Soft-charging Operation: Improving the Efficiency and Power Density of Switched-Capacitor Converters

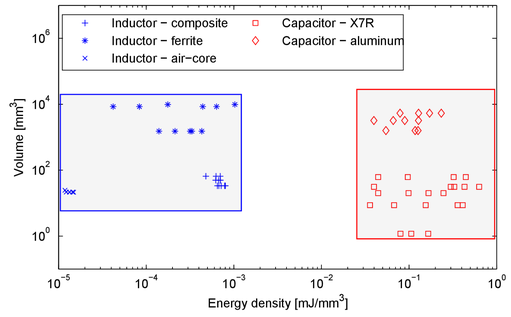
Yutian Lei, Robert Pilawa-Podgurski, University of Illinois

Abstract

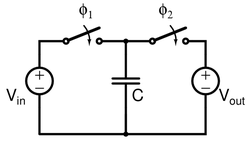
Traditionally, switched-capacitor converters (SC) converters have suffered from two major problems: large transient current and lossy output voltage regulation. Soft-charging SC converters are proposed as a hybrid SC converter topology that addresses both problems simultaneously. The proposed topology adds a single small inductor to the SC converter and achieves higher efficiency and power density than conventional SC converters. Unlike SC converters, it can maintain its efficiency for output voltages that are lower than the nominal value determined by the topology. A discrete prototype with a large step-down ratio of over 8-to-1 and a power rating of 65 W has been designed and built to demonstrate the potential of the hybrid converter.

Motivation

- Advantages of SC converters:
  1. Low device stress, especially at high conversion ratios
  2. Large energy density of capacitors
- Disadvantages:
  1. Poor capacitor energy utilization
  2. Only efficient at particular conversion ratios.

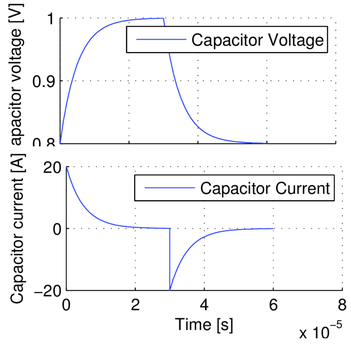


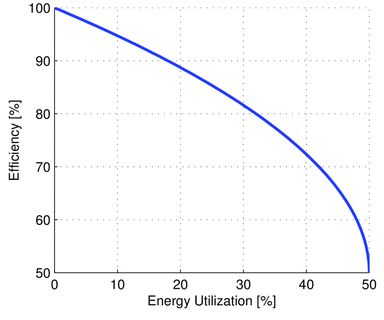
- Efficiency and energy utilization trade-off



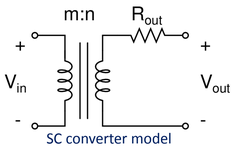
$$E_{loss} = C(V_{max} - V_{min})^2$$

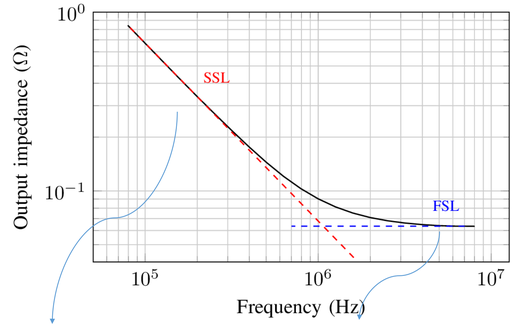
$$Utilization = \frac{{V_{max}}^2 - {V_{min}}^2}{\frac{1}{2}{V_{rated}}^2}$$



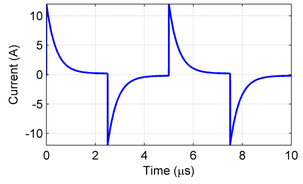


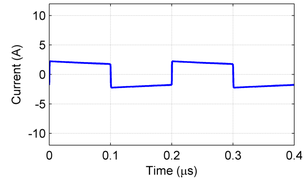
Output Impedance Curve[1,2]





Capacitor current:





Poor efficiency

Poor energy storage utilization

- The ideal operating point is in the SSL region, but with the output impedance the same as in the FSL.
- The solution is soft-charging operation, which decouples the power loss of the converter from the voltage ripple on the capacitors.

1. M. Makowski and D. Maksimovic, PESC 1995
2. M. Seeman and S. Sanders, IEEE TPEL 2008

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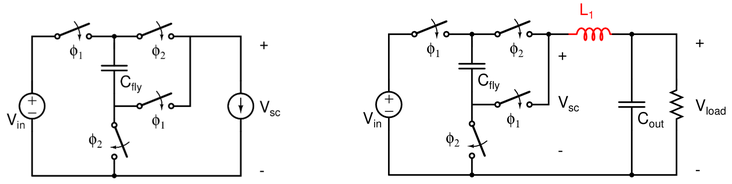
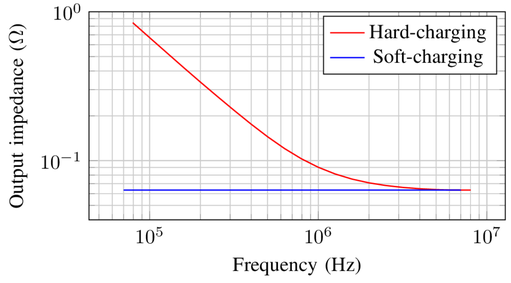
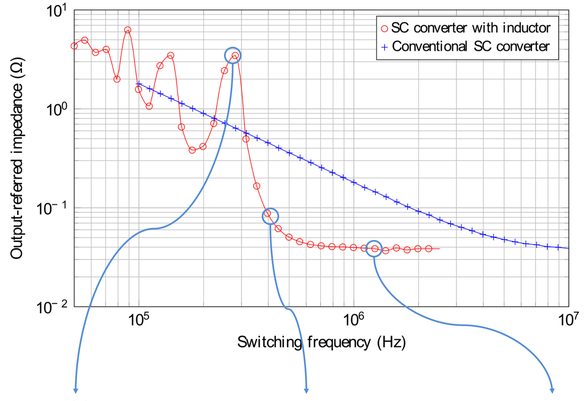
Soft-charging Operation

Soft-charging eliminates the current transient by using a current load (buck converter or an LC filter)[1,2]

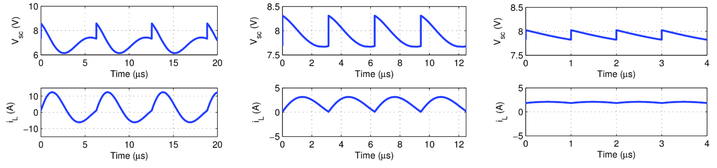
Output impedance in the SSL region is the same as in the FSL







$f_{sw} = 1/2\ f_{crit}$ $f_{sw} = f_{crit}$ $f_{sw} > f_{crit}$

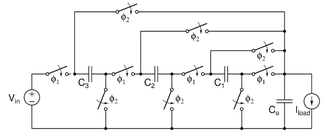


Full-wave resonant | Half-wave resonant (ZCS) | Soft-charging

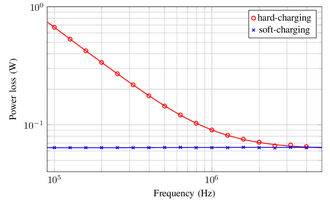
Extension to Other SC Topologies

- Requirements of soft-charging operation:
  - Constant current source load
  - No KVL violations within SC network
- Need a general method to formally analyse an arbitrary SC converter for applicability for soft-charging operation.[3]

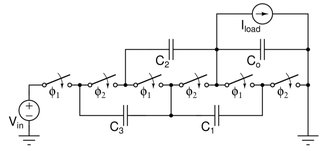
- Series-parallel:



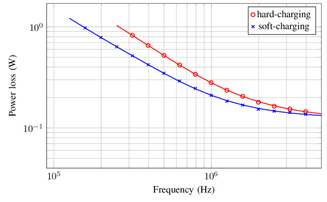
$$\boldsymbol{C} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$



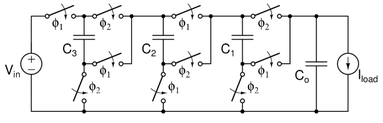
- Ladder:



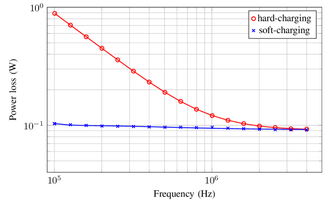
$$\boldsymbol{C} = \begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix}$$



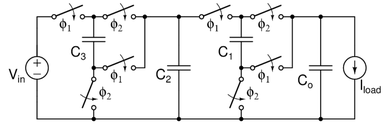
- Fibonacci:



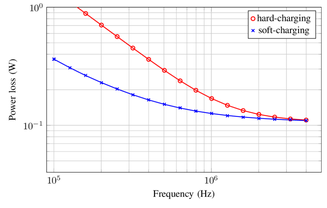
$$\boldsymbol{C} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$



- Doubler:



$$\boldsymbol{C} = \begin{bmatrix} 1 \\ \infty \\ \infty \end{bmatrix}$$



1. R. Pilawa-Podgurski, D. Giuliano, and D. Perreault, PESC 2008
2. Y. Lei and R. Pilawa-Podgurski, APEC 2014
3. Y. Lei and R. Pilawa-Podgurski, COMPEL 2013

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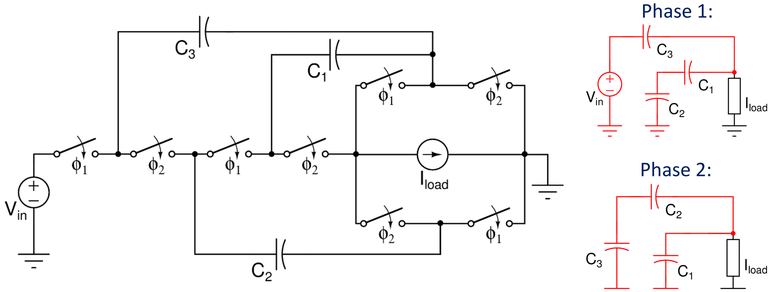
Soft-charging Operation of Dickson SC Converters

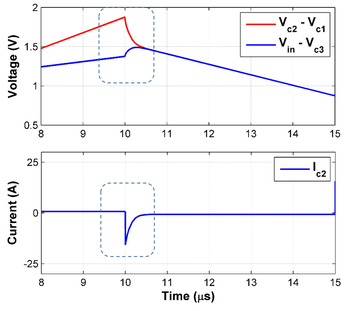
- Dickson converter has efficient utilization of switches, but inefficient utilization of capacitors, and therefore can potentially benefit significantly from soft-charging operation.



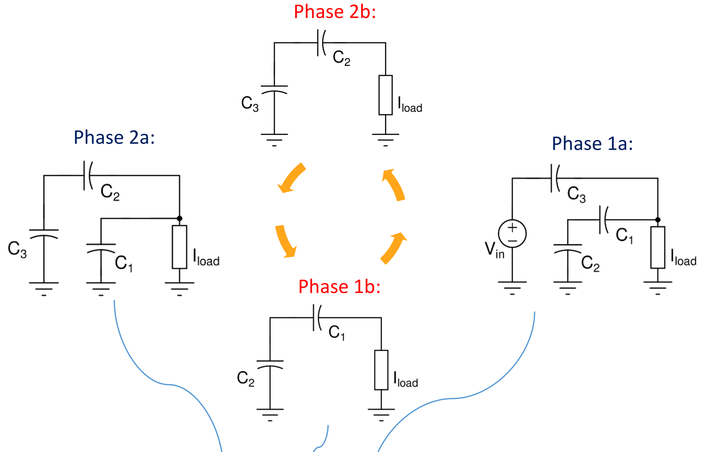
- KVL constraints:

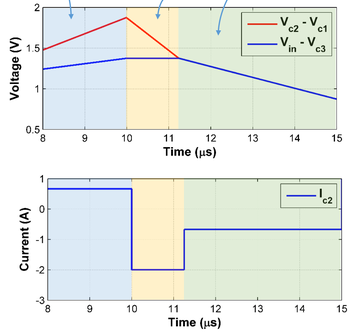
$$V_{in} - V_{c3} = V_{c2} - V_{c1} \qquad V_{c3} - V_{c2} = V_{c1}$$

- Cannot be satisfied at phase transitions.[1]

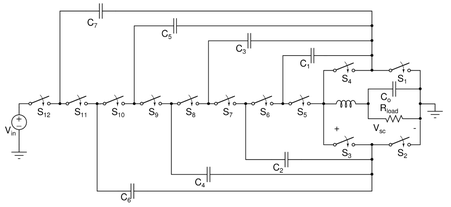


- Full soft-charging operation cannot be achieved.
- Solution: Split-phase control.[1,2]
- Two secondary phases introduced.
- By charging/discharging the selected branch, KVL constrains are satisfied.

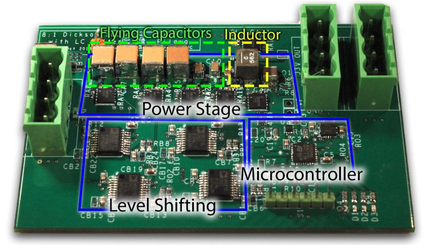


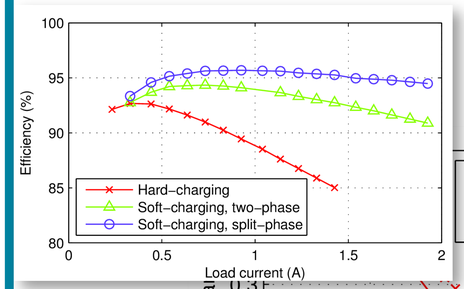


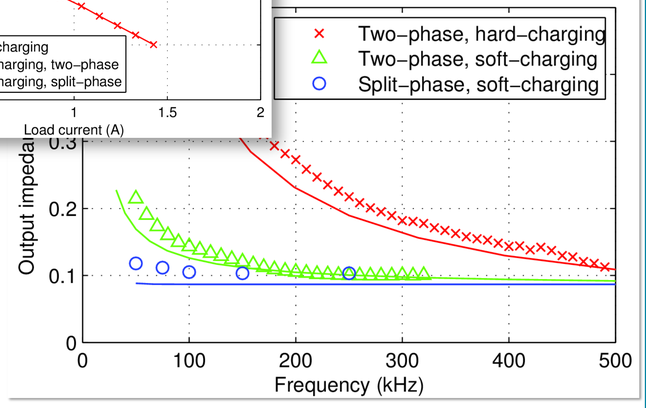
- Hardware prototype
- 12 GaN switches
- 7 flying capacitors of equal values
- 1 additional inductor for soft-charging operation



Tested Specifications	
V_{in}	200 V
V_{out}	25 V
I_{load}	3 A
f_{sw}	50-500 kHz
η_{peak}	95.5 %







1. Ryan May, Master Thesis, 2013
2. Y. Lei, Ryan May and R. Pilawa-Podgurski, COMPEL 2014

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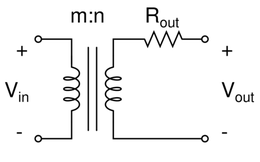
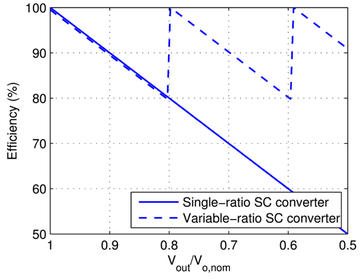
Lossless Regulation of Soft-charging SC Converters

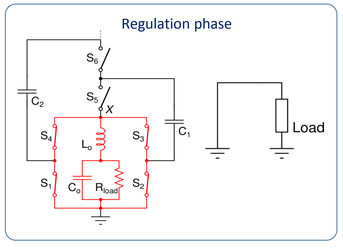
- Another problem of conventional of SC converters is the lossy output voltage regulation
- Regulation of output voltage is achieved by modulating the output impedance
- Regardless of method, the operation is lossy

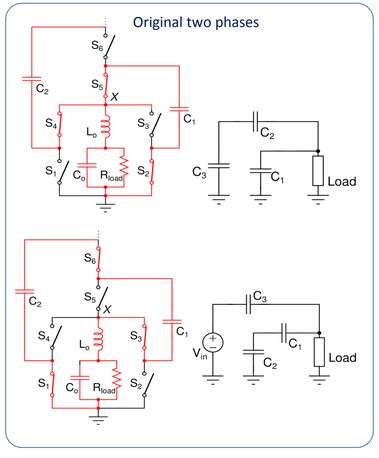


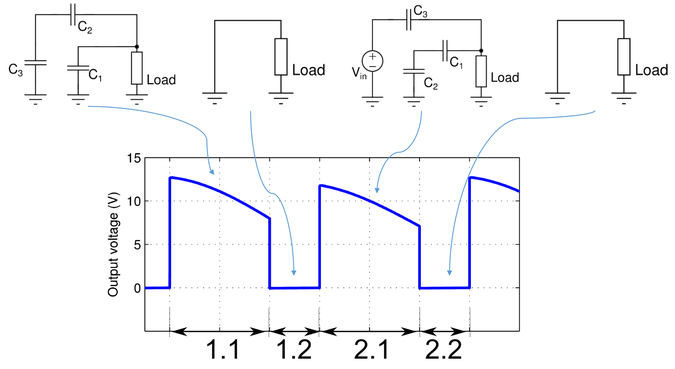
$$\eta = \frac{V_{out}}{V_{o,nom}} = \frac{NV_{out}}{V_{in}}$$



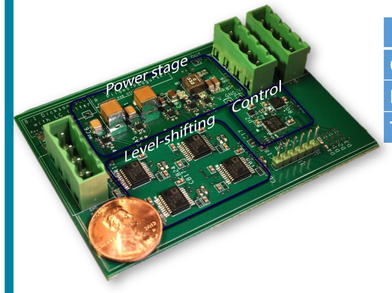
- Solution: form a switched-inductor cell using existing SC switches[1]



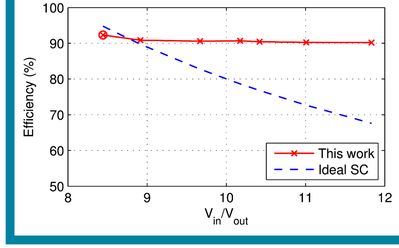


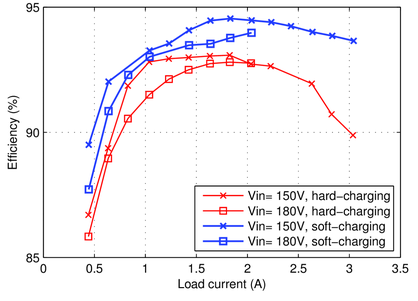


- Output voltage can be regulated by varying the relative during of the phases.
- Similar to pulse width modulation.
- No increase in switching frequency.



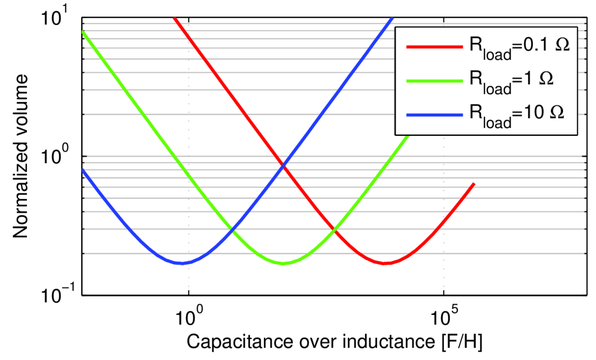
	Conventional	Soft-charging
Capacitor (mm³)	682	379
Inductor (mm³)	-	75
Total (mm³)	682	454





Optimization of Soft-charging and Resonant SC Converters

- With both energy storing capacitors and inductors, there is potential to optimize for the minimum passive component volume.



Summary

- Soft-charging operation improves both the efficiency and power density of SC converters.
- Split-phase control enables full soft-charging operation of Dickson SC converters.
- Lossless regulation achieved with soft-charging SC converters.
- Optimization is possible.

1. Y. Lei and R. Pilawa-Podgurski, APEC 2014