Next Generation Drivetrain Development and Test Program

Drivetrain Concepts for Wind Turbines
6th International Conference

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Agenda

• Next-generation drivetrain architecture

• Drivetrain technology development and testing
  o Gearbox and inverter software
  o 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).

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.

Similarities to:
- Winergy HybridDrive
- Moventas/The Switch FusionDrive
- ZF Wind Power etc.
NGD Design – Main Bearings

• Double tapered roller bearings *(from WindPACT Program)*
  o Support rotor axial loads and moments
  o Support planetary carrier
  o Oil lubricated
• Single-stage planetary gearbox†
  o Mechanical simplicity and journal bearings increase reliability
  o 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
  o Increase efficiency and energy production
  o Lower temperatures increase reliability
    – May reduce or eliminate tower cooling
  o Decrease pendant cable size and cost

• Inverter utility control algorithms
  o 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)
  
  o Medium-speed and medium-voltage†
  
  o Concentrated windings decrease manufacturing cost
  
  o Segmented stator decreases O&M cost

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

• Gearbox journal bearing and flex pin robustness
  o Validate load sharing behavior
  o Determine wear in rotor start-stop and dither conditions

• Inverter utility fault control effectiveness
  o Use Controllable Grid Interface (CGI) to emulate grid faults
  o 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
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

Torque = 21 kNm
Torque = 250 kNm
Rated torque = 417 kNm

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

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

• Grid interconnection requirements reviewed
  o Eastern and Western U.S. Interconnections, ERCOT, HECO, and PREPA

• Requirements impacting drivetrain selected for mitigation via power converter control algorithms
  o Symmetrical and asymmetrical grid fault responses
  o Frequency deviation response
  o Main shaft torsional mode active damping

Active Power Control
- Power Limiting / Curtailment
- Power Ramp Rate Limitation
- Frequency Regulation (Governor Response)

Reactive Power Control
- Voltage Regulation
- Power Factor / Reactive Power Capacity

Disturbance Ride-Through
- Over/Under Voltage Immunity
- Over/Under Frequency Immunity
- Prescribed Active/Reactive Current Response
- Mainshaft Damping (Not Provided on Original Testing)

Interconnection areas and fault types.
Illustrations by DNV KEMA
Asymmetrical Fault Control

• Traditionally via Positive Sequence Current (PSC) regulator
  o Reference currents that are sinusoidal and balanced (BPSC)
  o Results in 120 Hz power oscillations under unbalanced voltage conditions
  o Power oscillations result in gearbox torque oscillations

• New Positive-Negative Sequence Current (PNSC) regulator
  o Unbalanced currents reduce 120 Hz power and torque oscillations

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

Phase Voltages

Phase Currents

Generator Torque

BPSC – 120 Hz Oscillations

PNSC
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
  o Full conversion, passive rectifier (NGD topology)
    – Probably least severe fault torques
    – NGD measurements made for validation and commercialization purposes
  o Full conversion, active rectifier
  o Partial conversion, doubly-fed induction generator
    – Probably most severe due to direct utility connection of stator circuit

• Implementing PNSC with non-unity power factor may be complicated with certain (European) standards.
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Hybrid Si/SiC Inverter Module Testing

• Manufacture 4.5kV SiC barrier diodes

• Install SiC barrier diodes in commercial Si modules
  o Hybrid diode module in clamping location provides largest reduction in converter switching losses
  o IGBT module reduces losses to a lesser extent

• Test hybrid Si/SiC modules in 5 kV test stand
  o 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

Power Loss (Watts/Cell)

- **Switching Losses**
- **Conduction Losses**

![Diagram of Single Phase of Two-Level Inverter]

Substitute SiC Diode for Si Diode Only

- *Si Module*
- *Si/SiC Hybrid Module*

Q1 Gate Drive 1 - 3 kHz

Power Loss (Watts/Cell)

1.0 PU Switching Losses

0.6 PU Switching Losses*

Diode Reverse Recovery Current Carried by IGBT

IGBT Tail Current

IGBT Waveform

Diode Waveform

Diode Reverse Recovery Current Carried by Diode

Switching Interval

1.0 PU Switching Losses

0.6 PU Switching Losses*
Switching Waveform Results

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

IGBT Turn On Waveforms Si

Diode Reverse Recovery Current Si

IGBT Turn On Waveforms SiC

Diode Reverse Recovery Current SiC
Inductive Load, 3-Level NPC Circuit

Test Conditions:
- $V_{cc} = \pm 2,500\ \text{V}$, $V_{ge} = +15/-7\ \text{V}$
- $R_{gon} = R_{goff} = 2\ \Omega$
- $T_{case} = 85\ \degree\text{C}$
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

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

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, $\Delta T_j$
  - Case temperature thermal cycle change, $\Delta T_c$
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• Medium-speed, medium-voltage drivetrain developed
  o Main bearing, gearbox, generator, and inverter innovations
  o Paper study showed reductions in CAPEX, OPEX and COE

• Technology test program is assessing key innovations
  o Gearbox flex pin load sharing and journal bearing performance
  o Inverter utility fault control algorithm effectiveness
  o Hybrid Si/SiC module efficiency

Next generation drivetrain. Photo by Jon Keller, NREL 35206

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NGD Video Link
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Gearbox and Journal Bearings

Hybrid Power Converter Modules

Utility Fault Control Algorithms

Romax Technology

CREE

The Cinch

Miba

Wolfspeed

DNV GL

Powerex

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