Integrated Point-of-Load Converters

ARPA-E
Power Technologies Workshop
DOE Washington DC
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Presented by
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Center for Power Electronics Systems
Outlines

- High density Point-of Load Converters
- Integration Technologies
- Switching Technologies-Devices
- High Frequency Magnetic Materials
- Other applications

The underline objectives:
- Efficiency
- Density (form factors)
- Modularity
- scalability
IPEM Based System Integration
For Different Power Ranges and Applications

10-100 W IPEMs

- IR POWIR™
- TI SWIFT™
- Philips Pip20x
- CPES Monolithic VRM
- IR, Philips, On Semi, Intersil, Linear Tech,
  TI, Renesas, NSC, Power One, Infineon, ST, Maxim, Micrel,
  Volterra, Primarion, Fairchild, Analog

1-10 kW IPEMs

- Semikron IPM
- CPES Integrated EMI Filter
- CPES Flip-Chip-On-Flex Phase-Leg
- CPES Transmission Line Filter
- CPES Active IPEM
- CPES Passive IPEM
- ABB, Hitachi, IXYS, Toshiba, Semikron, Fuji,
  Infineon, Eupec, Powerex

10 kW - 10 MW IPEMs

- CPES 800 V, 40 A ZVZCT phase-leg
- 1.8 kV, 60 A, 3-level ZVZCT phase-leg
- CPES 4.5 kV, 4 kA ETO
- ONR, DOE, NSWC, Thales, Northrop Grumman, Rockwell Automation, General Dynamics, ABB, Bettis, Alstom, ACI, PEMCO, TVA

CPES industry consortium members or research sponsors
Present Power Delivery
for Computer Server Systems

1U Server Power Supplies
Present Power Delivery for Computer Server Systems

< 80%

< 87%

End-to-end efficiency < 70%
Redundant Power Conversion

AC

EMI Filter

PFC

DCX

BUCK

400 VDC

12VDC

POL

Processor Memory

POL

Chipset

POL

HDD

On Board Point-of-Load Converter

1U Server Power Supplies
Ultimate Distributed Power Architecture
For Servers and Telecom

Simple, Modular, Efficient & Scalable

AC

EMI Filter

PFC

PFC

PFC

DCX

DCX

DCX

POL

POL

POL

Processor Memory

Chipset

HDD

Boost 97-98%  96-97%  Buck 92-95%  = 85.5-90%

PFC

PFC

PFC

Boost 97-98%  96-97%  Buck 92-95%  = 85.5-90%
POL for Portable Equipment
Non-Isolated Buck Converters

Possible Applications

Cellular phone  MP3 Player  Digital Camera
PDA
Automotive Electronics
Telecom application ... Laptop
GPS
Lower Power POL
Monolithic Integration (<10W)
"Power Supplies on Chip"
- With integrated magnetics, <10W

**Significant challenges for inductor integration.**
Wafer Level Integration with Inductor

Vertical flux structure:
The plane of magnetic flux path perpendicular with the substrate.

At 1W level
Lateral flux structure:
The plane magnetic flux path is parallel with the substrate.
Power Density of POL Converters
-industry State-of-the-art

Wafer level integration

Power density

W/in3

Current

1A 10A 20A 40A

CPES
Center for Power Electronics Systems
Microprocessors and Moore’s Law

Due Core 120-140A @ <1V

Goal: 10 TIPS by 2015
Power Density of POL Converters

- industry State-of-the-art

Non-isolated POL

Wafer level integration

VR @ 20 A per unit, scalable
Power Density of POL Converters
- Industry State-of-the-art

Power density

Non-isolate POL

Wafer level integration

Isolate POL
Isolated DC/DC Converters
Two-Stage Bus Converters

Front End

AC

48V

First Stage

Second Stage

12V

Second stage

Second stage

150kHz

360kHz

800kHz

1.7MHz

< 300W/in3

< 500W/in3

1000W/in3
Matrix Transformer

3 Transformers @ Fs=1.7MHz

PCB: 12-Layer, 2OZ
Module size: 32x21x4 mm
Power Density of POL Converters
- CPES prototypes

Gen 1: POL with vertical flux

Gen 2: 2 phase POL with vertical flux coupled inductor

Gen 3: 2 phase POL with lateral flux coupled inductor

DCX

Power density
1000
700
500
300
100
W/in3
1A 10A 20A 40A

25%
100%

Lineage Power

LTM4600

EMERSON

Power-One

CPES

Fuji

VICOR

CPES

Lineage Power

LTM4600

EMERSON

Power-One

CPES

Lineage Power

LTM4600

EMERSON

Power-One

CPES
CPES POL: Gen 1

Bottom main layer
Laminate bottom and middle main layers
Print conductor paste into slot using Kapton tape as stencil

Top layer
16A/50nH LTCC inductor

+5V
Cdec
GND
Co
Vo
Gate Driver
HS MOSFET
LS MOSFET
PWM
Vin
Vsw
Dboot
Cboot
Efficiency
Vo=1.2V, 1.3MHz

260 W/in³

DBC Active Layer
PCB Active Layer

Io (A)

94.0%
92.0%
90.0%
88.0%
86.0%
84.0%

0 5 10 15 20 25
Power Semiconductor Devices

- Some devices are pushing Si boundary
- SiC offers promise for improvement

Modified from an Application Note of Powerex, Inc. Youngwood, PA.
MOSFET Technology

Current

40A

20A

100kHz

1MHz

Trench MOSFET

More Integration
Lateral MOSFET

Better Packaging
Trench MOSFET & Dr.MOS

Lateral-Trench MOSFET

VDMOS

MOSFET Technology
FOM for Low Voltage Devices

\[ \text{FOM} = (Q_{gd} + K_{gs}Q_{gs2}) \times \frac{1}{R_{ds}} \]

Vdss (V) vs. FOM = (Q_{gd} + K_{gs}Q_{gs2}) \times \frac{1}{R_{ds}}
# Packaging Issues:
Interconnect Resistances and Inductances

<table>
<thead>
<tr>
<th>Package Type</th>
<th>SO8</th>
<th>LFPAK</th>
<th>Direct FET</th>
<th>Dr.MOS</th>
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<tbody>
<tr>
<td>Ls</td>
<td>≈1.5nH</td>
<td>≈1nH</td>
<td>≈0.1nH</td>
<td>&lt;0.1nH</td>
</tr>
<tr>
<td>Ld</td>
<td>≈3nH</td>
<td>≈3nH</td>
<td>≈2nH</td>
<td>&lt;2nH</td>
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Packaging related loss: 60-70%

Die related loss: 30-40%

50-60%  40-50%  30%  70%

25-30%  70-75%
Semiconductor Device Technologies

Current

40A

30A

20A

10A

100kHz 1MHz

GaN based HEMT

VDMOS

Trench MOSFET

Lateral-Trench MOSFET

Lateral MOSFET
# Power Stage Roadmap

**12V to 1.2V @100A Buck**

<table>
<thead>
<tr>
<th>Year</th>
<th>Power Density</th>
<th>Efficiency</th>
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<tbody>
<tr>
<td>2006</td>
<td>1 MHz</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>2 MHz</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>5 MHz</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>10 MHz</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>20 MHz</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>20 MHz</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>60 MHz</td>
<td></td>
</tr>
</tbody>
</table>

*Courtesy from IR*
The frequency range for most conventional magnetic material is below 10MHz.
Emerging magnet materials

Granular film material (e.g. CoZrO)
(S. Ohnuma, T. Masumoto..., Research Institute for Electric and Magnetic Materials, Sendai, Japan)
(Weidong Li, R. Sullivan..., Dartmouth College)

Polymer bonded materials (e.g. Ferrite Polymer Compounds)
(K.W.E.Cheng', C.Y. Tang..., Hong Kong polytechnic Univ.)
(Jae Y. Park, Mark G. Allen..., Georgia Institute of Technology.)

Composite magnetic material
(Fe/SiO2 composite)
(John Q. Xiao, University of Delaware, USA)

Electroplated alloy material
(e.g. CoNiFe)
(S. Kelly, S. Roy..., National University of Ireland)

There are many ongoing research on developing the magnetic material suitable for more than 10 MHZ applications.
Core Loss Density vs Frequency

Iron powder
(Ferroxcube $U_i=40\Sim 90$)

Kool Mu
(Magnetics $U_i=60$)

NiZn
(Ferrocube 4F1 $U_i=80$)

MnZn
(Ferrocube 3F51 $U_i=650$)

Fe/SiO2 composite

Electroplated alloy
(CoNiFe)

Granular film
(CoZrO)

Calculation

Core Loss Density vs Frequency

Core-Loss Density ($Kw/m^3$)

Fs (KHz)

Delta B=40mT

1.0 \times 10^4

1.0 \times 10^3

100

10

1.0 \times 10^4

1.0 \times 10^3

100

10
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Modularization in Motor Drives

Intelligent Power Module (IPM)

Toshiba

Today, IPMs are used for more than 60% of the low HP drives
Commercialization of IPEM:
- Intelligent Power Module (IPM)

Industry trend

Fuji
Eupec/Infineon

Toshiba
Semikron
IR
Danfoss

Mitsubishi, Powerex, Hitachi, Rockwell, IXYS, ABB, Tyco ……
IPEM Based Power Supplies

200KHz AHB DC/DC
1U, 1X

200KHz AHB
1U, 1.6X density

5X density @ 1 MHz

EMI Filter
Active IPEM
Passive IPEM

Center for Power Electronics Systems
Sustainable Building Initiative
DC Electrical System Architecture for a Sustainable Building (Home)
Why Prefer DC?

Most of the Loads prefer DC sources
CPES Proposed PV Systems

Central system

Proposed PV Converters

String system

6 Modules

260V

380V DC bus

5 Strings

DC/DC Converter

CPES Proposed PV Systems

5 Strings

380V DC bus

PV Array

C1

C2

DC bus

L1

D1

T1

L2

D2

T2

L3

D3

T3

C11

T1

C15

T5

PV String

PV String

PV String

Isolated bus

PV String

PV String

PV String

PV String

DC bus

DC bus

DC bus
Driver’s Structure of Outdoor Lighting

For Street light & Backlight for large panel display
Acknowledgement

This work was partially supported by

Industry Partners
Integration of Active Components

Serial Communications Link & Auxiliary Power Supply
Integration of Passive Components

Active IPEM

Passive IPEM

Gate drivers, protection and sensors

E core
primary
hybrid winding
secondary
planar winding
primary
& secondary
planar windings
E core

Discrete Components
Figure of Merits (FOM: $R_{on} Q_g$)

*Courtesy from IR*
Integration by Co-Packaging

-- Dr.MOS

Ls=0.1nH

Power One

Synchronous buck PWM controller

Driver circuit

Low $R_{DS_{on}}$ FETs

On Semi

Philips