Aalto University
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Switched-Capacitor Power Converters
ELEC-L3520

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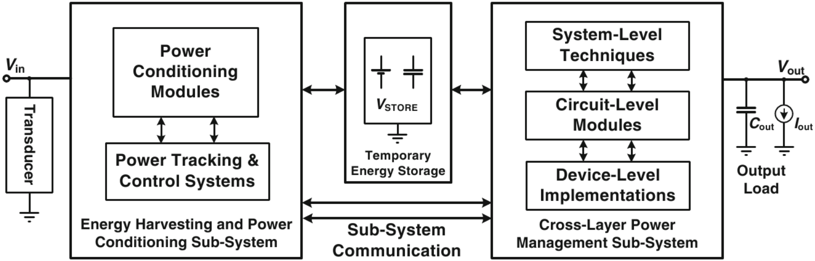
Outline

Lecture Overview

- Background and context: Low power systems
  - Power management $\rightarrow$ circuit requirements
  - Other DC-DC power converter types
- Switched capacitor power converters
  - Charge transfer
  - Charge pump topologies
- Loss mechanisms in SC power converters

Outline

Energy Harvesting Systems



- Power conditioning optimizes power harvesting
- Harvested energy is stored as usable voltage
- Power management optimizes power consumption

Power Management Algorithms

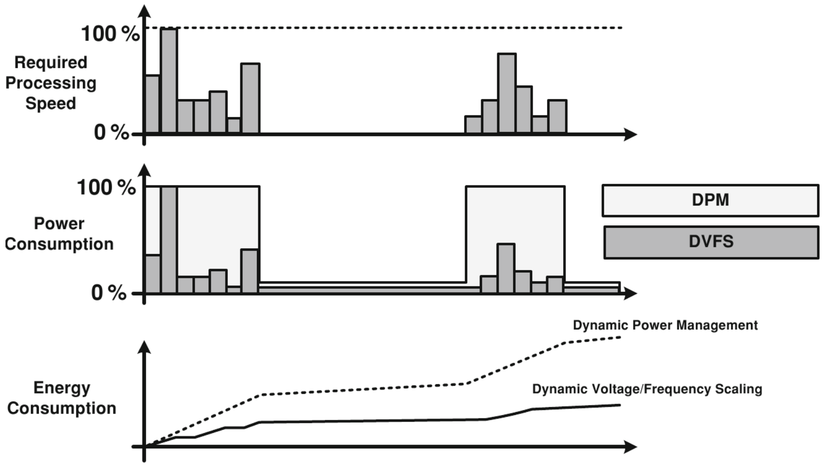
Dynamic power management, DPM

- Go to standby when possible
- Good for burst operation (e.g. RF TX)

Dynamic voltage/frequency scaling, DVFS

- Lower operating frequency during non-maximal processor load $\rightarrow$ saves power
- Lower supply voltage with frequency $\rightarrow$ saves energy

Power Management Algorithms



DC-DC Power Converters

- Circuit Level Power Management
- Regulate DC-input to reference voltage
  - Reference can be higher or lower
  - Same or reverse polarity
- Feed-back controller
- Efficiency!
- Varying line and output conditions
- Variable or multiple output levels (DVFS)

Outline

- Lecture Overview
- Background
- **Performance Metrics**
- DC-DC Converter Types
- Charge Pump Topologies
- Losses in SC Power Converters
- Conclusion

Efficiency

$$\eta = \frac{P_{out}}{P_{in}} * 100\% = \frac{P_{out}}{P_{out} - P_{loss}} * 100\%$$

- Most critical metric for power converters
- Loss mechanisms for SC power converters introduced later

Line Regulation

- Ability to maintaining desired V_{out}, when V_{in} fluctuates
- Essential for energy harvesting systems

$$\text{Line Regulation} = \left(\frac{\Delta V_{out}}{\Delta V_{in}}\right)\Bigg|_{I_{out}=const} \left[\frac{mV}{V}\right]$$

Load Regulation

$$\text{Load Regulation} = \left(\frac{\Delta V_{out}}{\Delta I_{out}}\right)\Bigg|_{V_{in}=const} \left[\frac{mV}{A}\right]$$

- V_{out} typically decreases as I_{out} increases
- Ability to maintain constant V_{out} with varying load conditions

Reference Tracking Speed

$$\text{Reference Tracking Speed} = \left(\frac{\Delta T}{\Delta V_{out}}\right)\Bigg|_{I_{out}=const} \left[\frac{s}{V}\right]$$

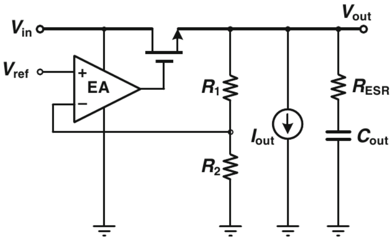
- How fast variable output tracks to new V_{ref}

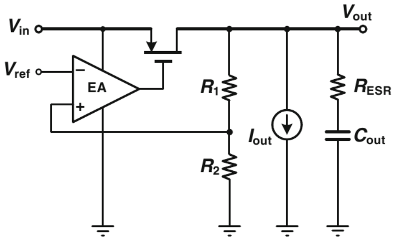
Other desired properties

- Monolithic solution
- Small die area
- Reconfigurability
- Noise

Outline

Linear regulators and LDOs

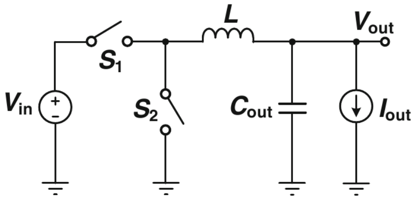




- Error amplifier + item Pass transistor as VCVS
- No switching noise
- Only step-down output
- η drops as V_{out} increases

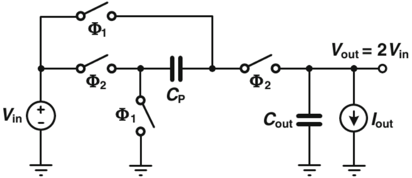
Switch Mode

- Good efficiency ($> 90\%$)
- Buck and Boost possible
- Duty-cycle PWM feedback
- Energy stored on the inductor released at different voltage
- Variable output possible but difficult



Switched Capacitor

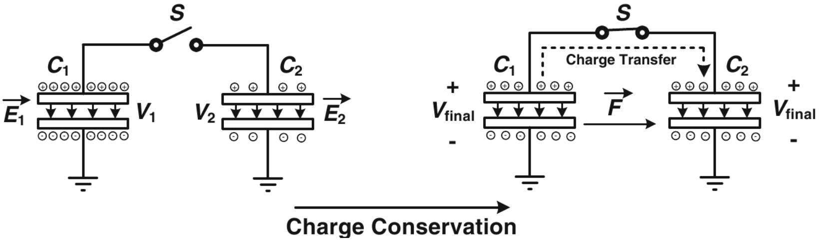
- Charge pump
- Feedback controller
- Monolithic solutions
- Variable V_{out} with reconfigurability
  - Highly efficient at these discrete voltages



Outline

Charge Transfer

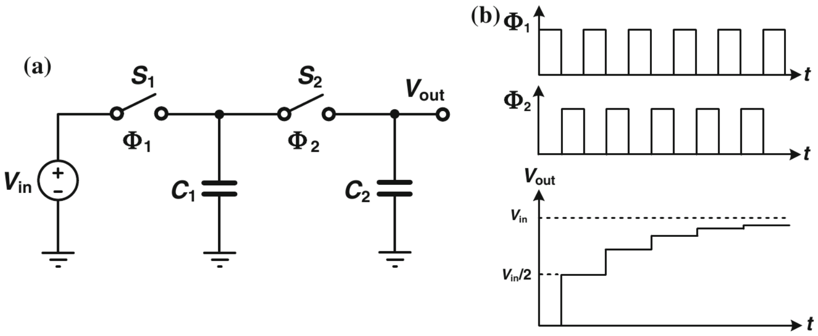
- Basic mechanism of charge pumps
- Based on conservation of charge



$$Q_{tot} = C_1 V_1 + C_2 V_2$$

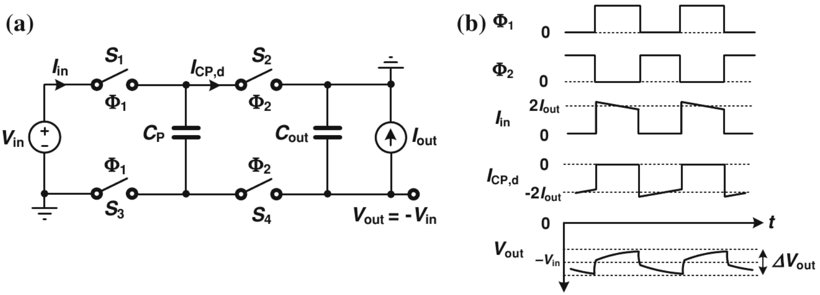
$$V_{final} = \frac{Q_{tot}}{C_1 + C_2} = \left(\frac{C_1}{C_1 + C_2}\right) V_1 + \left(\frac{C_2}{C_1 + C_2}\right) V_2$$

Charge Pump Startup



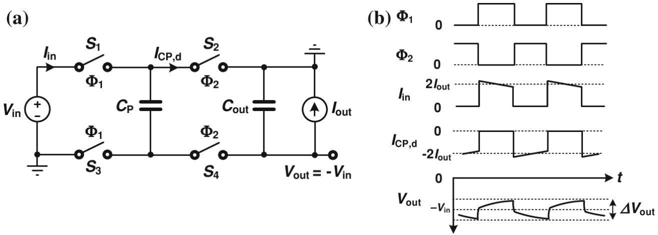
- Voltage replicator configuration
- Charge transfer doesn't match V_{out} to V_{in} instantly

Voltage Inverter



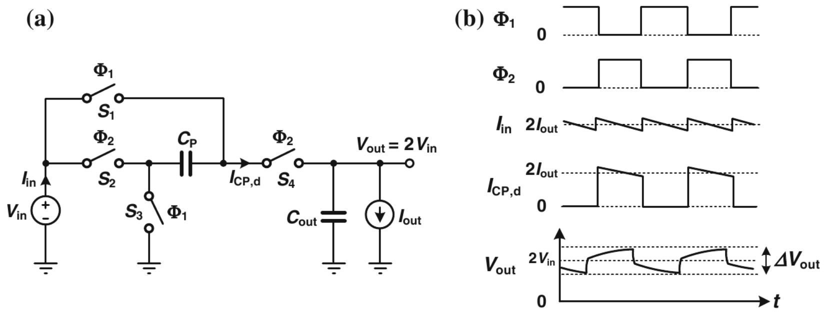
- C_1 discharges with I_{out} during phase 2
- Equal recharge in steady state
- Average I_{in} = average I_{out}
- Conversion gain, $CG = V_{out}/V_{in} = -1$

Voltage Inverter ΔV



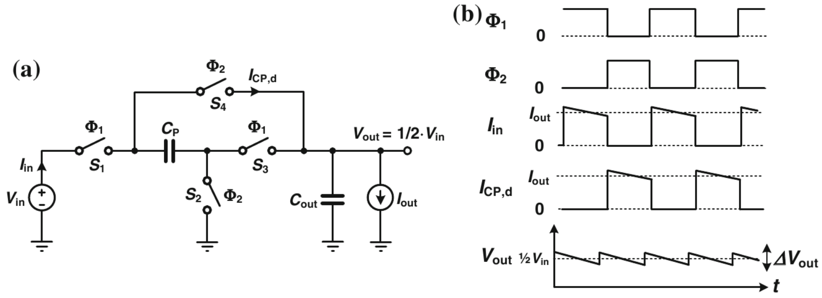
- ΔV measures output swing during one cycle
- I_{Cout} changes from $-I_{out}$ to I_{out} between the phases
- Step change in V_{out} equal to $2I_{out}$ ESR_{Cout}
- V_{out} changes also due to discharge
- $\Delta V = 2I_{out} * ESR_{Cout} + \frac{I_{out}}{2f_s C_{out}}$

Voltage Doubler



- C_p charged to V_{in} during phase 1
- $V_{out} = V_{in} + V_p$ during phase 2
- CG = 2, $I_{in,ave} = 2I_{out}$
- ΔV = $2I_{out} * ESR_{Cout} + \frac{I_{out}}{2f_s C_{out}}$

Step-Down Charge Pump



- Caps in series during charge, parallel during discharge
- CG = 1/2, $I_{in,ave} = 1/2 I_{out}$
- Charge delivered to output during both phases
- ΔV significantly improved
- ΔV = $\frac{I_{out}}{2 f_s C_{out}}$

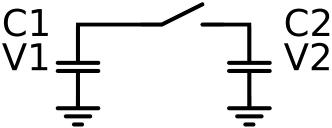
Outline

Redistribution Loss

- Energy lost when capacitors at different voltages are connected together

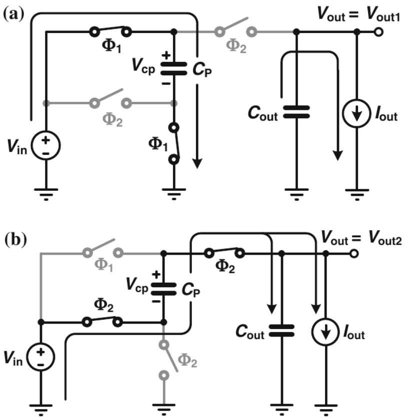
$$V_{final} = \frac{C_1 V_1 + C_2 V_2}{C_1 + C_2}$$

$$E_{loss} = \frac{1}{2} C_1 V_1^2 + \frac{1}{2} C_2 V_2^2 - \frac{1}{2} (C_1 + C_2) V_{final}^2$$



Redistribution Loss in Voltage Doubler

- When caps are connected, top plate of C_p is at $2V_{in}$
- V_{C_out} is lower: it has been discharged by I_{out}
- Charge distribution every cycle!



- V_{out} before and after redistribution, V_{out1} and V_{out2}

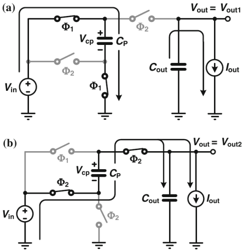
Redistribution Loss in Voltage Doubler

KQL:

$$C_p V_{in} + C_{out} V_{out1} = C_p (V_{out2} - V_{in}) + C_{out} V_{out2}$$

Discharging with I_{out}:

$$C_{out} (V_{out2} - V_{out1}) = I_{out} T_s$$



Leads to:

$$V_{out2} = 2V_{in} - \frac{I_{out}}{C_p f_s}$$

$$V_{out1} = 2V_{in} - \frac{I_{out}}{C_p f_s} - \frac{I_{out}}{C_{out} f_s}$$

$$P_{loss} = \frac{1}{2} f_s [C_p V_{in}^2 + C_{out} V_{out1}^2 - C_p (V_{out2} - V_{out1})^2 C_{out} V_{out2}^2]$$

Conduction Loss

- Switches have R_{on}

$$P_{loss} = (\sum_{k}^{n} ESR_{C_p} + \sum_{j}^{m} R_{on}) f_s \int_{nT}^{nT+DT} idt$$

- Is minimized with larger W transistors

Switching Loss

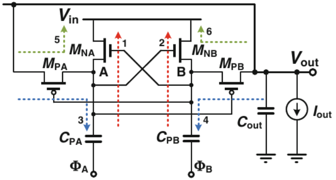
- Energy is required to charge switch transistor parasitic capacitances
- C_{GS} dominates and is set by dimensions

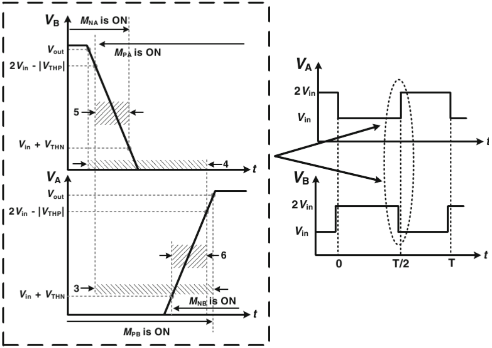
$$P_{loss,C_{GS}} = f_s \sum_i C_{GS,i} V_{GS,i}^2 = f_s C_{ox} \sum_i W_i L_i V_{GS,i}^2$$

Conduction and Switching Loss Optimization

- Larger devices (smaller R_{on}) have larger C_{GS}
- Different optimal width for each switch
- Defined $\frac{\delta P_{tot}}{\delta W_i} = 0$
- W_{opt} is affected by path configuration, input and output voltages, I_{out} and f_s

Reversion Loss





Outline

Conclusion

- DVFS requires multiple output voltage levels
- SC solution have advantages over linear regulators and switched mode power converters
- SC power converters use charge pumps based on charge transfer
  - Introductory charge pump topologies covered
- Loss mechanisms
  - Redistribution
  - Conduction
  - Switching
  - Reversion

Homework

- Shortly explain the operation of the cross coupled voltage doubler. What are its main benefits?
- Shortly explain what can be done to mitigate reversion power loss in the cross coupled voltage doubler.