THE OHIO STATE UNIVERSITY

Integrated Electric Drive with HV2 Modular Electric Machine and SiC Based Power Converters

Contract number: GRT00042850/60054279

The Ohio State University (Lead), Oregon State University, National Renewable Energy Lab

02/2016 to 01/2019

Principal Investigator: Longya Xu, The Ohio State University
Presenter: Julia Zhang (Co-PI), The Ohio State University

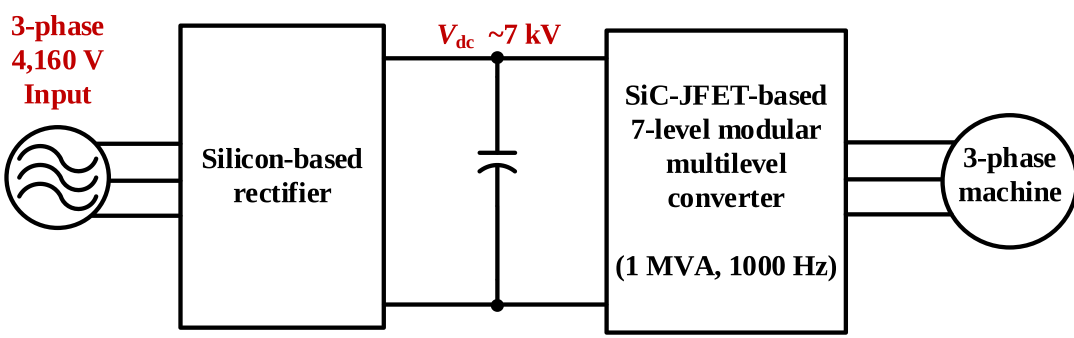
U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
June 13-14, 2017

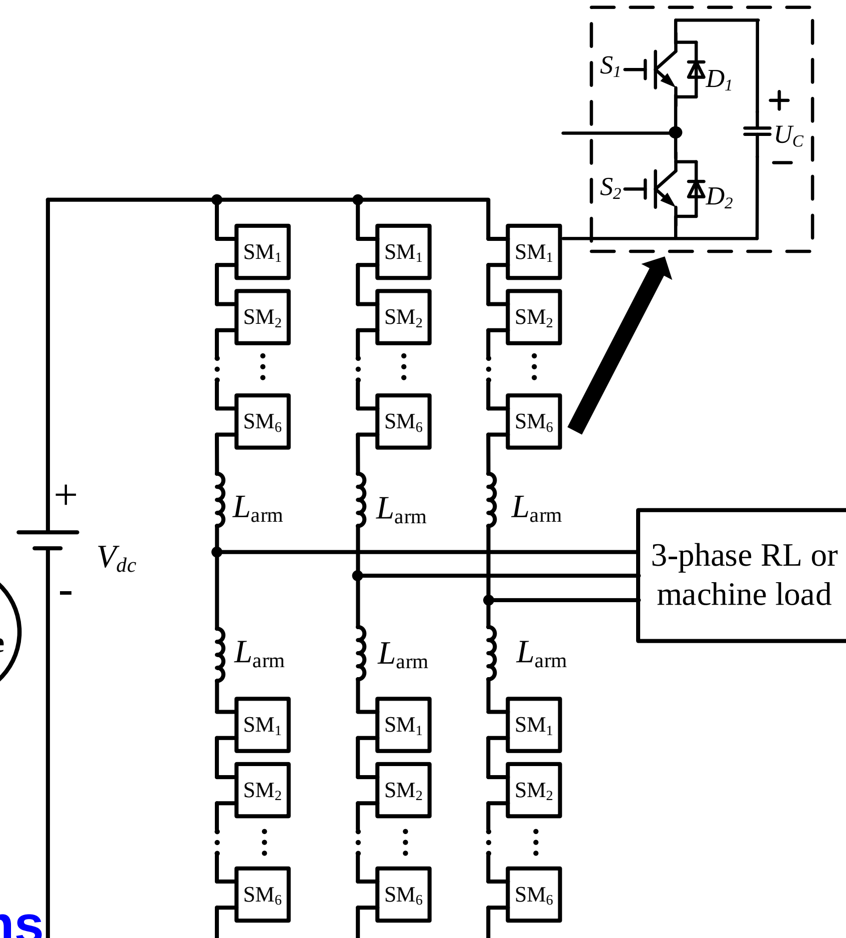
Outline

- ❑Project Objective
- ❑Technical Innovation
- ❑Technical Approach
- ❑Transition
- ❑Measure of Success
- ❑Project Management & Budget
- ❑Results and Accomplishments

Project Objective

- Design, build, and test a high voltage, high speed SiC-based variable frequency drive (VFD).
- Performance targets: power density>0.66 MW/m^3, efficiency 99% @1 MW/1 kHz.
- Major challenges:
  - Potential strong EMI
  - High number of sub-modules
  - High voltage insulation problems
  - Low speed control





Pilot project on transformer-less high voltage high speed machine drive systems

Technical Innovation: State-of-the-art

❑ Pros and cons of current practice and this project

3-level Neutral Point Clamped Voltage Source Inverter (3L NPC VSI)

- **Pros: least devices, low switching frequency**
- **Cons: unequal semiconductor-loss distribution**
- **Product price:** $186,000

9-Level Cascaded H-Bridge Voltage Source Inverter (9L HB VSI)

- **Pros: high drive power**
- **Cons: bulky and complicated zigzag transformer**
- **Product price:** $158,766

4-Level Flying Capacitor Voltage Source Inverter (4L FC VSI)

- **Pros: high bandwidth**
- **Cons: bulky and complicated zigzag transformer**
- **No information about product price**

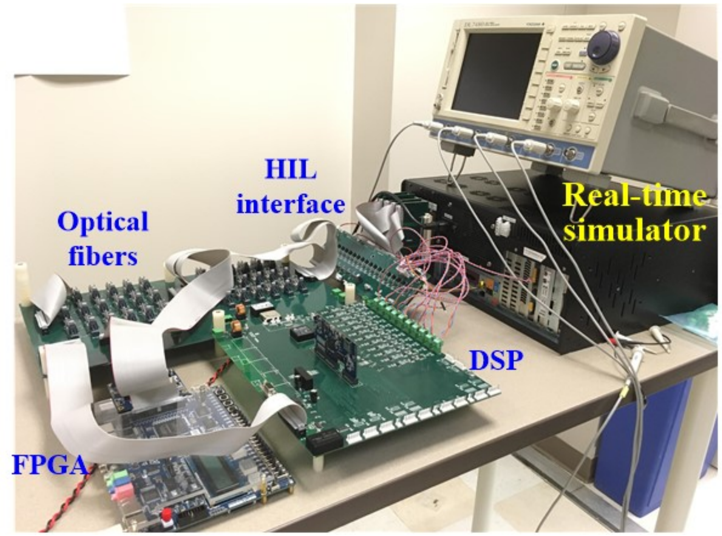
This project: 7-Level Modular Multi-Level Converter Voltage Source Inverter (7L MMC VSI)

- **Pros: high speed, high efficiency, upgradable to transformer-less with high voltage devices**
- **Cons: large number of sub-modules**
- **Estimated cost:** $120,000 (competitive, especially if wide bandgap device price is reduced, 50% of the total now)

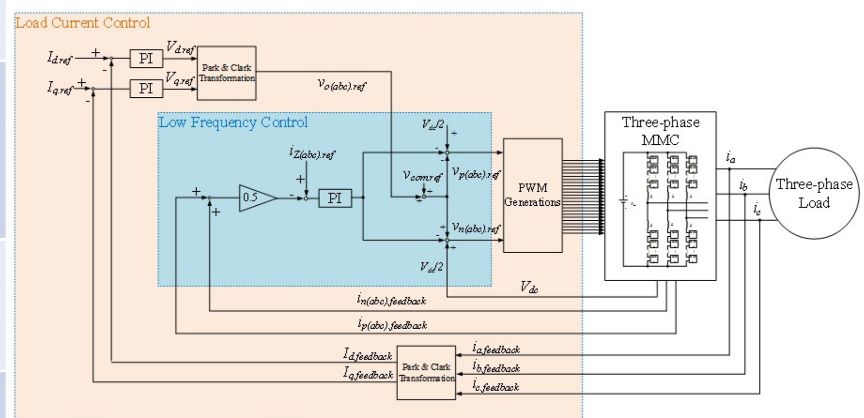
Technical Innovation: Innovations

Challenges	Innovative Solutions
High power: 1 MW, High voltage: 7-kV, High frequency: 1 kHz	Pilot project on transformer-less electric machine drives, SiC MOSFETs, modularized design methodology
Complex control algorithms with limited calculation time	DSP+FPGA structure
Potential strong Electromagnetic Interferences (EMI)	Fiber-optic signal transmission/improved layout design/multi-stage isolated auxiliary power supplies
PWM, fault signals and sensing signals from 36 modules	Modular control-card designs, multi-tier gate drives design
Low frequency control of MMC Drive	Improved low frequency control algorithms
High insulation requirement	Partial discharge monitoring and measurement

Hardware innovation example



Software innovation example



Technical Approach:

❑ Scientific/technological approach

- Define system requirements: performance and cost targets
- Evaluate hardware components: simulations and tests
- Submodule integration and function validation: hardware-in-the-loop and experimental tests.
- Machine and drive system integration: hardware-in-the-loop and experimental tests.
- System tests: across full voltage, current, and frequency ranges.

❑ Participants and responsibilities

- **The Ohio State University:** device characterization, design and build gate drive circuits and main circuits of SiC, control algorithm development, system integration, hardware-in-the-loop tests, experimental tests on a rotating dynamometer
- **Oregon State University:** design of controller and peripheral circuits, sensor selection and conditioning circuit design, control algorithm development and experimental verification.
- **National Renewable Energy Lab:** thermal analysis and packaging design

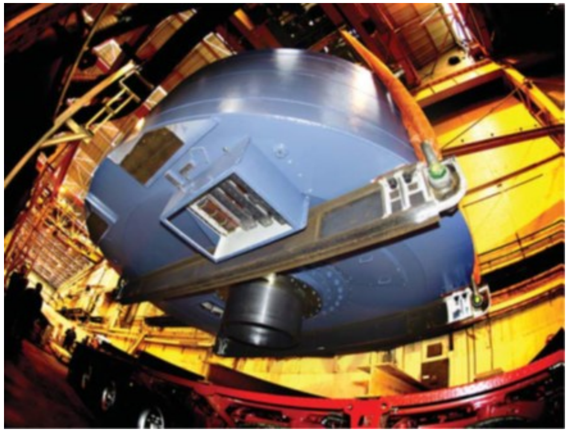
Technical Approach:

Potential project risks and unknowns	Mitigation method and timeline
The drive efficiency might not meet the target	Device selection and test, individual device and converter sub-module tests. Quarter II & III of Year 1
Costs of the drive system might not be competitive compared to existing technology	Reduce design margin, work with multiple component manufacturers to understand the tradeoff between cost and performance. Quarter I, II, & II of Year 1
Pre-mature insulation failure caused by fast switching transients and reflected waves.	Partial discharge monitoring and measurement. Quarter II of Year 2 to the end of project
Cannot find a 1-kHz 1 MVA machine for tests	Test current, voltage, frequency capabilities separately using 3 electric machines. Year 3 of the project

Transition

- Potential market:
  - High power gas turbine generator
  - Wind turbine generator
  - Compressors, pumps, fans for chemical, petroleum refining industries, natural gas infrastructure, mining industries, marine,
  - General industrial applications.
- Impact:
  - Reduced energy consumption
  - Improved process control

GE diesel and gas turbine generators



GE wind turbine generator

ABB hydrogen gas compressor

ABB medium voltage mill

Transition

- **Barriers to Adoption**
  - ✓ Large cost reduction of the proposed system?
  - ✓ Replace old equipment and installation of new systems?
  - ✓ Highly-qualified engineers with comprehensive knowledge of VFD and WBG devices?
- **Commercialization Plan**
  - ✓ **Technology documentation and dissemination (throughout this project):** publishing papers and reports, invite key industry members in the field to workshops and seminars.
  - ✓ **Reach out to commercialization partners (year 3):**
    - *Tier 1 manufacturers:* U.S. oil and natural gas equipment manufacturers such as Caterpillar and GE Oil and Gas.
    - *Tier 2 manufacturers:* U.S. electrical equipment manufacturers such as Emerson Network Power, GE Aviation, Rockwell Automation.
    - *Tier 3 manufacturers:* Foreign electrical equipment manufacturers operating gloabally including ABB, Siemens, Toshiba, and Alstom
    - *System integrators and operators:* oil and gas producers, renewable integrators, and utility companies to seek field demonstration opportunities.
  - ✓ **Secure investment, manufacturing, and application partners (year 3):** IKOVE VENTURE Partners (IVP), which is an OSU-based “Startup Nursery”, will advise the team on IP strategies, assist in forming detailed commercialization plans, securing financial investment, and engaging manufacturing and application partners.

Measure of Success

- Impacts
  - Replace some existing high power fixed-speed drive systems, 30% to 70% energy saving.
  - High frequency: significantly reduce the footprint and weight of existing high power fixed-speed drive systems.
  - Pilot project on transformer-less high voltage electric machine drive systems, elimination of bulky power transformer and related maintenance and cost.
  - Leverage high power wide bandgap power electronic device technology.
- How will it be measured? Compare the following parameters of the proposed system to an existing 1 MW low speed electric machine drive system.
  - Energy efficiency
  - Energy consumption
  - Weight, volume, and footprint of the drive systems
  - Cost of the overall system including the machine, drive, and supporting components.

Project Management & Budget

Project duration:

02/2016 to 01/2019

Total Project Budget	
DOE Investment	1,970,358
Cost Share	674,086
Project Total	2,644,444

Project timeline	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.1 Pros and cons of existing SiC MV/HV VFDs	■											
1.2 Characterize components, develop MMC sub-modules		■										
1.3 Preliminary design and analysis of SiC MMC			■									
2.1 Develop controller hardware and software			■									
2.2 Evaluate controller hardware and software	Go/no-go 1			■								
3.1 Build one phase leg, test it under reduced V/P					■							
3.2 Test one phase leg under full V/P						■						
4.1 Optimize and build three phase legs							■					
4.2 Test MMC at its full V/P using RL load	Go/no-go 2							■				
5.1 Integrate VFD and motor on test bed									■			
5.2 Develop and verify controls up to 75% load	Go/no-go 3									■		
6.1 Full load VFD system lab tests											■	
6.2 Working cycle tests												■
7.1 Final report, market transformation, commercialization												■

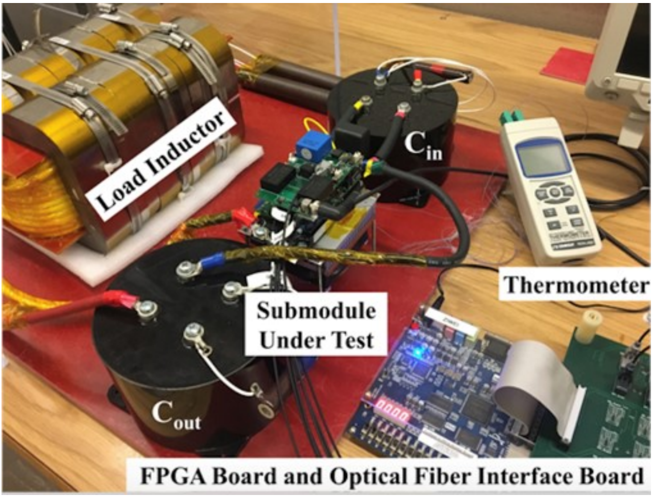
Results and Accomplishments

❑ Milestones and Accomplishments

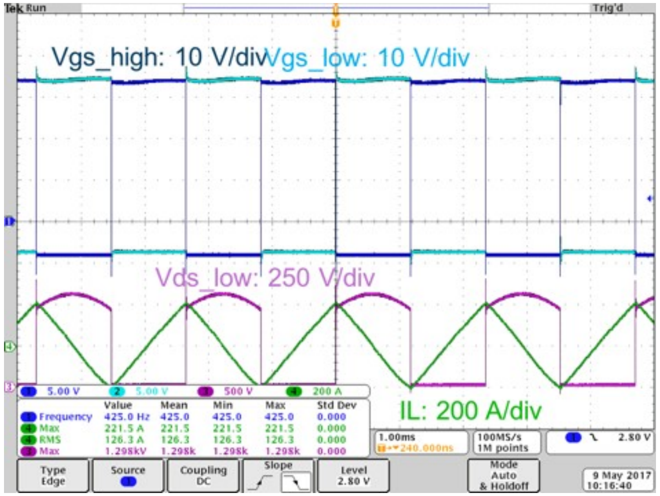
- State of the art review of existing SiC technologies of MV/HV variable speed drives (VFDs)
- Component characterization and modular multilevel converter(MMC) sub-module development
- Design and analysis of the SiC power converter
- Controller hardware and software development
- Built and tested one phase leg under reduced voltage/power

❑ Ongoing work

- 3-phase legs and test MMC at its full V/P ratings using RL loads
- Integrate VFD and motor on test bed, test system up to 75% load
- Full load VFD system lab tests and working cycle tests



Submodule test



Module full V/I test

One phase leg