L3520 Post-grad course

Hybrid SC, soft charging operation

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Outline

- Introduction
  - Hard vs soft charging concepts
- Soft charging modes
  - Two-phase operation
  - Split phase operation
- IC implementation
  - Stage outphasing method
  - Multiphase soft charging
- Conclusion & Homework

Introduction

Work faster, Work slower

Work harder, Work softer

What's the Big picture?

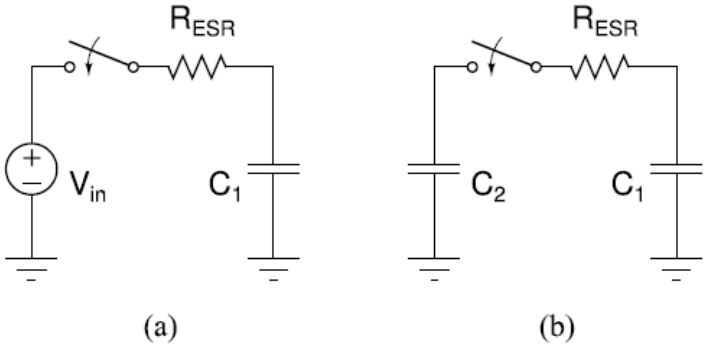
Introduction

Minimize losses and maximize output

Introduction

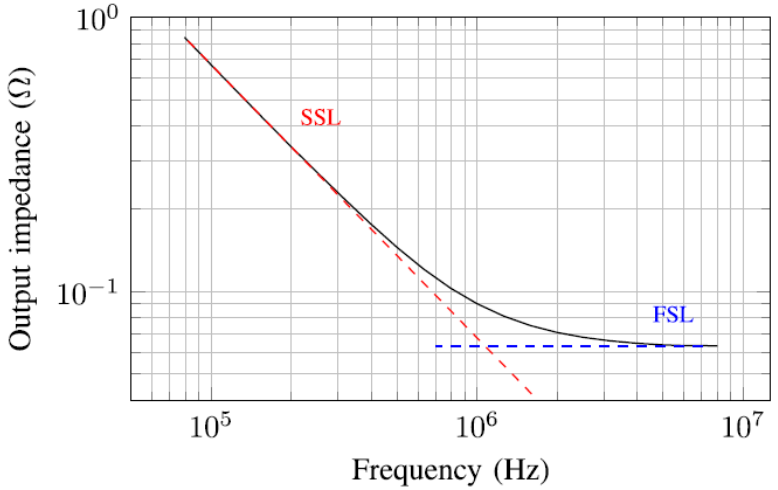
- The efficiency of SC converters can be observed from the output impedance and switching frequency relationship

- SC converter operating regions
  - Fast switching limit (FSL): conduction loss from ESR dominates, Zout is fsw independent
  - Slow switching limit (SSL): charge redistribution loss dominates, Zout is fsw dependent



$$P_{loss} \propto \frac{1}{f_{sw} * C_1}$$

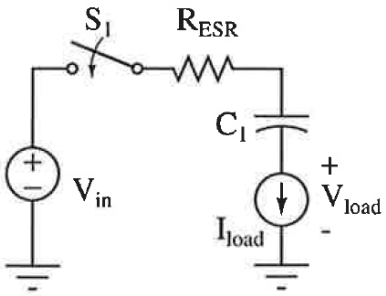
Basic or hard charging modes: with a voltage source or with another capacitor



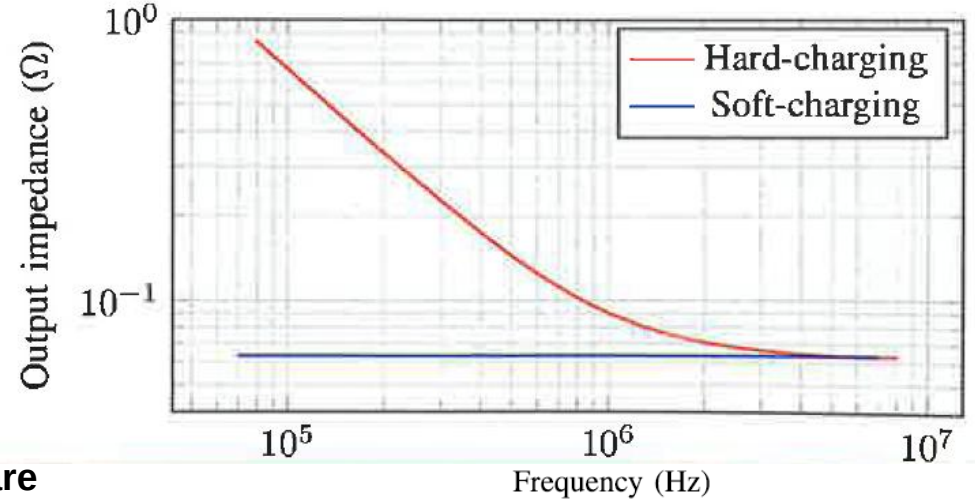
Hard vs Soft charging

- Hard charging: conventional charging method used in SC converters, which produces current transients at phase transitions

- Soft charging: output capacitor is removed and flying capacitors are controlled with a current source
  - eliminates the current transients during phase transitions
  - reduces the output impedance and losses in the SSL region

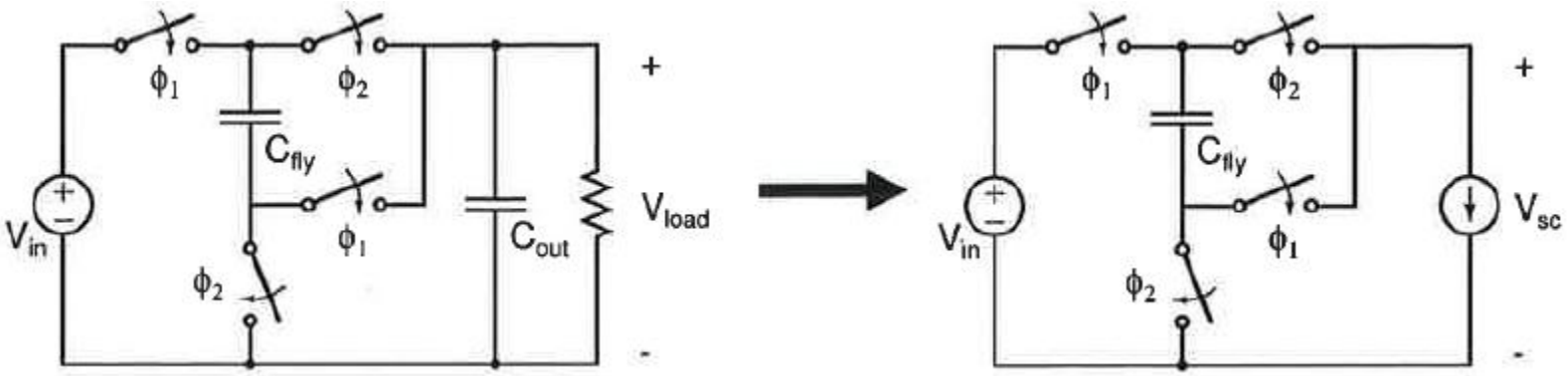


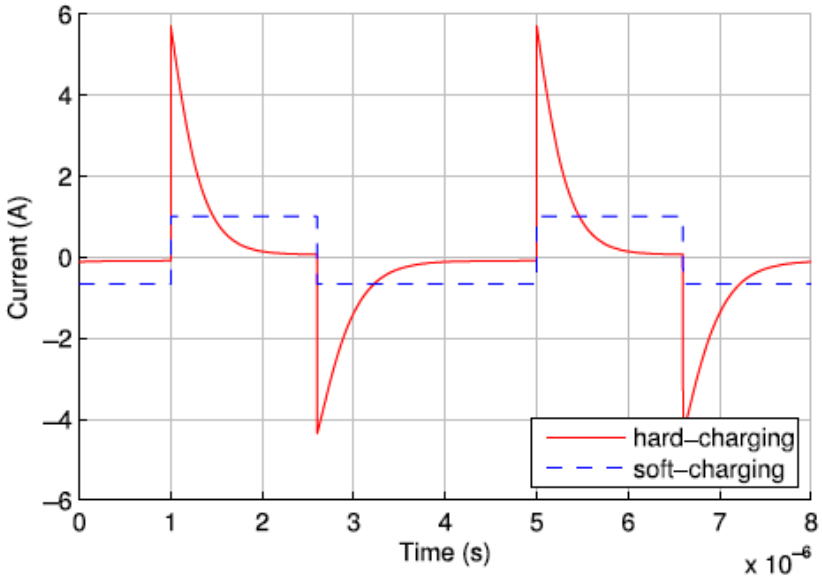
$$P_{\text{loss}} = I_{\text{load}}^2 R_{\text{ESR}}$$



Soft charging mode: capacitors are charged/discharged with a current source

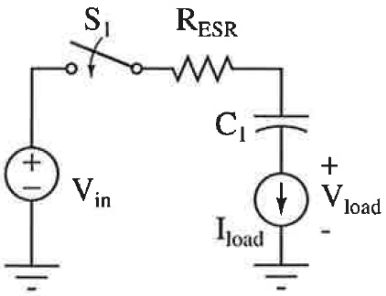
Hard vs Soft charging

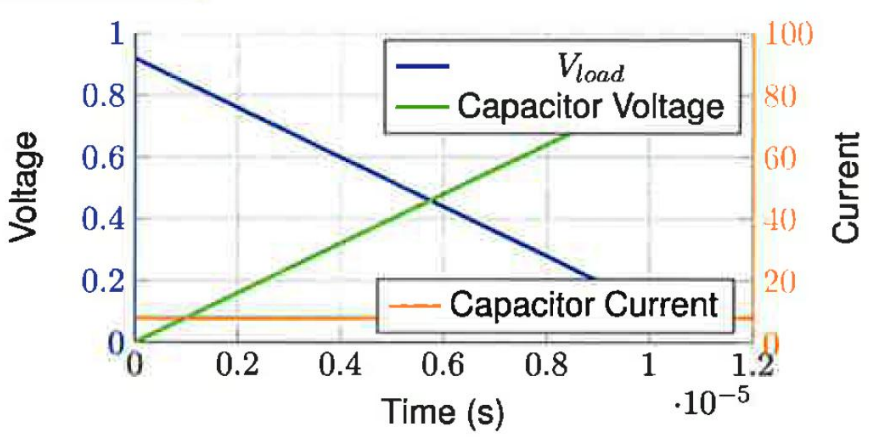




Soft charging requirements

- Requires a current load I_{load}
- V_{load} can change continuously to compensate the voltage mismatch between the flying capacitors and the load during phase transitions
- KVL for the capacitor network should be met during phase transitions

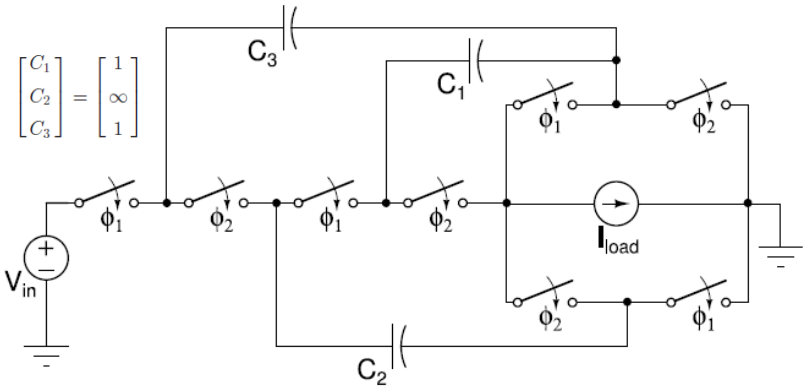




Soft charging operating modes

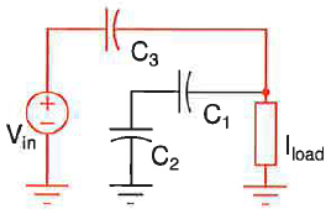
- Split-phase operation
  - uses intermediate states to reduce voltage mismatch within the capacitor network
  - drawback: not effective for complete soft-charging in all topologies

- Two-phase operation
  - achieves lower power losses and improved efficiency over hard-charging method
  - however, KVL for the capacitor network is not satisfied for all topologies



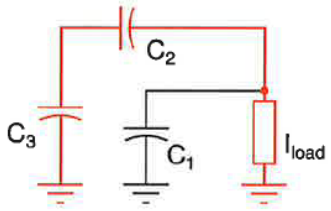
Dickson converter example: operating in two-phase mode

Phase 1



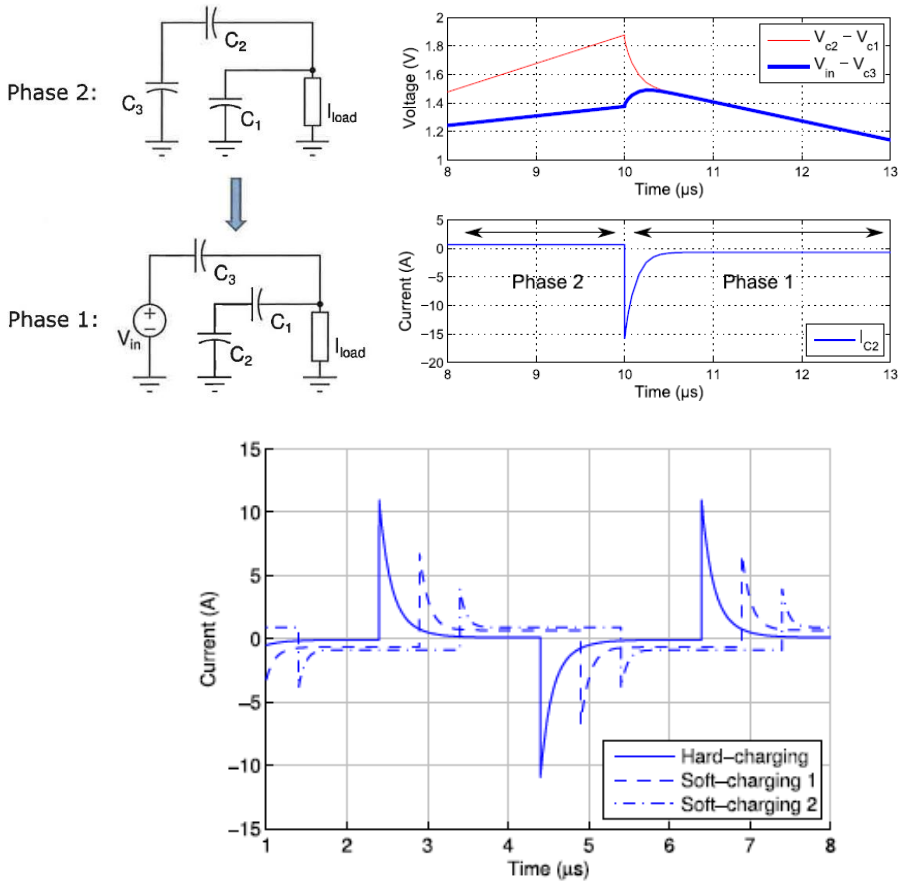
$$V_{in} - V_{c3} - V_{out} = 0$$
$$-V_{c1} + V_{c2} - V_{out} = 0$$
$$V_{in} - V_{c3} = V_{c2} - V_{c1}$$

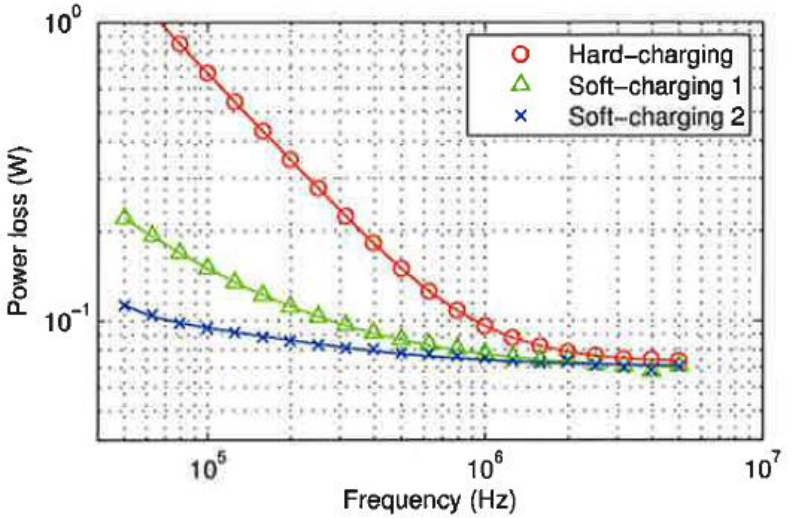
Phase 2



$$V_{c3} - V_{c2} - V_{out} = 0$$
$$V_{c1} - V_{out} = 0$$
$$V_{c3} - V_{c2} = V_{c1}$$

Two-phase operation

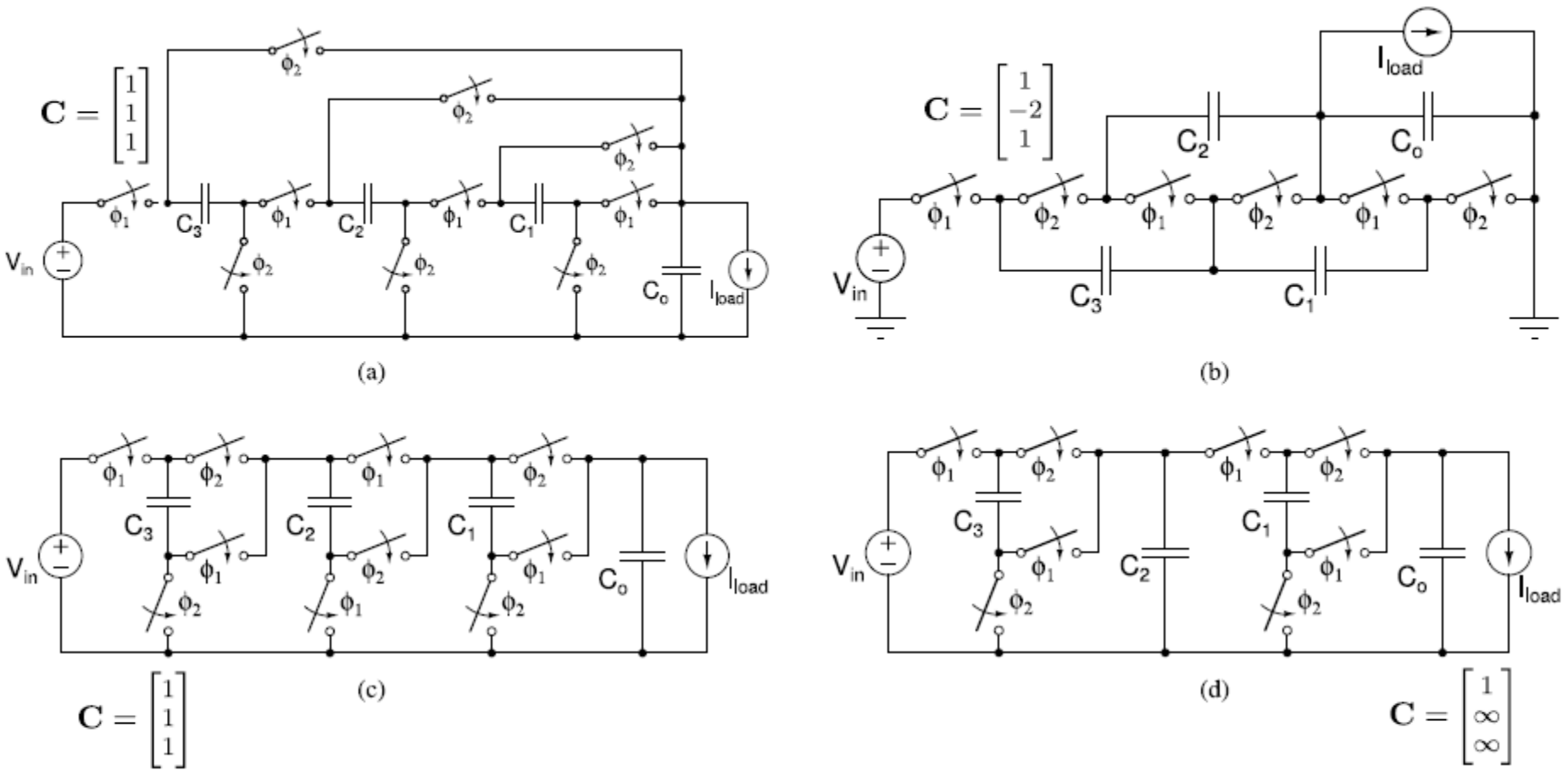




Configuration	C_1 (μF)	C_2 (μF)	C_3 (μF)	C_o (μF)
Hard-charging	10	10	10	100
Soft-charging 1	10	10	10	-
Soft-charging 2	5	20	5	-

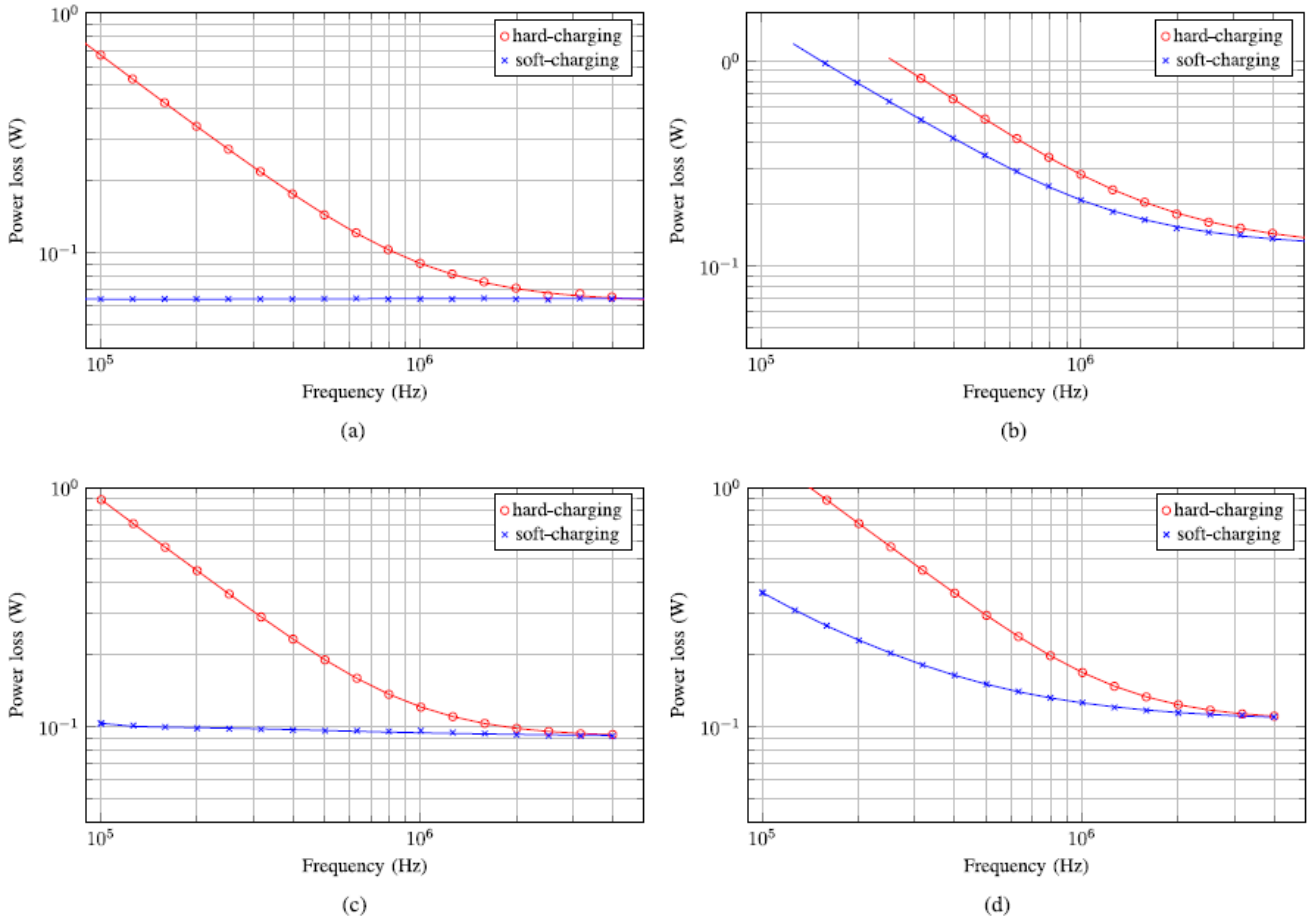
Incomplete soft charging: KVL constraints are not met during phase transitions

Soft charging: other SC topologies



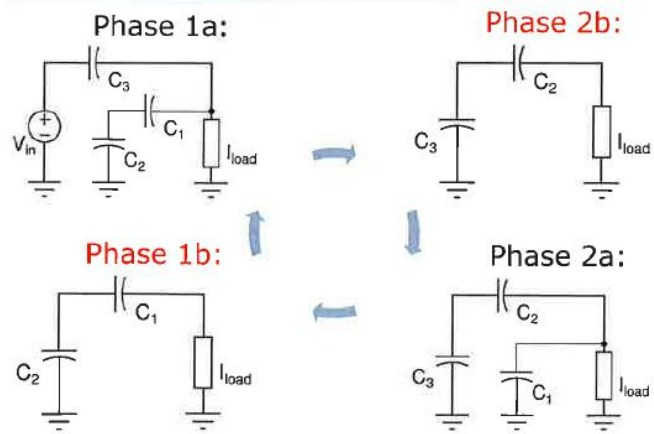
(a) Series-parallel, (b) Ladder, (c) Fibonacci, (d) Doubler

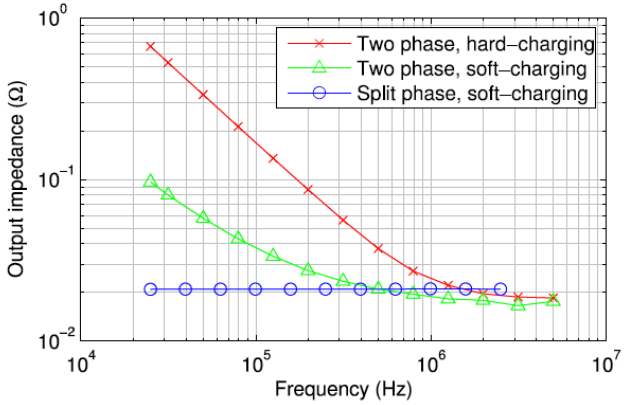
Soft charging: other SC topologies

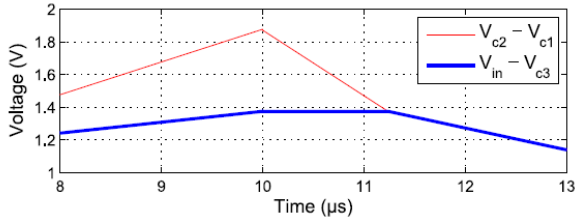


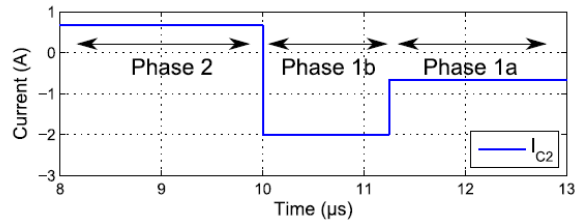
(a) Series-parallel, (b) Ladder, (c) Fibonacci, (d) Doubler

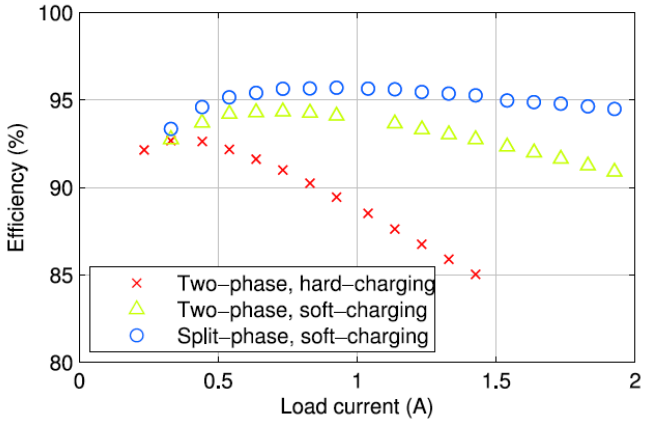
Split-phase operation











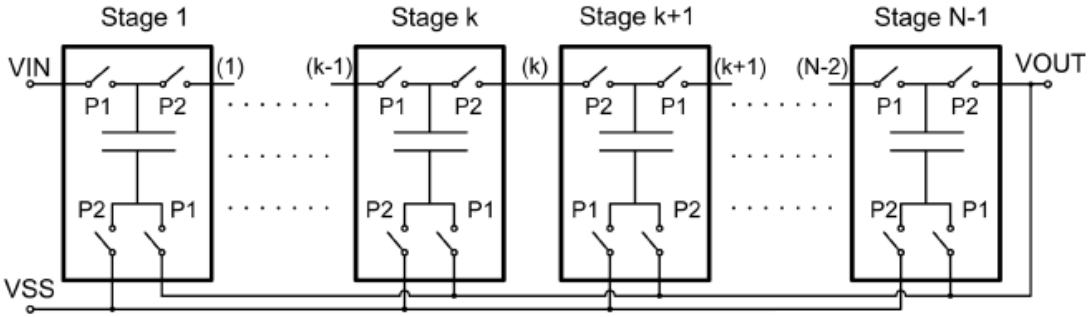
Complete soft charging is achieved in Dickson converter with split-phase operation.

IC implementation

- The efficiency of on-chip SC converters is limited by switch conduction losses, bottom plate parasitics and flying capacitor sizes

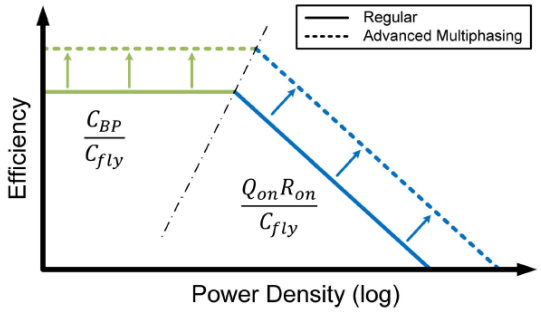
- The performance of the SC converter can be optimized by:
  - reducing power losses in SSL (Kc) and FSL (Ks) regions
  - relative sizing of capacitors and switches

- Only charge transfers between capacitors can be soft-charged

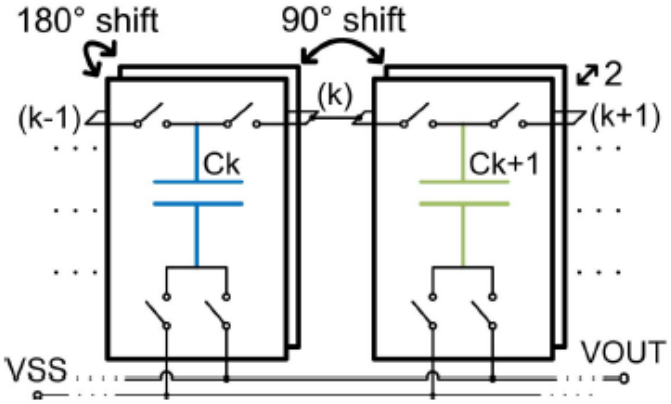


Regular N:1 Dickson SC converter

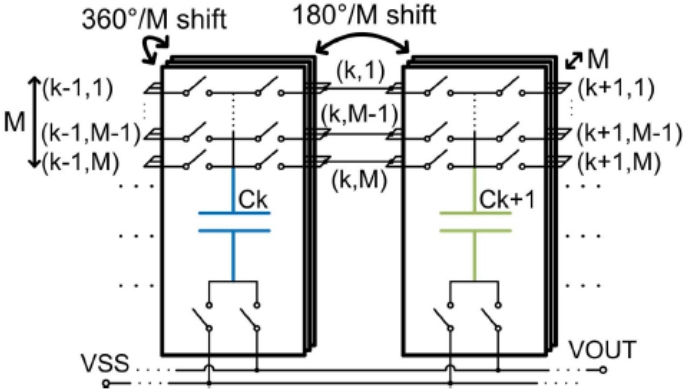
$$K_{c,\text{regular}} = \left(\frac{N-1}{N}\right)^2$$



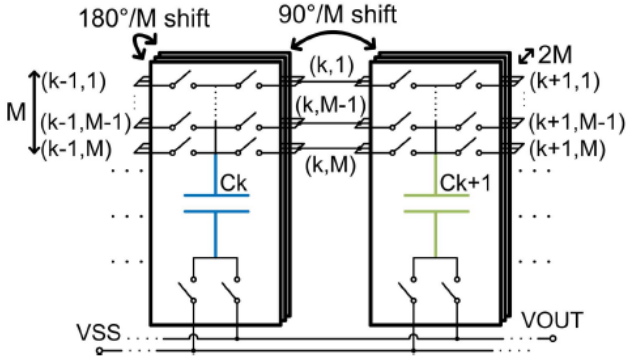
Stage outphasing (SO) vs Multiphasing



Stage outphasing (S = 2)



Multiphasing (S = M)

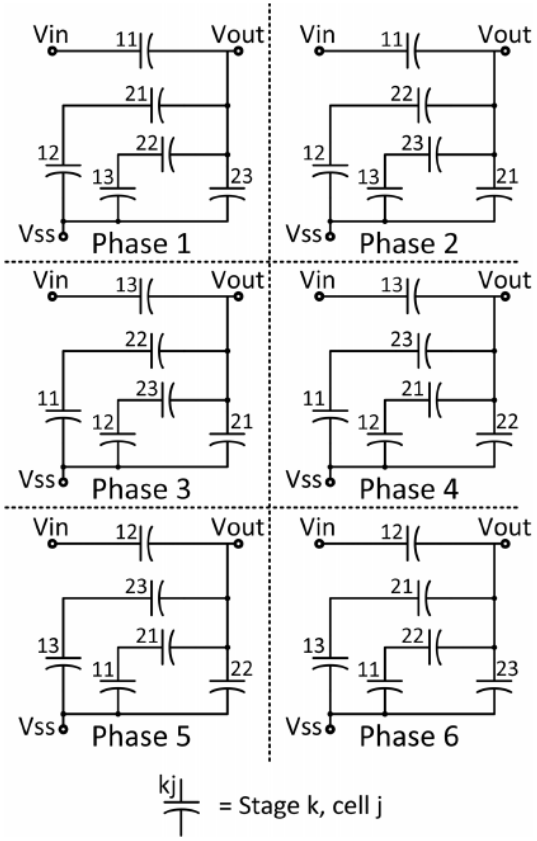


Multiphasing + SO (S = 2M)

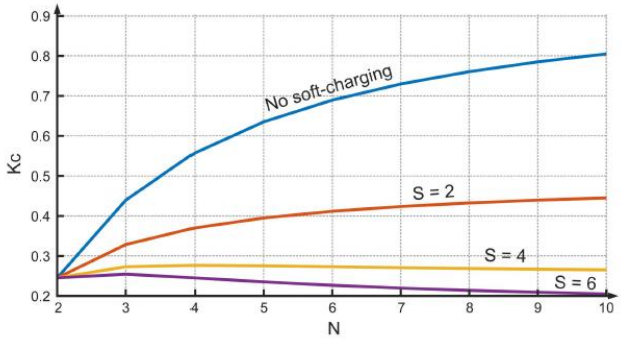
$$K_{c,\mathrm{sc}} = \frac{N-1}{N^2}\left(1+\frac{(N-2)}{S}\right)$$

$$K_{s,\mathrm{msc}} = \frac{4}{N}\left(2\sqrt{M}(N-2)+2N\right)\left(1+\frac{(N-2)}{N}\sqrt{M}\right)$$

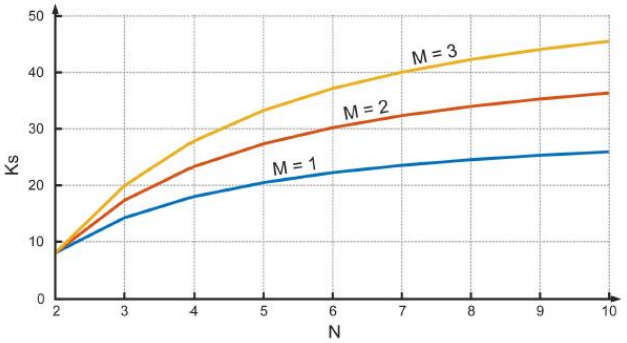
IC implementation: multiphasing + SO



Phase diagram of 3:1 Dickson converter

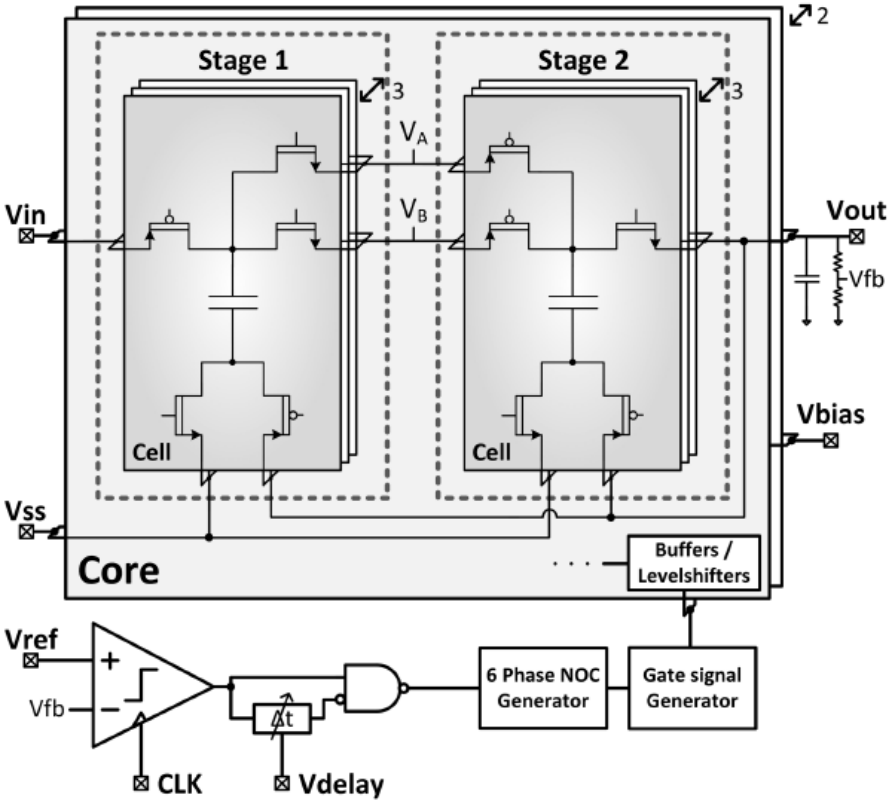


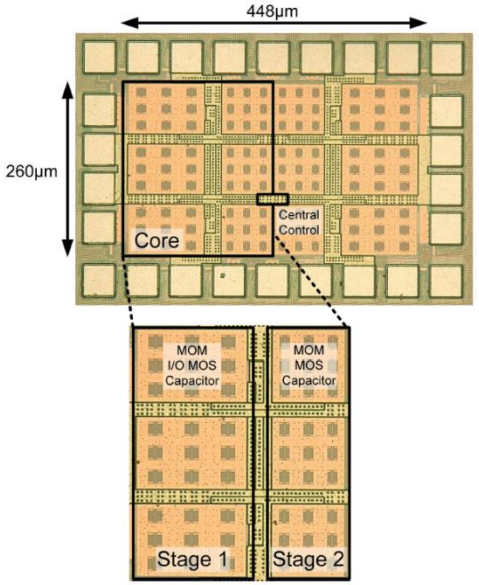
Increasing soft-charging factor or steps (S), reduces charge redistribution loss (Kc)

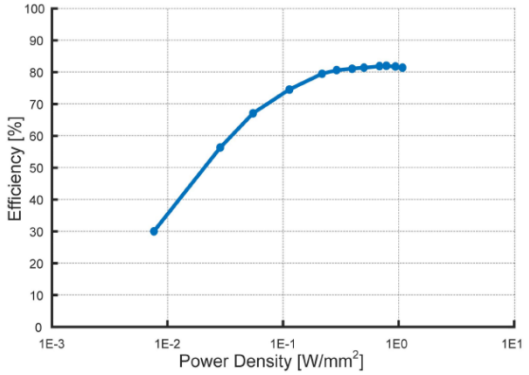


Increasing M, will eventually cause more losses from the switches (Ks) than are reduced in the capacitors

IC implementation: multiphasing + SO







3:1 SC converter with additional controller

Conclusion

- Soft charging technique can be used to improve the efficiency of common SC converters
  - some topologies are inherently soft-charging compatible while others require advanced techniques such as two- or split-phase modes

- Soft-charging implementation on IC
  - although SC converters benefit from monolithic integration, it also introduces additional design constraints and challenges
  - advanced multiphasing techniques can be used to optimize integrated SC converters for achieving higher efficiency

References

- 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.

- Y. Lei, R. May and R. Pilawa-Podgurski, "Split-Phase Control: Achieving Complete Soft-Charging Operation of a Dickson Switched-Capacitor Converter," in *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 770-782, Jan. 2016.

- N. Butzen and M. S. J. Steyaert, "Design of Soft-Charging Switched-Capacitor DC–DC Converters Using Stage Outphasing and Multiphase Soft-Charging," in *IEEE Journal of Solid-State Circuits*, vol. 52, no. 12, pp. 3132-3141, Dec. 2017.

- Fundamentals of Power Conversion Topologies: ISSCC 2019 Tutorial by R. Pilawa-Podgurski

- Google images repository

Homework

1. Describe briefly the concept of incomplete and complete soft charging in switched-capacitor converters.

2. Discuss an alternative method of achieving soft charging in switched-capacitor converters and identify the benefits and limitations of using the method.