Power Electronics for Fuel Cell Based Power Generation Systems

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NIST

(NIST/DOE Interagency Agreement)

Outline

I. Introduction

II. Technology Impact Analysis

III. Component Technologies

IV. Power Converter Architectures

V. Cost Estimates and Simulation

I. Introduction

Objective:

- **High-Megawatt Power Conditioning Systems (PCS) are required to convert:**
  - from power produced by Fuel Cells (FC) in future power plants
  - to very high voltage and power required for delivery to the grid

Motivation:

- **DoE SECA cost goals:**
  - FC generator plant $400/kW
  - including $40-100/kW for PCS
- **Today's PCS cost *(Fuel Cell Energy Inc.)*:**
  - FC generator plant $3,000/kW
  - including $260/kW for power converter (to 18 kV AC)

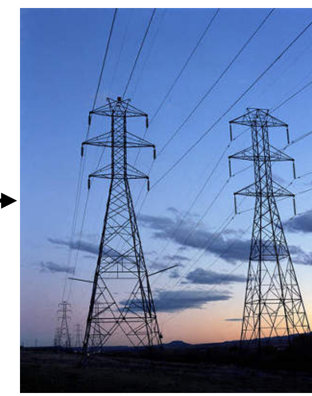
Fuel Cell Plant PCS

Fuel Cell Stack

Power Conditioning System (PCS)

$40-$100 / kW

60 Hz Step-up Transformer



Power Grid

$40-$100 / kW for PCS is a difficult stretch goal !

Federal and Industry PCS Program Coordination

- **NIST/DOE Inter-Agency Agreement**
  - NIST lead effort to determine expected impact of advanced technologies on future FC power plant PCS
- **Inter-Agency Power Group (IAPG)**
  - Form an interagency task group for high-megawatt power converter technologies under IAPG
- **Industry Roadmap**
  - Initiate a roadmap process to offer guidance for further development of high-megawatt PCS technology
- **National Science Foundation (NSF)**
  - Establish power electronics curriculums and fundamental research programs for energy systems technology

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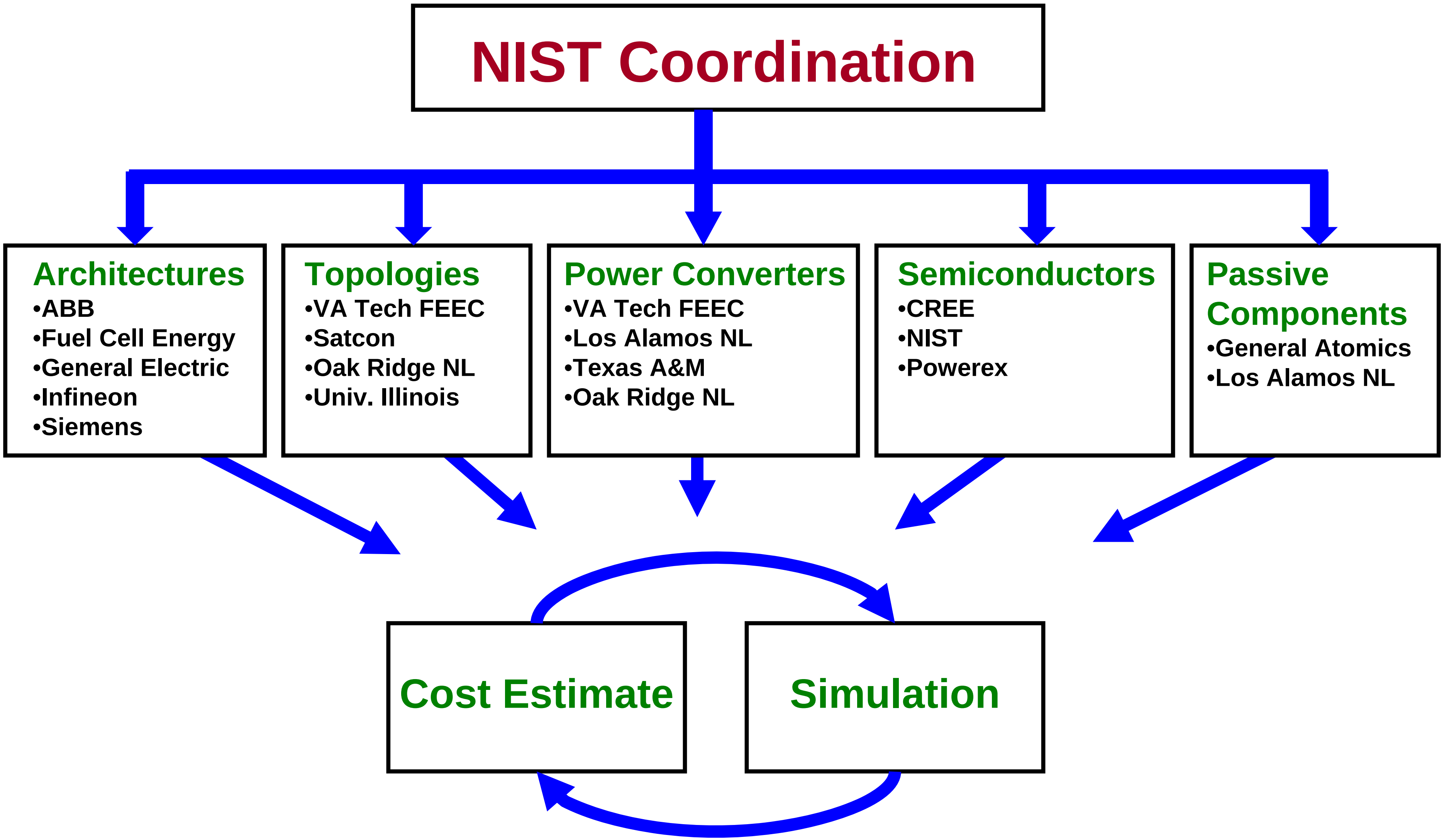
II. Technology Impact Analysis

- **Perform Independent Analysis of technologies that may reduce cost of PCS for future FC Power Plants**

- **Methodology for impact study:**
  - **Include input from broad power electronics, power component, and power engineering communities**
  - **Classify power converter architectures, topologies, and component technologies that may reduce cost**
  - **Perform tabular calculations of cost for each option using estimated advantages of new technologies**
  - **Use component modeling, and circuit and system simulations to verify and refine calculations**

Methodology for Impact Analysis:



Parameters of Impact Analysis

- **Boundary conditions and performance parameters:**
  - FC Stack: center tap ~700 V DC, 0.6 MW
  - Require individual FC stack current control with low ripple

- **Power electronics and/or transformer to 18 kV AC, and transformer from 18 kV AC to 300 kV AC transmission**

- **Converter cost components:**
  - Semiconductors
  - Module Packaging and Interconnects
  - Cooling System
  - Magnetics: Filter Inductors and
HF voltage isolation transformers
  - 60 Hz Transformer up to 18 kV
  - Breakers and Switchgear

300 MW PCS

~700 V DC

Approx. 500 Fuel Cells

~700 V DC

Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

18 kV AC

300 kV AC

$40-$100 / kW

Ripple < 2%
Stack Voltage Range
~700 to 1000 V
Future: 2X voltage ?

IEEE – 519
IEEE – 1547
Harmonic Distortion
Future: HVDC transmission ?

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A. Low-Voltage Semiconductors

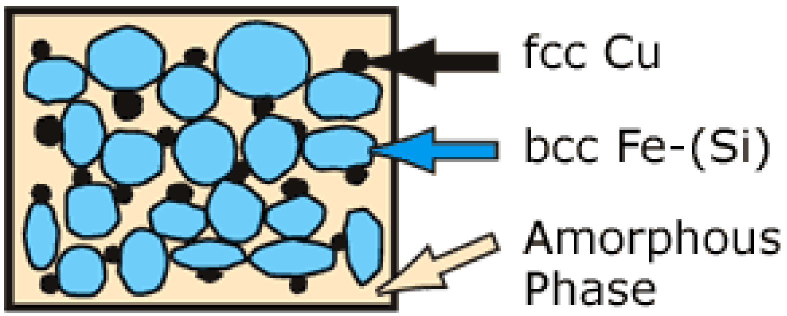
- **Baseline: 1200 V silicon IGBT with silicon PiN diode**
  - **1200 V is sweet spot for silicon IGBTs at 15 – 20 kHz switching due to speed voltage trade-off, high volume, and maturity**
  - **Mature technology; cost may not continue to decrease**

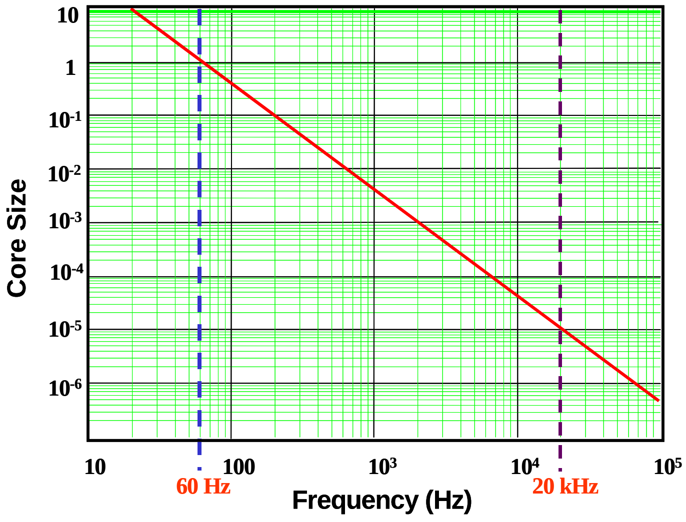
- **1200 V silicon IGBT switch with SiC Schottky diode**
  - **More efficient at 20 kHz → less loss, lower heat removal cost**
    → lower temperature and longer life
  - **Higher frequency → less filter inductor cost**
  - **Emerging commercial technology; cost continues to decrease**

  - ***What is cost break-point for 1200 V SiC Schottky diode?***

B. High-Frequency Transformer

- **Baseline: Traditional Ferrite Material**
  - Expensive processing for high-power, high frequency (HF)
  - Mature technology; cost may NOT decrease
- **HF magnetic materials: Nano-crystalline or Metglas®**
  - Size and cost decrease inversely proportional to frequency
  - Emerging commercial technology; cost continues to decrease
  - *What is cost break-point for HF magnetic material?*





C. High-Voltage Semiconductors

- **Baseline: High-Voltage (HV) Silicon devices (IGBT, IGCT)**
  - **Typically ~6.5 kV blocking voltage maximum**
  - **Requires multi-level inverter for 4160 V AC**
  - **Low switching frequency (< 500 Hz) requires larger filter**

- **High-Voltage, High-Frequency SiC Switch and Diodes**
  - ➢ **12 kV, 20 kHz SiC MOSFET switch and SiC Schottky diode:**
  - **Less inverter levels due to higher voltage**
  - **Less loss, lower heat removal cost**
  - **Less filter inductance required due to higher frequency**

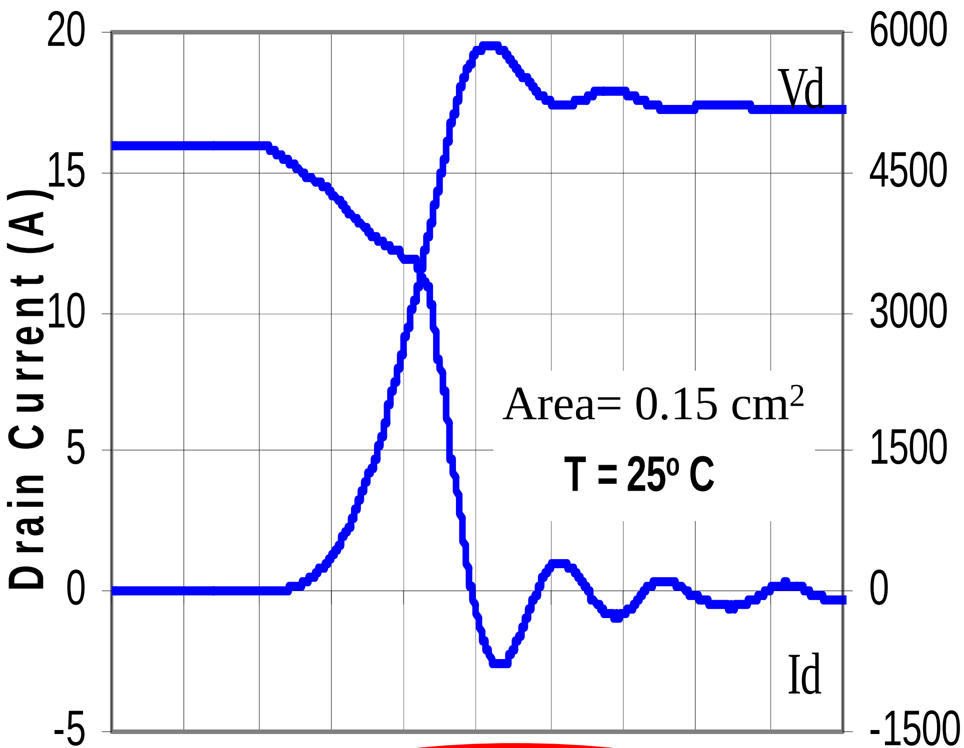
  - ➢ **15 kV, 5 kHz SiC IGBT switch and SiC PiN diode:**
  - **Higher current per die than SiC MOSFET, therefore lower cost**

  - ***What is cost break point for HV-HF SiC power semiconductors?***

DARPA HPE MOSFET

High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



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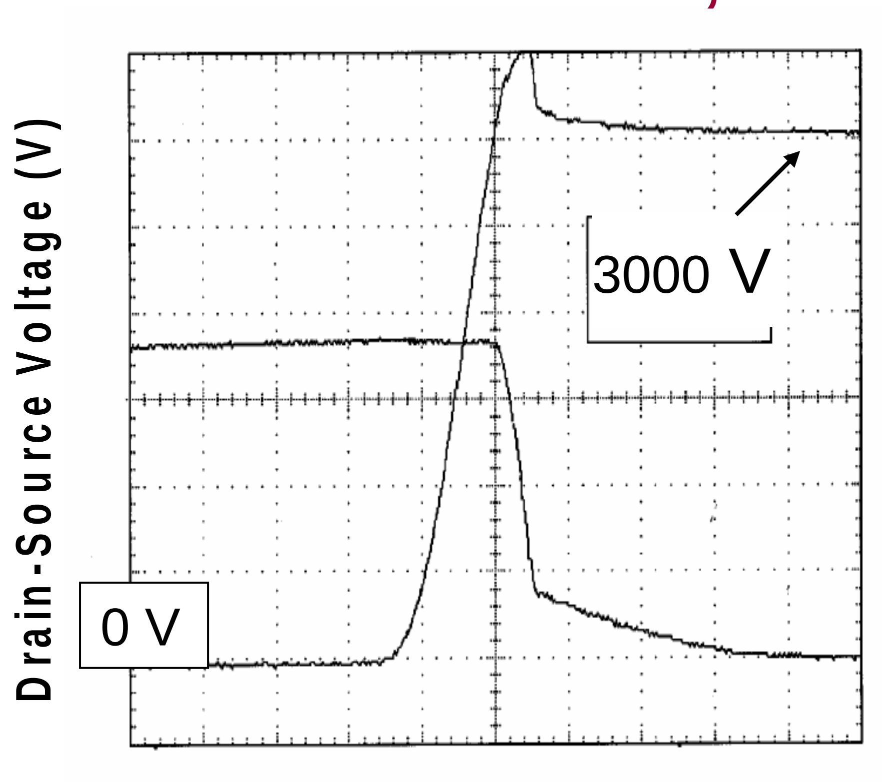
Silicon IGBT: 4.5 kV, 2us



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A. Hefner, et.al. “Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices,” *IEEE IAS Annual Meeting,* October 2006, pp. 330-337.

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IV. Power Converter Architectures

A. Low-Voltage Inverters (460 V AC):

- Require high current for each 0.6 MW FC
- and large number of Inverters for 300 MW Plant

B. Medium-Voltage Inverters (4160 V AC):

- Lower inverter current for each 0.6 MW FC
- Combine multiple FCs with single high power inverter

C. High-Voltage Inverters (18 kV AC):

- Replaces 60 Hz transformer with isolation from HF transformer
- Cascade enables: 18 kV AC inverter by series connection, and interleaved switching decreases losses and filter requirement

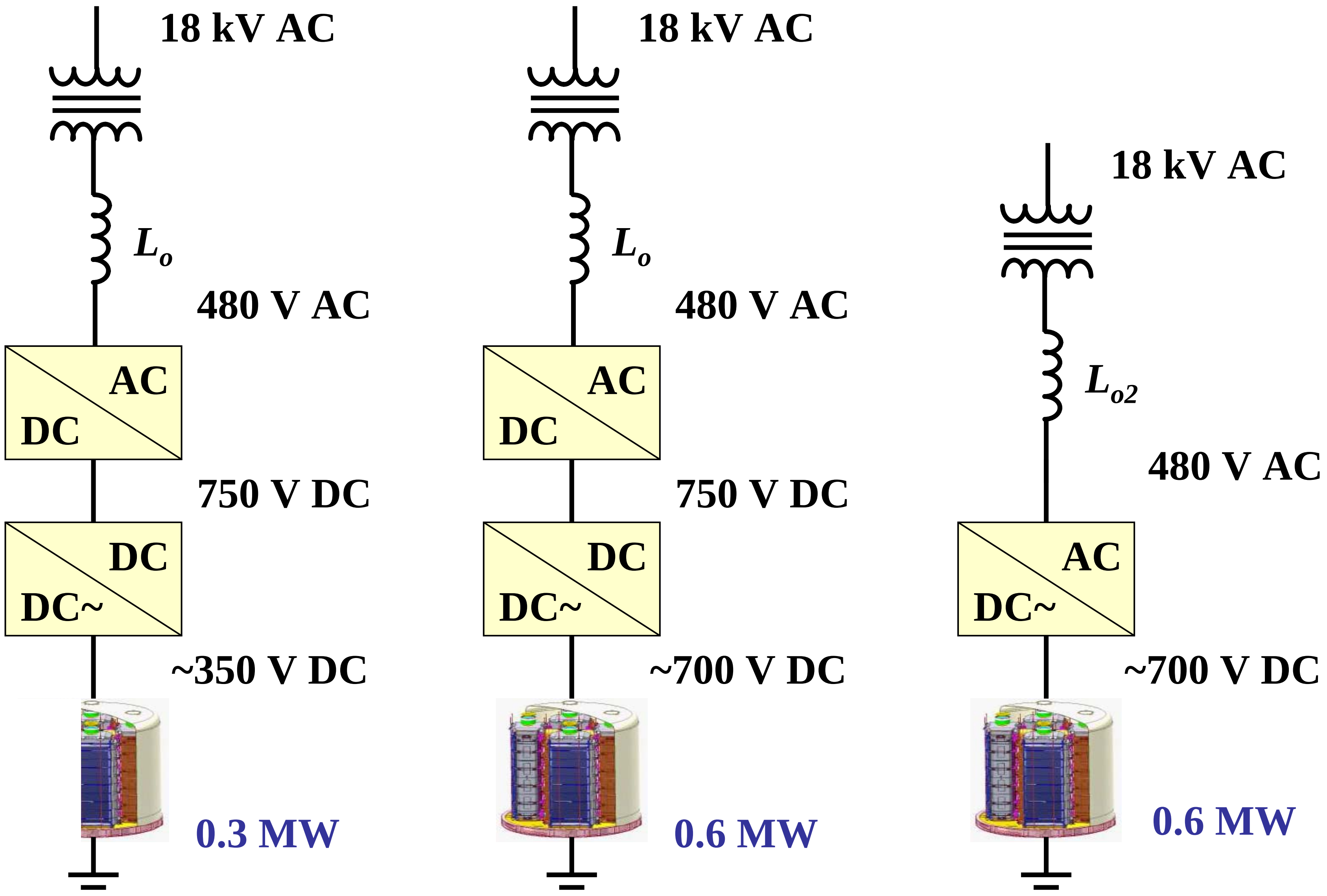
A. Low-Voltage Inverters

480 V AC Inverter,
60 Hz Transformer to 18 kV AC

1) ***First Generation:*** **~350 V FC, DC-DC to 750 V, 480 V AC Inverter**

2) ***Baseline:*** **~700 V FC (center tap), DC-DC to 750 V, 480 V AC inverter**
   - **1200 V is "Sweet spot" for silicon semiconductors due to market size and speed voltage trade-off**

3) ***Present Generation:*** **~700 V FC, 480 V AC Inverter**
   - **Fewer semiconductors due to single stage converter**



1) *First Generation* 2) *Baseline* 3) *Present Generation*

B. Medium Voltage Inverters

4160 VAC Inverter

60 Hz Transformer to 18 kV AC

MV DC Common Bus:

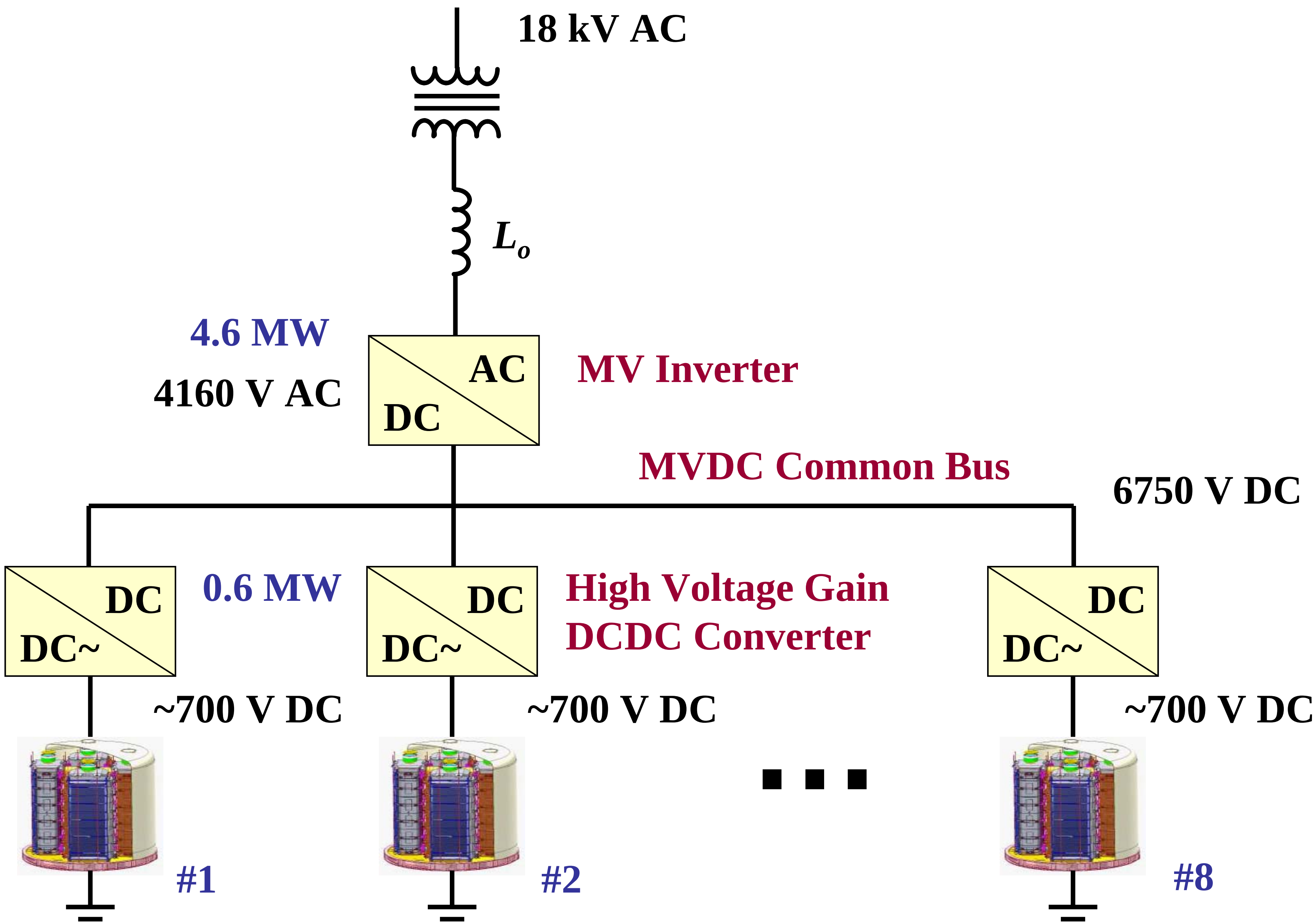
LV-to-MV DC-DC converters:

- Requires high voltage-gain DC-DC converter, HF transformer
- HV SiC diode rectifiers substantially reduce loss !

Common MV inverter:

- Silicon semiconductors require multiple levels for MV
- HV SiC semiconductors provide lower switching loss

1) MV DC Common Bus: LV-to-MV DC-DC, Common Inverter



C. High Voltage Inverters

18 kV AC Inverter,
No 60 Hz Transformer !

High-Voltage Cascade:

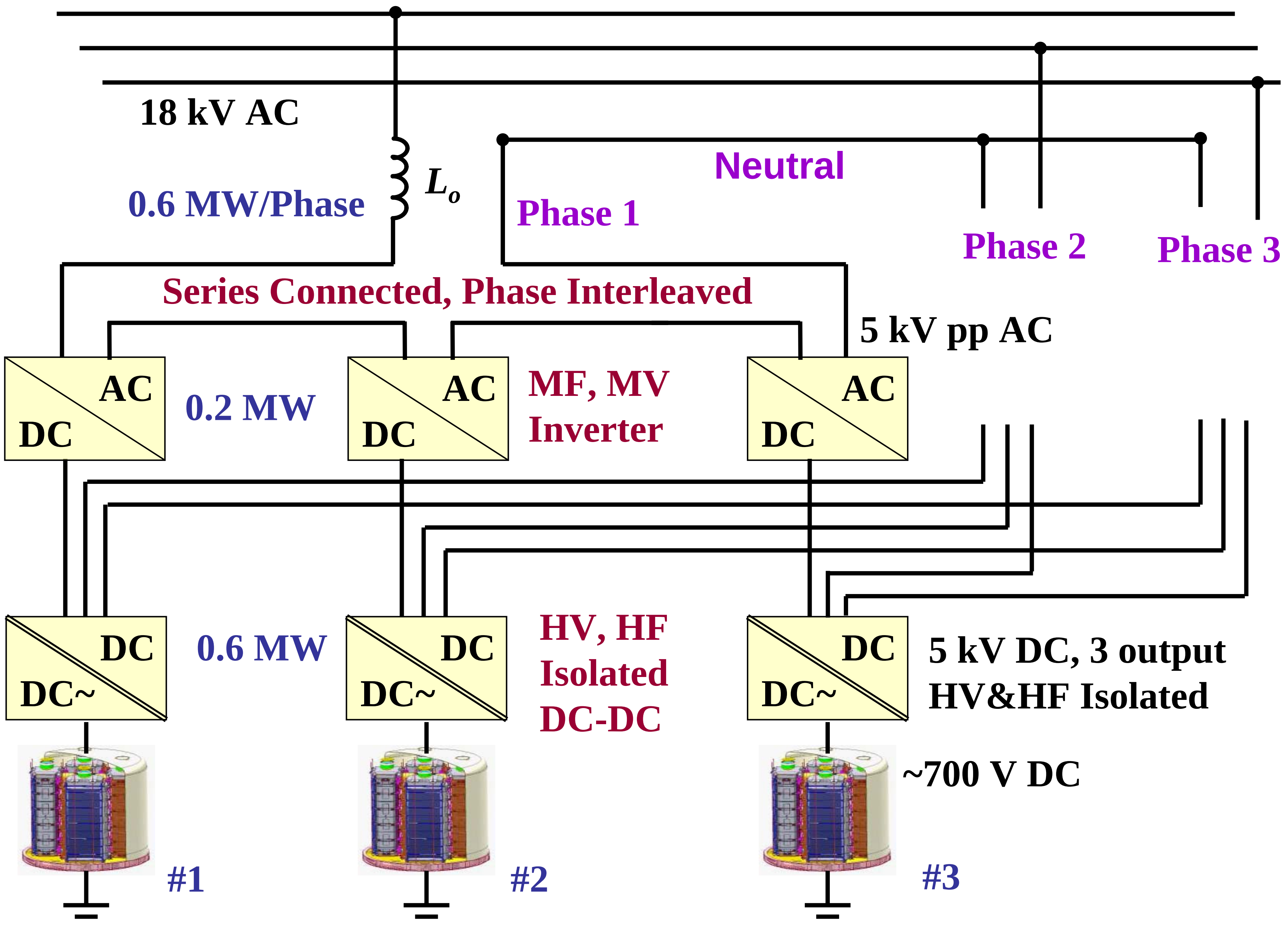
Series connected, voltage-isolated LV-to-MV DC-DC

- **Requires HV-HF isolation and output for each phase**

Medium-Frequency, phase-interleaved inverters

- **Y-Configuration:**
- **6.5 kV Silicon semiconductors require 6 levels**
- **12 kV SiC semiconductors require 3 levels**

HV-Cascade: Isolated MV-DCDCs, Interleaved MV Inverters



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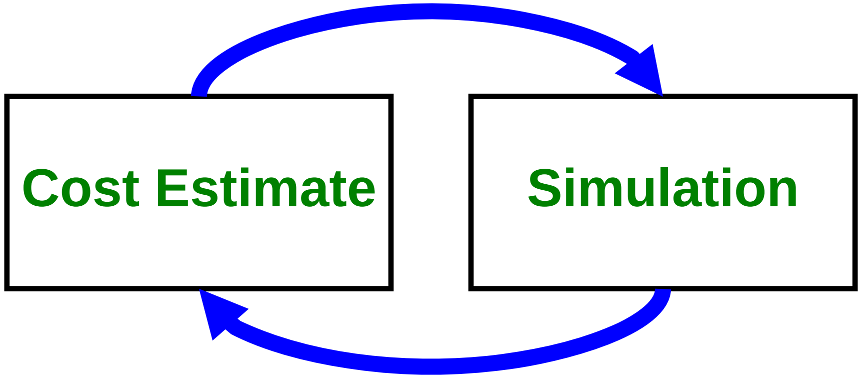
A. **Cost Estimate:** Tabular calculation of cost for each PCS option using estimated advantages of new technologies

B. **Simulation:** Component modeling, and circuit and system simulations to verify and refine calculations

- Physics based models for component technologies
- Simulation schematics for power converter topologies

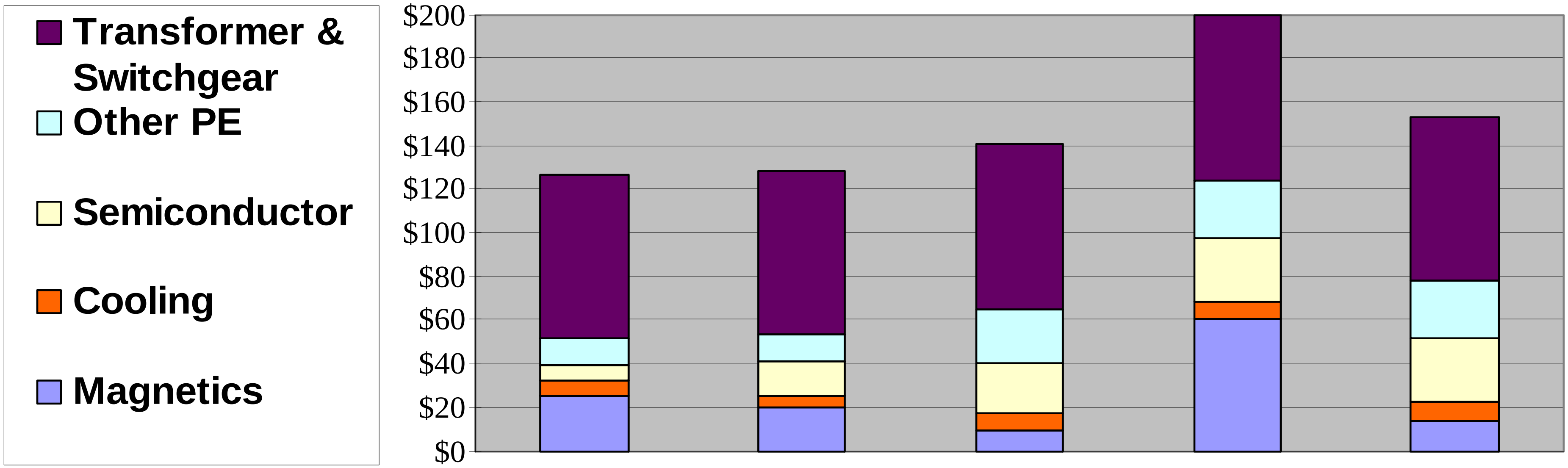


A. Tabular Calculations of Cost

- Future, high-volume costs: 5 to 10 years, 1 GW/yr

- Advanced Technology Goals and Cost Break Points
  - 1.2 kV Schottky diodes: $0.2/A
  - 12 kV Schottky diodes: $1/A
  - 12 kV Half-bridge SiC-MOSFET/SiC-Schottky: $10/A
  - 15 kV SiC-PiN: $0.4/A
  - 15 kV SiC-IGBT/SiC-PiN Module: $3.3/A
  - Nano-crystalline transformer: $2/kW
  - Power Electronics DC-DC, DC-AC: 150 % overhead
  - 60Hz Transformer and Switchgear: 50 % overhead

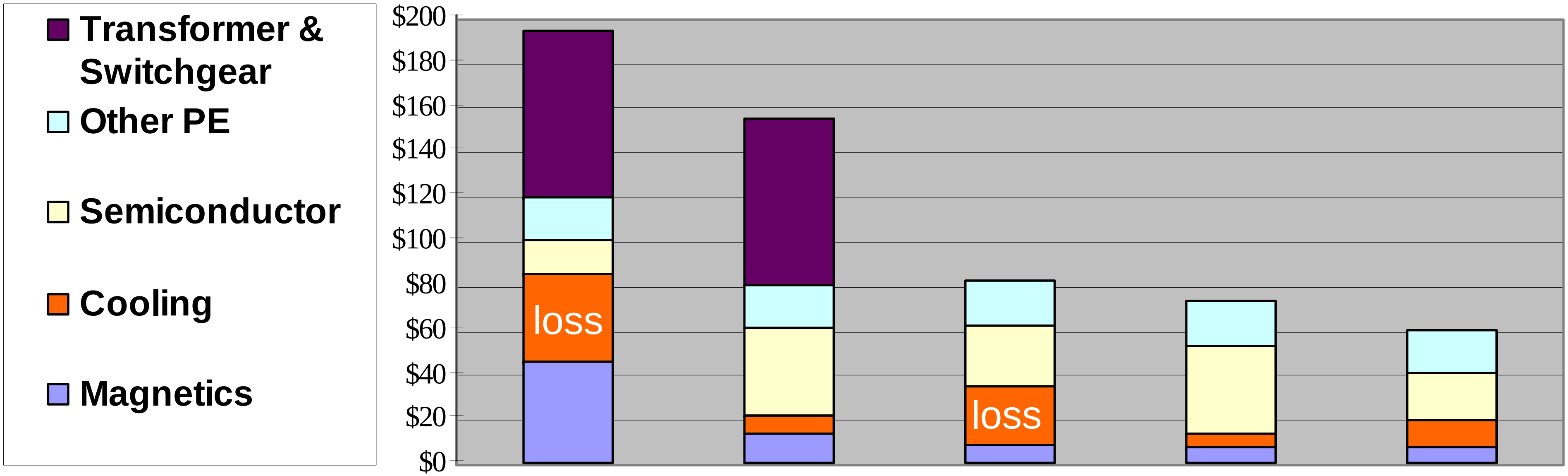
Preliminary $/kW: LV Inverter



Inverter Voltage	Low	Low	Low	Low	Low
Converter Stages	One	One	Two	Two	Two
LV-SiC Schottky		yes	yes	yes	yes
HF Transformer				Ferrite	Nano
60 Hz Transformer	yes	yes	yes	yes	yes

Risk Level:	Low	Moderate	Considerable	High

Preliminary $/kW: MV & HV Inverter



Inverter Voltage	**Medium**	**Medium**	**High**	**High**	**High**
HV-SiC Diode		**Schottky**	**Schottky**	**Schottky**	**PiN**
HV-SiC Switch		**MOSFET**		**MOSFET**	**IGBT**
HF Transformer	**Nano**	**Nano**	**Nano**	**Nano**	**Nano**
60 Hz Transformer	**yes**	**yes**			

Risk Level: **Low** **Moderate** **Considerable** **High**

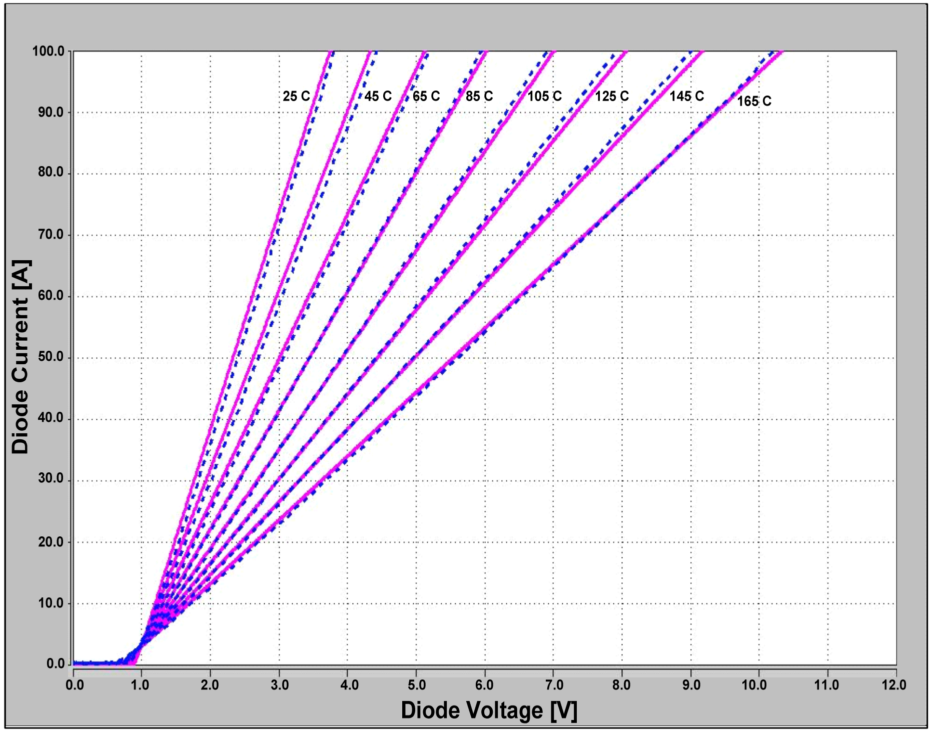
B. Component Modeling, Circuit and System Simulations

- **Physics based models developed for advanced component technologies**
  - **12 kV SiC Junction Barrier Schottky Diode (JBS)**
  - **12 kV SiC Power MOSFET**
  - **1200 V SiC Junction Barrier Schottky Diode (JBS)**

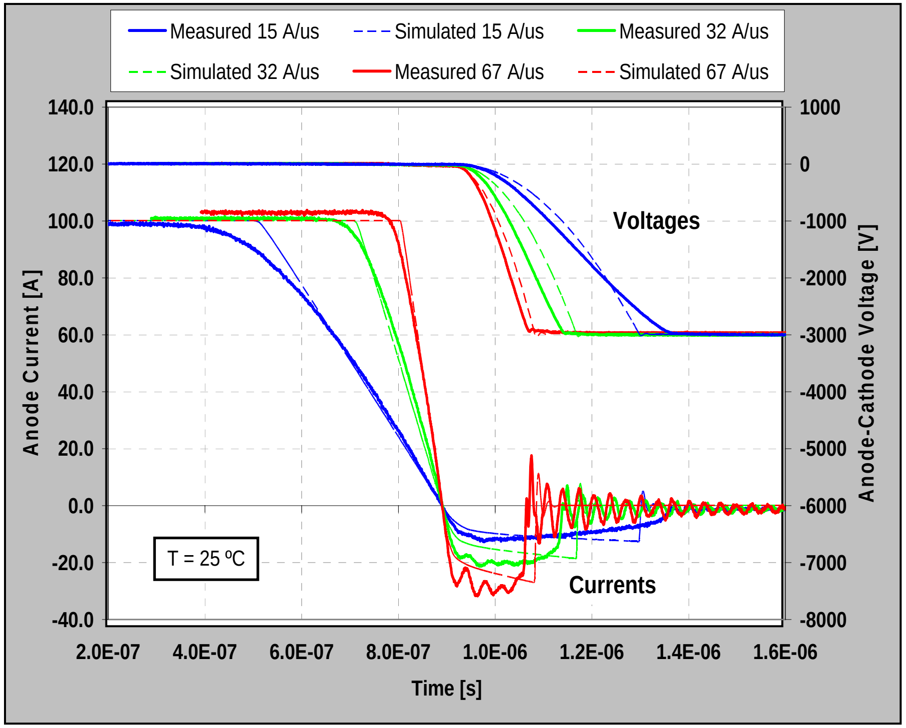
- **Models validated for static and switching characteristics**

- **Simulation schematics for power converter topologies**

Model Validation for 12 kV, 100 A SiC Junction Barrier Schottky Diode

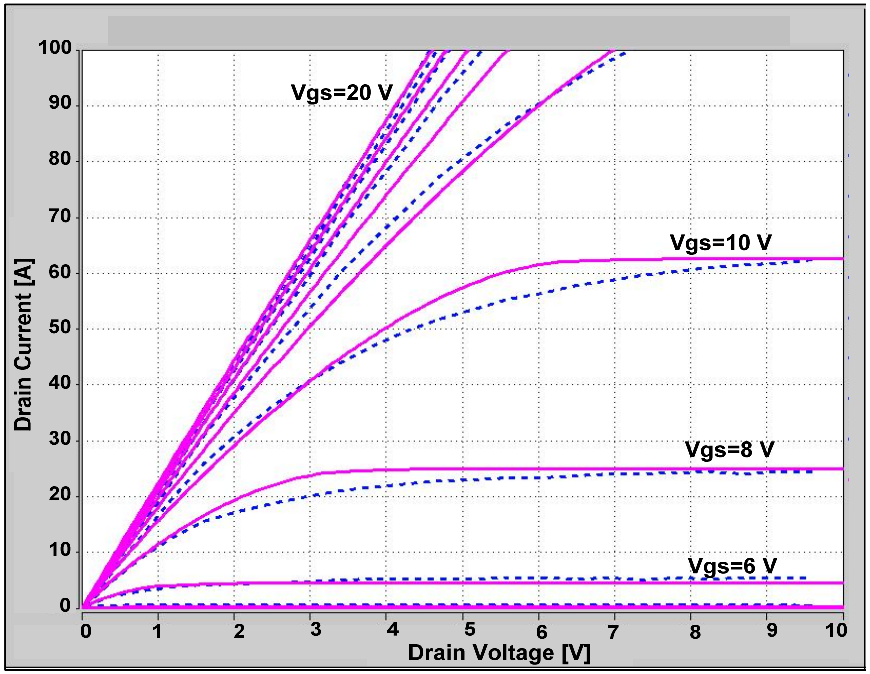


Forward Characteristics

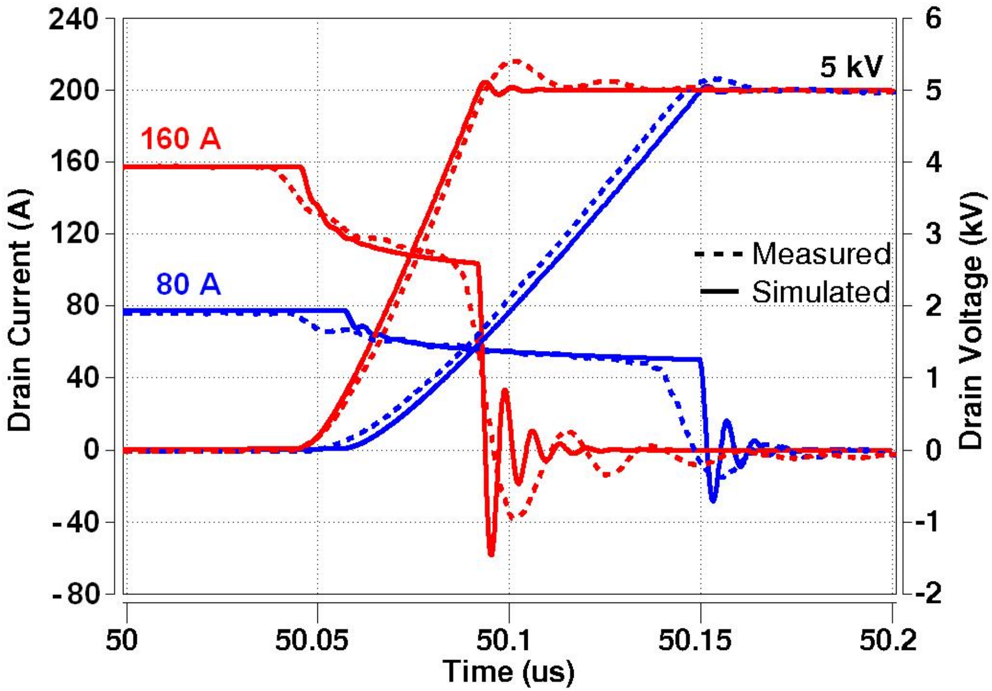


Reverse Recovery Switching

Model Validation for 12 kV, 100 A SiC Power MOSFET

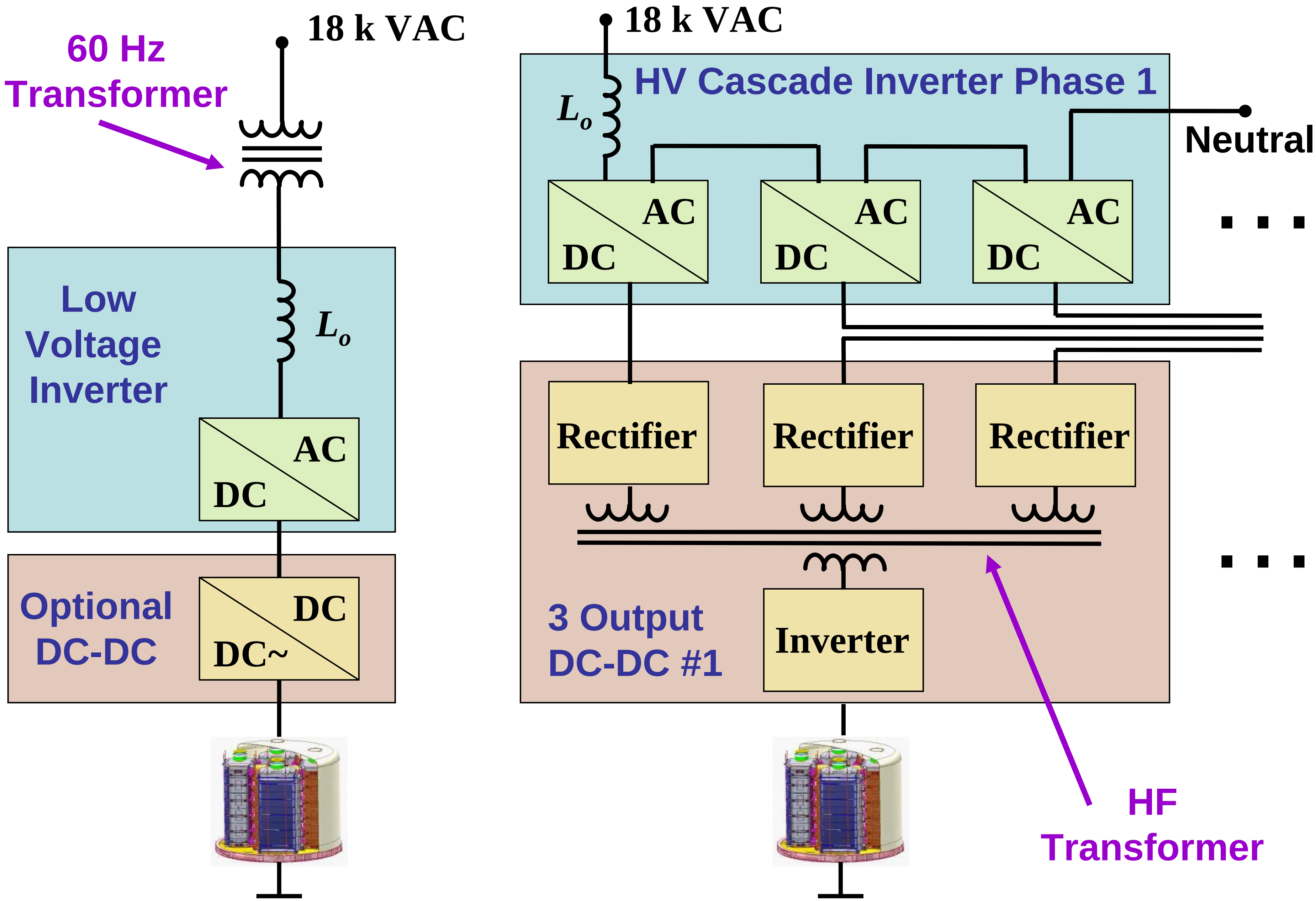


Forward Output Characteristics

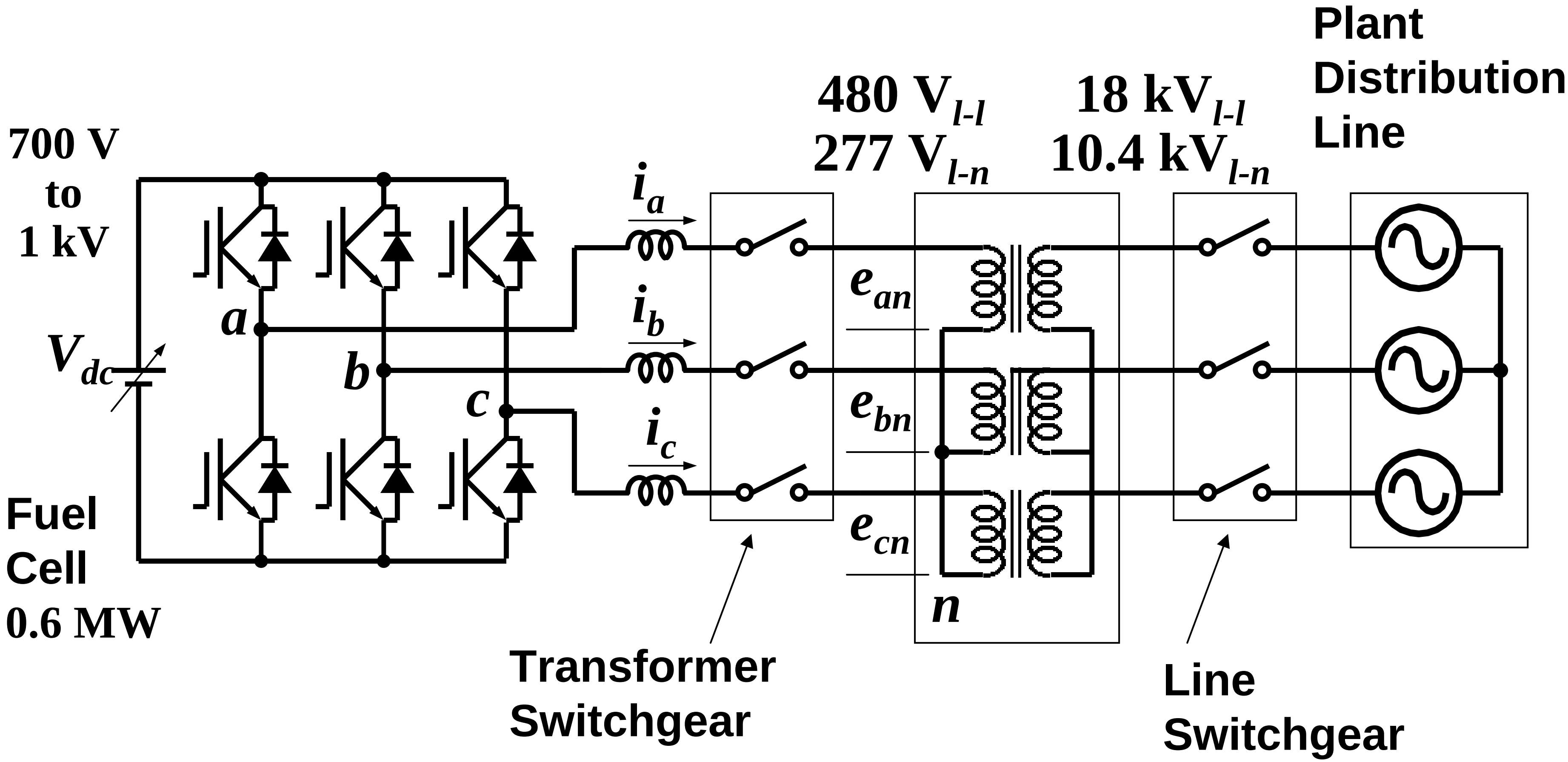


Inductive Load Switching

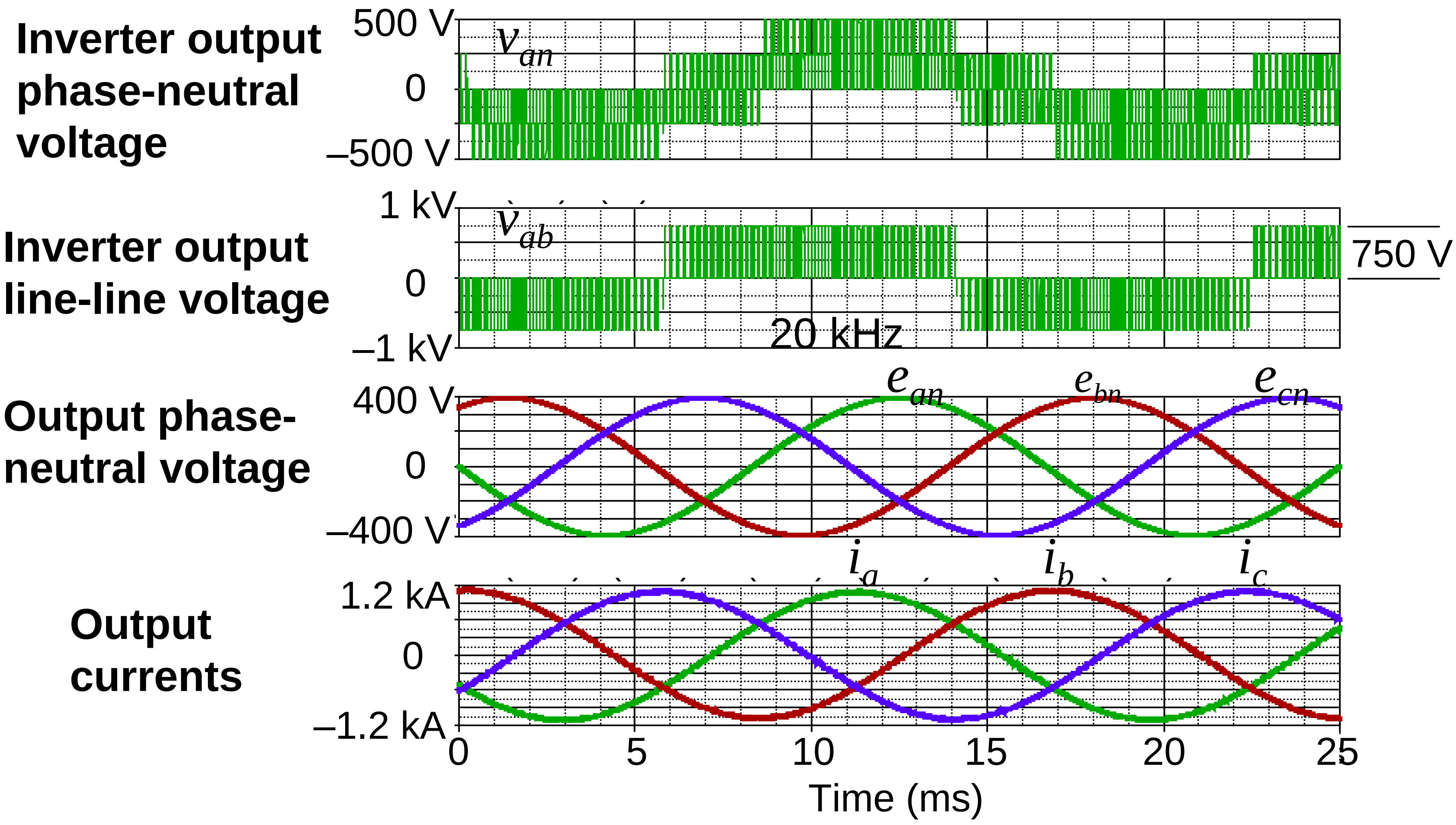
HF Transformer versus 60 Hz Transformer



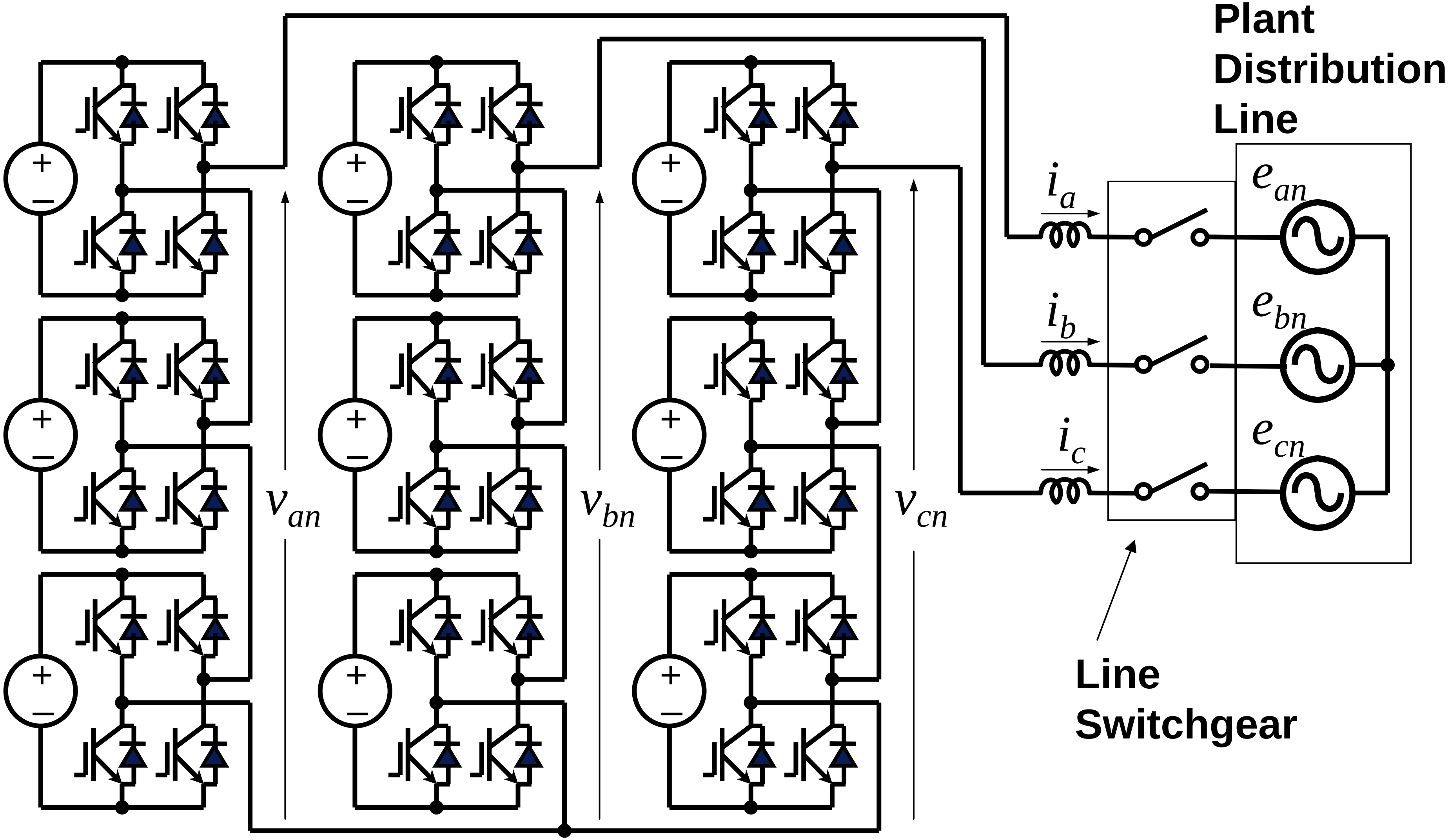
Low Voltage Inverter Schematic



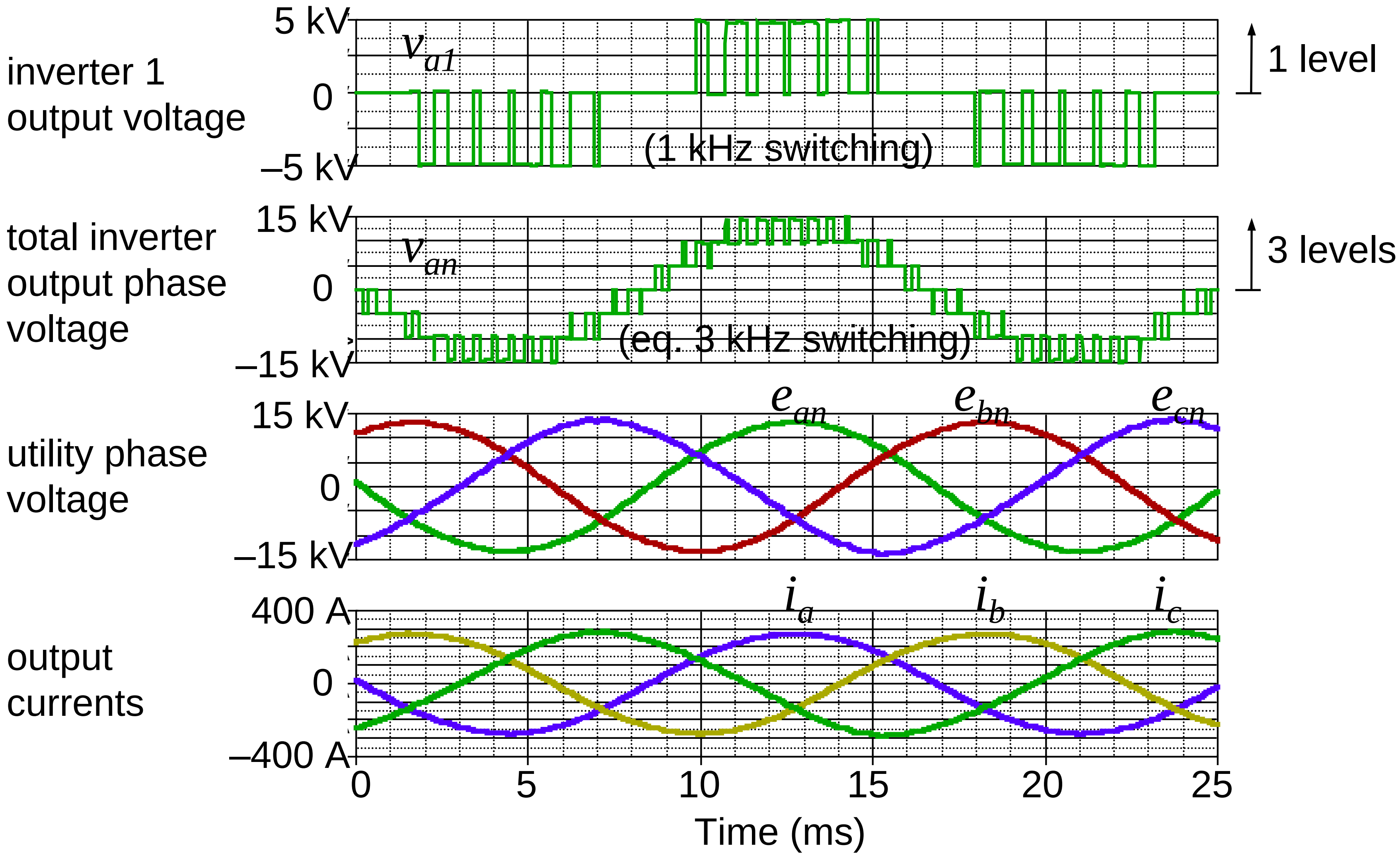
Lower Voltage Inverter Simulations



High-Voltage Y-Connected Cascade Inverter Schematic



High-Voltage Y-Connected Cascade Inverter Simulation



Conclusion

- The SECA goal of $40-$100 / kW for the Fuel Cell Plant PCS is a difficult stretch goal.
- Federal and Industry efforts have been initiated to address High-Megawatt PCS requirements.
- Analysis of technologies that may reduce cost of PCS for fuel cell power plants:
  - high-frequency magnetic materials
  - high-voltage high-frequency SiC semiconductors
  - 1200 V SiC Schottky diodes
- High voltage inverter may permit galvanic isolation via low cost HF transformer instead of costly 60 Hz transformer

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