Leistungselektronik – Grundlagen und Standardanwendungen
SS 2012

DC/DC Converter Fundamentals

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Technische Universität München
Elektrische Energiewandlungstechnik

Outline

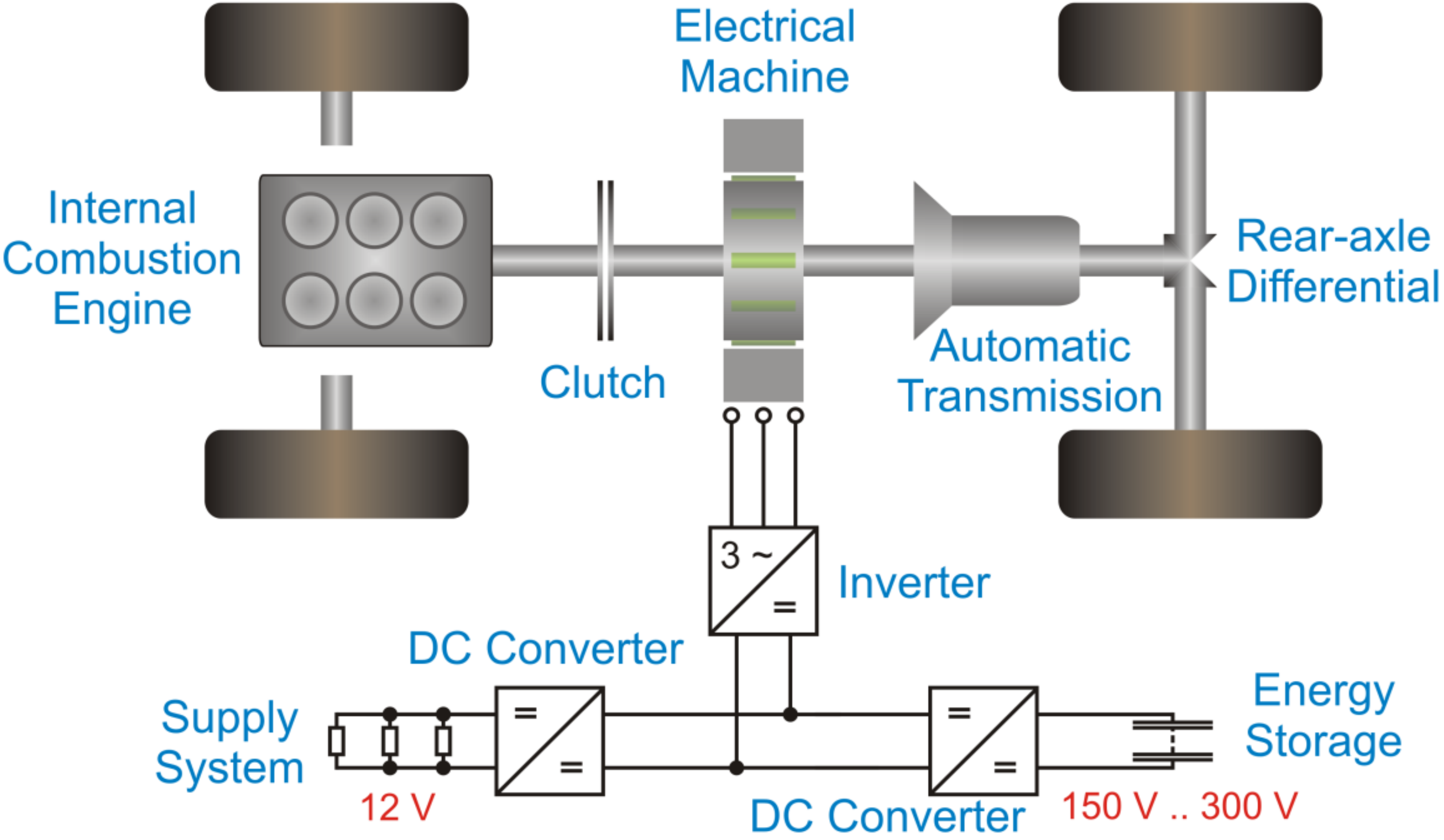
1. Overview on DC/DC Converter
2. One-Quadrant Converter
   - Buck Converter
   - Boost Converter
   - Buck-Boost Converter
   - Cuk Converter
3. Two-Quadrant Converter
4. Multi-Phase DC/DC Converter

Overview on DC/DC Converter

Fields of Application

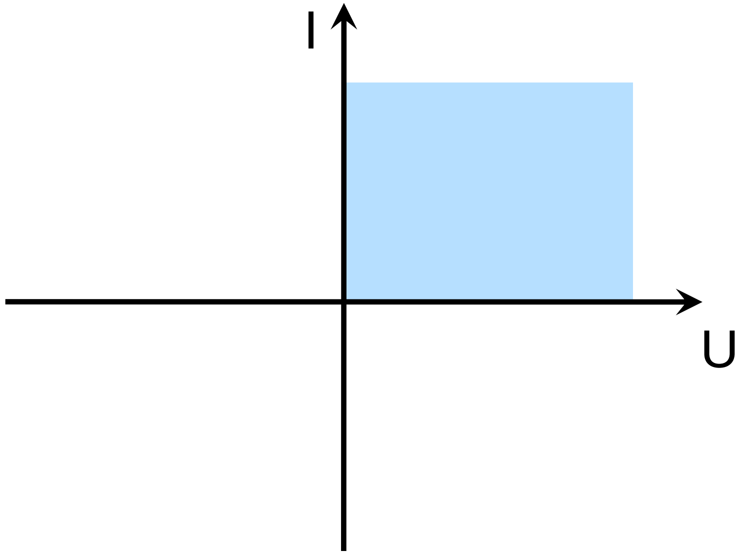
- Switched-Mode Power Supplies (≤ 300W)
  - Supply of µC
  - PC Power Supply
- Automotive (some kW)
  - Coupling of Multi-Voltage On-Board Supply Networks
  - Connection of Energy Storage Devices, Thermo-Electric Generators, Solar Panels, ...
- Controlled DC-Drives (several 10 kW)

Fields of Application in Vehicles



Buck Converter

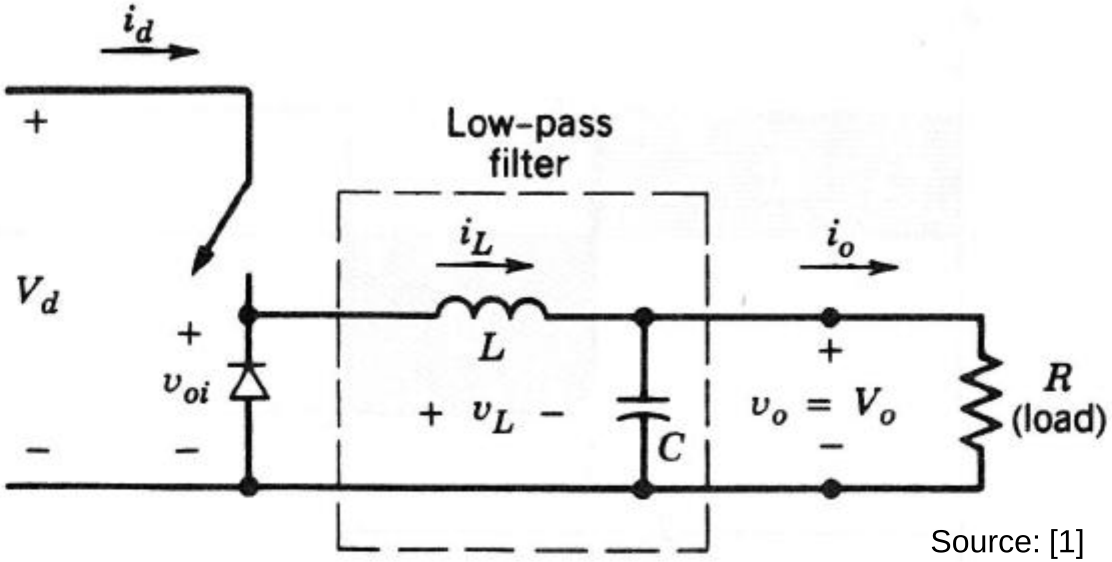
One-Quadrant Converter



Fields of Application:

- Unidirectional Coupling of Two On-Board Networks
- Connecting Components with Lower Voltage Level to a Higher Voltage On-Board Network

Buck Converter – Principle Circuit



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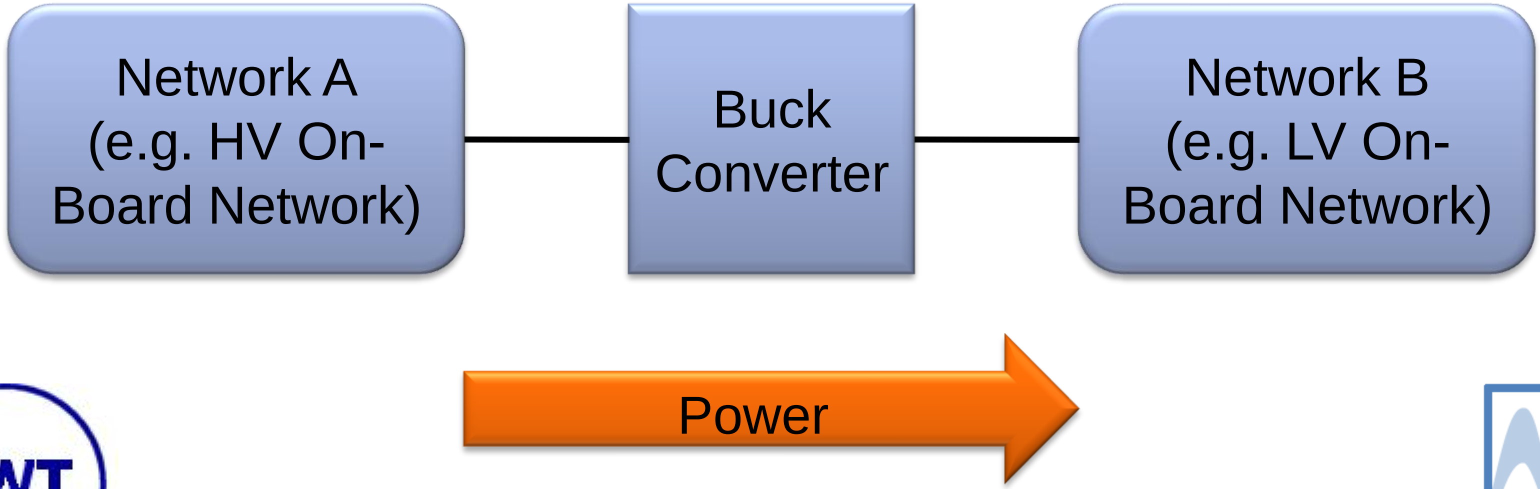

Network A (e.g. HV On-Board Network)

Buck Converter

Network B (e.g. LV On-Board Network)

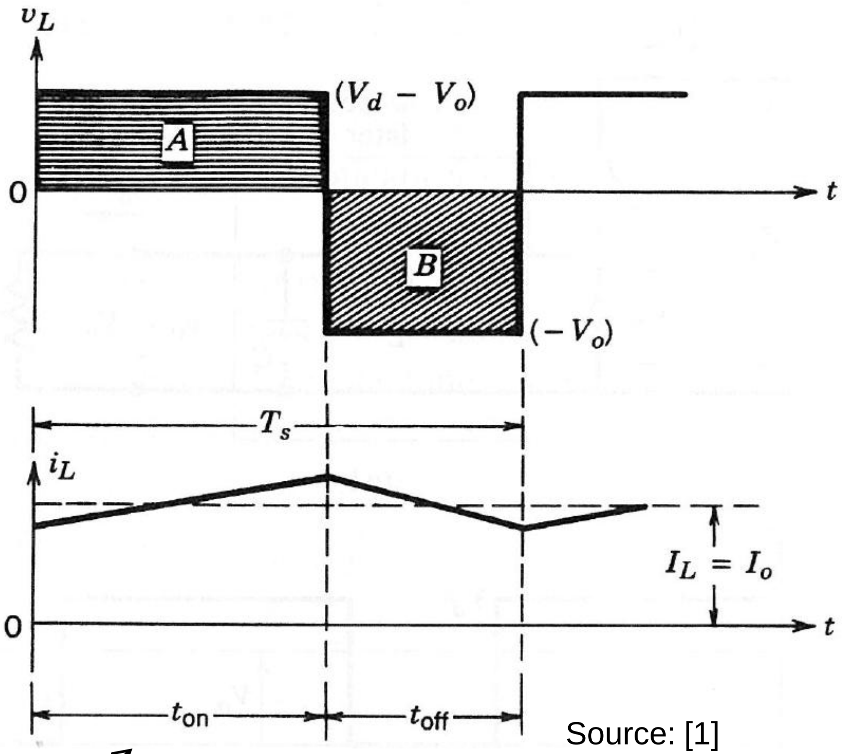
Power

Buck Converter – Switching States

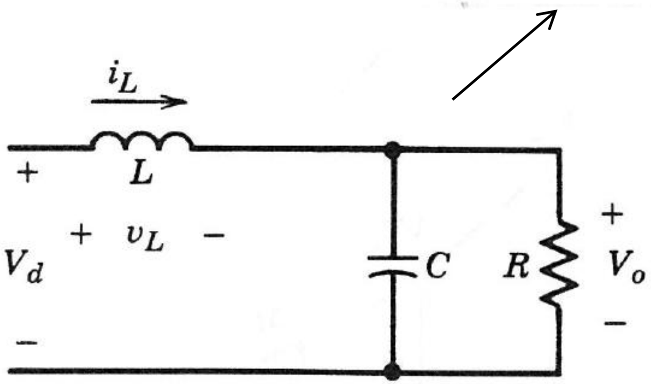
Assumption:

V_O = const.

$$T_s = t_{on} + t_{off}$$



Source: [1]



Source: [1]

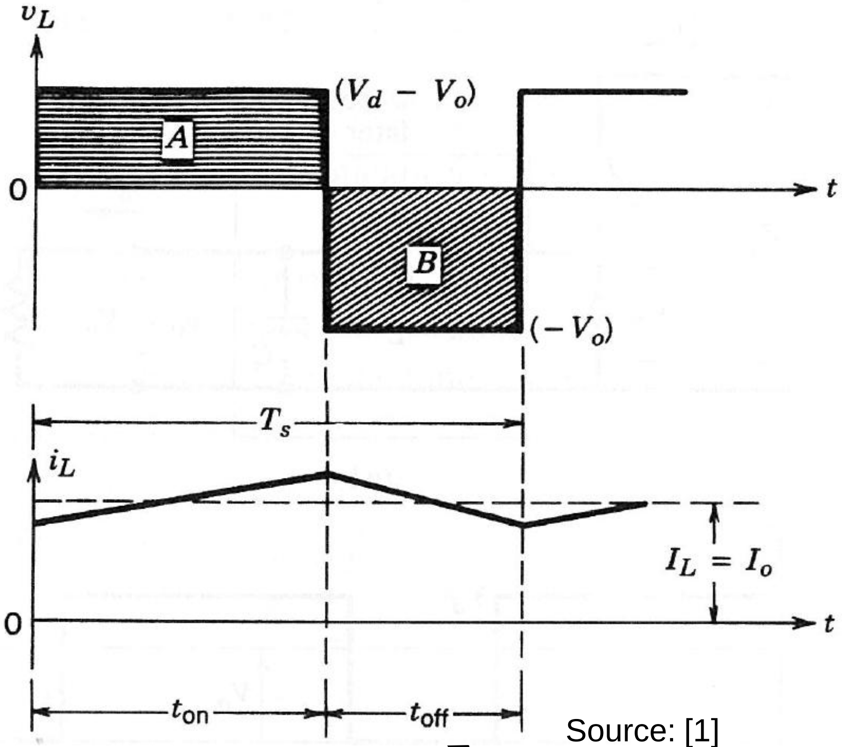
$$i_L(t) = I_{S,Bo} + \frac{V_d - V_0}{L} \cdot t$$

Buck Converter – Switching States

Assumption:

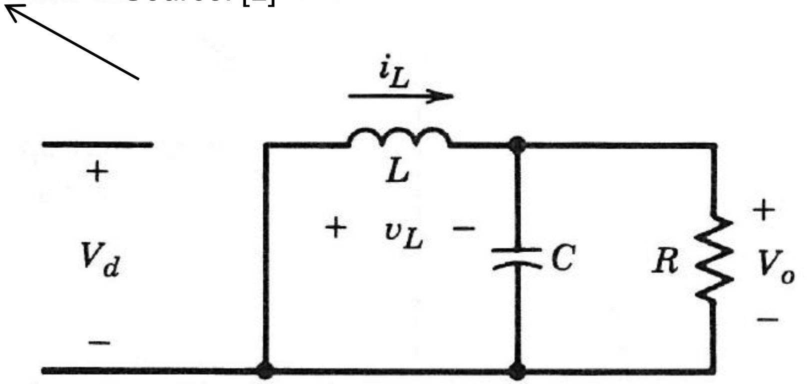
V_O = const.

$$T_s = t_{on} + t_{off}$$



Source: [1]

$$i_L(t) = I_{S,Up} + \frac{(-V_0)}{L} \cdot t$$



Source: [1]

Buck Converter – Switching States

Assumption:

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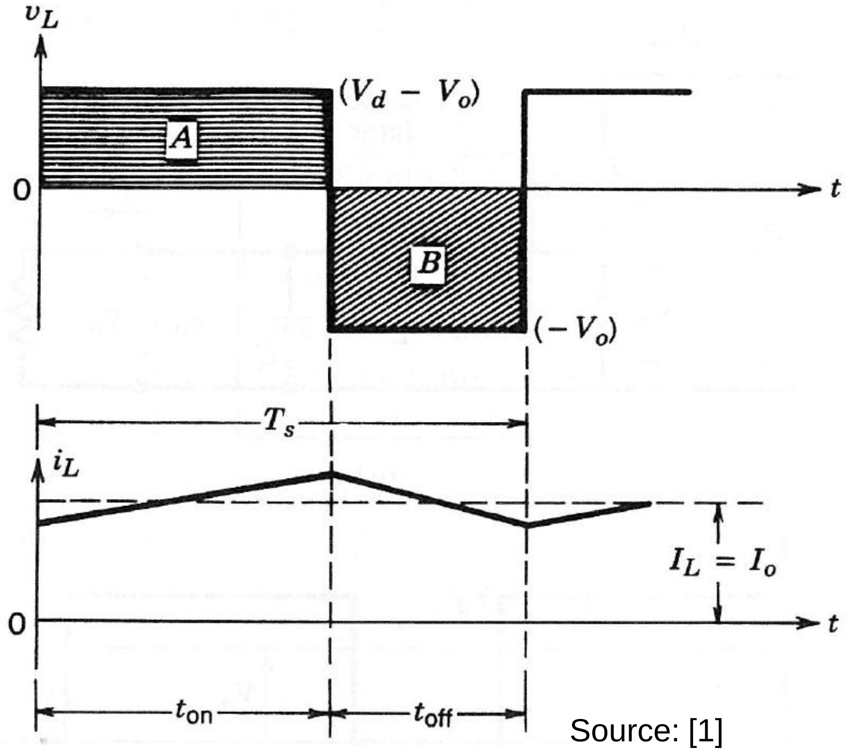
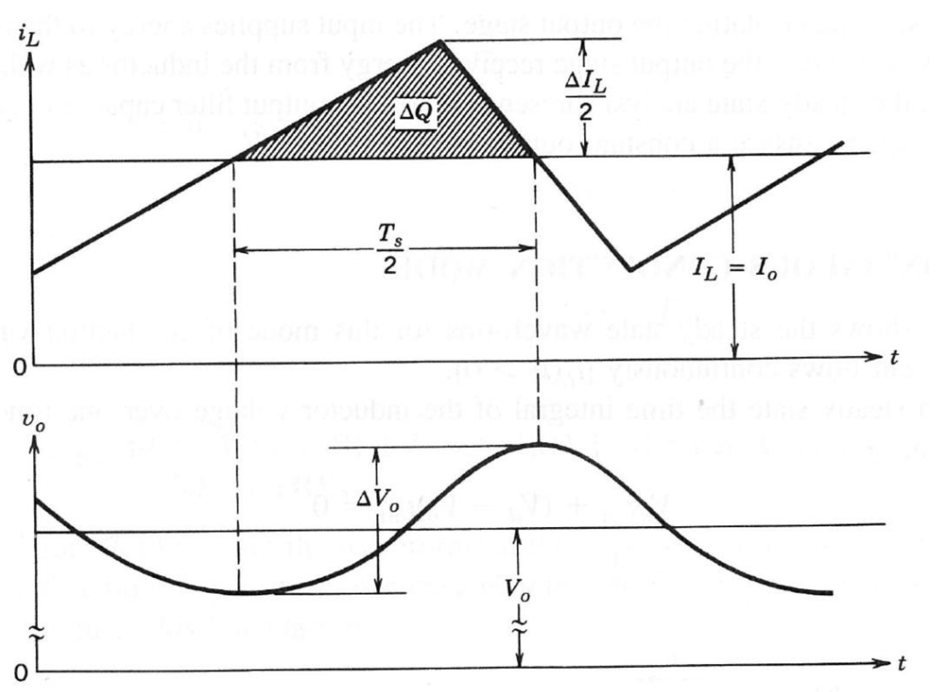


Source: [1]

Steady-State: Area A = Area B $$(V_d - V_0) \cdot t_{on} = V_0 \cdot (T_s - t_{on})$$

$$\frac{V_0}{V_d} = \frac{t_{on}}{T_s} = D$$

Buck Converter – Output Voltage



Source: [1]

$$\Delta V_0 = \frac{\Delta Q_0}{C} = \frac{1}{C}\cdot\frac{1}{2}\cdot\frac{\Delta I_L}{2}\cdot\frac{T_s}{2}$$

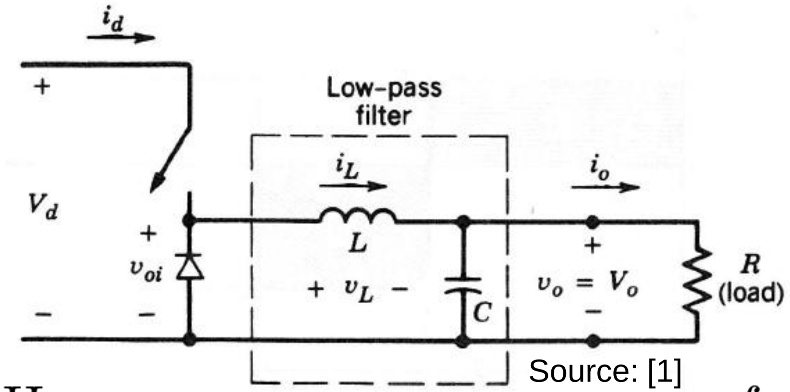
$$\Delta I_L = \frac{V_0}{L}\cdot(1-D)\cdot T_s$$

$$\Delta V_0 = \frac{T_s^2}{8C}\cdot\frac{V_0}{L}\cdot(1-D)$$

Buck Converter – Simulation Results

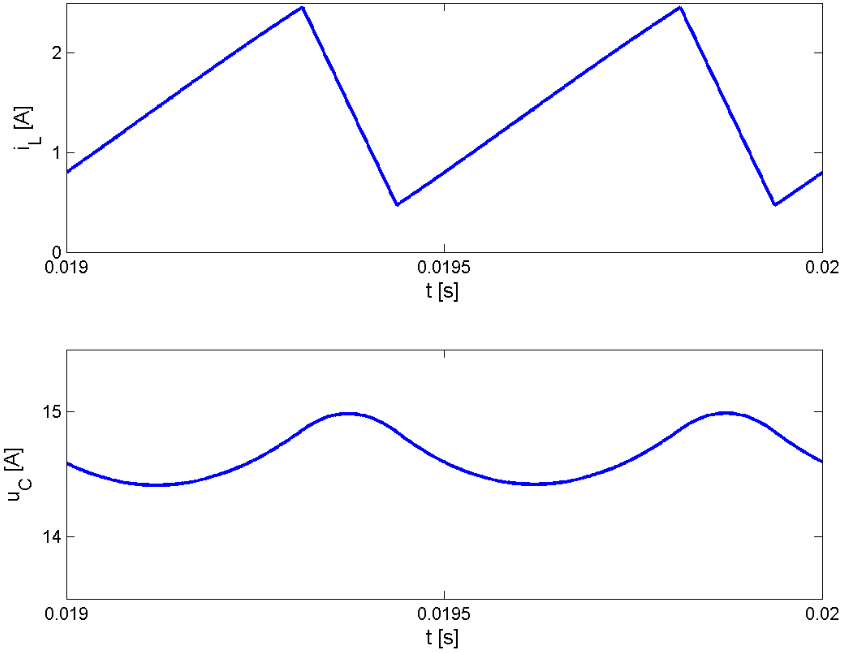
$$V_d = 20\ \mathrm{V}$$

$$D = 0.75$$

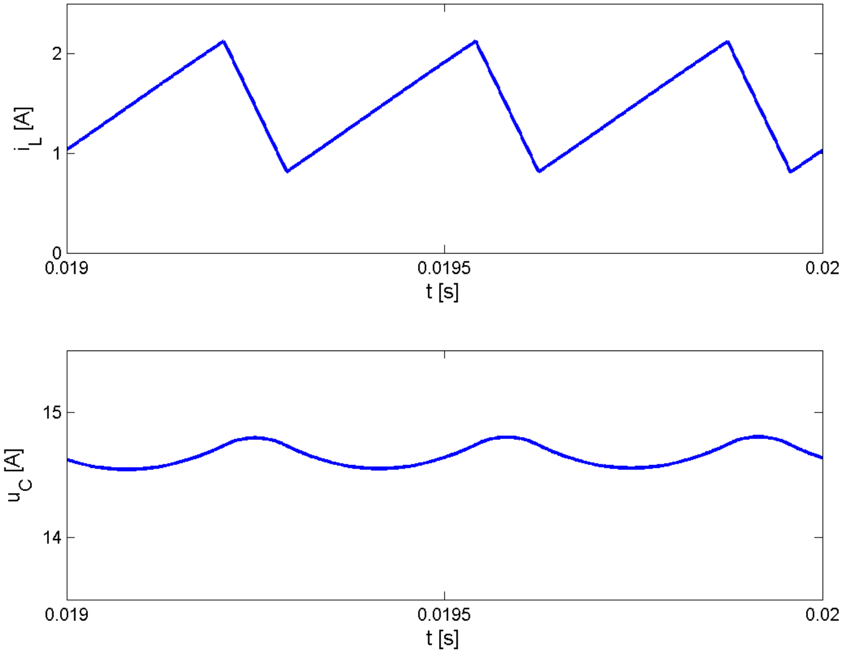


Source: [1]

$$f_s = 2\ \mathrm{kHz}$$

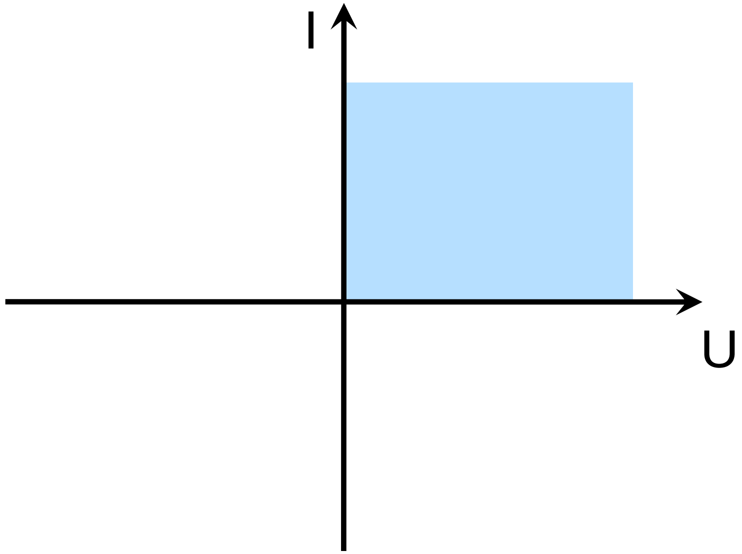


$$f_s = 3\ \mathrm{kHz}$$



Boost Converter

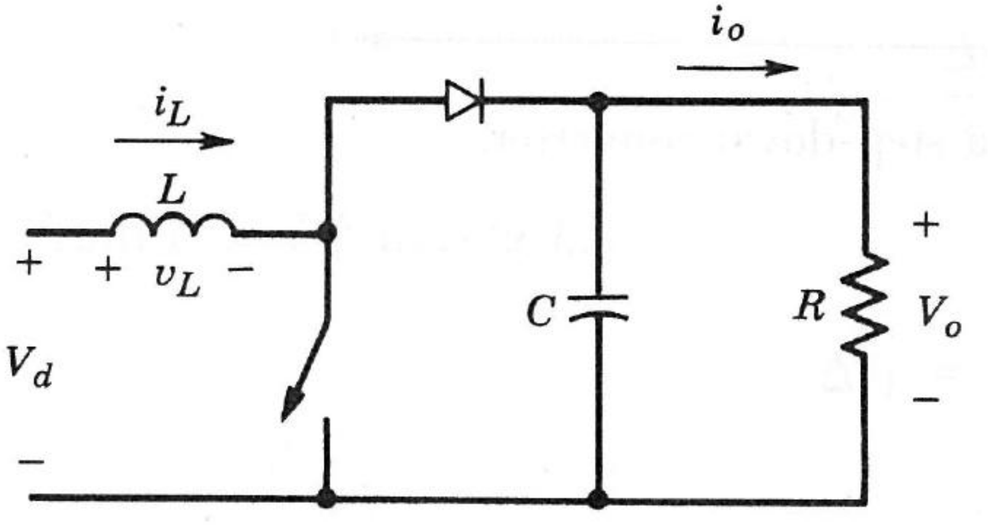
One-Quadrant Converter



Fields of Application:

- Unidirectional Coupling of Two On-Board Networks
- Connecting Components with Higher Voltage Level to a Lower Voltage On-Board Network

Boost Converter – Principle Circuit



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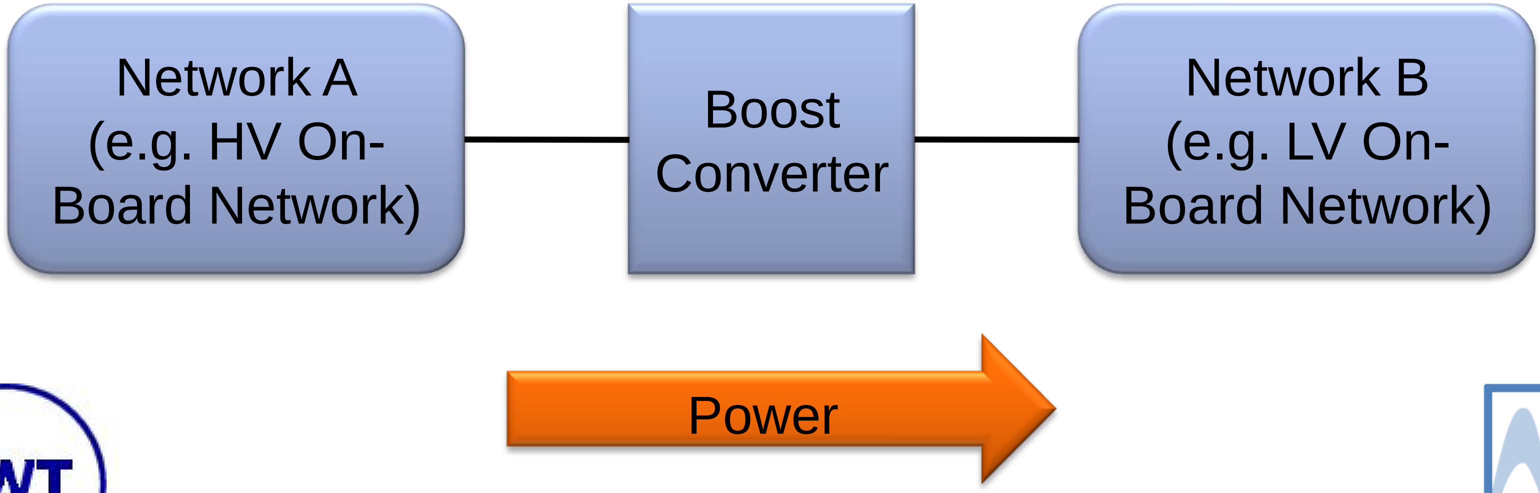


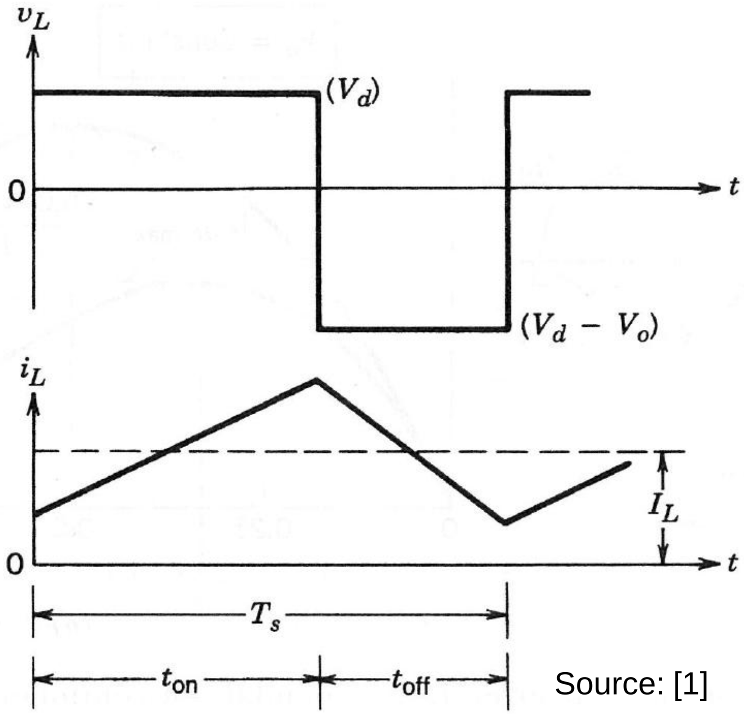
Network A (e.g. HV On-Board Network)

Boost Converter

Network B (e.g. LV On-Board Network)

Power

Boost Converter – Switching States



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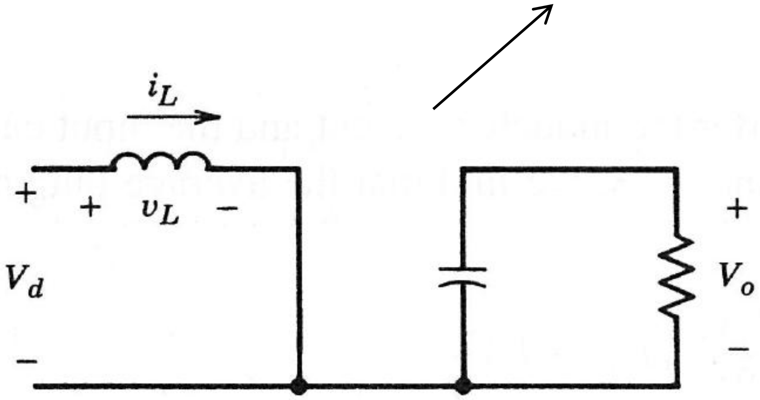
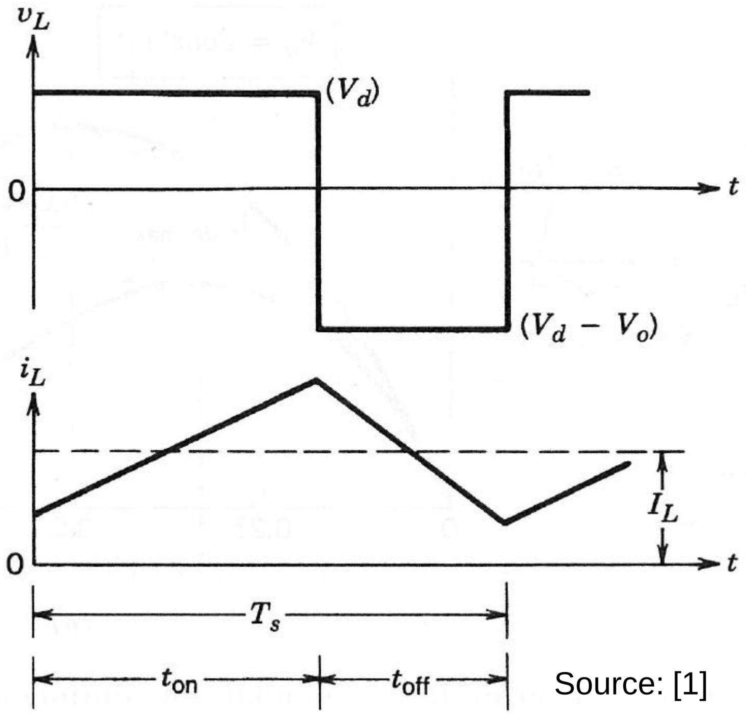


Source: [1]

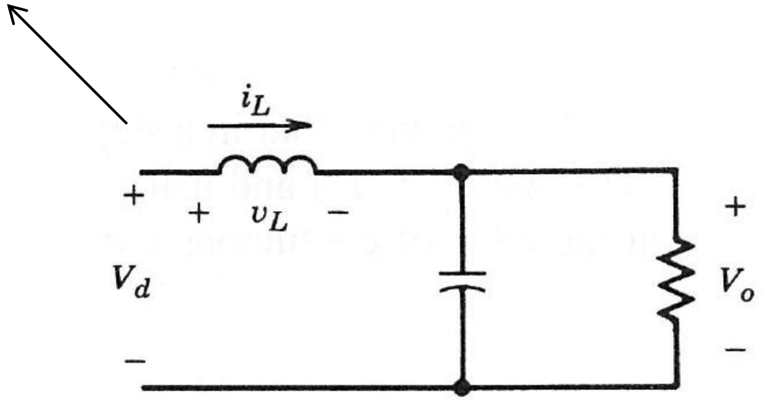
$$i_L(t) = I_{S,Bo} + \frac{V_d}{L} \cdot t$$

Boost Converter – Switching States



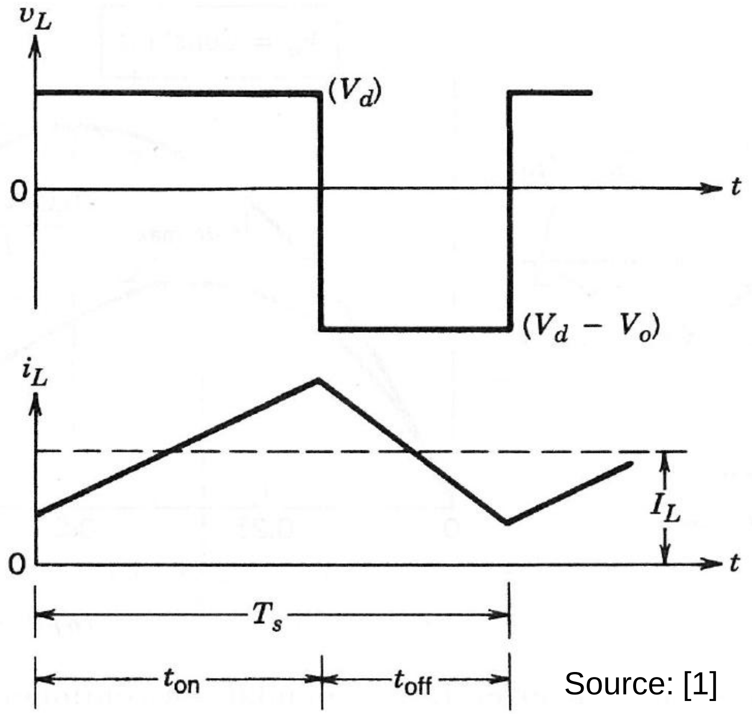
Source: [1]

$$i_L(t) = I_{S,Up} + \frac{V_d - V_0}{L} \cdot t$$



Source: [1]

Boost Converter – Switching States



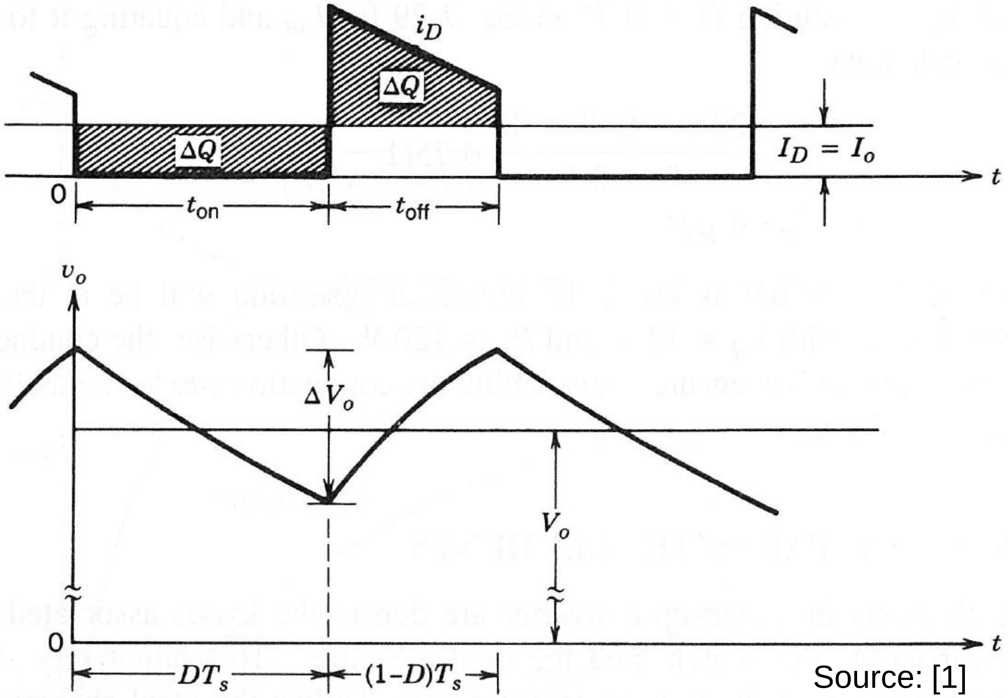
Source: [1]

Steady-State:

$$V_d \cdot t_{on} + (V_d - V_0) \cdot t_{off} = 0$$

$$\frac{V_0}{V_d} = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

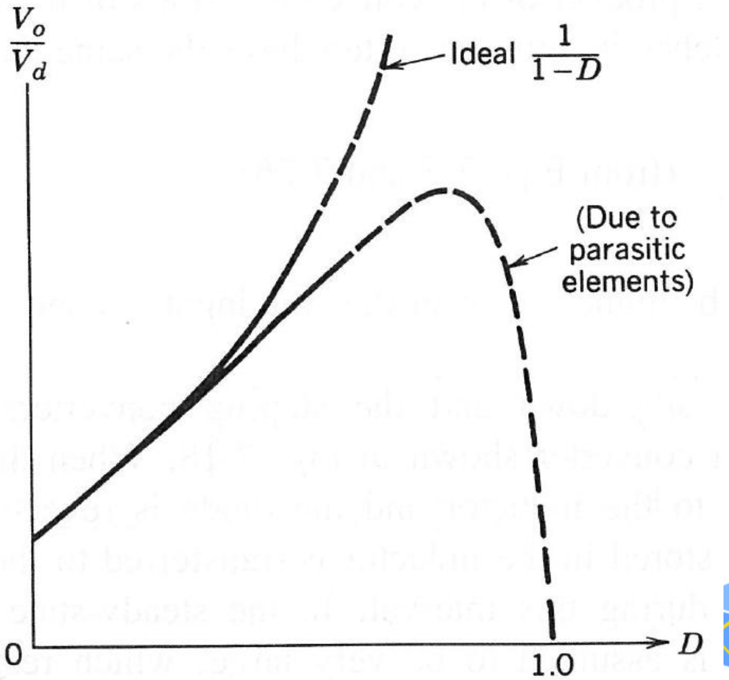
Boost Converter – Output Voltage



Source: [1]

$$\Delta V_0 = \frac{\Delta Q}{C} = \frac{I_0 \cdot D \cdot T_s}{C}$$

$$\Delta V_0 = \frac{V_0}{R} \cdot \frac{D \cdot T_s}{C}$$

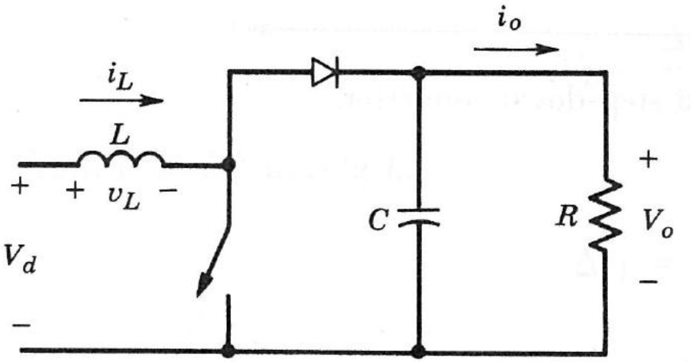


Source: [1]

Boost Converter – Simulation Results

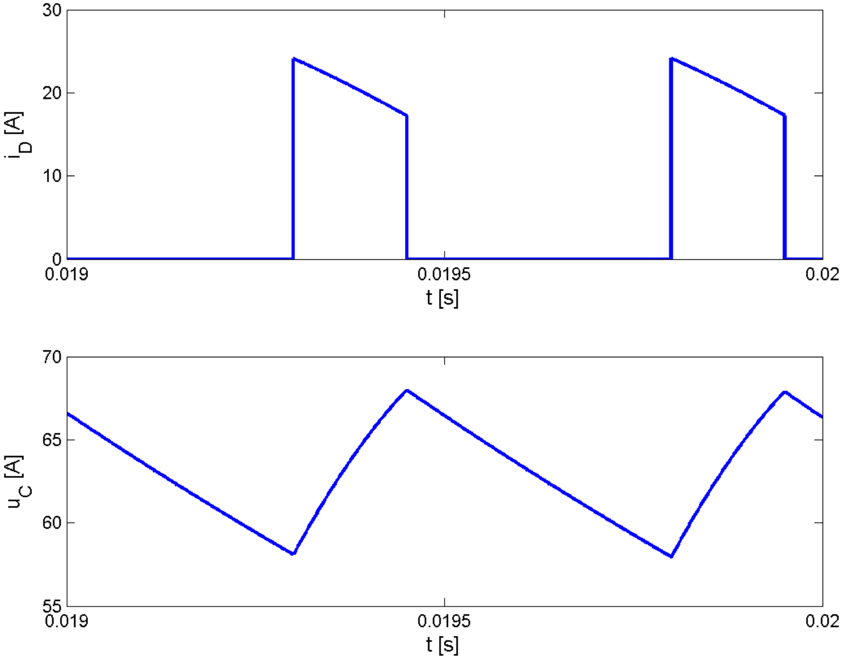
$$V_d = 20\ \mathrm{V}$$

$$D = 0.7$$

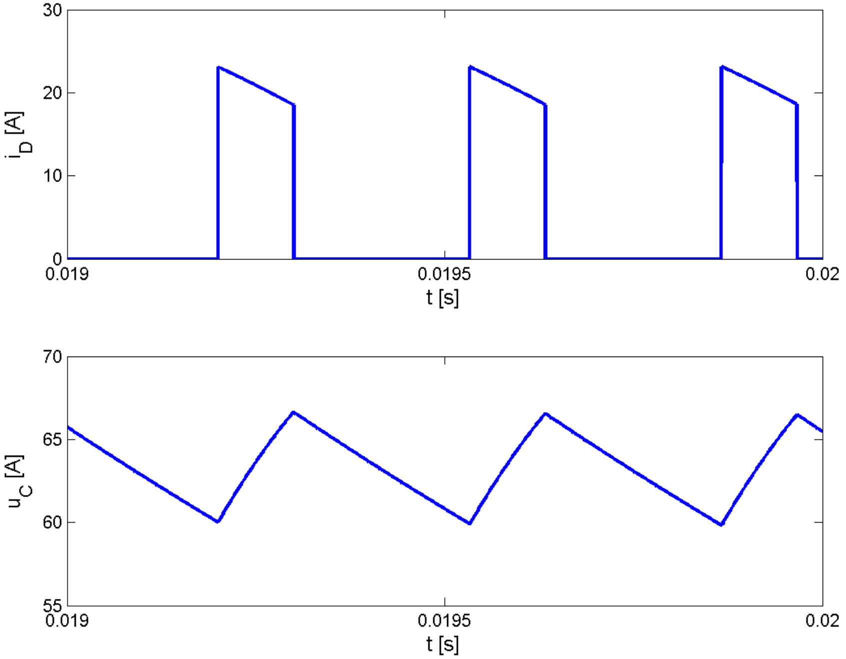


Source: [1]

$$f_s = 2\ \mathrm{kHz}$$

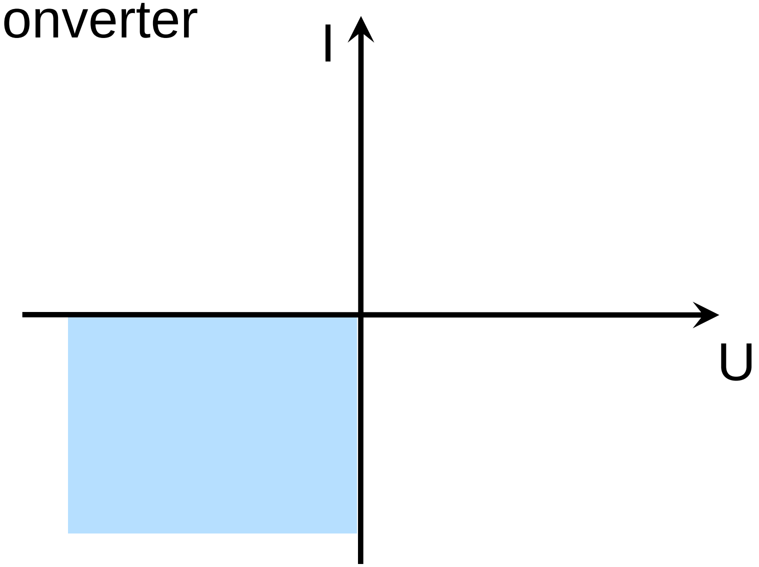


$$f_s = 3\ \mathrm{kHz}$$



Buck-Boost Converter

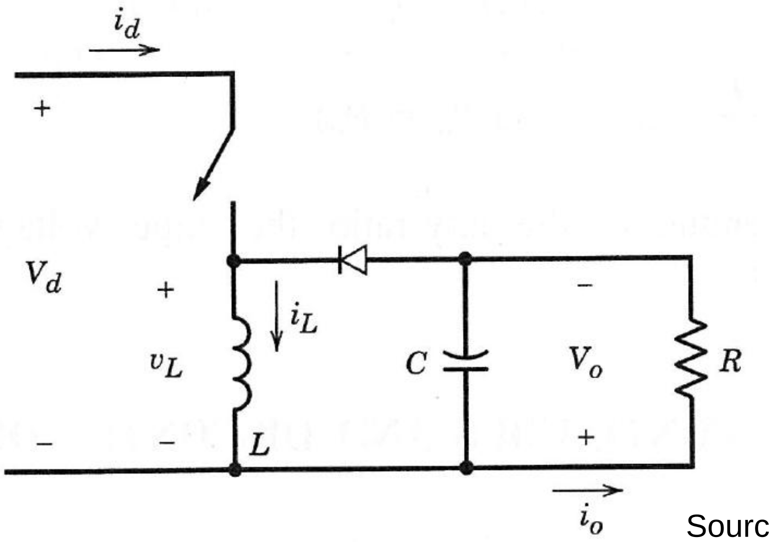
One-Quadrant Converter



Fields of Application:

- Voltage Inversion
- Connecting Components to a Lower/Higher Voltage On-Board Network

Buck-Boost Converter – Principle Circuit



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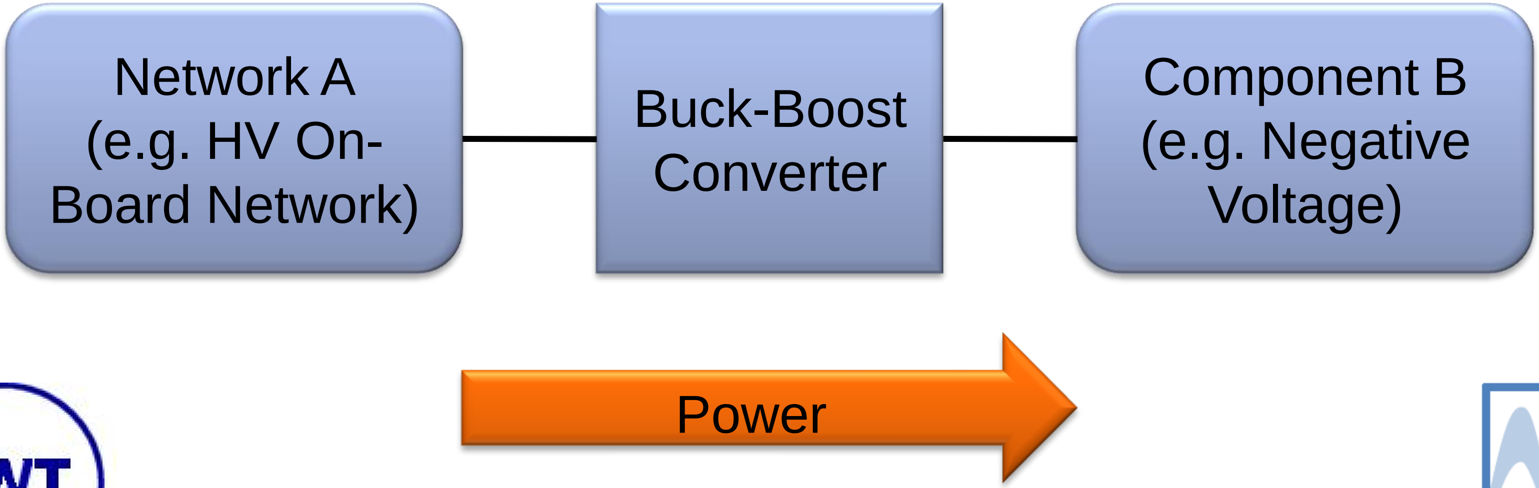


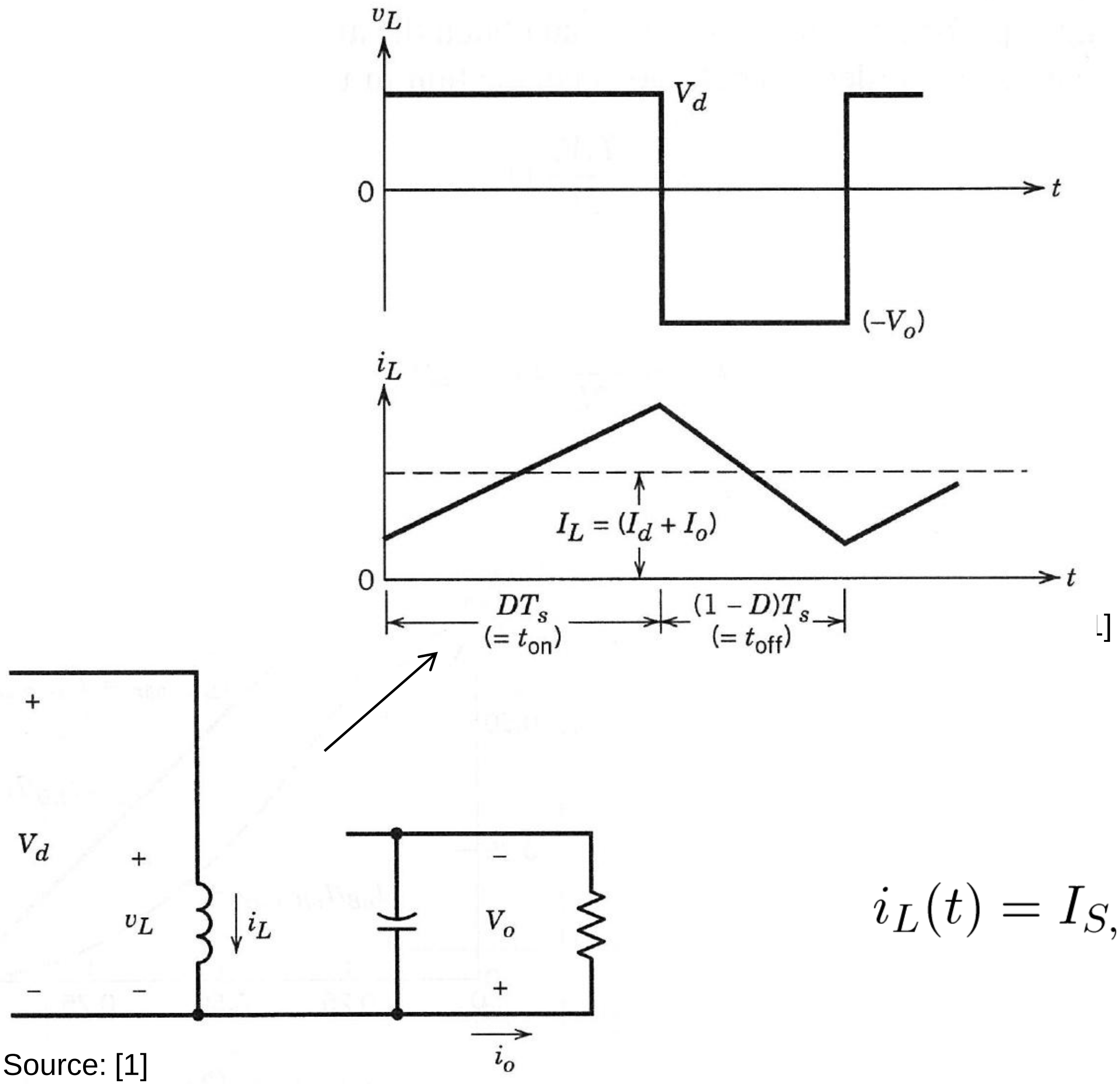
Network A (e.g. HV On-Board Network)

Buck-Boost Converter

Component B (e.g. Negative Voltage)

Power

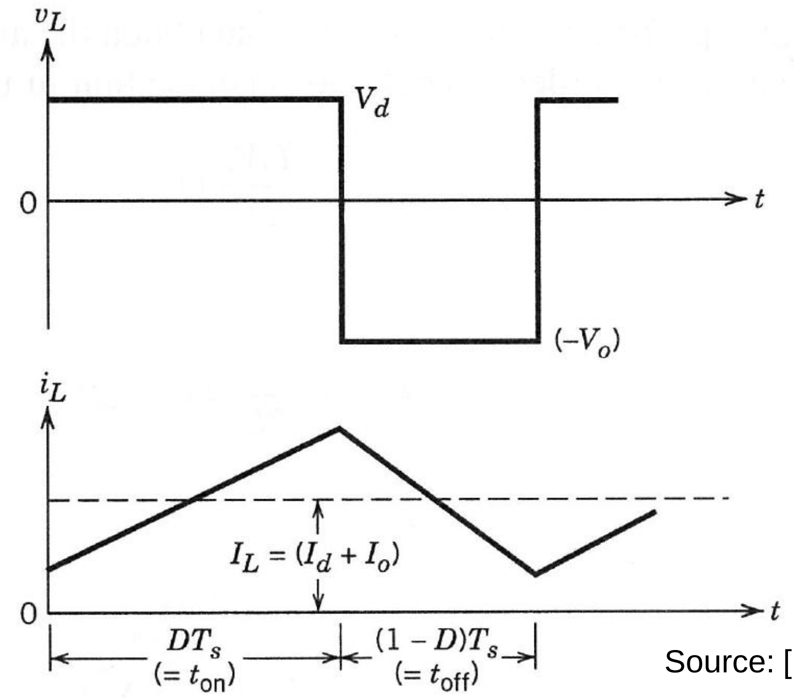
Buck-Boost Converter – Switching States



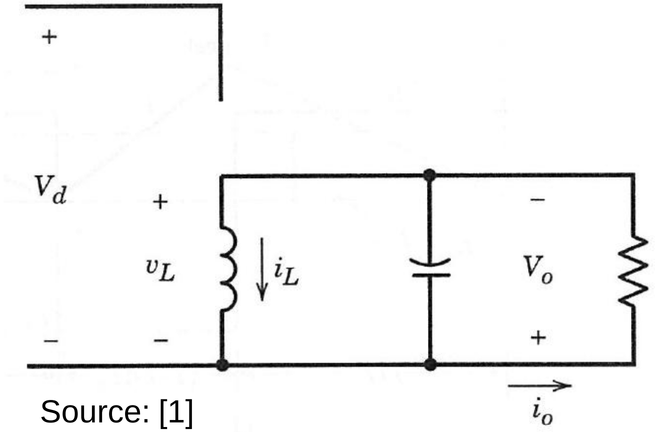
$$i_L(t) = I_{S,Bo} + \frac{V_d}{L} \cdot t$$

Source: [1]

Buck-Boost Converter – Switching States



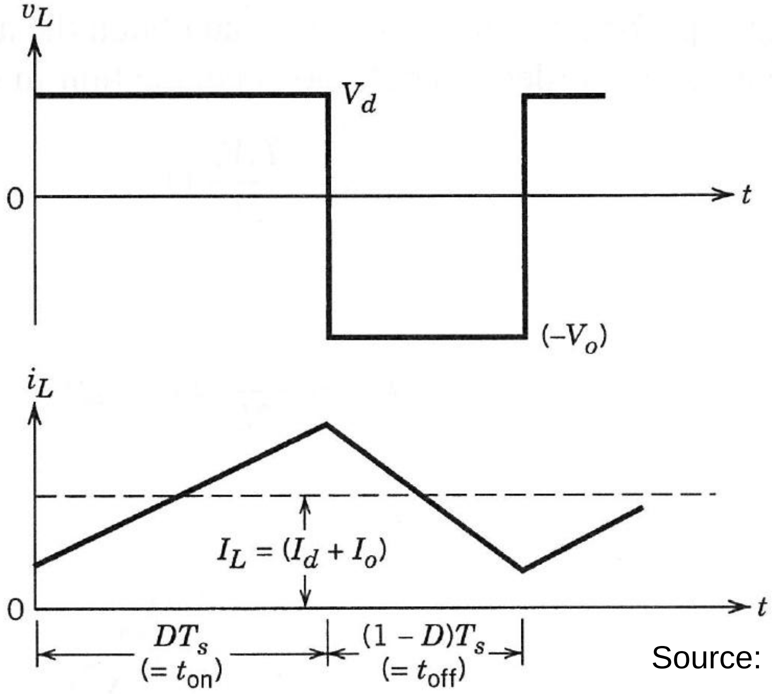
Source: [1]



Source: [1]

$$i_L(t) = I_{S,Up} + \frac{(-V_0)}{L} \cdot t$$

Buck-Boost Converter – Switching States

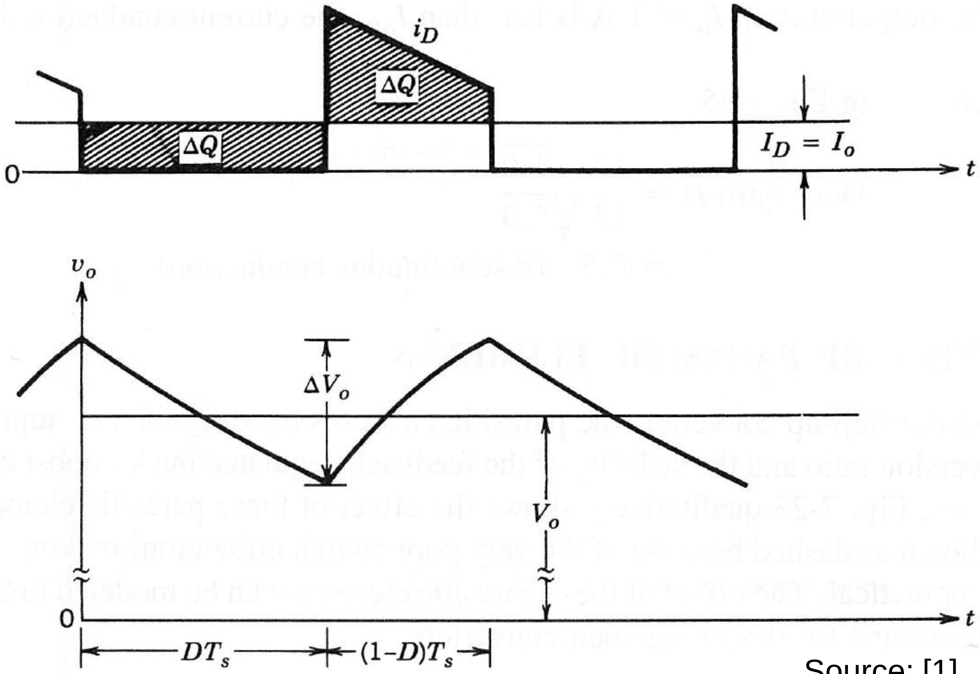


Source: [1]

Steady-State: $V_d \cdot D \cdot T_s + (-V_0) \cdot (1-D) \cdot T_s = 0$

$$\frac{V_0}{V_d} = \frac{D}{1-D}$$

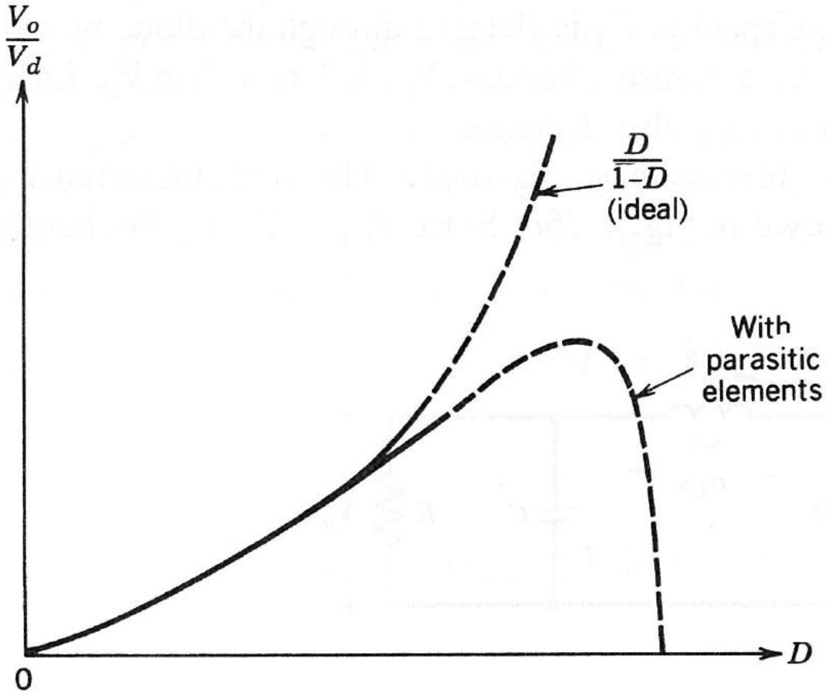
Buck-Boost Converter – Output Voltage



Source: [1]

$$\Delta V_0 = \frac{\Delta Q}{C} = \frac{I_0 \cdot D \cdot T_s}{C}$$

$$\Delta V_0 = \frac{V_0}{R} \cdot \frac{D \cdot T_s}{C}$$

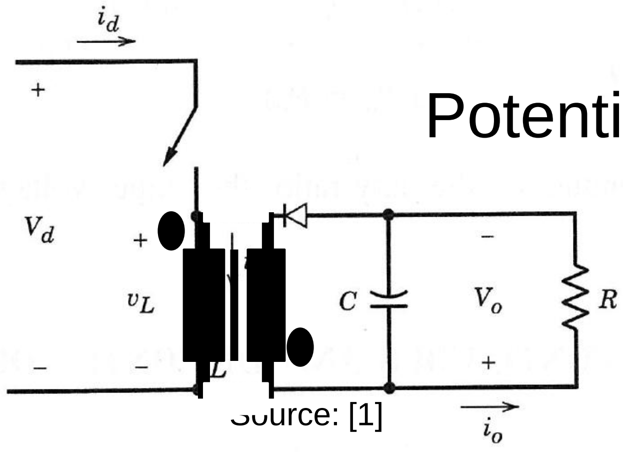


Source: [1]

Buck-Boost Converter – Simulation Results

$$V_d = 20 \text{ V}$$

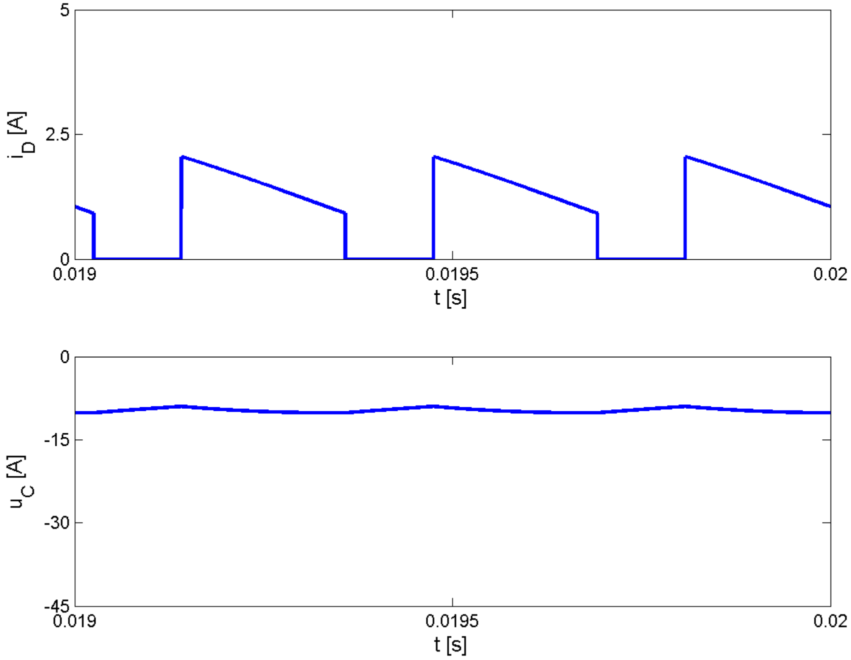
$$f_s = 3 \text{ kHz}$$



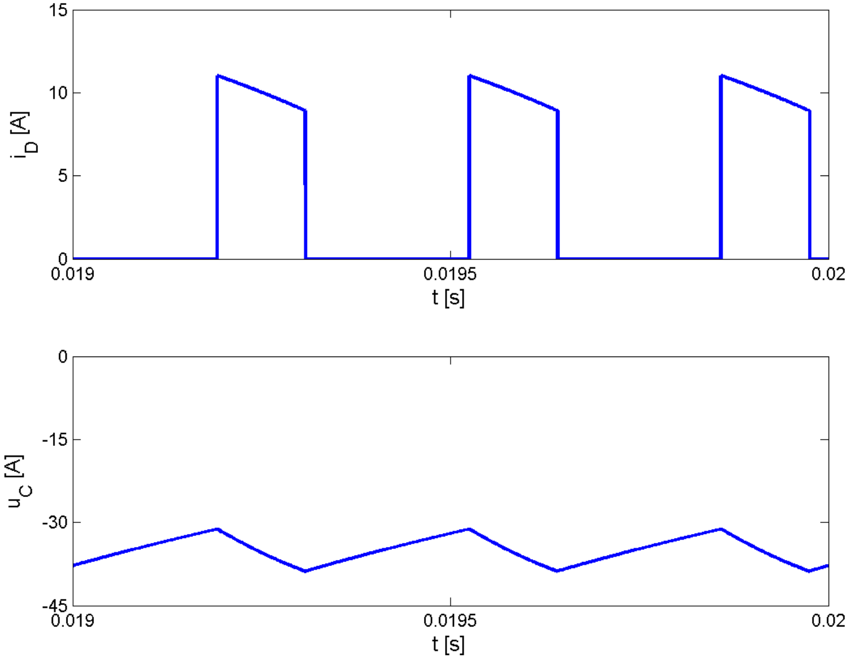
Source: [1]

Potentialtrennung ?

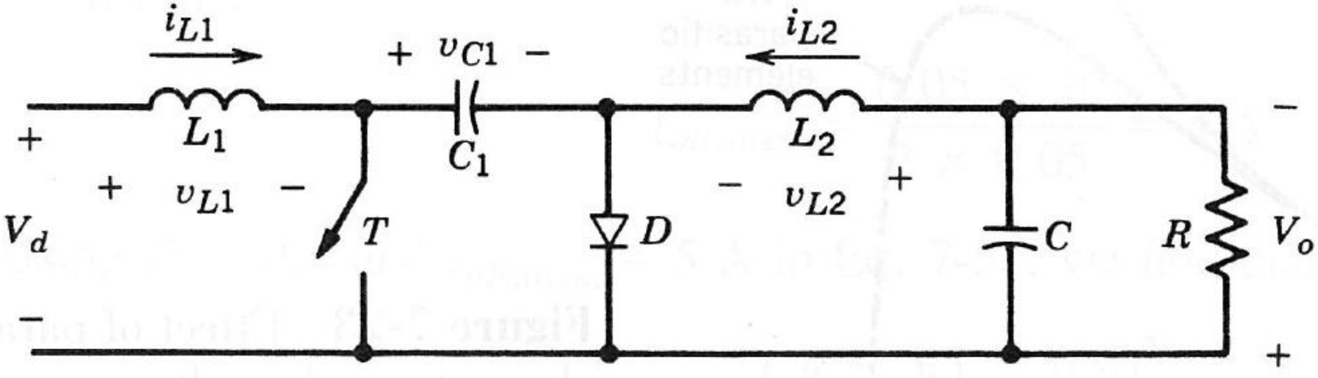
$D = 0.35$



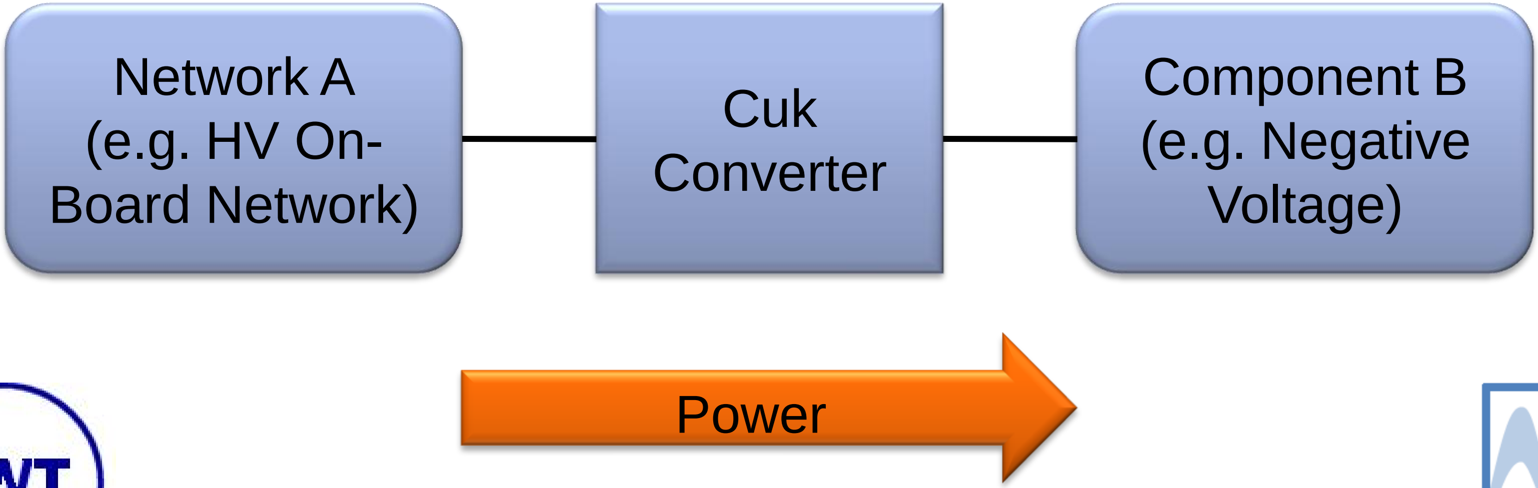
$D = 0.65$



Cuk Converter – Principle Circuit



Source: [1]



Network A (e.g. HV On-Board Network)

Cuk Converter

Component B (e.g. Negative Voltage)

Power

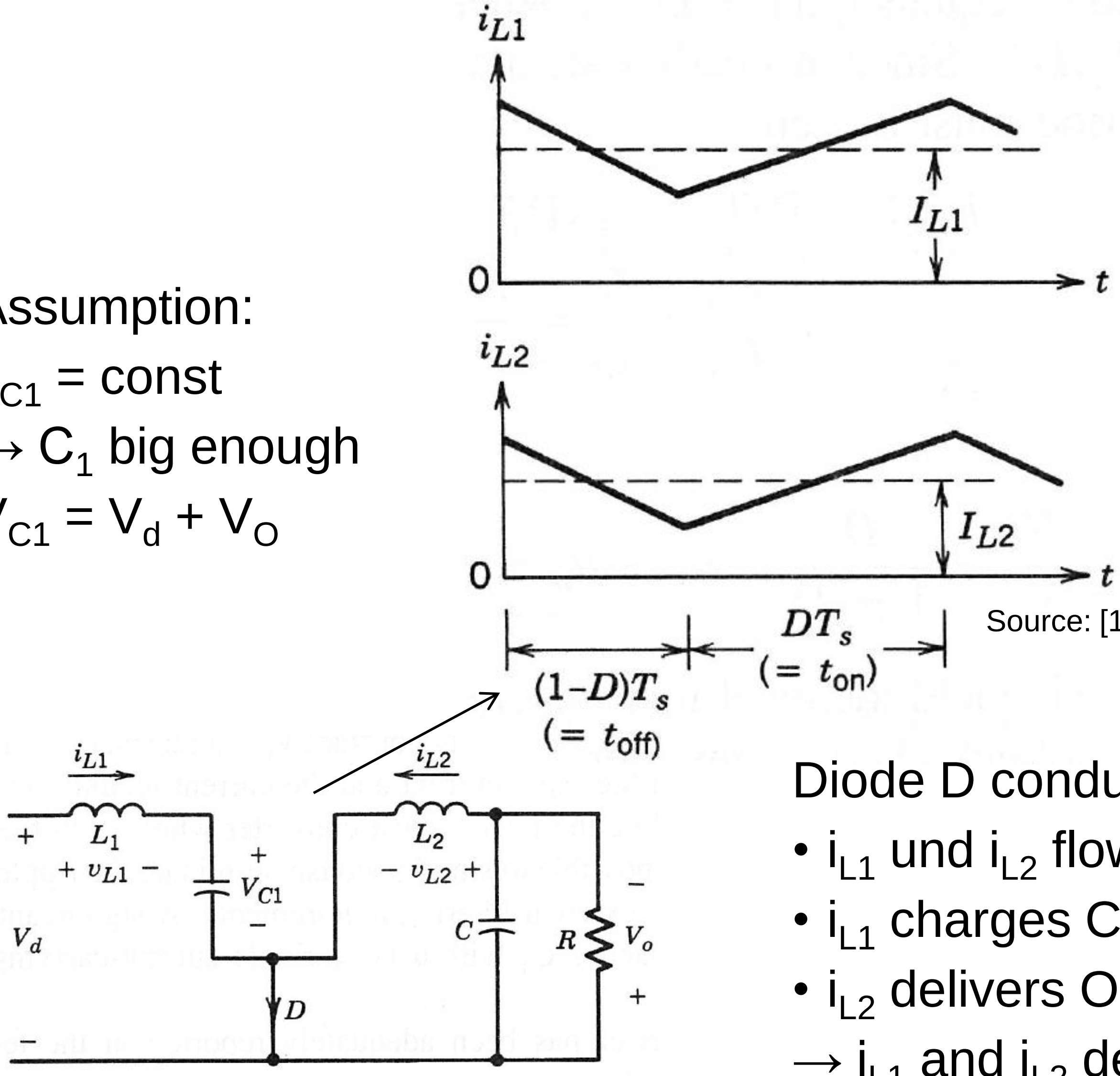
Cuk Converter – Switching States

Assumption:

v_{C1} = const

→ C_1 big enough

$V_{C1} = V_d + V_O$



Source: [1]

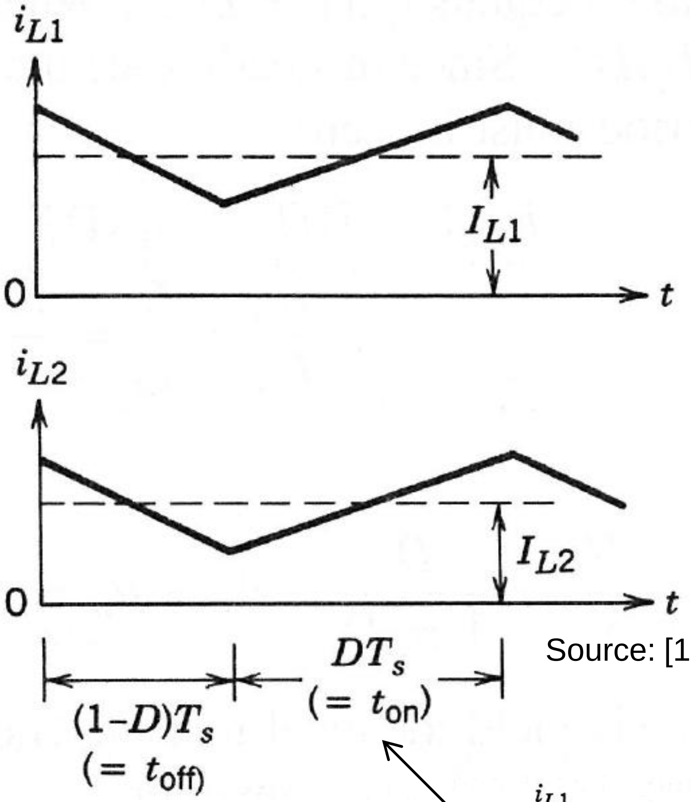
Source: [1]

Diode D conducting

- i_{L1} und i_{L2} flow through D
- i_{L1} charges C_1
- i_{L2} delivers Output Current

→ i_{L1} and i_{L2} decrease

Cuk Converter – Switching States



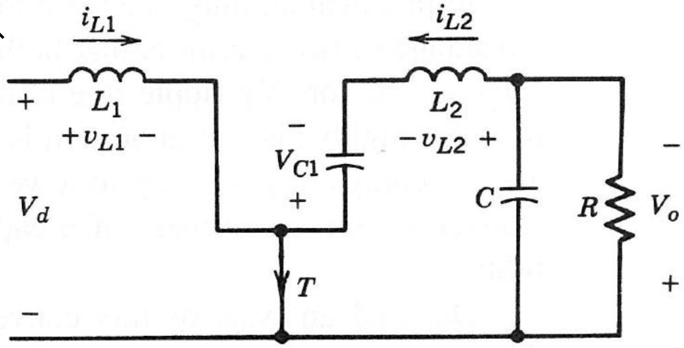
Source: [1]

Assumption:
v_{C1} = const
→ C_1 big enough
$V_{C1} = V_d + V_O$

Switch T conducting

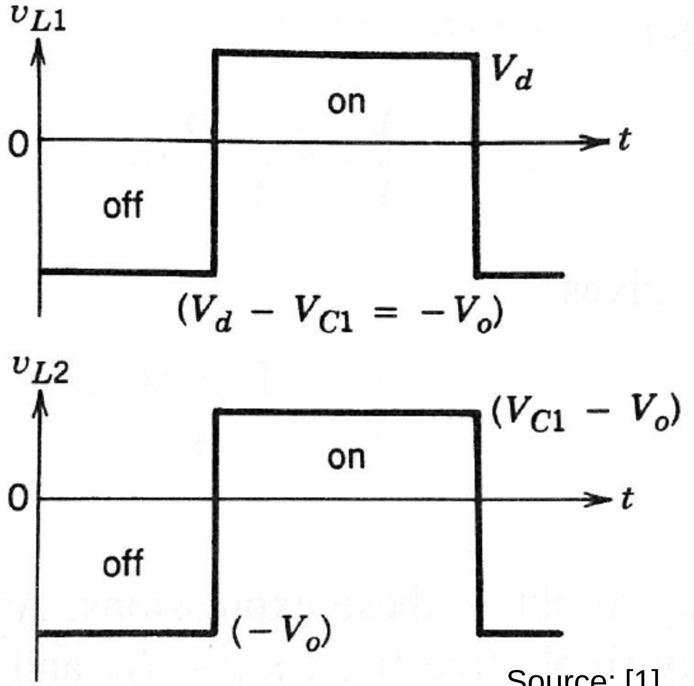
- i_{L1} and i_{L2} flow through T
- C_1 delivers Energy to Output and L_2
- Energy in L_1 rises

→ i_{L1} und i_{L2} increase



Source: [1]

Cuk Converter – Output Voltage



Source: [1]

Assumption:
v_{C1} = const
→ C_1 big enough
$V_{C1} = V_d + V_O$

$$V_d \cdot D \cdot T_s + (V_d - V_{C1})(1-D) \cdot T_s = 0$$

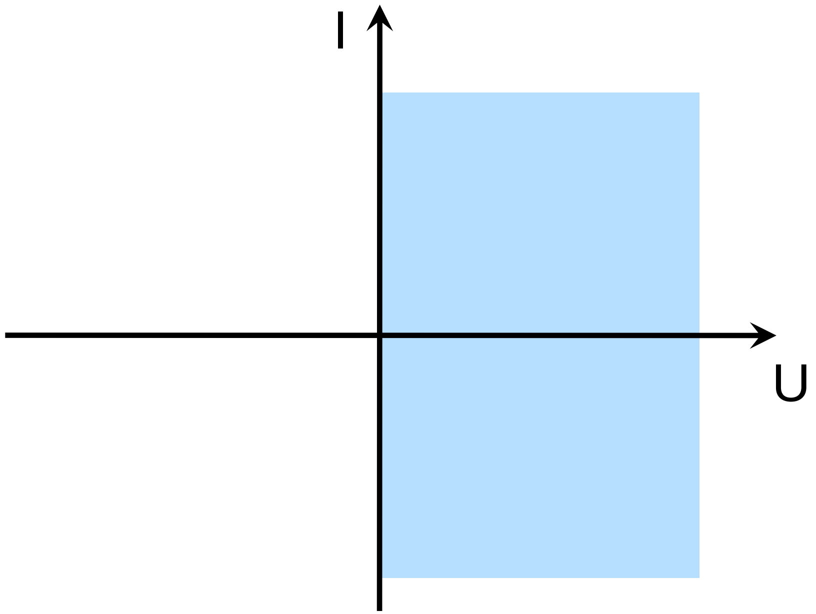
$$V_{C1} = \frac{1}{1-D} \cdot V_d$$

$$(V_{C1} - V_0) \cdot D \cdot T_s + (-V_0)(1-D) \cdot T_s = 0$$

$$V_{C1} = \frac{1}{D} \cdot V_0$$

$$\frac{V_0}{V_d} = \frac{D}{1-D}$$

Two-Quadrant Converters

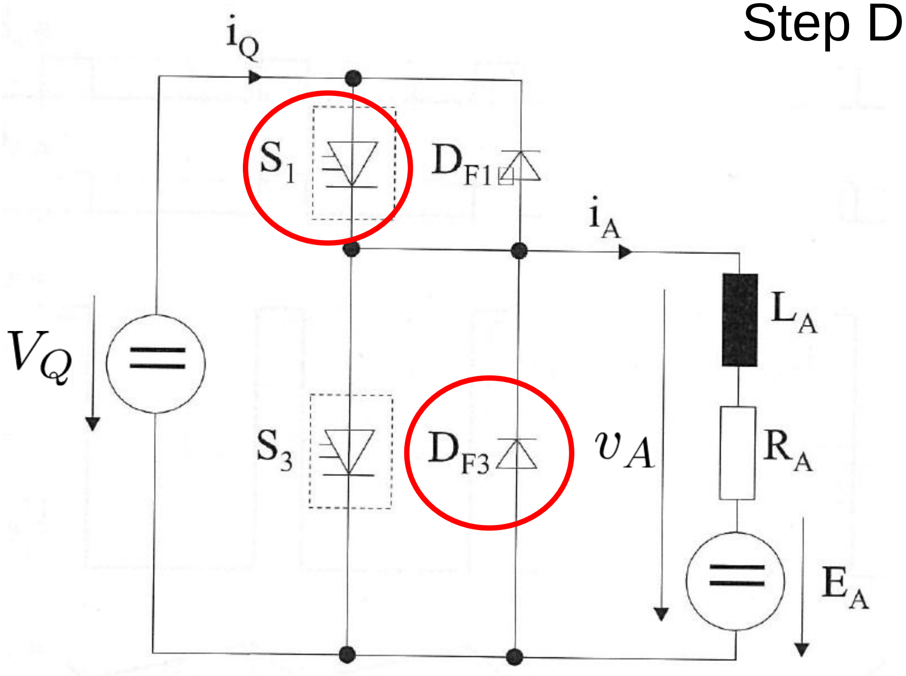


Fields of Application:

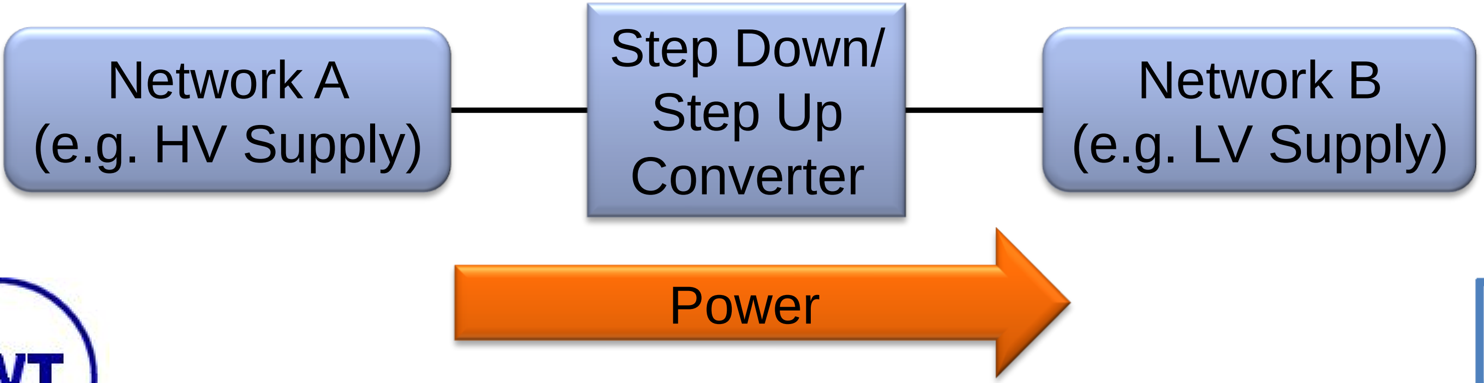
- Bidirectional Coupling of Two On-Board Networks
- Connecting Components with Lower Voltage Level to a Higher Voltage On-Board Network
- Current Inversion
- **Step Up-Step Down Converter**

Two-Quadrant Converters – Principle Circuit

Step Down Mode



Source: [2]



Network A
(e.g. HV Supply)

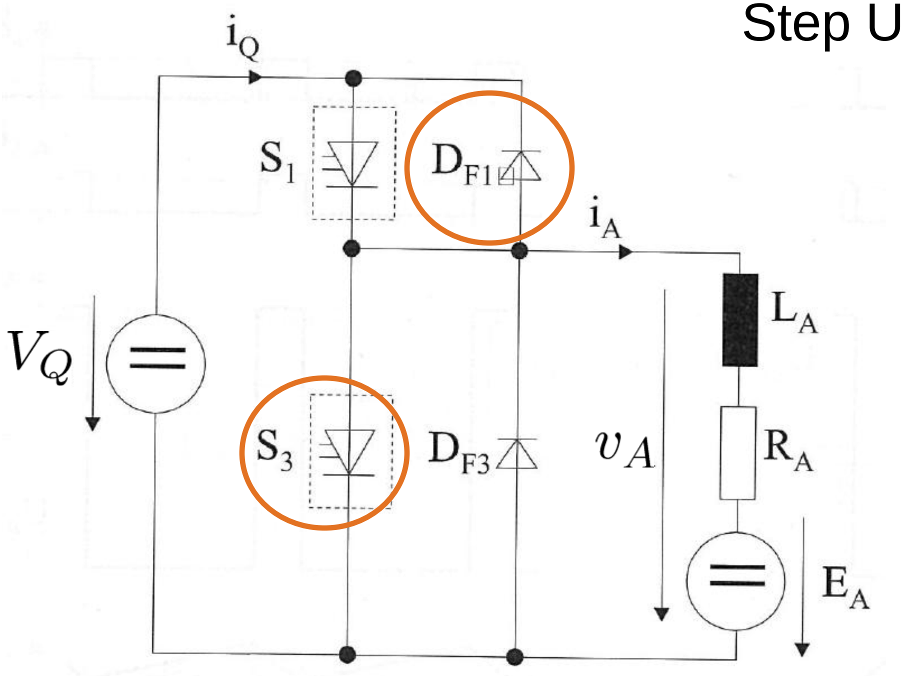
Step Down/
Step Up
Converter

Network B
(e.g. LV Supply)

Power

Two-Quadrant Converters – Principle Circuit

Step Up Mode



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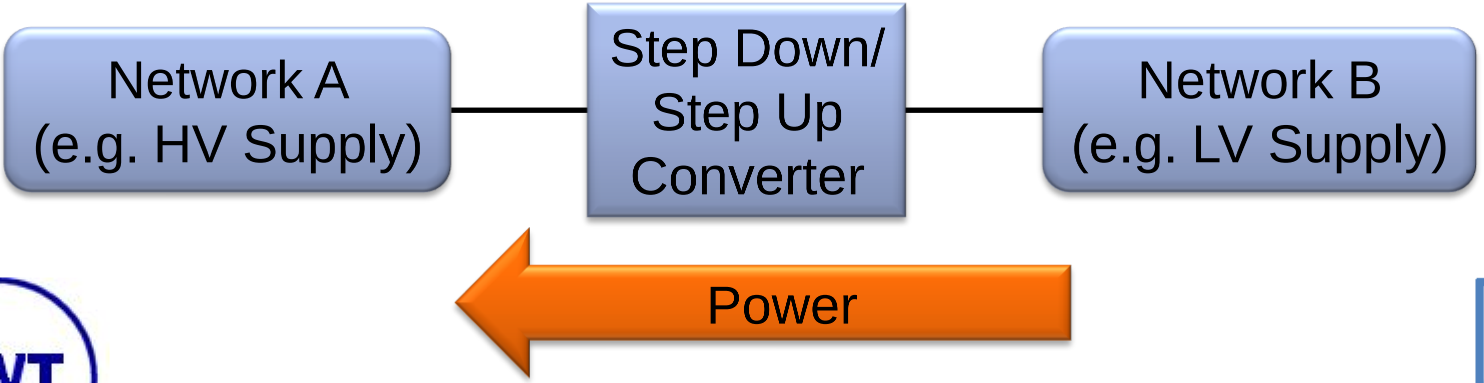


Network A
(e.g. HV Supply)

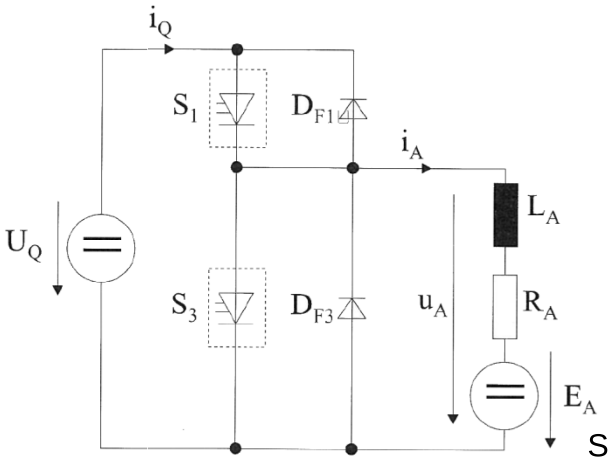
Step Down/
Step Up
Converter

Network B
(e.g. LV Supply)

Power

Step Down/Step Up Converter – Simulation

$$V_Q = 100\ \mathrm{V}$$
$$E_A = 50\ \mathrm{V}$$
$$f_s = 2\ \mathrm{kHz}$$



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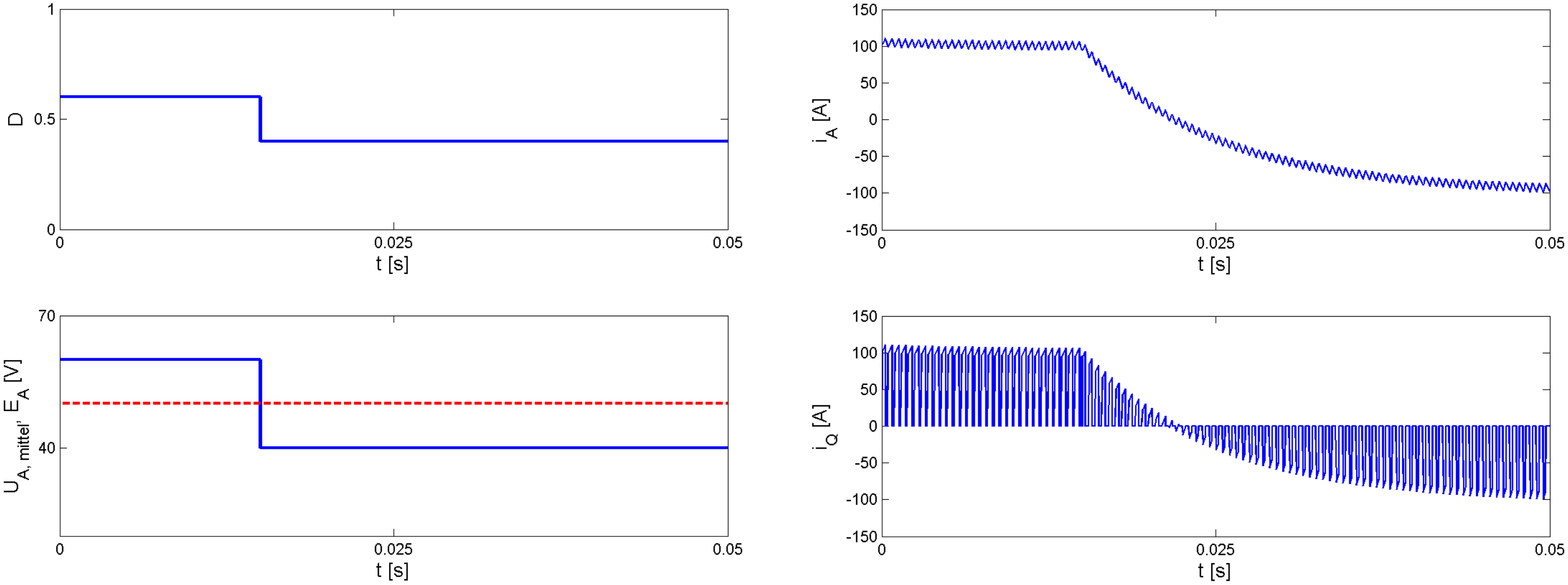
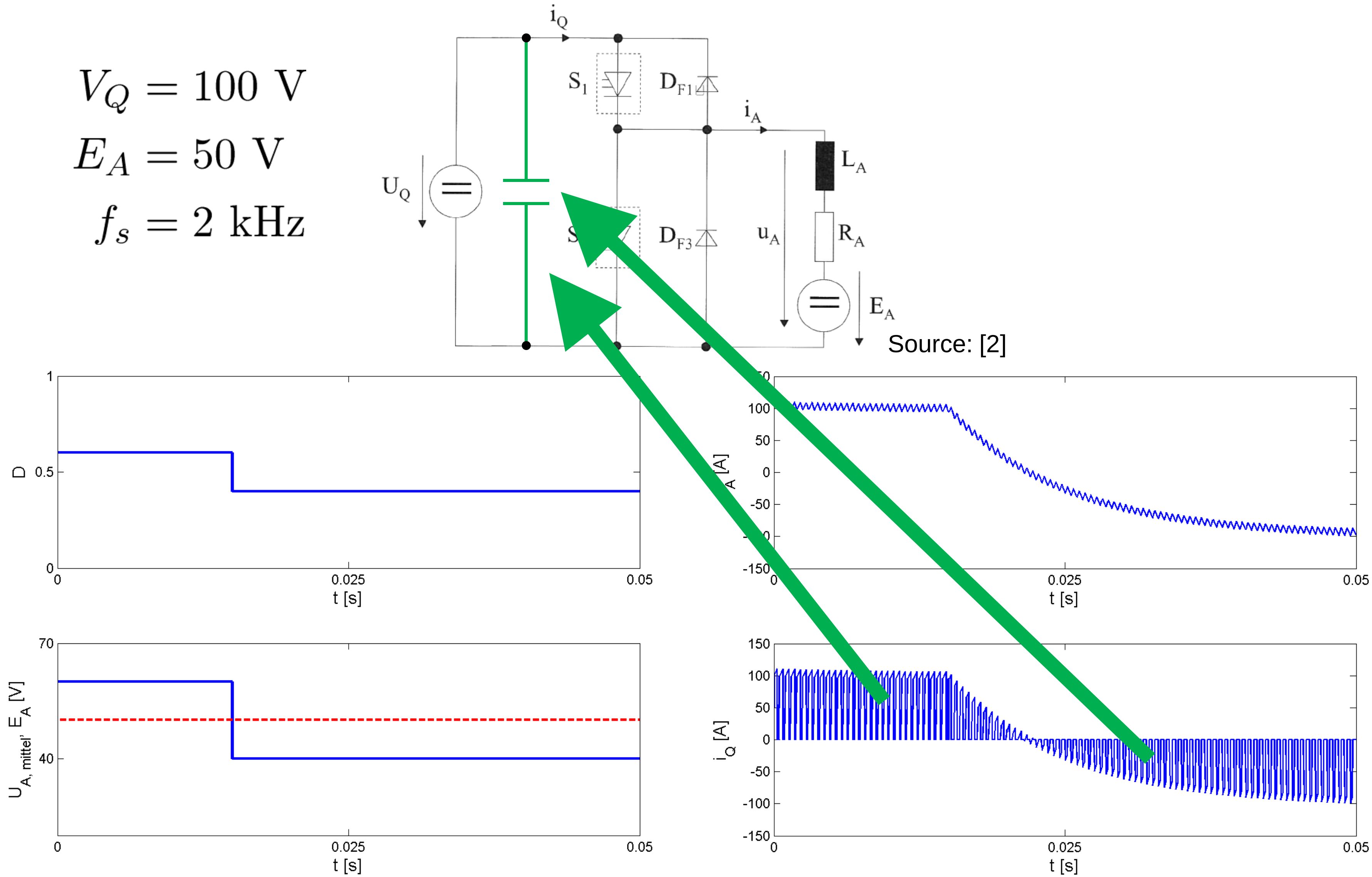


Step Down/Step Up Converter – Simulation

$$V_Q = 100\ \text{V}$$

$$E_A = 50\ \text{V}$$

$$f_s = 2\ \text{kHz}$$



Source: [2]

Step Down/Step Up Conv. – Requirements

Limited at High Power because of

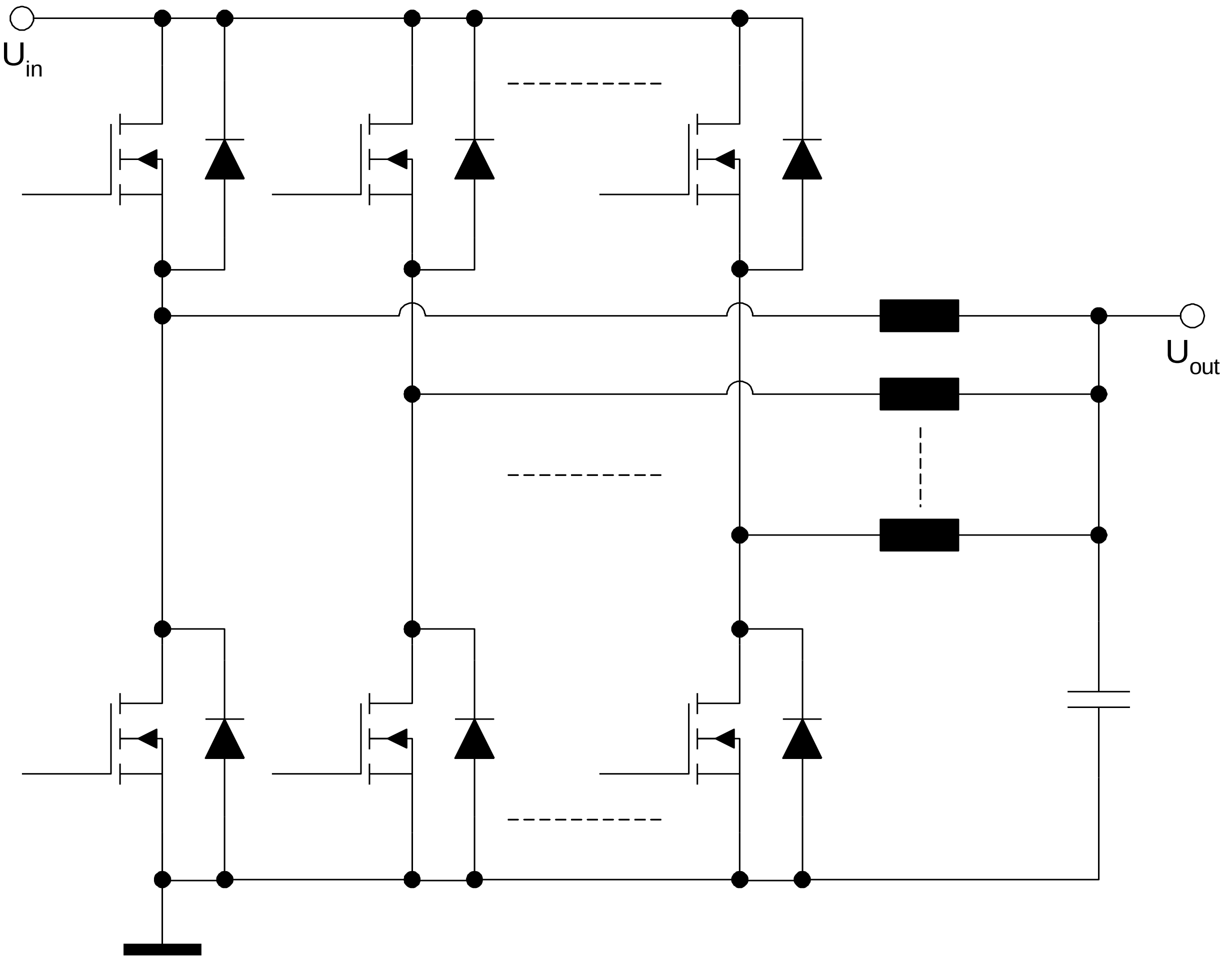
- Slow Switching of Large Semiconductor Devices
- Large Smoothing Inductances (due to High Current)
- High Ripple Current Stress in Smoothing Capacitor

Cost-Intensive Passive Components

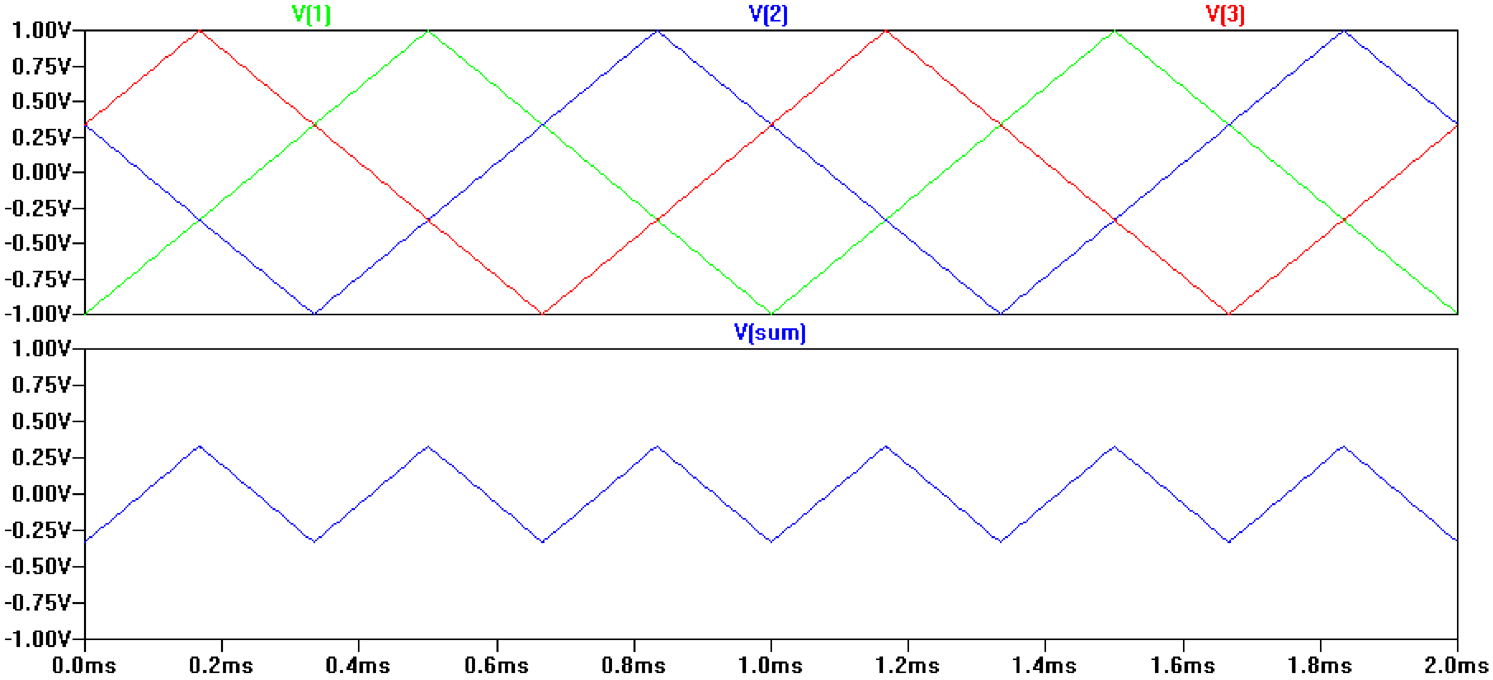
→ „Silicon instead of Passives“

→ Multi-phase DC/DC Converter

Half-Bridge – Multi-Phase Approach



Multi-Phase Approach



Ripple-Current Superposition of Individual Phases

Multi-Phase Approach – Pros & Cons

Advantages:

+ Less Current per Phase

+ Higher Modulation Frequency

+ Higher Effective Modulation Frequency by Phase-Shift in PWM Triggering

→ Compact and Cheap Set-Up

+ Modular Design possible

Disadvantages:

– Risk of Ring Currents

– Asymmetrical Phase Currents

Balancing Alternatives:

- Series Resistors
- Central Control
- Master-Slave Approaches
- Magnetically Coupled Coils
- Fuzzy Logic

DC/DC Converter – Losses

Ohmic Losses:

$$P_\Omega = R \cdot I_{out}^2$$

Switching Losses:

$$P_S = {}^1/_2 \cdot V_{out} \cdot I_{out} \cdot (t_1 + t_2) \cdot f_S$$

On-State Power Losses Transistor:

$$P_{rdson} = R_{ds} \cdot I_{in}^2$$

Gate-Triggering:

$$P_{gate} = Q_{gate} \cdot V_{gs} \cdot f_S$$

On-State Power Losses Diode:

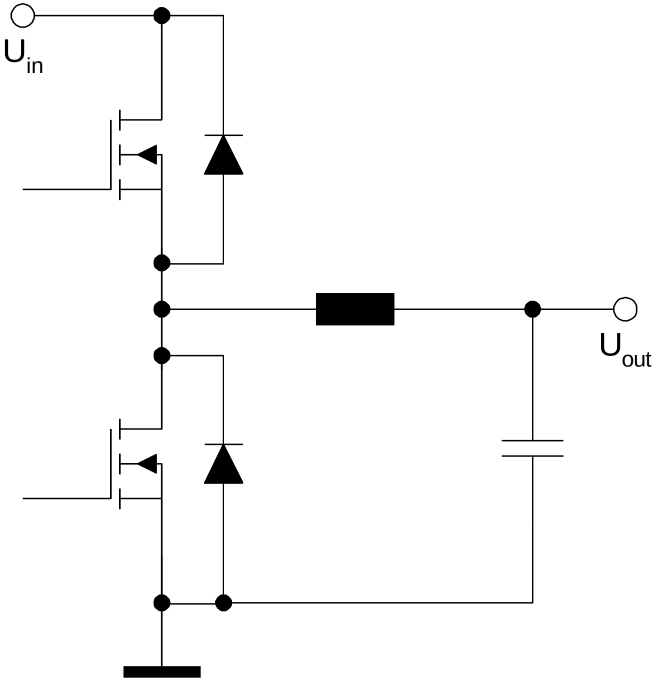
$$P_d = V_d \cdot I_{out} + R_d \cdot I_{out}^2$$

Reverse Recovery Diode:

$$P_{rr} = (I_{out} \cdot t_{rr} + Q_{rr}) \cdot V_{in} \cdot f_S$$

Total:

$$P_\Sigma = P_\Omega + P_S + P_{rdson} + P_{gate} + P_d + P_{rr}$$



Example: 2Q Converter

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