Power Electronics

DC/DC Converter Fundamentals

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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

- Internal Combustion Engine
- Clutch
- Electrical Machine
- Automatic Transmission
- Rear-axle Differential
- Inverter
- DC Converter
  - Supply System: 12 V
  - Energy Storage: 150 V..300 V
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

Network A (e.g. HV On-Board Network) → Buck Converter → Network B (e.g. LV On-Board Network)

Source: [1]

Power
Buck Converter – Switching States

Assumption:
\[ V_O = \text{const.} \]
\[ T_s = t_{on} + t_{off} \]

\[ i_L(t) = I_{S,Bo} + \frac{V_d - V_0}{L} \cdot t \]
Buck Converter – Switching States

Assumption:
\[ V_O = \text{const.} \]
\[ T_s = t_{on} + t_{off} \]

\[ i_L(t) = I_{S,U} + \left( -\frac{V_0}{L} \right) \cdot t \]

Source: [1]
Buck Converter – Switching States

Assumption:

\[ V_0 = \text{const.} \]

\[ T_s = t_{on} + t_{off} \]

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

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

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

Source: [1]
Buck Converter – Simulation Results

\[ V_d = 20 \text{ V} \]
\[ D = 0.75 \]

\[ f_s = 2 \text{ kHz} \]
\[ f_s = 3 \text{ kHz} \]

Source: [1]
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

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

Boost Converter

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

Source: [1]
Boost Converter – Switching States

\[ i_L(t) = I_{S,Bo} + \frac{V_d}{L} \cdot t \]
Boost Converter – Switching States

\[ i_L(t) = I_{SL} + \frac{V_d - V_0}{L} \cdot t \]
Boost Converter – Switching States

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**

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

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

Source: [1]
Boost Converter – Simulation Results

\[ V_d = 20 \text{ V} \]
\[ D = 0.7 \]

\[ f_s = 2 \text{ kHz} \quad f_s = 3 \text{ kHz} \]

Source: [1]
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

Network A (e.g. HV On-Board Network) → Buck-Boost Converter → Component B (e.g. Negative Voltage)

Source: [1]
Buck-Boost Converter – Switching States

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

Source: [1]
Buck-Boost Converter – Switching States

\[ i_L(t) = I_{S,U_P} + \frac{(-V_0)}{L} \cdot t \]

Source: [1]
Buck-Boost Converter – Switching States

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

\[
\frac{V_0}{V_d} = \frac{D}{1 - D}
\]

Source: [1]
Buck-Boost Converter – Output Voltage

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

\[ \Delta V_0 = \frac{V_0}{R} \cdot \frac{D \cdot T_s}{C} \]
Buck-Boost Converter – Simulation Results

\[ V_d = 20 \text{ V} \]
\[ f_s = 3 \text{ kHz} \]

\[ D = 0.35 \]
\[ D = 0.65 \]

Potentialtrennung?
Cuk Converter – Switching States

Assumption:
\[ v_{C1} = \text{const} \rightarrow C_1 \text{ big enough} \]
\[ V_{C1} = V_d + V_O \]

Diode D conducting
- \( i_{L1} \) and \( i_{L2} \) flow through D
- \( i_{L1} \) charges \( C_1 \)
- \( i_{L2} \) delivers Output Current
- \( i_{L1} \) and \( i_{L2} \) decrease

Source: [1]
Cuk Converter – Switching States

Assumption:
\( v_{C1} = \text{const} \)
→ \( C_1 \) 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
→ \( i_{L1} \) and \( i_{L2} \) increase

Source: [1]
Cuk Converter – Output Voltage

Assumption:

\( v_{C1} = \text{const} \)

\( \rightarrow \) \( C_1 \) big enough

\( V_{C1} = V_d + V_O \)

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

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

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

\[
V_{C1} = \frac{1}{D} \cdot V_0
\]

\[
\frac{V_0}{V_d} = \frac{D}{1 - D}
\]

Source: [1]
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

Network A (e.g. HV Supply) → Step Down/Step Up Converter → Network B (e.g. LV Supply)

Source: [2]
Two-Quadrant Converters – Principle Circuit

Step Up Mode

Network A
(e.g. HV Supply)

Step Down/Step Up
Converter

Network B
(e.g. LV Supply)

Source: [2]
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 Converter – Simulation

\[ V_Q = 100 \, \text{V} \]
\[ E_A = 50 \, \text{V} \]
\[ f_s = 2 \, \text{kHz} \]

Source: [2]
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:

\[ P_S = \frac{1}{2} \cdot V_{out} \cdot I_{out} \cdot (t_1 + t_2) \cdot f_S \]

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
References

[1] N. Mohan, T. Undeland, W. Robbins,

[2] D. Schröder,