Energy Research User Handbook

PROTOTYPES AND TESTBEDS TO VALIDATE THE ENERGY SOLUTIONS OF TOMORROW

ANDY BELL | DIRECTOR OF ACADEMIC PROGRAMS

As populations continue to grow within dense urban centers and our power usage expands to new areas like electric vehicles, there is an ever greater need to tackle the complexity of renewable energy sources, power monitoring, and smart grid control. Complexity is further compounded by the urgent need for sustainable, clean energy sources that can scale from research to distribution to optimization.

This book includes a select set of examples curated to show how researchers use NI solutions to solve some of the greatest challenges we face by measuring, controlling, and prototyping innovative and novel approaches to global energy needs. To learn more about how NI partners with academic researchers, visit ni.com/research.

andy.bell@ni.com

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www.utar.edu.my/main.jsp

Read the Full Case Study

Producing renewable energy within legal quality control limits

University Tunku Abdul Rahman | Yun Seng Lim and Jun Huat Tang

THE CHALLENGE

There can be fluctuations and flickers in power output to low-voltage distribution networks due to varying solar irradiance in photovoltaic (PV) systems.

THE SOLUTION

We used LabVIEW and NI hardware to develop an inexpensive dynamic load controller that can rapidly vary the power demand based on changes in the PV power output. The voltage issues and proposed solution are valuable to different parties, including the government, policy makers, utility companies, and PV system owners, to ensure growth of PV systems without compromising the quality of the customer electricity supply.

To study how the dynamic load controller can mitigate the flickers caused by the fluctuation in the power output of PV systems, we set up a low-voltage, three-phase distribution network. We connected a PV system and a 3 kW load controller to the distribution network. If the utility grid is used as the supply source, the flickers seen by the load controller consist of two portions: the background flickers introduced by the utility grid and the flickers caused by the intermittent power output of the PV system. We used the 15 kW generator to study the flickers purely generated by the PV system.

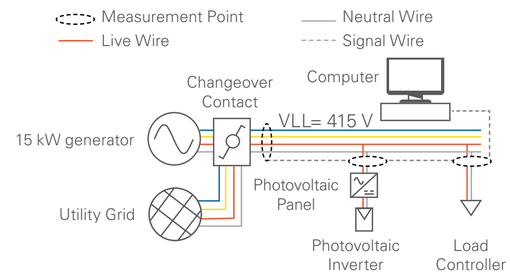
We measured the voltage, current, and power. Solid-state relays act as switches in the load controller, which we programmed using LabVIEW.

First, we examined the severity of flickers introduced by the PV system. We connected a 1.84 kW PV system to Phase A of the distribution network with a 15 kW generator as the supply source to the network. From our findings, we determined that:

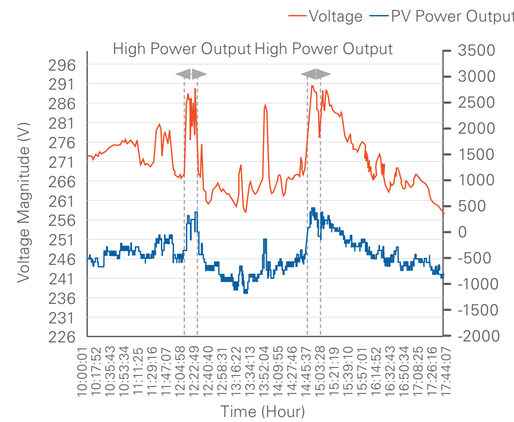
- Many high outputs happen within short durations throughout the day.
- Some of the high-power outputs drop down suddenly instead of gradually.
- The magnitude of reduction in the PV power output is significant at about 63 percent.

We based the proposed load controller on 200 W power resistors and solid-state relays. It reduced flicker by rapidly switching the resistors on and off to lower the impact of sudden increases and decreases in PV power output. The load controller used real power to change the network voltage because the voltage magnitude predominantly responded to real power changes in the distribution network where the resistance was bigger than the reactants. Furthermore, the amount of real power required by the load controller was small. Hence, our proposed load controller is an energy efficient, cost-effective, time-saving, and technically viable solution for flicker mitigation.

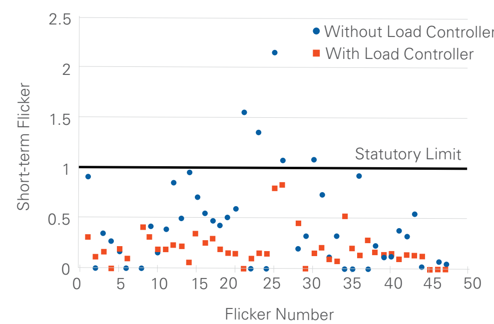
In our second experiment, we connected the PV system to the laboratory network with the 15 kW generator as the supply source. All the short-term flicker indices are reduced when the load controllers are in use and the maximum flicker is lower than the legal limit. When all the short-term flickers are reduced, the long-term flicker is also reduced to 0.458 kW, which shows that the load controller is an effective measure for mitigating voltage fluctuation and flickers.



Experimental Three-Phase Low-Voltage Distribution Network



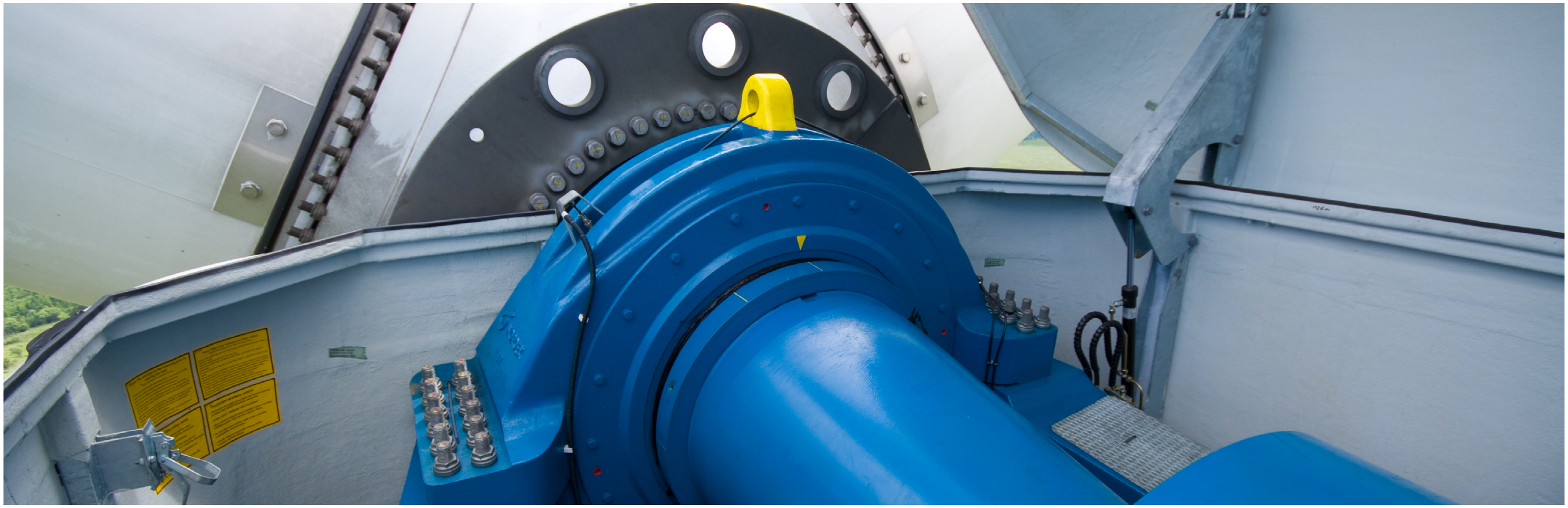
Voltage Fluctuation Caused by Intermittent Power Output of 1.84 kW PV Systems



Severity of Short-Term Flickers

> "The magnitude of reduction in the PV power [caused by fluctuation and flickers] output is significant at about 63 percent."

Yun Seng Lim, University Tunku Abdul Rahman



Creating the World's Most Powerful Renewable Energy Test Facility

Experimenting with turbines 3X more powerful than the industry standard

Clemson University Restoration Institute | J. Curtiss Fox, Mark McKinney, and Ben Gislason

www.clemsonenergy.com

Read the Full Case Study

THE CHALLENGE

Energy companies and graduate students would benefit from a state-of-the-art facility to test both the mechanical and electrical characteristics of a hardware innovation prototype for any energy resource on a utility scale (up to 15 MW) in a controlled and calibrated environment before deploying it on the actual grid.

THE SOLUTION

We delivered high-speed deterministic data acquisition, control, and communications for a 15 MVA hardware-in-the-loop (HIL) grid simulator using LabVIEW and PXI, CompactRIO, and FlexRIO hardware.

To create a 15 MW grid simulator three times larger than the largest common wind turbines in use today we required high-speed, high-resolution, deterministic data acquisition that could easily be reconfigured and expanded.

The system has four main components: power amplifiers, a reactive divider network, a real-time simulator, and a control interface.

The power amplifier is a three-phase 15 MVA arbitrary waveform generator capable of producing waveforms from 45 Hz to 65 Hz with specified voltage amplitude, relative phase angles, and harmonic content. This amplifier acts as a realistic power grid but has far greater control over grid characteristics and behavior.

The reactive divider helps engineers create fault scenarios. It consists of a set of variable inductors and resistors placed between the amplifier and the device being tested and as a shunt to ground.

To create a true HIL system, a real-time digital simulator (RTDS) is used to simulate realistic responses of a power grid. Using the RTDS with the power amplifier, the system can respond realistically to the effects of having the DUT connected to the system.

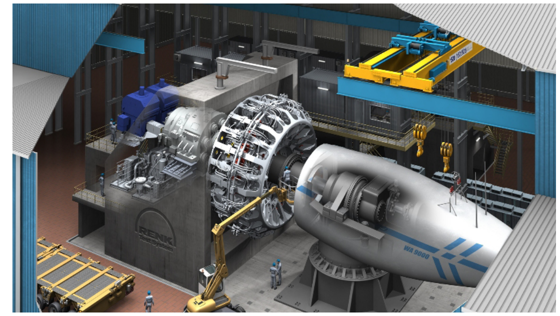
The controller transmits and receives voltage information for all three phases on a 12 kHz sync signal from the amplifier. This allows for exceptional control over the precision and harmonic content of the generated waveforms.

The RTDS can take actual voltage and current readings from a DUT and serve as a true HIL system. These measurements are routed from the DAQ device through the interface controller and to the RTDS. The RTDS then integrates these voltages and currents into the simulated grid and responds exactly as a real-world grid would.

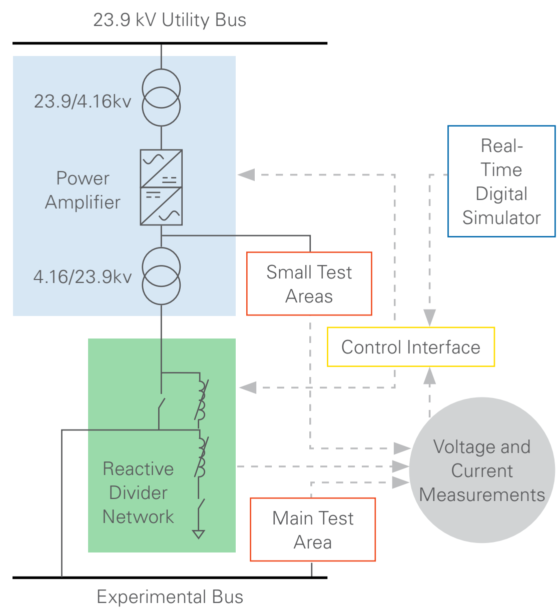
NEXT STEPS

This facility is unique because it can simulate and test the entire cyber-physical system, including the electromechanical machine of the wind turbine, the dynamics of the power grid, and the cyber control system software algorithms.

Researchers can test both the mechanical and electrical characteristics of hardware prototypes on a utility scale in a controlled and calibrated environment before deploying them on the actual grid.

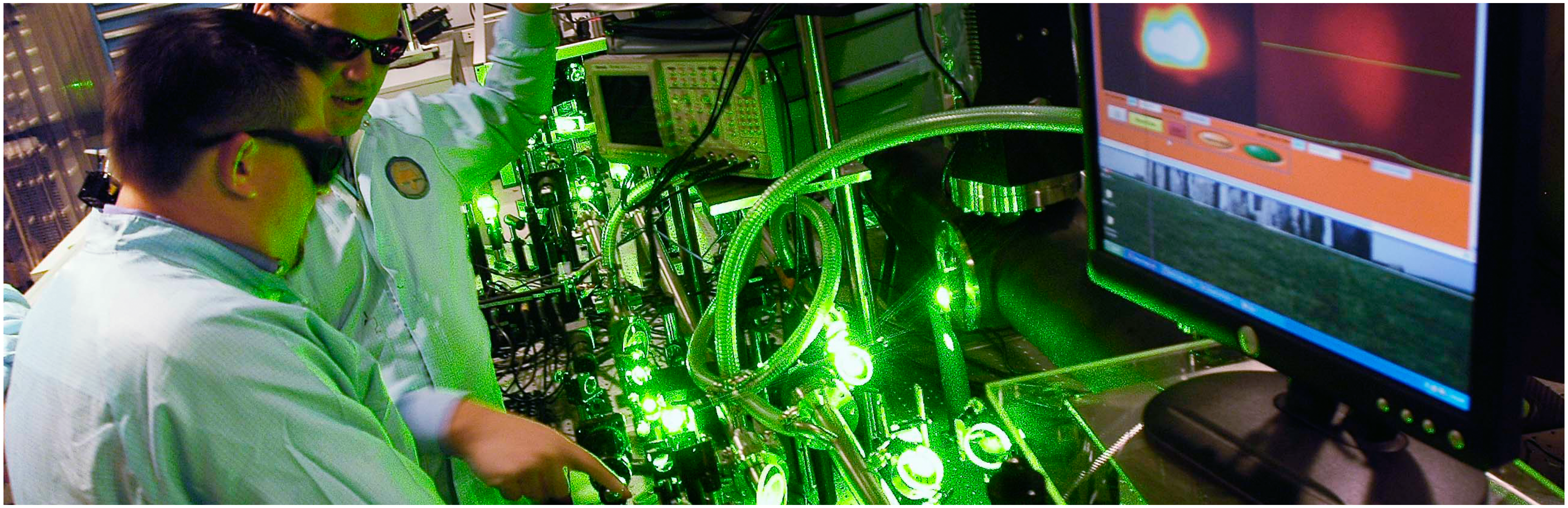


15 MW Wind Turbine Drivetrain



Simplified Diagram of the eGRID Grid Simulator

> "The DoE is counting on wind power to provide 20 percent of US energy by 2030, and [the Duke Energy eGRID centre] supports this objective."
>
> J. Curtiss Fox, Duke Energy eGRID Director, Clemson University Restoration Institute



Controlling the World's Most Powerful Laser

Petawatt power for unlocking the mechanics of fusion

University of Texas at Austin | Dr. Erhard Gaul

www.ph.utexas.edu

Read the Full Case Study

THE CHALLENGE

The High Intensity Laser Science Group at The University of Texas at Austin had a goal to build and accurately control a laser that delivers pulses of extremely high power in the petawatt range to conduct high-energy density physics research such as the study of particle fusion and the behavior of matter in extreme conditions.

THE SOLUTION

We used LabVIEW and PXI instruments to precisely control the charging, firing, amplification, and targeting of the world's most powerful operating laser.

The Texas Petawatt Project is an ongoing venture of the High Intensity Laser Science Group at The University of Texas at Austin. The laser proved to be the most powerful, fully operational laser in the world at 1.1 PW (one quadrillion watts), which is about 2,000 times greater than all US power generation plants combined.

The process for delivering a high-energy laser includes six major phases: charging, generating the short-pulse laser, stretching, amplifying, compressing, and final targeting. Before initiating the firing sequence, we charge large capacitors for a few minutes to provide the laser with ample firing energy.

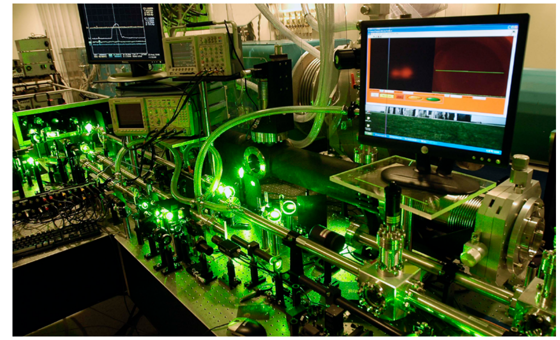
After charging, we fire the beam, which begins as a seed laser; a small, full-spectrum beam of light pulses generated by an average-size laboratory laser. We then "stretch" that light pulse, which carries only one-billionth of a Joule of energy, through a series of mirrors and lenses that lengthen the pulse duration and sequentially separate the light into its different frequencies. Next, we propagate the beam of light through a series of amplifiers, which consists of lenses, laser crystals, and mirrors of sequentially increasing size. The amplifiers create a very large laser beam that is approximately 12 inches in diameter and carries 250 J of energy.

We then direct the stretched and amplified pulse into a compressor tank that concentrates it back into a shorter pulse. When we compress the stretched pulse to a short pulse, its peak power increases greatly to within the petawatt range. We use mirrors to direct the compressed beam from 12 inches in diameter into its final, concentrated size that is narrower than a human hair.

For many experiments, we fire the beam into a steel sphere into which we deliver a mist of special gas. The laser ignites the gas particles in a powerful burst that lasts about 150 fs, depending on the experiment. By observing the results of these experiments, we gain knowledge on a variety of principles from the nature of the beginnings of our universe to the application of fusion for alternative energy.

NEXT STEPS

The laser facilitates high-energy density physics experiments with principles such as particle fusion for alternative energy research and other applications of controlled and extremely compacted energy. For example, in addition to effectively studying the possibilities for future fuel sources, on a small scale, we can create the conditions of supernovas including the plasma associated with various astrophysical phenomena.



Our diagnostics and controls system manages all aspects of laser operations.

> "The laser was documented to reach 1.1 PW (one quadrillion watts), which is about 2,000 times greater than all US power generation plants combined."
>
> Dr. Erhard Gaul, The University of Texas at Austin

Flow Testing of Prototype Nuclear Fuel

Keeping high-performance research reactors in line with regulations

Oregon State University, Department of Nuclear Engineering and Radiation Health Physics | Wade R. Marcum

www.ne.oregonstate.edu

Read the Full Case Study

THE CHALLENGE

The US Department of Energy (DoE) mandated that all civilian nuclear research and test reactors consist of a fuel composition, such as low-enriched uranium, that mitigates the desire for proliferation. However, some high-performance research reactors could not convert to a new fuel without drastically compromising their ability to function properly.

THE SOLUTION

There is currently an effort to research, develop, and qualify a new fuel that satisfies the DoE's mandate while maintaining acceptable performance and safety requirements. Oregon State University and the Idaho National Laboratory collaborated on an experimental program that involved hydro-mechanically testing a generic fuel element. Our group designed and built a large-scale thermal hydraulic test facility called the Hydro-Mechanical Fuel Test Facility (HMFTF). We used CompactRIO, PXI, LabVIEW, high-fidelity instruments, and quality experimental methods to fully quantify all flow conditions required to mechanically deform a prototypic nuclear fuel.

At the HMFTF, we performed flow testing on this new fuel composition to identify the hydraulic characteristics that may lead to safety issues. The DAQ system and programmable automation controller (PAC) connected to a single network switch that could upload any sensing channel to the server and the HMFTF control center as required.

The PAC system featured two CompactRIO chassis, each holding up to eight sensing modules. These modules sensed and controlled system pressure, water level, fluid temperature, flow, and valve position for all components in the facility.

We regulated system pressure in the facility through the main feed pumps (MFPs) and their pressure setpoints relative to the sensed output from controlling pressure indicating transmitters. Water level was maintained in a similar manner to system pressure. We regulated it through a VSD-controlled make up pump with a setpoint relative to the sensed output from the level indicating transmitter located in the accumulator.

We controlled fluid temperature through band heaters wrapped around the primary loop piping system. They responded through the output temperature sensed at the outlet of each pump.

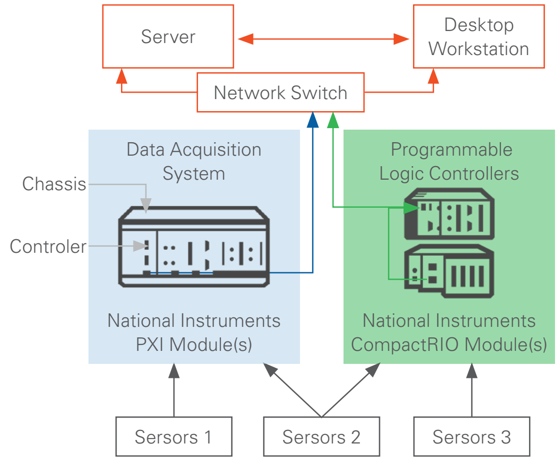
We regulated flow via one flow control valve per MFP. Independent vortex flow meters monitored flow in each of the MFP branches. The signal was sent to both the DAQ system and PLC since it was both a logic and quality assured parameter. A corresponding output signal was sent to an electro-pneumatic converter that drove the flow control valve positioners to their appropriate positions.

All DAQ system and PAC acquisition information was passed through the software interface and saved onto a controlled storage space.

NEXT STEPS

At the HMFTF, we performed flow testing on this new fuel composition to identify the hydraulic characteristics that may lead to safety issues. This experimental program supported the qualification of a new fuel type, so we conducted it within a nuclear-compliant quality assurance program, which included the highest quality standards for conduct, performance, acquisition, and synthesis of the experimental work.


Physical Arrangement of the HMFTF



Sensor Arrangement

> "The test section was 6.5 feet long. It included 25 ultra-high precision pressure transducers to measure the individual subchannel dynamic pressure of each tested element, three pressure indicating transmitters to measure bulk flow rate, three thermocouples to measure fluid temperature, and the ability to connect 96 strain gages to a single test element to acquire elastic and plastic plate deformation."

Wade R. Marcum, Department of Nuclear Engineering and Radiation Health Physics, Oregon State University

Preventing Catastrophic Failures in High-Voltage Electrical Equipment

Modular instrumentation for online partial discharge monitoring

Eletrobras Cepel | André Tomaz de Carvalho, Hélio de Paiva Amorim Júnior, and Caio Fleming Ferreira de Carvalho Cunha

www.cepel.br

Read the Full Case Study

THE CHALLENGE

Electrical insulation is the weak spot of any high-voltage equipment. The equipment's normal duty cycle subjects insulation materials to vibration and thermal cycling, which makes them age and lose their dielectric properties. It is therefore necessary to assess the health of the insulation in such equipment with a view to the continuity of power supply and reduction of failures.

THE SOLUTION

We aimed to implement an online partial discharge (PD) monitoring and analysis system for hydroelectric power plant generators to aid the predictive diagnosis of stator electric insulation. We developed a modular instrumentation system (IMA-DP) for online monitoring of PD in hydrogenerators using PXI modular instrumentation and signal processing algorithms implemented with LabVIEW. We have adopted the system as an effective predictive maintenance tool.

Partial discharge (PD) monitoring is an effective way to assess insulation integrity in high-voltage electrical equipment. PD measurement offers high sensitivity, permits the localization of defects, and is the only technique that can monitor generators while in use (online). Theoretically, PD measurement could have detected the estimated 89 percent of failures that occurred in insulation.

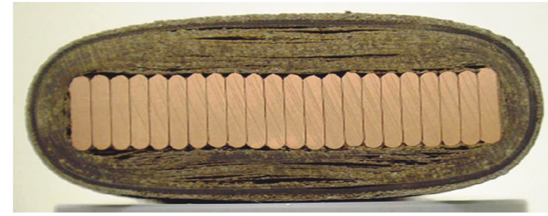
PDs are localized dielectric breakdowns of a small portion of a solid or fluid electrical insulation system under high voltage stress, which does not bridge the space between two conductors.

We developed the PD Analysis and Instrumentation System (IMA-DP) to measure the PD in the high-frequency band (<30 MHz). We added a switch module for sequential measurement of up to 16 channels, significantly reducing monitoring costs per channel. The digitizer sends the acquired raw data to the FPGA over a peer-to-peer connection for processing in real time. Final processing and consolidation of results happens in the embedded controller. We used LabVIEW as the only programming language for the data acquisition, FPGA programming, signal processing and analysis, database, and reporting interfaces.

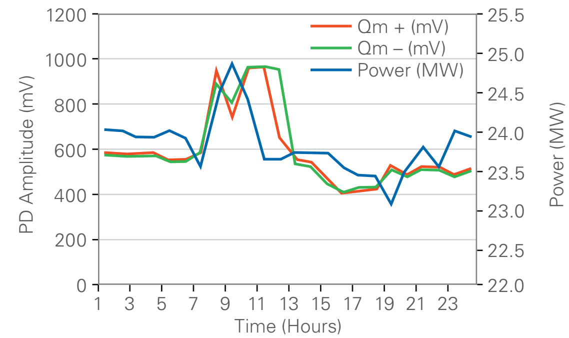
We achieved an important result in 2009 when the IMA-DP successfully detected an early defect during the reconditioning process of one generator of the Coaracy Nunes hydroelectric plant. IMA-DP indicated abnormal PD patterns distinct from the other phases on the V phase of Generating Unit 3. An inspection on the stator coils revealed deterioration of surface points of bars between the front bar and the bottom bar on the bottom of the magnetic core. After the manufacturer made the repair, a subsequent measurement revealed that the defect had been corrected because PD levels were uniform and within acceptable values in the three phases.

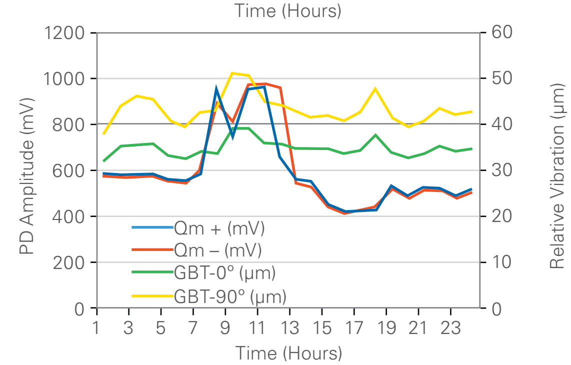
NEXT STEPS

Continuous PD monitoring has also helped us study the correlation between PD levels and other monitored quantities including correlation between the instantaneous value of generated active power and the monitored PD levels, and correlation between PD levels and relative vibration on a generator.



Cross section of a generator bar shows cavities in which PD may occur.

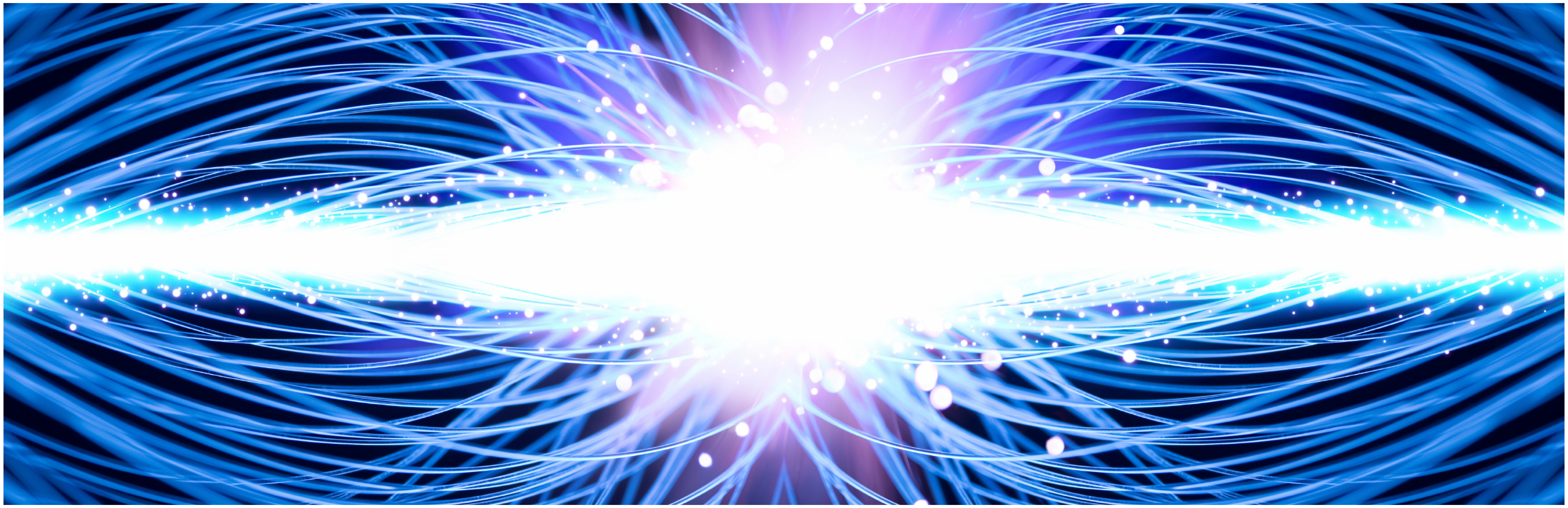




(top) Correlation between PD levels and generated power on a hydro generator of Coaracy Nunes plant. (below) Correlation between PD levels and relative vibration in the guide bearing of the turbine on the same generator.

> "We achieved an important result in 2009 when the IMA-DP successfully detected an early defect during the reconditioning process of one generator of the Coaracy Nunes hydroelectric plant."

André Tomaz de Carvalho, Researcher at CEPEL



Extending Plasma Life Span for Fusion Energy Research

Setting world records for fusion energy output

National Institute for Fusion Science, Department of Helical Plasma Research | Shuji Kamio

www.nifs.ac.jp/en/

Read the Full Case Study

THE CHALLENGE

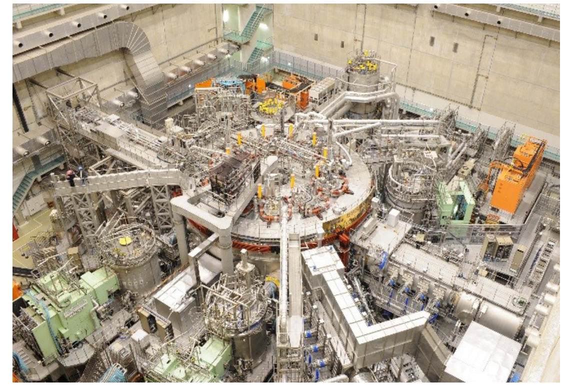
One of the most critical issues for the realization of fusion energy is sustaining high-performance plasma at a steady state and for a long duration. However, high-temperature plasma has not yet been sustained longer than several minutes. We aimed to sustain confinement of a high-performance plasma at more than 10 million °F and 10 trillion/cc, which requires complex processing during the experiment.

THE SOLUTION

We developed the Large Helical Device (LHD) that could generate and sustain a long-duration plasma, but required stable plasma parameters and stable injection heating power. We used NI solutions to create a steady-state plasma control system using FPGA technology that could sustain high-performance plasma for an extended period.

Inside the LHD, a plasma at a temperature of more than 10 million ˚F (20 million ˚C) is generated and sustained as a long-duration plasma. To sustain the plasma for a long period of time, we need to continuously supply plasma heat and gas fuel as required. When we supply less gas fuel, the plasma becomes thinner and vanishes. When we supply too much gas, the plasma vanishes either by cooling or by thickening. If the heat is not strong enough, the plasma becomes cold and vanishes. Maintaining the health of the devices while sustaining high-power heat (at megawatt levels) requires sophisticated technology.

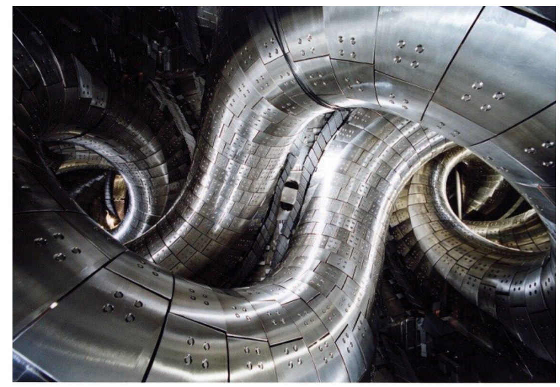
To stabilize plasma parameters, various observed information such as plasma density, temperature, and optical emission are important for feedback control. Using these parameters, we derive the next quantities for gas fuel and heating power. However, heating power control is difficult within a fusion reactor because of the magnitude of the microwave energy involved, which is greater than thousands of household microwave ovens. The voltage of the transmission lines exceeds 30,000 V, and unintentional power reflection causes the transmitter to break down or the cooling water to leak onto the antenna head. These types of accidents sometimes cause terrible damage to the heating devices. Thus, in the past, we required two or three operators for complex monitoring and response.



The LHD With Heating Devices and Other Instruments

Stabilizing the plasma parameters and stabilizing the injection heating power are distinct challenges, which are also linked to each other. Therefore, we developed an integrated system using CompactRIO with FPGA. This empowered us to complete the complex operation, which includes the data collection, calculation, and control signal output, at high speed with very deterministic and reliable timing intervals.

We have sustained high-performance plasma for more than 48 minutes at more than 10 million ˚F and 10 trillion/cc. This temperature is higher than the temperature on the surface of the sun. The total heating power of 3.4 GJ exceeded by more than three times the world record of 1.0 GJ set more than a decade ago.



The Superconductor Coils Inside the LHD Vacuum Chamber

NEXT STEPS

Our system is useful for inputting the target plasma parameters and for driving discussion on strategies and approaches for future experimentation. FPGA control helped us reduce the number of people involved in the operation, which means that responses to problems are quicker and more accurate. The system also helps prevent unexpected equipment damage.

> "We have sustained high-performance plasma for more than 48 minutes at more than 10 million ˚F and 10 trillion/cc. This temperature is higher than the temperature on the surface of the sun. This total heating power of 3.4 GJ exceeds by more than three times the world record of 1.0 GJ set more than a decade ago."
>
> Shuji Kamio, National Institute for Fusion Science, Department of Helical Plasma Research

Creating a Reliable, Cost-Effective Solar Forecasting for Smart Grids

Overcoming challenges caused by multidirectional energy flow on the grid

Nanyang Technological University | Sivaneasan Balakrishnam, Research Fellow

www.ntu.edu.sg

Read the Full Case Study

THE CHALLENGE

The intermittent nature of solar power can cause reliability issues that affect coordinated energy management.

THE SOLUTION

Nanyang Technological University developed a system that performs real-time data acquisition of solar parameters for accurate solar forecasting and coordinated energy management for efficient integration of solar photovoltaic, fuel cell, and energy stores into a smart grid.

Typically, the distributed energy resources within the smart grid include photovoltaic (PV), wind turbine, fuel cell, and battery energy storage systems (BESS). The bidirectional power flow of the BESS in the smart grid can deliver and absorb energy based on the charging/discharging requirement. The power flow of the upstream grid is also bidirectional as the system can absorb power from the wider grid.

We can ensure a reliable, cost-effective energy solution for the smart grid by controlling the active and reactive power injected by the distributed energy resources (DERs) responsive to changes in weather conditions and respond to incentives from service providers to curtail load demand at times of peak or off-peak demand. This requires a highly efficient and robust coordinated energy management system (CEMS) to schedule the power flows to the loads between grid supply and DERs using advanced control strategies with an intelligent communication interface.

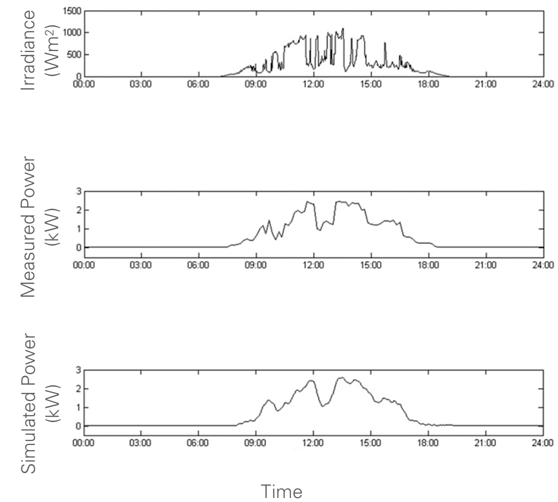
Reliability issues caused by the intermittent nature of solar PV can be overcome by an accurate solar power forecasting algorithm using real-time solar irradiance and temperature data. The amount of solar power generated depends on the weather conditions and solar PV panel physical specifications such as efficiency, azimuth, and tilt angle. This information serves as the input to the solar power forecasting algorithm. The energy management system can use the forecasted solar power to control the charging and discharging of the BESS to buffer the PV output.

We measured output power from a smart meter connected to an actual PV system while also simulating output power obtained using our model. Both the measured and simulated output power closely follow the variations of actual solar irradiance. The simulated output power corresponds well to the measured output power with a mean absolute percentage error of only 3.93 percent.

PV systems have non-linear voltage and load characteristics, so the operating point of the PV system depends on the connected load. To ensure the PV system in the smart grid testbed operates at maximum possible output power, we implemented an improved maximum power point tracker (MPPT) algorithm using LabVIEW. We applied the current sweep and estimation perturb and perturb (EPP) algorithm to extract the maximum available power at each time instant.

SUMMARY

The developed smart grid testbed proved the applicability of the proposed energy solution to overcome the impact of intermittent energy generation of renewable energy resources. We used diverse, flexible products from NI to perform incremental research and easy integration with our existing system. Using the built-in driver hardware in LabVIEW, we significantly reduced development time for the CEMS software.



Comparison of Measured and Simulated Solar PV Output Power

"Reliability issues caused by the intermittent nature of solar PV can be overcome by an accurate solar power forecasting algorithm using real-time solar irradiance and temperature data. The simulated output power corresponds well to the measured output power with a mean absolute percentage error of only 3.93 percent."

Sivaneasan Balakrishnam, Research Fellow, Nanyang Technological University

Automating Measurements for a Tidal Stream Turbine Testbed

www.southampton.ac.uk

Read the Full Case Study

Building a body of data for large-scale deployment decisions

University of Southampton | Dr. Bradley Keo

THE CHALLENGE

Tidal stream turbines are a new renewable energy technology, which means that large-scale industrial farm deployments currently have little data upon which to base deployment decisions. Understanding how these turbines behave in different currents and how they interact with one another is key to maximizing return on investment. But gathering flow data is a slow, labour-intensive process and not scalable to all possible scenarios or turbine designs.

THE SOLUTION

The University of Southampton designed and built a measurement testbed that can automate a preconfigured series of flow measurements anywhere within the test area. This testbed can reduce the labour required to collect data.

Traditionally, multiple single-point flow measurements were taken by hand. Any one experiment may require hundreds of individual-point measurements within an x,y,z space, making this a labour-intensive task susceptible to human error.

We designed an automated positioning rig with the aim to reduce the labour required to collect data in such experiments. The rig involves a two-axis automated motion system (the entire rig can also be slid manually in a third axis) for positioning multiple flow-measurement probes anywhere within the flume's working section. The flume is 21 meters long, 1.37 meters wide, and can operate at depths of up to 0.5 meters.

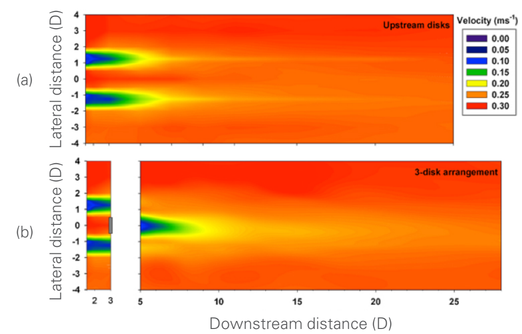
We used LabVIEW to automate the probe motion and simultaneously acquire data by interfacing with the probe's own bespoke software. This removed the need for human input at any stage other than to set up and start an experiment. When sampling multiple single-point measurements, this reduced the time to acquire data from four hours to 20 minutes per experiment.

NEXT STEPS

Manual labour time has been reduced to approximately 5–10 percent of the previous requirement during similar experiments. The automated system also collects data with improved spatial resolution and accuracy, leading to greater research output and allowing the research group to secure additional industrial marine energy consultancy work that can help fund future developments.

21 m Circulating Flume Facility at the Chilworth Hydraulics Laboratory

Automated Rig in Position and Recording Data



Velocity Flow Mapping Showing Wake Interaction Behind Multiple Small-Scale TST

"We chose NI hardware and software due to compatibility [with existing sensors] and ease of initial setup. These solutions also deliver the greatest flexibility for future equipment developments within the laboratories."

Dr. Bradley Keogh, Research Fellow, University of Southampton

Measuring the Health Effects of Noise Generated by Wind Farms

Investigating low-frequency amplitude modulated noise

The University of Adelaide | Dr. Kristy Hansen

www.adelaide.edu.au

Read the Full Case Study

THE CHALLENGE

Wind farm noise has a much greater effect on the health of people living in rural communities than would be expected based on the A-weighted decibel level they experience. Many people suffer from sleep deprivation and some even leave their homes, which creates tension in these communities. Future proposed wind farm developments are met with resistance.

THE SOLUTION

Developing a better understanding of the noise characteristics that cause annoyance is vital to noise mitigation approaches so wind turbines become more acceptable to the communities in their vicinities. The University of Adelaide developed a reliable, cost-effective system to gather data. The system can withstand harsh environmental conditions and requires minimal setup time.

To gather our results, we acquired microphone data at 10,200 Hz sample rate. We measured the noise floor of the system at 27 dBA in an anechoic chamber, which is low enough for our purposes. We programmed the system to acquire data continuously for up to two weeks using a single, continuous binary file for later analysis.

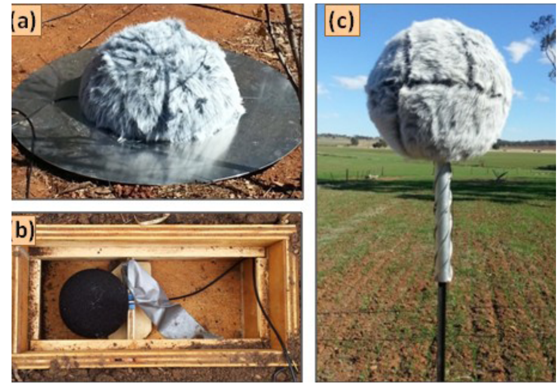
According to ISO Standard 389-7, which specifies the threshold of hearing for free-field tonal noise, the peaks we measured should not be audible to a person with normal hearing. However, the large amplitude sidebands adjacent to the main tonal peaks indicate the high degree of amplitude modulation. This increases the likelihood that the tones would be perceptible. Draft NSW Planning Guidelines for Wind Farms suggests applying a 10 dBA penalty where tonality and amplitude modulation are identified.

Noise in the mid- to high-frequency range is selectively attenuated by the walls and roof at a typical residence, so the low-frequency noise would dominate the inside listening environment. This would be perceived as more annoying than a well-balanced spectrum of equal loudness. Moreover, resonances in an average-size room are well separated at low frequencies, causing a large variation in sound pressure level as a function of a person's location in the room. Therefore, to characterise the noise level inside the room properly, distributing additional microphones is required.

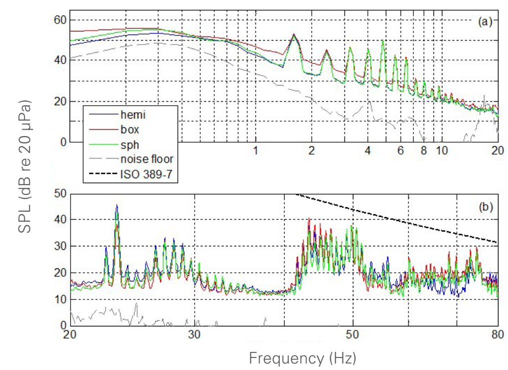
Our analysis indicates that at noise levels that may be deemed compliant when averaged over a 10-minute period, the time-dependent peaks in sound pressure could conceivably be above this threshold at low frequencies. According to ISO Standard 226, the margin between audibility and annoyance is known to be small for low-frequency noise; hence, a small increase in sound pressure level above the audibility threshold would cause annoyance.

NEXT STEPS

We could not have identified the blade-pass frequency and harmonics or the frequencies of the tonal peaks with a standard third-octave analysis. In addition, it would have taken more time to identify the amplitude modulation through analysis of third-octave data. The frequencies of the tonal peaks and extent to which they are amplitude modulated, which involves sound source characterisation on a model wind turbine, is important for future work at the University of Adelaide. Quantification of the tonality and amplitude modulation in combination with listening tests will provide information for improvement of standards related to wind turbine noise.



Windshields used for outdoor measurements include: (a) Hemispherical windshield (on ground), (b) Box windshield (underground), and (c) Spherical windshield (1.5 m).



Night time narrowband spectra with frequency resolution of 0.1 Hz. Results are presented for microphones with hemispherical, box, and spherical windshields and the ISO Standard 389-7 curve is shown for comparison.

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> Dr. Kristy Hansen, The University of Adelaide