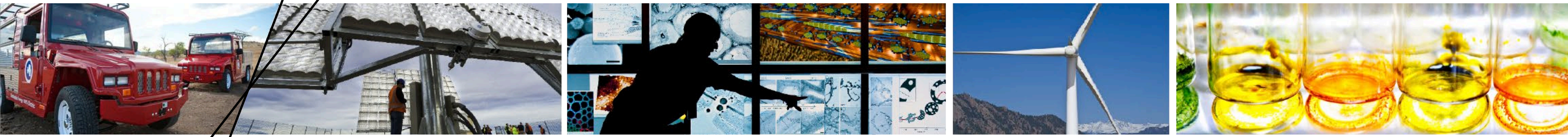
Next Generation Drivetrain Development and Test Program



Drivetrain Concepts for Wind Turbines 6th International Conference

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Chris Halse, Romax Technology, Inc.
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Bremen, Germany
November 30, 2015

NREL/PR-5000-65497
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Agenda

- **Next-generation drivetrain architecture**
- **Drivetrain technology development and testing**
  - Gearbox and inverter software
  - Medium voltage inverter modules
- **Summary**

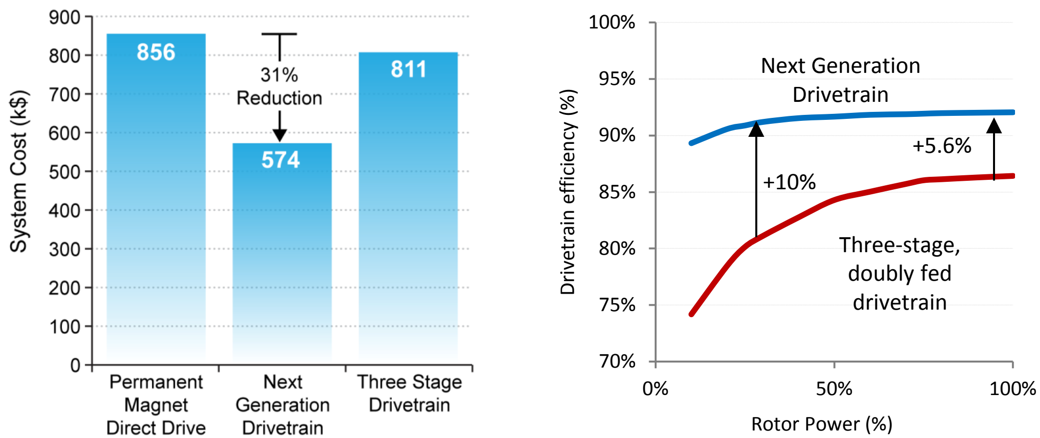
Next-Generation Drivetrain (NGD) Architecture

The NGD is an integrated, medium-speed, medium-voltage drivetrain, featuring advances in the gearbox, generator, and power converter that increase efficiency, reliability, and annual energy production (AEP) while reducing operation and maintenance (O&M) and cost of energy (COE).

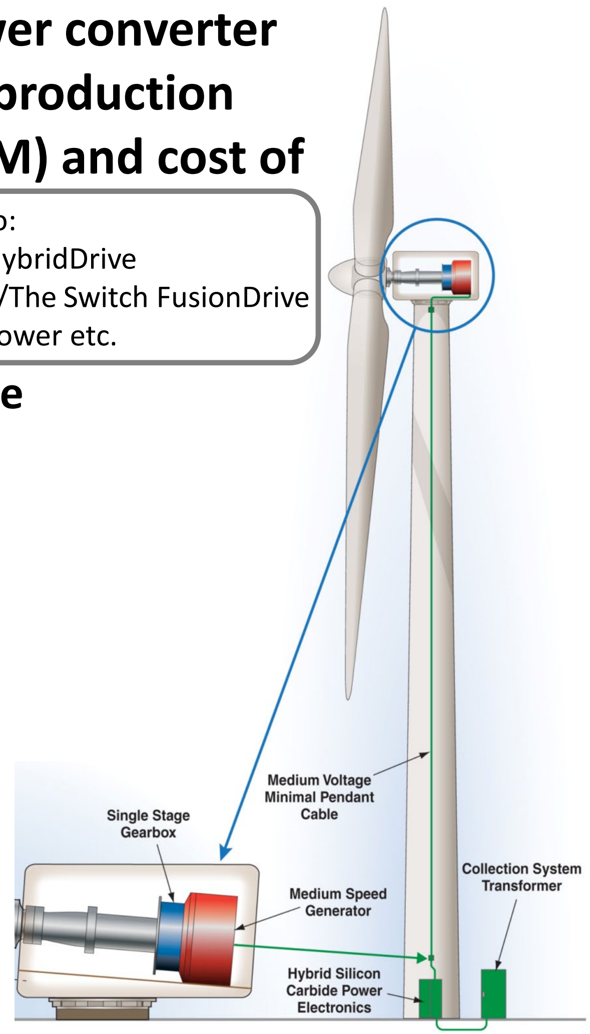
Similarities to:
- Winergy HybridDrive
- Moventas/The Switch FusionDrive
- ZF Wind Power etc.

NREL's research on the NGD has two phases:

- **Phase I - Investigated NGD benefits; found 5% AEP increase and 13% COE decrease at 5 megawatts (MW)**
- **Phase II - Designed, built, and tested key technologies.**



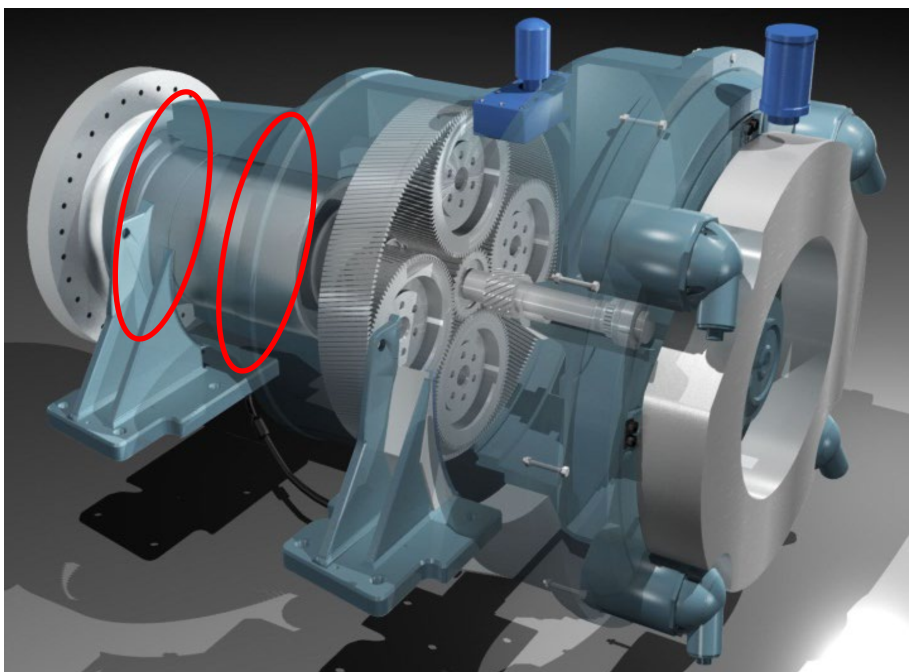
Comparisons of drivetrain cost and efficiency at 5 MW.
Illustration by Al Hicks, NREL



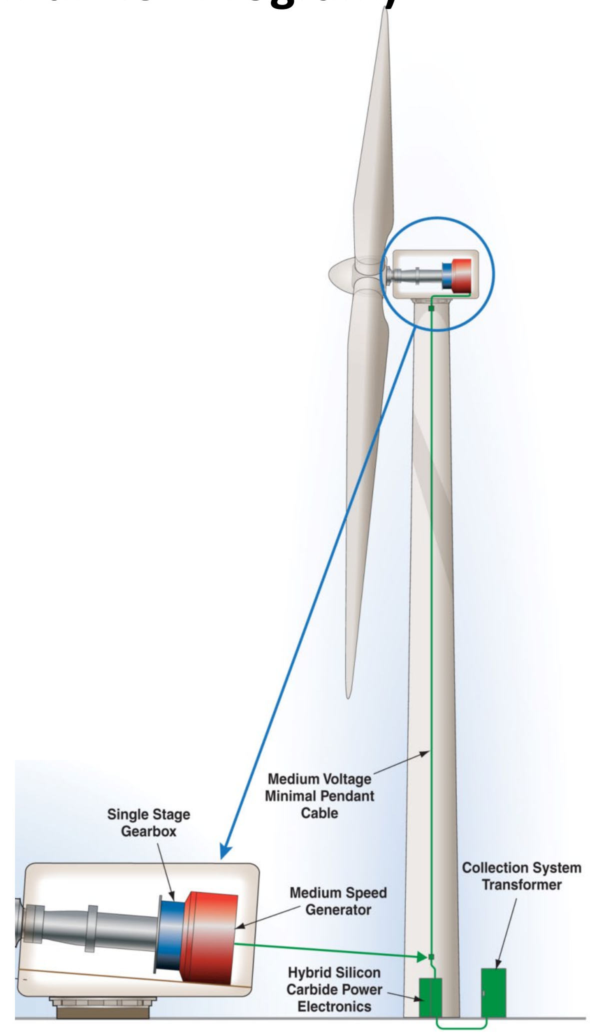
NGD wind turbine concept.
Illustration by Al Hicks, NREL

NGD Design – Main Bearings

- **Double tapered roller bearings (from WindPACT Program)**
  - Support rotor axial loads and moments
  - Support planetary carrier
  - Oil lubricated



NGD gearbox and generator. *Illustration by Josh Bauer, NREL*



NGD wind turbine concept.
Illustration by Al Hicks, NREL

NGD Design - Gearbox

- **Single-stage planetary gearbox†**
  - Mechanical simplicity and journal bearings increase reliability
  - Multiple planets, flex pins, and premium steel‡ increase capacity

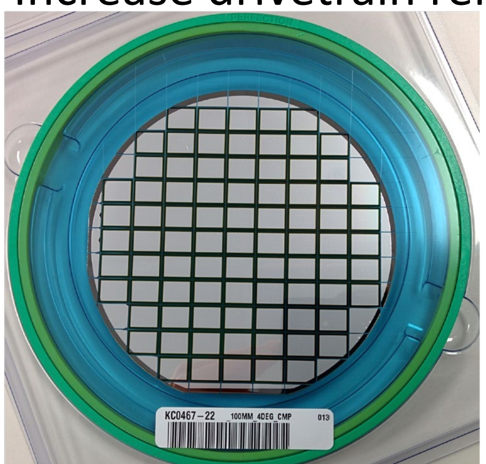
†Two-stages may result in lower drivetrain capital cost

‡Not part of Phase II design, build, and test program

NGD gearbox planetary section. ***Photos by Chris Halse, NREL 33353 and Jon Keller, NREL 33341***

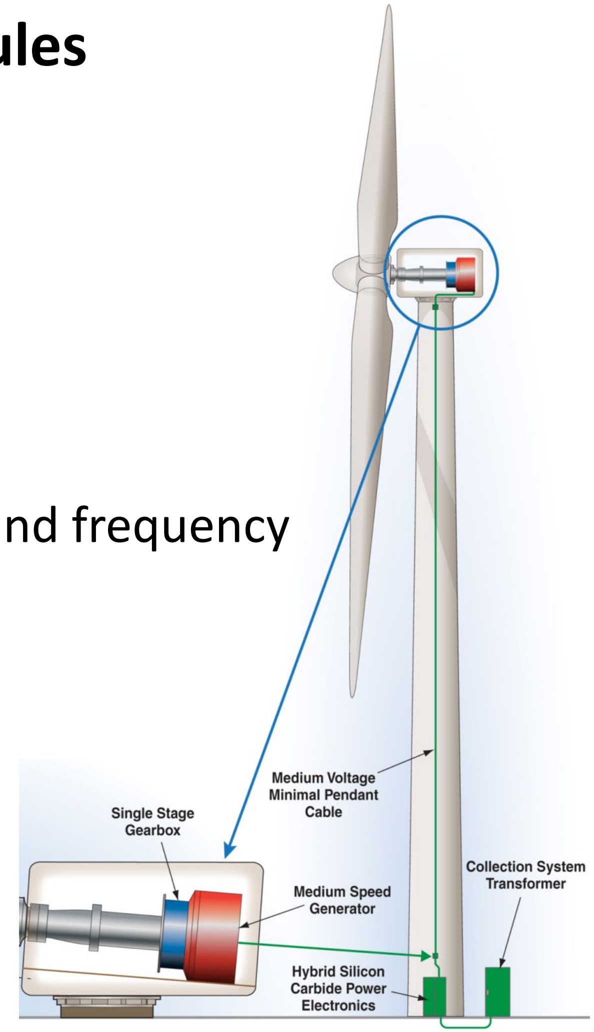
NGD Design – Power Converter

- **Medium-voltage, 3-level neutral point clamp design with hybrid Silicon/Silicon-Carbide (Si/SiC) modules**
  - Increase efficiency and energy production
  - Lower temperatures increase reliability
    - May reduce or eliminate tower cooling
  - Decrease pendant cable size and cost
- **Inverter utility control algorithms**
  - Increase drivetrain reliability and support voltage and frequency



Silicon Carbide diodes.
Photo by CREE

Medium-voltage hybrid module.
Photo by Powerex

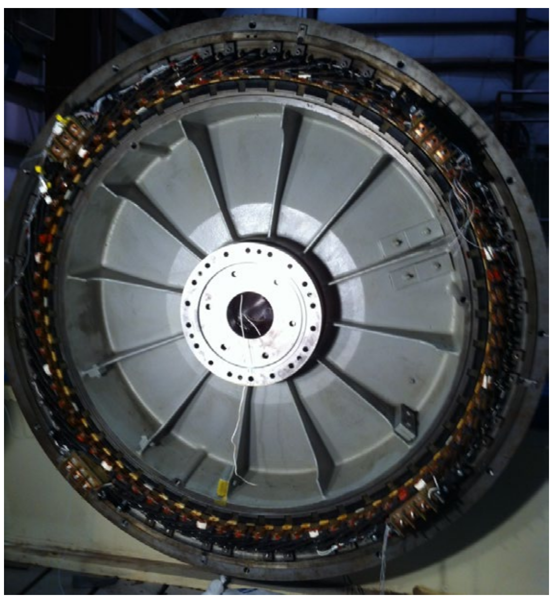


NGD wind turbine concept.
Illustration by Al Hicks, NREL

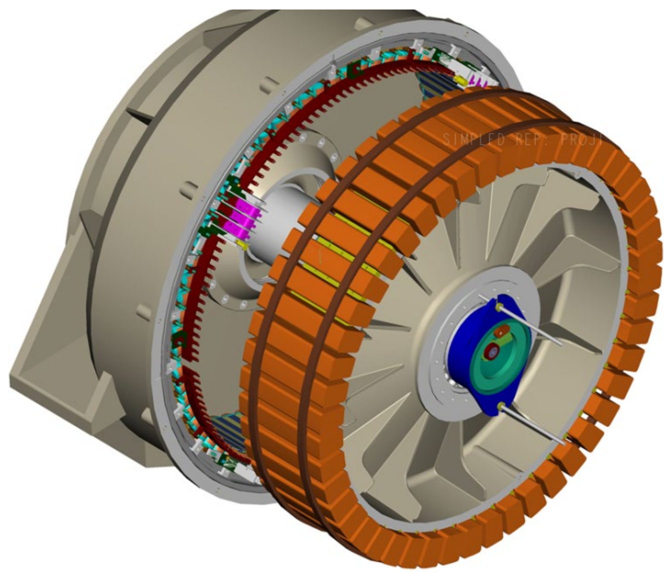
NGD Design - Generator

- **Permanent Magnet (from WindPACT Program)**
  - Medium-speed and medium-voltage†
  - Concentrated windings decrease manufacturing cost
  - Segmented stator decreases O&M cost

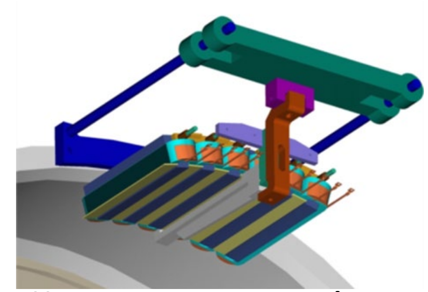
†Not part of Phase II design, build and test program



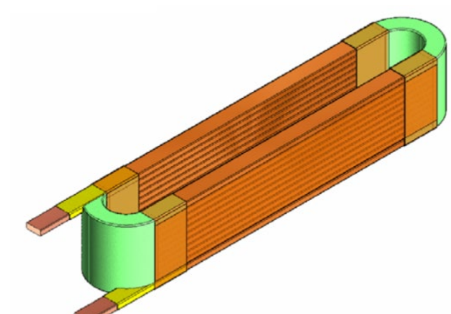
Generator rotor.
Photo by Jon Keller, NREL 33343



Uptower rotor extraction.
Illustration by
Global Energy Concepts



Uptower stator extraction.
Illustration by
Global Energy Concepts



Edge-wound concentrated winding.
Illustrations by Global Energy Concepts

Agenda

- ✓ **Next-generation drivetrain architecture**
- **Drivetrain technology development and testing**
  - Gearbox and power converter software
  - Medium voltage hybrid modules
- **Summary**

Dynamometer Testing

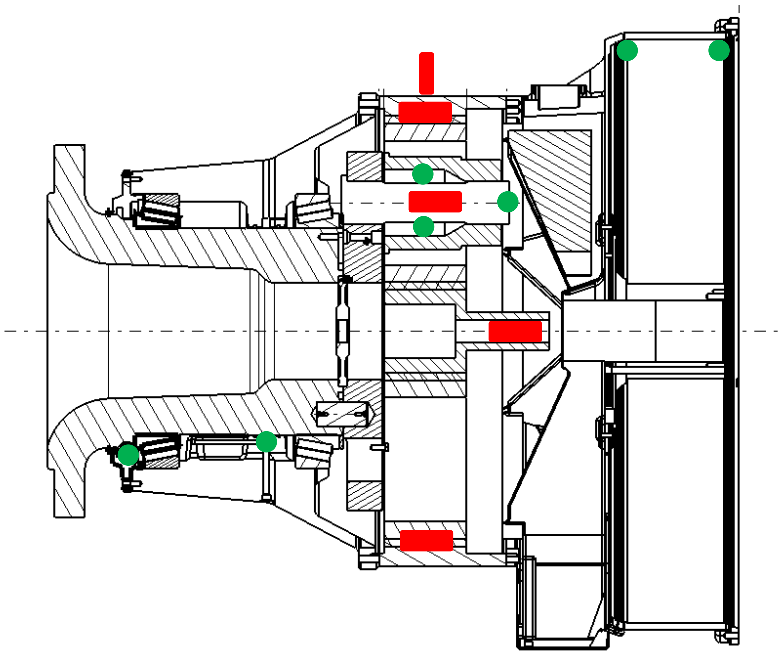
- **Gearbox journal bearing and flex pin robustness**
  - Validate load sharing behavior
  - Determine wear in rotor start-stop and dither conditions
- **Inverter utility fault control effectiveness**
  - Use Controllable Grid Interface (CGI) to emulate grid faults
  - Validate torque oscillation reduction

Next generation drivetrain.
Photo by Jon Keller, NREL 35206

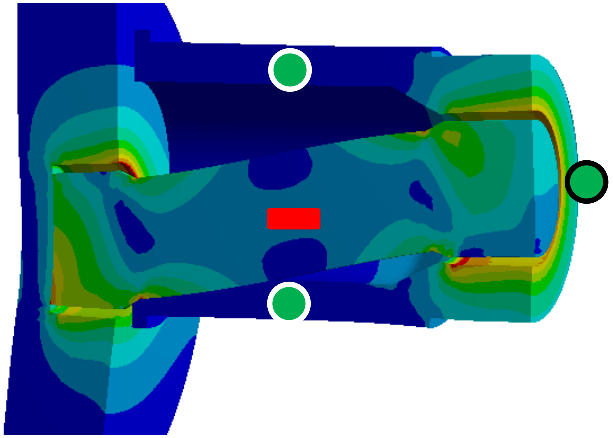
Controllable grid interface.
Photo by Mark McDade, NREL 29069

Flex Pin and Journal Bearing Tests

- **Planetary loads**
  - Generator torque
  - Ring gear tooth load (4 locations, 8 tooth gauges)
  - Flex pin bending strain (4 pins)
  - Gearbox vibration
- **Journal bearing operations**
  - Oil supply pressure and temperatures
  - Oil particle count and oil analysis
  - Journal temperatures and wear inspection
- **Dynamometer and grid conditions**
  - Speed, torque, etc.
  - Active and reactive power
  - Grid frequency
  - Inverter phase voltages and currents

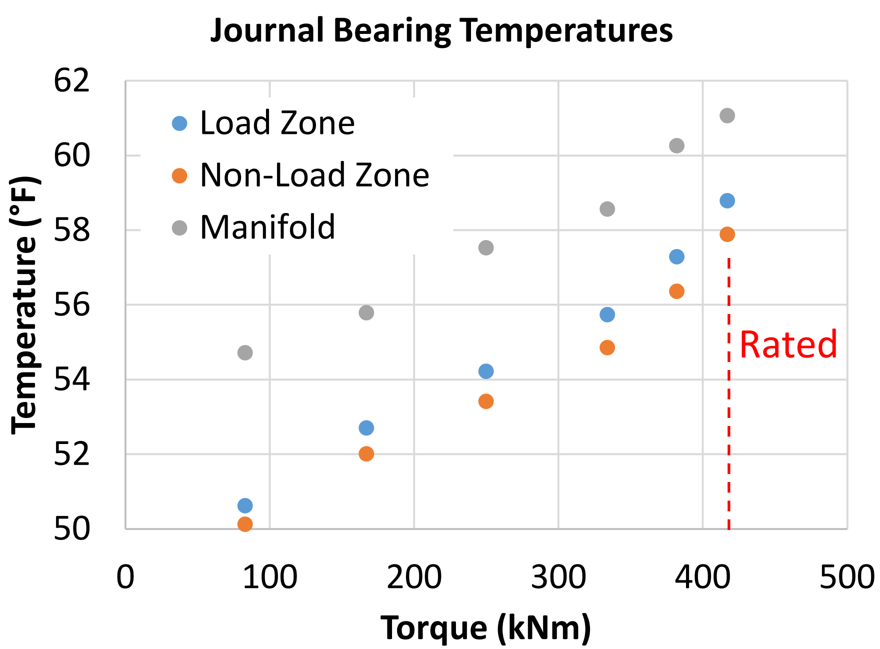


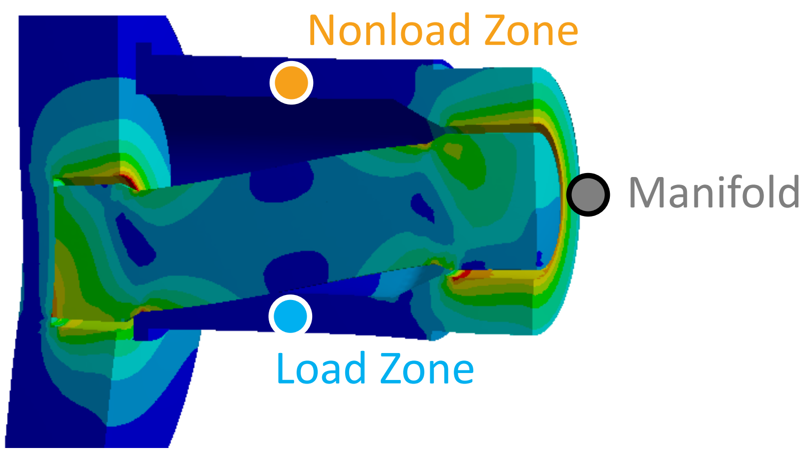
NGD instrumentation. Illustration by Romax Technology



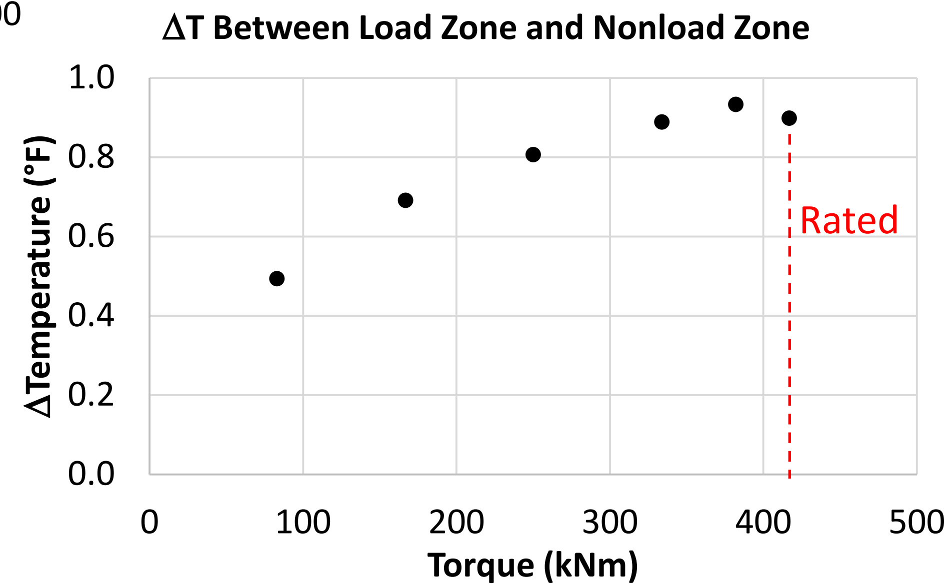
Flex pin stresses. Illustration by Romax Technology

Journal Bearing Temperature





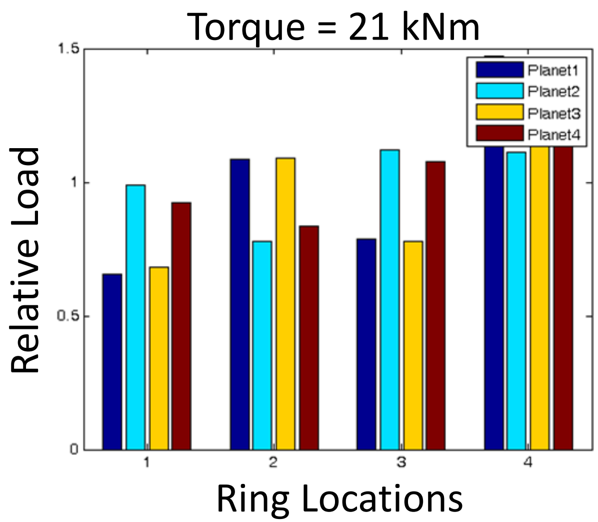
Journal Temperatures.
Illustration by Romax Technology

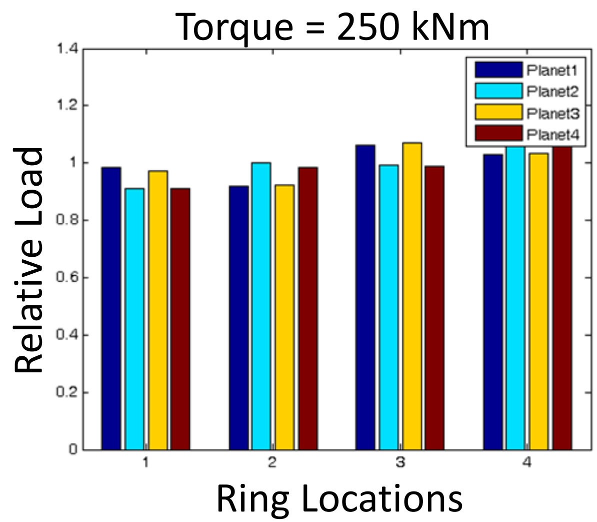


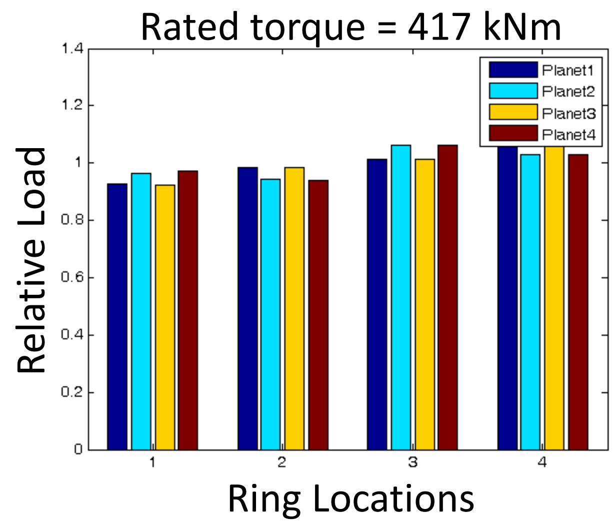
Temperature equilibrium point at higher torque where loaded and nonloaded sides maintain a temperature differential. Temperatures are the steady-state average of all four pins.

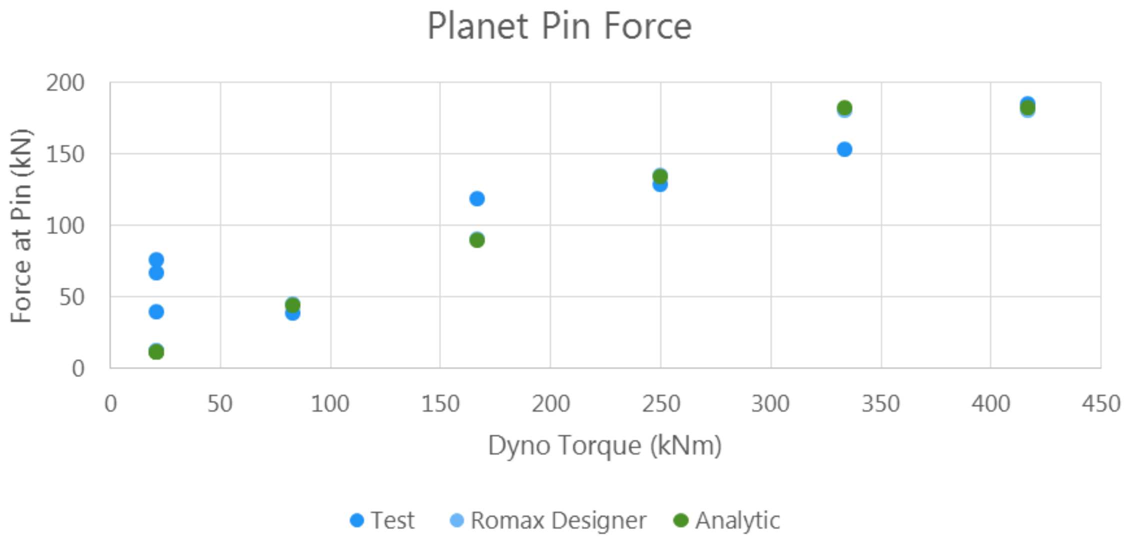
Planetary Load Share

- **As torque increases, flex pins balance loads**





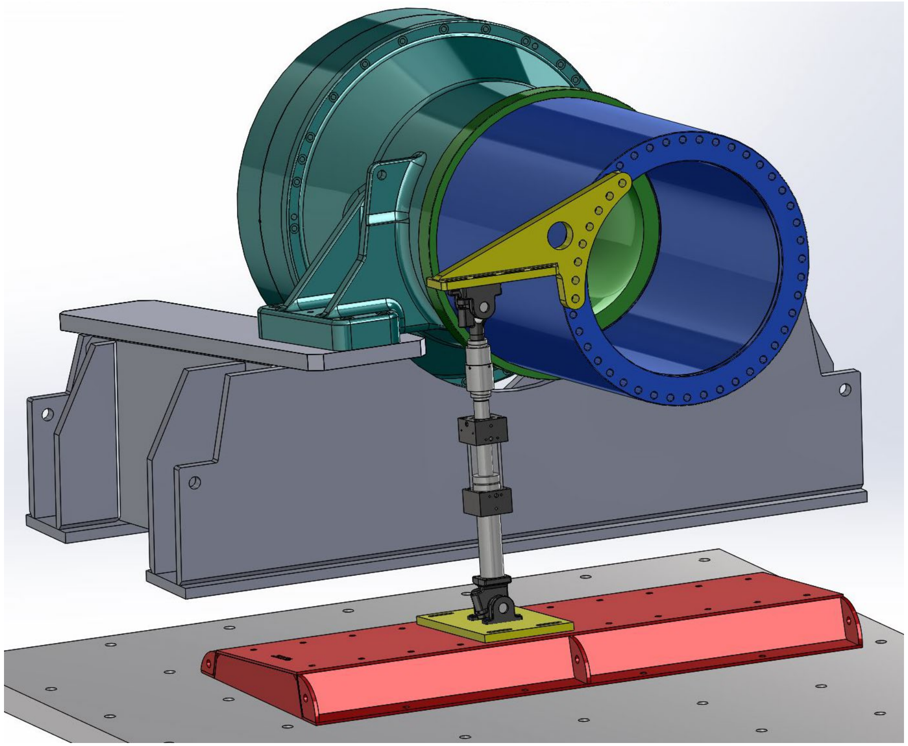




Measured planet pin forces correlate with design values, especially at higher torque.

Upcoming Gearbox Tests

- **Start-stop tests**
  - 5,000 cycles from 0 to 10 RPM in 10 seconds
- **Rotor dither tests**
  - Unlocked: 14,400 cycles over ±5° at 1/6 Hz
  - Locked: 86,400 cycles over ±¼° at 1 Hz

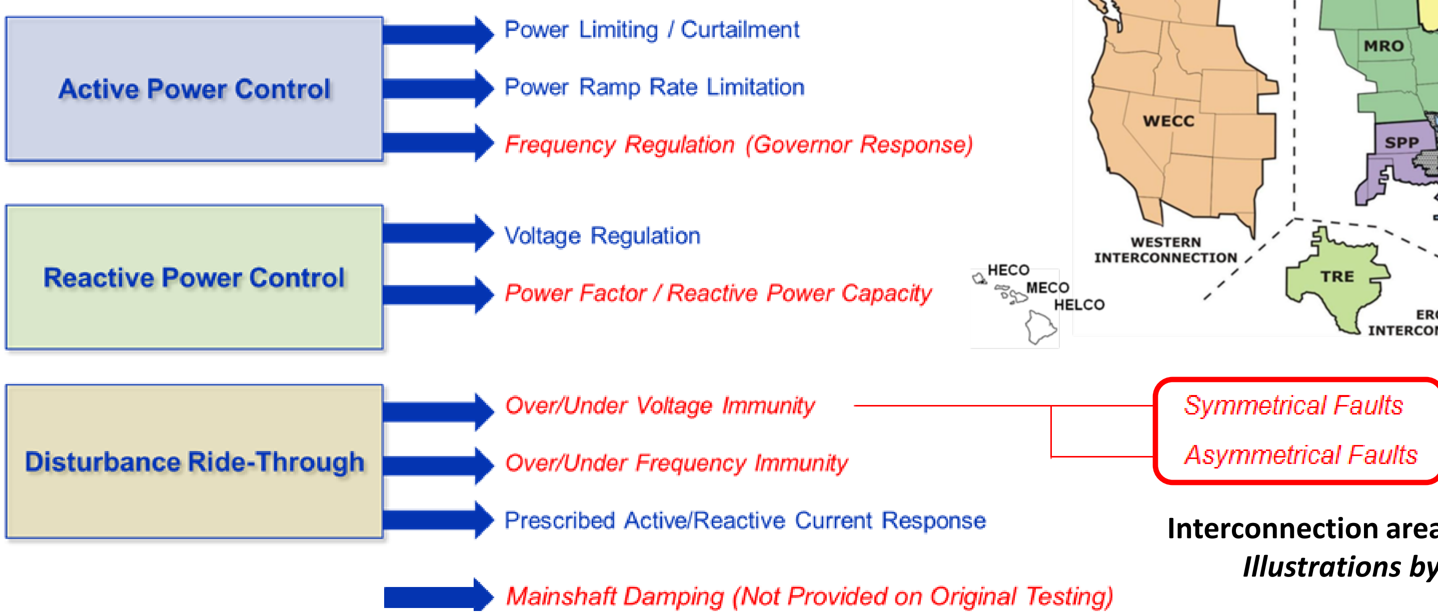


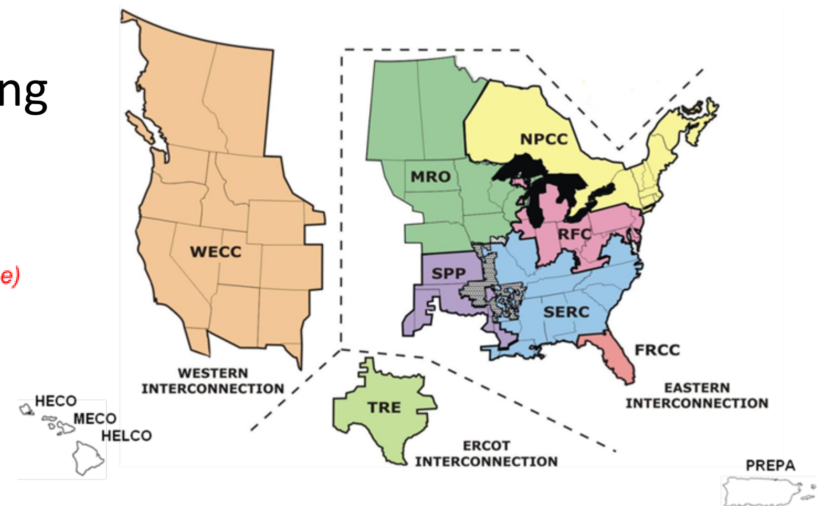
Rotor dither test setup.
Illustration by Lambert Engineering

- **Post-Test Teardown Inspection**
  - Spindle and journal bearing surfaces
  - Sun, planet, and ring gear contact patterns

Utility Faults

- **Grid interconnection requirements reviewed**
  - Eastern and Western U.S. Interconnections, ERCOT, HECO, and PREPA
- **Requirements impacting drivetrain selected for mitigation via power converter control algorithms**
  - Symmetrical and asymmetrical grid fault responses
  - Frequency deviation response
  - Main shaft torsional mode active damping



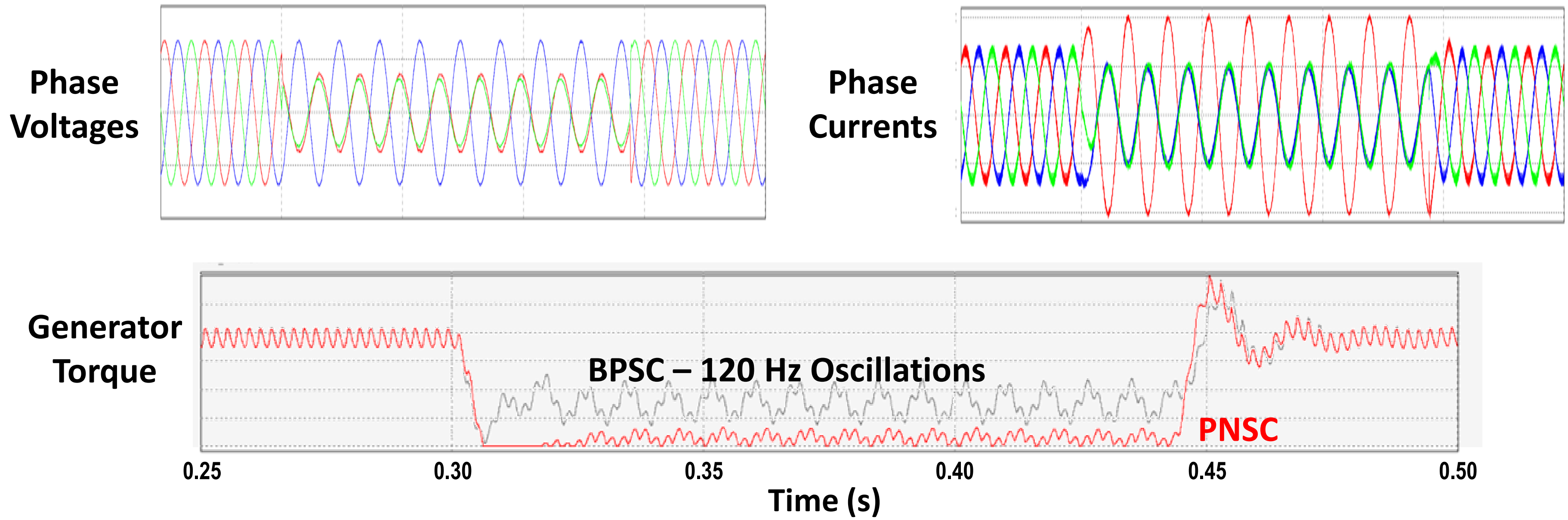


Interconnection areas and fault types.
Illustrations by DNV KEMA

Asymmetrical Fault Control

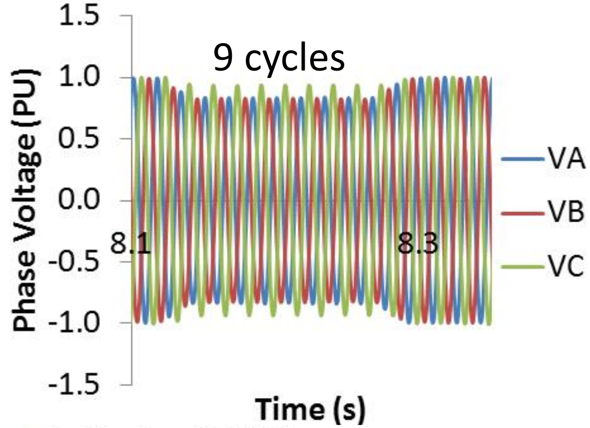
- **Traditionally via Positive Sequence Current (PSC) regulator**
  - Reference currents that are sinusoidal and balanced (BPSC)
  - Results in 120 Hz power oscillations under unbalanced voltage conditions
  - Power oscillations result in gearbox torque oscillations
- **New Positive-Negative Sequence Current (PNSC) regulator**
  - Unbalanced currents reduce 120 Hz power and torque oscillations

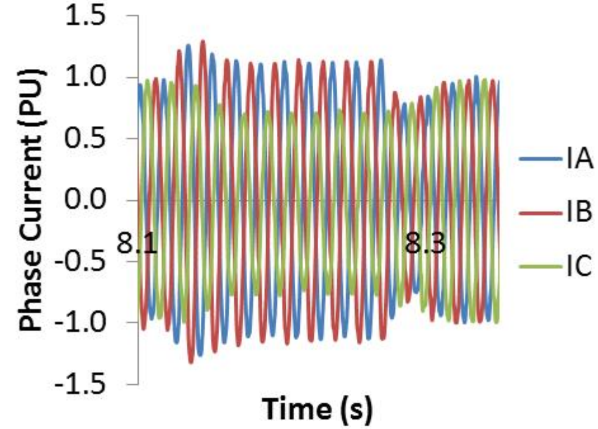
Simulation of Phase-to-Phase Fault at High Side of PadMount Transformer

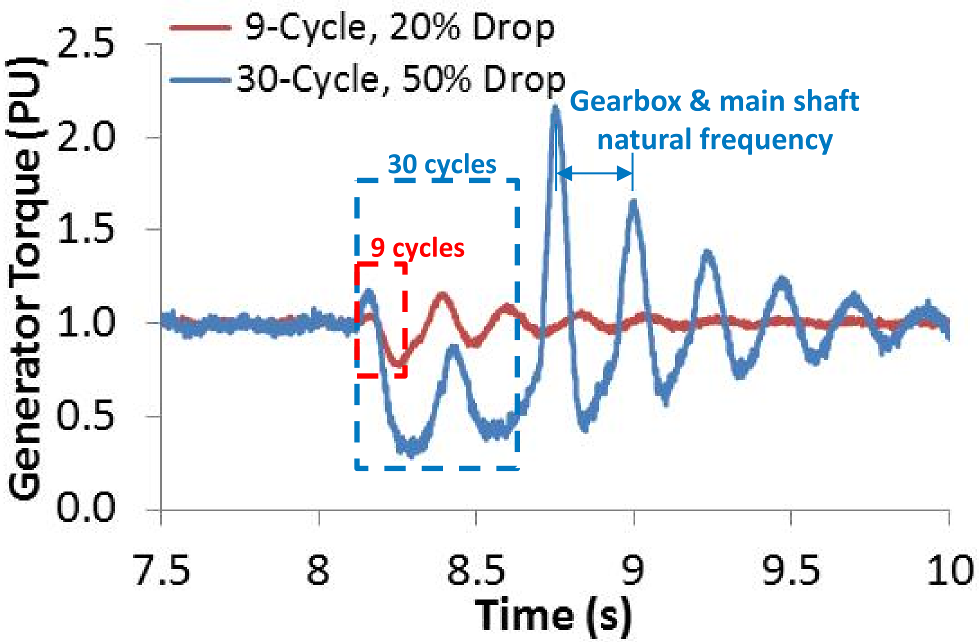


Example Asymmetric Fault Test

- **2-phase faults, PNSC damping not enabled yet**







Drop of 20% voltage = ±20% torque

Drop of 50% voltage = +117% torque

Drop of 80% voltage = ?? torque

IEC 61400-21, Table 1, Case VD1-3

Fault Control Comments and Caveats

- **Fault torques highly dependent on drivetrain technology**
  - Full conversion, passive rectifier (NGD topology)
    - Probably least severe fault torques
    - NGD measurements made for validation and commercialization purposes
  - Full conversion, active rectifier
  - Partial conversion, doubly-fed induction generator
    - Probably most severe due to direct utility connection of stator circuit

Worthy of future study

- **Implementing PNSC with non-unity power factor may be complicated with certain (European) standards.**

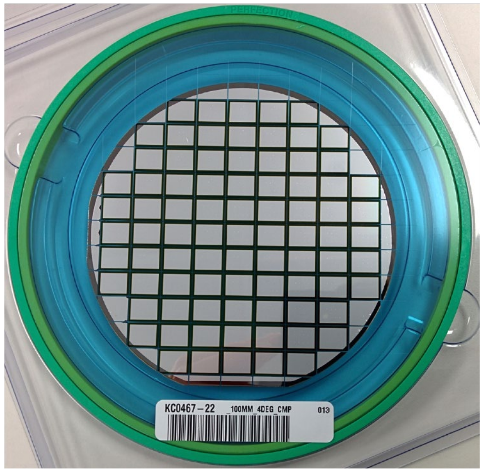
Agenda

✓**Next-generation drivetrain architecture**

- **Drivetrain technology development and testing**
  - ✓Gearbox and power converter software
  - o Medium voltage hybrid modules
- **Summary**

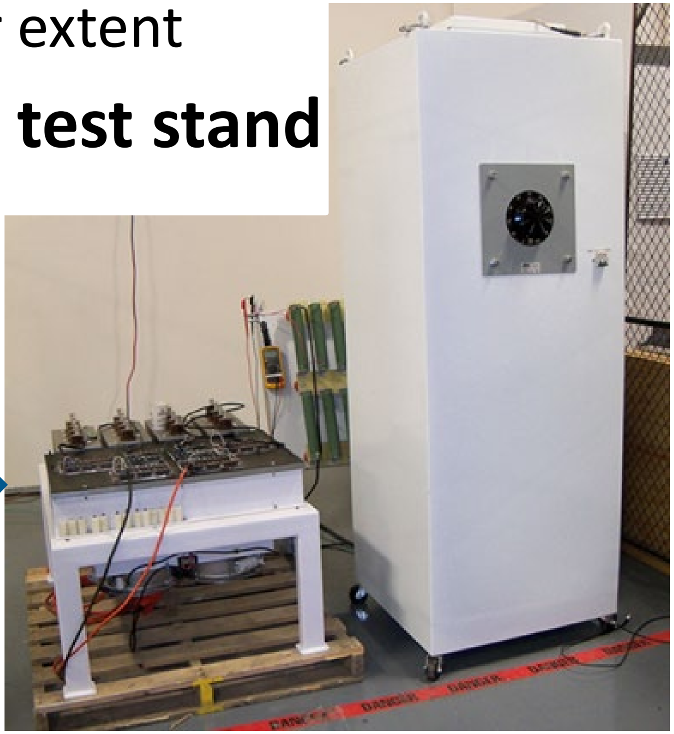
Hybrid Si/SiC Inverter Module Testing

- **Manufacture 4.5kV SiC barrier diodes**
- **Install SiC barrier diodes in commercial Si modules**
  - Hybrid diode module in clamping location provides largest reduction in converter switching losses
  - IGBT module reduces losses to a lesser extent
- **Test hybrid Si/SiC modules in 5 kV test stand**
  - Validate switching loss reduction



10 mm x 8 mm 4.5 kV/40A SiC barrier diodes.
Photo by CREE

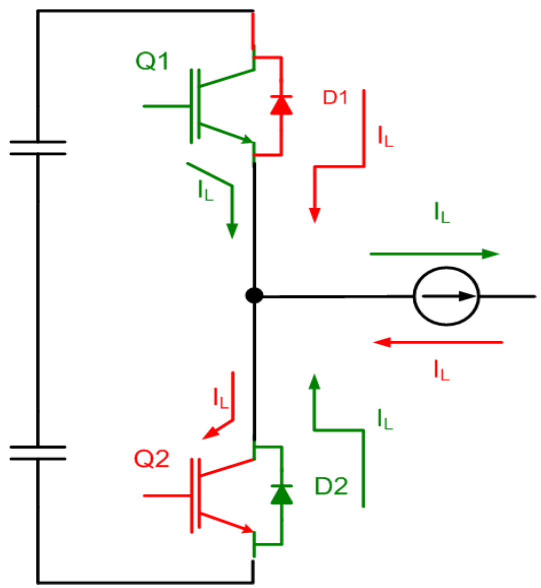
Medium-voltage hybrid module.
Photo by Powerex

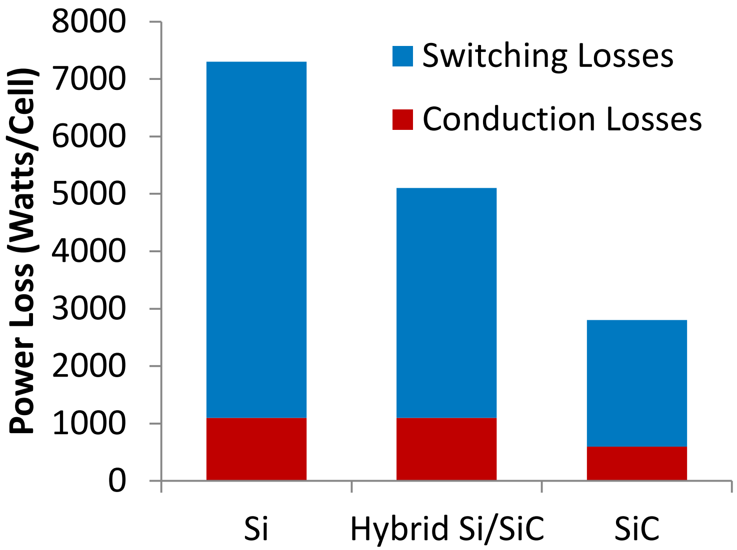


2.3 MW medium voltage module test stand.
Photo by DNV KEMA

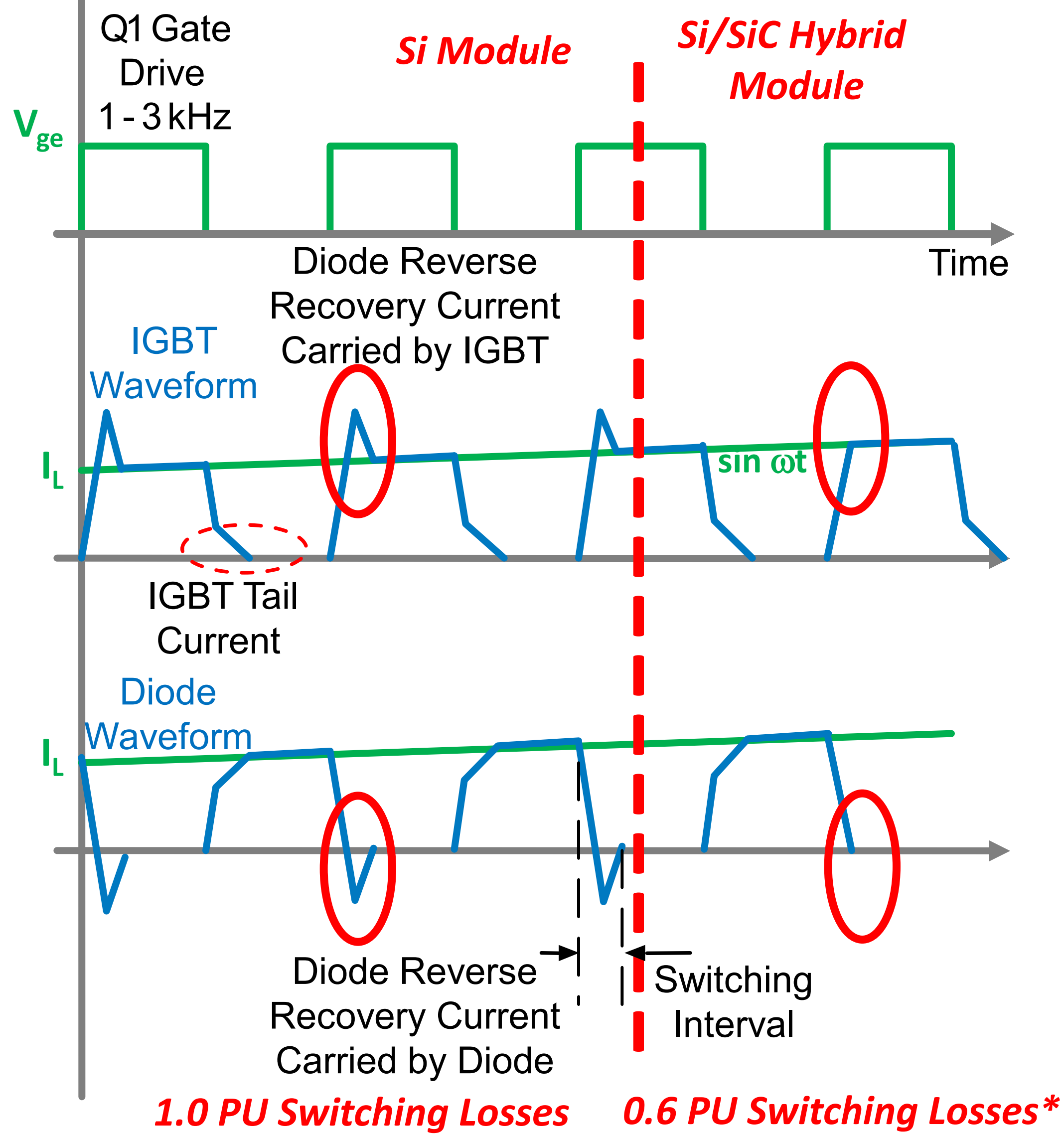
Switching Waveforms and Losses

Single Phase of Two-Level Inverter



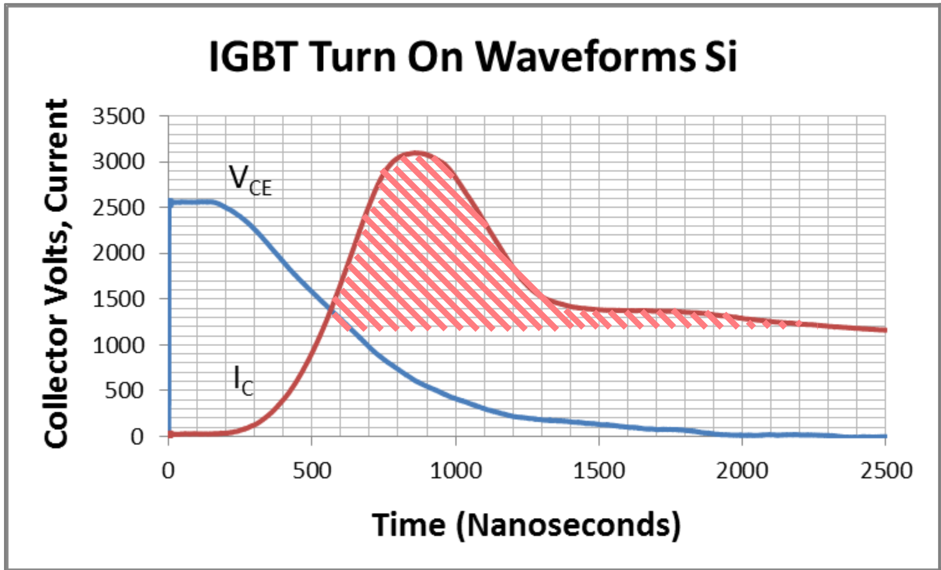


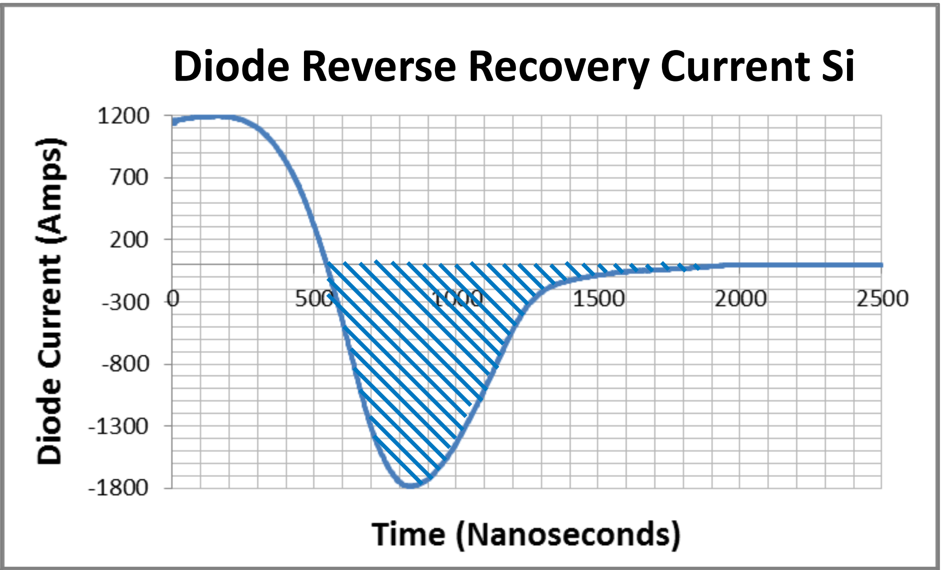
Substitute SiC Diode for Si Diode Only

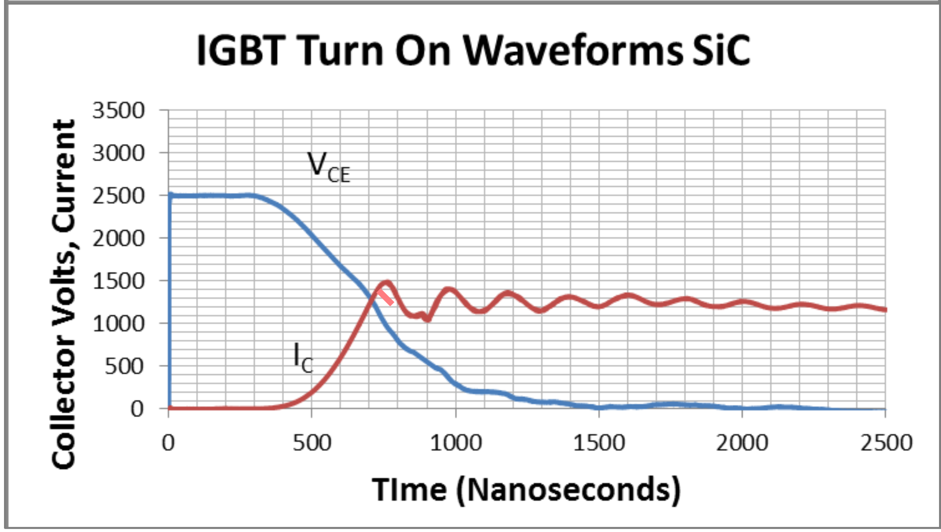


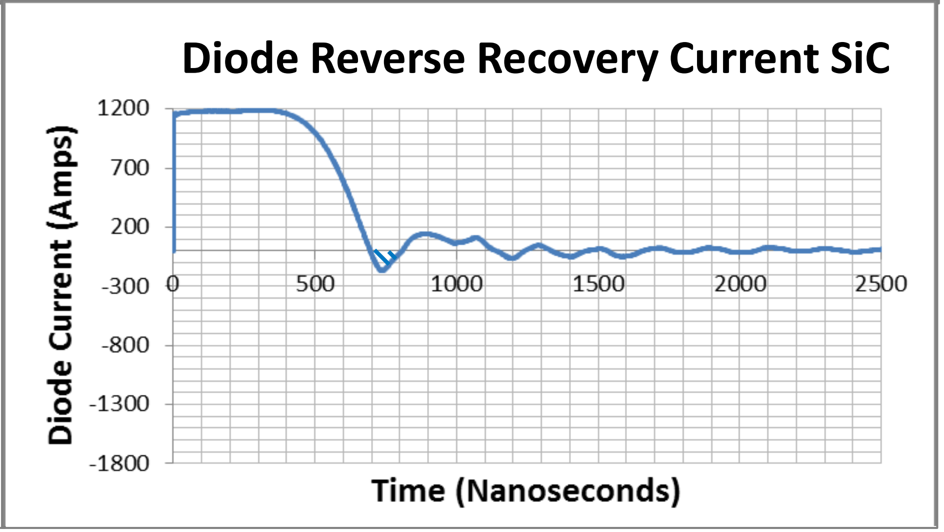
Switching Waveform Results

- IGBT Turn-On, Diode Turn-Off at 1,200 Amps

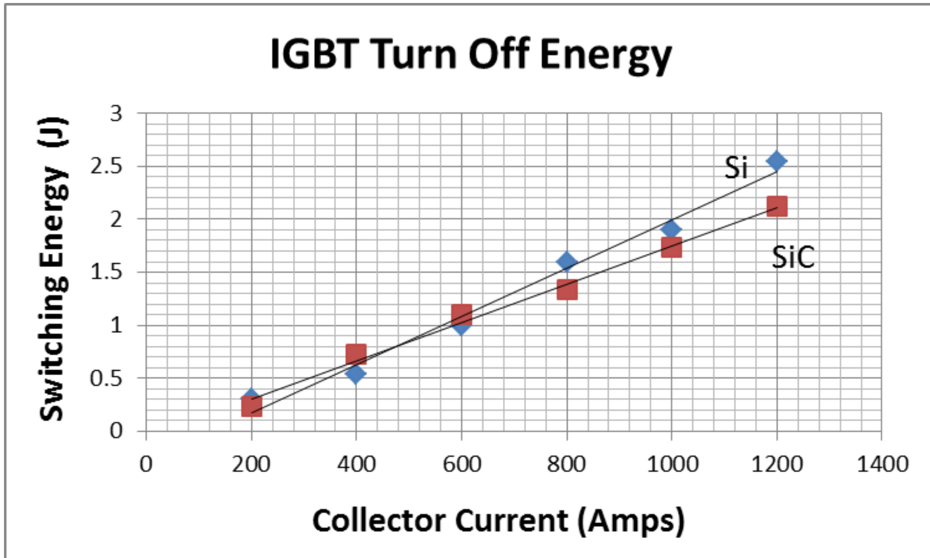


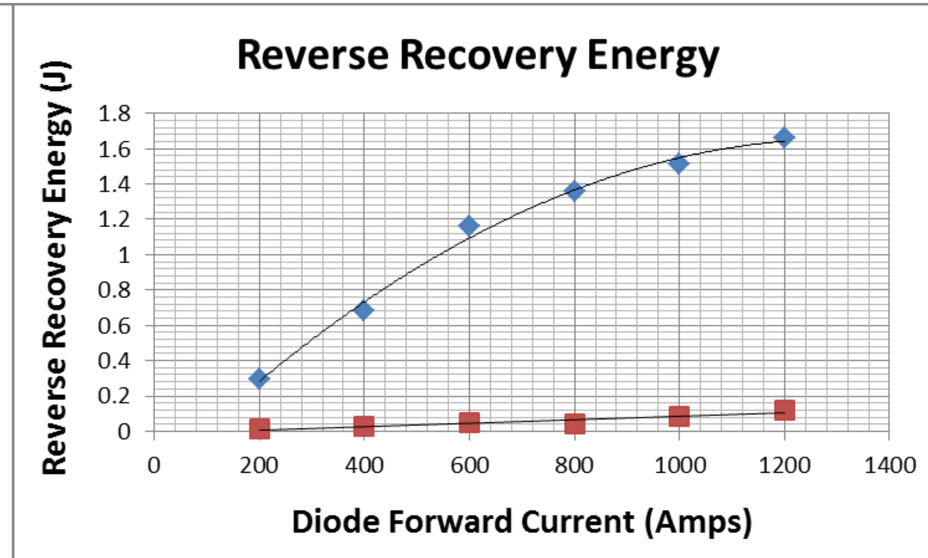


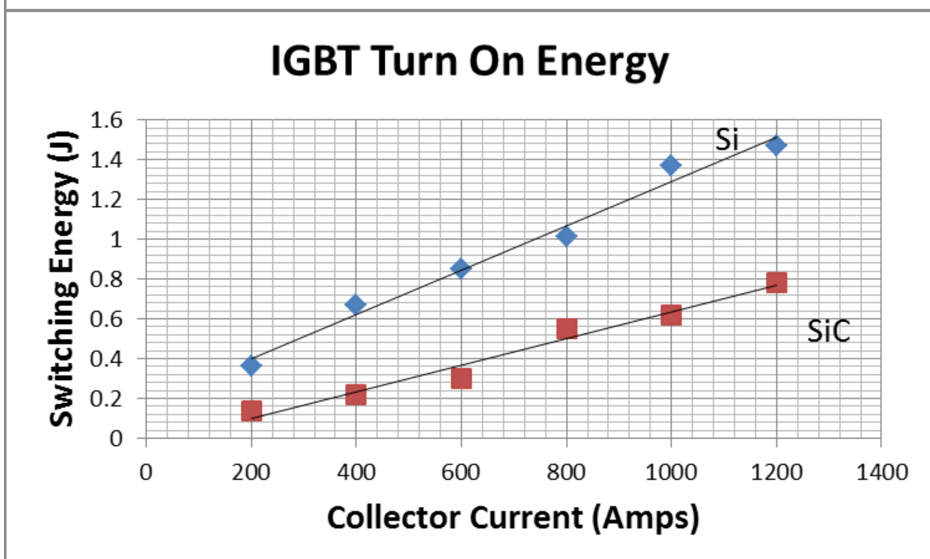




Switching Energy Results







Inductive Load, 3-Level NPC Circuit

Test Conditions:

V_{cc} = ±2,500 V, V_{ge} = +15/-7 V

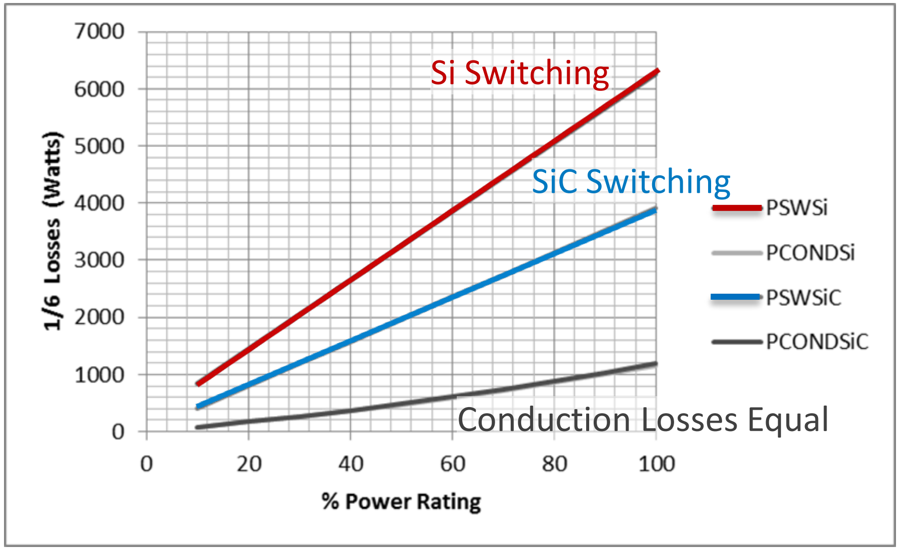
R_{gon} = R_{goff} = 2 Ω

T_{case} = 85 °C

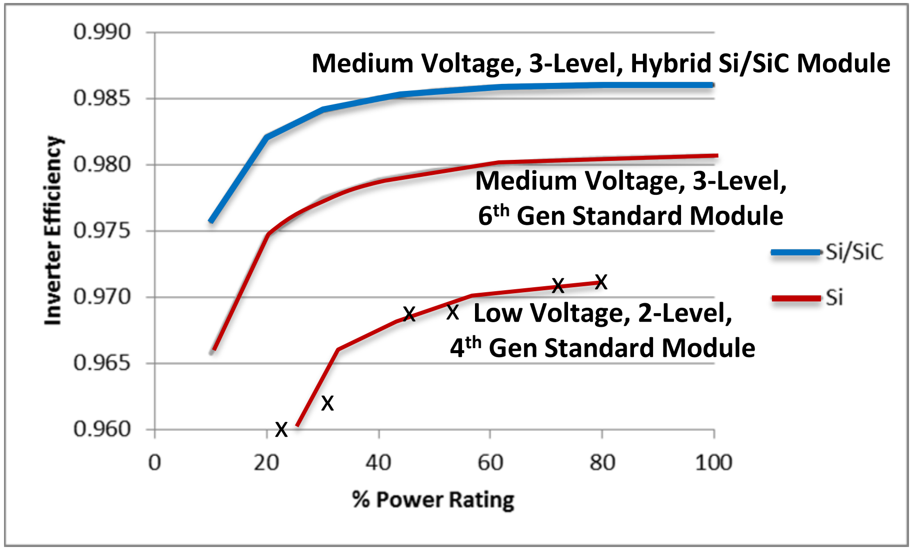
Inverter Loss and Efficiency Estimates

- **Switching losses reduced up to 12.6 kW with hybrid modules**
  - 2.1 kW per cell for 6 cells sized for 2.3-MW inverter
- **Conduction losses essentially the same**

Inverter Losses[1]



Inverter Efficiency



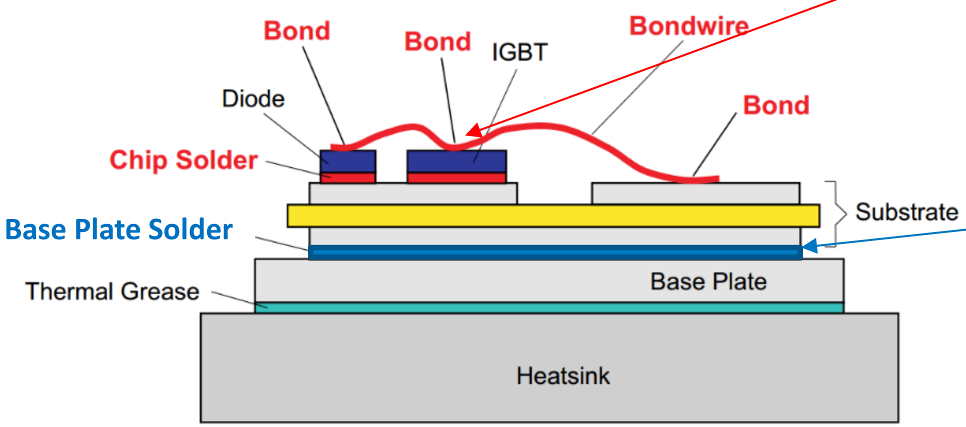
X – Inverter Efficiency Data Taken at NREL in 2007

100% Corresponds to 400 A, 3.3 kV, 5 kV_{DC}, f_s = 1 kHz, Unity Power Factor, and 2.3 MW

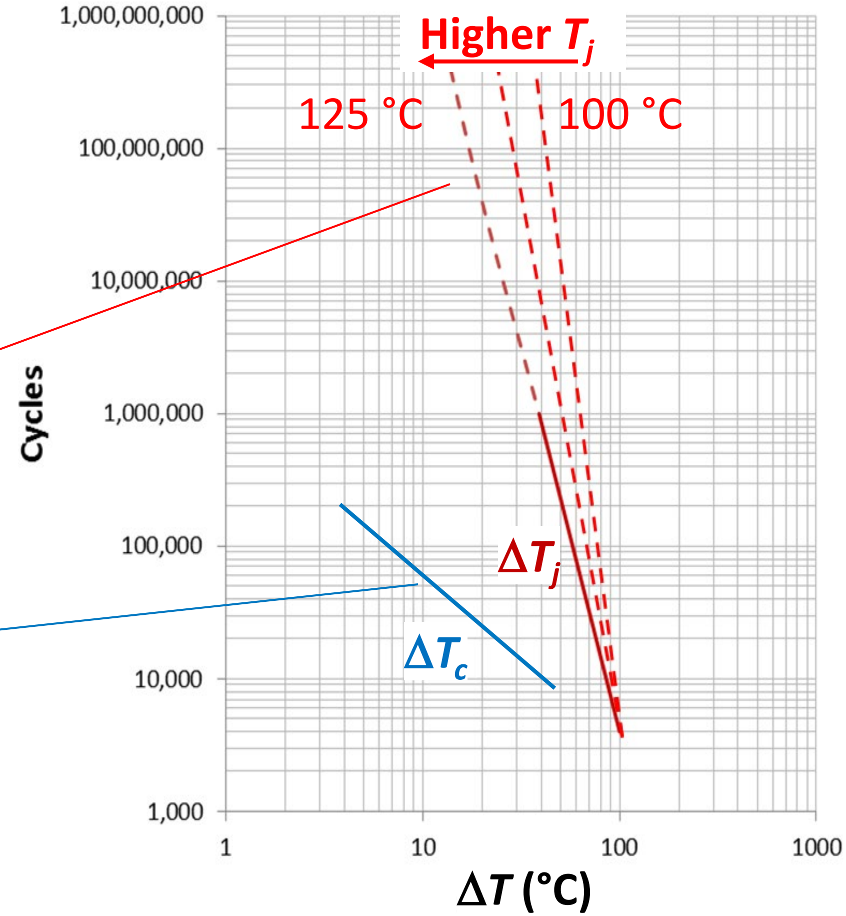
[1]Tomta, G., and Nielsen, R., “Analytical Equations for Three Level NPC Converters”, 9th European Power Electronics Conference Proceedings, EPE 2001.

Module Reliability

- **Increasing efficiency reduces inverter and module temperatures**
- **Reducing module temperatures increases their reliability**
- **Module reliability related to 3 factors:**
  - Junction average temperature, T_j
  - Junction temperature change over power cycle, ΔT_j
  - Case temperature thermal cycle change, ΔT_c



Module Cross Section



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- **Drivetrain technology development and testing**
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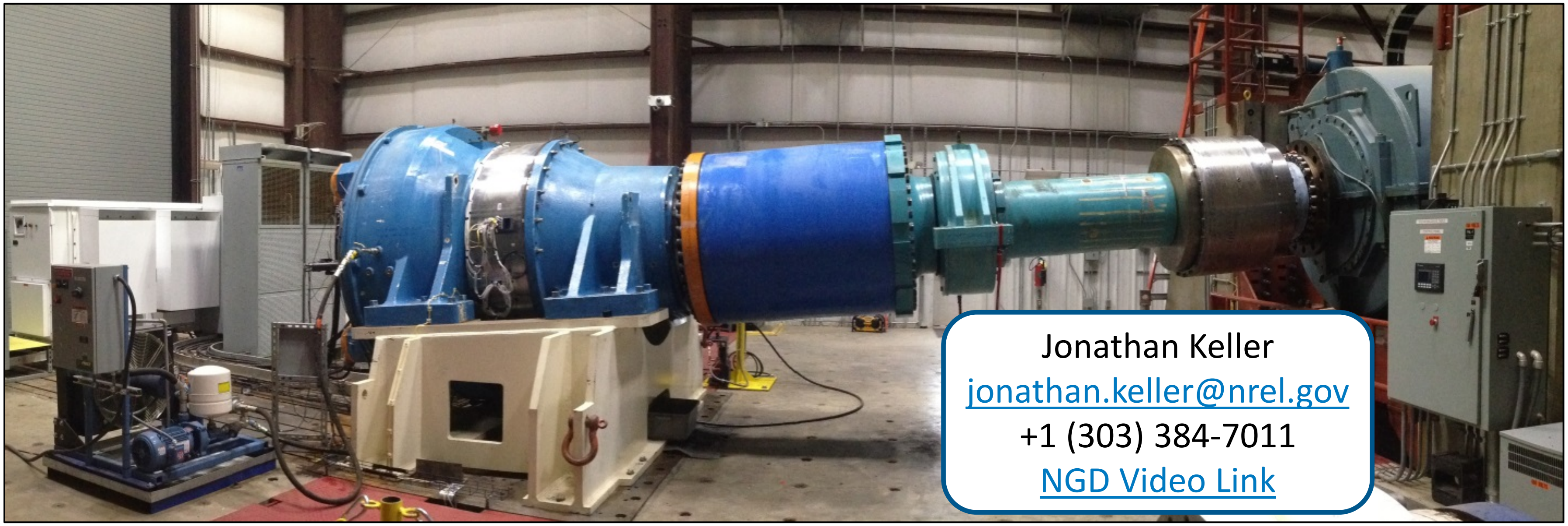
  - ✓Medium voltage hybrid modules
- **Summary**

Summary

- **Medium-speed, medium-voltage drivetrain developed**
  - Main bearing, gearbox, generator, and inverter innovations
  - Paper study showed reductions in CAPEX, OPEX and COE
- **Technology test program is assessing key innovations**
  - Gearbox flex pin load sharing and journal bearing performance
  - Inverter utility fault control algorithm effectiveness
  - Hybrid Si/SiC module efficiency



Next generation drivetrain. ***Photo by Jon Keller, NREL 35206***

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NGD Video Link

Acknowledgments and NGD Project Team

Funding

U.S. Department of Energy
FOA # DE-FOA-0000439

Prime contractor, testing and COE Analysis

National Wind Technology Center (NWTC) at NREL

Technology design, manufacturing, engineering analysis and licensing

Gearbox and Journal Bearings	Hybrid Power Converter Modules	Utility Fault Control Algorithms
Romax Technology	**CREE**	**The Cinch**
Miba	**Wolfspeed**	**DNV GL**
	Powerex	

Interested Cost Share Partner
Vattenfall