Circuits and Topologies: Review and Trends

Bruno ALLARD, Univ. Lyon
Aleksandar PRODIC, Univ. Toronto

PwrSoC for Next Generation Power Delivery & Management

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CPES
Ferric
Kyutech
Samsung
INSA Lyon
Qualcomm
Point the Gap
Global Foundries
SVP Dongbu Tech
Texas Instruments
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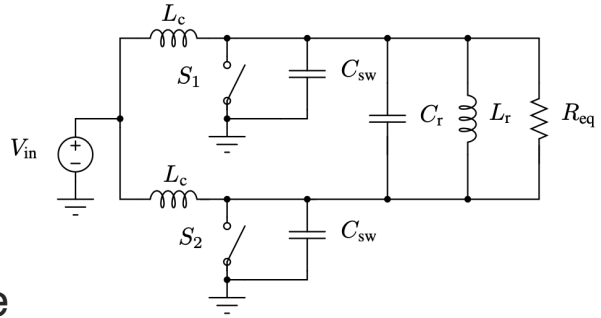
Agenda

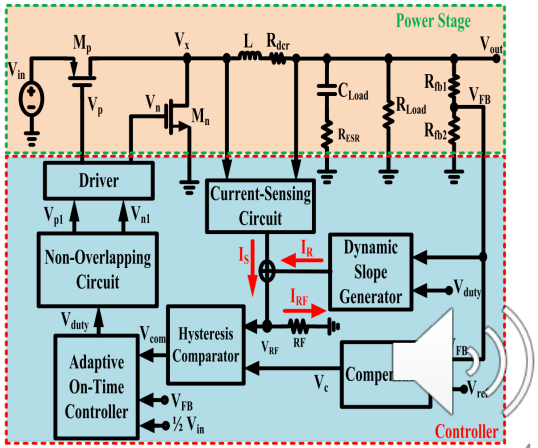
- Review of sub-topics 2010-2021

  Available at http://pwrsocevents.com
- Main subtopics
  - HF/VHF converters
  - SC and hybrid converters
  - Control for fast dynamics
  - Ultra low-power converters
- Trends

Motivations

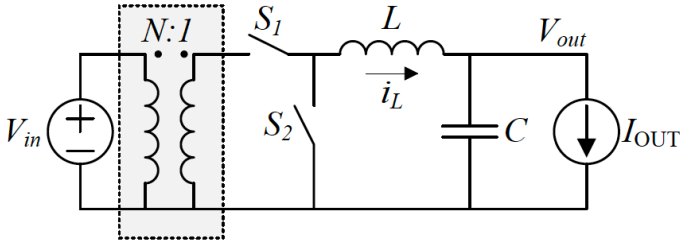
1. X. Zan and A. -T. Avestruz, "100MHz Symmetric Current-Mode Class D Wireless Power Transfer," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, doi: 10.1109/JESTPE.2022.3148973.
2. A Laspeyres et al, “An improved monitoring of gate leakage current on SiC Power MOSFETs using source driver topology,”, PCIM Europe Conference, 2022
3. J. -J. Chen, Y. -S. Hwang, W. -M. Jiang, C. -H. Lai and J. Ku, "A New Improved Ultra-Fast-Response Low-Transient-Voltage Buck Converter With Transient-Acceleration Loops and V-Cubic Techniques," in IEEE Access, vol. 10, pp. 3601-3607, 2022, doi: 10.1109/ACCESS.2022.3140279.





High Density DC-DC Converter:

Key → Reduce passive component volume



$$\Delta i_{pp} \propto \frac{V_{in}}{f_{sw} L} \rightarrow \left[\frac{V-s}{H}\right]$$

$$\Delta v_{out,pp} \propto \frac{\Delta i_{pp}}{f_{sw} C_{out}} \rightarrow \left[\frac{A-s}{F}\right]$$

Strategy 1: Increase frequency

- Smaller inductor, capacitor
- Increase in frequency dependent losses (winding, core, gate drive etc.)

- Strategy 2: Change Architecture
  - Reduce inductor ΔV
  - Multi-level or multi-stage converter
  - Possible double efficiency penalty

- Do Both?

Jason T. Stauth, IEEE PwrSoC, 2016

IEEE PwRSoC revisited

Baoxing Chen

Fully integrated isolated dc-dc converters and isolated **half bridge gate driver** with integral power supply

David Perreault

Architectures, Topologies and Design Methods for Miniaturized **VHF Power Converters**

Elad Alon

Supply Impedance and Voltage Conversion Requirements for CMOS Digital ICs

Eduard Alarcon

Optimization and implementation of a **multi-level buck converter** for standard CMOS on-chip Integration

Seth Sanders

What about **switched capacitor** converters

Jose Cobos

Fast dynamics with non linear control – merits and limitations

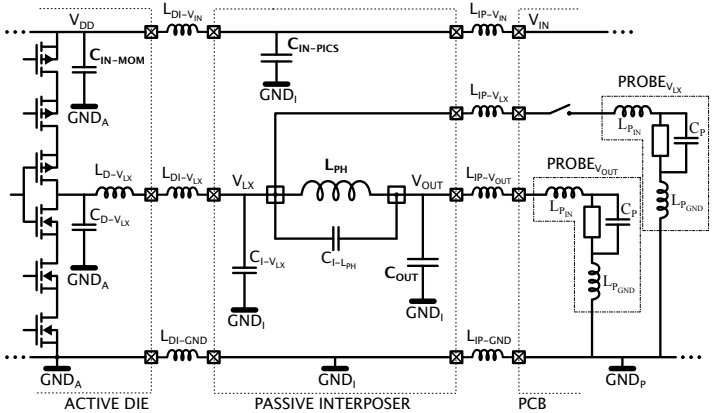
IEEE PwRSoC revisited

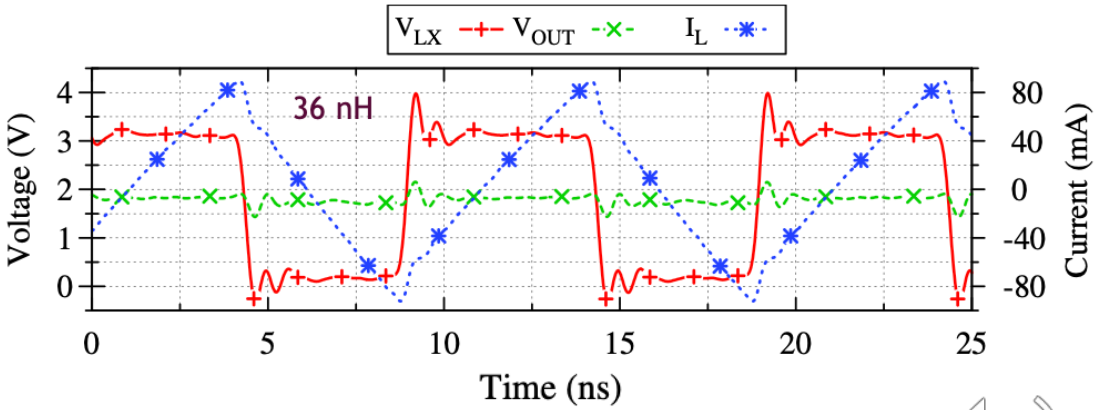
Rais Miftakhutdinov
PSiP and PwrSoC Based Opportunities and Solutions for **High Power Systems**
Eby Friedman
Small Area Power Converter for Application to **Distributed On-Chip** Power Delivery
Olivier Trescases
Gate-Charge Recovery for Light-Load Efficiency Improvement in **High-Frequency** DC-DC Converters
David Anderson
Compact, Cost-effective, Efficient Power: Is there a **sweet-spot** for integration?
Seth Sanders
Integrated Power Conversion – The **Switched Capacitor** Approach
Gabriel A. Rincón-Mora
Energy-Harvesting Switching Converter ICs

HF vs VHF

HF converter targets the increase in frequency (+100 MHz) of classical topologies

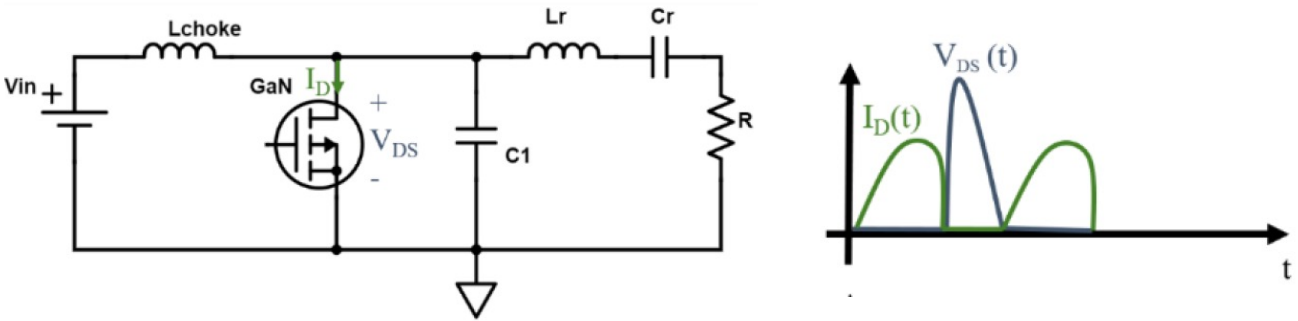
F. Neveu et al., "A 100 MHz 91.5% Peak Efficiency Integrated Buck Converter With a Three-MOSFET Cascode Bridge," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 3985-3988, June 2016, doi: 10.1109/TPEL.2015.2502058.





HF vs VHF

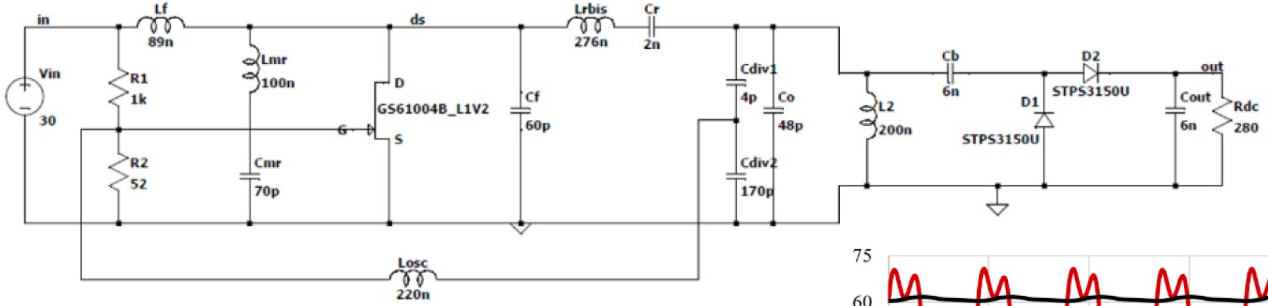
- VHF is now understood for converter with one switch (a minimum of switches), over 300 MHz



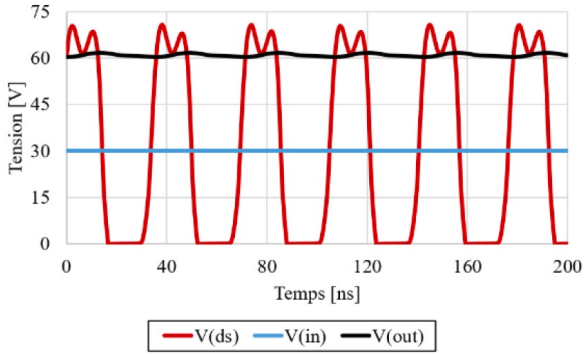
S. Aldhaher, D. C. Yates and P. D. Mitcheson, "Modeling and Analysis of Class EF and Class E/F Inverters with Series-Tuned Resonant Networks," in IEEE Transactions on Power Electronics, vol. 31, no. 5, pp. 3415-3430, May 2016.

HF vs VHF

R. Makhoul et al., "A Very High Frequency Self-Oscillating Inverter Based on a Novel Free-Running Oscillator," in IEEE Transactions on Power Electronics, vol. 34, no. 9, pp. 8289-8292, Sept. 2019.



Pout=12W @ f=30MHz
72% efficiency



IEEE PwRSoC revisited

Gerhard Maderbacher, Stefano Marsili, Christoph Sandner

Digital Control Options for **Embedded DC-DC Converters** in CMOS SoC

Robert Pilawa

Soft Charging **Switched Capacitor** CMOS Power Converters-Increasing Efficiency and power Density Using a Merged Two-Stage Architecture

Rinkle Jain

Enabling Aggressive Dynamic Voltage and Frequency Scaling in Many Voltage Domains using Distributed Switched Capacitor Voltage Regulators

Aleksandrar Prodic

Mixed-Signal IC Controllers and Low Volume SMPS

David J. Perreault, Antohny Sagneri

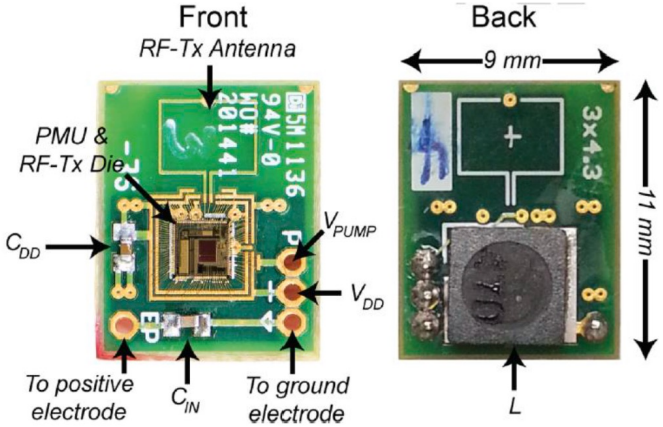
Design of Miniaturized, Isolated dc-dc Converters Operating at **Radio Frequencies**

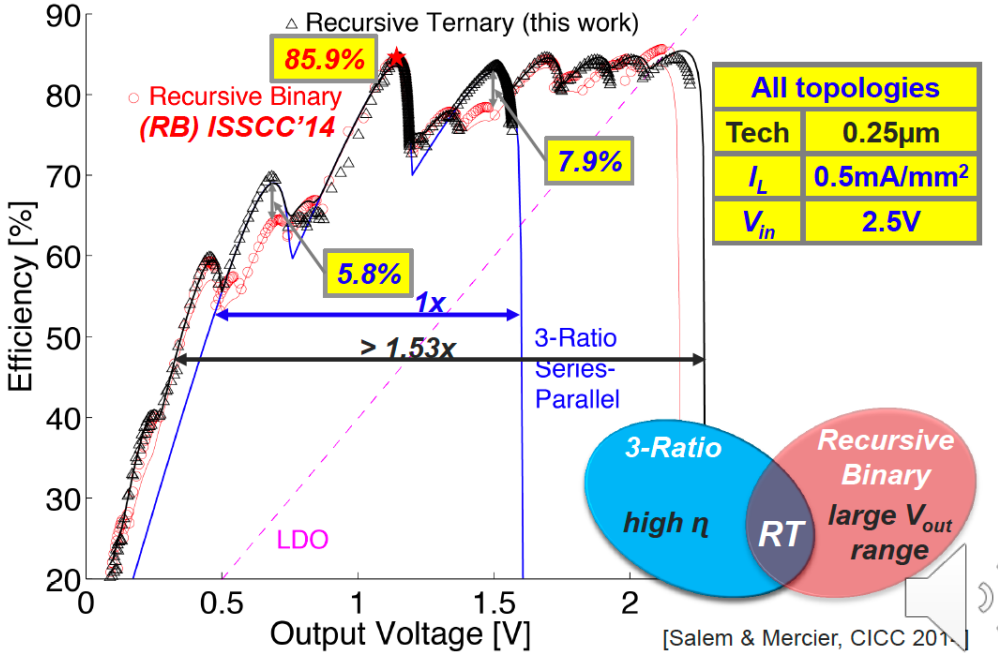
Yogesh Ramadass

A 330nA Charger and Battery Management IC for Solar and Thermoelectric **Energy Harvesting**

Energy harvester

Patrick P. Mercier et al., Energy extraction from the biologic battery in the inner ear, Nature Biotechnology, vol. 30, n°12, 2012





IEEE PwRSoC revisited

David Perreault
Miniaturized **High-Frequency** Integrated Power Conversion for Grid Interface
Brian Ma
VHF Switching Power Converters with 1A/ns Scale Load Current Slew Rate
S.M. Ahssanuzzaman
High Power Density Power Management IC Module with **On-Chip Inductors**
Christophe Vaucourt
µDC/DC Modules: Fully Integrated DC-DC Converters
Christoph Sandner
Towards a **PowerSoC** Solution for Automotive Microcontroller Applications
Bruno Allard
State of the art of **high switching frequency** inductive DC-DC converters in SoC context

Seth Sanders, Univ. Berkeley, 2014, The Road to Integrated Power Conversion via the Switched Capacitor Approach

IEEE PwRSoC revisited

Jeff Morroni
Hybrid topologies
Mor Peretz
Fully-Integrated Digital Average **Current-Mode Control** Voltage Regulator Module IC
Brian Ma
Driving GaN Power Devices: Design Strategies and Circuit Techniques
Martin Haug
Integrated wide-input range converters (7-switch SC)
Stefano Saggini
Power MOS **gating optimization** for balancing efficiency vs. reliability in hard-switching converters
Amit Jain
FIVR **Control** topology and design for distributed loads

Dusan Graovac
Embedded power technologies for automotive
Jason T. Stauth
Resonant switched-capacitors converters

IEEE PwRSoC revisited

Christopher Schaef

Potential of **Hybrid** Converters in Computer Platform Power Delivery

Hanh-Phuc Le

Converter Topologies for Large Conversation Ratios: A Story from Switched-Capacitor to **Hybrid** Architectures

Toke Andersen

Towards **integration** of offline multi-MHz power Supplies

Alexandre Prodic

Control of Emerging Converter Topologies and High-Performance Controllers for High-Frequency Low-Power SMPS

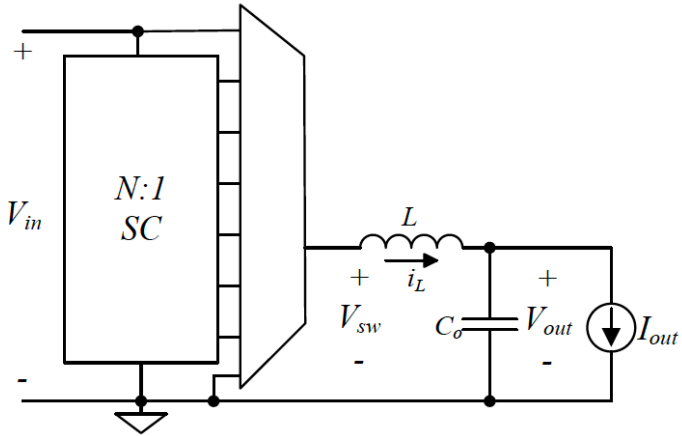
Frederik Spliid

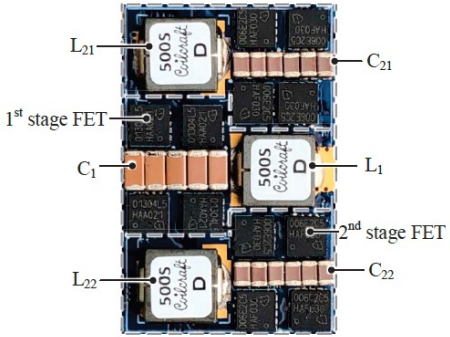
Stacked **Class E resonant** Very High Frequency converter for European mains power factor Correction

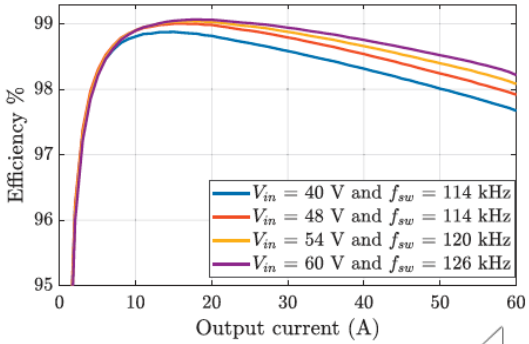
Sheng-Hsiang (Joe) Pan, A Monolithic Capacitor Current Constant On-Time Controlled Buck Converter AchievingNear Optimal Response without Stability Trade-off

Hybrid converters

T. Ge, Z. Ye, R. A. Abramson and R. C. N. Pilawa-Podgurski, "A 48-to-12 V Cascaded Resonant Switched-Capacitor Converter Achieving 4068 W/in3 Power Density and 99.0% Peak Efficiency," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1335-1342, doi: 10.1109/APEC42165.2021.9487264.







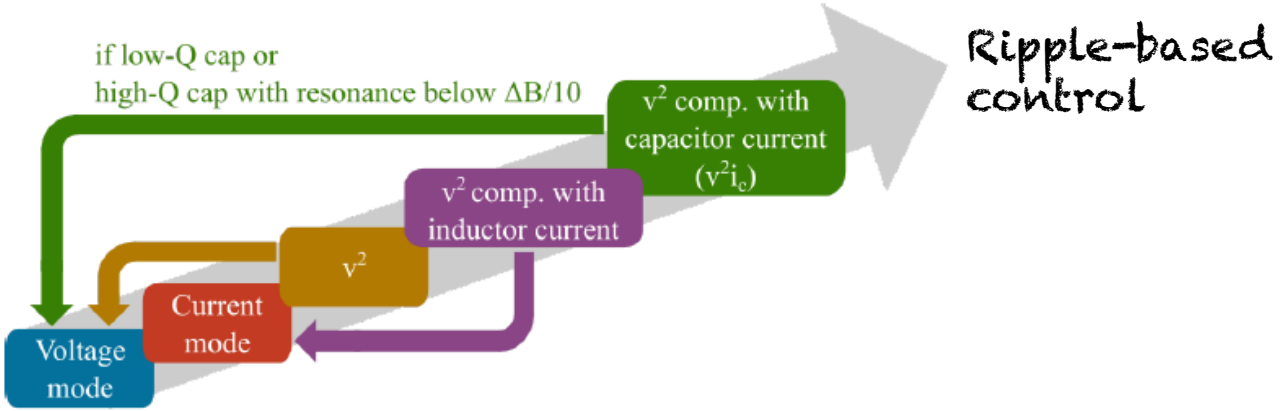
IEEE PwRSoC revisited

Xavier Branca
CMOS Laser Diode **Driver** for Time of Flight Applications
Hanh-Phuc Le
CMOS Active **Gate Driver** for Fast Control of WGB Power Transistor Commutations
Alexandar Prodic
Topological and **Control Solutions** for Reduced Voltage Swing Hybrid Dc-Dc SMPS
Jason Stauth
Hybrid Switched Capacitor Converters: Topologies, Trends, and Comparison

Bernhard Wicht, Monolithic GaN - Unleashing the Potential by Integrating Power, Sensing and Control

Control

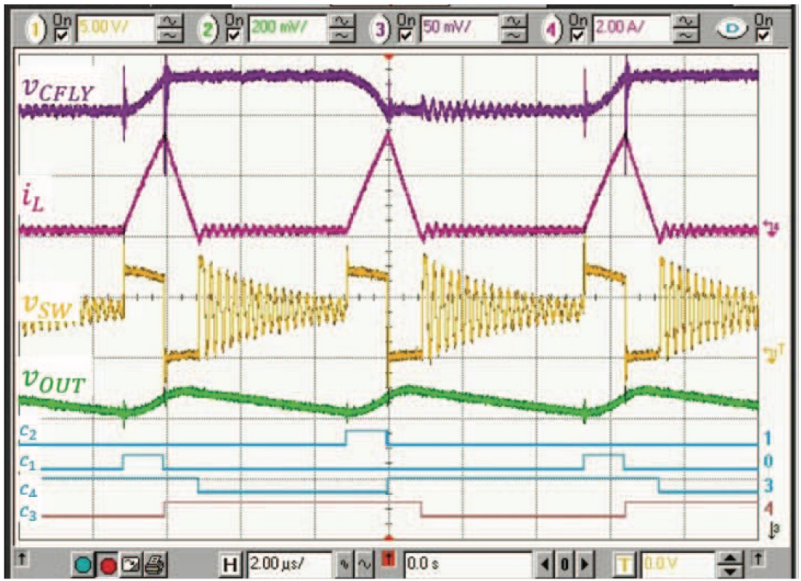
O. García et al., "Teaching digital control of switch mode power supplies," 2011 IEEE Energy Conversion Congress and Exposition, 2011, pp. 1904-1908, doi: 10.1109/ECCE.2011.6064018.



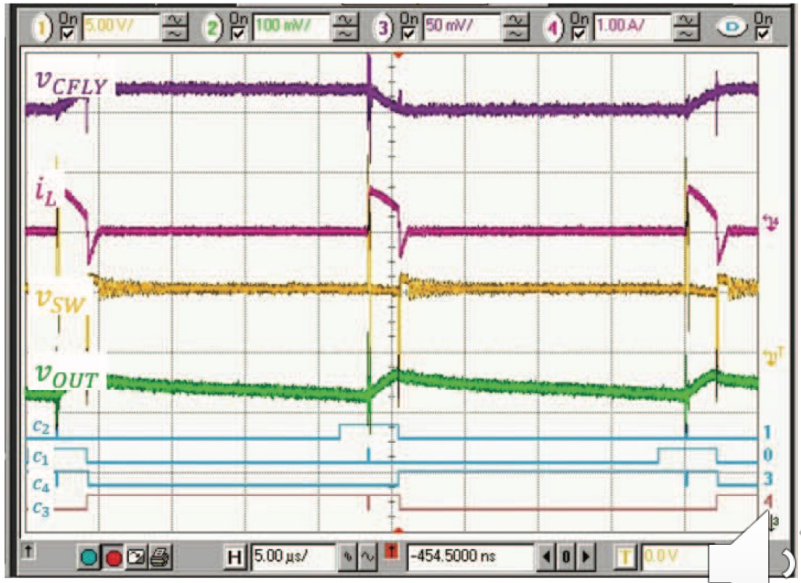
T. McRae et al., "Flying Capacitor Voltage Programed Mode Control for Switched-Capacitor Converters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 3, pp. 2082-2094, Sept. 2020, doi: 10.1109/JESTPE.2019.2953309.

Control

N. Vukadinovic et al., "Discontinuous conduction mode of multi-level flying capacitor DC-DC converters and light-load digital controller," 2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL), 2017, pp. 1-7



I_{out}=200mA



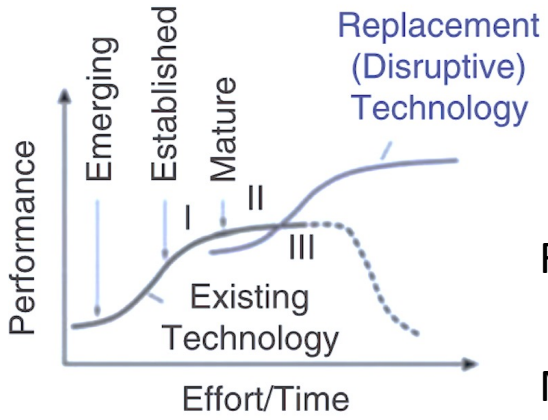
I_{out}=50mA

Revisited - summary

2008	2010	2012	2014	2016	2018	2021
Gate driver	High power	Embedding in SoC	HF inductive	Gate driver GaN		Gate driver
VHF	High Freq	VHF	VHF		Class-E	
Multi-level	Distributed	Distributed	HF	Motor drive	Off-line	Heterogeneous
Switched-Capacitor	SC	SC	On-chip inductors	Hybrid - Resonant	Hybrid	Hybrid
Fast Dynamics	Harvesting	Mixed-signal control	PwrSoC for automotive	Current control - Digital	Optimal response	Control-volt swing
Requirements	Sweet-spot	Harvesting	µDC/DC			

Ted DiBene, INTEL, 2012, Fine Grain On-die Integrated Magnetics: Breaking the Power/Performance Barriers

Global view



SC converter

Monolithic VRs

One transistor VHF

Ultra-low power

Fast response

Monolithic driver

Digital control

On-chip inductor DC/DC

Higher power level

Heterogeneous integration GaN/Si

+100MHz, +10A, multi-phase buck

Monolithic GaN converter

Hybrid

Off-line voltage level

Adaptative gate driver

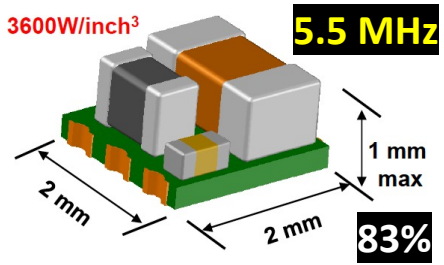
2008 2010 2012 2014 2016 2018 2021

Trends

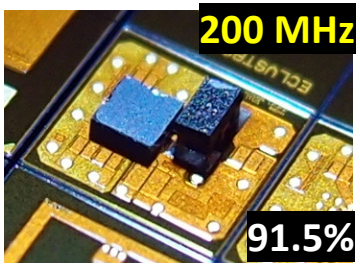
- **Advanced Packaging Architectures for Heterogeneous Integration: embedding is a key enabler for active devices and passive devices**

D. Jordan et al., "High Q-Factor **PCB Embedded** Flip-Chip Inductors With Multilayer CZTB Magnetic Sheet for Power Supply in Package (PwrSiP)," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 1, pp. 102-110, Feb. 2021, doi: 10.1109/JESTPE.2020.2983125.

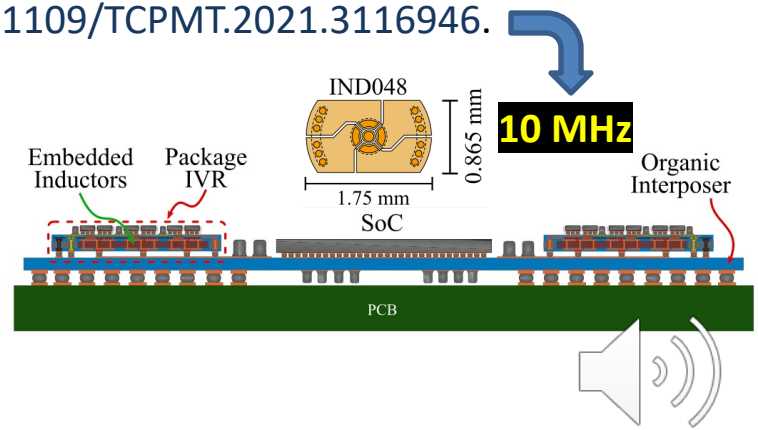
C. Alvarez Barros et al., "Embedded Inductors Using **Composite Magnetic Materials** for 12–1-V Integrated Voltage Regulators," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 11, no. 12, pp. 2183-2192, Dec. 2021, doi: 10.1109/TCPMT.2021.3116946.



Christophe Vaucourt,
Texas Instruments, PwrSoC'14



F. Neveu,
IEEE TPE 2016

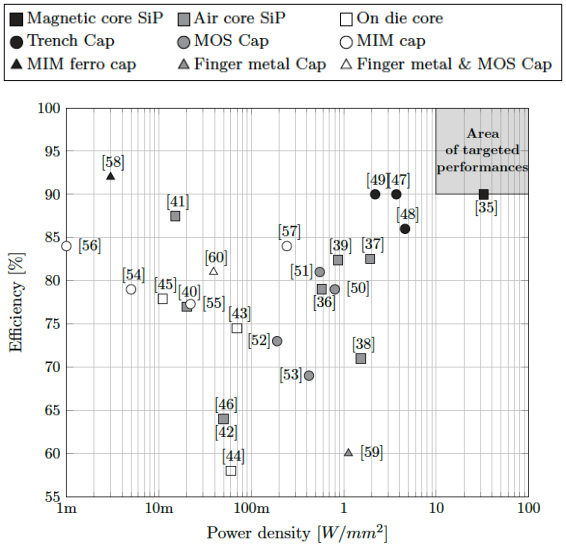


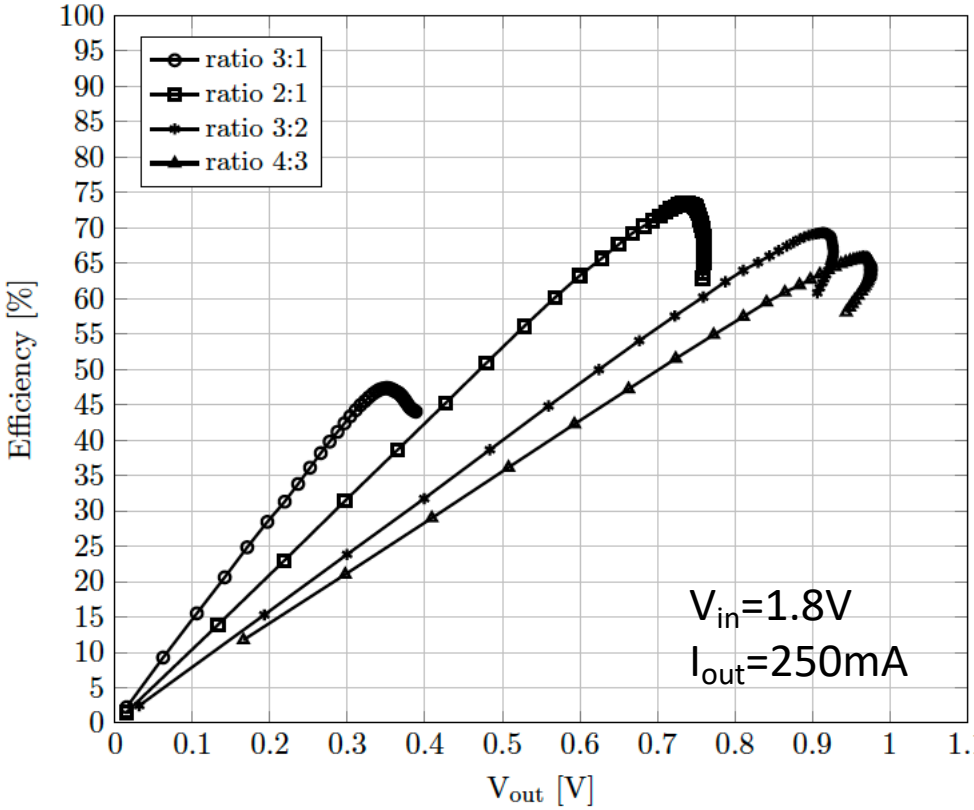
Trends

- Minimizing the Energy Footpri[illegible] Regulators

T. Souvignet et al., "A Fully Integ[illegible] Modulation Control in 28-nm FD[illegible] no. 7, pp. 4984-4994, July 2016

1,





Trends: HF & VHF converters

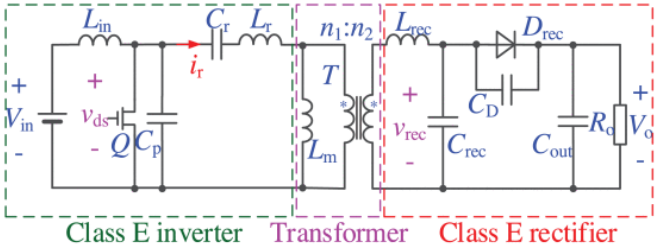
Y. Guan, C. Cecati, J. M. Alonso and Z. Zhang, "Review of High-Frequency High-Voltage-Conversion-Ratio DC–DC Converters," in *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 2, no. 4, pp. 374-389, Oct. 2021, doi: 10.1109/JESTIE.2021.3051554.

TABLE III
SUMMARY OF HIGH-FREQUENCY HVCR TOPOLOGIES

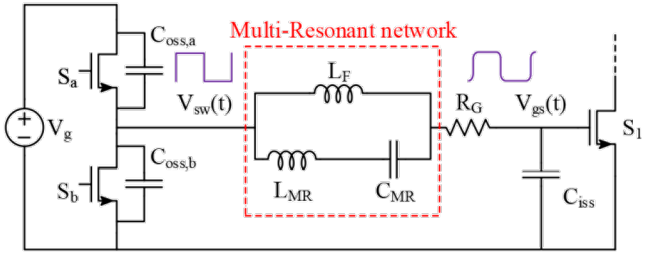
Transformer-based	inductor-based	SC	hybrid
High-voltage High-power	Low input voltage Low-power High step-up Low current ripple	Low-power High integration	Large voltage range Renewable Grid

Trends: HF & VHF converters

J. Dai, et al., "Design of a 20MHz eGaN FET-Based Isolated Class E DC-DC Converter," 2018 1st Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia), 2018.

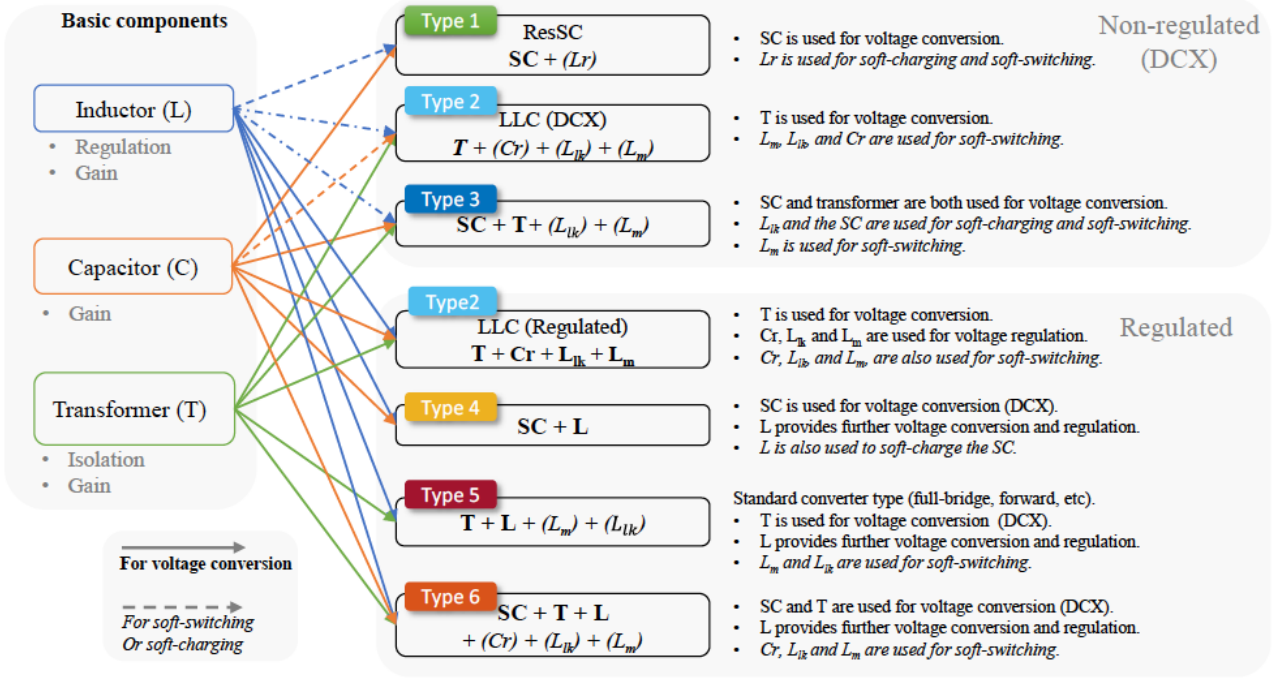


Wang, Y., Lucia, O., Zhang, Z., Guan, Y. and Xu, D. (2020), Review of very high frequency power converters and related technologies. IET Power Electronics, 13: 1711-1721



Trends: hybrid SC + transformer

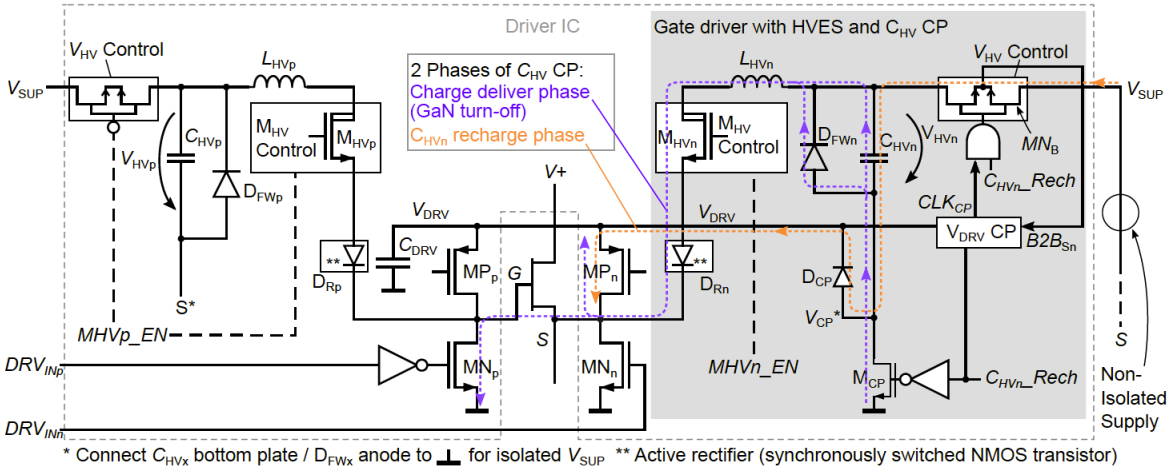
C. Li et al., "A Comparative Study of Hybrid DC-DC Converters by Indirect Power," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1294-1301.



Trends: gate drivers

IEEE Power Electronics magazine, « Recent advances in Gate Driver ICs for WBG FETs », 2019

A. Seidel et al., "Integrated Gate Drivers Based on High-Voltage Energy Storing for GaN Transistors," in IEEE Journal of Solid-State Circuits, vol. 53, no. 12, pp. 3446-3454, Dec. 2018



Conclusion

- IEEE PwrSoC workshop philosophy and perimeter is well-known and enables regularly a strong discussion among engineers
- Topic “topologies & Control” focuses primarily on system-level demonstration
- Emerging ideas coexist with mature ideas (revisited wrt technology improvements)
- Low-power is one application area but
- Supported by technology progress, converters are investigated for high power level or high voltage level
- Gate drivers include more and more monitoring functions and adaptative operation flavors: they tend to be complex system and monolithic integration is investigated
- Control scheme is limited only by imagination but complex scheme may introduce stability issues difficult to track