The Future of Power Electronics Design

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Definition of Power Electronics

- The intersection between the Energy and Electronics Industries
- Power Electronics Industry started in the 1970’s:
  - Power conversion existed from the dawn of the electrical age but made little use of “electronics”
  - 1973 The fourth Power Conversion conference in Pasadena adopts the name of “Power Electronics”
  - 1976 Silicon General introduces the SG1524 PWM controller IC
  - 1977 Abraham Pressman publishes “Switching and Linear Power Supply, Power Converter Design”
  - 1979 International Rectifier patents the HEXFET
Historic price/performance trends within the Power Electronics Industry (1975 to 2015)

- **Five key performance metrics:**
  - **Control complexity:**
    - SG1524 (72 transistors) → DSP ( Millions of transistors)
    - Driven by Moore’s Law – I.E. 40% compound annual growth
    - Control complexity enables efficiency improvements
  - **Conversion efficiency:**
    - <50% ⇒ >97% – Power converter surface area scales according to conversion losses
  - **Power density:**
    - 0.2W/inch³ ⇒ 50W/inch³ – I.E. 15% compound annual increase
    - Tends to scale with switching frequency
  - **Switching frequency:**
    - 1kHz ⇒ 250kHz – I.E. 15% compound annual increase
  - **Product cost:**
    - Dollars per watt ⇒ Cents per watt
    - The volumetric cost of power converters tends to be constant
The Growth of Power Electronics

• In 1975, less than 1% of all U.S. electricity flowed through power electronics
• In 2005, 30% of all U.S. electricity flowed through power electronics
• By 2030, it is estimated that this percentage will increase to 80%*
• This growth rate is approaching twice the global growth rate for total world energy consumption

• Where this growth leads to:

  *I predict that in the future the total energy processed by power electronics will eventually exceed the total global energy production*

  • 2015 total world energy consumption was $10^{21}$J increasing at 2.4% CAGR
  • Hence there will be the need for trillions of power converters that will process many terawatts of power

• We are heading towards a total overlap of the Electronics and Energy Industries

*www.energy.gov/eere/amo/power-america*
The Proliferation of Power Electronics

Power Electronics will inevitably process the same energy several times over.

- Solid State Utility Transformers
- PV Inverters
- LED Lighting
- EV Charger & Powertrain
- Flat-screen TV
- Home Energy Storage
- Variable Frequency Drives (VFD) HVAC & Appliances
- Computer, Phone Charger, etc…
Factors Driving the Growth of Power Electronics

• **Move away from dependence on fossil fuel**
  • Finite resource – “The Stone Age did not end for lack of stone, and the Oil Age will end long before the world runs out of oil.” - Sheikh Yamani (1973)
  • Climate change – green house gas emission reduction targets

• **Renewable energy**
• **Energy Efficiency**
• **Electric Vehicles**
• **Cost reduction**
  • Relative cost of switched mode converters compared to “copper & iron”
  • Reducing cost of renewable energy versus the increasing cost of traditional energy generation

• **Move from “dumb loads” to “smart loads”**
  • Smart grid – data connectivity
  • Energy management
  • Internet of Things (IoT)
Growth due to PV alone...
Control Complexity

- Enables technology advancement:
  - Converter model driven control
  - Synchronous rectification
  - Adaptive control
  - ZVS & ZCS commutations
  - Resonant switching etc…

- Cost of complexity keeps reducing:
  - Moore’s law
  - Standardized designs
  - Market growth – higher production volume

Incremental cost of control complexity is almost zero!

Most modern digital control designs simply try to emulate 1970’s analog controllers!
The Power Conversion Paradox

The Power Conversion Paradox:

- The physical size of a power converter determines the circuit parasitics
- These circuit parasitics determine the magnitude of the conversion loss
- The magnitude of this conversion loss determines the physical size of the power converter due to thermal constraints

- This paradox creates multiple possible design paradigms:
  - Converter surface area is driven by the magnitude of the conversion loss
  - Converter volume scales proportional to the loss^{3/2} (Super-linear)
  - Super-linear scaling due to “cube/square” relationship between volume/area
  - There is an inherent thermal advantage in making power converters smaller
Reductio ad absurdum argument:
• If power conversion efficiency is 100%:
  • Hence zero losses
  • No need for surface area
  • Zero volume
  • Zero cost
  • An absurd concept – how to build this?

A natural example:
• The current & flux density created by an electron orbiting a nucleus is many orders of magnitude greater than what we find in Power Electronics designs
• The dimensions of an atom are 24 orders of magnitude smaller than a typical power supply

Closing thoughts:
• Typical current densities in IC’s are 100 times larger than found in Power Electronics designs
• What size can we build Power Electronics designs with?
• A search for new design paradigms
• “There’s Plenty of Room at the Bottom” – Richard Feynman 1959

“As you know electronics just gets smaller and more efficient as time goes on…Maybe the inverter will be 98% efficient and the size of an iPhone and made all out of ceramic!”

Greentechmedia.com (SDTVMARK, September 1, 2011)
Design Complexity – State of the art: Enphase

- Custom ASICs:
  - Main power controller
  - Auxiliary support ICs
- Custom Magnetics
  - Including custom core designs
- Custom Power Semiconductor:
  - Si Superjunction MOSFETs
  - SiC MOSFETs
  - GaN 4 Quadrant Switch (4QS)
- Custom gate drivers
- Custom Power Line Communications (PLC)
- Custom connectors
- Custom enclosures
How we will get to the Future:

• Enabling technology for the Power Electronics industry
  • WBG – GaN & SiC – 100 to 1,000 times the performance of silicon
  • New structures – e.g. Bi-directional GaN eHEMTs

  There is much more value to WBG than simply trying to replace IGBTs with SiC MOSFETs!

• New design paradigms:
  • Power supply topology – Hard-switched Trapezoidal ➔ Resonant switched sinewave
  • Switch structures – uni-directional ➔ Bi-directional for AC converters
  • Switching frequency – VLF/HF ➔ MF/HF/VHF/UHF (5 orders of increase possible)
  • Magnetics – MnZn ➔ NiZn & air cored
  • System architecture – Discrete ➔ Distributed
  • Integration techniques – FR4 PCB & Mechanical ➔ Chip scale & nano-technology
  • Control – DSP ➔ Custom ASICs

Power Electronics – the last frontier for semiconductor integration
Prediction for Power Conversion in 20 Years Time…

- Control Complexity – Billion transistor controller ASICs
- Conversion Efficiency >99%
- Power Density >1kW/inch^3
- Switching Frequency = >10MHz
- Product Cost <$0.01/W

The global Power Electronics industry will grow into a multi-trillion dollar revenue per annum market

- Huge business opportunities
- Exciting career opportunities
$C_{oss}$ Hysteresis in Advanced Superjunction MOSFETs

Paper ID#1065 - Industry Session T05 Tuesday 8:30am

Si Devices and Power Module Packaging Session

Questions?
The Future of Power Electronics Design

Michael Harrison, Enphase Energy

Four decades ago, power electronics consisted of thyristor controlled line-frequency transformers with linear regulators, or maybe self-oscillating circuits driving saturable magnetics. Then the first analog PWM integrated circuits were introduced, enabling closed-loop control of power converters. Of course the speed and complexity of the analog controllers grew, while the cost went down. Efficiency figures seemed to parallel the decade (70’s, 80’s, etc.). More recently digital control of power converters has become the norm. This has enabled more complex operational modes which improve performance and efficiency, while still driving the cost and size downwards. We are now at a point where the incremental cost of control complexity is nearing zero – to the point where we can not ignore the economies of adopting complex control schemes at the expense of the more primitive methods of the past, only because they were easy to understand. This presentation will look at the trends in power converter performance and design philosophy from a control perspective, and project where we go in the future, and what kinds of role the power electronic designers of the future will play in our industry.

• Presentation time 20 minutes followed by 5 minutes of questions
  • 12 slides = 1 minute, 40 seconds per slide