Medium Voltage Integrated Drive and Motor

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Calnetix Technologies
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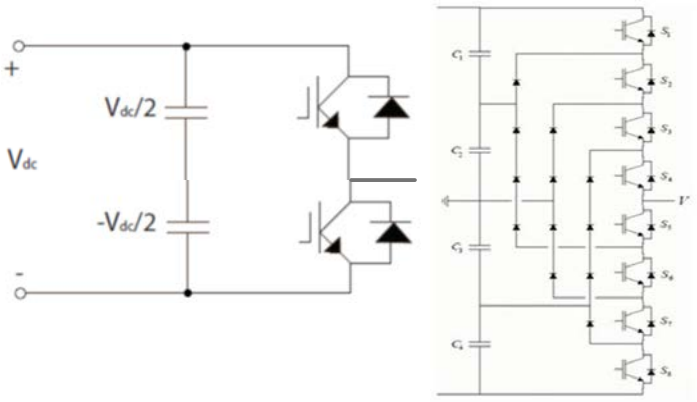
Project Objective

- Project Goal
  - Develop medium voltage, VSD (Variable Speed Drive) and PMSM (Permanent Magnet Synchronous Machine)
    - >15 kRPM motor and >1 MW power level
- Applications
  - Oil & Gas industry for gas compression
  - Expander for power generation
- Issues Addressed
  - Efficiency, footprint (mobility and offshore applications), operating life (unmanned site)
  - Current technology is turbine, engine driven or induction motor with gear drive train
  - Bulky, poor operating life and load response, low efficiency and environmentally unfriendly
- Challenges and Difficulties
  - Developing high efficiency small size bi-directional inverter using state of the art high efficiency wide band gap devices having extremely high switching speeds
  - Stator and Rotor construction to meet the high speed operation with long operating life
  - Managing circulating bearing currents due to high switching frequency of VSD inverter
  - Maintenance free bearing for long operating life

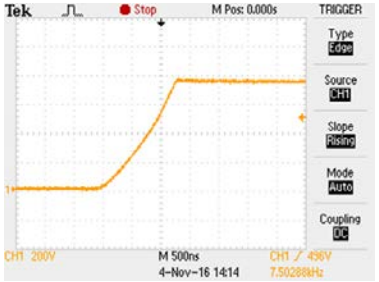
Technical Innovation

- Existing technology limitations
  - Turbine or engine driven compressors
    - Early generation
  - Induction motors operating at 3.6 krpm with gear train to increase speed typically >15 kRPM
    - Second generation and large overall footprint
  - Fixed speed, low operating life and efficiency, auxiliaries required, and high maintenance
- New approach and trade-offs
  - Two level inverter utilizing 10 KV Silicon Carbide (SiC) modules rather than multilevel topology
  - Allows fast acceleration and deceleration, simple controls, fewer parts, and modular
  - High dv/dt and higher device cost
  - Permanent Magnet Synchronous Motor (PMSM)
    - High efficiency, small size
    - Complex rotor design, rotor magnet retention
  - Magnetic Bearing
    - Maintenance free operation, minimizes auxiliaries
    - Elimination of bearing currents
    - Adds to design complexity and increased cost
  - Motor
    - Incorporating best commercially available insulation system
    - Integrating dv/dt filter to smoothen the high switching transients of two level SiC device

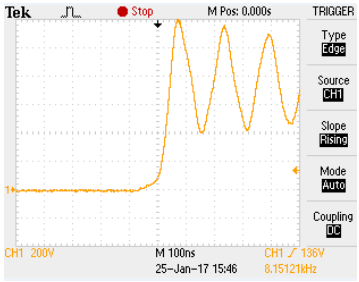


Technical Approach

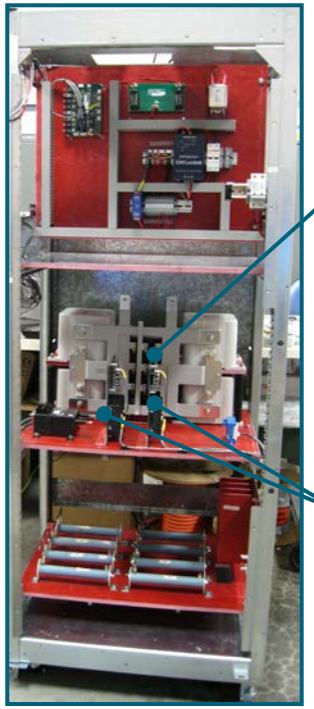
- VSD Design
  - Validate existing Calnetix sensorless VSD controller in a high dv/dt environment
    - Existing controller controls Silicon (SI) IGBT switching device
      - dv/dt < 1,000 v/µsec
    - Improved controller switching an SiC device
      - dv/dt > 15,000 v/µsec
  - Developing a half-bridge medium voltage two level switching inverter
  - Partners:
    - Cree/Wolfspeed for 10KV dual SiC module and high speed gate driver board
    - CTM magnetics for medium voltage L-C filter
  - Risks and Unknowns
    - 10 kV SiC device is relatively new
    - Cost model is high today
    - Impact of high dv/dt not fully understood



Si device
dv/dt ≈ 666 v/µsec
Load current = 200 Amps



SiC device
dv/dt ≈ 15,000 v/µsec
Load current = 200 Amps



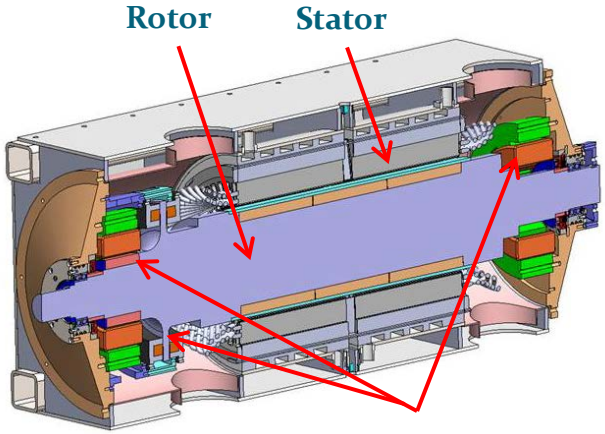
10 kV SiC module

Gate Driver board

Half-Bridge Module Inverter Cabinet

Technical Approach

- 1.6 MW Machine
  - High speed medium voltage (4,160 VAC)
  - Permanent magnet synchronous machine
  - Magnetic bearing levitation
- Partners
  - BRG Machinery – Magnetic bearing
  - Electric Motor & Contracting Company – Stator assembly
  - Laser Technologies – Laminations and stacking
  - KenCoil – Stator coil forming
- Risks and Unknowns
  - Stator cooling with MV insulation system
  - Mitigation of dv/dt
- Execution Attributes
  - Calnetix has had multiple successes in launching product lines and companies using core technologies consisting of permanent magnet synchronous machines, magnetic bearings, and associated controls



1.6 MW Machine Layout

Transition (beyond DOE assistance)

- Industry Drivers
  - Industry is strongly on the lookout for electric direct drives for compressors, pressure let down expanders, large gas turbine generators
  - Both pipeline owners and direct operators desire better efficiencies and lower operating costs (reliability/ lower down time/ fewer auxiliaries)
- Business Model and Value
  - Calnetix's business model is to directly work with Original Equipment Manufacturers (OEM)
  - Typical OEM's
    - Compressor/turbine manufacturers
  - Typical Applications
    - Pipeline owners, gas gathering entities, terminal owners
  - Benefits
    - Land based applications: Higher availability and lower operating costs
      - Less maintenance, less equipment, lower down time
    - Offshore applications: Higher capacity and smaller footprint/volume
      - Increased service intervals and less equipment

Transition (beyond DOE assistance)

- Commercialization Approach
  - Work with a medium/ large compressor OEM or end user to apply in compression for beta testing
  - Concept demonstration to the industry followed by a dedicated product development for actual power and speed for a family of existing compressor trains
- Technology Sustainment Model
  - Reinvestment in the developed technology by expanding the technology to the whole family of Calnetix drives and motors
  - Partnering with early adopter customers to apply the technology in other areas of merit and interest
    - Calnetix is in process of exploring flywheel based grid stabilization

Measure of Success

- Measure of Success
  - Successful commercialization will provide a pathway to enter primary applications such as compression for liquefied natural gas (LNG) tankers, air compression for air separation, and offshore platform gas compression
  - Impact of applications will be as follows:
    - Improved efficiency
    - Elimination of transformers
    - Savings in cost of electricity
    - Maintenance free
- Energy/Economic Impact
  - Higher efficiency
  - Lower footprint
  - Fewer auxiliaries
  - Lower operating costs
- Success is highly reliant on SiC device cost reducing over a period of time
- If price is secondary, SiC is device of choice for high switching frequency to control high speed machines

Project Management & Budget

- Project Duration
  - 3 year project
  - May 2016 through April 2019
- Project task and key milestone schedule
  - Budget Period 1: 17 months (Drive Controls Validation, MV Motor Design and MV Drive Development)
  - Budget Period 2: 9 months (Packaging, Design, and Fabrication)
  - Budget Period 3: 10 months (Validation Testing)
  - For each task, there are several subtasks that are tracked to ensure progress is being made
  - On a monthly basis, Calnetix is reporting to DOE related to milestone or go/no-go task items

Total Project Budget	
DOE Investment	$3,985,810
Cost Share	$996,705
Project Total	$4,982,515

Results and Accomplishments

- Results to Date
  - Software Controls (1.2 kV SiC)
    - Validation tests demonstrated SiC devices are compatible with existing Calnetix controls
    - SiC devices switch almost 10 times faster than corresponding Si devices
    - SiC losses were less than 1/3 of corresponding Si losses
  - Preliminary Motor Design
    - Preliminary motor design completed predicting a 98.2% motor efficiency
    - Rotordynamic FEA simulation of rotor predicts subcritical operation with 82% rotordynamic margin @ 110% of rated speed (16.5 kRPM)
    - Thermal FEA analysis demonstrates rotor will be < 150 °C and stator winding will be below 180 °C at rated speed and load
  - Half-Bridge Module Inverter Cabinet
    - Design, analysis and assembly completed
    - Major components for MV testbed installed and tested up to 700 VDC
  - Volumetric Analysis
    - Preliminary VSD and motor footprint is close to FOA target

Estimated Volumetric Performance Metrics

Components	Parameters	FOA Goal	Existing Technology	Projected
VSD	Footprint (m^2/MW)	0.791	1.645	0.97
	Inverse Vol. Density (m^3/MW)	1.515	4.545	1.77
Motor	Footprint (m^2/MW)	0.625	2.5	0.5
	Inverse Vol. Density (m^3/MW)	0.25	2.0	0.27

- Work to be Completed
  - Test half-bridge module inverter assembly
  - Continue development of VSD per half-bridge module inverter assembly test results
  - Finalize 1.6 MW machine design and manufacture
  - Test VSD and 1.6 MW machine at Calnetix