Aalto University
School of Electrical Engineering

Hybrid Switched Capacitor Power Converters: Resonant Operation

Okko Järvinen

Department of Electronics and Nanoengineering
Aalto University, School of Electrical Engineering

15.5.2019

Outline

Outline

Introduction

Resonant Operation

Resonant SC Topologies

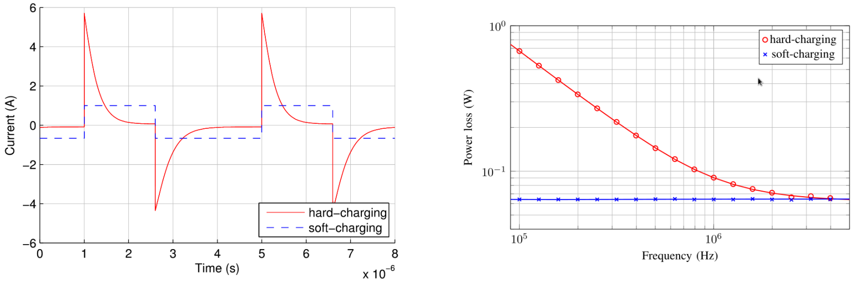
Implementation Examples

Conclusion & Homework

Introduction

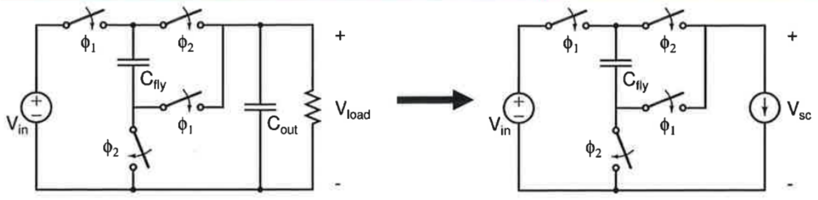
- In SC power converters, capacitors are typically charged/discharged by other capacitors or voltage sources $\rightarrow$ high current transients $\rightarrow$ reduced efficiency
- The transients can be reduced by
  - Large capacitors
  - High switching frequencies
  - Interleaving
  - **Soft-charging & resonant operation**

Introduction



- Soft-charging $\rightarrow$ reduced current transients $\rightarrow$ reduced losses

Introduction



- Soft-charging achieved by using a current-source load
- Current-source load allows instant voltage change at its terminal → the voltage mismatch between flying capacitor and load can be accommodated

Outline

Resonant Operation

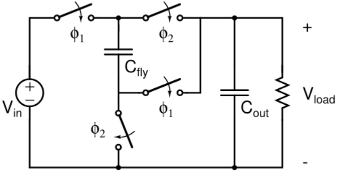
- The goal is to achieve soft-charging operation in order to minimize charge redistribution losses
- Soft-charging can be achieved using current-source load

Resonant Operation

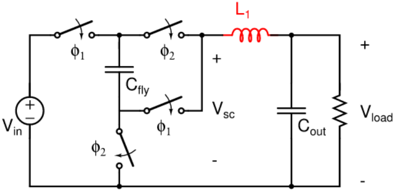
- The goal is to achieve soft-charging operation in order to minimize charge redistribution losses
- Soft-charging can be achieved using current-source load
- Or an inductor!

Resonant Operation

- 2-to-1 SC power converter with output inductor
- Inductor allows instant voltage change at its terminal $\rightarrow$ behaves as a controlled current source



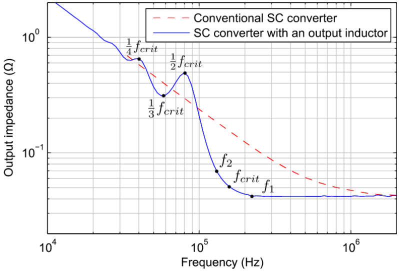
(a)



(b)

Resonant Operation

- Output inductor can lower the output impedance compared to conventional SC converter
- Same efficiency as conventional SC converter, but with lower frequency or smaller capacitor values



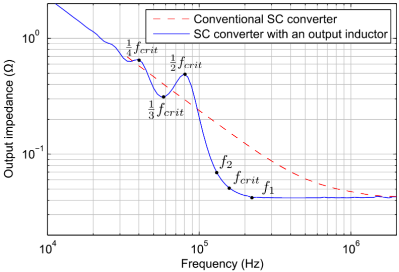
$$P_{loss} \propto \frac{1}{f_{sw}}, \frac{1}{C_{fly}}$$

Resonant Operation

Resonant frequency is

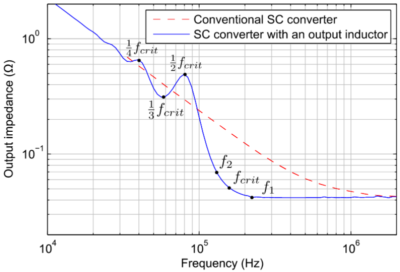
$$f_{crit} = \frac{1}{2\pi\sqrt{LC}},$$

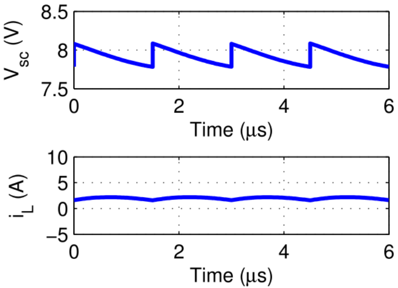
where C is the collective capacitance in series with the inductor.



Resonant Operation

- In this case, $f_{sw} = f_1$
- Current transients eliminated $\rightarrow$ soft-charging

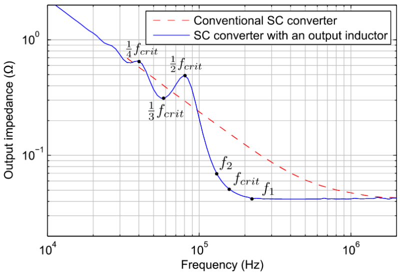


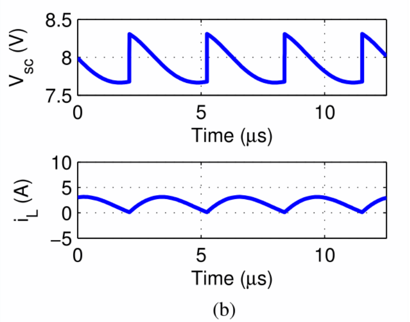


(a)

Resonant Operation

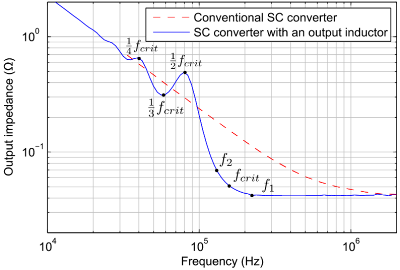
- In this case, $f_{sw} = f_{crit}$
- Current reaches zero $\rightarrow$ zero-current switching (ZCS) achievable at the resonant frequency

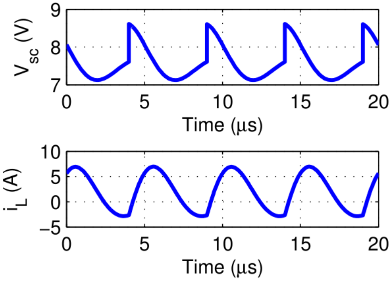




Resonant Operation

- In this case, $f_{sw} = f_2$
- Current becomes negative as well → RMS value increases → impedance increases





(c)

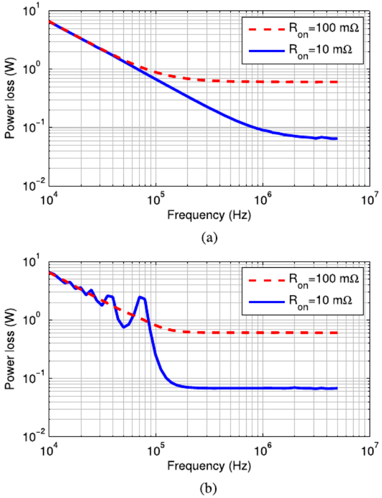
Resonant Operation

- For conventional SC, switch on-resistance determines the region of operation

$$f_{crit} = \frac{1}{2\pi R_{ESR} C}$$

- For resonant SC, the critical frequency is decoupled from the resistance

$$f_{crit} = \frac{1}{2\pi\sqrt{LC}}$$



Resonant Operation

- Soft-charging operation
  - As flat current profile as possible
  - Good for heavy loading where conduction loss dominates
- Resonant ZCS operation
  - Slight current variance to allow zero current at switching instants
  - Good for lighter loads or high frequency operation where switching loss dominates

Common Goal

Improved efficiency

Outline

Introduction

Resonant Operation

Resonant SC Topologies

Implementation Examples

Conclusion & Homework

Resonant SC Topologies

- Full ZCS operation on all switches can be achieved if the topology is compatible with **full soft-charging operation**
  1. Current-source load
  2. No voltage-mismatch among flying capacitors during phase transitions
- Typically achievable with just one inductor at the output

Resonant SC Topologies

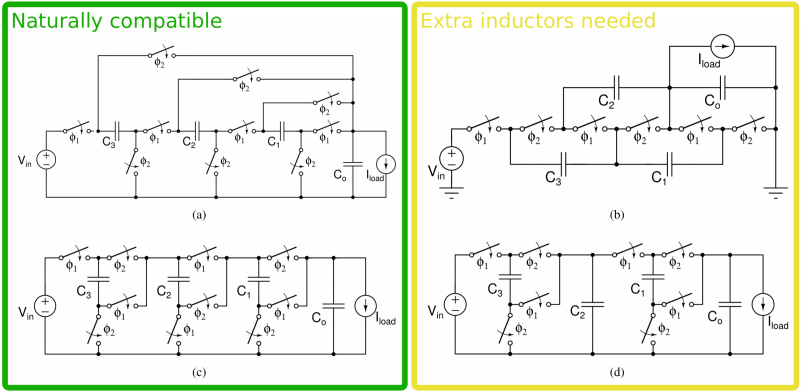
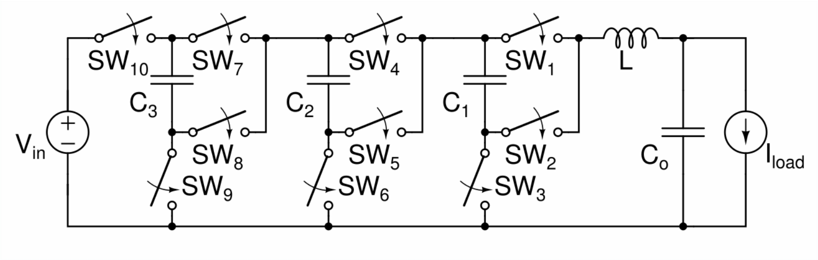


Fig. 13. Common SC converter topologies. (a) 4-to-1 series–parallel. (b) 3-to-1 ladder. (c) 5-to-1 Fibonacci. (d) 4-to-1 doubler.

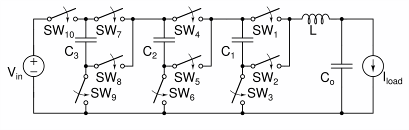
Resonant SC Topologies
Fibonacci

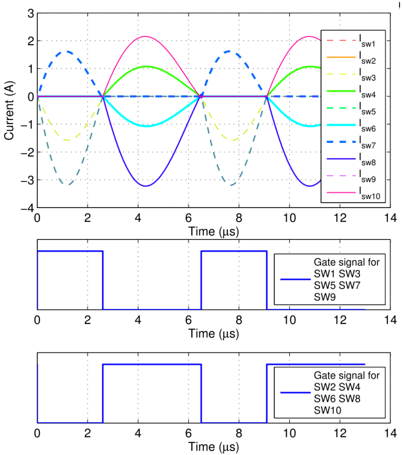


- Single inductor added to output enables ZCS resonant operation

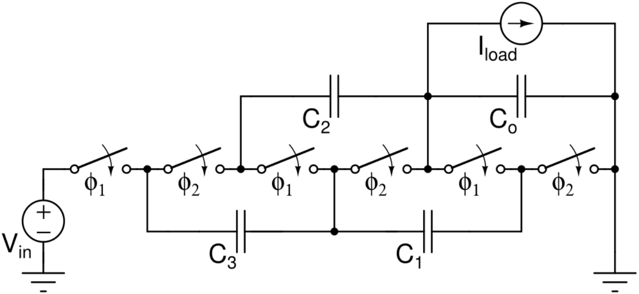
Resonant SC Topologies
Fibonacci

- During the switching instants, all switch currents are effectively zero → resonant ZCS operation





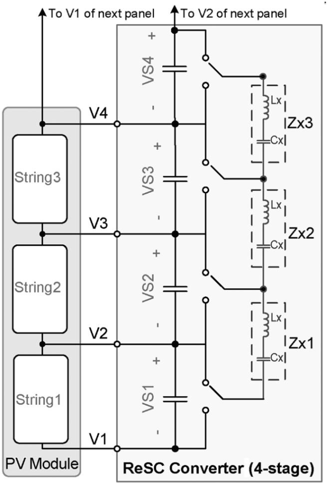
Resonant SC Topologies
Ladder



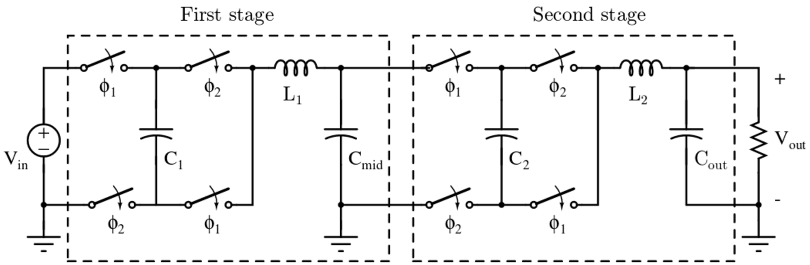
- Not naturally compatible with full soft-charging
- Can be made compatible by adding an inductor in series with every capacitor

Resonant SC Topologies
Ladder

- Series inductors L_X added
- Even with multiple additional inductors, the resonant ladder converter can be useful for balancing series-connected loads
  - Solar PV systems
  - Battery equalizers
  - Series-stacked digital loads



Resonant SC Topologies
4-to-1 Doubler



- One inductor added at the output of each stage
- For N-to-1 doubler can be operated in resonant ZCS mode with $\sqrt{N}$ inductors

Outline

Introduction

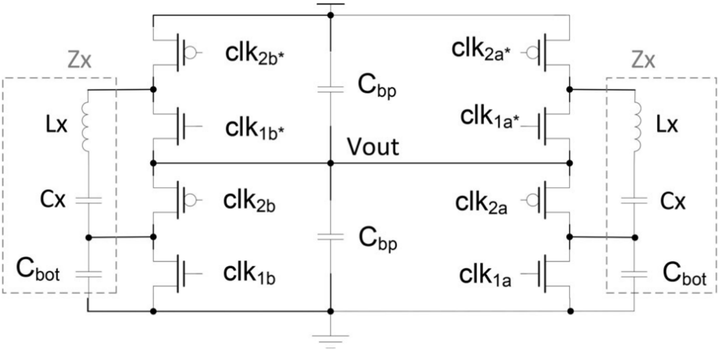
Resonant Operation

Resonant SC Topologies

Implementation Examples

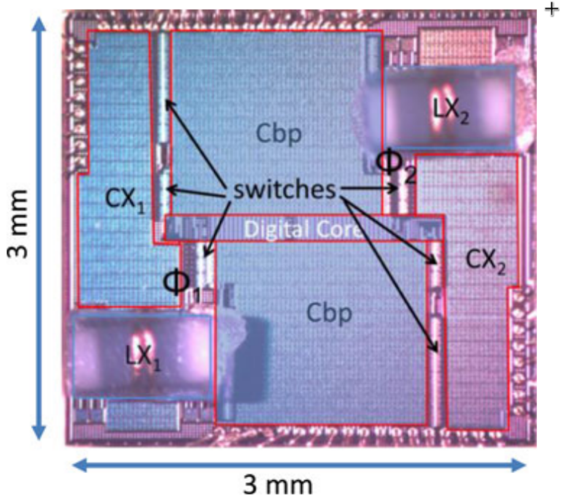
Conclusion & Homework

Implementation Examples
1: Resonant 2-to-1 Converter [4]

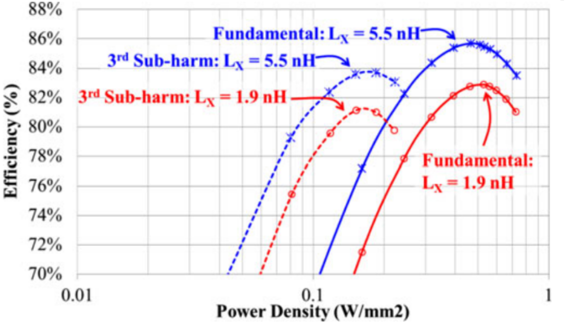


- Two-phase 2-to-1 converter

Implementation Examples
1: Resonant 2-to-1 Converter [4]



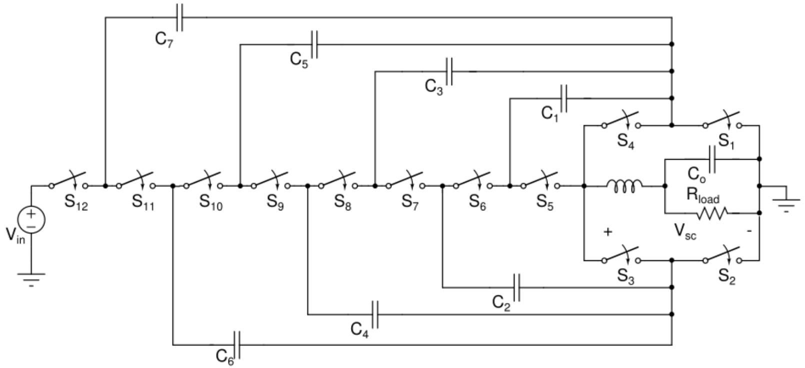
Implementation Examples
1: Resonant 2-to-1 Converter [4]



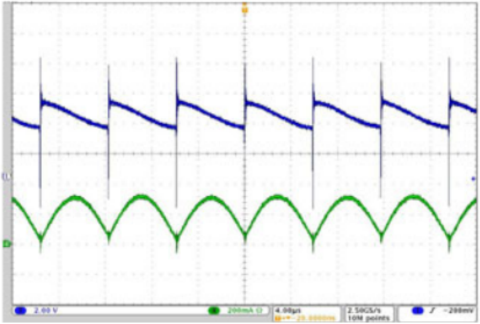
- $f_{sw} = 30\ MHz$, $P_{out} = 3.35\ W$

Implementation Examples

2: Resonant 8-to-1 Dickson SC Converter [1]

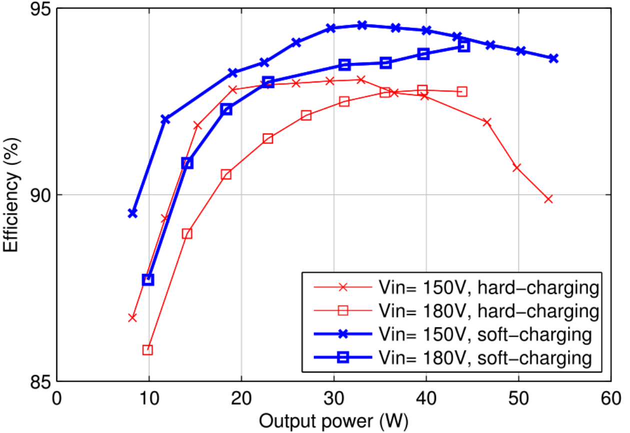


Implementation Examples
2: Resonant 8-to-1 Dickson SC Converter [1]



- Resonant ZCS operation at $f_{crit} = 90\ kHz$

Implementation Examples
2: Resonant 8-to-1 Dickson SC Converter [1]



- $f_{sw} = 250\ kHz,\ P_{out} = 53\ W$

Outline

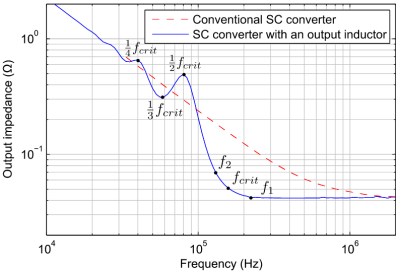
Conclusion & Homework

- Soft-charging can be achieved with an inductor

$\rightarrow$ High-efficiency operation at lower frequency or with smaller capacitors

- Operating at the resonant frequency of the circuit, zero-current switching can be achieved

$\rightarrow$ Minimized switching loss due to ZCS operation, minimized charge redistribution loss due to soft-charging



Homework

Briefly explain how the on-resistance of the switches affects the resonant operation of the hybrid SC converter.

See Section III in:
Y. Lei and R. C. N. Pilawa-Podgurski, "A General Method for Analyzing Resonant and Soft-Charging Operation of Switched-Capacitor Converters," in IEEE Transactions on Power Electronics, vol. 30, no. 10, pp. 5650-5664, Oct. 2015.

References

1. Y. Lei and R. C. N. Pilawa-Podgurski, "A General Method for Analyzing Resonant and Soft-Charging Operation of Switched-Capacitor Converters," in IEEE Transactions on Power Electronics, vol. 30, no. 10, pp. 5650-5664, Oct. 2015.
2. Z. Ye, Y. Lei and R. C. N. Pilawa-Podgurski, "A resonant switched capacitor based 4-to-1 bus converter achieving 2180 W/in^3 power density and 98.9% peak efficiency," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, TX, 2018, pp. 121-126.
3. J. T. Stauth, M. D. Seeman and K. Kesarwani, "A Resonant Switched-Capacitor IC and Embedded System for Sub-Module Photovoltaic Power Management," in IEEE Journal of Solid-State Circuits, vol. 47, no. 12, pp. 3043-3054, Dec. 2012.
4. K. Kesarwani, R. Sangwan and J. T. Stauth, "Resonant-Switched Capacitor Converters for Chip-Scale Power Delivery: Design and Implementation," in IEEE Transactions on Power Electronics, vol. 30, no. 12, pp. 6966-6977, Dec. 2015.