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

Fred Wang and Leon Tolbert
University of Tennessee, Knoxville
Oak Ridge National Laboratory

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Summary of Survey Results

- The latest HV SiC data available from commercial vendors were collected
  - 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
- Si MV drive applications and technologies were summarized
  - Pumps, fans, compressors dominate traditional applications
  - Renewables and transportations are emerging applications
  - LV IGBT based CHB and MV IGBT/IGCT based multi-level NPC are most popular inverter topologies; multi-pulse diode rectifiers and PWM active rectifiers are widely used front-end
- 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

Outline

- **Objective**
- **Technical Approach**
- **Comparison**
  - ➢ **Transformer and front end rectifier**
  - ➢ **Inverter**
  - ➢ **Motor, gearbox, and compressor system**
- **Summary**
- **Research Needs**

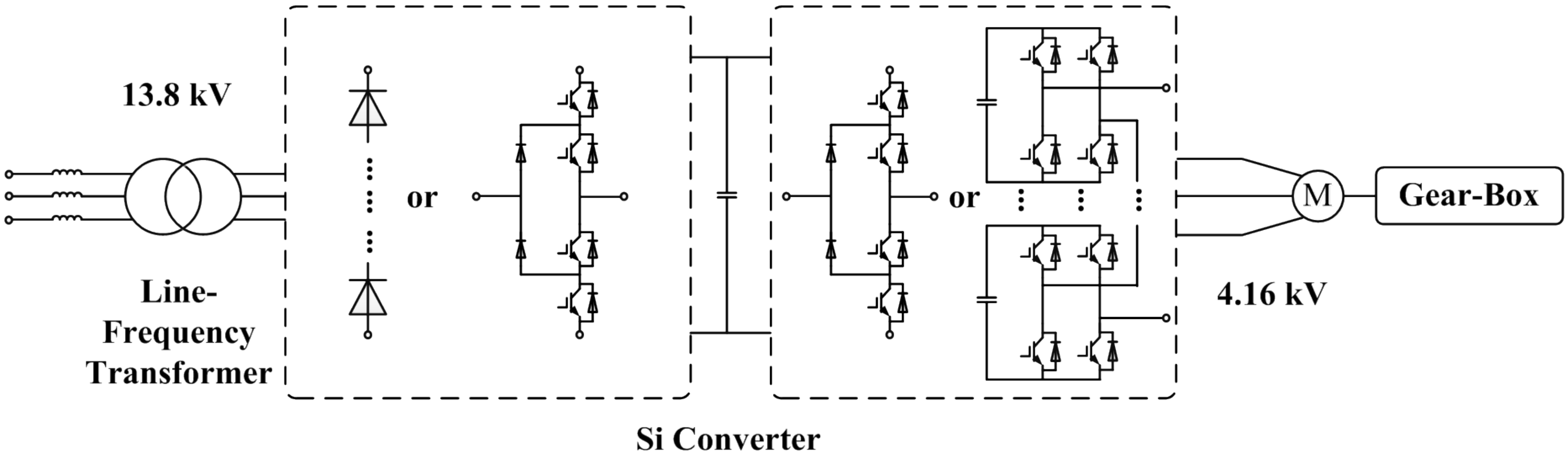
Technical Approach

- Select a benchmark system
- Compare Si based low-speed MV drive solution to a SiC based MV direct drive solution
  - ➢ Divide the comparison into three parts:
    1. transformer and front end rectifier
    2. inverter
    3. motor and gearbox (compressor)
  - ➢ Select the best available solution for each part for both Si and SiC technologies
  - ➢ Perform comparison through design as well as using available product and prototype information
  - ➢ Focus on efficiency, power density, and footprint
- Determine the key design parameters for SiC MV drive

Benchmark System

System Specifications and Assumptions

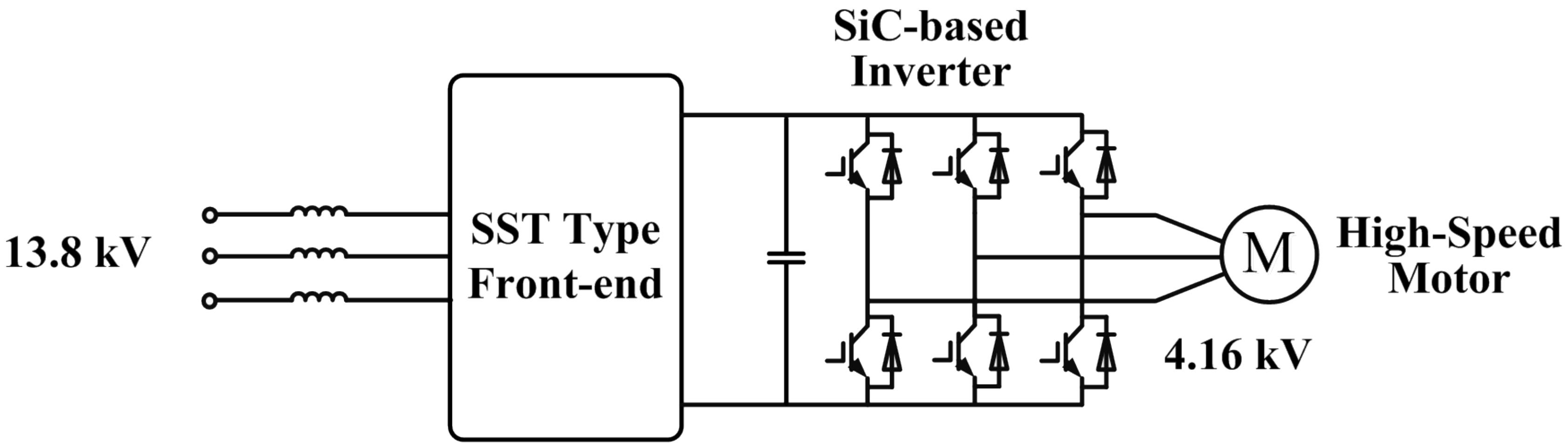
Power	Grid Voltage	Motor Voltage	Direct Drive Frequency	Motor Power Factor
1 MVA	13.8 kV, 60 Hz	4160 V	300 Hz	0.9



Typical Si Based Low-speed MV Drive Configuration

- Based on survey and analysis, the most popular Si MV drive solution is 3-level NPC inverter with multi-pulse front end diode rectifier
- Regeneration not required

SiC MV Direct Drive System



SiC Based MV Direct Drive Configuration

- 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

Comparison Group Selection

Transformer and Front-end Rectifier

Group	Configuration
1	60 Hz transformer + multi-pulse diode rectifier
2	Solid-state-transformer (SST) type (AC/DC + high frequency DC/DC)

Inverter

Group	Topology	Switching Device	Junction temp.	Rated frequency	Switching frequency
1	3L-NPC	6.5 kV/ 250 A Si IGBT	125 ^{o}C	60 Hz	1 kHz
2A	2L-VSI	15 kV/ 10A SiC MOSFETs (Cree) * 30 in parallel	125 ^{o}C	300 Hz	10 kHz
2B	2L-VSI	15 kV/ 10A SiC MOSFETs (Cree) * 30 in parallel	200 ^{o}C	300 Hz	10 kHz

Motor and Gearbox (compressor also included as in the commercial products)

Group	Configuration
1	Low speed motor + gear box
2	High speed motor

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Front-End Comparison: Efficiency

- Efficiency of the GE Phase II SSPS is expected to be 98%
- Efficiency of the conventional transformer plus the multi-pulse rectifier is also assumed to be 98%. This assumption is based on the information from the HPE project for a conventional transformer. The diode-rectifier is highly efficient. The multi-pulse rectifier will require phase-shifted multi-winding transformers, which may yield a penalty in efficiency and size

Front-end Efficiency Comparison

Group	Topology	Efficiency
1	60 Hz Transformer + 18-pulse diode rectifier	98%
2	SST type (GE SSPS Phase II)	98%

Note GE SSPS II with switching frequency of 40 kHz.
- The comparison between SSPS I with switching frequency of 20 kHz shows similar efficiency and power density
- Unidirectional power

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Front-End Comparison: Size & Weight

Dimension and Size Comparison (note: height scaled to 72")

Group	Power	Topology	Dimension & size	Dimension & size (Scaled for 1 MW)	Power Density
1 A	3 MW	Transformer + Rectifier	168"W x 60"Dx81"H ($13.38\ m^3$)	102"W x 37"D x 72"H ($4.47\ m^3$)	$0.22\ kW/dm^3$ (ratio 1.0)
1 B	2.2 MW	18-pulse diode rectifier	63"W x 39"D x 87"H ($3.56\ m^3$)	46"W x 29"D x 72"H ($1.59\ m^3$)	$0.63\ kW/dm^3$
2	3 MW	SST type (GE HPE phase II)	60"W x 50"D x 72"H ($3.54\ m^3$)	35"W x 29"D x 72"H ($1.2\ m^3$)	$0.83\ kW/dm^3$ (ratio 3.78)

Weight Comparison

Group	Power	Topology	Weight	Weight (Scaled for 1 MW)	Specific Power
1 A	3 MW	Transformer + Rectifier	35,000 lbs	11,667 lbs	0.188 MW/ton (ratio 1.0)
1 B	2.2 MW	18-pulse diode rectifier	N/A	N/A	
2	3 MW	SST (GE HPE phase II)	4,000 lbs	1,333 lbs	1.65 MW/ton (ratio 8.75)

Note the linear scaling of transformer with power is an approximation

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Inverter Comparison Strategy

Strategy:

- Perform detailed design comparison between a Si 3L-NPC and a SiC 2L-VSI with the same input and output voltages (6.75 kV DC and 4160V AC), and different output frequencies (60 Hz for Si and 300 Hz for SiC)
- The two will maintain the same switching frequency and output frequency ratio
- Voltage and current margins are kept close for the Si and SiC devices: the Si inverter uses 6.5 kV, 250 A commercially available Si IGBT modules, while the SiC inverter uses 30 paralleled 15 kV, 10 A SiC MOSFETs.
- Design focused on efficiency, cooling system, and passives (DC link capacitor).
- Actual size will be scaled based on a real Si MV drive inverter

Group	Topology	Switching Device	Junction temp.	Rated frequency	Switching frequency
1	3L-NPC	6.5 kV/ 250 A Si IGBT (Infineon FD250R65KE3-K)	125 ^{o}C	60 Hz	1 kHz
2A	2L-VSI	15 kV/ 10A SiC MOSFETs (Cree) * 30 in parallel	125 ^{o}C	300 Hz	10 kHz
2B	2L-VSI	Same as 2A	200 ^{o}C	300 Hz	10 kHz

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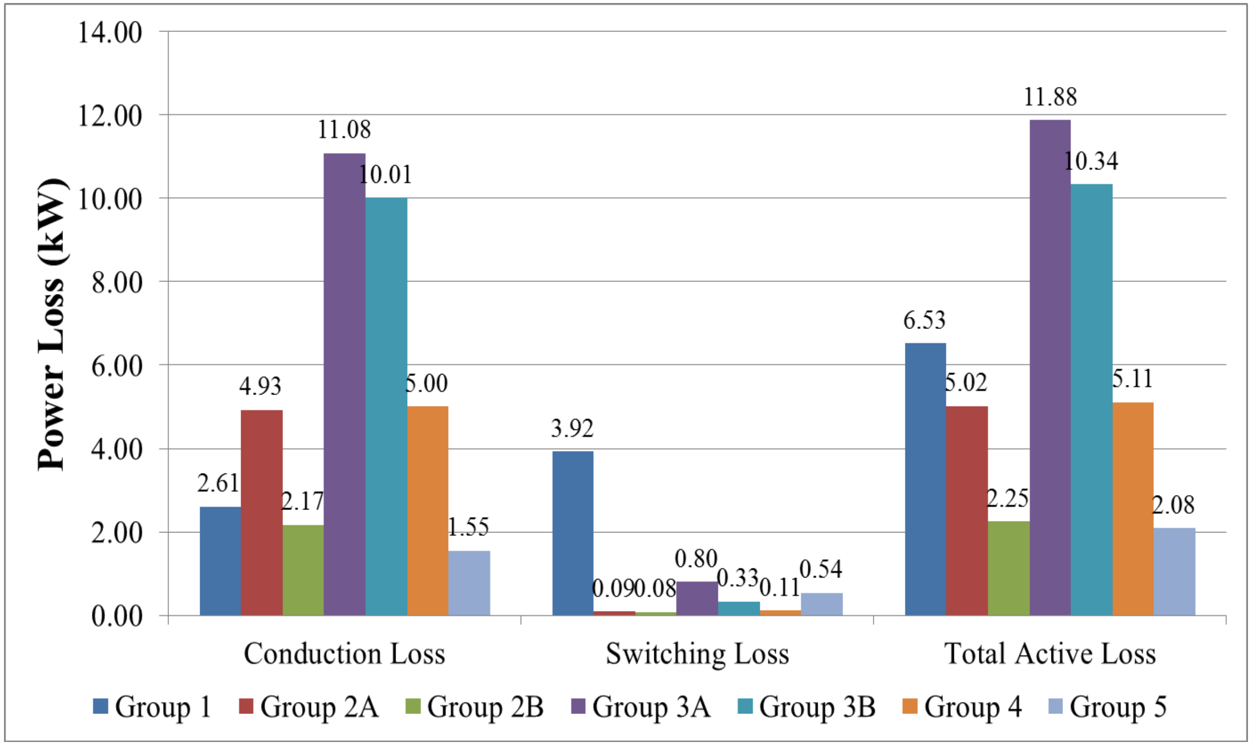
Groups for Efficiency Comparison

1st group	MV Si based three-level neutral point clamped inverter
2nd group	MV SiC based three-level neutral point clamped inverter
3rd group	Low voltage Si based cascaded H-bridge
4th group	Low voltage SiC based cascaded H-bridge
5th group	MV SiC based two-level voltage source inverter

Power Loss Comparison



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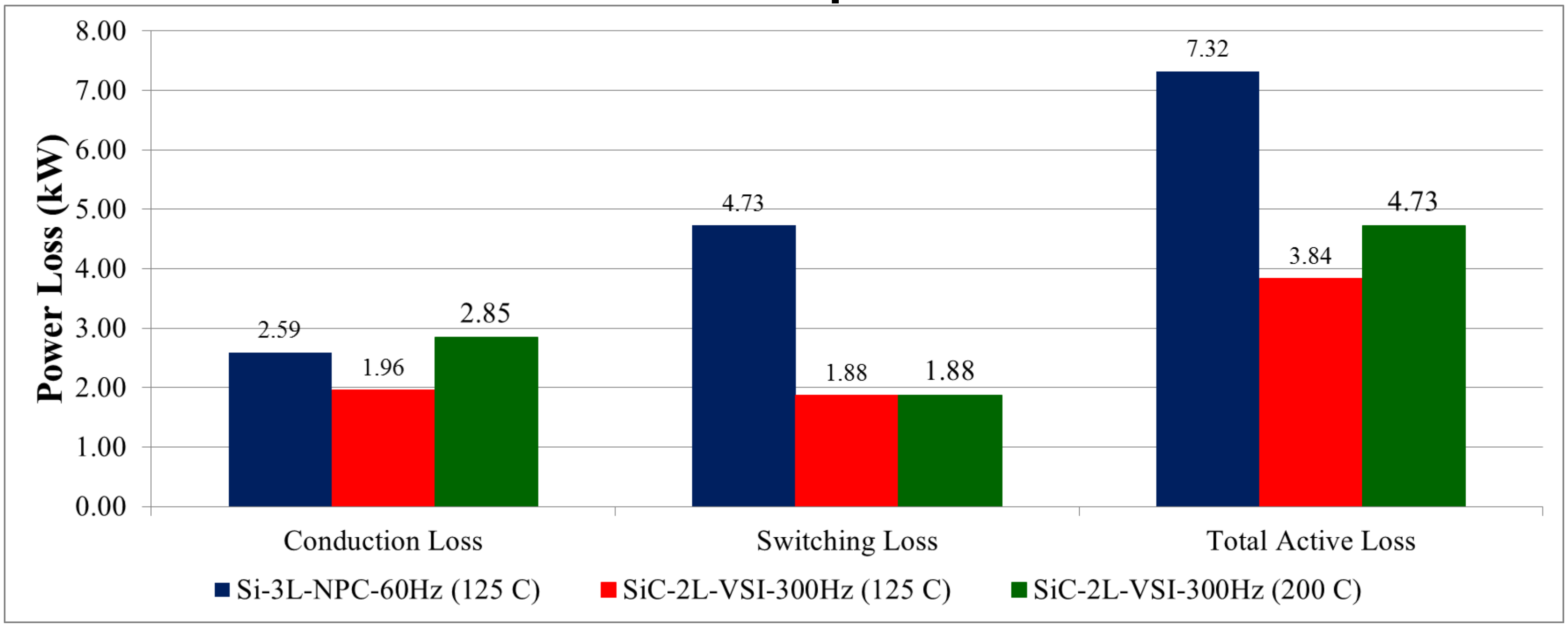
Loss & Efficiency Comparison

Loss Comparison



Efficiency Comparison

Group	Operating Temperature	Efficiency
Si based 3L-NPC	125 ^{o}C	99.27 %
SiC based 2L-VSI	125 ^{o}C	99.62%
SiC based 2L-VSI	200 ^{o}C	99.53%

Cooling System Comparison

- **Thermal impedance data for 6.5 kV, 250 A Si IGBTs are available, but not for 15 kV, 300 A SiC MOSFETs.**
- **Low voltage (1.2 kV) SiC MOSFET data has been scaled based on the relationship between HV and LV Si IGBT to infer the HV SiC MOSFET data.**
- **The case-to-ambient thermal resistance ratio is then obtained, as listed in the table below, and was used to calculate the cooling system size and power density.**

Group	Ambient Temperature	Junction Temperature	Required $R_{case\text{-}ambient}$	Heatsink Size Ratio
Si 3L-NPC	50 ^{o}C	125 ^{o}C	0.0068	1.00
SiC 2L-VSI	50 ^{o}C	125 ^{o}C	0.0184	0.37
SiC 2L-VSI	50 ^{o}C	200 ^{o}C	0.0306	0.22

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DC Bus Capacitor Comparison

A number of factors affect the DC link capacitance selection. The extreme case would be that in one switching cycle, the rectifier input power drops to zero while the inverter keeps the maximum output power.

$$C = \frac{P_{max}}{(V_{dc}\Delta V \pm \frac{1}{2}\Delta V^2) f_s}$$

where

$P_{max} = 1\ MW, V_{dc}\ 6.75\ kV. \Delta V$ for the commecial drive is ~5%, C can then be obtained

Group	Switching frequency f_s	Required capacitance ($\Delta V = 337\ V$)	Ratio	Note
Si 3L-NPC	1.0 kHz	439 μF	1.00	For SiC case, the front-end also has capacitors, which can further reduce the capacitance need
SiC 2L-VSI	10.0 kHz	43.9 μF	0.1	
SiC 2L-VSI	10.0 kHz	43.9 μF	0.1	

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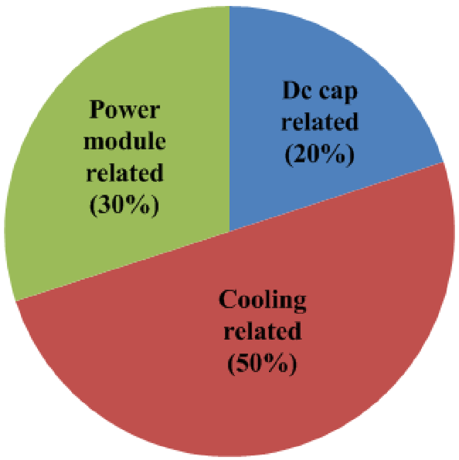
Size and Footprint Comparison

- For the inverter, the size and footprint are primarily determined by the DC bus capacitor, cooling system, and power modules.



Size breakdown assumption

Commercial MV Drive Size (GE innovation series 2300V 18-pulse non-regenerative drive)

Type	3L-NPC
Power rating	2.2 MW
Inverter Dimension and Volume	63'' W x 39'' D x 87'' H ($3.56\ m^3$)
Scaled for 1 MW system	46"W x 29"D x 72"H ($1.59\ m^3$)

Inverter Size and Power Density Comparison (Ratio)

Groups	Cooling system (50%)	DC capacitor (20%)	Power module (30%)	Footprint comparison	Power density comparison
Si 3L-NPC	1.00	1.00	1.00	1.00	1.00
SiC 2L-VSI	0.37	0.10	1.00	0.51	1.98
SiC 2L-VSI	0.22	0.10	1.00	0.43	2.33

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Motor and Gearbox Comparison Strategy

Strategy:

- Si based high speed compressor direct drives are commercially available. The comparison presented is between the high speed motor based compressor system and the low speed motor plus gearbox based compressor system.

Motor and Gearbox Comparison Groups

Group	Configuration
1	Low speed motor + gear box driven compressor
2	High speed motor direct-coupled compressor

Three High Speed Compressor System Examples

Company	Model
GE	ICL
MAN	Hofim
Siemens	STC-ECO

Only the first two systems were analyzed due to data availability

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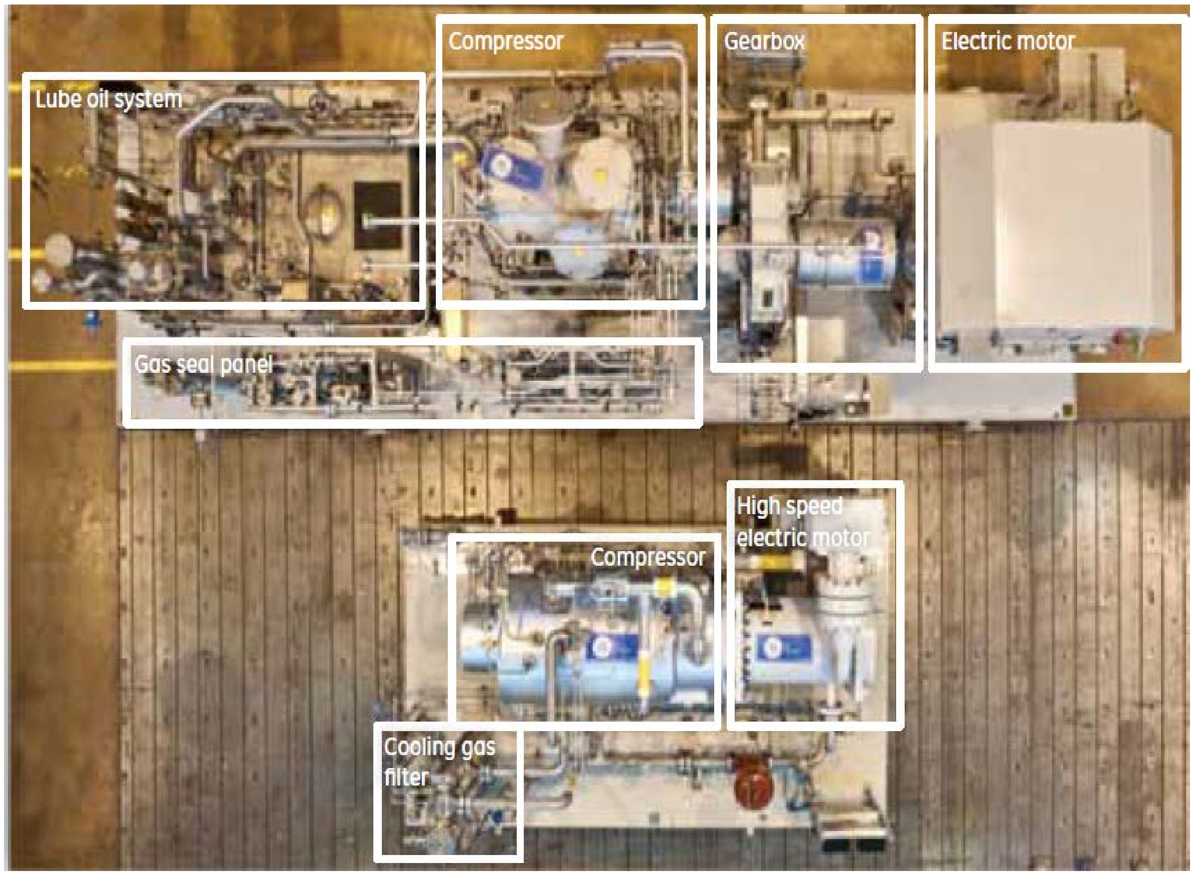
GE ICL Footprint Comparison

A rough calculation shows that the footprint of the high-speed direct-coupled system is only 41% of the traditional low-speed system with gearbox.



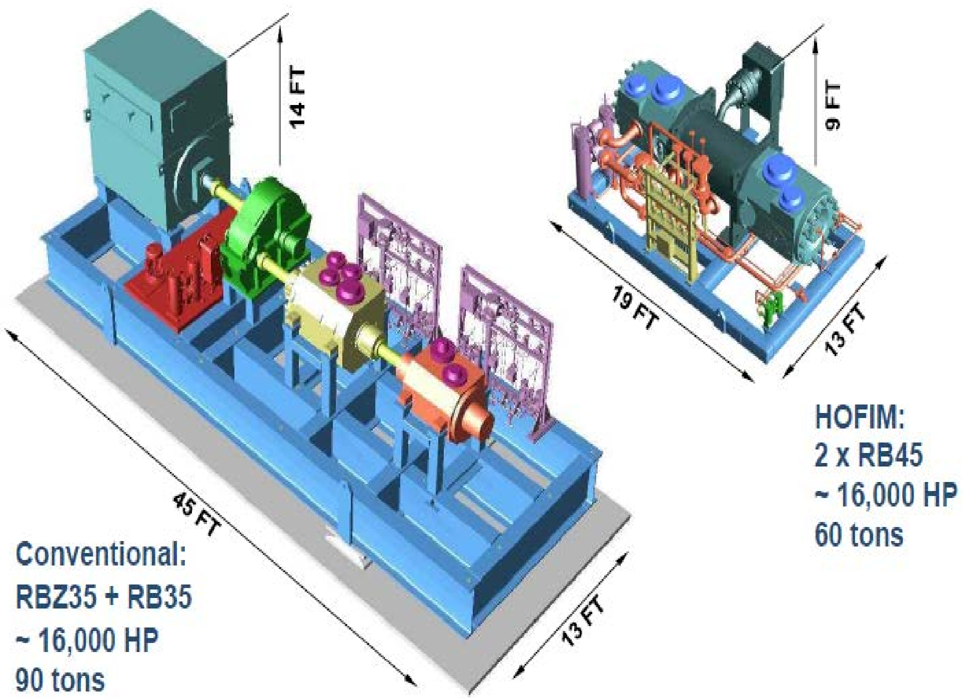
Low-speed compressor with gearbox

High-speed direct-coupled compressor

HOFIM Footprint & Weight Comparison

HOFIM vs. Low-speed

Type	Volume (W*D*H)	Weight	Power	Power density	Specific power	Power density per footprint	Volume Scaled to 1MW
HOFIM	5.79m*3.96m*2.74m ≈62.95m^3	60 tons	12 MW	190.63 kW/m^3	200 kW/ton	523 kW/m^2	5.25 m^3
Low speed	13.72m*3.96m*4.27 m ≈232m^3	90 tons	12 MW	51.72 kW/m^3	133.3 kW/ton	220 kW/m^2	19.33 m^3



Footprint:
The HOFIM compressor system occupies **only 42%** of the conventional low-speed system.

Weight:
HOFIM is approximately **2/3 the total weight** of a conventional compressor system.

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Summary: Separate Comparison

	Configuration	Loss	Efficiency	Size (1MW)	Power density
Front-end	Transformer & diode rectifier	20 kW	98%	102”W x 37”D x 72”H ($4.47\ m^3$)	$0.22\ kW/dm^3$ 0.188 MW/ton
	SST Type	20 kW	98%	35”W x 29”D x 72”H ($1.2\ m^3$)	$0.83\ kW/dm^3$ 1.65 MW/ton
Inverter	Si 3L-NPC (T_j = 125 ^oC)	7.32 kW	99.27 %	46”Wx29”Dx72”H ($1{,}59\ m^3$)	$0.63\ kW/dm^3$
	SiC 2L-VSI (T_j = 125 ^oC)	3.84 kW	99.62%	23”W x 29”D x 72”H ($0.80\ m^3$)	$1.25\ kW/dm^3$
	SiC 2L-VSI (T_j = 200 ^oC)	4.73 kW	99.53%	20”W x 29”D x 72”H ($0.68\ m^3$)	$1.47\ kW/dm^3$
Load	Low speed motor + gearbox + compressor	-	-	156”W x 45”D x 168”H ($19.33\ m^3$)	$0.05\ kW/dm^3$ 0.13 MW/ton
	High speed motor + compressor	-	-	66”W x 45”D x 108”H ($5.25\ m^3$)	$0.19\ kW/dm^3$ 0.2 MW/ton

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Summary: Combined Comparison (1)

Front-end Rectifier and Inverter

Group	Configuration	Loss	Efficiency	Size & Power Density	Footprint & Density
1	Si low speed MV drive with transformer	27 kW	97.3 %	6.06 m^3 0.17 kW/dm^3	3.3 m^2 303 kW/m^2
2A	SiC high speed MV direct drive with SST (T_j = 125 ^oC)	24 kW	97.6%	2.0 m^3 0.5 kW/dm^3	1.09 m^2 917 kW/m^2
2B	SiC high speed MV direct drive with SST (T_j = 200 ^oC)	25 kW	97.4%	1.88 m^3 0.53 kW/dm^3	1.03 m^2 971 kW/m^2

Summary: Combined Comparison (2)

MV Drive and Motor/Compressor System

Group	Configuration	Size & Power Density	Footprint & Density
1	Si low speed MV drive with transformer, low speed motor + gearbox + compressor	25.39 m^3 39.4 W/dm^3	7.83 m^2 128 kW/m^2
2A	SiC high speed MV direct drive with SST, high speed motor + compressor (T_j = 125 ^oC)	7.25 m^3 137.9 W/dm^3	3.0 m^2 333 kW/m^2
2B	SiC high speed MV direct drive with SST, high speed motor + compressor (T_j = 200 ^oC)	7.13 m^3 140.2 W/dm^3	2.94 m^2 340 kW/m^2

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Summary

- **A design comparison has been carried out for a 1 MW compressor system contrasting:**
  1. **A Si based MV drive with a line-frequency transformer, low speed (60 Hz) motor and gearbox**
  2. **A SiC based MV direct drive with solid-state-transformer and high speed (300 Hz) motor**
- **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 (?).

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Potential Research Needs

- High voltage SiC devices and modules – required and/or desired device characteristics and performance; low parasitics for high switching transients.
- Drive architecture and converter circuit topologies – to take full advantage of high voltage SiC device properties; simple, compact, low loss, and reliable.
- Converter packaging and layout – to meet the voltage blocking requirements while keeping the parasitics low
- Passive components and filters – Select and design magnetics, capacitors and filters to match the need of SiC devices; additional filter needs to deal with high dv/dt, di/dt, and common mode noises.
- Gate drives – fast transients and high voltages will pose new challenges regarding cross-talk, interference, and isolated power supplies. Different short-circuit characteristics of SiC in comparison with Si may require new protection schemes.

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Potential Research Needs

- Thermal management – SiC has higher temperature capability than Si. Higher temperature operation combined with higher current densities and increased integration may require innovative cooling technologies.
- Reliability – need to assess the system level impact of SiC.
- Design methodology – New types of drives, combined with the fast switching of SiC, may require more integrated design approaches.
- Motors: High voltage SiC based medium voltage drives can operate at higher frequencies and fast dv/dt. Certain types of motors may be better suited for these drives than others. Motor insulation shat voltages, and bearings may be issues.
- To accommodate retrofit applications, need to make the drives motor friendly.

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