Proceedings

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Workshop on

High-Megawatt Direct-Drive Motors and Front-End Power Electronics

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Proceedings Prepared By

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List of Abbreviations

AC	Alternating Current
CMOS	Complementary Metal Oxide Semiconductor
CO2	Carbon Dioxide
COG	Chemical, Oil and Gas
DC	Direct Current
DOE	Department of Energy
dV/dt	Change in voltage divided by change in time
EMI	Electromagnetic Interference
ESS	Electricity Storage System
EV	Electric Vehicle
FY	Fiscal Year
GOSP	Gas Oil Separator
GTL	Gas-to-Liquids
GW	Giga Watt
GWh	Giga Watt-hour
HF	High Frequency
HMW	High Megawatt
HTS	High Temperature Superconductor
Hp	Horsepower
HV	High Voltage
HVDC	High Voltage Direct Current
HV-HF	High Voltage High Frequency
Hz	Hertz
IGBT	Insulated Gate Bipolar Transistor
IEEE	Institute of Electrical and Electronic Engineers
JBS	Junction Barrier Schottky
JFET	Junction Field Effect Transistor
kHz	kilohertz
kg	kilogram
kRPM	thousand rpm
kV	kilo Volts
kVA	kilo Volt Ampere
kW	kilo Watt
kWh	kilo Watt-hour
LNG	Liquefied Natural Gas
LV	Low Voltage
LTS	Low Temperature Superconductor
m3	cubic meters
MgB2	Magnesium Boride
MD	Maryland
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
MV	Medium Voltage
MVA	Mega Volt Amperes
MW	Megawatt

NIST	National Institute of Standards and Technolohg
MWh	Megawatt hour
MHz	MegaHertz
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
PCS	Power Conditioning System
PE	Polyethylene
PiN	Positive intrinsic Negative
PM	Permanent Magnet
PP	Polypropylene
PV	Photovoltaic
R&D	Research and Development
RPM	Revolutions per Minute
SECA	Solid State Energy Conversion Alliance
Si	Silicon
SiC	Silicon Carbide
SST	Solid-State Transformers
THD	Total Harmonic Distortion
US	United States
US$	United States Dollars
VAC	Volts AC
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
WBG	Wide Band Gap

1. Summary

On September 4, 2014, 39 invited participants convened at NIST (National Institute of Standards and Technology) headquarters in Gaithersburg, MD to participate in the NIST/DOE Workshop on High-Megawatt Direct-Drive Motors and Front-End Power Electronics. This was the second of two Workshops at NIST on this subject in 2014. The driver for holding these Workshops is the fact that approximately 14% of the total electricity consumed in the United States flows through large-power electric motors (1-50 MW); e.g., for the Chemical, Oil, and Gas industry. Many of these motors drive 10,000 to 20,000 RPM mechanical loads through a large gearbox and use mechanical throttles rather than power-electronics based VSDs to control flow, which is relatively inefficient. Improving the efficiency of the drive systems represents a larger potential payoff for the US economy.

A transition to all-electric drive compressor trains has the potential to markedly increase the efficiency of industrial and pipeline compression systems. A study by GE for large-scale compressor systems, the all-electric drive approach (remote central station gas-fired combined cycle ~300 MW, 58% efficient) has a projected efficiency of 39.8% compared with 25.4 % for an on-site gas turbine driven mechanical drive approach. The reduction in CO2 emissions is about 45%

A conceptual all-electric drive system has been proposed by DOE. This new approach eliminates the conventional transformer and gearbox from the compressor machinery chain. Big 60 Hz transformers can be replaced by much smaller high frequency transformers. A VSD drives a high speed motor that directly drives the compressors. This approach is offers a system that is 5X smaller and more efficient and would be offered as a packaged unit in a single container.

Minimum System Requirements for a demonstration of this technology have been suggested by DOE as:

- Input: > 13.8kV (L-L)
- Input voltage to VSD: > 2kV (Medium Voltage Class); Use of Solid State Transformer (SST) for isolation and voltage step down from 13.8 kV (L-L) is **optional**. Standard 60Hz line transformer can be used for the demonstration.
- Switching frequency: > 5 kHz
- Motor fundamental electrical frequency: > 500 Hz
- Speed > 15000 rpm
- Output: Power > 1MW

This all-electric drive requires advanced components that utilize SiC rather than Si because of its higher efficiency, higher operating temperature, higher blocking voltage, and higher switching frequency. The following markets have taken advantage of the improved performance that results from utilization of SiC based components in place of lower performance Si based components:

- AC Medium Voltage Drives Applications
- Railway Applications (3.3 kV SiC already being adopted in Japan rail)
- Grid-tied Solar Applications
- HVDC Applications (Off-shore wind, hydro)
- Grid-tied Power Distribution (Energy-intensive structures such as factories, data centers)

Currently high voltage (>6.5 kV) semi-conductors needed for these systems are not commercially available at attractive prices. Devices with ratings of 10-15 kV would be preferred for these VSD-High Speed Motor Systems. Significantly lower prices are potentially available in the future. Cree, the largest US manufacturer of 1.2 kV SiC MOSFETS reports that in 2013 the single unit price for those items was $0.78/A (volume purchases are priced lower per unit). They estimate that by 2017, that that price could be reduced to $0.18/A for volume purchases assuming that sales increased by 2.5 orders of magnitude by that date.

Other vendors are utilizing various approaches such as foundries where vendors can produce custom designed items for multiple customers utilizing equipment that has been used previously for Si component production. This approach avoids capital investment by chip companies for in-house production facilities. Monolith Semiconductors predict that by utilizing the foundry approach, 1.2 kV and 1.7 kV MOSFETSs will drop in price to $0.10/A and $0.15/A respectively by 2020.

2. Introduction

Goals of the April 16-17, 2014 and September 4, 2014 Variable Speed Drive Workshops

The goal of the High Megawatt Variable Speed Drive Technology Workshop held previously on April 16-17, 2014 was to "identify the applications and approaches where advanced HMW machine technologies, front end power electronics, and their integration might provide substantial benefit" (see http://www.nist.gov/pml/high_megawatt/april-2014_workshop.cfm). (Hefner)

At that Workshop, it was reported that a significant reduction of the energy consumed world-wide could be achieved by transitioning large-power motor applications to VSD motors:

- Approximately 14% of the total electricity consumed in the United States flows through large-power electric motors (1-50 MW); e.g., for the Chemical, Oil, and Gas industry

- Many of these motors drive 10,000 to 20,000 RPM mechanical loads through a large gearbox and use mechanical throttles rather than power-electronics based VSDs. (Hefner)

That Workshop defined potential benefits of advanced HMW machine technology, front end power electronics, and their integration which included:

- High-Electrical-Speed Direct-Drive Motors (high-speed VSD and machine would eliminate need for large gear box and mechanical throttles)

- "Transformer-less" Medium-Voltage Drives (small, high frequency transformer integrated within the VSD would replace large 60 Hz grid-step-down transformer)

- Integrated Motor-Drive System (grid-to-load system delivered as one unit would reduce size, weight, and cost) (Hefner)

The September 4, 2014 Workshop on High-Megawatt Direct-Drive Motors and Front-End Power Electronics focused on defining:

- The cost/performance metrics that would quantify the benefits of an integrated direct-drive high-speed motor system solution (grid interface, high-speed MV drive, and gearless high-speed motor) versus today's baseline solution;

- Key milestones for the required HMW power electronics/machine technology development needs;

- Considerations for subsequent scaling of the integrated high-speed direct-drive motor solution to high manufacturing volume and higher MW levels (from initially ~1 MW to >30 MW). The goal of the September 4, 2014 Workshop was to roadmap machine designs/concepts, power conditioning system (PCS) architectures, and advanced technologies needed to implement the most promising approaches; and define how to quantify benefits. (Hefner)

DOE has targeted the following metrics for WBG-based VSD machinery trains

- 4x improvement in volumetric power density.
- 3x reduction in foot print.
- 2% improvement in overall efficiency. (Agarwal)

3. Brief Summaries of Key Points of Presentations

A. Motor Markets

In 2012, the world-wide market for medium–voltage (MV) motors was 4.5 Billion US$. A large fraction of this market was in the Chemical and Oil and Gas industries (COG). In the United States alone, there are over 900 interstate natural gas pipeline compression stations. CO2 transportation networks are growing in size and number (Agarwal). Each year, there are thousands of new oil and gas compressor and pump installations. More than 30% of these have a VFD (Variable Frequency Drive) and motor (Englebretson). In addition to these new installations, it has been estimated that a minimum of 3,700,000 hp of the existing motors on these interstate pipelines must be replaced in next 15 years. (Arshad).

Both the natural gas and CO2 pipeline systems typically utilize networks of 25 MW gas turbines (30% efficient) coupled with compressors (82 % efficient). The overall efficiency for that combination is 25 % efficiency.

One approach to achieving higher efficiency would be to store natural gas and use that stored gas to produce electricity in large (>300 MW) high efficiency (~60%) gas turbine combined cycles power plants and transport that electricity by wire to compressor stations. The use of Variable Speed Drives (VSD) on the motors at the compressor stations could eliminate the 20-40% efficiency lost with conventional flow control systems that employ throttles and other mechanical devices to control flow rate.

High RPM Direct Drive Motors have the potential to significantly reduce size and cost of large compressor systems in COG applications.

This new approach eliminates the conventional transformer and gearbox from the compressor machinery chain. A VSD drives a high speed motor that directly drives the compressors. This approach is offers a system that is 5X smaller and more efficient and would be offered as a packaged unit in a single container. It offers economic benefits for applications in harsh environments such as downhole for example where temperatures are typically in the range of 250-350C. All of the power electronics are inside the machines and cabling costs can be reduced. (Agarwal)

- Big 60 Hz transformers can be replaced by much smaller high frequency transformers
- Motor size reduced by 5x – cheaper, less magnets
- 20-40% energy per motor system is saved due to Variable Speed Drive – pay-back resulting from electricity savings is < 3 years
- Gear Box eliminated
- Up to 5x smaller foot-print () (Agarwal)

A study by GE for large-scale compressor systems, the all-electric drive approach (remote central station gas-fired combined cycle ~300 MW, 58% efficient) has a projected efficiency of 39.8% compared with 25.4 % for an on-site gas turbine driven mechanical drive approach. The reduction in CO2 emissions is about 45%

All Electric Drive		Direct Mechanical Drive	
Component	**Efficiency, %**	**Component**	**Efficiency, %**
Remote 300 MW Combined Cycle	58	On-site 8 MW Simple cycle gas turbine	34
		Other Gas turbine auxiliary losses	91
Transmission	95		
Transformers	97		
Variable Frequency Drive	98		
Motor	96.5		
Compressor	78	Compressor	82
Overall	39.8		25.4

(Raju)

Chemical and Oil and Gas Industry Applications

There are a large number of specific applications In the Chemical and Oil and Gas industries for improved performance and lower cost motors and drives that would be used in these industries

Upstream, Midstream, and Downstream Chemical and Oil and Gas Industry Applications

Segment	Sub-segment	Applications
Upstream	**Oil Production** (enhanced oil recovery)	• Gas Reinjection • Gas Lift
	Gas Production (enhanced gas recovery	• Gas Depletion • Gas Export
	Oil & Gas Processing	• Gas Gathering • Gas Oil Separation (GOSP) • Treatment (Impurity Removal) • Gas Liquefaction (LNG&GTL)
Midstream	**Oil & Gas Transmission**	• Pipeline Booster Stations
	Oil & Gas Storage & Distribution	• Gas Injection / Withdrawal • Branch Line Booster Stations
Downstream	**Oil Refining**	• Pumps • Compressors

	(gasoline, naphtha, kerosene, gas oil and more …)	
	Petrochemical Plants (Olefins (butadiene, ethylene, aromatics),Styrenics (styrenes, EB, SM), Polymers (PP, PE) and many more …)	• High pressure compressors • Extruders, pelletizers • Mixers • Pumps • Fans
	Chemical Plants (Process air, Nitric acid production	• Integrally geared compressors • Large axial & radial compressors
	Air Separation (Technical gases, refrigeration)	• Large axial and radial compressors • Integrally geared compressors

(Arshad)

Additional upstream applications for MV AC drives are used in a wide variety of in upstream oil and gas applications

- FPSO (Floating Production Storage and Offloading)
- Re-built tankers with drilling equipment, pumping, compression and generating units on deck. Compact process modules due to limited space on deck required
- For marginal field development or deep-water production
- Marine certified equipment (ABS, DnV, BV, Lloyds etc.)
- Pumps and compressors
- Onshore plant installations
- Offshore platforms
- Reliable operation in harshest industrial environments (Ex)
- Redundancy requirements (usually 3 x 50% or 2 x 100% installed capacity)

(Arshad)

B. Integration of Mechanical and Drive Technology for High-Speed Motors

In has been noted that high power compressors represent a very large fraction of the Medium Voltage compressor drive market. Most of the compressors in service today are driven by gas or steam turbines. The high speed stand-alone electric drive compressor offers significant potential advantages over the turbine driven system. .

High Power Compressor Drivers - Drive Train and Integration Technologies

Drivetrain Concept	**Gas or Steam turbine driver**	**High speed stand-alone**
Technology	Gas or process steam is energy source Generally gearless, but large oil system for gas turbines	Motor directly coupled to compressor, no gear box Always needs VFD Oil-lube or Magnetic bearings
Technology Features	High noise and CO_2 emissions Large space & weight	Highest efficiency No gear maintenance
Advantages	No grid connection (e.g. Remote locations, high cost for electricity,	Eliminates gear and large lube system, oil-lean With Magnetic Bearings: oil-free

(Arshad)

There are significant system integration possibilities and benefits resulting from combinations of any combination of two or more of the following - Variable Speed Drive, Motor, Compressor or other load or Bearings These changes enable joint design and system optimization, footprint reduction, minimize cabling and interconnection, common cooling strategies, and simplifies purchasing, installation, commissioning, control (Englebretson)

Potential system advantages include, increased reliability, reduced maintenance, increased efficiency (total system, part load, and starting), Reduced environmental impact (oil, exhaust, noise), and improved flexibility and control. However there are a number of electromagnetic, thermal and mechanical issues that must be addressed.

Electromagnetic Issues	**Thermal Issues**	**Mechanical Considerations**
Stator - High speed, few turns, low inductance	High power density	Centrifugal forces, rotor retainment, and structural integrity
Insulation - High dV/dt from drive switching frequency	Stator or rotor conductor loss	Mechanical Friction and windage losses
Losses - Core loss increasing with frequency	Insulation temperature and lifespan	Mechanical resonance, balance vibration and oscillations

	Magnet temperature	
	Thermal expansion and cycling	

(Englebretson)

High speed motors offer the potential for significant volume and weight reductions compared to today's conventional motors that operate at 1800 rpm

Comparison of High Speed versus Conventional 2 MW Motors

	Conventional-1,800 rpm	**High Speed - 22,500 rpm**
Volume	3.1 m^3.	0.85 m^3
Weight	4848 kg	1787 kg

High speed motors offer a number of design challenges that must be considered.

- Rotor dynamic performance
  - Mode separation and margin across entire speed range
  - Supercritical rotor complicates bearing design and reliabili
- Thermal management
  - High power density requires liquid cooling in the stator
  - Eddy current losses require use of Litz wire or Roebel coils in the stator winding
  - Core losses require use of thin laminations (0.18 mm or less)
  - Unconventional air circulation schemes to overcome pressure drop at air gap
  - Oil film bearings are lossy. Magnetic bearings are preferred
  - Power quality (or lack thereof) affects rotor heating
  - High efficiency is critical
- Stress management
  - Rotor containment
  - Magnetic bearing rotating components
- Torque pulsation
  - Large air gaps and good power quality reduce torque pulsation
- Motor insulation and coil design
  - Litz wire or Roebel coils to limit eddy current losses
  - Corona and grading tape use in medium voltage to reduce insulation stress and overheating
  - Lead design must consider skin effect
  - Thermal conductivity v. dielectric stress
  - End turn length
- Power quality
  - Drive and motor ideally designed in conjunction
  - Limitations on switching frequency in drives can produce low and high order harmonics
  - Magnet configuration in PM machines can affect power quality (Guedes-Pinto)

The characteristics of Variable Frequency Drives for High Speed Application include

- High frequency drives are usually de-rated versions of commercial low frequency drives
- Low switching frequency is not conducive to good power quality
- Compliance to IEEE 519 does not guarantee good motor performance
- Current THD 2% or better to reduce rotor heating and prevent catastrophic rotor failure
- Interleaving can support high fundamental frequency without increasing switching frequency
- Low voltage cell design offers opportunities to improve power quality and efficiency – Drive segmentation
- Use of SiC MOSFET
- High switching frequency (>10 kHz) (Guedes-Pinto)

Among the cost considerations are

- Torque
- Electric machine size is a function of torque (D^2L)
- Machine topology
- Embedded PM cost > Wound field synchronous > Surface mounted PM > Induction
- Bearing topology
- Magnetic bearing cost > oil film > anti-friction
- Operating speed and voltage class
- Stator winding complexity
- Cooling scheme
    - Can vary substantially depending on machine size, topology, air and water circuits (Guedes-Pinto)

TWMC (TECO Westinghouse Motor Company) VersaBridge Multi-Level Topology incorporates a number of SiC-based components in their Future Vision

	Existing	**Future Vision**
Semiconductor Solution	IGBTs + Diodes (Si based)	IGBT + SiC Diode SiC Transistor +Diode
Transformer Solution	Iron core transformer	None – motor winding and VSD matched High frequency core
Slice	Power converter + Transformer	Power converter (+ Transformer)
Cooling	Liquid Cooling	Advanced Liquid Cooling
Control	Distributed Control	Enhanced Distributed Control
Solutions	Series & Parallel Solutions	Series & Parallel Solutions

(Guedes-Pinto)

GE offers a line of high-speed oil & gas machines referred to as the Integrated Compressor Line (ICL). These machines feature

- Direct-drive high-speed Induction motor / Permanent Magnet motor
- MV drives typically limited to fundamental frequency in the range of 100 Hz; typical switching frequency of 1 kHz
- High-speed direct drives in compression systems require up to 1 kHz fundamental
- Requires multi-level topologies and filtering with Si devices
- Simpler 2L or 3L topologies using high switching frequency of SiC devices can enable this application

Integrated Motor and Drive allow:

- Higher power density/smaller system footprint
- Reduced EMI issues/cabling
- Reduced system cost
- High temperature capability of SiC can be effectively used to minimize/simplify cooling loops

SiC Performance Entitlement (smaller system footprint, lower system cost, higher efficiency, reliability/harsh environments) have been reached with multi-discipline integration

- Advanced Insulation Systems
    - High thermal stability/temp.
    - High voltage, thin film insulation
    - High dV/dt pulse resistant
    - High thermal conductivity
    - Chemical resistant
- Advanced Magnetic Material
    - Advanced lower-cost high-performance permanent magnets
    - Advanced soft magnetic material:
        - Dual-phase motor laminates with locally patterned low μ regions for flux path control
- Advanced Manufacturing
- Advanced Motor Controls
- Advanced Motor Topologies
- Advanced Power Converters
- Monitoring and Diagnostics
- Thermal Management
    - Micro-channel cooling jacket
    - Micro-channel cooling jacket & EW spray
    - Micro-channel cooling jacket & slot cooling tubes

Power-electronics transformers is used for both AC/AC or DC/DC applications. The Integrated High Frequency (HF) Transformer is the enabler for 10x size reduction via utilization of 10 –

100 kHz. Substantial benefits at the systems level are accomplished through tight integration of advanced HF transformers with SiC bridges The overall system benefits include improved compactness, efficiency, and controllability.
(EL-Refaie)

GE has accumulated superconducting machine experience with the following topologies:

- Conductors: LTS, HTS, MgB2
- Machine Type: Wound field synchronous, Homopolar Inductor Alternator
- Magnetics: Iron core, Airgap winding, Air core
- Mechanical Configuration: rotating field winding stationary field winding

Superconducting machines, if cost-effective, can benefit from SiC-based drives similar to conventional machines

(EL-Refaie)

Advanced Magnet Materials

Currently the most popular Permanent Magnet (PM) material used in advanced motors is Nd-Fe-B based. In recent years Rare Earth Elements (REE) such as Nd which have been required for PM have been in short supply, prompting development efforts on non-REE materials for PM. The REE supply crisis is over for now.

The most popular soft magnetic material is FeSi (3.2wt.%). Increasing the Si content to 6.5% improves the magnetic properties to an optimum level, but that material is very brittle and difficult to fabricate.
(Cui)

C. WBG Devices Cost and Development Roadmap

The performance improvement potential of WBG-based components particularly SiC-based is very large due to their higher operating temperature, higher blocking voltage, higher efficiency, and higher switching speeds. However their incorporation in systems to replace Si-based components has been limited by early concerns about their reliability and cost. Their excellent reliability has been demonstrated in long term field operations and no longer in doubt. However, the price of these high performance components is still above similarly-rated Si-based components.

The following markets have taken advantage of the improved performance that results from utilization of SiC based components in place of lower performance Si based components:

- AC Medium Voltage Drives Applications
- Railway Applications (3.3 kV SiC already being adopted in Japan rail)
- Grid-tied Solar Applications
- HVDC Applications (Off-shore wind, hydro)
- Grid-tied Power Distribution (Energy-intensive structures such as factories, data centers) (Casady)

Other potential applications for drive systems containing SiC components include:

- Energy Storage Systems (ESSs) for Grid-tie
- Solid-State Transformers
- Navy Warships: 4.16-13.8 kV, Multi-MW
- Electric Locomotives: 3 kV, Multi-MW
- HV Circuit Breakers (Olejniczak)

Predicted Performance Benefits of Silicon Carbide

A study at the University of Tennessee - Knoxville evaluated the benefits of high-speed SiC drives for integrated direct-drive motor. Initially the study collected the latest HV SiC data available from commercial vendors which revealed that:

- Voltage ratings are in the range of 3.3 kV to 22.5 kV with current ratings below 50 A
- The most popular device types are SiC MOSFET and JBS Schottky diodes
- SiC devices exhibit significantly better conduction and switching characteristics

Benefits of HV SiC can be realized in four ways

- Direct substitution – improved efficiency and power density
- Simplified topology – further loss reduction and increased power density
- Enable high speed motor drive
- Improve front-end rectifier

The high speed direct drive compressor with transformer-less front-end rectifier is identified as a suitable "killer" application for HV SiC devices

- The transformer and front-end rectifier are replaced by a SiC based, solid-state transformer (SST) type front-end rectifier
- The inverter is replaced with the simple two-level VSI
- With the high speed motor, the gearbox can be eliminated
- No regeneration

The conclusions of a study comparing a Si based 1 MW MV compressor system drive equipped with a line-frequency transformer, low speed (60 Hz) motor and gearbox with a SiC based MV direct drive with solid-state-transformer and high speed (300 Hz) motor were that:

- SiC MV drive has slightly better efficiency (~97.5%), much higher power density (500 W/l vs. 150 W/l), and a much smaller footprint (1.0 m^2 vs. 3.3 m^2).
- Considering the motor and compressor, the impact of a SiC direct drive on power density can maintain a similar ratio (140 W/l vs. 40 W/l). The footprint ratio is also similar (3.0 m^2 vs. 7.8 m^2)
- The key performance metrics for SiC MV drives:
  97.5% efficiency, 500 W/l power density, and 1.0 m^2/MW footprint
- The key design parameters for SiC MV drives can include: output frequency > 300 Hz, input and output current harmonics < 5% for typical grid and motor load conditions, SST switching frequency > 20 kHz, SiC device rating > 10 kV (?).

Suppliers of SiC based chips, devices, components and integrated packages

Four companies, Cree, APEI, Monolith Semiconductors, and United Silicon Carbide Inc. which have adopted different approaches to lowering the cost of SiC based chips, devices, components and integrated packages reported on their efforts at the Workshop

Cree

Cree is the largest US producer of SiC MOSFETS, SiC Schottky diodes, and all-SiC power modules. It is a vertically integrated (from raw materials to finished products) $1.65 B annual business with virtually all revenue based on SiC substrates. Its cost reduction strategy is based on increasing production volume as the route to lowering costs.

In 2013, Cree reports that 1.2 kV SiC MOSFETS had a single unit price of $0.78/A (volume purchases are priced lower per unit). They estimate that by 2017, that that price could be reduced to $0.18/A for volume purchases assuming that sales increased by 2.5 orders of magnitude by that date.

In 2014, Cree reports that 3.3 kV SiC MOSFETS have a single unit price of $17.50/A (volume purchases are priced lower per unit). They estimate that by 2016, that price could be reduced to $3.60/A for volume purchases assuming that sales increased by 4 orders of magnitude by that date

For 10 KV SiC MOSFETS in 2014 their current price for single units is $60/A. They estimate that by 2018, that that price could be reduced to $10/A for volume purchases assuming that sales increased by 4 orders of magnitude by that date.

The Cree Field Failure Rate Data for SIC MOSFETS and diodes since January 2004 through March 2014 is 0.12 FIT (Fails per Billion hours. That rate is 10 times lower than the typical silicon-based items. SiC diodes were first released in 2001 and SiC MOSFETs were first released in 2011. Most of the data was accumulated with the diodes (Casady)

Monolith Semiconductor

Monolith is a fabless semiconductor manufacturing company. They provide design information to existing 150 mm Si foundries, 150 mm SiC wafer suppliers and assembly information. Monolith owns all SiC design and SiC process IP. Based on the information provided, their vendors deliver finished 900V, 1.2kV, and 1.7kV+ SiC diodes and MOSFETs to Monolith. The advantage of this fab-less approach to Monolith is that their process is compatible with existing Si processing equipment and allows the use of high volume in-place 150 mm CMOS foundry lines for low-cost manufacturing. No capital investment in processing equipment is required

Recent accomplishments include

- Demonstrated 1200V, 5.5 mOhm-cm2 SiC MOSFETs with stable operation at 225°C.
- Transferring their SiC processes into a high-volume, 150 mm silicon foundry. They are targeting to run SiC wafers in parallel with silicon wafers on the same process tools.
- Demonstrated initial SiC processes, including demonstrating 1700V SiC implanted PiN diodes.

The Advantages and Challenges of this fabless approach are:

Advantages:

- Lower cost – piggyback on large silicon volumes
- Don’t have to reinvent the wheel
- Matured manufacturing and quality systems – think automotive
- Fast time to market and scaling to high volume as demand picks up

Challenges:

- Convincing a high-volume silicon automotive fab to run a new material
- Lack of flexibility of processes
- Lack of SiC-specific tools
- IP control
- Risk allocation

They predict that 1.2 kV and 1.7 kV MOSFETSs will drop in price to $0.10/A and $0.15/A respectively by 2020. (Banerjee)

United Silicon Carbide Inc. (USCi)

United Silicon Carbide Inc. is a semiconductor company pioneering the development of high efficiency Silicon Carbide (SiC) devices including Schottky Barrier Diodes, JFETs, MOSFETs, Bipolar Junction Transistors, application specific products, SiC IC's and Foundry Services. The Pros and Cons of utilizing foundry services are outlined below

Pros

- Silicon foundries bring a lot of established baseline expertise and manufacturing discipline
- High uniformity and high throughput processing equipment
- Foundries of sufficient scale with a solid (non-SiC) base business can offer reduced process costs
- By aggregating the SiC business from multiple companies, they can generate more economies of scale
- Capital efficient for ramping volume production

Cons

- Most foundries need consigned equipment to enable a SiC process
- Concerns about IP protection – exclusivity can defeat the cost benefit from volume aggregation.
- Speed of technology development
- Volume projections in the near term 2-3 years are still too low to justify large investments
- Capacity and engineering resource allocation

SiC fabrication is subject to the following issues

- Total fab volume and utilization drive costs – must find SiC volume drivers, or share the factory with other volume contributors
- High cost tools with limited throughput drive up costs – SiC has several such bottlenecks in epi, implant, backgrind, saw. These are being rapidly improved
- Epi cost dominates present day SiC high voltage costs – area needing rapid improvement in throughput without worsening quality
- For pure unipolar devices (JBS Schottky, MOSFET, JFET), several large chips needed for meet the current requirements.

The foundry model brings down wafer down costs, allows volume ramp with targeted capital expenditures, and brings Si high volume manufacturing capability to SiC. This translates both to stable high yields, as well as the ability to quickly deliver large volumes. Technological progress is needed and ongoing to drive down epitaxy costs for >3300V devices. (Bhalla)

APEI

APEI is a small company (~ 50 employees) which is focused on manufacturing low-cost high-voltage SiC power modules. Their specialty is the development of standard packaging. They have developed a HV SiC MCPM Design with a focus on the low cost manufacturability.

Other recent studies have concluded that significant size and weight reduction are possible in systems where 6.5 kV Si-based components are replaced with 12 kV SiC based components. Replacing Si with SiC components in an ABB SVC Light Energy Storage System reduced mass by a factor of 20-28 depending on operating conditions. For systems that replaced a passive transformer with a Solid State Transformer, volume was reduced by factors of 5-20 depending on operating conditions.

A limited number of >10 kV SiC R&D sample parts are presently being fabricated. There are no catalog parts. The market price for these sample parts is unknown at this time.

4. Responses to Key Questions

(To be added later)

The previous April 2014 HMW workshop goal was to "identify the applications and approaches where advanced HMW machine technologies, front end power electronics, and their integration might provide substantial benefit" (see http://www.nist.gov/pml/high_megawatt/april-2014_workshop.cfm). The September 2014 workshop (detailed goals defined in a separate document) will focus on defining: 1) the cost/performance metrics that would quantify the benefits of an integrated direct-drive high-speed motor system solution (grid interface, high-speed MV drive, and gearless high-speed motor) versus today's baseline solution; 2) key milestones for the required HMW power electronics/machine technology development needs; and 3) considerations for subsequent scaling of the integrated high-speed direct-drive motor solution to high manufacturing volume and higher MW levels (from initially ~1 MW to >30 MW).

Key Questions:

1) What are cost/performance metrics that would quantify the benefits of megawatt scale integrated direct-drive high-seed motor system solutions (grid interface, high-speed MV drive, and gearless high-speed motor, 10,000 -20,000 rpm) versus today's baseline solution?

    1a) What are representative cost per megawatt metrics for each stage of today's baseline solution, and what is expected total cost reduction for an integrated system and how would it be quantified in a proposed demonstration?

    1b) What are maintenance requirements and lifecycle cost issues for today's baseline solution, and how might proposed integrated solutions quantify lifecycle cost benefits?

    1c) What are energy loss components of today's baseline solution, and how might proposed integrated solutions quantify efficiency benefits?

    1d) What are footprint reduction metrics that would best quantify the benefits of the integrated solution?

    1e) What are factors that would need to be demonstrated to insure scalability of new solutions to high-volume low-cost manufacturing?

2) What are key milestones for the required HMW power electronics/machine technology development needs?

3) How will integrated direct-drive high-speed motor systems scale to high-megawatt (>30MW) and what are future markets (10 years) for these systems?

    3a) What are the applications for >10 MW motors (e.g., in oil and gas)?

    3b) What are system specifications and performance requirements for larger >10MW motors (e.g., application speed requirement might be 3,000-4,000 rpm versus 10,000-20,000 rpm for 1 MW applications?

    3c) What are additional technology needs to ensure scalability to high MW (e.g., higher voltage semiconductors >15 kV, power electronics topologies, machine types, etc.)?

5. Appendices

A. Final Workshop Agenda

Agenda for NIST/DOE Workshop on
High-Megawatt Direct-Drive Motors and Front-End Power Electronics

(September 4, 2014)

8:30am Convene

1) Introduction Session:

Introduction of participants

Previous HMW Workshops & Workshop Goals and Key Questions – Al Hefner

DOE EERE Needs for Program Planning – Anant Agarwal/ Ziaur Rahman

ABB – Applications of High-RPM DD Motors in COG Industries (NG, LNG) – Waqas Arshad

GE OG – Applications for High-Speed Motors in Oil and Gas Industries – Ravi Raju

Break 10-10:30am

2) Panel: Integration of Mechanical and Drive Technology for High-Speed Motors (Tom Lipo):

ABB/Baldor – Motor mechanical/drive system integration – Steve Englebretson

UTK – Benefits of high-speed SiC drives for integrated direct-drive motor system – Leon Tolbert and Fred Wang

GE Electrical Machines – Integration of SiC power devices into high-power motor drives – Ayman EL-Refaie

Teco Westinghouse – High-Speed direct-drive motors enabled by SiC power devices – Paulo Guedes-Pinto

LUNCH 12:00-1pm

Panel discussion period

3) Panel: WBG Devices Cost and Development Roadmap (Leo Casey):

Cree – Power products roadmap plans for commercialization of SiC power switches and power diodes from 2012-2020 – Jeff Casady

Cree – Power products reliability data and pricing forecasts for power module, power MOSFET and power diode products from 650V to 15kV. – John Palmour

United SiC – Economic viability of SiC power commercial foundry approach – Anup Bhalla

Monolith – Foundry process integration and product roadmap and cost projections for 1200V/1700V devices – Sujit Banerjee

APEI – Manufacturing low cost SiC module packages – Kraig Olejniczak

Break 3:00 -3:30pm

Panel discussion period

4) Panel: Advanced Motor and Drive Technology (Ravi Raju):

PNNL – Magnetic Materials for Motors – Jun Cui

NCSU – High-voltage, high-frequency SiC power electronics – Subhashish Bhattacharya

Panel discussion period

5pm Adjournment

B. List of Workshop Participants

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C. List of Workshop Presentations

Agarwal, Anant
Next Generation of Electrical Machines

Arshad, Waquas
Medium Voltage Drives, High MW Motors - Chemical Oil & Gas (COG) Industry Applications

Banerjee, Sujit
Redefining Power Conversion with Cost-Effective Silicon Carbide Technology

Bhalla, Anup
SiC Manufacturing in the Foundry Model

Casady, Jeff
Power products commercial roadmap for SiC from 2012-2020
Power products reliability data & pricing forecasts for 650V-15kV SiC power modules, MOSFETs & diodes

Cui, Jun
Magnetic Materials for Motors

EL-Refaie, Ayman
GE Electrical Machines-Integration of SiC Power Devices into High-Power Motor Drives

Steven Englebretson
Mechanical/Drive System Integration, High Megawatt Direct Drive Motors

Guedes-Pinto, Paulo
High Speed Direct Drive Motors Enabled by SiC Power Devices

Heffner, Allen
Workshop on High-Megawatt Direct-Drive Motors and Front-End Power Electronics

Olejniczak, Kraig J
Manufacturing Low-Cost High-Voltage SiC Power Modules

Raju, Ravi
Motor Drives for Oil and Gas Applications

Wang, Fred
SiC High-speed MV Direct Drive vs. Si Low-speed MV Drive in Compressor Applications