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

DE-EE0007253
Energy Efficiency & Renewable Energy
BP1 8/1/2016 – 10/31/2017

Geraldo Nojima &
Steven Castelein
Eaton Corporation

U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
June 13-14, 2017

Powering Business Worldwide

Project Objective

Goal: Develop an 1MW, 4160V Integrated Medium Voltage Variable Speed Drive (VSD) and 15,000 rpm permanent magnet motor for gas compression applications eliminating the gear box, decreasing size and increasing efficiency and reliability of critical processes. Effectively lowering the total system cost.

Problem with state-of-the-art Gas Compression Systems:

- Motor size is too big (8x).
- System size is too big (2.7x) due to the required gear box and its lubrication system which also impacts negatively system reliability and efficiency (6%).

Challenges:

- The performance of the 10kV, 480A Silicon Carbide (SiC) MOSFET modules, operating at 15x the switching frequencies of Silicon (Si) IGBT.
- The ancillary components to support the 10kV, 480A SiC MOSFET for Medium Voltage applications have not been vetted out: gate drivers, transformers, inductors, dielectrics, capacitors, control system and EMI suppression.
- The control of Mega Watt Class Medium Voltage 15,000 rpm Permanent Magnet Motor with no position sensors.
- High dV/dt (100kV/μs),
  - Produce unprecedented electromagnetic interference (EMI) challenges
  - Requires a sine filter between VSD output and the motor

Current State

- Present Megawatt Class Gas Compression Systems uses:
  - Si IGBT which are limited to 500Hz switching frequency
  - 60Hz is the motor fundamental frequency
  - Requires a 4 pole, 1,800 rpm induction motor
  - Motor is 8x larger versus a 15,000 rpm motor
  - Requires 1:9 gearbox to reach the 15,000 rpm gas compressor speed
  - Gearbox requires ancillary lubrication system
  - Gearbox limits system efficiency to around 90%
  - Reliability is limited by the wear and tear of the mechanical parts and the presence of the gearbox exacerbates this problem; by removing it only two mechanical systems remain: motor and compressor

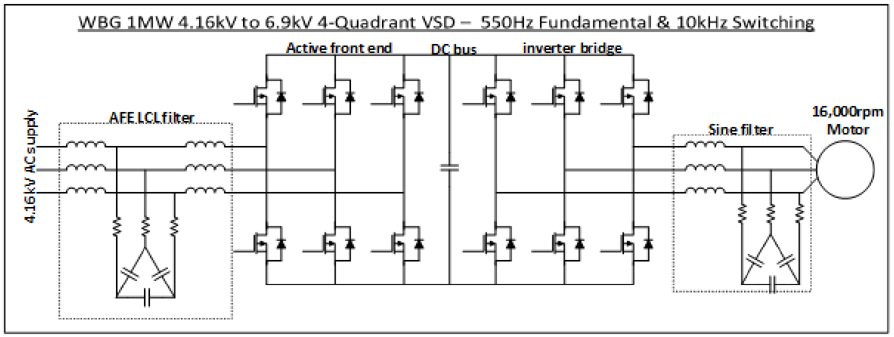
Powering Business Worldwide

Technical Innovation

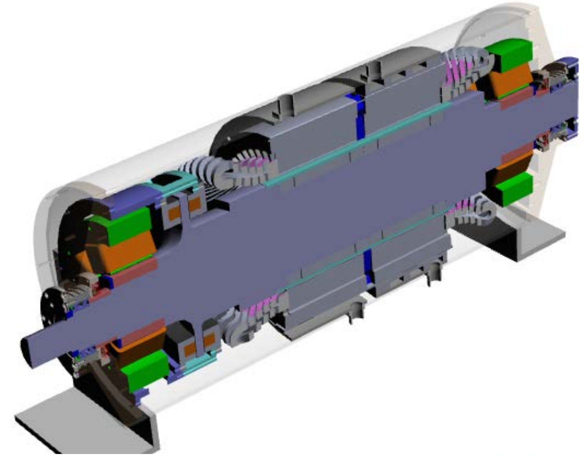
- Eaton's solutions:
  - 10kV, 480A SiC MOSFET based bidirectional Variable Speed Drive (VSD)
    - 2-level inverter bridge~~,~~
      - 8kV DC Link
      - 8kHz switching frequency
      - Custom dielectric system and low inductance busbar
    - Active-Front-End Rectifier with LCL input filter
      - Provides bi-directional power flow and eliminates the need for 24 pulse rectifier
      - Provides DC link voltage regulation in case of power flow transients due to load fluctuations on the high speed motor and thus eliminating nuisance over voltage trips
    - Output sine wave filter
    - Output fundamental frequency 600Hz
  - Gapless Co-based Nano Crystalline Strain Annealed Inductor Core
    - High frequency, high efficiency, low EMI
  - Medium Voltage 15,000 rpm Permanent Magnet Synchronous Motor (0.25 m^3/MW), using permanent magnet bearings. It is 8x smaller vs current state-of-the-art implementation
- Eaton's Success Factors:
  - Encapsulation technology
  - Advanced system modeling and simulation capability
  - Extensive Medium Voltage VSD design expertise and manufacturing experience

Design

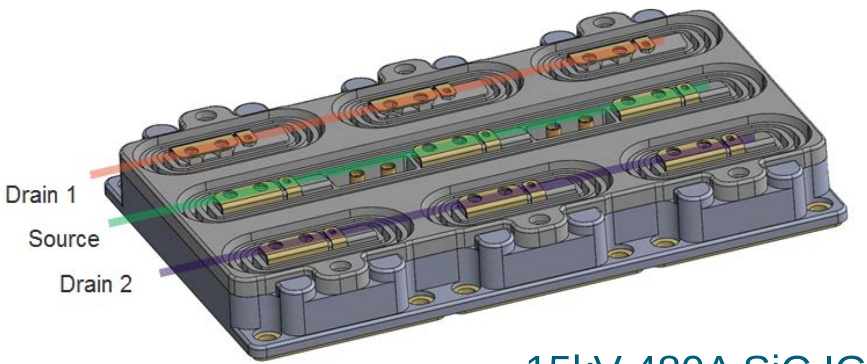
2-Level Topology – Bi-Directional



PM Motor

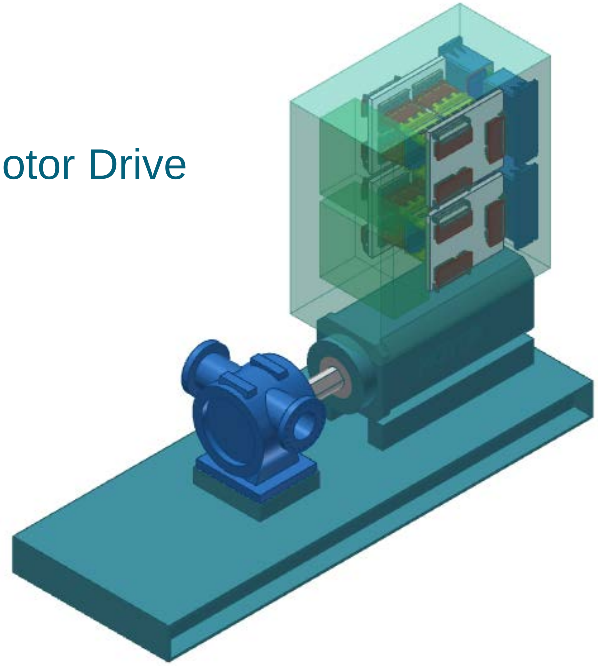


10kV 480A SiC MOSFET GEN 3 Dies Short Circuit Protection



15kV 480A SiC IGBT

Integrated Motor Drive



Approach

- **Project Team**
  - Eaton's Medium Voltage Power Conversion Lab and Corporate Research
  - Voice of the Customer input: Petrobras, Eaton Sales, Bessemer, Dresser-Rand
  - SiC MOSFET Dies & Modules: Cree Wolfspeed
  - Medium Voltage High Speed Permanent Magnet Synchronous Motor (MV HS PMSM): Calnetix
  - Magnetic Core Material: CMU (with NASA and NETL)
  - Gate Driver and Control Hardware in the Loop (CHIL) support: Professor Bhattacharya/NCSU
  - MVHS PMSM Motor design and Motor Control Support: Professor Lipo and Dr Luis Garces
- **Eaton Capabilities**
  - Medium Voltage Power Conversion R&D Laboratory in Arden, NC
  - OPAL-RT with FPGA for CHIL, MIL and SIL
  - Simulink, PLECS, EMTP-RV and ANSYS
  - Low and Medium Voltage Drive R&D, Manufacturing and Commercialization

Technical Approach

- **Risks**
  - Motor Power Density and Efficiency – Low
  - MOSFET Die Yields – Low
  - MOSFET Module Performance – Medium
  - Gate Driver Performance - Medium
  - Gate Driver Power Supply Performance - Low
  - Filter Design - Medium
  - Drive Design (EMI, THD, Common Mode) – High
- **Mitigations**
  - Redesign, De-Rating

Powering Business Worldwide

Transition (beyond DOE assistance)

- Who cares: Any market where floor space, increased reliability and/or energy cost is a premium (First adopters: Oil and Gas)
- End User: Oil & Gas, Onshore and Offshore Gas Compression, Gas Separation and High Speed Lubrication Applications.
- Commercialization approach: OEM to Compressor Manufacturer.

Measure of Success

- Measurements of success:
  - Technical:
    - Foot print and volume, efficiency and reliability
    - Demonstrated performance of the ancillary components
    - Prototype demonstrated in emulated environment
  - Operations
    - Ability to industrialize the various ancillary components
  - Commercial:
    - Ability to create a value proposition to generate commercial interest from end users and OEMs.
- Potential Energy Impact
  - Potential savings per 1MW system
    - 24/7 operations and $0.20kWh
    - 6% * $0.20/kWh *1000 kW * 365 * 24 = $105k/year

EATON
Powering Business Worldwide

Project Management & Budget

- 3 Year Project
- BP1 key milestone schedule

Task 1 Project Management	
Continuation Application	7/31/2017
Executed IPMP	Comp
Gate 1 PROLaunch	7/31/2017

Task 2 Requirements Definition	
Sytems Specification	Comp

Task 3 Device Mfg	
Deliver 160 devices	6/30/2017

Task 4 Module Mfg	
Deliver 5 Modules	8/15/2017

Task 5 High Speed Motor Design	
Motor Requirements	Comp
Preliminary Design	Comp
Receive Long Lead Time	9/30/2017

Task 6.0 Drive Design

Task 6.1 Design, Simulation, Comp Spec	
Model MOSFET	7/31/2017
Model Gate Driver	7/31/2017
Power Loss Budget	9/30/2017

Task 6.2 Gate Driver Development	
Gate Driver Prototype	10/31/2017

Task 6.3 Gate Driver Power Supply Development	
Power Supply Prototype	10/31/2017

Task 6.4 Strain Annealed Soft Magnetic Inductor	
Material Prop. Report	7/31/2017

Task 6.5 2-Level VSD Design	
Phase Leg Design	7/31/2017
Preliminary Controls	10/31/2017

Total Project Budget	
DOE Investment	$5,345,930
Cost Share	$1,336,483
Project Total	$6,682,413

Powering Business Worldwide

Results and Accomplishments

- Accomplishments
  - Produced 149 short circuit enhanced MOSFET GEN3 10kV 15A dies
    - Measured 270mΩ vs target of 350mΩ, module with 7.5mΩ per 480A module
  - Produced 4 10kV, 480A MOSFET modules
  - Completed Electro Magnetic design HS-PMSM and releasing long lead-time items, achieved 0.25m^3/MW and 97.8% efficiency
  - Produced 40kg Co-based Nano Crystalline Strain Core Material
  - Completed System Model and created CHIL setup
  - Completed preliminary testing Gate Drivers and Power Supply
  - Created solid model VSD and releasing materials for the H-bridge
- Next steps
  - Produce additional MOSFET dies and modules
  - Complete detail design, produce and test HS-PMSM
  - Strain anneal core material, produce and test Inductors
  - Test Gate Drivers and Power Supply with 10kV 480A MOSFET Module
  - Refine, run simulation and data analysis of the System Model and CHIL
  - CHIL and physical testing motor control approach
  - Detail design, produce and test VSD
  - Integrate and test VSD and HS-PMSM

Powering Business Worldwide