SatCon?
SatCon Highlights
Technology ... Applications ... Products

**Technology**

- **1985 MIT-DRAPER**
- **Patriot - 1992**
- **BEACON - 1997**
- **WEC/NG - 1999**
- **FMI & HiComp - 1998**
- **Magmotor - 1997**

**Applications**

- Energy Storage
- Renewable Energy
- Distributed Energy
- Grid Support

- **Technology Development**

**Today**

- 200 Employees
- 3 Divisions

**Technology Development**

- MIL-38534 Class K
- Outdoor Electronics with 5+ year Warranty
- R&D, e.g. SiC Applications WORK
SatCon’s Focus is Grid Electronics – getting electrons on and off the Grid, reliably, efficiently, enhancing Power Q, improving System Dynamics

AE Technologies → Power Conditioning → Power Distribution

Distributed Generation
- Photovoltaic
- Fuel Cell
- Micro Turbine
- Wind Turbine
- Battery Energy Storage
- Flywheel Energy Storage

Advanced Power Storage

DC-DC Chopper

DC Loads
- Active Rectifier

DC-AC Inverter
- Static Switch

AC Loads

Bi-Directional Inverter

Systems Integration Key to Meeting Requirements of AE Power Plant
Solar Inverter Product Line

POWERGATE™

- Highest efficiency listed for approved CEC inverters in its power rating
- First 100 kW inverter shipped for European market
- Only 500 kW solar inverter rated by the California Energy Commission

Additional Inverter Applications
Fuel Cells, Wind, …
As Resource (Wind, PV, FC ...) Penetration grows it becomes Integral to Grid Stability and Control, SO ...

- Customer interface electronics, inherently destabilizing?
- Renewable resource potentially at odds with grid
- Or, could enhance, P, Q, dP/dt, nf, ABC

IEEE1547
UL1741
CEC Rule 21
519
...
IEC
Inverter is the Glue

- Cost
- Performance
  - Power quality
  - Overload
  - ...
- Reliability

- A Grid Inverter is not just a motor drive
- Could be much more than a thermal power plant
Inverters’ Role in the Solar Value Chain

- Inverters make the solar power useful
- Represents approximately 7% to 10% of system cost

2005 Global Average Prices

Value Chain Opportunity

Economic Analysis

Representative Cost Comparison of Electrical Energy Generation

- Coal
- Hydro-Electric
- Big Wind
- Diesel (Local)
- Natural Gas
- Big Solar
- Small Wind (Future)
- Low-Head Hydro (Future)
- Small Solar
- Small Wind (Today)
- Diesel (Remote)

$/kWh

- Capital Costs
- Fuel Costs
- Typical Sale Price
- Typical Co-Gen Subsidy
Some) Grid Technology Developments

- **Materials**
  - Composites, e.g. cable
  - Replaces steel core conductor
  - 2x rating
  - Eliminates sag caused by load, ambient
  - Fewer structures along right-of-way
  - Reduces line losses
  - Eliminates bi-metallic corrosion, fatigue issues
  - Super conductors?

- **Devices**
  - Silicon Carbide (devices + related)
  - Solid state breakers
  - HV, HT Electronics

- **Distributed sensing**
  - Temp, volt, I,

- **Communications**
- Nuclear
- Demand side control
- Micro-grid
- Storage
- Efficiency (technology)?
- Improvements (FC, PV, Wind, ...)
- EV/HEV
- Biofuels, synthetic, cellulostic, ...
- Off-Shore Wind
- Storage, Storage, Storage, ...

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*Figures:*

- Figure 1: Energy use in the U.S. between 1970 and 2006.
- Figure 2: Human development index vs. per capita electricity use for selected countries.
- Figure 3: U.S. Energy R&D 1975-2004.
### Si → Si/SiC → SiC

<table>
<thead>
<tr>
<th></th>
<th>Silicon SOA</th>
<th>Hybrid Si/SiC Design</th>
<th>Full SiC Design</th>
</tr>
</thead>
</table>
| **Size/Density/Efficiency** | 10 -- 100 W/in³  
(16 W/in³ for SSIM) | 15 -- 150 W/in³  
(25 W/in³ for SSIM)  
(70% Vol., 50% Switching,  
~75% P) | 35 -- 350 W/in³  
(80 W/in³ for SSIM)  
(30% Vol., 20% P) |
| **Cooling**          | 80°C max. liquid or 25 ºC Air | 80°C max. liquid or 25 ºC Air | >100°C liquid or 40-50 ºC Air |
| **Response Time**    | 10 ms for 5.6 kHz with V and I loops | 5 ms for 10 kHz with V and I loops  
1 ms for 100 kHz with dead-beat control | 50 µS for 100kHz with dead-beat control |
| **High Temperature Design** | Si limits entire system to < 125ºC | Si limits entire system to < 125ºC | Partial High-Temperature design if needed  
(analog degradation) |
| **Overload Capability** | 100-500 ms | 2+ seconds | 10+ seconds |
| **Robustness/Reliability** | 10-20,000 hr. MTBF | 20-50,000 hr. MTBF | 50-100,000 hr. MTBF |

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Optimize Key Metric  
Cost  
Range  
LCC  
Life  
...
Realizing Potential of Wide Band Gap

- Power Circuits
- Power Components, active and passive
- Signal Electronics
- Control
- Software
- Thermal Management
- Mechanical Design & Packaging

Full benefit comes from addressing all areas

SiC devices are NOT drop in replacements

Is the performance acceptable?
Are the devices reliable?
Are they consistent (matched)?
What are the next hurdles?
Some Cost Considerations

Assume: SiC will reach 3x Si, diode is ½ of active, LC product goes down by 4, choose L or C

<table>
<thead>
<tr>
<th></th>
<th>Today’s Si Design</th>
<th>Hybrid Si/SiC-1</th>
<th>Hybrid Si/SiC-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductors</td>
<td>4.11</td>
<td>6.81</td>
<td>6.81</td>
</tr>
<tr>
<td>Magnetics</td>
<td>9.83</td>
<td>4.91</td>
<td>2.455</td>
</tr>
<tr>
<td>Filter Caps</td>
<td>1.7</td>
<td>0.85</td>
<td>1.7</td>
</tr>
<tr>
<td>Heatsinks + Hardware</td>
<td>2.4</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Fans</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sum (% of total parts cost)</td>
<td>19.04</td>
<td>14.77</td>
<td>13.165</td>
</tr>
</tbody>
</table>

Percentage Costs for Si/SiC Inverter

1% increase, 2% improvement round-trip efficiency
For the 100kW Inverter, feeding a 200kWHR battery, once per day charging cycle 2kWhR saving of off-peak energy, 2kWhR of peak electrical energy.
German feed in tariff for PV as an indicator (~55 c€/kWh) we could argue that the 1% of efficiency is worth US $1/day, or with a 20% return on investment approximately $1,800
on the order of 10% of the parts cost of the inverter and so the increase in cost of the semiconductors in moving to a hybrid Si/SiC IGBT module is easily justified in savings due to improved efficiency
Or CEC have put a monetary value on KW capability of up to $3.50/watt and so the 1% efficiency improvement would have a direct monetary value in a subsidy situation of up to $3,500. Could be more for roundtrip and with 2 stage

Other factors: EMI, Snubbers, metal, MOVs, Electrolytics!, …
### Medium Voltage Drives Today

**ABB, NishiShiba, Siemens, ...**

<table>
<thead>
<tr>
<th>VSI-NPC Voltage Source Inverter Neutral-Point Clamped</th>
<th>VSI-MF Voltage Source Inverter Multilevel-Fuseless</th>
<th>VSI-NPC Voltage Source Inverter Neutral-Point Clamped</th>
<th>LCI Load Commutated Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps, fans, conveyors, extruders, mixers, compressors, grinding mills, suitable for retrofit of existing motors</td>
<td>Compressors, extruders, pumps, fans, grinding mills, conveyors, marine propulsion, bar and rod mills, blast furnace blowers, gas turbine starters</td>
<td>Pumps, fans, conveyors, extruders, compressors, grinding mills, marine propulsion, rolling mills, mine hoists</td>
<td>Compressors, pumps, fans, blast furnace blowers, pump storage plants</td>
</tr>
</tbody>
</table>

- **ABB**
  - ACS 1000
  - ACS 1003

- **NishiShiba**
  - ACS 5000

- **Siemens**
  - ACS 8000

- **...**
  - MEGAARVE-LCI

### Voltage, frequency, performance tradeoff

- **Air (A) / Water (W)**
  - A: 315 kW–2 MW
  - W: 1.8–5 MW
- **Diodes:** 12/24-pulse rectifier
- **IGCTs:** 3-level VSI, sinusoidal output
- **2.3/3.3/4.0/4.16 kV**
  - Optional: 6.0/6.6 kV with step-up transformer
- **66 Hz (optional 82.5 Hz)**
- **> 45 Hz (max: 1:1.5)**

- **Water (W)**
  - W: 3–27 MW
- **Diodes:** 36-pulse rectifier
- **IGCTs:** 5-level VSI-MF, 9-level output waveform
- **6.0–6.9 kV**
  - Optional: 4.16 kV
- **75 Hz (higher optional)**
- **> 30 Hz (lower optional)**

- **Air (A) / Water (W)**
  - A: 2–31 MW
  - W: 7–72 MW / higher on request
- **Diodes:** 12/24-pulse rectifier (LSU) or IGCT
  - Active rectifier (ARU)
- **IGCTs:** 3-level VSI, 5-level output waveform
- **3.0–3.9 kV**
  - Optional: 2.3 kV
- **75 Hz (Twin: 250 Hz)**
- **> 6.25 Hz (max: 1:5)**
- **Customized**

- **LSU**
- **ARU**

- **Soft start of large synchronous motors and generators**
- **Fuseless**

**Notes:**
- Sinusoidal output
- Constant network power factor over whole speed range
- DTC (Direct Torque Control)
- Fuseless

**Medium Voltage Drives Today**
Fully Rated Inverter provides Many Possibilities

- Controllable (remotely)
- Supply Real Power, $P$, regulate battery

- Reactive power, $Q$, $(|P + jQ| < S_{\text{INV}})$

- Active Damping (stabilizing)
- Fault Clearing
- Rapid Dynamics
- Unbalanced, non-linear sourcing
- Active Filtering, harmonic cancellation

- NOT an Electrical Machine!!
Increasing Penetration of Renewables

Denmark
• 14% of Electrical Energy
• New Control Regs.
Harmonization?
Electronic Capability?
Power Distribution Options -- Battle

Thomas Edison and Joseph Swan

Pearl St, NY, 1882
Edison
85 Customers, 400 Lamps

\[ d = \sqrt{\frac{2\rho}{\omega \mu}} \]

But
• Skindepth
• \( \phi \) Imbalance
• Reactive power
• Peak to RMS

Edison was missing what?
Loads Today?
Sources Today
Storage?

AC won (pre-electronics)
• Transformer isolation
• Impedance (V) transformation
• Grounded Secondary (safety)
• AC \( \rightarrow \) DC, easy

Move it at HV

George Westinghouse and Nikola Tesla

ADC Hydroelectric Plant
Niagara Falls 1895
Westinghouse, Tesla, Stanley

Today, DC wins for T

Edison was missing what?
Sources Today
Storage?

FC \( \rightarrow \) dc/dc \( \rightarrow \) HVDC ?
Power Electronics Can Provide the Solution - but at what cost?

Who is doing the System Design…?

"Power Electronics is just a Commodity"

System Design and Specification are driving the Power Electronics Cost

FROM FC2000
Power Level and Circuit Topology define a balance of voltage and current that gives minimum cost.

For a conceptual converter topology the curves might look like this:

FROM FC2000
300V to 800V best for 10kW to 100kW power range, 800V and higher best for higher powers

Some general principles:-

Higher voltage semiconductor devices switch slower
Conversion frequencies must be lower at high voltages

High efficiency is difficult to achieve economically when power is the product of low voltage and high current

FROM FC2000
“Power Quality” is multi-dimensional – some attributes are more important to some users

- Necessary to meet load-specific power quality:
  - Harmonic content
  - Transient performance
  - Frequency tolerance
  - Load Circuit Protection
- Stand alone systems may not be required to beat/meet all utility characteristics
  - Saves components
  - Simplifies design
  - Reduces overall cost of system
- Smart Load and Non Invasive Load Monitoring
  - Intelligent control in place of grid imitation

FROM FC2000
Don’t judge distributed power electronics $/kW costs based on motor drives

Motor drives are the most power dense and hence lowest $/kW of all DC/DC and DC/AC power conversion equipment - they have the lowest passive component count.

Typical numbers for very high power density designs:

| DC/DC or DC/AC Power Converter | 7kW/liter |
| DC/AC 3Φ Motor Drive | 28kW/liter |

In high volume production cost follows power density (& weight) so that cost expectation for DC/DC & DC/AC Power Converters should be 3 to 4 times the $/kW of motor drive converters.

FROM FC2000
Hardware confirms the power density ratio

100kW motor drive inverter
1.3 ft^3, 56lb
DC input 320V

15kW Fuel Cell Converter
1.5 ft^3, 65lb
DC input 48V/48V

FROM FC2000
Big Inverters

- $200/kW?
- Extended Warranty?
- Performance?
- Research? - devices (SiC, GaN, … . Packaging, gate drives, control, passives, …. overload capability topology? Device dependent, say truly symmetric, bi-directional IGCT, 10kV+, building blocks, resonant transformers (isolation?), step-up to 25kV? CSI, …