Session 4a

Lai

Multilevel Converters for Large-Scale Fuel Cell Power Plants

DOE Workshop on Development of Large Scale Inverters Systems (>100 MW) for Coal-Gas Based Fuel Cell Power Plants

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Dr. Jason Lai
Virginia Tech
Future Energy Electronics Center
Blacksburg, VA 24061-0111

Outlines

- Technical Issues and State-of-the-Art Large-Scale Power Electronics
- Configurations of Fuel Cell Power Conditioning Systems
- Multilevel Converter Based Fuel Cell PCS
- Control of Paralleled Inverters
- Device Requirements
- Summary

Photograph: a 400-kW current source DC-DC converter

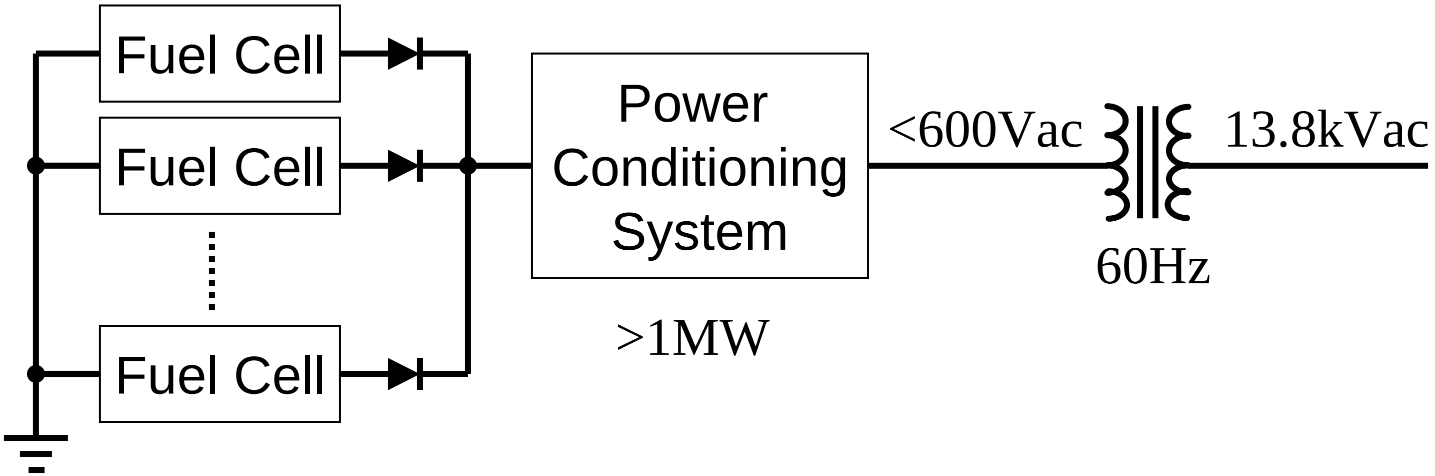
Issues

- **Parallel/Module size – what's the best size for a single module (1MW, 10MW, …, etc.)?**
- **Fuel cell voltage level – low-voltage stack versus high-voltage stack, what's the limit of fuel cell voltage level?**
- **Voltage stacking method – stacking fuel cells versus stacking converters, problem with common voltage.**
- **Semiconductor device – silicon versus silicon carbide, HV device versus LV device. What are needed?**
- **Circuit topology – voltage source versus current source converters, multilevel versus multiphase converters**
- **Fuel cell current ripple – potential problem with single-phase inverter induced fuel cell current ripples**

State-of-the-Art High Power Electronics

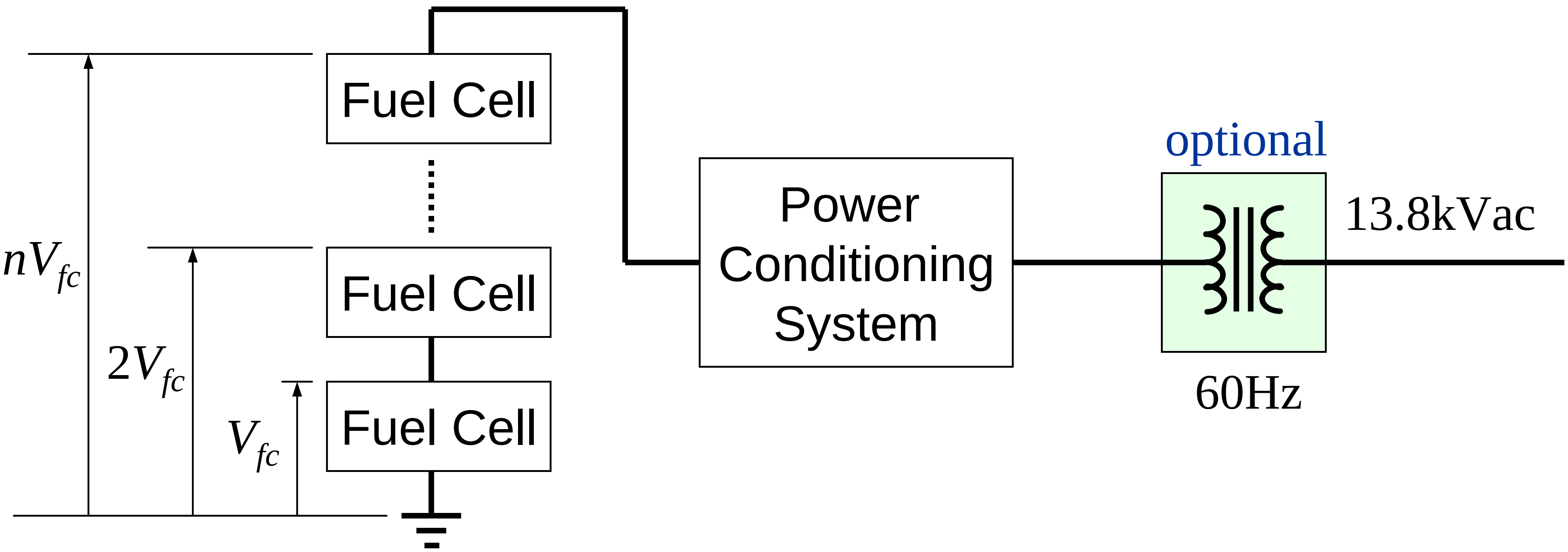
- >1GW Level Pacific Intertie HVDC System
  - DC Link Voltage: ±500kV
  - Power Level: 3100MW
  - Circuit Topology: Current Source Inverters
  - Device: 6.5kV Thyristors stacked up for 133kV blocking
  - Switching Frequency: 60Hz
  - Problems: >5 acres of land for LC filters
- >100MW converters for reactive power compensation
  - Circuit Topology: multiple pulse (48-pulse) with transformer isolation
  - Device: 6.5kV GTO
  - Switching Frequency: <500Hz
- >1MW Distributed Generation
  - 1.5MW to 5MW wind power generation
  - 1MW to 2.4MW fuel cell power plants
  - IGBT based with switching frequency >5kHz

Configuration with Paralleling Multiple Fuel Cells and a Large PCS



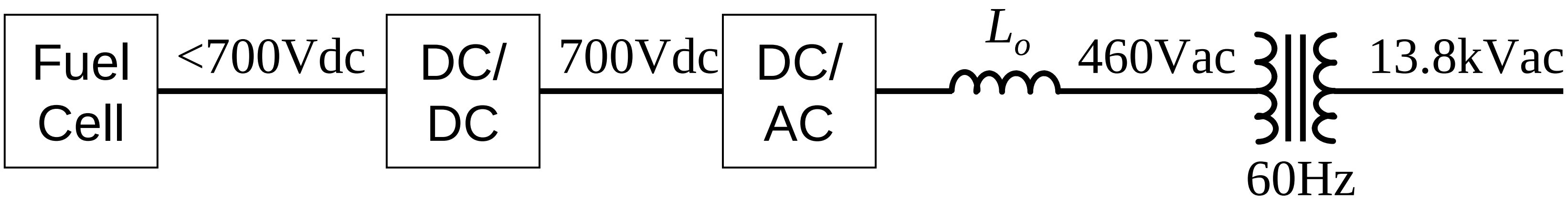
- **Multiple sub-MW fuel cells in parallel**
- **MW-level power conditioning system**
- **Low voltage power electronics**
- **Low frequency transformer (bulky, expensive)**
- **Need diode to block circulating current between fuel cells (lossy)**

Configuration with Series Connected Fuel Cells and a High-Voltage PCS



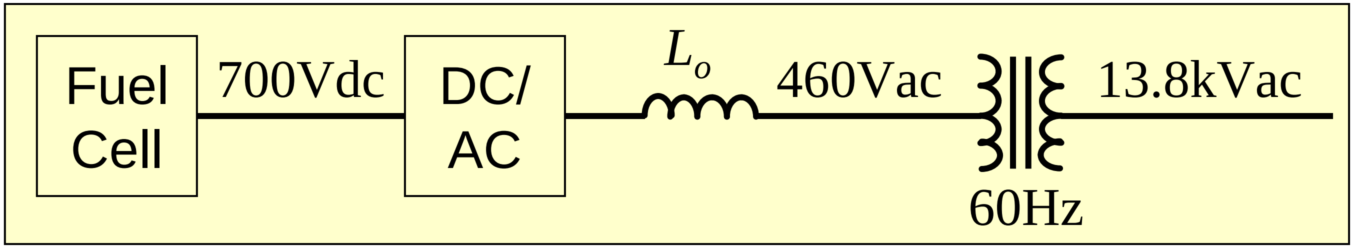
- **Multiple fuel cells connected in series to obtain high voltage**
- **High voltage power electronics is needed**
- **Low-frequency transformation becomes optional depending on how high is the power electronics output voltage**
- **Problem is common-mode (CM) voltage of top level fuel cells**

Low-Voltage Power Electronics Options



1. Fuel cell + DC-DC converter + DC-AC inverter + LF transformer

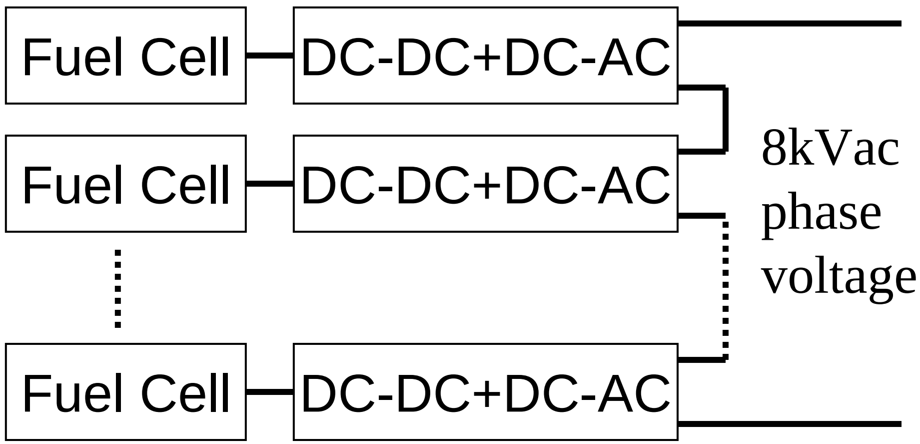
- Fuel cell independently sends power to grid regardless its output level
- Fixed dc bus allows output inductor L_o to be optimized

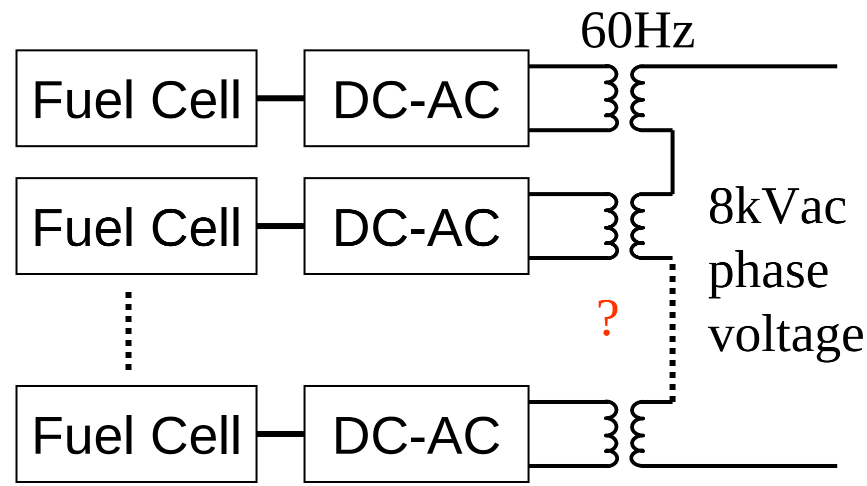


2. Fuel cell + DC-AC inverter + LF transformer

- Fuel cell sends power out only at sufficiently high enough output levels
- Variable dc bus needs large output inductor L_o

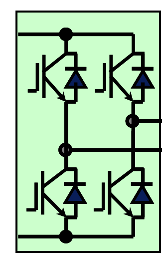
Options with Cascaded Multilevel Inverters



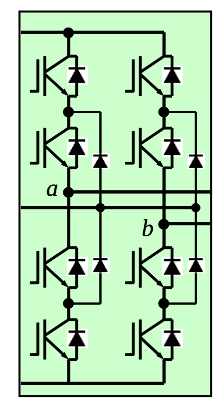


Two options to avoid high common mode voltage on upper level fuel cells

1. Add DC-DC in front of DC-AC
   - Need isolated DC-DC converter
   - Cost and complexity are nontrivial
2. Add low-frequency transformer after DC-AC
   - Low-frequency square-wave transformer is not practical unless DC-AC inverter is high-frequency PWM modulated
   - Low-frequency ripple is a problem to fuel cells



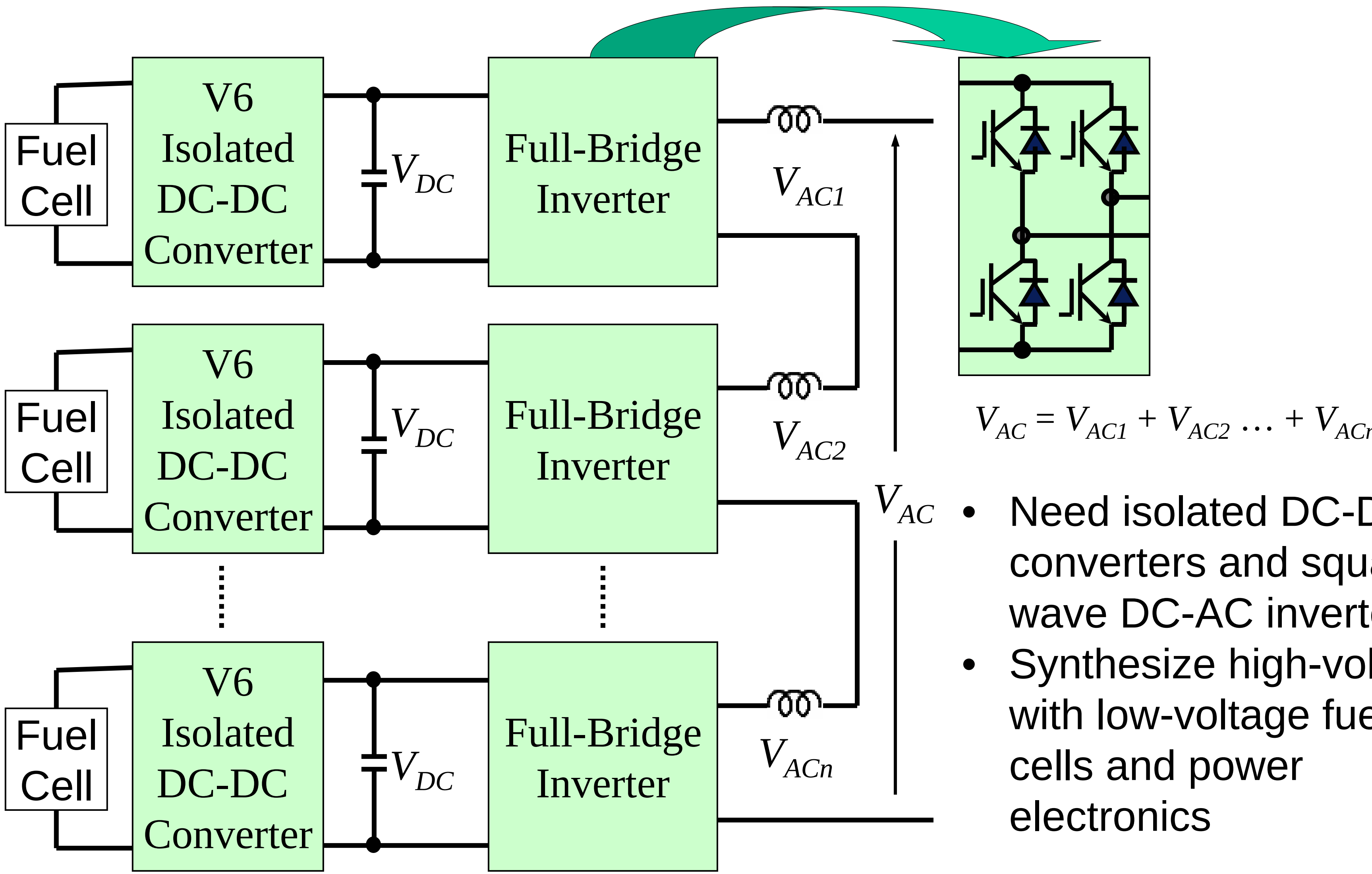
2-level



3-level

DC-AC Inverter Options

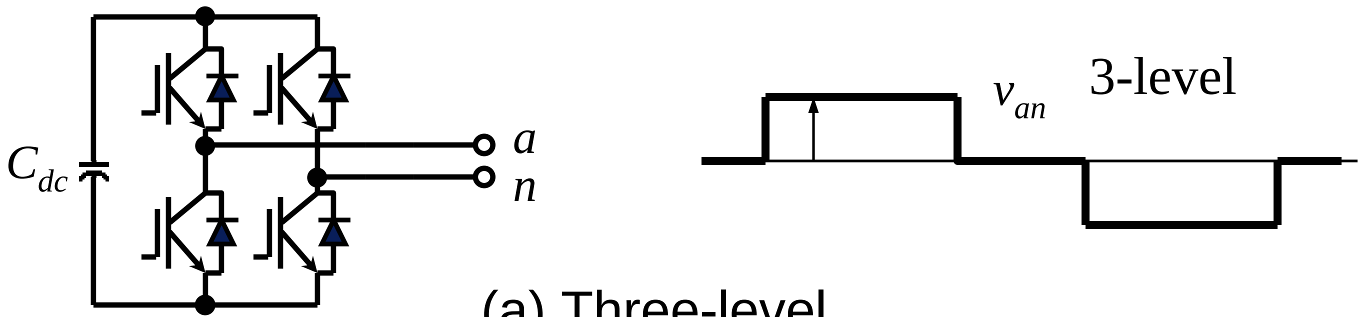
MW Power Plant Using Full-Bridge Inverters Cascaded for High-Voltage AC Systems



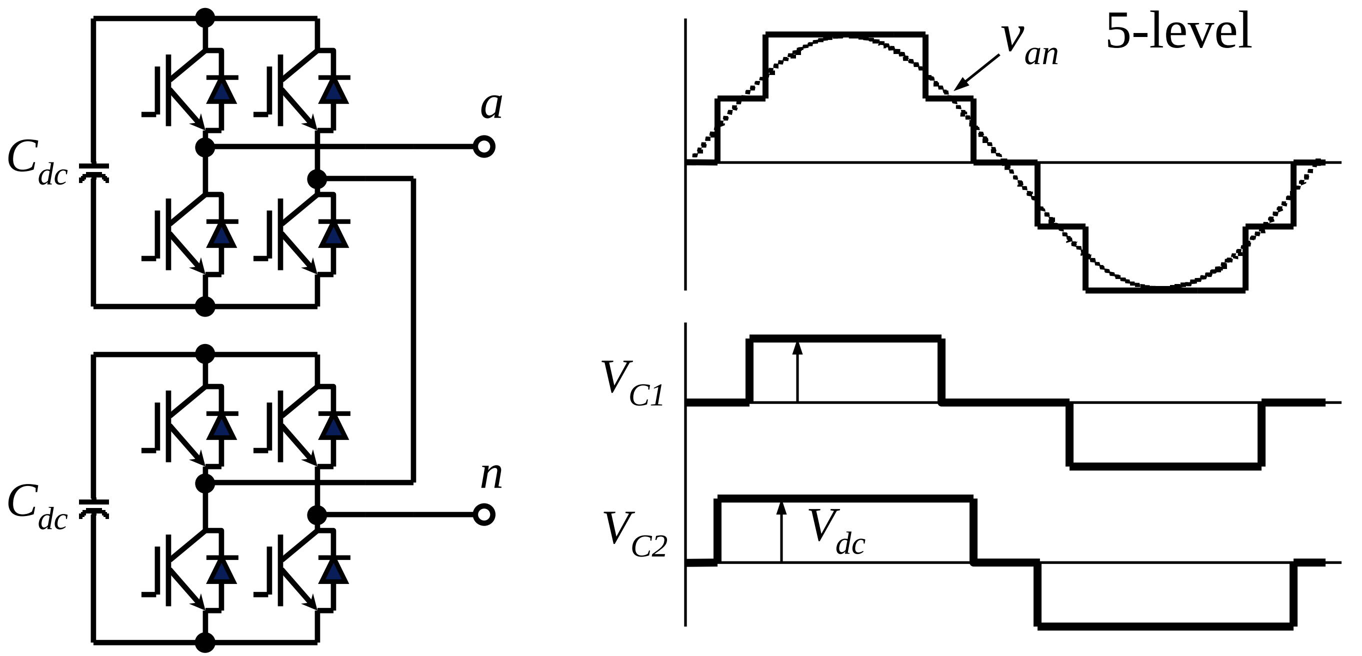
$$V_{AC} = V_{AC1} + V_{AC2} \ldots + V_{ACn}$$

- Need isolated DC-DC converters and square-wave DC-AC inverters
- Synthesize high-voltage with low-voltage fuel cells and power electronics

Voltage Waveform of Cascaded Full-Bridge (FB) Inverters

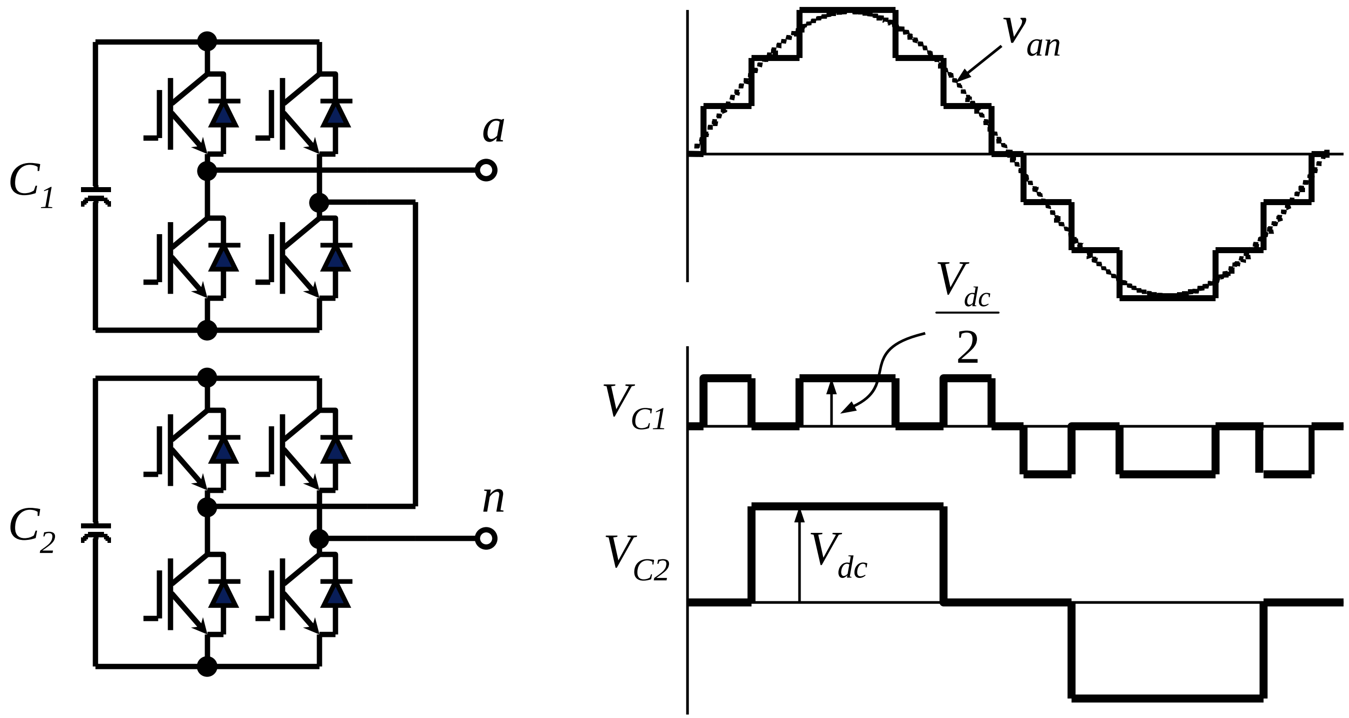


(a) Three-level



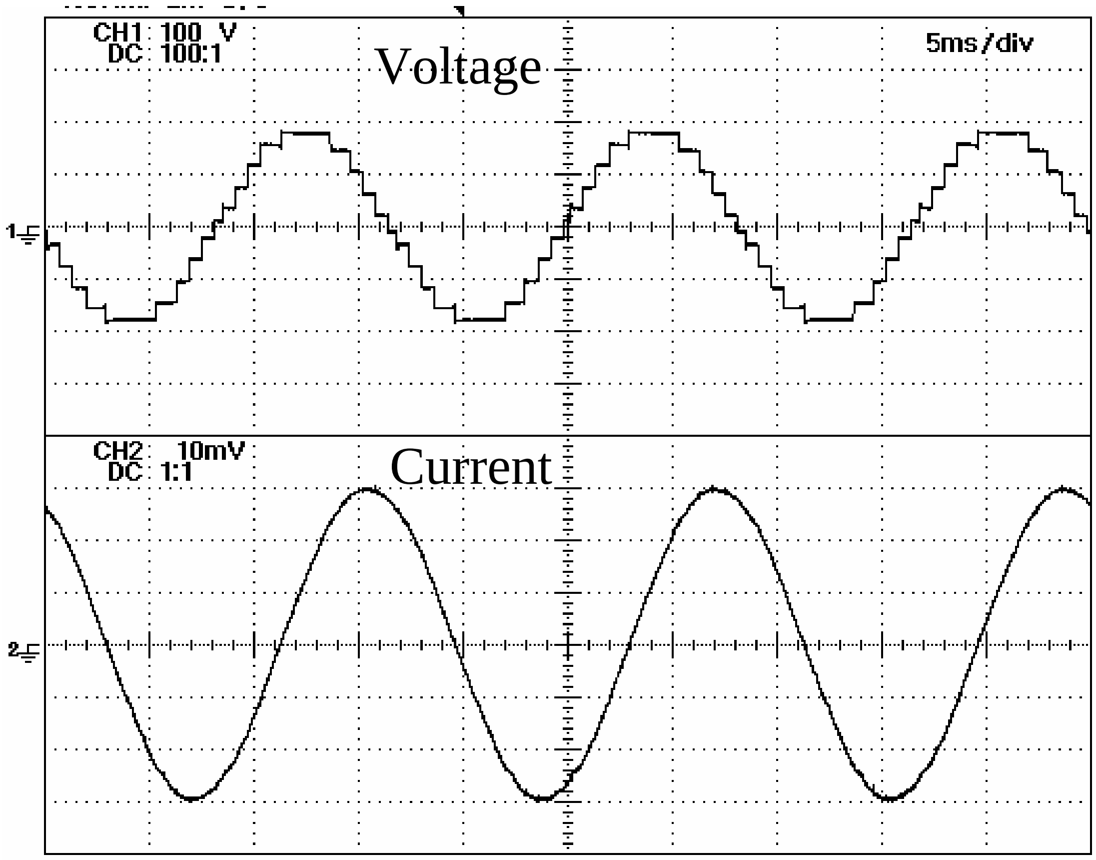
(b) Five-level

Achieving More Levels with Unequal DC Bus Voltages for Cascaded Inverter



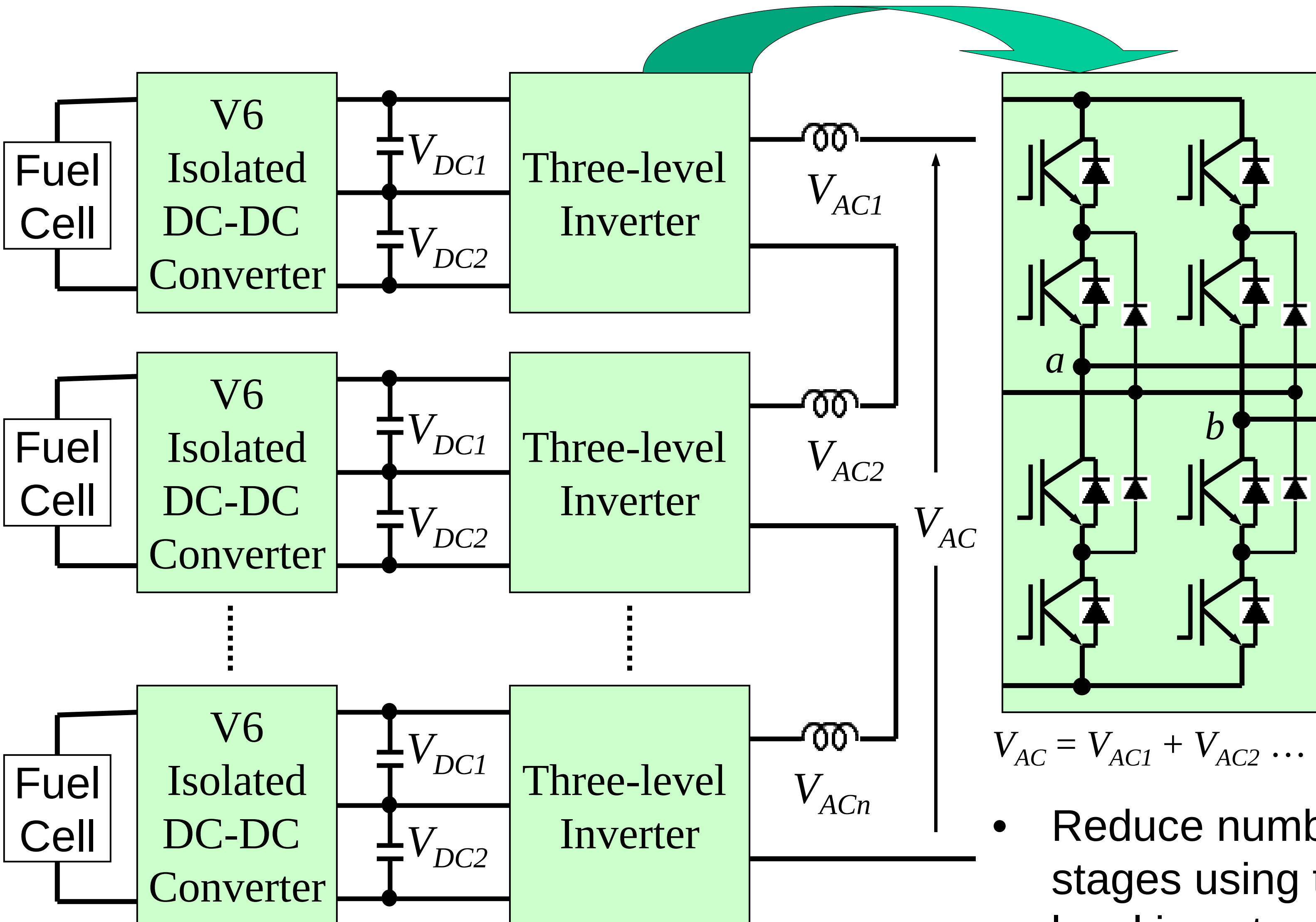
- **With unequal voltage levels, the output waveform has more ways to synthesize**
- **Two sets of cascaded inverters achieves 7-level output waveform**

Voltage and Current Waveforms of 11-Level Cascaded Inverter



- 11-level staircase voltage with cascaded inverters
- Only inductor is used as the filter to obtain clean sinusoidal current

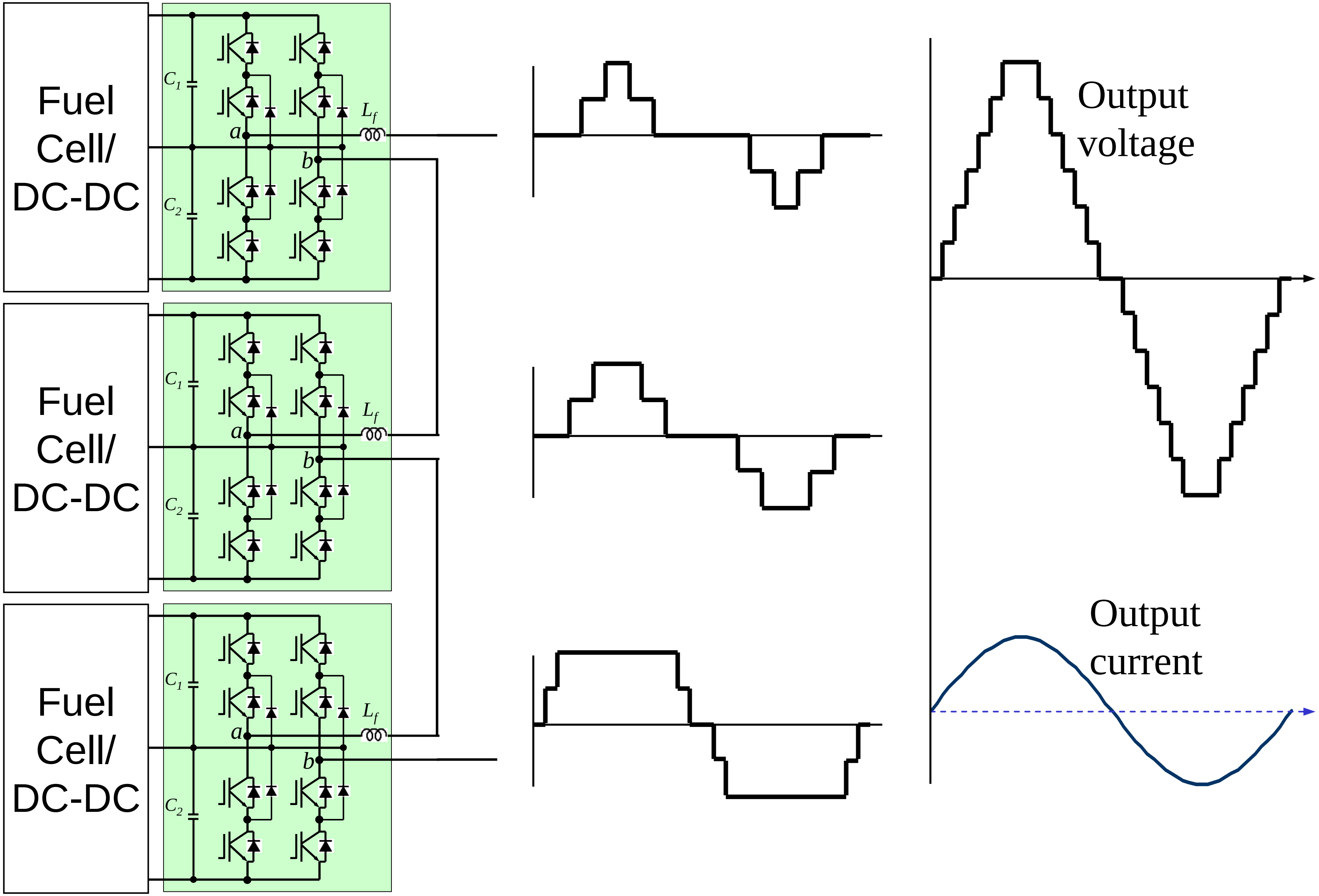
MW Power Plant Using Three-Level Inverters Cascaded for High-Voltage AC Systems



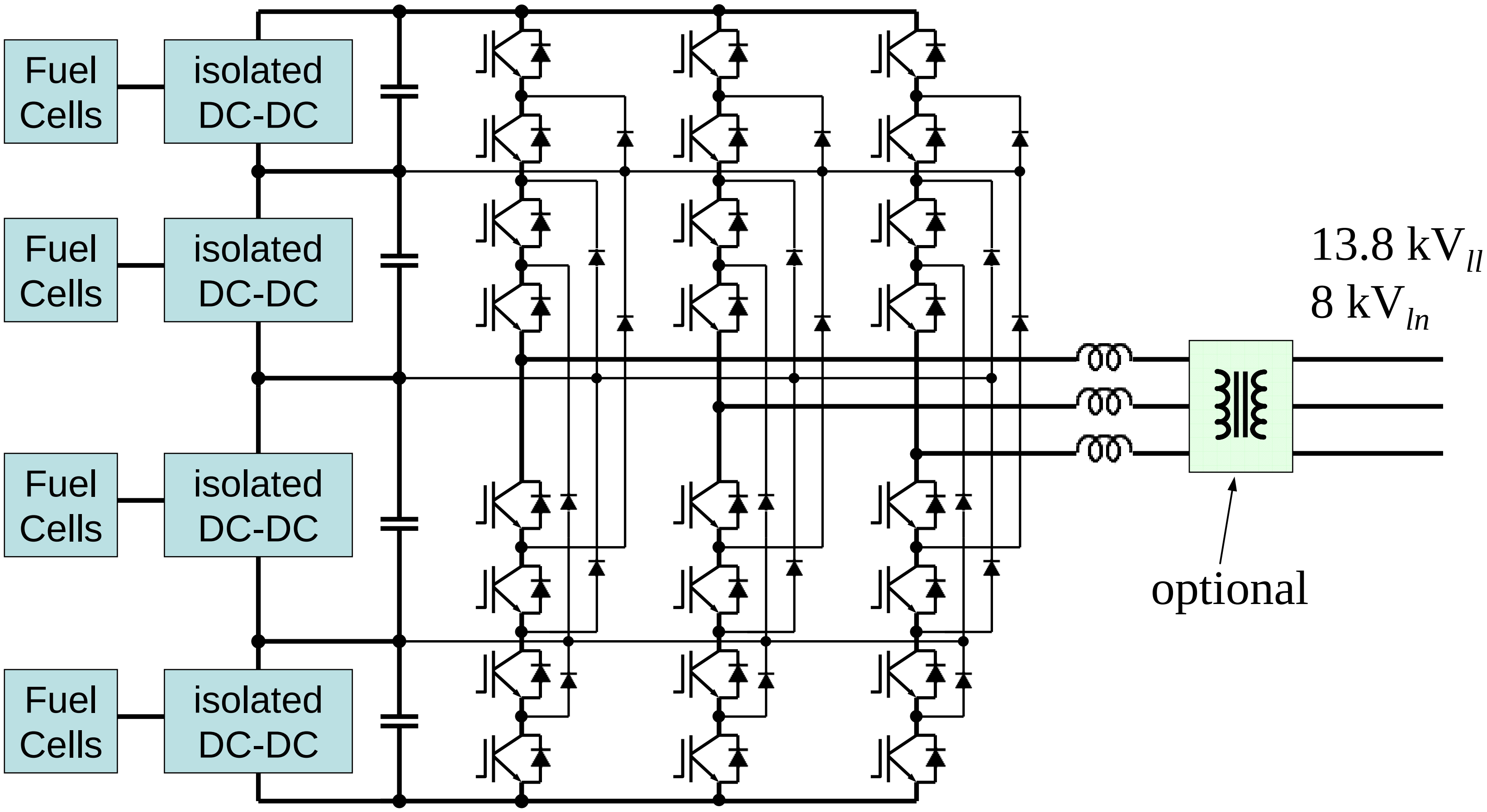
$V_{AC} = V_{AC1} + V_{AC2} \ldots + V_{ACn}$

- Reduce number of stages using three-level inverters

Cascaded Inverter with 13-Level Output



Use Fiver-Level Diode-Clamp Inverter for Possibility of Direct High Voltage Connection

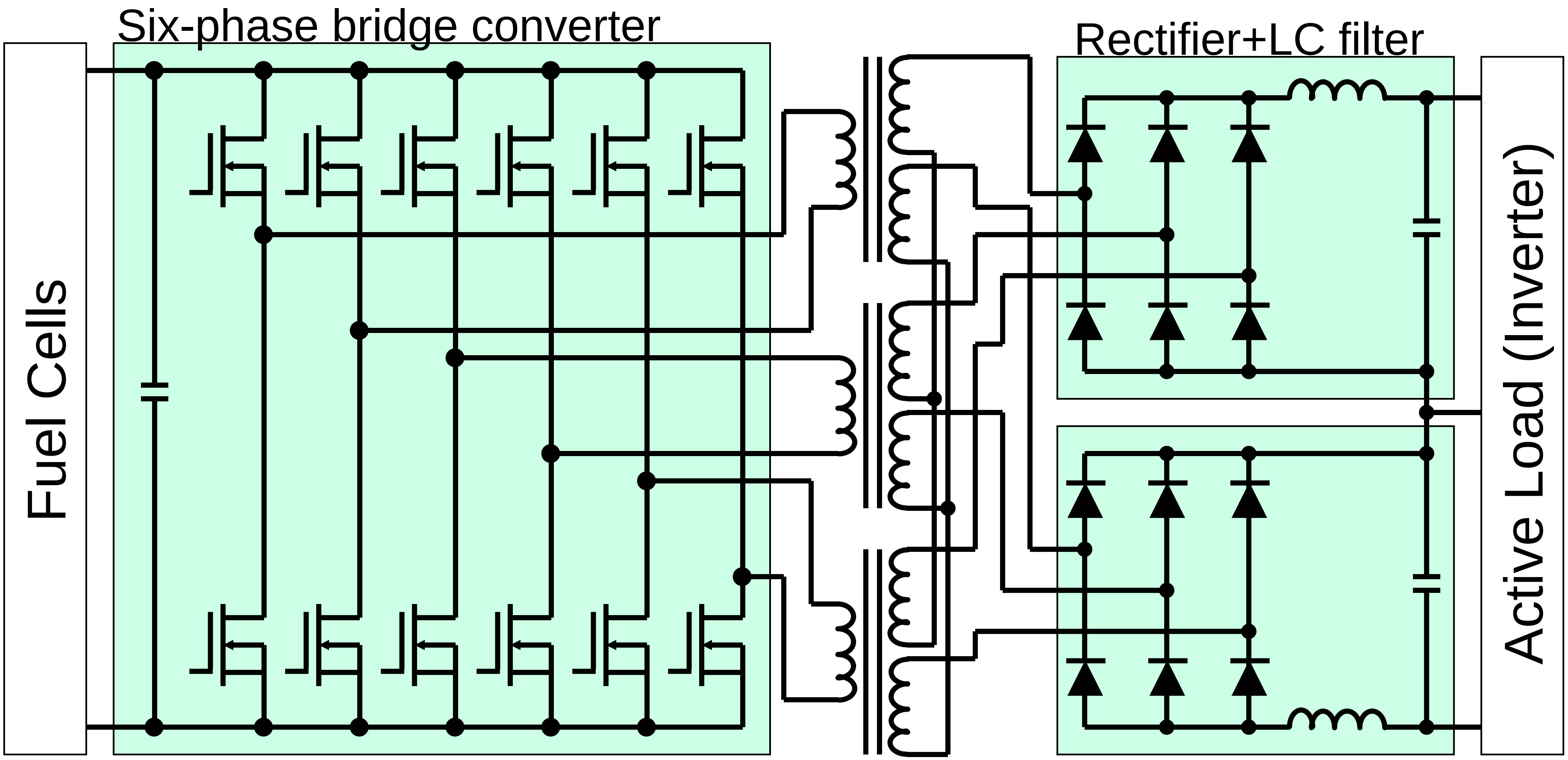


- Need isolated DC-DC to avoid CM voltage and to boost DC bus voltage
- Given 10-kV SiC device, low-frequency transformer can be eliminated
- Sensors and controls are non-trivial with 5-level inverters

DC-DC Converter is Essential for Most Topology Options

- Except for low-voltage power electronics with “fuel cell + inverter + transformer” option, all other circuit topologies need DC-DC converter for at least one of the following reasons:
  - ✓ Avoid excessive CM voltage in series fuel cell stacks
  - ✓ Isolate fuel cell output for cascaded inverters
  - ✓ Boost voltage for multilevel inverter inputs
  - ✓ Regulate voltage for inverter inputs
- Options of high-power DC-DC converters
  - ✓ Full-bridge converter
  - ✓ Multilevel converter
  - ✓ Three-phase DC-DC converter
  - ✓ V6 DC-DC converter

V6 Converter – Ideal for Fuel Cell Power Conversion

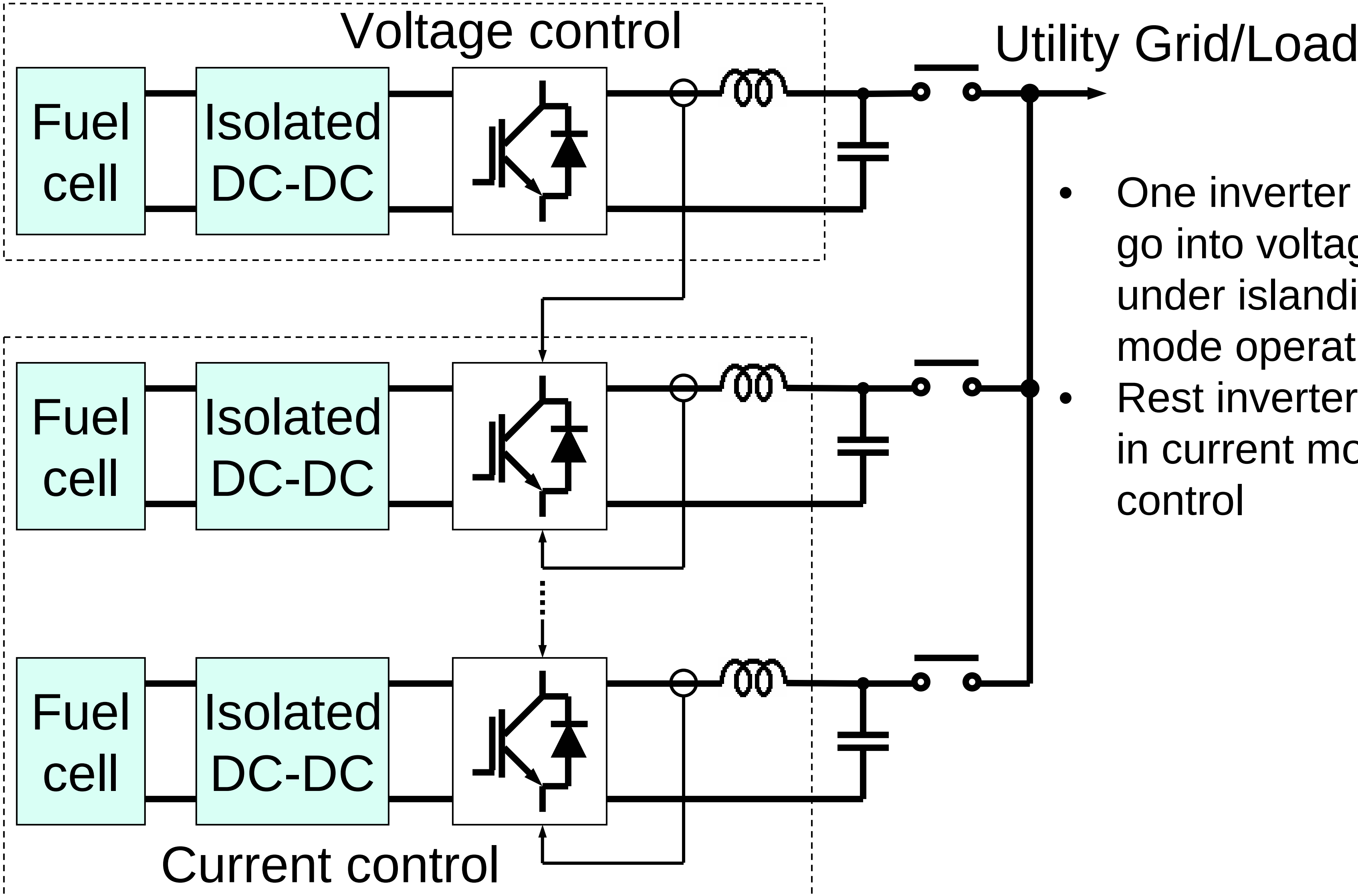


- Three full-bridge phase-shift modulated converters interleaved operation
- High-frequency ripples are cancelled ➔ minimizing filter size and loss
- Y-connected transformer secondary resets circulating current to achieve high efficiency zero-voltage zero-current (ZVZCS) switching

Options of Paralleling Fuel Cell Inverters

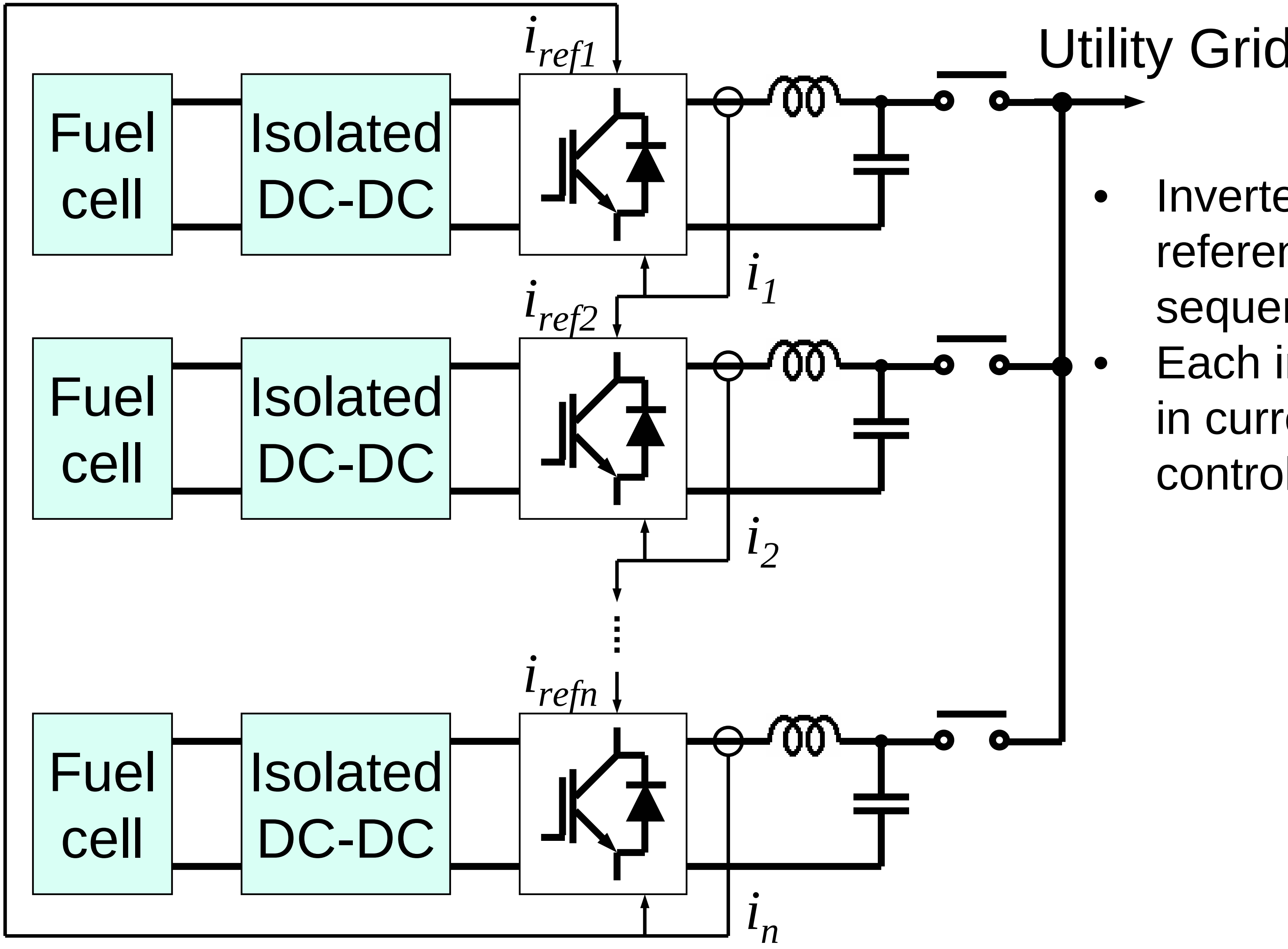
- **Mix voltage mode and current mode for universal applications that can run both grid-tie and islanding modes**
- **Circular chain current control to send current command sequentially**
- **Current distribution control with a center controller to determine current command for each inverter**

Parallel Fuel Cell Inverters with Mix of Voltage and Current Control Modes



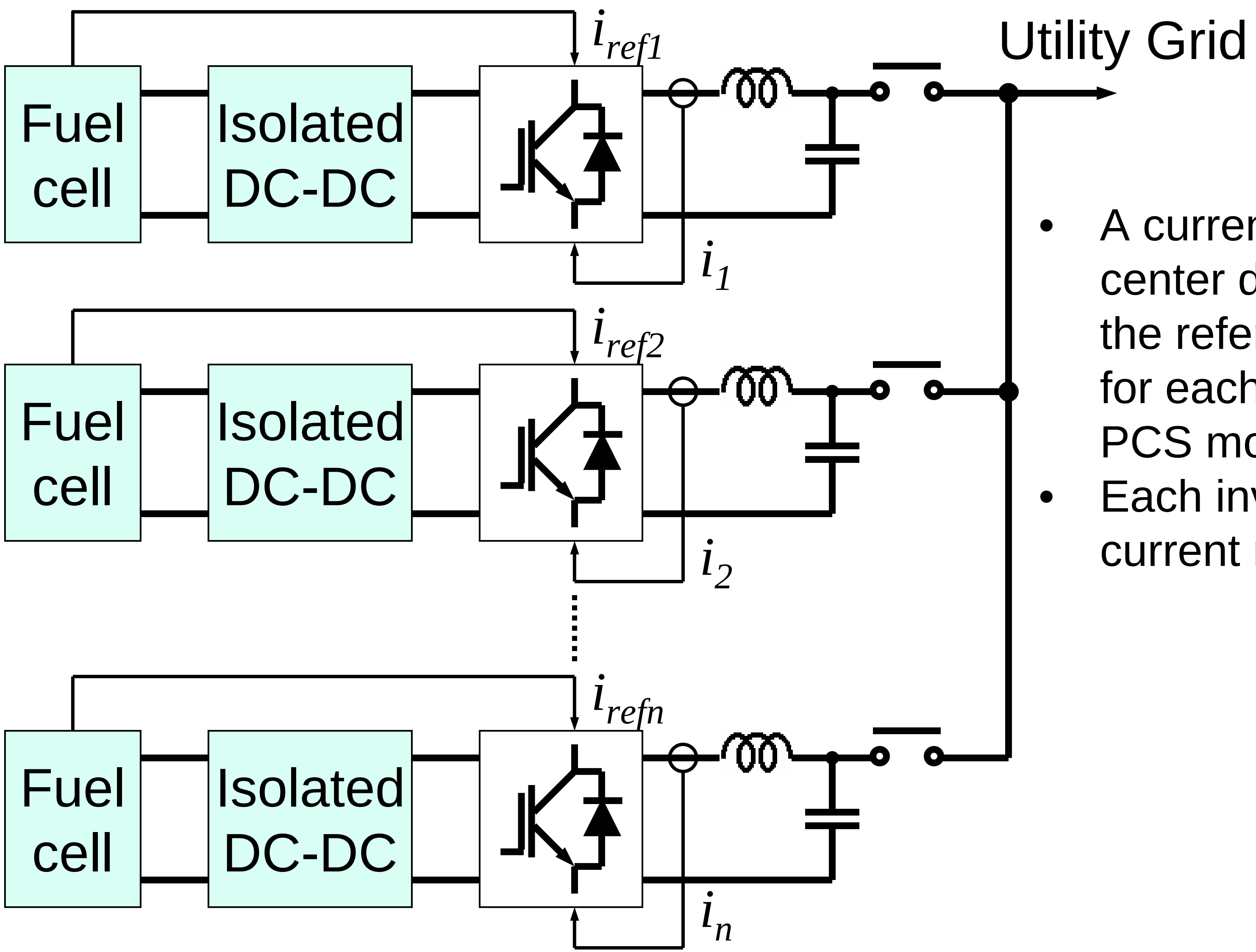
- One inverter can go into voltage under islanding mode operation
- Rest inverters run in current mode control

Parallel Fuel Cell Inverters with Circular Chain Control



- Inverter determines reference current sequentially
- Each inverter runs in current mode control

Parallel Fuel Cell Inverters with Current Distribution Control



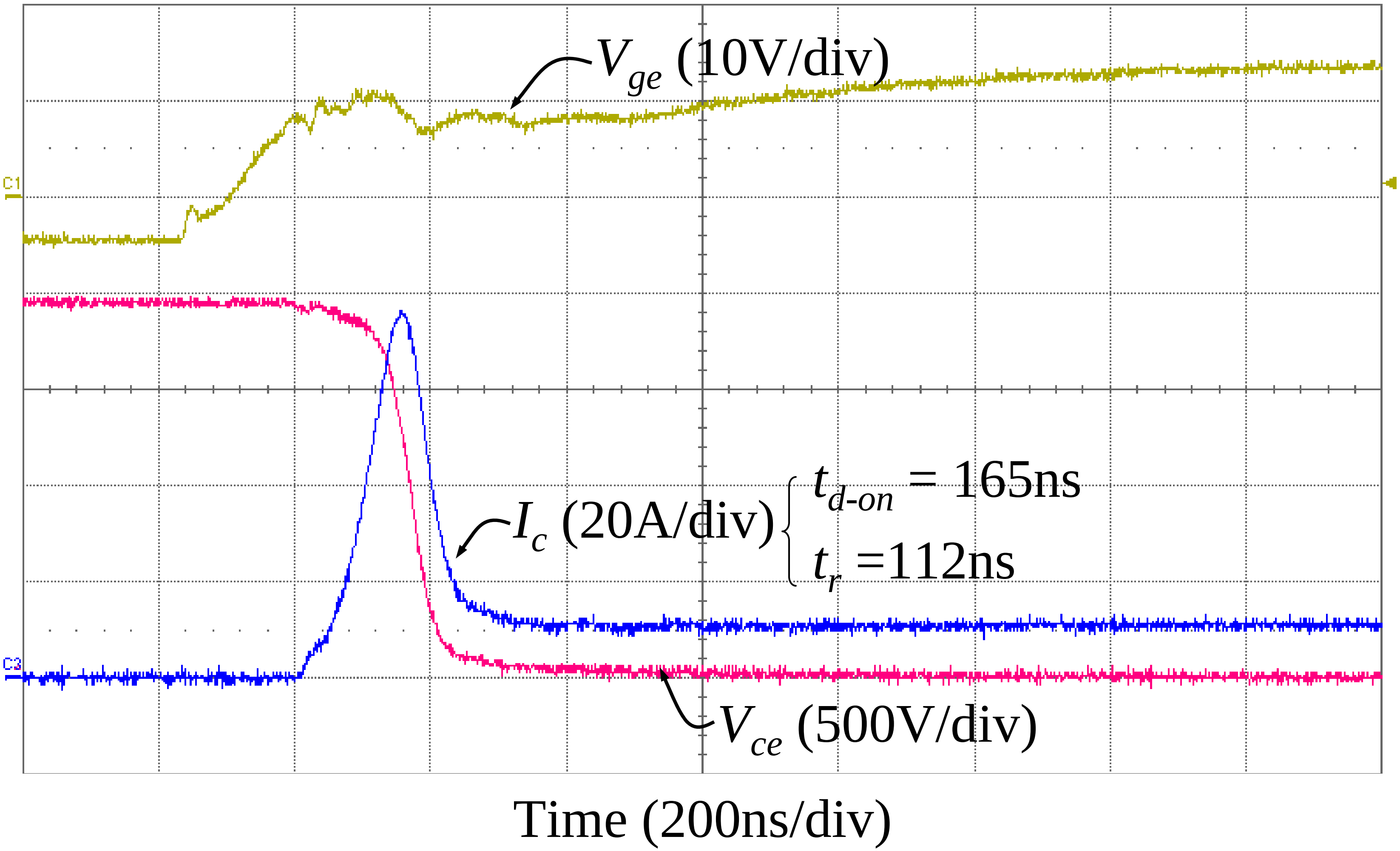
- A current distribution center determines the reference current for each fuel cell-PCS module
- Each inverter runs in current mode control

What Semiconductor Devices are Needed?

- For low-voltage power electronics options
  - ✓ 1200V-level SiC Schottky diodes to reduce the turn-on loss
  - ✓ >1kA Si IGBT
- For cascaded inverter options
  - ✓ 1200-V level SiC Schottky diodes for DC-DC converter output
  - ✓ >1kA Si IGBT
- For diode-clamp multilevel inverter options
  - ✓ 10-kV SiC device (MOSFET or IGBT)
  - ✓ 10-kV SiC diode

HV-IGBT Turn-on with Si Diode

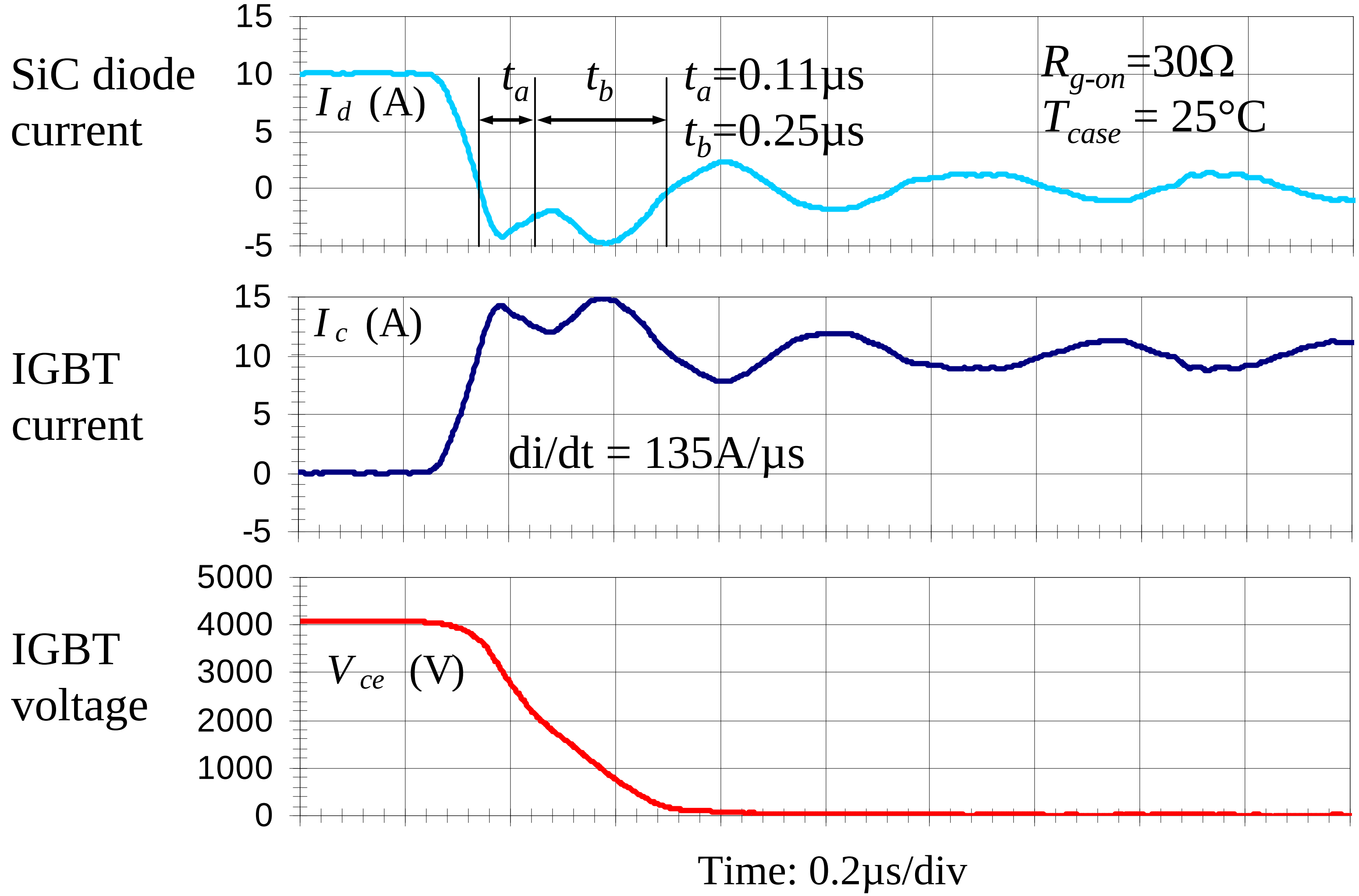
V_{dc} = 2000V, I_c = 11A, $R_{g\text{-}on}$ = 15Ω, E_{on} = 11.2mJ



HV-IGBT Turn-on with SiC Diode

V_{dc} = 4000V, I_c = 10A, $R_{g\text{-}on}$ = 15Ω, E_{on} = 3.5mJ

Significant reduction in turn-on loss even with a higher bus voltage



Summary

- Three possible options for multi-MW fuel cell power plants
  - ✓ Low-voltage DC-AC inverter + low frequency transformer
  - ✓ Low-voltage power electronics including DC-DC and DC-AC + cascaded inverters
  - ✓ High-voltage power electronics including DC-DC and diode clamped multilevel inverters
- High-power high-efficiency DC-DC converters are needed for multilevel inverter based fuel cell power plants
- Multilevel inverters allow significant reduction on current ripples and their associated losses
- Cost reduction can be realized with passive component size reduction
- High-power SiC Schottky diodes are needed for most circuit configurations