Power Electronics

Rajeev Ram, Program Director, ARPA-E

2010: 30% of all electric power flows through power electronics
2030: 80% of all electric power will flow through power electronics
What is Power Electronics?

“The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited to the load.”

AC/DC Conversion

DC/DC Conversion

AC/AC Conversion

DC/AC Conversion

Power Source → Control → Load

Battery → Control → Phone

Solar → Control → Wind Turbine
• 30-50% of cost for dimmable LED luminaire
• 20% energy loss in industrial motors due to mechanical throttling
• 20% of material cost for HEV is power electronics
• ‘No bleed’ More Electric Airplanes give 41% reduction in non-thrust power
• Switches convert DC to Distorted AC
• Inductors (L) and Capacitors (C) clean AC
• Transformer changes AC voltage level
Magnetics and Cost
– largest, most expensive part of the converter

>92% Dimmable LED Driver (comm. 37-50% of luminaire cost)

AC/DC Converter

Magnetics

1MW Photovoltaic Inverter ($0.2/W)

40% Magnetics

\[ Z = j\omega L \]
At hi-frequency, Loss Increases

Energy lost in rotating recalcitrant domains…
requires soft magnets, low coercive fields

Energy lost induced electrical current…
requires electrically insulating material
(>1 mOhm.cm)

- Ferromagnetic coupled particles or 2D flakes/laminates
- High resistivity (300 ~ 600 μΩ·cm) controls eddy-current loss
Miniature (Fast) Magnetics Needs Fast Switches

- Bandgap (energy to ‘free electron’) increases
  - Breakdown voltage increases
  - Drift region can be decreased

Reduces transit time
Increases frequency
Reduces on-resistance

Wide Bandgap Materials: SiC, GaN, etc.
ADEPT Project Example: SiC IC Bi-Directional Battery Charger

Arkansas Electric Power International (APEI): $3.9 M, 3 years

Toyota Prius PHEV

600V SiC IC with full CAD design environment
High temperature, air cooled packaged
ADEPT Project Example: 20kV & 0.4 MW Transistors for Solid-State Substations

Cree Inc.: $5.2 M, 2 years

Improved SiC IGBTs
High voltage (20kV)
98% Efficient
50 kHz
Improved reliability & lifetime
High device yields

Improved technologies
50% reduction in total power conversion losses
100X reduction in high power transformer weight
ARPA-E Supported Power Electronics Innovation

**Distribution & Transmission**

- >13 kV, 50kHz SiC transistors

**Automotive**

- Toyota Prius PHEV

**Industrial**

- Inverter drives motor

**Lighting**

- Existing 25 W AC-DC SSL Driver
  - **Power Stage:** 130 mm x 45 mm x 25 mm
  - **300X reduction in power stage volume**

**Share of Electricity Consumed by Major Sectors of the Economy, 2008**

- Industrial: 26%
- Commercial: 36%
- Residential: 37%
- Transportation: 28%
- Residential and Commercial: 40%
- Electricity: 40%
- Industrial and Commercial: 40%

Primary Energy Use by Sector, 2008
Solar ADEPT
Agile Delivery of Electrical Power Technologies
Balance of System

Source: Rocky Mountain Institute
**Power Electronics Additionality for BOS**

- **Reducing Module and BoS Costs**
  - Cell, Module electronics compensates materials variability
  - Streamlined engineering and installation
  - AC modules
  - Lightweight central inverters

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Rocky Mountain Institute, 2010
UTILITY SCALE SOLAR

Goal: Consolidate the number of inverters
   20 MW installation will have
   20 x 1MW inverters

Barrier: Longer wiring, limited by loss

Approach: Higher DC bus voltages
   DC/DC boost converters at module string (w/ MPPT)

Goal: Improve power quality while delivering cost
   high frequency electronics - improved EMI, reduced harmonics

Barrier: - Low loss, high-voltage switches and magnetics
   - Utility ‘ownership’ of line frequency transformer

Approach: Wide-bandgap switches with advanced magnetic materials
COMMERCIAL ROOFTOP SOLAR

Goal: Module level MPPT (>98%)

Barrier: Cost & reliability

Approach: DC/DC or DC/AC module integrated converters

Goal: Light weight, roof-top inverter [controversial]

99%, 200-500kW, eliminates DC conduit and wiring

Barrier: High-frequency switches and magnetics

AC switches (for current drive architectures)

Approach: Wide-bandgap switches with advanced magnetic materials
MICROINVERTERS

Barriers to adoption:

• Cost to Install
• Risk Averse Customers
• Cost to Maintain/Repair (multiple point of failure)
SUB-MODULE CONTROL

Goal: Improved yield without compromising cost ($1-2 per module) or reliability

Barrier: >99% efficient for improved yield + MPPT function for cost of a diode

Approach: Single chip DC/DC converter in Silicon
MULTISTAGE INVERTER

BASE CASE

PV Strings → Combiner → Central Inverter → Transformer → Utility Grid

1/10 the weight, 1/3 lower losses, ½ the manufacturing cost

<table>
<thead>
<tr>
<th>Product</th>
<th>Power (Watt)</th>
<th>Weight (lbs)</th>
<th>Lbs/kW</th>
<th>CEC Efficiency</th>
<th>Est. Mfg Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVPowered</td>
<td>35K</td>
<td>1200</td>
<td>34</td>
<td>95.5%</td>
<td>$10K</td>
</tr>
<tr>
<td>SatCon</td>
<td>30K</td>
<td>1204</td>
<td>40</td>
<td>95.0%</td>
<td>$10K</td>
</tr>
<tr>
<td>Ideal Power Converters</td>
<td>30K</td>
<td>80</td>
<td>2.7</td>
<td>97.0%</td>
<td>&lt;$5K</td>
</tr>
</tbody>
</table>

Hi-voltage switches and hi-frequency transformer
**SCALING NANOCOMPOSITE MATERIALS**

*Magnetic Metal*

(3~5 nm Co Particles)

*Ceramic*

(Al₂O₃, ZrO₂, etc.)

- Ferromagnetic (coupled particles)
- High resistivity (300 ~ 600 μΩ·cm) controls eddy-current loss

![Graph showing magnetic properties](image)

**Source:** C Sullivan, et al.

From micron thin-films to mm scale inductors & transformers for 3 – 10 kW, 1 MHz
## SOLAR ADEPT TARGETS

<table>
<thead>
<tr>
<th>System Categories</th>
<th>Cost</th>
<th>Voltage &amp; Power</th>
<th>CEC Efficiency</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>$0.05/W</td>
<td>&gt;3 converters /module</td>
<td>&gt;98% cell-to-AC MPPT</td>
<td>Single-chip DC/DC Inside Module Frame</td>
</tr>
<tr>
<td>Sub-module converter (Smart bypass)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Category 2</td>
<td>$0.20/W</td>
<td>&gt;600 V &gt;250 W</td>
<td>&gt;98% cell-to-AC</td>
<td>&lt; 2 lbs</td>
</tr>
<tr>
<td>Microinverter (Residential)</td>
<td></td>
<td></td>
<td></td>
<td>Integrated: &lt; 10 parts</td>
</tr>
<tr>
<td>Category 3</td>
<td>&lt;$0.10/W</td>
<td>100kW</td>
<td>&gt;98% cell-to-AC MPPT</td>
<td>&lt; 50 lbs</td>
</tr>
<tr>
<td>Lightweight (Commercial)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category 4</td>
<td>$0.10/W</td>
<td>&gt; 2 MW scalable</td>
<td>&gt;98% module-to-grid</td>
<td>&lt; 1000 lbs</td>
</tr>
<tr>
<td>Utility-scale Converters</td>
<td></td>
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</tr>
</tbody>
</table>
GREEN ELECTRICITY NETWORK INTEGRATION (GENI)
Designing Power Flow

\[ I = Y \times V \]
Minimizing the cost of fuel to deliver power is Hard (NP)
Must search through many choices of generator outputs for achieving a desired load

What kind of control?
- Linear vs. Non-linear
- Deterministic vs. Stochastic
- Time-invariant vs. Time-varying
- Continuous-time vs. Discrete-time
Controlling Power Flow

**Power Flow Control**

- Feed-forward control
- Assume:
  - Linear
  - Deterministic
  - Time Invariant
- Central control

**Error (Frequency, Voltage)**

- Feedback control
- Account for
  - Non-linearity
  - Dynamics
- Distributed or local control
Benefits of Routing Power

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation

**Today: Uncontrolled Flows**

- **Base Case:** 3.4 MW sent; 0.34 MW recd
- BAU case requires upgrade of 3 inter-regional paths, for a total of 186,000 MW-MILES
- Power flow control to route power along underutilized paths, 36,000 MW-miles of new lines needed, only 20% of BAU

**Power Routing**
ROUTING POWER TODAY

Utility: AC Universal Power Flow Controller

Private: Multiterminal HVDC
**NEXT GENERATION HARDWARE**

- A fail-normal mode
- Fractionally rated converters
- High-voltage components
  \(\textbf{Target} < \$10/\text{Watt}\)

- HVDC fault protection
- High capacity, low cost cable
- High-voltage, uncooled
  \(\textbf{Target} < \$200/\text{Watt}\)

**ADEPT Goal:** 13kV SiC GTO
Control Challenges

- Traditional control theory assumes centralized feedback control.
- Not always feasible for large-scale distributed systems:
  - Inability to communicate with all subsystems
  - Incomplete/imperfect information
  - Complexity of centralized decision-making
  - Asynchrony
  - Heterogeneous decision-makers with different objectives and uncertain responses

Networked control (Developed since 2005)

- Several layers: Physical, communication, and decision network
  - The physical layer consists of several distributed subsystems, coupled through
    and/or economics, via static and/or dynamic constraints.