10kV Integrated SiC VSD and High-Speed Motor for Gas Compression Systems

DE-EE0007253

Energy Efficiency & Renewable Energy

BP1 & BP2 8/1/2016 – 10/31/2018

Eaton Corporation
Geraldo Nojima
& Steven Castelein

U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
July 17-19, 2018

Overview

Timeline

- DOE-NGEM Award issued August 2016
- Projected End date October 2019
- Project 63% complete

Barriers

- Performance 10kV SiC Modules
- Ancillary components
- Control HS-PMSM Motor
- EMI: dV/dt≥100kV/µsec & di/dt≥30kA/µsec

Budget

	BP1 Costs 8/1/2016-10/31/2017	BP2 Costs 11/1/2017-10/31/2018	BP3 Costs 11/1/2018-10/31/2019	Total Planned Funding 8/1/2018-10/31/2019
DOE Funded	2.6M	2.4M	0.4M	5.3M
Project Cost Share	0.7M	0.6M	0.1M	1.3M
Cost Incurred	2.9M	1.1M	-	4.0M

Partners

- Cree – SiC Devices and Modules
- Calnetix – High Speed Permanent Magnet Synchronous Motor
- Carnegie Mellon University – Nano Crystalline Magnet Materials
- North Caroline University – Control Hardware in the Loop, Saber Simulations, Dies and Gate Driver evaluations
- Novus – Systems Engineering
- PWP – System Simulation and Control Hardware in the Loop
- Petrobras – end-user, application & standards guidance

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Project Objective(s)

The Object of this Project for Energy Efficiency Improvement

- Megawatt-class high-speed gas compressor systems are essential to several key industries. In their applications, size and efficiency have been essentially unchanged for decades particularly due to the use of step-up gearboxes. The end users are interested in reducing system footprint and volume, lower maintenance costs and significantly increase energy efficiency and reliability.

Relevance of this work to energy use and efficiency in the manufacturing sector

- This project aims to: increase efficiency by several percentage points, increase system reliability, significantly reduce maintenance costs and reduce structural requirements and cost by reducing the size of multi-megawatt-class high-speed gas compressors.
- The DOE-NGEM energy efficiency increase requirement is a minimum of 3%. Eaton is aiming at a 6% gain.

Intended benefits

- The energy savings are significant considering the 3% to 6% percent gain on gas compressor systems that are usually multi-megawatt in size. Other fringe benefits are: the huge system reliability gain by eliminating the high speed gearbox with its lubrication system which together with the targeted motor size reduction by a factor of eight will reduce the overall system footprint and volume.

Challenges

- Wide bandgap high voltage semiconductor modules are novel and relatively untested. Their capabilities are much higher than those of a state-of-the-art silicon based semiconductor module which brings several challenges regarding measurement, control, electromagnetic interference and dielectric compatibility. These semiconductor modules are essential to achieve the goals outlined above.

Technical Innovation

State-of-the-art and current limitations

- State-of-the-art multi-megawatt-class high speed gas compressor solutions require the use of a large low speed (1,800rpm) induction motor coupled to a gear box which carries a significantly sized lubrication system. The typical power level of an offshore gas compressor is 11MW delivered at 15,000rpm. The motor size is proportional to the torque it delivers at its nominal speed and the lubrication system will consume around 10% of the energy besides creating another point of system failure.
- Today's typical compressor system has 14m^3/MW inverse volumetric power density and 7.5m^2/MW footprint with an efficiency of 90%.

Eaton approach

- The planned approach is to use a megawatt-class, medium-voltage, four pole motor with a speed increased from 1,800rpm to 15,000rpm controlled by a novel adjustable speed drive with a fundamental frequency of 500Hz that allows the motor shaft to be coupled directly to the compressor's, effectively eliminating the need for a step-up megawatt-class gearbox and its lubrication system. The motor size is reduced by the ratio of 15,000rpm/1,800rpm (≈8.3) due to the reduction of the required torque at 15,000rpm.
- The approach is to design and produce:
    - a 15,000rpm 500Hz megawatt-class, four-pole medium voltage permanent magnet synchronous motor
    - a megawatt-class, bi-directional power flow, medium voltage 500Hz fundamental frequency, power dense adjustable speed drive using 10kV silicon-carbide MOSFET modules switching at 10kHz
- Compressor system with the above innovations will have a maximum 7.4m^3/MW inverse volumetric power density and 3.0m^2/MW footprint with a minimum system efficiency of 93%.
- System and system maintenance costs will be reduced due to the elimination of the step-up multi-megawatt gear box and its lubrication system. This also greatly increases the system reliability. Infrastructure costs will decrease due to the significant smaller footprint and higher power density. Power consumption cost is reduced due to the significant increase in efficiency.

End-user value propositions

- Oil & Gas compressors, gas separation process equipment and others will enjoy a more reliable and less costly system which will positively impact their productivity and bottom line.

Technical Innovation

	Current State	DOE-NGEM
Ultra-low loop inductance bus bar	80 nano-Henry	4.1 nano-Henry
Gate driver power supply coupling capacitance:	5.0 pico-Farad typical (5pF means 0.5A noise @ 100kV/µsec with 8kV step)	Zero pico-Farad
High voltage power semiconductor modules	6.5kV 750A Si IGBT	10kV 640A SiC MOSFET 15kV 350A SiC IGBT
3-phase Two-level Inverter Bridge Maximum Output Voltage	2.4kV w/ 6.5kV Si IGBT	5kV w/ 10kV SiC MOSFET 7.2kV w/ 15kV SiC IGBT
3-phase Three-level NPC Inverter Bridge Maximum Output Voltage	5kV w/ 6.5kV Si IGBT	10kV w/ 10kV SiC MOSFET 15kV w/ 15kV SiC IGBT
High frequency, low loss, *temperature stable inductance* filter inductors	• Metglass • Ferrite • Iron Alloy Powder • KoolMu	Nanocrystalline Cobalt-based Strain Annealed Magnetic Core

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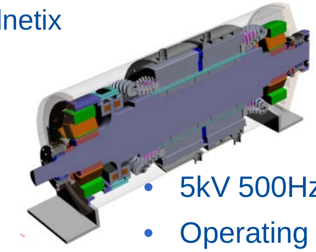
New Technologies

SiC MOSFET

- Designed & manufactured by CREE
- XHV-6 (36 die/Single Switch)
  - Max. Phase Current: 640A
  - Drain-source Resistance ≈7.5mΩ
- XHV-9 (12 die/Half Bridge)
  - Max. Phase Current: 320A
- Drain-source Voltage 10kV
- Measured dV/dt ≥100kV/μsec
- Measured di/dt ≥30kA/μsec

High Speed Permanent Magnet Synchronous Motor (HS-PMSM)

Calnetix

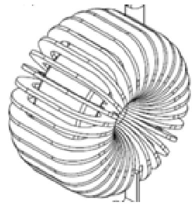


- 5kV 500Hz 4-pole
- Operating Speed 15,000 rpm
- Power Density 0.25m^3/MW
- Efficiency: 97.8%

Nano crystalline Strain Annealed Gap-less HF Core Material

Carnegie Mello University & NASA

- 10kHz operation
- Permeability=25
- Low Losses
- Temperature Stability



Ultra Low Inductance 3-phase Inverter Busbar

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Busbar Loop Inductance

- 4.0 Nano-henry for half-bridge modules
- 7.1 Nano-henry for single-switch modules

Control Hardware in the Loop (CHIL)

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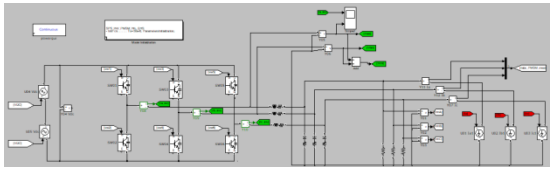

- **Physical Hardware:** Eaton's SPX Controller
- **FPGA:** Gate Driver, Input Filter, AFE, Inverter. Output Filter, HS-PMSM
  Step time 5ns, Update time 800ns

HS-PMSM Motor Control

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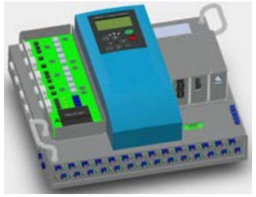
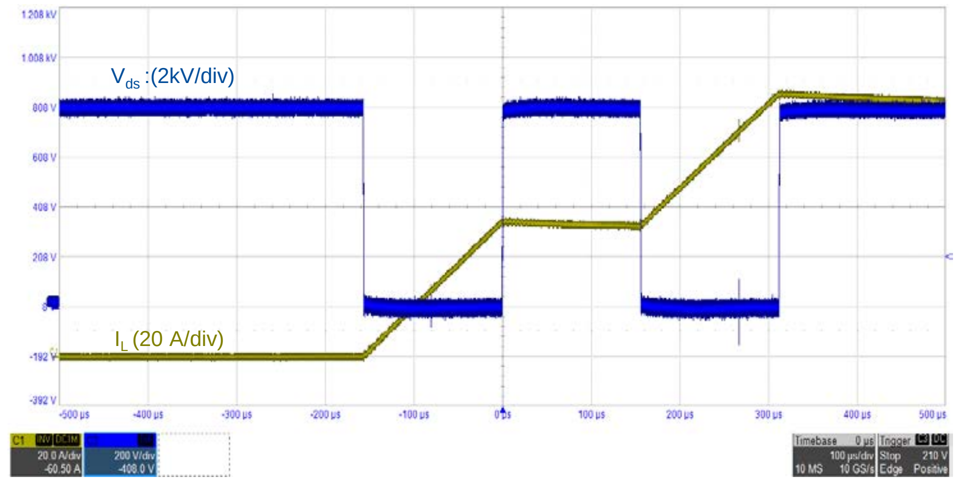
- Switching Frequency 10kHz
- Sensor less HS-PMSM Control
- EMC for >100kV/μs



Results and Accomplishments

- Results to Date
  - Control Hardware in the Loop
    - Validated 10kHz switching frequency and sensorless control of permanent magnet motor
  - Full H-Bridge testing
    - Successful testing at 8kV
  - Adjustable Frequency Drive (AFD)
    - Completed AFE and Inverter Design
  - SiC MOSFET
    - Produced sufficient 10kV dies
    - Started Spice detailed modeling
  - HS-PMSM Motor
    - Completed design and started fabrication
  - Inductors
    - Manufactured and validated core material

XHV-9 module high side switching at 8 kV using 20mH air-core load inductor and 7.1 nH commutation loop inductance



- Work to be Completed
  - Design packaging, prototype test VSD
  - Fabricate, Assembly and Test HS-PMSM
  - Finalize assembly 10kV SiC MOSFET Modules
  - Fabricate test stand
  - Test System

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Transition (beyond DOE assistance)

Strategy for further technology development and transition to the commercial marketplace:

- Prove the new 15,000rpm motor and the new 500Hz silicon-carbide adjustable frequency drive longevity and reliability both analytically and empirically
- Applicable Standards certification
- Develop the ancillary components (capacitors, inductors and transformers) for higher voltage & frequency <u>and</u> lower parasitics
- 10kV & 15kV Silicon-carbide Power Semiconductor Modules Package with lower than 5nH loop inductance and compliance to IEC-1287 partial discharge requirements and is able to operate at significantly higher temperatures than 150 degrees Celsius

Commercialization partners

- Petrobras of Brazil and Dresser Rand are involved by providing:
  - Application and testing guidance
  - Applicable standards
  - Beta site for evaluation in a real-life scenario

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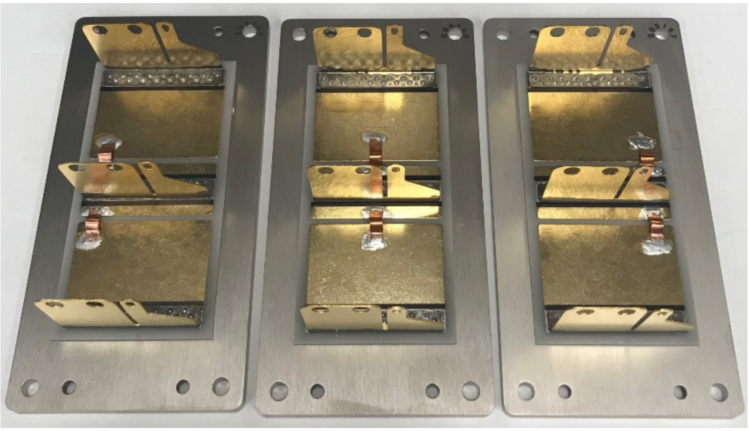
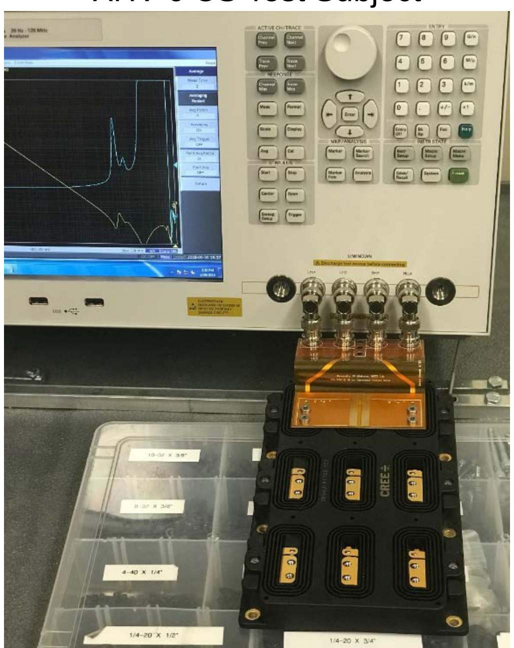
Measurement-Based Parasitic Modeling of XHV-6 CS

XHV-6 Test Subject Internals with Shorting Straps

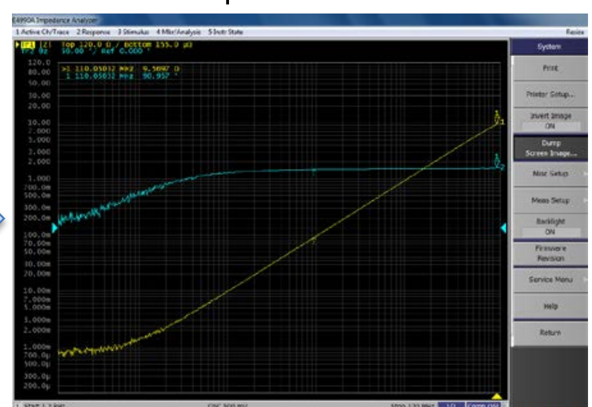


Impedance Measurement of XHV-6 CS Test Subject

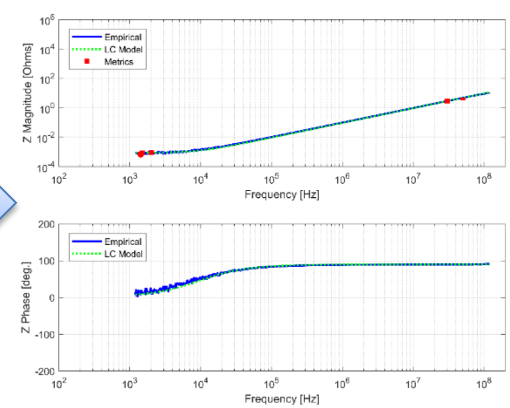


- Goal: investigate dynamic current sharing and gate-loop timing characteristics for XHV-6 CS
- First step is determining inter-die and die-terminal parasitics for power & gate-loops
- Power loop empirical characterization is complete
  - XHV-6 CS test subject created with shorting straps at each die position
  - Each die position was characterized in the frequency domain up to 120 MHz
  - Each measurement result was curve-fit to a series RL equivalent circuit in MATLAB
- Gate-loop characterization will be performed next
- Resulting models will be implemented in LTspice for subsequent analysis / trade studies

Measured Impedance of Die Position



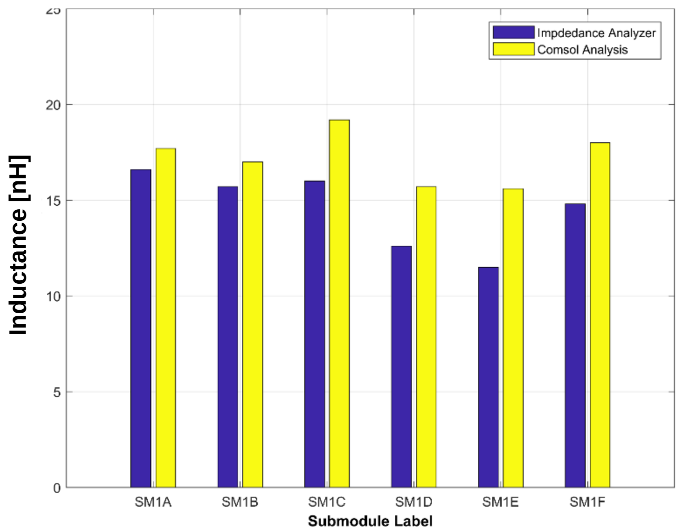
Curve Fit to Series RL Model in MATLAB



POC: Andy Lemmon, Assistant Professor, The University of Alabama, lemmon@eng.ua.edu

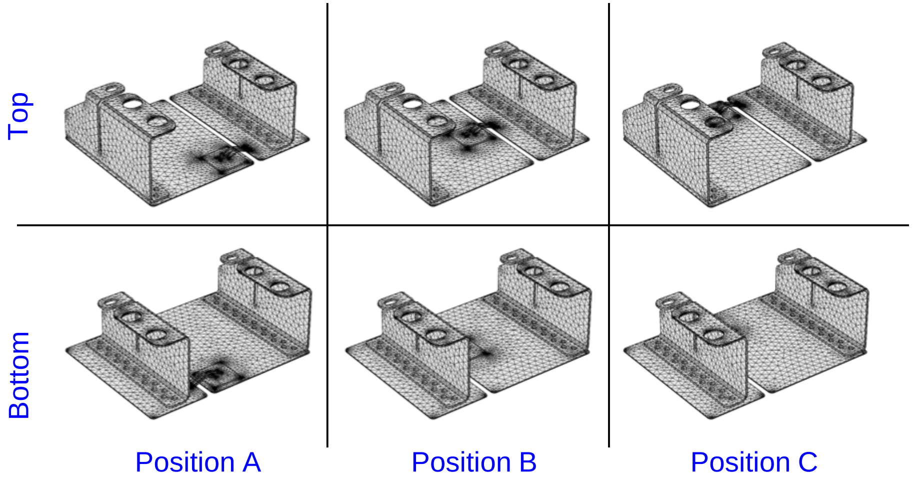
FEA Analysis Compared with Measurement Results

Comparison of Measured & Modeled
Die Position Inductances [50 MHz]

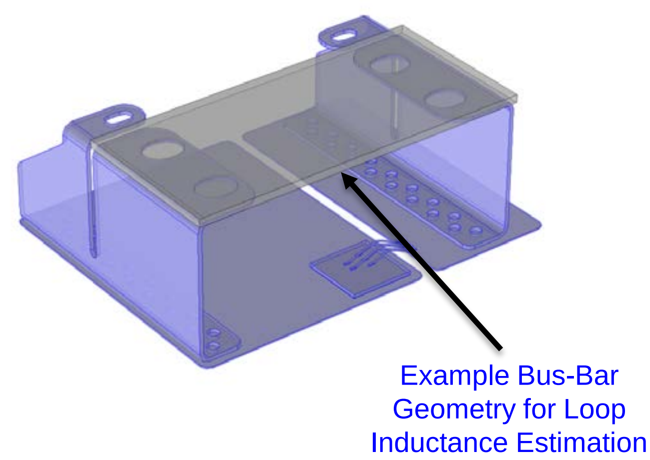


- The XHV-6 CS power loop geometry has also been analyzed in FEA using COMSOL Multiphysics
- An approach similar to the empirical measurements was adopted (one-die-at-a-time analysis)
- Calibrating this simulation against measured impedances will enable this model to be used in optimization / trade studies
- Initial simulation results indicate good agreement with empirical measurements (within 2-3 nH)
- Gate-loop geometry will be analyzed next

Individual Die Positions Isolated in COMSOL



De-featured, Single-Die Position Model Showing Bus-Bar



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Questions?