Active Soft-Charging Control for Hybrid and Resonant Switched-Capacitor Converters

Berkeley Power and Energy Center

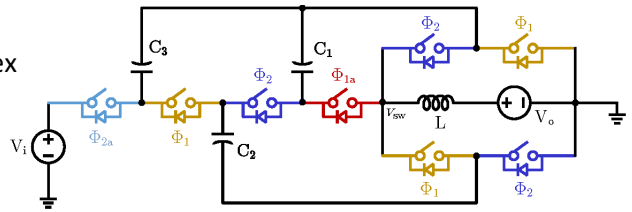
Motivation and Application

Dickson-derived converters are increasingly used for both **fixed-ratio** and **direct-to-PoL** applications in the datacenter and transportation space. They can achieve **very low switch stress** (i.e. Volt·Amp product), which means that lower-voltage (and therefore less lossy) switches can be used compared to other topologies for a given output power.

Split-Phase Control

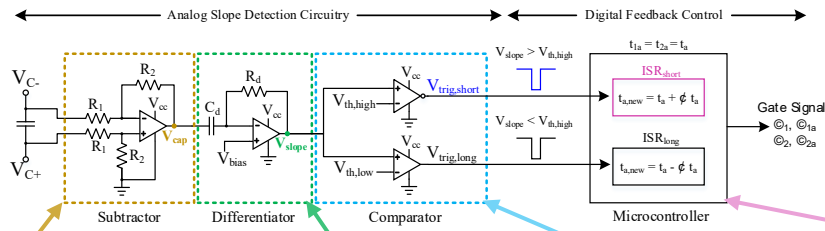
Certain Dickson topologies require more complex **split-phase control schemes** [1] in order to achieve full soft-charging of all fly capacitors. Split-phase control timings can be complex to calculate and vary depending on **component tolerance, circuit non-idealities, and operating condition,** necessitating **active control** [2], [3].

4:1 resonant Dickson converter

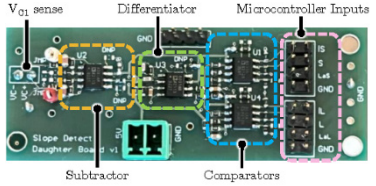


The conventional two-phase operation is split into phases {1a, 1b} and {2a,2b}

Analog Sensing Circuitry



Control Daughterboard



Differential capacitor voltage sensed and signal-conditioned

Slope detect circuit triggers on large step discontinuities

Polarity of step discontinuity shows whether split-phase timing is too short or too long

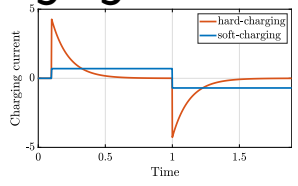
Interrupt service routine (ISR) increases or decreases split-phase timing accordingly

- The analog circuitry is flexible in implementation, and stages can be combined into single package op-amps or off-loaded into internal microcontroller comparator units to increase density.

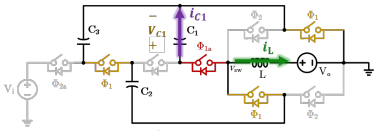
Capacitor Losses: Hard-Charging vs. Soft-Charging

Hard-charging: large charge redistribution loss, spiky currents.

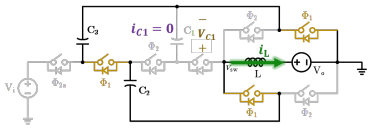
Soft charging: no charge redistribution loss, smooth / resonant currents.



Phase 1 Split-Phase Operation



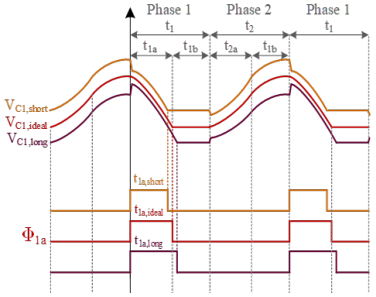
Phase 1a



Phase 1b

If the {1a,1b} and {2a,2b} transitions occur at the wrong time, hard-charging occurs, resulting in **current spikes** and **discontinuous capacitor voltages.**

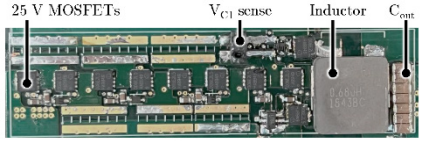
These voltage steps can be sensed, allowing the controller to auto-tune split-phase times to achieve soft-charging operation.



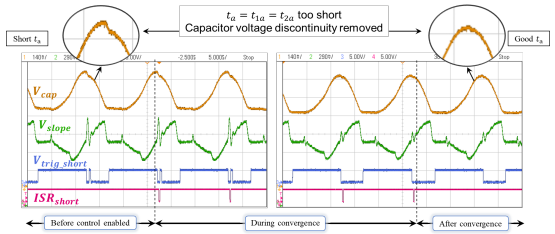
Experimental Verification

- An 8-to-1 resonant Dickson converter was used for validation.
- The control scheme was able to converge on soft-charging split-phase timing when 1) initialized in a hard charging-condition, and 2) when enabled during load step transients.

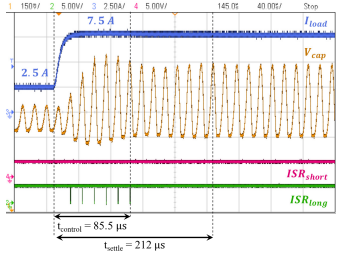
8:1 Dickson Converter



Steady-State Convergence



Load Step Transient



Smooth capacitor voltages signify soft-charging operation

Operating Conditions

Parameter	Value
V_{in}	48 V
V_{out}	6 V
$I_{out,max}$	10 A

References:

[1] Y. Lei et al., "**Split-Phase Control: Achieving Complete Soft-Charging Operation of a Dickson Switched-Capacitor Converter**", *IEEE Trans. on Power Electronics*, vol. 31, no. 1, pp. 770-782, 2015. [2] R. A. Abramson et al., "**An Active Split-Phase Control Technique for Hybrid Switched-Capacitor Converters Using Capacitor Voltage Discontinuity Detection**," *2023 IEEE 24th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Ann Arbor, MI, USA, 2023. [3] N. M. Ellis, H. Sambo and C. N. Robert Pilawa-Podgurski, "**Closed-Loop Split-Phase Control Applied to the Symmetric Dual Inductor Hybrid (SDIH) Converter**," *2023 IEEE 24th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Ann Arbor, MI, USA, 2023.

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