High-Density High Efficiency Resonant Switched Capacitor Converter For Chip Scale Power Conversion

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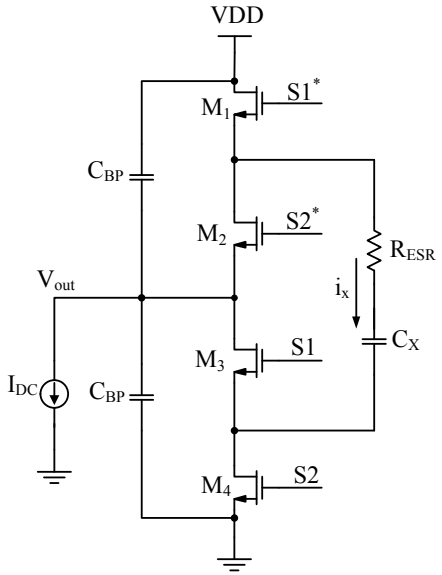
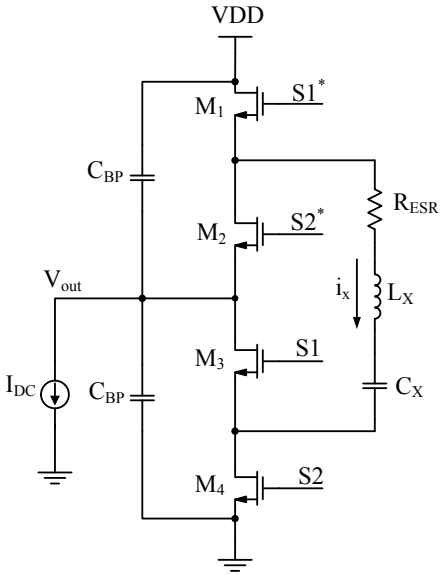
Abstract

- The advent of portable computing and low voltage digital circuitry places increasingly higher demands on both on-chip and off-chip DC-DC converters
- Switched Capacitor (SC) converters have emerged as the prime high-density high conversion ratio architecture for both Point-of-Load converter and Integrated Voltage Regulator applications
- Resonant Switched Capacitor (ReSC) converter build on similar architecture like SC converter but provide improved trade-offs between switching and conduction loss.
- The ability to implement variable conversion ratios make ReSC converters attractive for further exploration.



2:1 Switched Capacitor Converter

- Eliminate inductors and utilize high-density capacitors
- Achieve higher device utilization figures of merit compared to traditional inductor based topologies
- They benefit from the emergence of high density deep-trench capacitors



2:1 Resonant Switched Capacitor Converter

- Built on similar architecture like the SC converters
- Maintain favorable device utilization figures of merit
- Small magnetic component (few nH) resonates out the reactive impedance of the capacitor

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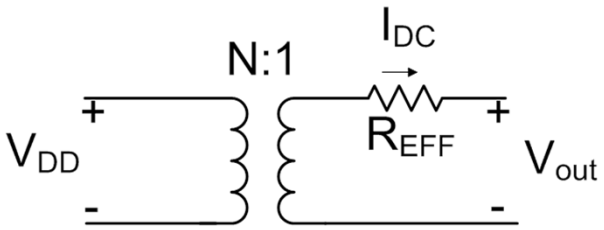
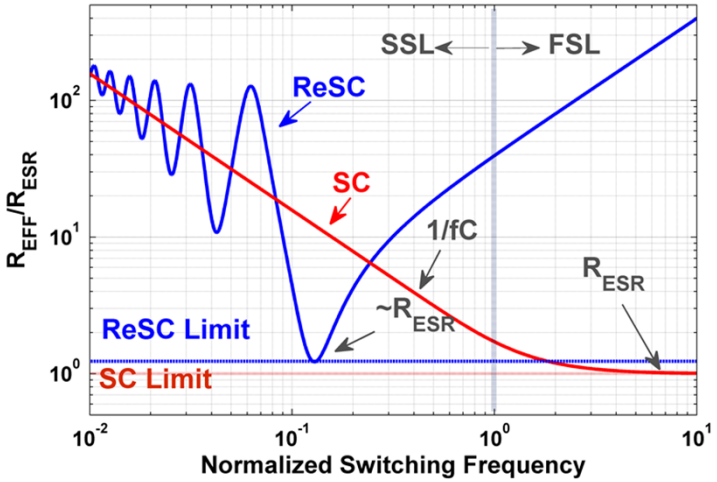
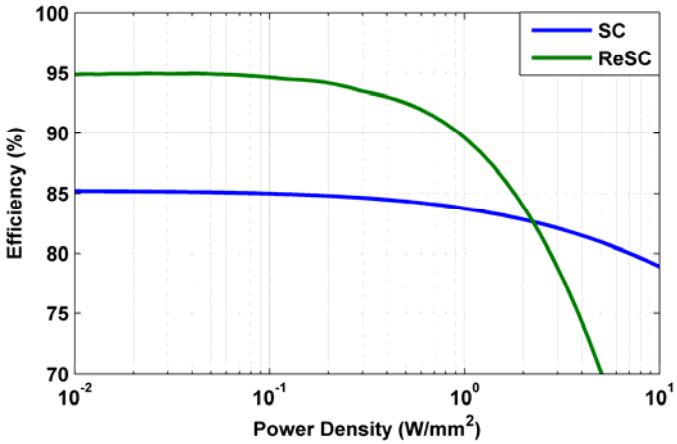


Transformer Model



- R_{EFF} models the effective output impedance of the converter
- SC: In fast switching mode the energy transfer is limited by ESR
- ReSC converter achieve similar effective resistance as SC converter but at a lower frequency
- Opportunities for fundamental or sub-harmonic operation



- Pareto Frontier for 2:1 SC and ReSC converter in 32nm SOI process with MOS capacitors. Die Area = 10 mm^2
- Off- chip 0402 inductors with 4-phase interleaving for ReSC converter
- R_{insp} = 130 Ω-µm, C_{insp} = 3 fF/µm^2, C_{den} = 10 fF/µm^2

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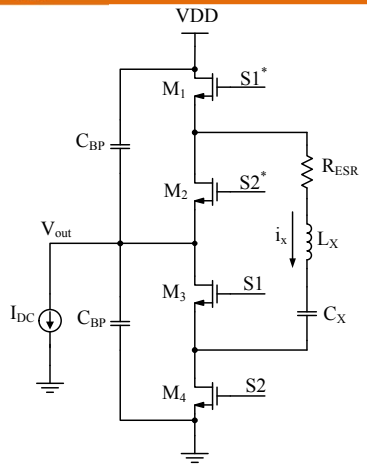
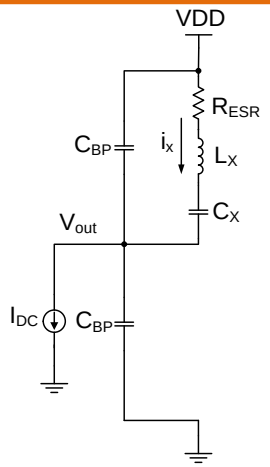
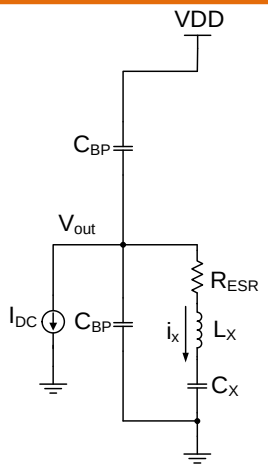
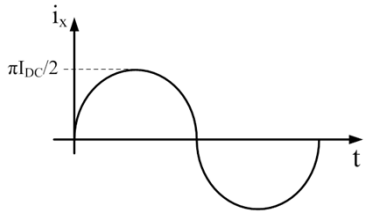
Indirect ReSC Converter



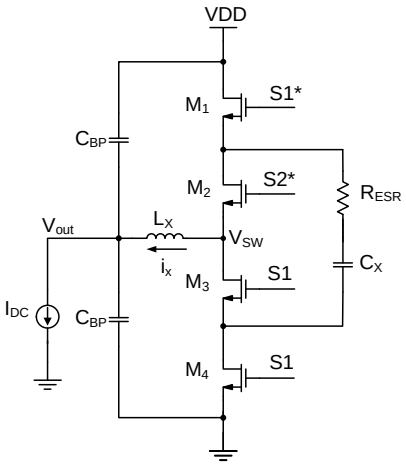


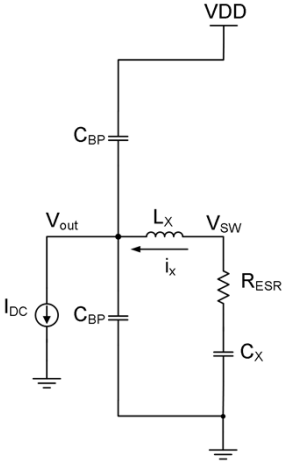


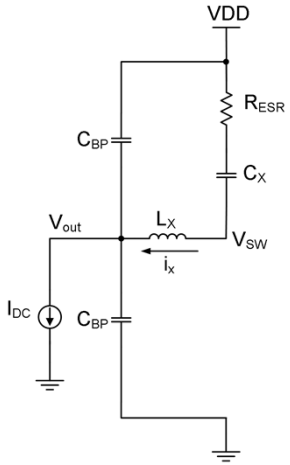


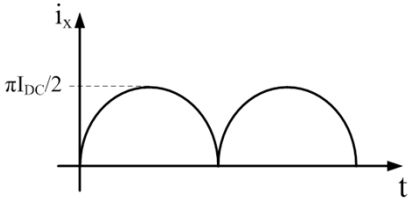
- Inductor is alternately connected in the two states
- Bidirectional current flow
- Entire Power Transfer is at the resonant frequency
- Inductor ESR is AC resistance of the inductor

Direct ReSC Converter









- Similar to 3-level topology but operation is at the resonant frequency
- Inductor is connected to output in both states
- Unidirectional current flow
- 80% of the Power flow is at DC
- Inductor ESR is substantially lower

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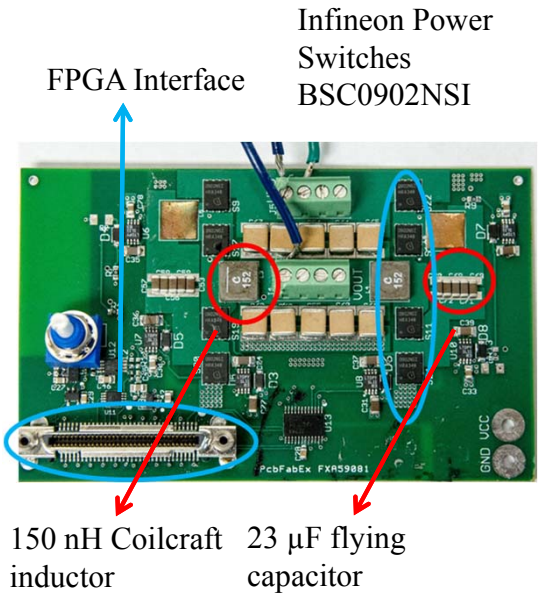
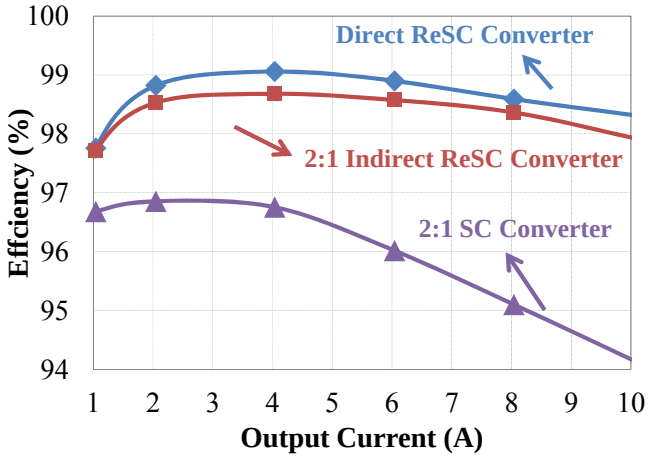


- A 4-layer prototype PCB was built to compare the two topologies and also compare the results with the SC conveter
- The input-output voltage was 24-12 V which matches with the common automotive range
- Coilcraft inductors with a modest value of 150 nH were used as flying inductor (L_X) while 5 AVX capacitors in parallel, each with a value 4.7 µF with 50 V breakdown voltage, were used as flying capacitor (C_X)
- To provide a fair comparison of the respective topologies, the same inductance and capacitance values were used in all cases. Additionally, the same layout was used for all three topologies to keep loop parasitics the same. Gate drive circuitry was also kept the same to keep similar rise/fall time at each switch.



- The resonant topologies were operated at the resonant switching frequency of 115 KHz while the switching frequency of SC converter was varied to reduce switching loss at light loads
- Due to parasitic inductance in the power loop, the maximum switching frequency for the SC converter was limited to 240 KHz.
- SC converter shows more than twice the power loss of direct and indirect ReSC converter at 5 A load current.
- Direct ReSC converter achieves even higher efficiency than the direct ReSC converter due to lower high frequency losses in the inductor as expected.

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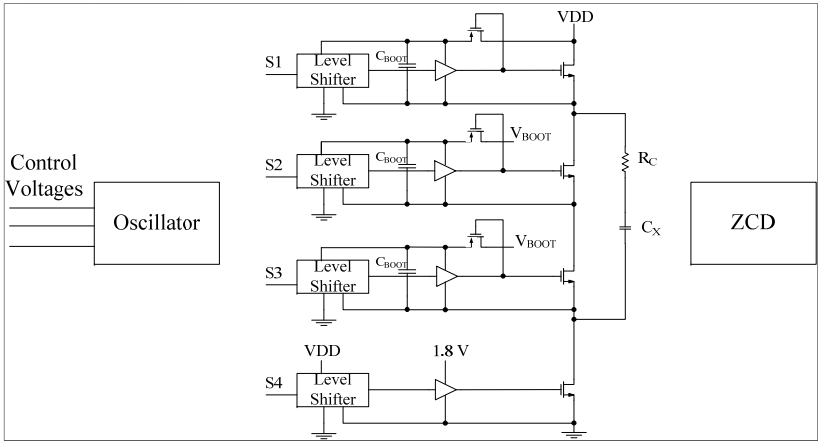
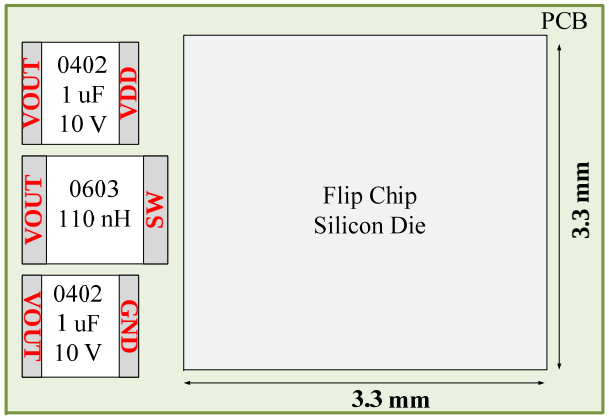
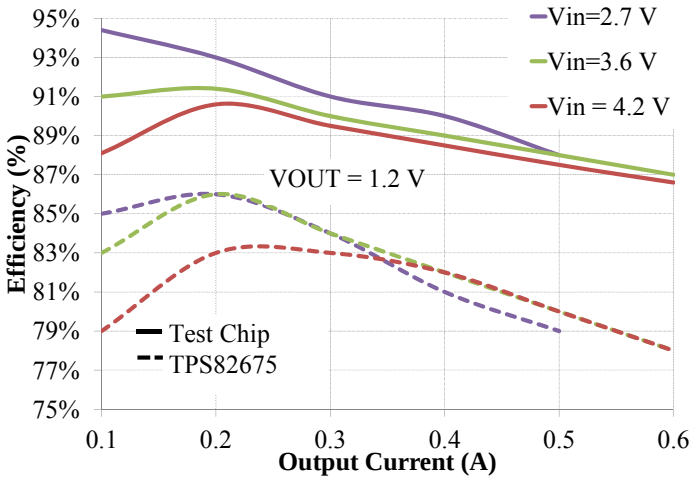




- Input Voltage –> 2.7 V – 5.5 V
  Output Voltage -> 1.2 V
- 0.18 µm CMOS process
- All NMOS power train
- On chip flying capacitors
- 3 off-chip components
- Zero Current detection to enable soft switching .
- On chip oscillator enables variable conversion ratio by using quasi resonant techniques for operation.



Efficiency > 7% throughout entire load range

References:

[1] M. D. Seeman and S.Sanders, “Analysis and Optimization of Switched-Capacitor DC-DC Converters”, IEEE TPEL, Mar. 2008

[2] J. T. Stauth, M. D. Seeman, and K. Kesarwani, “Resonant Switched-Capacitor Converters for Sub-module Distributed Photovoltaic Power Management,” IEEE TPEL, 2013

[3] K. Kesarwani, R. Sangwan and J. T. Stauth, “Resonant Switched Capacitor Converters for chip scale power delivery: Modeling and Design,” IEEE COMPEL, June 2013.

[4] K. Kesarwani, R. Sangwan and J. T. Stauth, “A 2 phase 2:1 Resonant Switched Capacitor converter delivering 4.3 W at 0.6 W/mm² with 85 % efficiency”, ISSCC, 2014.

[5] K. Kesarwani, R. Sangwan and J. T. Stauth, “High Density Power Converters for Sub-Module Photovoltaic Power Management”, IEEE ECCE, 2014