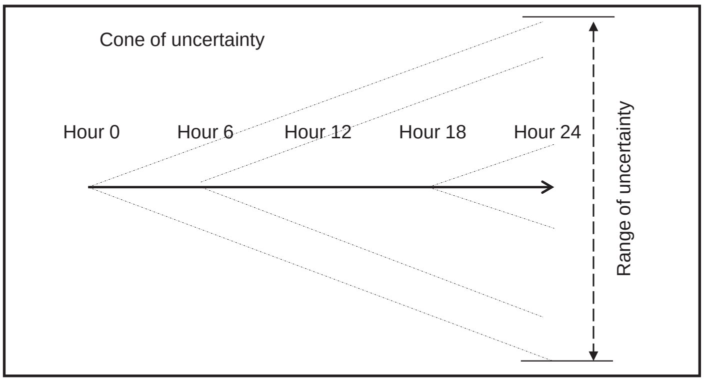


Figure 3: Uncertainty of forecast as function of lead time

Objective Functions

Given the objective function of deterministic optimization problem, there are a variety of choices in defining the objective function of the stochastic version of the deterministic problem. None of the choices is objectively superior to the others. The "best" choice depends mainly on the risk attitude of the stakeholders who are affected by the outcome of the stochastic optimization. Rational choice depends on risk attitude and risk tolerance capacity. Common choices include the following:

- Risk neutral – minimizes the expected value of a cost function: $\min_x(E(f(x,w)))$.
- Risk aversion – minimizes the sum of the expected value plus a multiple of the standard deviation: $\min_x(E(f(x,w)) + m * std(f(x,w)))$.

- Extreme risk aversion - minimizes the worst (maximum) case cost value: $\min_x(\max_w f(x,w))$.

The extreme risk aversion formulation is often referred to as "robust optimization" in the literature, although there is nothing inherently robust about it.

Constraint modeling

In stochastic optimization, constraints can be handled in two ways:

- Deterministic enforcement - All constraints must be satisfied under all uncertainties, $g(x,w) \leq 0, \forall w$.
- Expectation enforcement - Constraints are satisfied on average, $E(g(x,w)) \leq 0$.

Under large uncertainty, deterministic constraints enforcement may not have feasible solution. While expectation enforcement can make the stochastic optimization technically feasible as defined, there is no guarantee the resulting solution is feasible for implementation.

Stochastic Security Constrained Unit Commitment

Security constrained Unit Commitment is key in both the day ahead market and the real time market in operating the power system securely and economically. The objective function and key constraints are shown here. (Other constraints omitted for simplicity.)

$$\min_{\{x,u,p\}} J = \sum_{t=1}^{T} \sum_{i}^{N} \{C_i(g_i(t),t) + u_i(t)c_i^{ST} + x_i(t)c_i^{NL}\}$$

$$\sum_{i}^{N} \{g_i(t) - d_i(t)\} = 0, \ \forall t$$

$$f_i^{min} \leq \sum_{j}^{N} A_{i,j}\{g_i(t) - d_i(t)\} \leq f_i^{max}, \ \forall i, \forall t$$

The transmission constraints are affected by not only the amounts, but also the locations, of renewable powers. This feature limits the use of aggregations of renewable power to reduce the number of uncertainties. The number of uncertainty scenarios can grow to astronomical numbers even for problems with modest sizes. Assuming ten wind farms with only two possible output states in a 24 interval optimization, the number of scenarios is in the order of 10 raised to the 72th power.

Solution Strategies

Direct solution - The deterministic equivalent is solved directly. This approach is suitable only when the number stages and number of uncertain outcomes per stage are small.
Uncertainty space truncation and aggregation – This strategy attempts to reduce the number of scenarios to consider, hoping to achieve computational tractability. The interval approach reduces the uncertainty distribution to an interval characterized by a low and a high limits. Markovian model is used to reduce the number of uncertainty states. While a significant improvement over the interval approach, Markovian uncertainty model introduces hiden simplifications that affect the optimal solution. The difficulty in decoupling the uncertainty information state (path independent under Markovian model) and the decision state (path dependent under inter temporal coupling) limits the benefit of path independence in Markovian model. While Monte Carlo sampling could be used to limit the number of scenarios, It still requires large number of samples. Solution from random samples also invites repeatability and fairness questions.
Distributed/parallel solution strategies based on Sampling Average Approximation, Bender's decomposition, and Modified Lagrangian Relaxation such as Progressive Hedging are also popular among researchers.

ABB Funded Research

A recent university project funded by ABB explored a hybrid modeling and solution strategy to solve the stochastic security constrained unit commitment problem.

- Lagrangian relaxation to relax coupling transmission and power balance constraints, resulting in problem decomposition by power plant
- Surrogate sub-gradient method to speed up multiplier update for dual problem optimization and to avoid slow convergence due to oscillation
- Branch and cut method to solve sub-problem more efficiently

The project evaluated the effectiveness of these strategies and generated useful insight to applying stochastic optimization in security constrained unit commitment.

Summary

The growth of renewable power in electric power system increases uncertainty and presents new challenges to resource scheduling. Stochastic optimization is a non-hardware solution in a multi-pronged strategy(including energy storage, demand response) towards cost effective integration of renewable powers. Stochastic optimization has its unique challenges, from uncertainty characterization, selection of uncertainty stages, choices of objective functions, choice of constraint enforcement, to the development of computationally tractable solutions. Credible and realistic uncertainty modeling and effective solution techniques will remain an area of active research as the levels of renewable power in power systems reach new heights.

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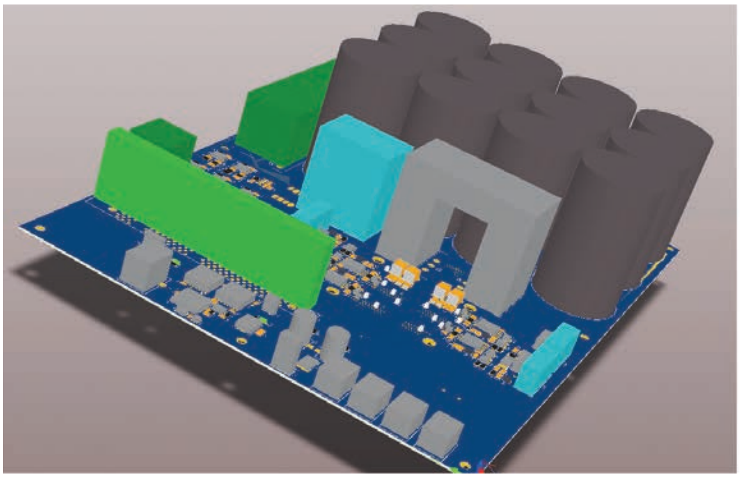
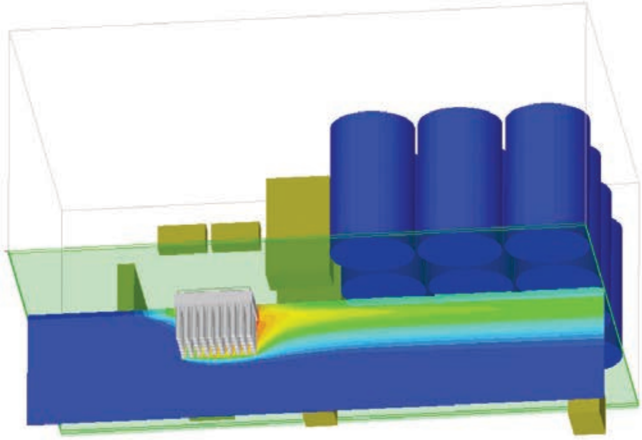




The Promise of GaN in Power Converters

Dr. Jing Xu, Dr. Joonas Puukko, Dr. Liming Liu and Dr. Sandeep Bala

Candidacy announcement

Power converters are central to many ABB products, ranging from low voltage power supplies that process a few watts to High Voltage Direct Current (HVDC) stations that process hundreds of megawatts. For decades power converters have been built using Silicon (Si) semiconductor devices. Although Si devices continue to improve steadily, these incumbents are now being challenged by a new breed of semiconductor devices fabricated with wide-band-gap (WBG) materials.

Gallium Nitride (GaN) is one such promising WBG material. Compared to Si, GaN has a higher band-gap (3 times), a higher electric breakdown field (10-15 times), and a larger saturated electron drift velocity (2-2.5 times). The higher band-gap implies lower intrinsic leakage currents and potentially higher operating temperatures in the GaN semiconductor. The higher electric breakdown field makes it possible to use less material of GaN to block same voltage as Si, which could translate to lower semiconductor costs. The higher electric breakdown field also enables higher concentration of electrons in the device drift region which leads to a lower on-state resistance from this region in the semiconductor. The higher saturated electron drift velocity is one of the properties that allows for the design of GaN devices that switch faster. The aforementioned characteristics of the material make GaN power devices appear superior to equivalent Si devices.

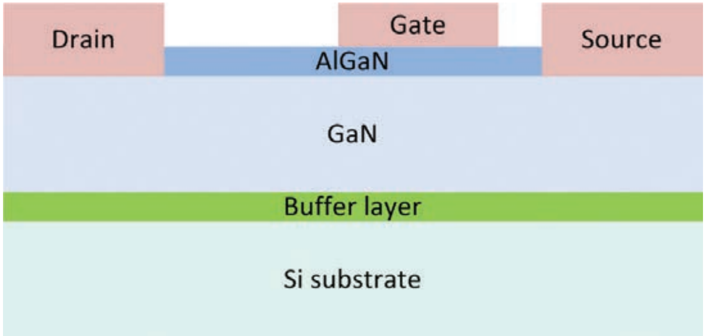
The vast majority of GaN devices on the market today are high electron mobility transistors (HEMTs) with rated breakdown voltages at or below 650 V. A typical HEMT structure is shown in Figure 1. The main conduction path in a HEMT is a highly conductive layer called the two dimensional electron gas (2DEG), which is formed by growing a thin layer of AlGaN on top of a GaN crystal. The GaN crystal itself is typically grown on a Si substrate using the same fabrication facilities as for manufacturing Si devices. This approach allows for lower processing costs compared to the approach of using bulk GaN as the substrate. In volume production such HEMTs are expected to be competitive (or even superior) in terms of cost compared to similarly rated Si power devices. The list of companies making a long term bet on GaN power devices include established players like Infineon, Panasonic, and ON Semiconductor, as well as startups like Transphorm, GaN Systems, and Efficient Power Conversion (EPC).

Stump speech

Power electronic circuit designers find certain properties of GaN HEMTs attractive: improved "body diode" performance and very low (or even zero) reverse recovery charge, lower output capacitance (for a given on-state resistance), and lower gate charge. These properties allow for the use of higher switching frequencies and more efficient circuit structures, the benefits of which are seen as higher power densities and overall cost reduction.

The first example of an incumbent Si solution that is ready to be toppled by a GaN solution is the power factor correction (PFC) rectifier, which converts input ac from the grid to a dc bus to be fed to a load. Figure 2(a) shows the existing Si-based

Figure 1: Typical GaN HEMT structure - simplified, not to scale.



solution - a diode bridge followed by a boost converter; Figure 2(b) shows the GaN-based solution - a bridgeless totem-pole PFC rectifier. The bridgeless solution eliminates diodes in favor of synchronous rectification; this results in lower conduction losses. But its implementation with Si devices is hampered by the reverse recovery of the devices. The reverse recovery of GaN HEMTs is practically zero, which not only allows for an efficient implementation of the bridgeless solution, but also helps to mitigate current spikes in the devices during switching. Reductions in losses of greater than 50% have been reported in the literature, and this improvement in efficiency translates directly to reduced heatsinking requirement, smaller physical size, and lower cost.

The second example where GaN could replace Si is in resonant converters like LLC-resonant converters, which convert dc from an intermediate bus to the dc required by a load. Figure 3 shows one possible implementation of an LLC-resonant converter. Such converters achieve lower losses through zero voltage switching (ZVS) and zero current switching (ZCS), and are popular in power supplies up to a few kW. The total charge stored in the output capacitance of a GaN HEMT is an order of magnitude smaller than in an equivalent Si MOSFET, resulting in a shorter dead-time, or more active time, for power transfer. This advantage can be parlayed into the use of the same circuit at higher power, or into a design with lower RMS currents, lower circulating losses, and lower fringe-field losses in the transformer. Either way, GaN enables an increase in power density and/or efficiency.

GaN devices also enable new applications like converters switching at frequencies greater than 1 MHz. The gate charge of a GaN HEMT is much lower than that of an equivalent Si MOSFET. Lower gate charge means lower gate drive losses. With Si, these losses are significant near 1 MHz, but with GaN it is possible to increase the switching frequency without incurring the gate drive loss penalty.

Around the world numerous demonstrations ranging from a few watts to a few kilowatts have shown the advantages that GaN devices can bring to a variety of applications. Recently Google's Little Box Challenge was won by a group that used GaN HEMTs in a 2 kVA photovoltaic inverter. They achieved a power density of about 145 W/in^3 (nearly 3 times the target) and efficiency levels comparable to existing photovoltaic string inverters. We at ABB are also evaluating how these benefits can be realized in our products.

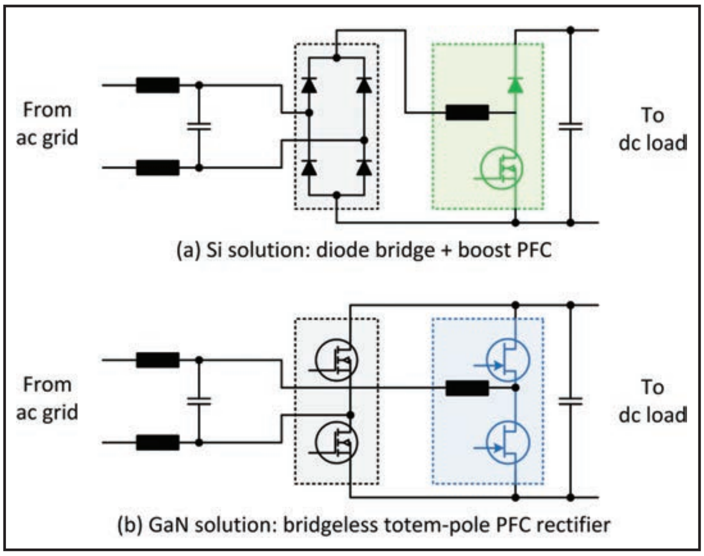


Figure 2: PFC rectifier using (a) Si; (b) GaN.

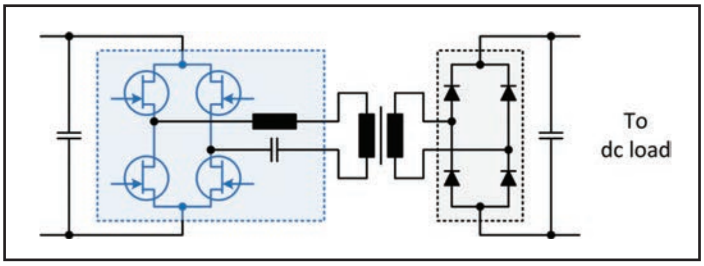


Figure 3: LLC resonant converter using GaN

Moderated debate

The skeptics are quick to point out the challenges associated with using GaN in power converters. In the short term the hurdles are cost and proof of reliability, but device manufacturers have been making steady progress with both. Next, power converter designers are asked to focus on the value of using GaN devices in the converter. In order to extract full value, however, one must fully utilize the capabilities of GaN devices, and this can be done only if one considers not only the electrical design, but also the physical design. Using these very fast, very small chips in the hardware of a switching power converter system requires us to overcome two major challenges: physical layout and thermal management.

Inadequate physical layout can lead to stray inductances that lead to dire consequences. Stray inductances originate mainly from the power loop and gate loop areas created by the length and spacing of the drain, source, and gate leads. The first generations of GaN devices were offered in traditional discrete through-hole packages such as the well-known TO-220 and TO-247 that introduce stray inductances of the order of 20 nH.

With switching speeds well above 100 A/ns, GaN devices would see voltage spikes of magnitude

$$v_L = L \cdot \frac{di_L}{dt} = 20\,nH \cdot 100\frac{A}{ns} = 2000\,V$$

across the drain-source terminals during a switching transient. Such a voltage spike would be sufficient to break down the devices, which are rated at 650 V or below. To avoid catastrophic failure the switching speeds have to be limited, which increases the switching losses of these devices. It is not possible to reach the performance levels promised by GaN technology with such packages.

Improved physical layout can be achieved with surface mount packages such as the PQFN (power quad flat, no-lead). Such packages have parasitic inductances of a few nH, allowing faster switching speeds and higher efficiencies. But these packages are cooled mainly through the copper traces of the PCB in contrast to the TO-packages which can be directly mounted on a heatsink. Inadequate thermal management limits the maximum power that can be handled by a single device.

To overcome the thermal limitation of PQFN packages, a flip-chip arrangement can be used. Here the semiconductor die is turned upside down inside the package; the electrical contacts of the lateral GaN die face towards the PCB, and the substrate side of the die points away from the PCB. The substrate can then be used as a thermal pad and a heatsink can be attached directly to the package to provide improved cooling performance.

Further improvements in thermal management may, however, be required, because the heat flux density from the device to the heatsink may increase when we use GaN instead of Si. For a semiconductor device, the heat flux density is the semiconductor losses divided by the active semiconductor area. The active area of GaN devices may be only 30% of the size of comparable Si devices, because GaN devices have lower specific on-state resistances. In the hypothetical case of Figure 4, a GaN converter is designed for higher efficiency with only 60% of the semiconductor losses of its Si counterpart. In this case the heat flux density of the GaN device is twice that of the Si device:

$$\frac{Loss_{Si}}{Area_{Si}} = \frac{10\,units}{10\,units} = 1\,unit;\ \frac{Loss_{GaN}}{Area_{GaN}} = \frac{6\,units}{3\,units} = 2\,units.$$

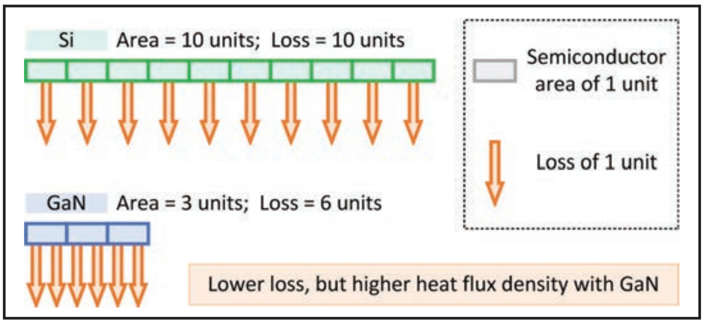


Figure 4: Illustration of the thermal management challenge with GaN

To accommodate the higher heat flux density with GaN devices, the heat extraction path - comprising of the semiconductor package, the thermal interface material, and the heatsink - must have a smaller thermal resistance than a typical setup with Si devices. More advanced materials or cooling methods such as heat sinks with heat pipes may be needed to reduce the thermal resistance to an acceptable level.

At the time of writing this article GaN HEMTs are almost exclusively available as discrete components. We have already seen a rapid evolution of these packages to deal with the issues related to physical layout and thermal management. In the future we may see higher power GaN modules, which may enable wider adoption of this technology. Together with our partners, we at ABB are exploring the use of new materials, new packaging designs, and new thermal management technologies to overcome the challenges of bringing GaN devices into our future products.

“Yes, we GaN!”

Much work remains to be done before GaN devices appear in ABB products, and despite the challenges at this stage, we remain optimistic about the possibilities. At ABB Corporate Research, we have been evaluating the suitability of these devices for a variety of applications. Given where the technology is today and where it will be in 5 years, GaN clearly holds great promise for a number of applications including photovoltaic inverters, uninterruptible power supply systems, electric vehicle chargers, and datacenter power supplies, among others.
ABB has vast experience in all these applications, and we are blending these experiences with new discoveries in our labs. By developing technologies that overcome the unique challenges imposed by this potentially groundbreaking technology, we hope to see GaN devices live up to their promise.

Radial Electromagnetic Gear with Nested Permanent Magnet Generator for Wave Energy Conversion

Dr. Colin Tschida, Dr. Wen Ouyang, Dr. Steven Englebretson and Dr. V.R. Ramanan

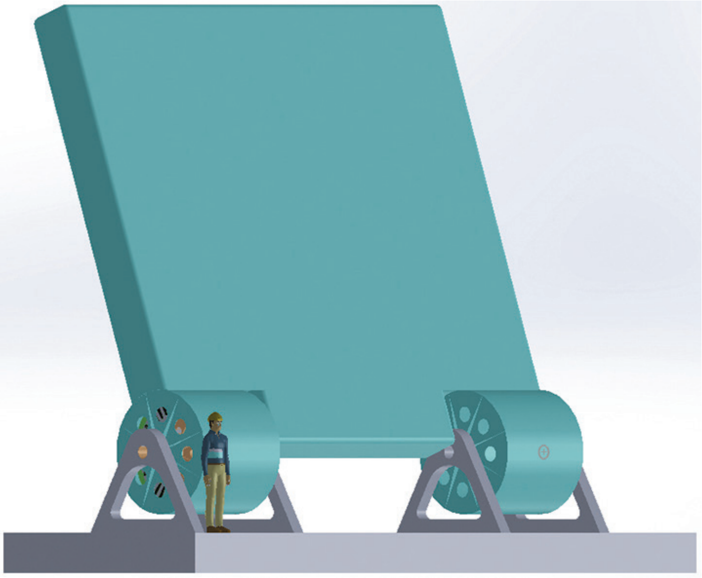
A radial flux, magnetically geared generator developed at ABB USCRC in conjunction with Texas A&M is discussed. The machine is low speed and high torque targeted at wave energy applications where it is desirable to reduce components subject to mechanical wear while also providing overload capability. To date, the authors are not aware of an example of a similar machine of this size and rating. Some of the compromises required to realize the mechanical design of the machine are briefly discussed.

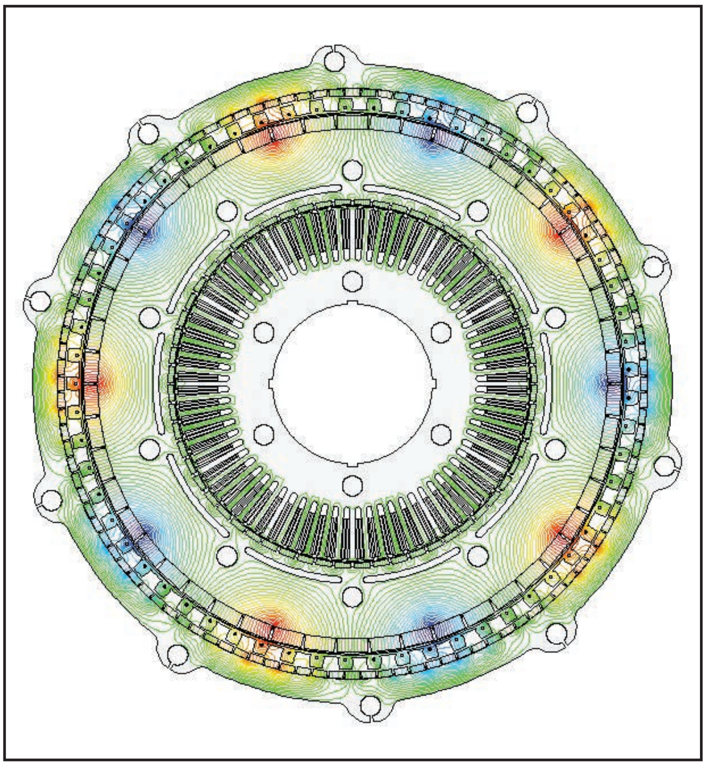
Introduction

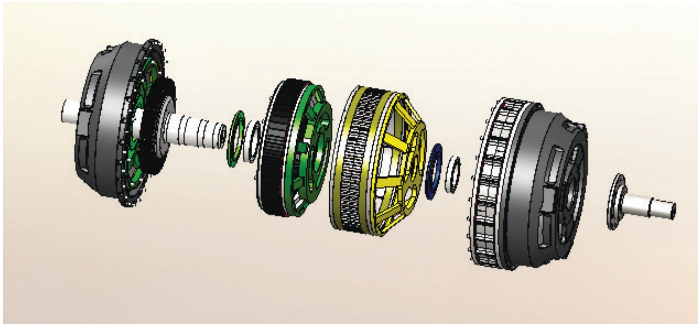
Renewable energy is a growing field that presents many challenges for the power industry. In areas where commercial energy production is well established, e.g. wind and solar, the nature of these challenges is well understood and solutions to their unique problems are often well developed. However, commercial technologies for ocean energy harvesting only began to appear in 2008 [1], and as a result there are many technical challenges that the industry has yet to overcome. One of the technologies under development by our partner, Resolute Marine Energy (RME), uses a mechanical flap moved by the action of near-shore ocean waves to harvest mechanical power. Because the wave energy converter (WEC) is necessarily subsea, it is desirable to reduce the number of components that experience mechanical wear and therefore increase the system reliability. The WEC also faces high peak-to-average load requiring a power-take-off design capable of handling momentary "overloads." From a machines perspective, this suggests developing a direct drive generator. However, the WEC is characterized by high torque and low angular speed, which is a difficult design region for direct drive electric generators.

The development of the machine is stepwise with three machines being investigated at increasingly larger scale: 1 kW 300 rpm, 10 kW 30 rpm, and a paper design for a 40 kW 2 rpm machine. Figure 1 indicates scale of the final 40 kW machine paired with the WEC.

Figure 1: Full scale design showing approximate size of generator and WEC. Person is 1.8 m (5'10") for scale.







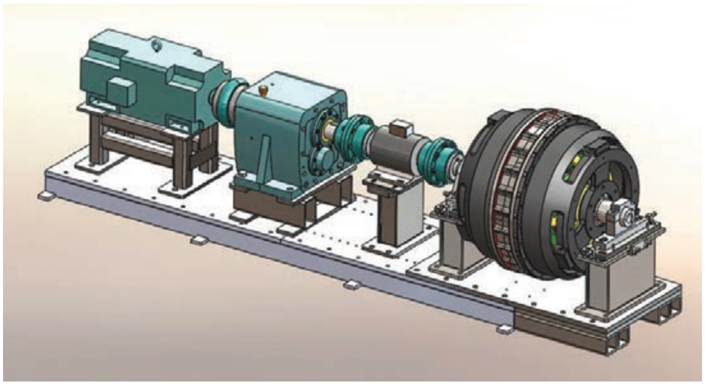


Figure 2: Electromagnetic simulation of the full generator. | Figure 3: exploded view of generator. | Figure 4: Test bench with drive machine (left) and generator (right). Gear box and torque transducer are also shown

During the first phase, the suitability of various machines was investigated with our partner Texas A&M wherein three prototypes were developed to investigate promising topologies. As a result of this initial investigation, it was concluded that an electromagnetic gear may provide a compelling solution to our unique requirements, and this is the subject of our current work. Texas A&M is a leading university in the area of electromagnetic gears, including application for wave energy [2]-[3].

The goal of this article is to briefly discuss the electromagnetic design, mechanical design, and the required compromises to realize the prototype.

Electromagnetic Design

The generator design is a radial electromagnetic gear (Figure 2) analogous to a traditional mechanical planetary gear with a nested inner generator. To maximize torque production, the machine is an outer rotor configuration with an inner high speed rotor. The rotors are electromagnetically coupled via the modulator. The two sets of magnets on the high speed rotor acting for the gear and generator are magnetically decoupled using the rotor core, bolt holes, and flux barriers. The low speed outer rotor has 136 poles; the stationary modulator has 74 teeth; the high speed rotor has 12 poles; and the generator has 40 poles. The resulting gear ratio is 11.33.

Mechanical Design

One of the goals of this project is to provide insight into how this variety of machine could be constructed at the intended scale. In light of this, some components in this machine were designed so that they could be scaled up. For example, the modulator and high speed rotor are made from segmented laminations where they could have been single piece.

The primary challenge of constructing this machine is the delicate nature of the modulator held in place between the two rotors. This difficulty is compounded by the additional requirement of providing non-magnetic, non-conductive axial stand-off between the gear modulator and the structural components. To put this into perspective, the assembled core of the gear modulator has a mass of roughly 30 kg, a diameter of about 700 mm, and is subjected to anticipated peak torques of 4,000 N*m. This load is supported 40 mm away from the structure. An exploded view of the generator is shown in Figure 3 and the anticipated test rig is shown in Figure 4.

Compromise with the Mechanical Design

The original electromagnetic design calls for the modulator teeth to be suspended in the air-gap. Iteration with the mechanical design of the machine resulted in the selection of a bridged structure as shown in Figure 5. Although this structure creates a significant leakage path, reducing the gear torque by a few percent, it has the benefit of acting as a harmonic filter, roughly halving the total magnet losses, while at the same time shielding the stack bolts from stray flux. By adding bridges to the modulator, the second moment of the area of the structure is increased by orders of magnitude and radial deflection into the air-gap is drastically reduced, relaxing mechanical requirements on the rotors.

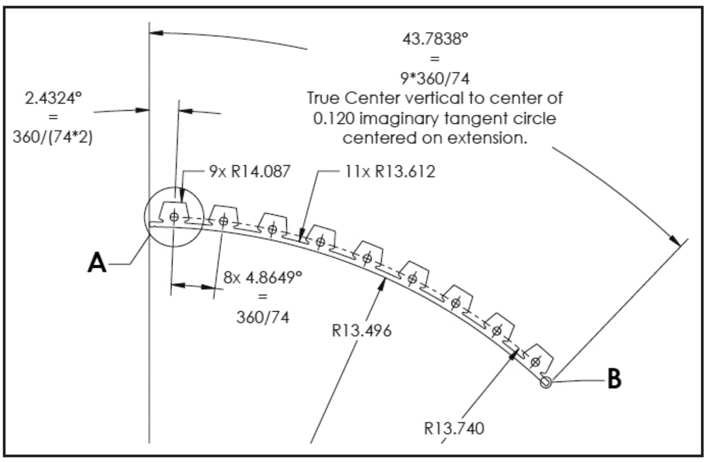
Initial electromagnetic designs called for 73 modulator teeth. The odd number reduced torque ripple but resulted in unbalanced radial magnetic forces. Mechanical design is greatly complicated by the lack of factorization: segmentation is tricky and can increase part count. As a result, a compromise was reached with a 74 tooth modulator to simplify design, aid assembly, and balance radial forces.

Conclusion

The development of a magnetically geared generator for very low speed applications was described. The generator is in its final design phase, and prototype assembly and testing is expected to be completed this summer. Lessons learned from the design and testing of this scale machine will be used to outline improvements possible in mechanical and electromagnetic design of the full scale machine.

Disclaimer:

Figure 5: modulator lamination segment.



Project Partners

- ABB, USCRC, Raleigh, USA
- Resolute Marine Energy (RME), Boston, USA
- Texas A&M University, USA
- Baldor Electric, USA

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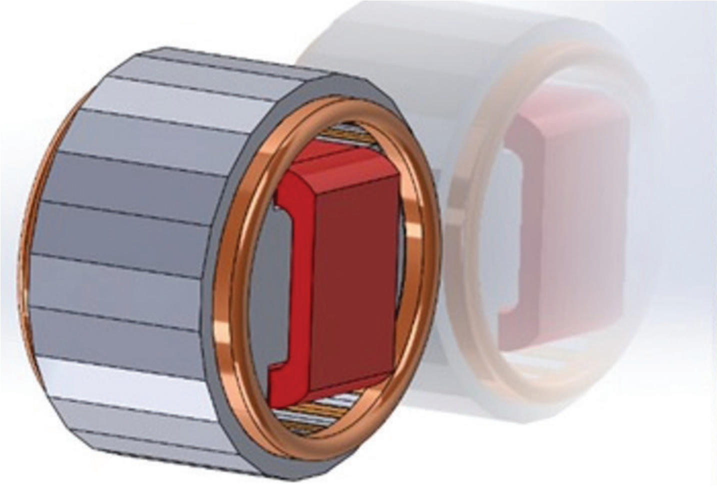


Auto-balancing Transformers: Addressing Distribution System Reliability and Efficiency Requirements

Dr. Parag Upadhyay, Dr. Matthew Henriksen and Dr. Mirrasoul Mousavi

Introduction

ABB US Corporate Research has embarked on the development of a novel distribution transformer to address feeder efficiency and reliability challenges of the electrical grid. The concept apparatus leverages the built-in redundancy in multi-phase distribution circuits to help balance three-phase currents in the primary circuits. This technology also provides reliability benefits by maintaining supply continuity in the event of single-phase and double-phase faults. As the first step, the concept has been validated through a demonstrator at the Corporate Research Center in Raleigh as a part of a local discretionary research project. The core objective of this research was to investigate the technical feasibility and demonstrate in a lab setting the application of a novel auto-balancing distribution transformer concept that offers new and innovative ways to enhance feeder efficiency and reliability.

The concept transformer delivers the basic core functions of a conventional transformer, however its innovative and unique design enables advanced functions that are increasingly needed in active distribution systems to mitigate the adverse effects of distributed energy resource (DER) integration, loading unbalances, and single and double-phase outages. All of these benefits are envisioned to be packaged into a single electromagnetic device henceforth referred to as an auto-balancing transformer. If successful, it will be the first-of-its-kind transformer to deliver efficiency and reliability benefits in one apparatus.

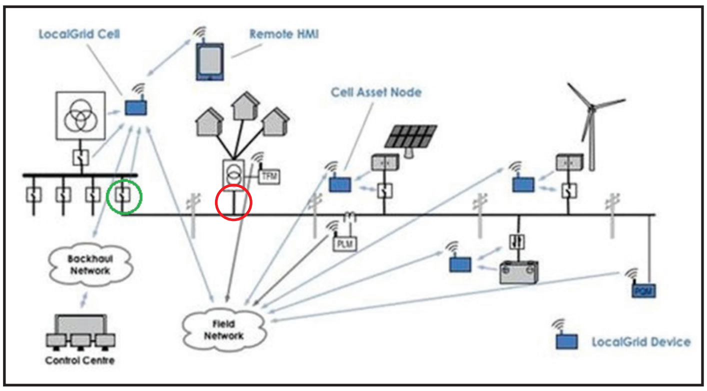
Power losses in transmission and distribution systems typically amount to ten percent, of which the vast majority occur in distribution systems due in part to unbalanced loading, fixed phasing, asymmetrical topology, and other factors. Balancing primary feeder currents across the three phases reduces line losses which can lead to significant energy savings and enhanced feeder efficiency. From a reliability perspective, the concept transformer taps into the built-in redundancy in distribution topologies where single or double-phase loads may be fed from any of the three-phase sources available at the tap or lateral level during single-phase outages.

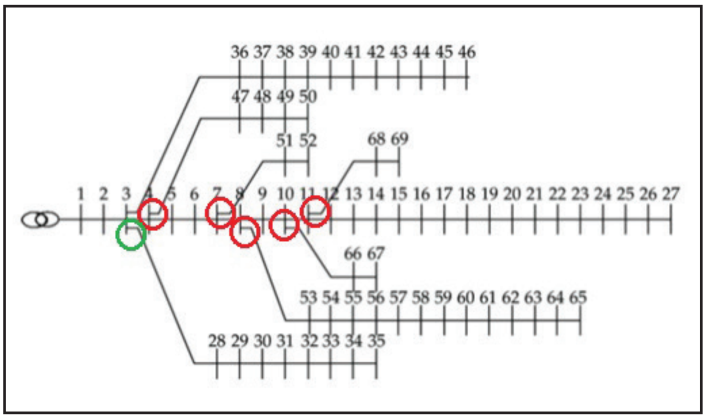
Problem Description

In reference to Fig.1, typical power distribution networks in the ANSI designs feature a large number of single-phase loads fed from a three phase feeder through a pole-top or pad-mount service transformer. This can cause an inherent unbalance on the 3-phase primaries and lead to oversized conductor requirements and higher distribution losses.

Voltage imbalance occurs primarily due to unbalanced line impedances or unbalanced line loading at the tap/lateral level.

Fig.1 Distribution feeder network





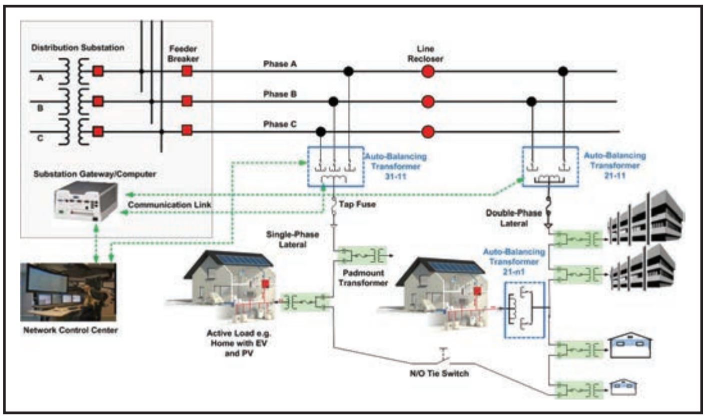


Fig.2 Schematic showing proposed installation of concept auto-balancing transformer (green) as replacement of one of the conventional distribution transformer (red) | Fig.3 Field demonstration scenarios

The current trend of integrating DERs certainly delivers many benefits but it also poses unprecedented challenges for operational planning in particular. Since the line configuration and structure is fixed after construction, manual re-balancing on an interval basis is currently the best practice to mitigate excessive voltage imbalance. The proposed transformer concept aims to deliver a transformational solution to tackle emerging challenges at their origination point and where the low voltage delivery system connects to the medium voltage (MV) feeder backbone as depicted in Fig. 2 and Fig. 3. Integrating this controllable device in a Distribution Management System (DMS) will offer new options to address evolving system operation, reliability, and efficiency requirements.

The patent-pending transformer concept derives its operating principles from the "synchro" transducer [1-3] where a secondary winding is movable on-demand to compensate for the imbalance introduced from the primary or secondary side. This technology could lead to significant energy savings at the system level and grid reliability enhancements nationwide. The concept is being evaluated through a staged process, starting with the laboratory scale proof-of-concept before system cost-benefit analysis, design development and scale-up for application in a distribution feeder in collaboration with a partner utility to be identified in due course. ABB is a market leader in power and automation technologies including transmission and distribution transformers. This invention promises an immediate impact if the proposed concept successfully passes the feasibility, scale-up, and commercialization phases.

Potential benefits:

The potential benefits of incorporating this novel auto-balancing apparatus in distribution engineering and operations include

Benefits to utility and end-customer
• Reduces unbalance on three-phase distribution feeders • Reduces line losses • Helps with voltage profile regulation at the feeder head • Provides partial restoration options in the event of a single-phase feeder fault • Reduces conductor size in new distribution network designs • Improves reliability and saves energy nationwide

The ultimate goal of this initiative is to develop an actual prototype through a pragmatic process that includes concept demonstration, laboratory and field prototyping, and testing. The laboratory concept demonstration at low power was achieved based on the schematics of Fig. 5.

An unbalanced load was created using a resistive load bank that is fed through the concept transformer. The transformer creates 3-phase unbalanced currents on the primary side as a function of secondary winding angular position and the load. The current waveform images included in Fig. 6 illustrate the balancing concept achieved. The upper three waveforms in Fig. 6a show the variations in the primary currents as the secondary winding (the rotor) is rotated to vary the coupling between the load and primary phases. The green line below the three waveforms shows the load current unaffected by the rotor motion. Fig. 6b is a close-up that illustrates the rotor position at which the primary currents are balanced.

The reliability benefit with a loss of one phase was also demonstrated through the same setup. In reference to Fig. 7, it was observed that the transformer was able to maintain the power level with one primary phase disconnected, albeit at a different rotor position.

The proof-of-feasibility tests successfully demonstrated how the auto-balancing concept can compensate for primary phase imbalances that may arise from changes in the secondary load as well as maintain power delivery to the secondary load despite the loss of a single-phase. The optimized design and system impact analysis will be the subject of future work.

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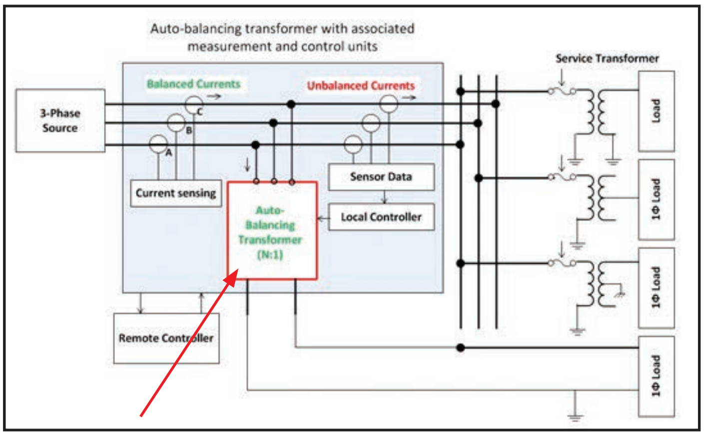
Fig. 4 Demonstrator circuit with unbalance load and auto-balancing transformer balancing the currents in the lateral feeder. | Fig. 5 Laboratory concept demonstration



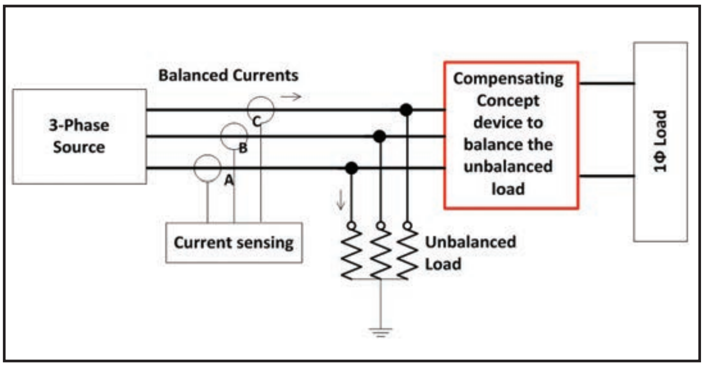
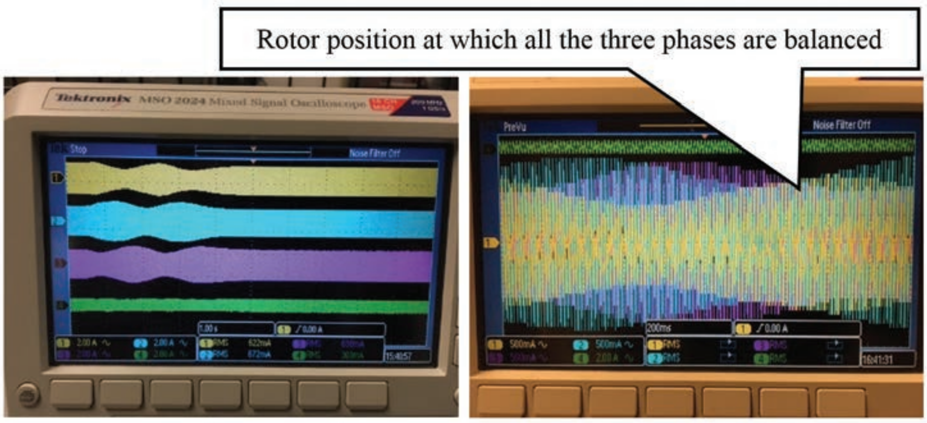
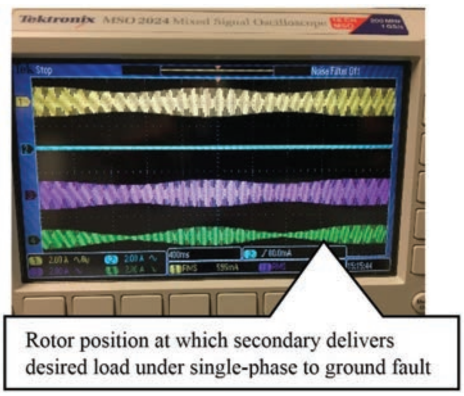


Fig. 6 The waveforms showing three phase current magnitude changes at a broader scale by changing the angular position of the rotor, while the load current in "GREEN" is unaffected with the rotor positions. | Fig. 7 Wave form demonstrating how the single-phase load can be delivered through the two healthy phases during the single-phase black-out.



(a) (b)



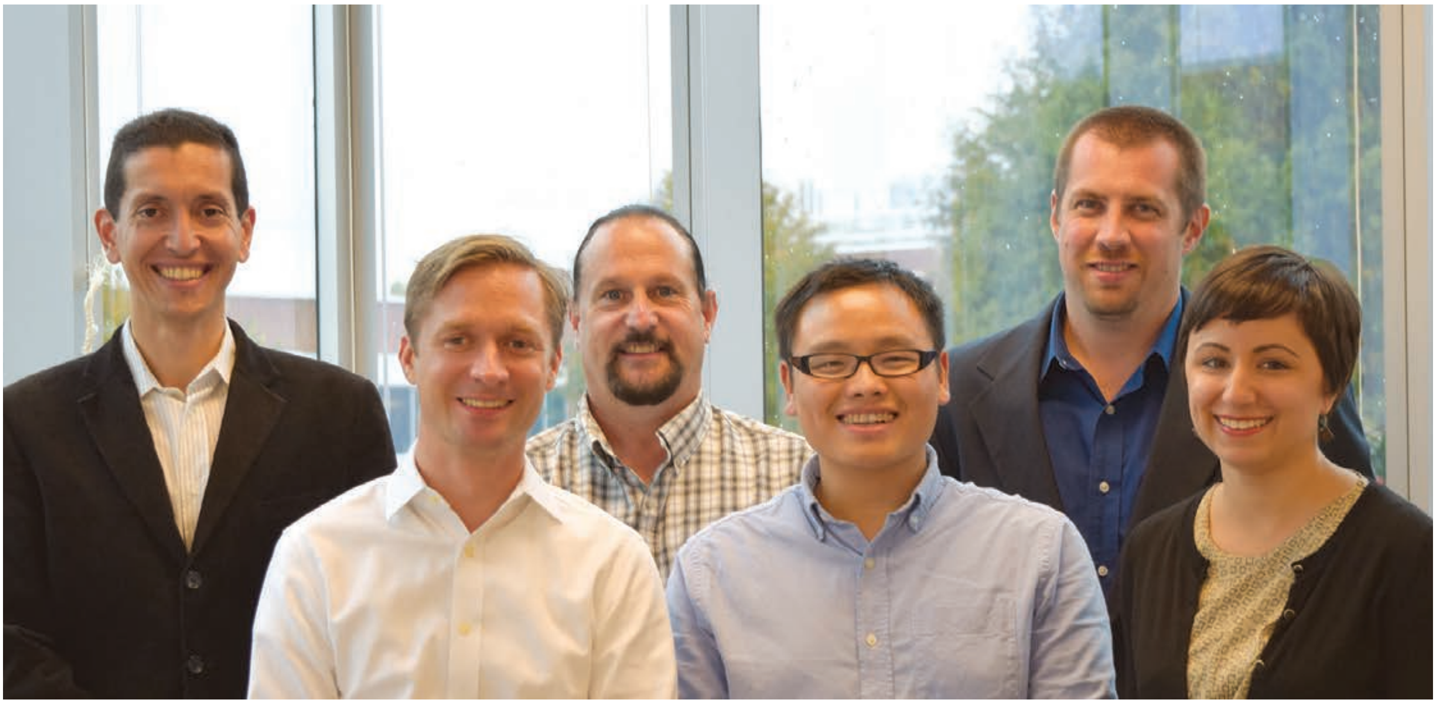


Figure 1 From left to right (rear): Cherif Ghoul, Michael Baldock, Darren Tremelling. Front: Nikolaus Zant, Sheng Zhong, Kate Murphy. Not pictured: Elio Perigo

Materials Research Team in the U.S.

Dr. Kate Murphy, Cherif Ghoul, Dr. Darren Tremelling, Dr. Nikolaus Zant

Have you ever wondered why your tires have less grip in the winter or why your plastic cup deforms when you drink hot coffee? The answer lies in the glass transition temperature or T_g of the polymer used. When it's cold and the outside temperature approaches or crosses the T_g of your tires, they become hard and tend to slip on the road. Similarly, boiling coffee brings your plastic cup above its T_g and makes it so soft that it deforms helplessly.

This characteristic of polymers is also important for many of ABB's products and is typically a parameter that is optimized during any new technology development for parts that contain polymers. For instance, HVDC cables typically operate at elevated temperatures, so it's important to monitor T_g closely in developing them.

T_g measurements are made using a device called differential scanning calorimeter or DSC (pictured in figure 2) and are among the many factors that can be analyzed in the materials research group in Raleigh, NC. Thermal properties of materials are important because they dictate the behavior of ABB products in changing climatic conditions over the course of the year.

2015 was an important year for ABB's Advanced Materials and Manufacturing group. In light of growing opportunities for new materials and manufacturing methods across the company's portfolio, the Raleigh team expanded its headcount and its lab capabilities, which include a full line of thermal analysis devices.

The materials research team (pictured above) brings experience from motor design and insulation materials to mechanics, chemistry, and semiconductors, and has already delivered cost-saving results.

But it is poised to do much more.

The group has made recent investments in equipment for testing thermal, magnetic, electrical, and mechanical properties of various materials. The team now has the capability to thoroughly characterize polymers, dielectrics, and magnets, for example. ABB has also purchased a world-class injection molding machine to use in prototyping, and has located it at North Carolina State University's Center for Additive Manufacturing and Logistics (CAMAL).

This collaborative arrangement yields benefits for both ABB and NC State: the ABB team has access to enough space for a very large machine, and the university is able to use it for teaching or other academic purposes when it would otherwise be idle. Both groups also benefit from each other's years of experience and expertise in manufacturing. The collaboration with CAMAL extends to other areas, too.

In recent years, additive manufacturing has moved beyond rapid prototyping to the production of functional parts. New materials have enabled the manufacture of 3D printed objects with mechanical, electrical, thermal, or magnetic properties sufficient for use in products. So, it makes sense that the team's remit would include this technology.

At CAMAL, the ABB team has access to a suite of industrial and desktop printers that represent almost every commercialized additive manufacturing method currently available. This allows for the development of new materials for additive manufacturing, as well as new means of using them in multicomponent parts.

When developing new products, scientists at USCRC also design their own materials. They mix and react an extensive range of plastics and microscopic additives by using an extruder to create the right material for every application.

The mission of the global research area of materials is to investigate new technologies for future ABB products, and the organization provides value to all areas of ABB's businesses where materials play a significant role. The team stretches over the globe in 5 centers and includes Switzerland, Sweden, Poland and China in addition to the US.

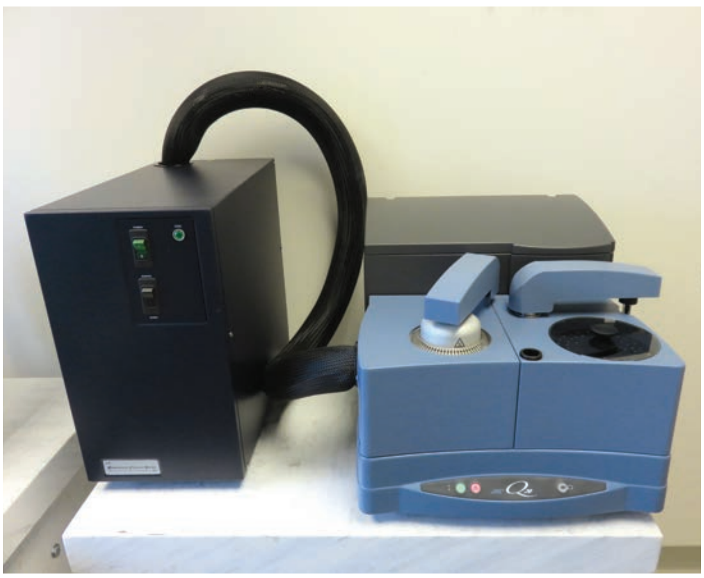
The local team in Raleigh provides expertise in polymer formulation and processing, magnetic materials, mechanics, chemistry, semiconductors, and dielectrics.

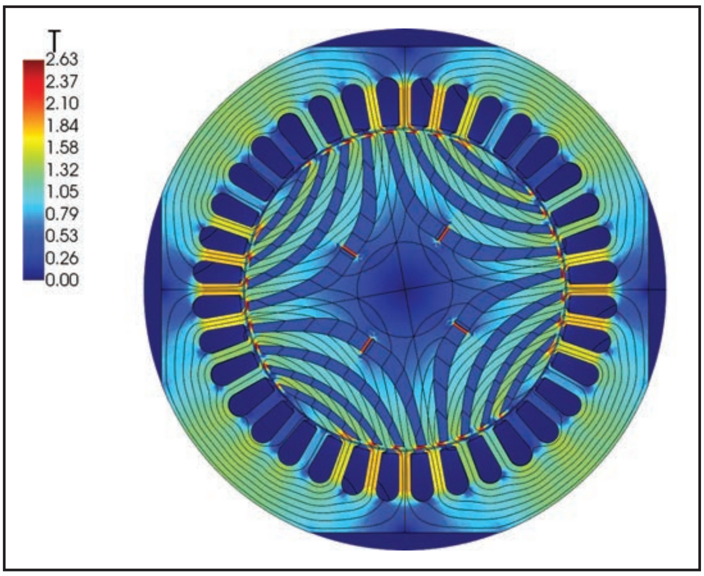
Magnetic materials are of particular interest to ABB. The team, together with partners worldwide, drives the development of new compounds and fabrication technologies to ensure ABB customers get the maximum in performance at a competitive cost.

Often this involves evaluating commercially available processes and materials, but then adapting them to the particular needs of a given business. ABB also has a number of proprietary design tools that support this process and allow the team to deliver commercially viable solutions. For example, the Raleigh CRC ranks among state-of-the-art facilities for computational simulation of (electro)magnetic applications, a key advantage that enables ABB to achieve a deeper level of understanding about magnetic materials than is typical in the industry. The colorful display in figure 3 below is from one of these tools and displays the magnetic flux of a design for an electrical machine.

Ultimately, the goal of the AMM team is to bring new technologies into products, prototypes and demonstrators by clarifying the potential benefits and minimizing risk related to future investments. With a solid team armed with a powerful array of tools, USCRC is well positioned to deliver on these objectives.

Figure 2 Differential scanning calorimeter | Figure 3 Magnetic flux display





Robotic Flexible Panels Painting

Dr. Remus Boca, Dr. Srinivas Nidamarthi

Introduction

There are many manual painting systems in used today that are difficult to automate with a robot. In general paint systems booths are toxic environments and the human painter carries a lot of equipment for process and protection. Flexible panels are difficult to manually paint uniformly with the same thickness and coverage. These flexible panels might bend in a different way every time they are brought to the paint booth, and while they are in the paint booth they remain static. Because same flexible panels bend differently due to their weight this make introducing robotic paint systems unrealistic for this types of parts. In case an existing robotic painting system is used, it takes many hours or days to manually program a robot, program that is unique only for the existing bended part.

Robotic paint systems are used in many applications with different type of parts, parts that are rigid or where the bending is consistent from part to part. Usually fixtures are used to accurately position the parts or a vision system is used to detect a part location and then an offset is applied to an existing robot program to update the robot path.

In order to solve this robotic flexible panel painting challenge a 3D sensor based robotic system was developed to automatically generate a robot program for each unknown bending panel. This robotic system allows a paint expert with no knowledge of the robot program (as the robot program is automatically generated) to operate the system. The paint expertize is required to set up all paint parameters for the specific panel.

Description

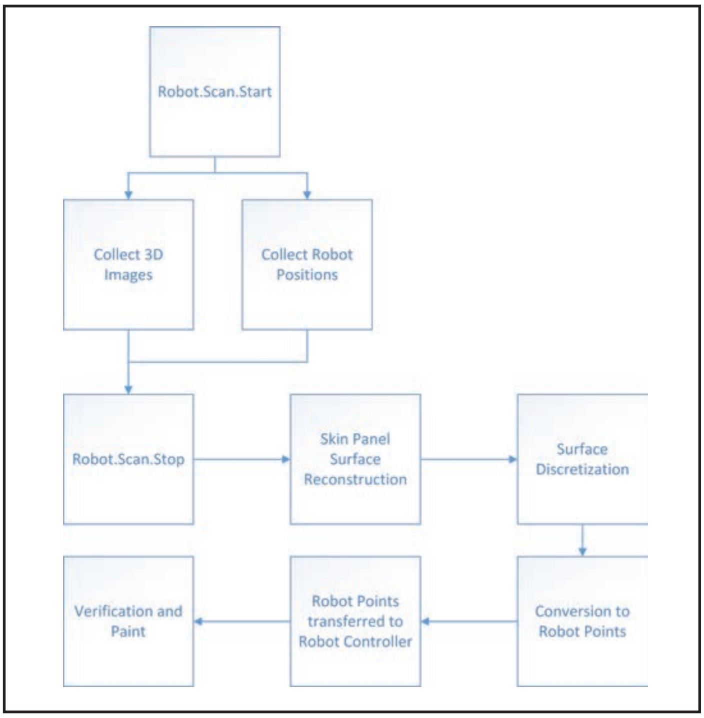
The developed robotic system consists of an IRB Paint Robot 5400 with track, a PrimeSense 3D type camera attached on the robot that output depth images at 30Hz, flexible bendable panels, paint gun with an optional pointer tool to check accuracy, and a Lenovo Thinkpad W540 laptop computer.

The track of the robot needs to accommodate the maximum length of the flexible panels. The length of the panels can be from meters to tens of meters.

The algorithmic processing flow is divided in following blocks (Figure 2).

Robot action for start scanning is implemented as a selectable button on the teach pedant. After the scanning and processing is completed, two other selectable options are displayed: 1) validate, which means a dry-run to verify the path and 2) run the path with the paint process parameters.

Figure 2



Procedures

The following steps have been implemented and integrated into an ABB's Paint Application.

A. Move and Collect 3D Images

The robot scanning program is hardcoded, it is defined ahead of time. After the robot mounted camera is positioned above the scanning area of interest, two acquisition loops are started as in Figure 3.

B. Surface Reconstruction

The streams of data, the robot and the image streams, are not correlated during the acquisition. The timestamps and the tracking of the start motion in each stream are used to correlate the timestamps. The difference of the streams when the motion starts is calculated as a global offset. Then the steps to correlate both streams are as in Figure 4.

After the streams are correlated, each 3D image is transformed using the known hand-eye transformation, the transformation between the camera and robot tool0, and then transformed using the correspondent robot pose. After all images are referenced in the same coordinate system, a post segmentation step is performed to extract the panel surface from the global point cloud.

C. Surface Discretization

After the surface was reconstructed, or the 3D model of the panel was generated, the surface is processed and points are uniformly generated along the u,v surface directions. The steps on u,v are customizable by the paint expert and depends on the type of paint gun used. The uniformly generation of these points along the surface and right on the surface is important from an accuracy point of view for the robot path. Normal on each point is calculated. Example of discretized surfaces are shown in Figure 5 and Figure 6.

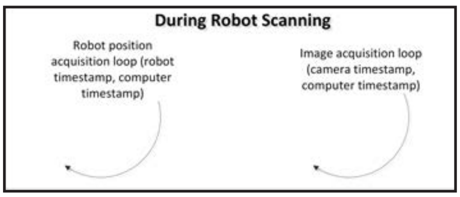


Figure 3

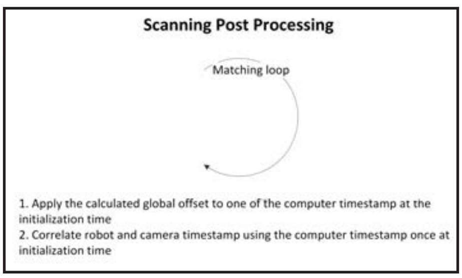
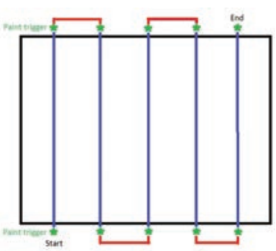


Figure 4



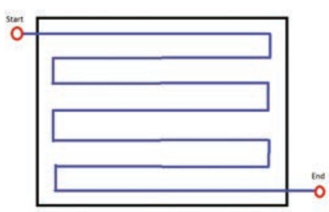


Figure 7
Figure 8

D. Conversion to Robot Points

A strategy is needed to connect the points so a continuous robot path is generated. In the case of a paint path, robot points are needed to be generated above and below the edge of surface so that the return path to the next index is inserted. The reason for the return path is that paint gun needs to be turned off while is not on a surface and then on again while it's entering a surface. Different strategies to connect the robot points are shown in Figure 7.

E. Verification and Paint Run

After the robot points / program was transferred to the robot controller, the paint expert can check the robot path by running a dry mode verification. Also, the pointer tool can be used for touching up the surface to check the accuracy of the generated robot program. If the validation is ok, then a full paint program run is performed.

Discussion and Future Work

The sensor based robotics paint system presented in this review briefly describes the steps and algorithms that enable painting challenging flexible panels. The simplification and automation of the robotic paint process make it useful to be used by paint experts without much knowledge of a robotic system. This system can be enhanced and further improved by adding additional functionality for segmentation and surface processing to handle more complex parts.

References

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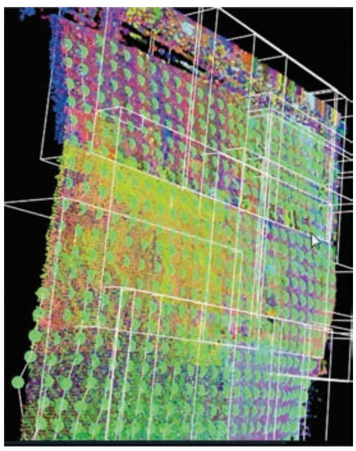


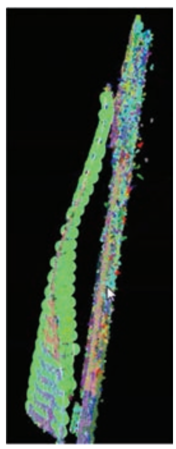
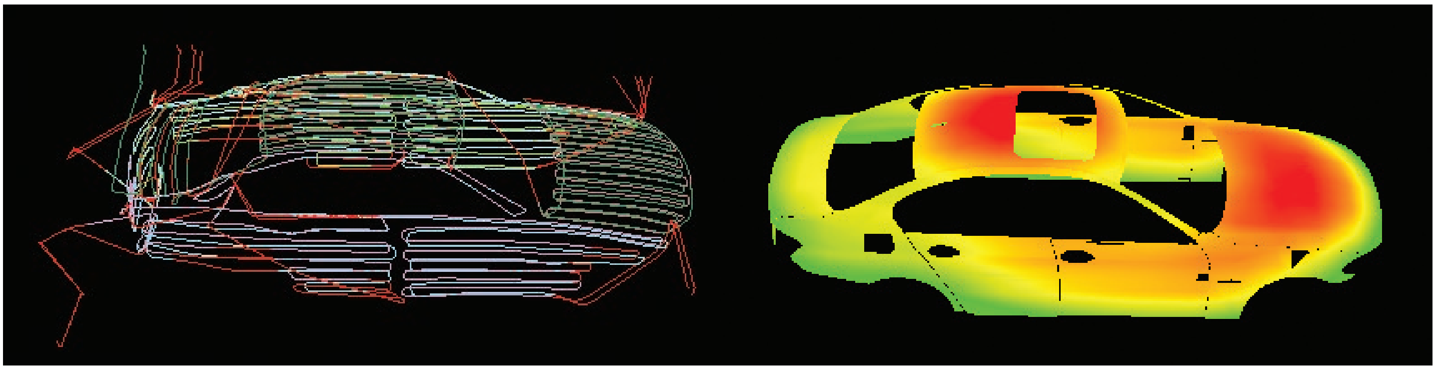


Figure 5
Figure 6



Robotic Paint Deposition Simulation

Ms. Xiongzi Li, Mr. Oeyvind Landsnes, Mr. Steinar Riveland

Introduction

Robots have been widely used in the automotive industry and painting is one of the most common processes. In order to achieve uniform coverage, the programming of a painting robot is both time consuming and costly. It will be ideal if a simulation tool is available to predict the paint thickness deposition on the surface before going to the verification test. It will save time, lab resources and effort.

Due to the geometric complexity and various complex spray patterns, paint thickness simulation has been a challenge topic for a long time. Research has been done to develop computationally tractable analytic deposition models for electrostatic bell (ESRB) atomizers, which have become widely used in the automotive painting industry [3]. While the results of their experimental study look pretty good for flat surfaces, the deposition model has limitations with respect to predictions of paint deposition on highly curved surfaces since the model doesn't take into consideration of the electrostatic effects near the curved surface [3].

The painting process is also studied by applying the Computational Fluid Dynamics (CFD) to simulation to predict the film builds on surfaces. Some authors have focused on what is happening near the atomizer or spray gun nozzle while others are staying away from the atomization zone or nozzle and study in the area near the surface [4-6]. A traditional full-fledged CFD simulation is usually quite computing intensive and not practical for real time visualization for users.

Recently we have developed a simplified paint thickness simulation technology to help the user to visualize the paint coverage on a surface [1]. Our simulation still follows the same basic procedures as in all of those approaches to simulate fluid dynamics by means of CFD.

Methodologies

The details as how to simulate the single robot paint deposition can be found in our previous work [1]. A simplified method has been used to solve the Navier-Stokes equations.

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\nabla \cdot \mathbf{u})\mathbf{u} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{F}$$

(Navier-Stokes equations for incompressible flow)

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{u} + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

$$\frac{\partial \rho}{\partial t} = -(\mathbf{u} \cdot \nabla)\rho + \kappa \nabla^2 \rho + S$$

(Equations for velocity field & equation for density field)

Procedures

The following steps have been implemented and integrated into ABB's RobotStudio Painting PowerPac.

A. Load Robot Programs

The CAD models of the car, robots, tools and conveyor together with the robot programs are imported into the 3D graphics simulation software. Figure 1 shows a typical car painting line with 9 robots and a conveyor.

B. Record Path Trajectories

During the simulation of the robot programs in the software, at each time stamp, each robot's six joint values, tool data used, digital IO values for paint brush on/off, etc. are recorded.

C. Simulate Paint Deposition

Once we have the recorded data in the previous step, we will process the data and output the data for paint deposition simulation. At each time stamp, we can calculate each robot's TCP position relative to the moving car body's local coordinate system. These positions are the input for the simulation in the following steps.

D. Define Simulation Grids

The geometry (physical bounds) of the paint deposition simulation is defined as a 3D grid. It is the local bounding box of the car surface with buffer cells in each dimension. The size of the cell in the grid will affect the simulation speed. A smaller cell size means slower simulation speed with more resolution. The typical cell size is from 20 mm to 50 mm.

E. Re-mesh CAD Model

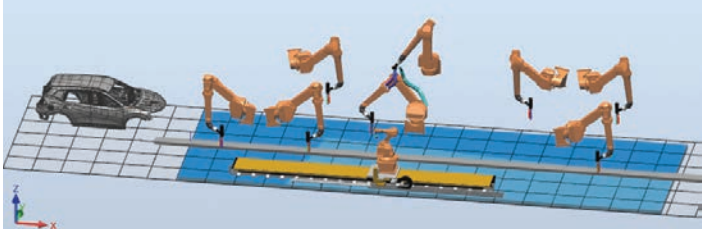
The simulation is performed on the CAD model of the car surface that will be painted. The CAD model is first meshed into triangles and then re-meshed by intersecting it with the grid cells. The re-meshed model is aligned with the grid cells. We can then go through all the grid cells and specify each cell by using one of the following types: air, air/solid, solid. To intersect the cube with triangles, we will first intersect one of the 6 faces of the cube with one triangle. Once all the line segments are calculated, they are re-arranged in order. The duplicate points and line segments are removed.

At each time step of the simulation, paint is injected into the simulation grid if the paint trigger signal is turned on. Based on the paint programs, positions of the robot at each time step is interpolated in the simulation space.

F. Model the Force

The physical modeling is then defined, different spray patterns may be modeled differently. As for the electrostatic bell (ESRB) atomizers, forces are modeled to represent the effects of the shaping air, the spinning, the acceleration along the path trajectory, etc.

Figure 1: A typical car painting line



G. Define Boundary Conditions

We take a simple approach for boundary conditions. Once the paint get into the cell typed as “air/solid” or “solid”, both the velocity and force become zero, the paint density will be first added to the paint thickness storage array and then be taken away from the future calculation.

H. Solve the Equations

After the preprocessing, the simulation is started and the equations are solved iteratively as a steady-state. The density of the paint in each cell of the grid is calculated at each time step. The paint thickness of each re-meshed CAD model cell is calculated as the sum of the density going through the cell.

I. Display the Thickness in Relative Color Map

During the simulation in the 3D graphics window, the paint thickness data is visualized as a relative color map (the red color indicates the maximum thickness and the green color indicates half the maximum thickness, etc.). The color map can be viewed in both 2D and 3D.

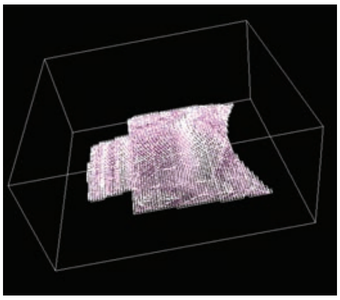
Simulation Results

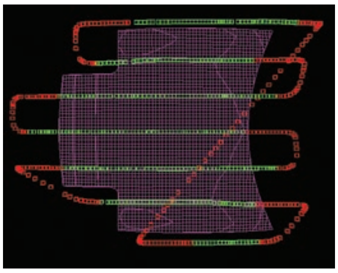
Simulations for the whole car body with multi-robot conveyor tracking system works have been conducted. Compared to the CFD based simulations, which may take several hours or days, the proposed simulation method can complete the relative paint deposition on car within one half hour

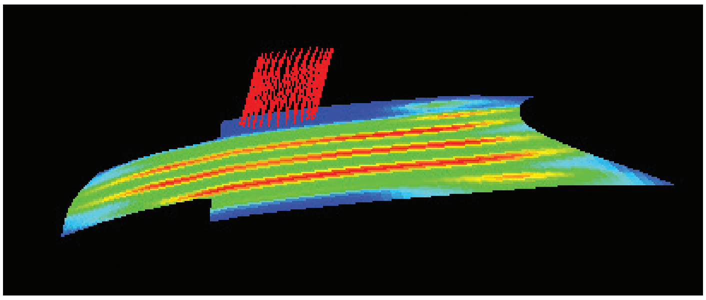
Discussion and Future Work

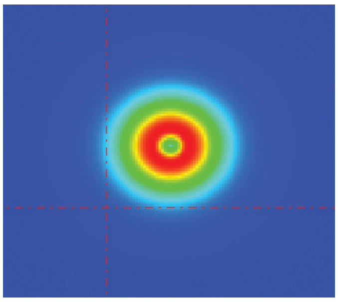
The simulation work presented in this review laid the foundation for the paint process optimization in the future. It achieved the first step by visualizing the simulation result to assist the paint robot programmer to tune the robot program and control parameters in the painting process for a multi-robot automotive painting line. Next step is to validate the simulated paint thickness distribution result to actual paint thickness distribution. Then an optimization method can be developed to automatically and systematically tune the painting process parameters and modify the robot path to improve both efficiency and quality of the painting line.

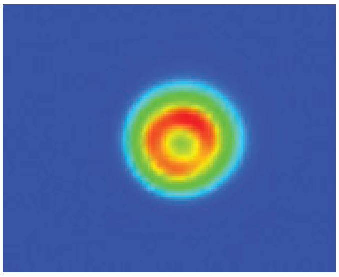
Figure 2: Simulation grid for one of the car surfaces – car hood | Figure 3: Interpolated Robot Trajectory (The green color means positions with paint turned on and the red color means positions with paint turned off) | Figure 4: Force Modeling. Re-meshed Surface. The red lines in cylinder shape represent the forces.











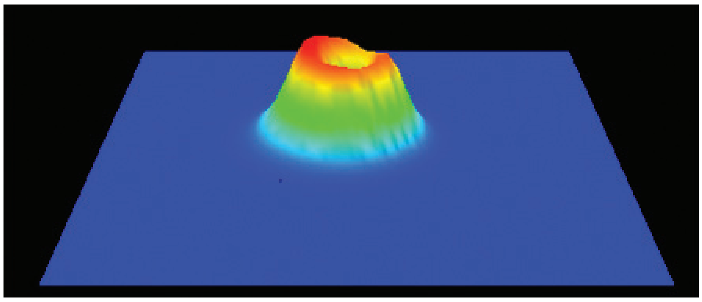


Figure 5: Virtual Applicator Stationary Spinning Atomizer Profile. Top View in 2D. | Figure 6: Simulated Stationary Spinning Atomizer Profile. Top View in 2D | Figure 7: Simulated Stationary Spinning Atomizer Profile. 3D View.

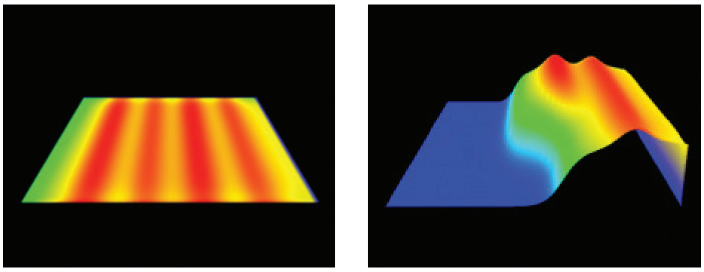


Figure 8: Color Map of Paint on a Planar Surface. 2D View (top) and 3D View (bottom).

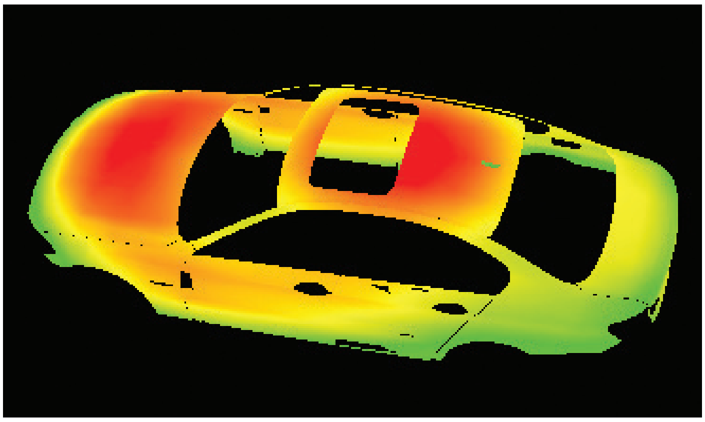


Figure 9: Simulated car body

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A Proven Method for Reducing Costly Interruptions of Knowledge Workers

Dr. Vinay Augustine, Mr. Patrick Francis, Dr. Nicholas Kraft, Dr. Xiao Qu, Dr. David Shepherd and Mr. Will Snipes

Introduction

Two knowledge workers walk into the breakroom. The first, Tom, has been experiencing many interruptions lately. He explains why they are taking such a big toll on his productivity:

Tom: How long does it take for you to fall asleep?

Bob: 10 minutes.

Tom: Now imagine that when you are close to falling asleep, someone walks in and interrupts you, how long will it take you to fall asleep now? Those few seconds you had left, or will you have to start again to 'sink back' to where you were?

Bob: I'll have to start again.

Tom: Great. Same thing. Just like falling asleep, it takes me a while to 'sink' into focus mode, and it takes me a while to get back to it once I'm interrupted, except that I also forget half of what I was doing. [1]

As you can see, interruptions can have a large impact on an individual's productivity.

Problem Description

At ABB, as in any large company, there are countless sources of interruptions: a Skype message from a remote teammate, an office-mate who stops by to chat, or a popup from an incoming email. In the past, we absentmindedly sacrificed our productivity to these interruptions. Today, savvy workers and companies are realizing interruptions have a real cost.

Interruptions, in fact, actually have two costs: the cost of the interruption itself and the cost of restarting the original work. The time spent on the interruption itself is often productive—responding to a colleague's question or a customer's query are important business functions—but time spent restarting a task is pure waste. And this time is not insignificant. Recent studies show that knowledge workers take from 15 to 30 minutes to restart work after an interruption (see [2], [3], or [4]).

Solution Description

Should we aim to eliminate all interruptions? Certainly not, as some interruptions are vital to business. Yet we can manage interruptions, optimizing their timing, ultimately making knowledge workers' days more productive AND more pleasant.

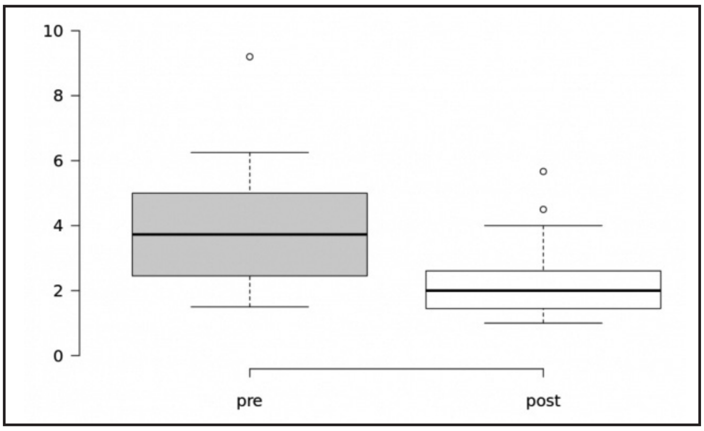

Figure 1: We have conducted Focus Light pilots in over 12 ABB locations. | Figure 2: Interruptions per day without (pre) and with (post) the Focus Light.

In collaboration with researchers from the University of Zurich (Manuela Züger, André Meyer, and Thomas Fritz) we have developed a simple approach to managing interruptions: we mount a small light, called a Focus Light, on the desk of each worker and automatically calculate and display the worker's focus state. When the worker is clearly busy (according to keyboard and mouse activity) the light, and the worker's Skype status, turn red; when less busy the light, and Skype, turn green. Those about to interrupt the worker now have a clear indicator of their busyness, and can make a more informed choice. While it is still necessary to occasionally interrupt a busy co-worker, many disruptive interruptions that used to demand immediate attention turn into emails that can be handled later or conversation held until the next coffee break.

Pilot Description

In order to evaluate this solution we have conducted a variety of pilots. Our most recent pilots were run over five week periods. These pilots were initiated by interested group organizers, who contacted the Focus Light team, and they proceeded as follows. The group organizer would provide emails for his pilot group. Next, our team would send out links to the software specifically designed for that pilot group. The users would install the software and wait for the pilot period to officially begin. Note that there were about 70 participants in total.

Once the pilot period officially began users were asked, via email reminders and in-tool popups, to log each interruption that occurred during their work day. To log an interruption users had to only press the "Pause" key on their computer and select a severity for that interruption (1-5). After this first week of logging, the light was installed. During this second week, as users and co-workers acclimated to working with the lights, interruptions were not logged. During the third week users logged interruptions as before. For the fourth and fifth weeks users simply used the lights without logging and at the end of the fifth week users completed an exit survey.

Pilot Results

During the pilot we asked participants to log interruptions for two periods—five consecutive business days before installing the light and five after. Of course, when piloting in a business setting many subjects missed one or more days of the pilot due to vacation, sickness, or travel. Thus, during our data analysis we only considered data from participants that logged interruptions for at least three days per logging period (total of at least six days). This left us with 28 of the original 70 participants.

As shown in Figure 2 users experienced a median of 3.73 interruptions per day before having the Focus Light but only 2.0 per day with the Focus Light (45% decrease per day). To verify that this practical difference was statistically significant, we ran the Wilcoxon signed-rank test (paired and non-parametric), which showed the difference was significant with a $p<0.0005$.

As shown in Figure 3, most users experienced less interruptions per day after installing the light. For instance, the user on the far right of Figure 3 experienced 4.6 fewer interruptions per day after installing the light. Notice how only 4 of the 28 participants experienced more interruptions (left of Figure 2) while 23 of the 28 experienced less interruptions (right of Figure 2).

We also interviewed 20 users who had started a pilot at least 1-2 months prior to the interview date. From these 20 interviews we found that 18 were still using the light (90%) and 17 planned to use it indefinitely (85%). More detailed results from this interview process will be made available in an upcoming publication

Pilot Testimonials

In addition to the quantitative data, we collected feedback via an anonymous survey at the end of the pilot. While we did not solicit testimonials, in the "Other Feedback" portion of the survey users were very positive, writing:

"I definitely think it resulted in less interruptions both in person and via Skype. This resulted in more focus and ability to finish work."

"I love it! I would like to see it recognize more programs I specifically use, but it has been a big help. Thank you!!"

"Great tool to show availability in the office. It is otherwise impossible for the factory workers to know [my] availability, as they do not use Lync."

"[The Focus Light] project seriously helps [the] productivity of developers while they are… concentrated on [an] activity. Recommended for all development teams."

Conclusion

The results of our pilot clearly show that the Focus Light is effective at reducing interruptions. Yet is this result important from a practical point-of-view? When considering that recent studies show that a single interruption can easily waste 30 minutes of time, a reduction of nearly two interruptions per day amounts to saving an hour per day per employee. Thus, an initial investment of about $30 per employee increases user productivity by 13%, on average.

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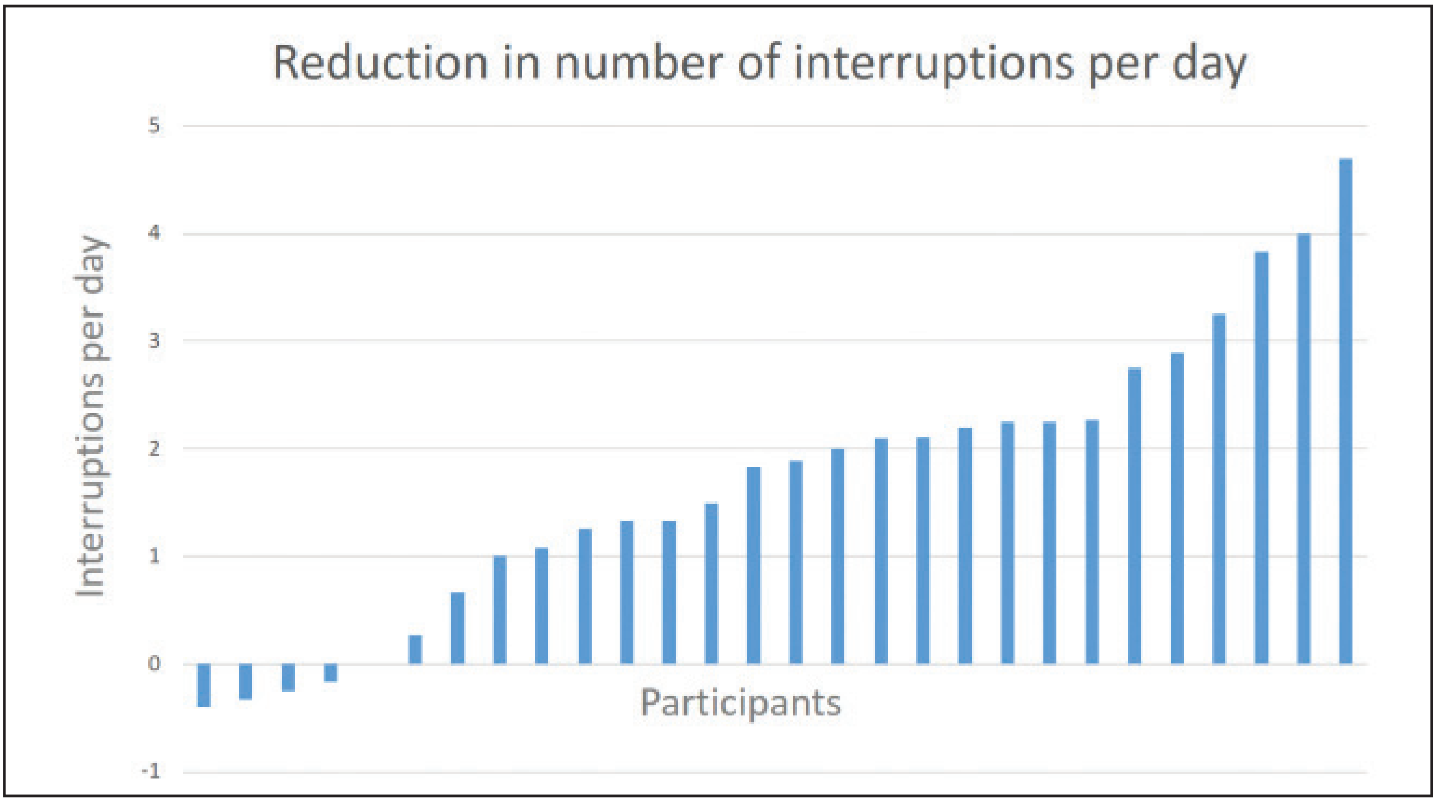
Figure 3: Reduction in interruptions for each user per day after adopting the Focus Light – each bar represents the reduction for a single user (e.g., the last user eliminated 4.6 interruptions per day)



The Intelligent Alarm Management System

Dr. Aldo Dagnino

Introduction

Complex processing industries such as, oil and gas production facilities, and power generation sites need sophisticated distributed control systems to keep their processes and operations working successfully. A distributed control system allows engineers to control production processes and produce high-quality products. Alarms are important elements of a distributed control system as they alert plant operators on operating conditions that are about to exceed a design or a process limit. Alarms are also essential elements in the safety of the operation as they provide an alert that can prevent costly damages to the operation. Due to the sophisticated digital technology embedded in distributed control systems, alarms are easy to configure and deploy. This condition has caused a dramatic increase in the number of alarms that an operator has to address. For this reason it is important to have an alarm management system that helps eliminating nuisance and redundant alarms, identifying predictive alarm patterns, and focusing on the most important alarms.

The Intelligent Alarm Management System

To respond to the alarm management needs of complex control systems and the ever growing number of alarms being incorporated in production systems, ABB Corporate Research has developed the Intelligent Alarm Management (IAM) system, that uses data mining techniques and state-of-the-art visualizations to help alarm analysts focusing on the most important alarms during an emergency situation, identifying predictive alarm patterns, and streamlining the number of alarms shown to the operator. The IAM system can be used by analysts during alarm rationalization meetings and alarm process improvement activities to investigate patterns and trends of historical alarm occurrences and streamline and prioritize the alarms shown to the operator by re-programming alarms in the control system.

When selecting a particular production facility the analyst selects the time period of historical alarm data that wishes to analyze. The IAM system provides a software module that allows the analyst to prepare or pre-process the raw alarm data to be able to conduct the different alarm analyses. Figure 1 shows the data pre-processing stages required to analyze the alarm data in the IAM system. The data pre-processing begins when the raw historical alarm datasets are received from the customers. Typically, these datasets come from an AlarmInsight database, a Symphony Plus database, or any other database format that the customer uses.

The raw dataset is visually inspected and discussed with customers' experts to fully understand the attributes and structure. During this inspection, the quality of data is assessed and a plan for data cleaning and pre-processing is developed. Data is then cleaned to ensure there are no missing value entries, and the dataset contains alarms with their respective activation time stamps and return to normal time stamps. In the case of other single events or operator actions, their associated time stamps are also preserved. Once the data is cleaned and pre-processed, the dataset is then transferred into the Global Alarm Data Model (GLAM), which can be used to conduct the different analyses.

Once the raw historical alarm data has been properly pre-processes the analyst can conduct five types of analyses as: (a) Deep De-chattering; (b) Sequence analysis; (c) Hiding Rules analysis; (d) Critical Event analysis; (e) and Alarm Flood Analysis. Figure 2 shows the user interface that the analyst accesses to conduct the above analyses.

Common Concepts in Analytic Models in IAM

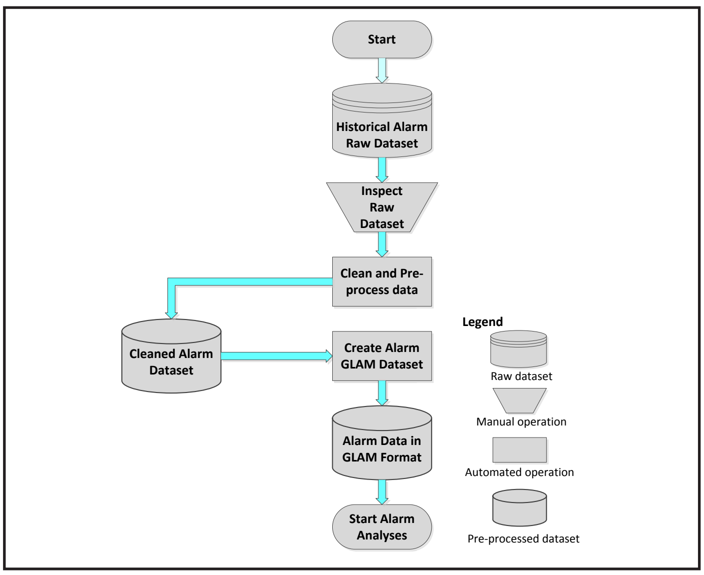
The analytic models developed in the IAM system share common concepts of building blocks such as basketization, ranking metrics, and alarm lifetime and alarm time gap. The first concept refers to the creation of "baskets", "bins", or "containers" that are used to break up a large sequences of time-stamped alarms to then then conduct the desired analyses. The analytic models developed use three types of baskets: (a) containment baskets; (b) equal time-slice baskets; (c) focused critical event baskets.

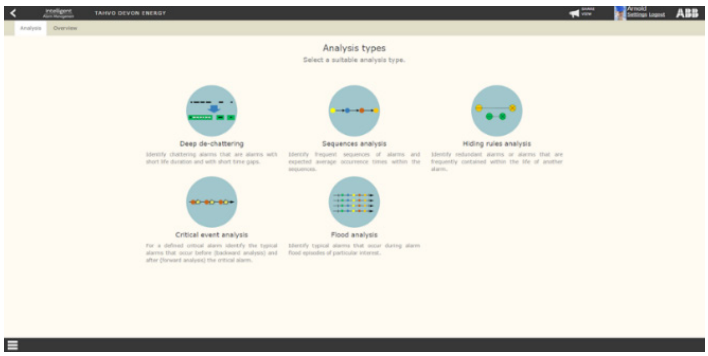
Containment baskets are used in the Hiding Rules analytic model and are created when an alarm is partially or fully contained within the life time of other(s) alarm. Equal time-slice baskets are used in the Sequence Mining analytic model and they are used to break down the entire alarm data log into equal slices of time of length t_{Ets}. Equal time-slice basketization is used to facilitate the computation of sequences. The typical size of the equal time-slice baskets is 20 minutes, based on heuristic experience and this is the default value for the analyses. However, the size of these baskets could be 40 minutes or 60 minutes. Focused critical event baskets are used in the Critical Event Analysis model. These baskets have a particular size based on time and the typical or default size is tFCEV is 20 minutes. The focused critical event baskets are created around a critical event CE and can be backward or before a critical event or forward or after the critical event. The focused critical event baskets help identify alarms contained within the time window before and after the critical event. The size of the focused critical event baskets can also be 40 or 60 minutes.

Metrics have been developed to rank the results of the analyses conducted. The results of the Hiding Rules model, Sequence Analysis model, and Critical Event Analysis model are in the form of rules. In order to select "interesting" rules from the set of rules, it is necessary to compute certain metrics or measures of significance on the rules obtained. As part of each analytic model, we calculate a set of metrics that are used to rank or prioritize the resulting rules of the different analyses. The metrics include: (a) Support; (b) Confidence; (c) Togetherness; (d) Significance. The Support value of X (supp (X)) with respect to the set of observations T is defined as the proportion of the observations in the dataset that contain the item-set X. The Confidence value of the X.Y rule (conf (X.Y), with respect to the set of observations T is defined as the proportion of the observations in the dataset that contain the item-set X.Y over the number of observations of X in T. The Togetherness value of the X.Y rule (tog (X.Y), with respect to the set of observations T is defined as the proportion of the observations in the dataset that contain the item-set X.Y over the number of observations of X or Y in T. The Significance value of the X.Y rule (sig (X.Y), with respect to the set of observations T is defined as the proportion of the observations in the dataset that contain the item-set X.Y over the number of observations of Y in T.

Two other important concepts are the alarm life time and alarm time gap. The Life Time of an alarm is defined as the elapsed time between its activation time and it return to normal time. The Time Gap between two alarms is simply the amount of time that exists between the return to normal of an alarm and its re-activation time.

Figure 1: Alarm Data Pre-processing in the IAM System | Figure 2: Intelligent Alarm Management Analysis Types





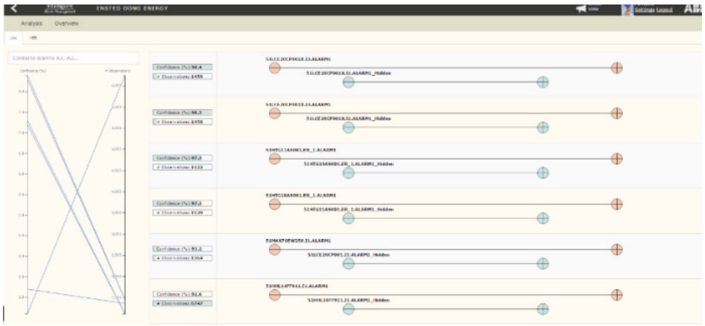


Figure 3: Sequence Analysis Visualization | Figure 4: Hiding Rules Visualization

Analytic Models in the IAM System

As mentioned above, an alarm analyst using the IAM system has several analytic options as shown in Figure 2. It is also important to notice that a user needs a sophisticated user interface and visualization capabilities to be able to analyze the results of the analyses. This is also an important feature that the IAM system offers as several visualization options were investigated during the project.

An analyst selects the alarm Deep De-chattering model to identify chattering alarms and remove them from a historical alarm log file. In the model, an alarm is considered as chattering if: (a) has a short life span; (b) the gap between occurrences of an alarm is short; (c) an alarm has a short life span and short time gap between occurrences. The model identifies chattering alarms and flags them so the analyst and domain experts can select which chattering alarms can be removed, in order to have a "cleaner" dataset for further analyses.

The Sequence Analysis model allows to analyze a large log of alarm historical data and determine the sequences of alarms that frequently occur together as shown in Figure 3. These alarm sequences can be of any length. The Sequence Analysis model also calculates the average time between each element in the sequence as well as the minimum and maximum time in the observations and the standard deviation for each element in the sequence.

The Hiding Rules model is based on the concept that certain alarms in an alarm management system may not need to be displayed to the operator in a plant as they are directly or indirectly addressed by addressing another alarm. This model then is aimed at reducing alarms that can be considered as "redundant". The Hiding rules visualization in the IAM system is shown in Figure 4. An important concept used in this model is the lifetime of alarms. An alarm B is hidden by an alarm A if the activation time of alarm B falls in between the lifetime of alarm A. Hence, alarm B can be fully hidden by alarm A if both the activation time and return to normal time of alarm B fall within the lifetime of alarm A. Alarm B can be partially hidden by alarm A if the activation time of alarm B falls within the lifetime of alarm A and the return to normal time of alarm B is outside the lifetime of alarm.

Critical Event analysis can be conducted forward or backward and within a selected time window. Forward critical event analysis identifies alarms that occur after a critical event occurred within a selected time window. Backward critical event analysis identifies alarms that occur before a critical event within a selected time window.

An analyst selects the Alarm Flood analysis to identify typical floods of alarms that occur during an episode of particular interest. An episode could be bringing equipment back to service after preventive maintenance, or re-starting equipment after a tripping event.

IAM Productization

The Intelligent Alarm Management system has been developed in collaboration with two ABB product groups AlarmInsight and Symphony Plus. The ABB consulting Services group also contributed with their alarm management domain expertise. Selected customers from the above product groups shared their historical alarm data to develop the analytic models in the Intelligent Alarm Management system. The models and visualizations developed are applicable to any industry sector and will be productized and integrated into the AlarmInsight and Symphony Plus products.

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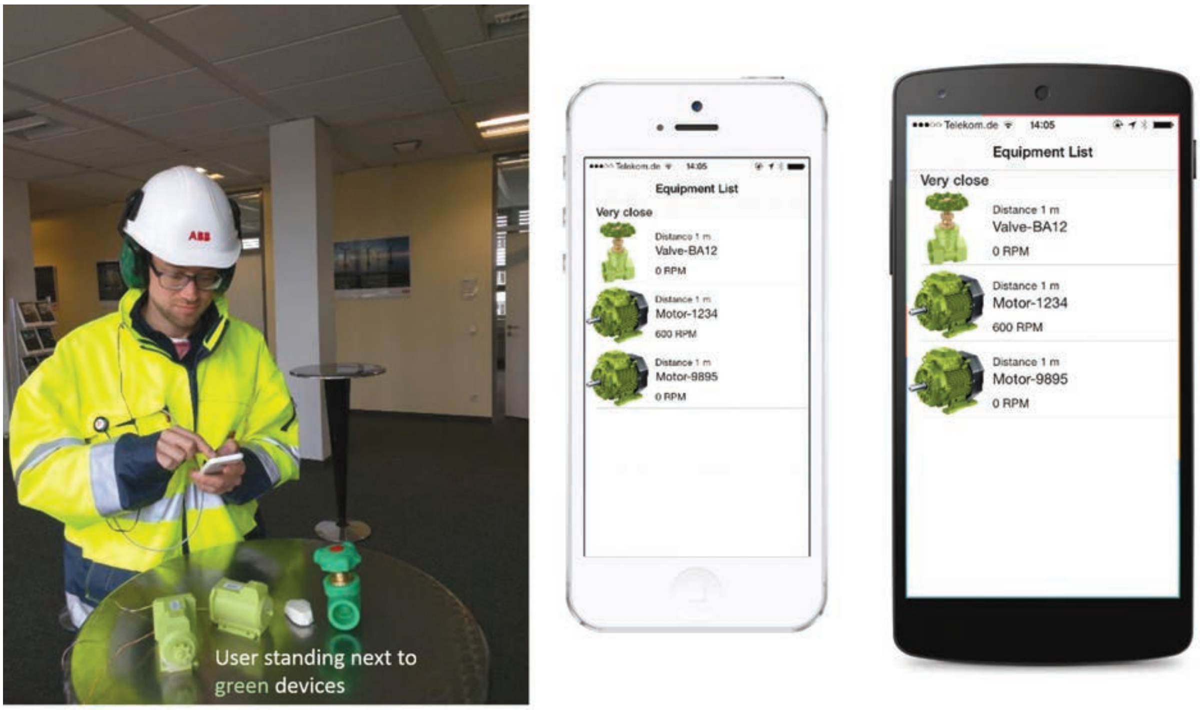


Location Aware Mobile Systems

Shakeel Mahate and Jonas Bronmark

Introduction

We present an innovative approach to reduce the cognitive overload on field operators, who have to work in dangerous, noisy, and highly stressful environmental conditions. The cognitive overload for field operators is very high, any technology solution should not add to this load, instead, it should realize the current location of the operator and automatically detect the devices and equipment in the vicinity. In the future, field operators will be able to use Mobile devices and tablets to connect to Industrial Control systems, our research project designed and implemented a prototype that highlights how we can utilize various location signals such as Bluetooth Low Energy Beacons and GPS to identify nearby devices. Our prototype allows field operators to access and control devices without requiring any effort to find or navigate complex hierarchies.

Mobile Systems in Industry: Overview & Trends

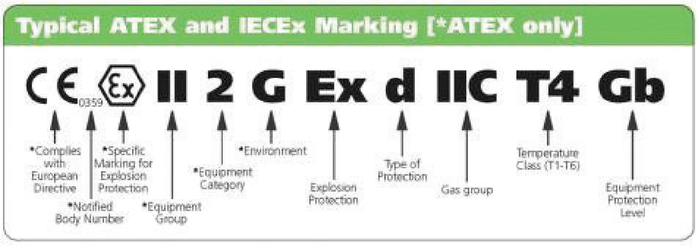
We would be hard pressed to find anybody who does not own a smartphone, the rate of adoption of smartphones is staggering. ABB's Industrial customers have realized the impact of smartphones, tablets, and wearable devices, and its potential to provide up-to-date information, to accurately update the view of a plant, to communicate, to share among many other capabilities. Industries are recognizing that the mobile devices can reduce operational costs and improve safety in the plant. Many operators currently bring their own smartphones to work, with the exception of hazardous work environments, such as chemical plants, nuclear power plants etc.

There is growing trend among industrial customers to identify WiFi network coverage and cellular coverage in the plant. Industrial customers are installing WiFi wireless access points throughout a plant and ensuring that all field operators can have access to internet and to mission critical software on their mobile devices. Customers are determining gaps in their cellular coverage and working with network consultants to eliminate gaps in coverage. This is a long-term trend and it will continue to play a major role in plant operations.

In addition to network coverage, industrial customers are also setting competence centers for mobile devices and applications. Some industrial sectors have selected a recommended set of mobile devices that can be used in a plant. This is becoming necessary to have control over the types of mobile devices being used to access mission critical information and to eliminate risks.

Industrial sectors that have to comply with strict industry regulations for hazardous environments, such as Explosive Atmosphere ATEX Zone 1 or Zone 2, are required to use ruggedized and certified mobile phones and tablets. It is also prudent to select ruggedized mobile devices that can survive drops, water, and other environmental conditions.

We have seen that the preferred mobile platform of choice is Android because of the hardening requirements mandated by the industrial requirements. This might change in the future as more hardware vendors support other mobile operating sys-



DETECTED ACTICITY	DESCRIPTION
IN_VEHICLE	The device is in a vehicle, such as a car.
ON_BICYCLE	The device is on a bicycle
ON_FOOT	The device is on a user who is walking or running
RUNNING	The device is on a user who is running
STILL	The device is not moving
TILTING	The device angle relative to gravity changed significantly
UNKNOWN	Unable to detect the current activity
WALKING	The device is on a user who is walking

Figure 1: Typical Explosive Atmosphere (ATEX) Certification | Table 1: Detected Activities on Android Devices

tems. The choice of mobile operating system is also dictated by geographical regions and industry sectors.

In order to roll out mobile applications to field personnel, industrial customers are relying on internally hosted App Stores or App Marketplaces. Mobile applications authorized by the IT departments are hosted on the App Store and available for installation on approved mobile devices. The App Stores and IT departments are mandating that BYOD (Bring Your Own Devices) to work to have security profiles, which require encryption, strong pins, and ability to erase devices if they are reported as lost.

Currently, industrial customers are mostly using mobile smartphones for communications with control rooms and other experts. They are utilizing short text messages and cameras to capture and report any incidents.

As more and more industrial customers start using mobile devices in the field, they will demand access to the Industrial Control Systems and other mission critical software that were tied to desktop computers locked inside a control room. While anticipating this trend, ABB Corporate Research is also trying to answer how we can make the task of the field operator easier and to remove the technological burden of finding the information required to do their job.

Location Awareness: Capabilities & Challenges

Mobile devices contain many more sensors than a typical desktop computer.

By its nature, a mobile device is carried by the user and is not tied to a particular place or location. The mobile operating system can track the motion of the device and can predict whether it is being removed from a pocket, or is the user travelling in an automobile, or is the user climbing up or down stairs, or is the device simply at rest on a table. All of these cues about the status of the device are available to the apps via the programmable SDKs (Software Development Kits) supplied by the operating system provider, such as Google, Apple, and Microsoft.

Mobile devices also have GPS sensors to accurately pin point the location of a device in physical space, based on the availability of cellular and GPS signals. The problem of determining the precise location is greatly hampered inside buildings and plants. Users might have access to WiFi signals and various software techniques exist to pin point indoor location based on WiFi signals.

The mobile ecosystem is not restricted to the list of sensors available on the phone or tablet. Wearable devices such as watches, glasses, safety helmets, safety vests, keyboards can extend the capabilities of the mobile device. Most of these wearable and add-on devices use Bluetooth for communications with the host device.

Mobile devices can also communicate with NFC (Near Field Communications devices), QR Codes (Quick Response Code), Barcodes. These interactions require a field operator to touch the mobile device to a NFC tag, or take a picture of the QR code or barcode to find more information about a device or access help system. Based on our interactions with the field operators and Industrial customers, we find that this activity adds to the cognition load of an operator, and distracts from the current activity of the operator.

Additionally, traditional control systems were designed for use in Control Rooms, where control room operators have access to large number of displays, and very comfortable working environment. Control room operators can have multiple dashboards open to access critical points, and use keyboard shortcuts and hyperlinks to quickly access information.

Field operators have access to a limited display real estate and the interaction with the mobile device is very limited. They can use voice commands and gestures to access information. However the noisy outdoor conditions and gloves restrict the amount of interaction modes with the devices.

Location Awareness: Approach

The ABB Corporate Research team investigated how field operators would interact with control systems in the field using mobile devices.

The ideal scenario would allow the operator to launch a mobile application which would display the devices close to the operator without requiring any manual effort, such as scanning QR codes, NFC tags, or typing in a command. We call this approach Location Awareness.

Bluetooth Low Energy (BLE) Beacons are very small footprint devices powered by battery or power supply that are positioned in multiple areas in a plant. Each device typically costs less than US $5.00 - $10.00. Some WiFi vendors are embedding BLE radios in the access points.

The battery powered BLE devices can last five years or more, on a single battery. These devices emit Bluetooth signals on a periodic basis, once every minute. The information being broadcast by these beacons is configurable and is dictated by the various industry standards. There are currently three major industry specifications as described in Table 2.

The beacons can be configured to broadcast a 16-bit UID (Universal ID). Each beacon transmits a different UID. The mobile devices read the transmitted IDs without requiring any effort from the user. These signals are read by the device when it enters an area where the beacon exists. The range of the signals is dependent upon various environmental factors and BLE device. Based on our experience, the range of the BLE signal maps very well to our idea of vicinity. Each beacon defines a 5-10 meter radius zone and can be used to identify multiple devices that reside in that zone. If two beacons are placed very close to one another, the mobile device would receive the 16 bit UID transmitted by all of the nearby beacons. Again this maps very will to our innate idea of space, we are in a threshold area and that multiple devices are within reach.

We built an iOS Mobile App prototype that passively reads the BLE 16 bit UIDs. As the field operator navigates a physical space and opens our Mobile App, the BLE 16 bit UIDs are sent to a server, which informs us about the devices that correspond to the UID. Based on this information, we are then able to display the nearby devices, and allow the field operators to display real-time data from Control Systems, and other critical data.

We presented this prototype to field operators and they were able to appreciate the usability of the Mobile App and the ease with which they were able to access the devices and interact with them.

The concept of Location Awareness is an ongoing research topic for ABB Corporate Research and we have some more interesting ideas in the pipeline.

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Table 2: Various industry beacon specifications | Figure 2: Location Aware Mockup

Beacon Specification	Key Highlights
Eddystone	Open beacon format from Google that works with Android and iOS devices. Supports multiple broadcast frame types such as URL, UID and Telemetry. Managing a fleet of beacons is made possible by monitoring health status transmitted by telemetry frames.
iBeacon	Closed beacon format from Apple. Only supports iOS devices. Only one type of broadcast frame.
AltBeacon	Open beacon format from Radius Networks, in response to the closed iBeacon specification. Only one type of broadcast frame.

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