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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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Lecture outline

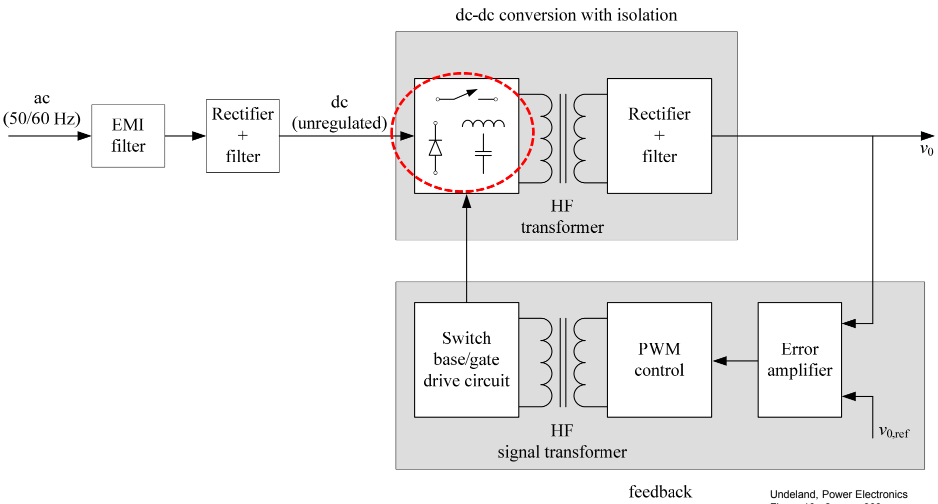
Step-Down (Buck) DC/DC converter

- The step-down converter
  - ❖ Continuous conduction mode (CCM)
  - ❖ Discontinuous conduction mode (DCM)
  - ❖ Boundary conditions between CCM and DCM
  - ❖ Output voltage ripple
- The operation of a PWM and its purpose
- Brief description of the Tutorial, PSpice and Practical exercises
- Summary

Learning outcomes

- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the purpose of controlling the desired quantity and the need for a controller circuit within the power electronic converter.
- Analysis of ideal DC/DC converters (e.g. buck, boost, buck-boost, flyback, the forward, the push-pull, half-bridge and full-bridge converters) in CCM and DCM operation.
- Operating principles of single-phase and three-phase AC/DC inverters with different modulation strategies (e.g. PWM and square wave operation).
- Operation of multilevel converters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.
- Operation of single- and three-phase diode rectifiers operating with voltage-stiff and current-stiff DC-side. Investigating the impact of line impedance within the converter circuit for current commutation.
- Operation of single- and three-phase thyristor rectifiers operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink. Gaining a basic understanding of component life time.
- Utilizing the software Cadence PSpice to simulate basic power electronic circuits and the practical labs to have a firsthand experience of how real DC/DC converters operate.

Switch-mode power supply



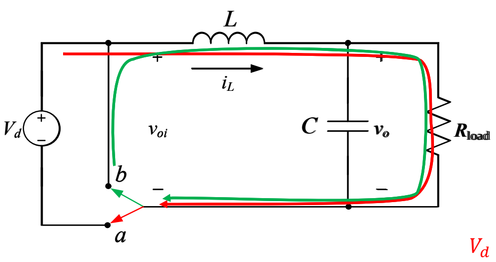
Undeland, Power Electronics
Figure 10 - 2, page 303

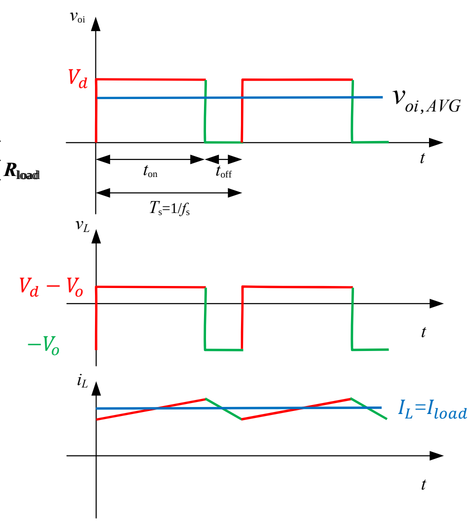
The Step-Down DC/DC converter

Assumptions

- All active and passive components are ideal
- We have no losses (input power = output power)
- The source impedance is zero
- Converter is in steady-state condition and the
  - average inductor voltage is zero
  - average capacitor current is zero
- Very large output capacitor => constant output voltage
- Non-ideal behaviors such as losses and voltage ripple are considered after derivations using the ideal assumptions

The Step-Down DC/DC converter





$$\frac{v_{oi,AVG}}{V_d} = \frac{t_{on}}{T_s} \qquad \frac{V_0}{V_d} = ?$$

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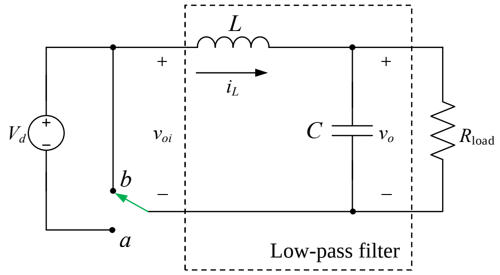
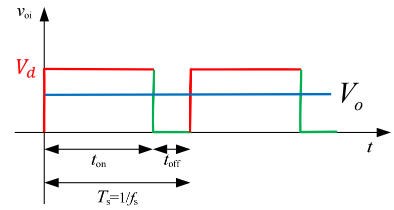
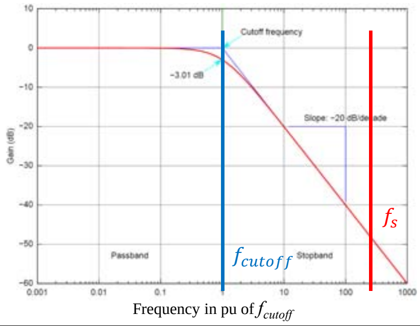
The Step-Down DC/DC converter







L and *C* helps to filter out higher order harmonics with $f_{cutoff} \ll f_s$. How?

$$\frac{v_o(\omega)}{v_{oi}(\omega)} = H_{Lp}(\omega) \approx \frac{1}{1 - LC\omega^2} \Rightarrow f_{cutoff} \approx \frac{\sqrt{1+\sqrt{2}}}{2\pi\sqrt{LC}}$$

The corner frequency, $f_c = \dfrac{1}{2\pi\sqrt{LC}}$

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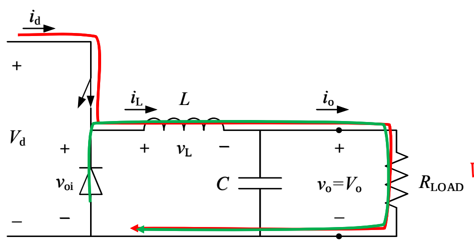
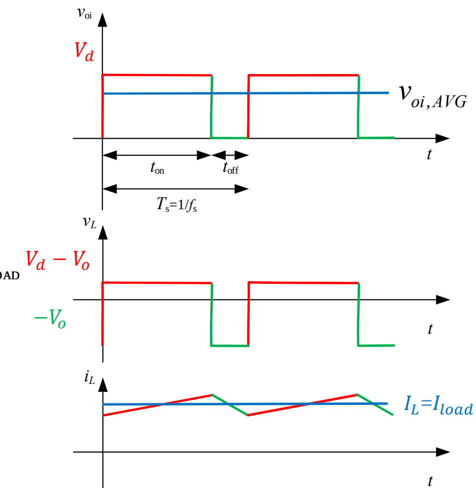
The Step-Down DC/DC converter





$$\frac{V_{oi,AVG}}{V_d} = \frac{t_{on}}{T_s} \qquad \frac{V_0}{V_d} = ?$$

Ex.: plot curves

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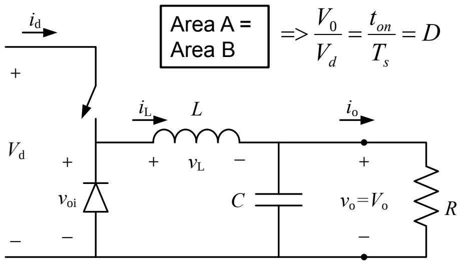
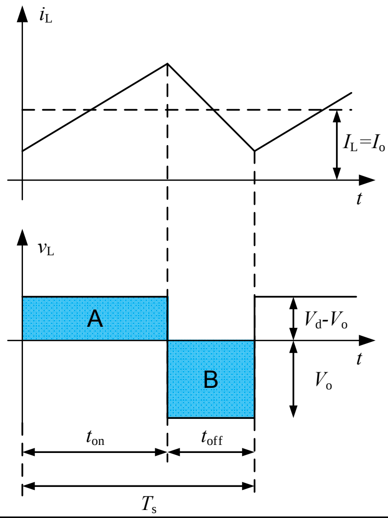
The Step-Down Converter – Continuous Conduction Mode (CCM)

- The converter is operating in steady-state.
- No net storage of energy over one switching period

Area A = Area B $\Rightarrow \dfrac{V_0}{V_d} = \dfrac{t_{on}}{T_s} = D$





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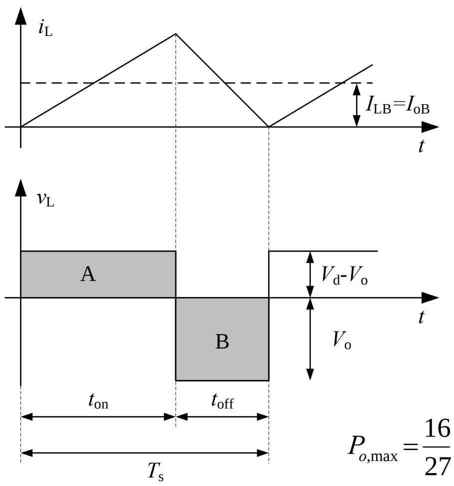
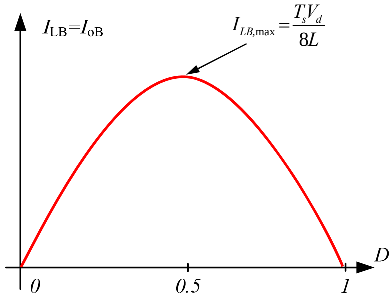
The Step-Down Converter Boundary to CCM

$$I_{LB} = \frac{D(1-D)T_s V_d}{2L} = 4D(1-D)I_{LB,\max}$$



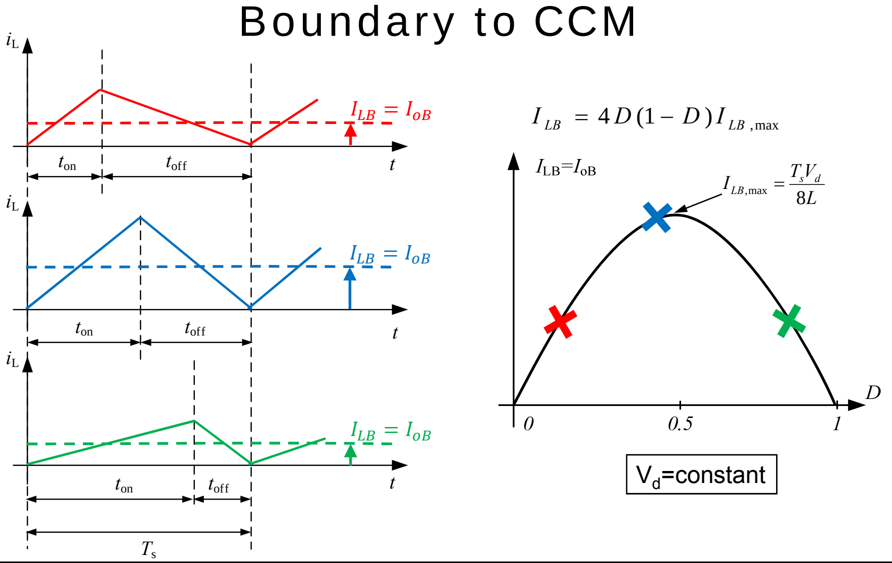


V_d=constant

$$P_{o,\max} = \frac{16}{27} V_d I_{LB,\max} ?$$

Ex.: derive expressions

The Step-Down Converter Boundary to CCM



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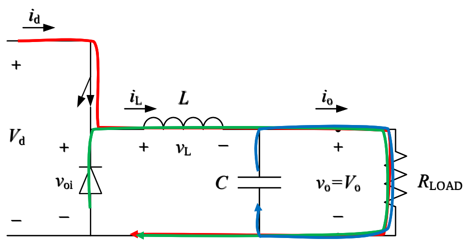
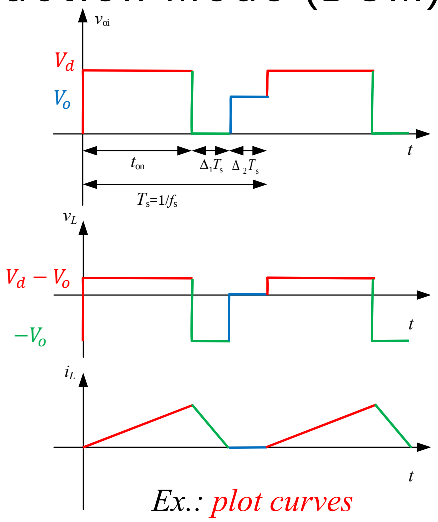
The Step-Down Converter Discontinuous Conduction Mode (DCM)



$$\frac{V_0}{V_d} = \frac{D}{D+\Delta_1} \neq D \, (\text{for } \Delta_2 > 0)$$



Ex.: plot curves

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The Step-Down Converter Discontinuous Conduction Mode (DCM)

- The converter is operating in steady-state.
- No net storage of energy over one switching period

Area A = Area B

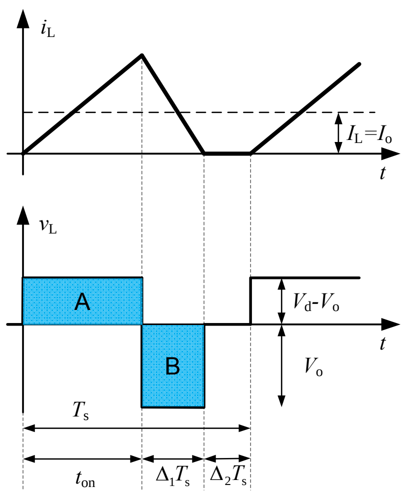
$$\Rightarrow \frac{V_0}{V_d} = \frac{D}{D+\Delta_1}$$

$$\Rightarrow \Delta_1 = \frac{2LI_0}{DT_s(V_d - V_0)} - D$$

$$\Rightarrow \frac{V_0}{V_d} = \frac{D^2}{D^2 + \frac{I_0}{4I_{LB,\max}}}$$

$$I_{LB,\max} = \frac{T_s V_d}{8L}$$

Ex.: Derive expressions



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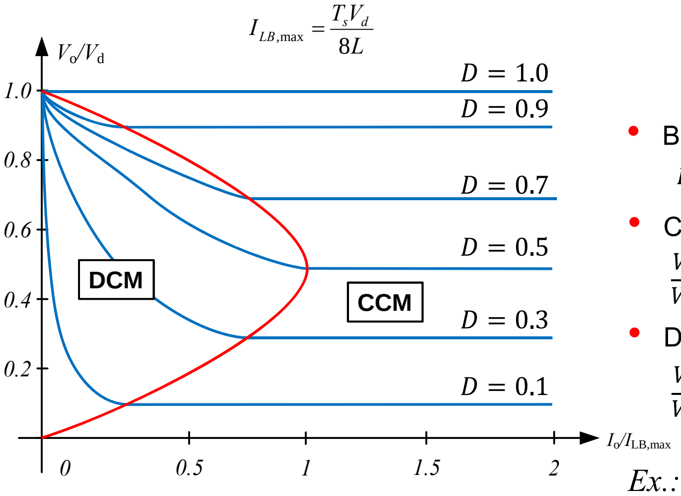
The Step-Down Converter – Boundary Between CCM/DCM with Constant V_d

$$I_{LB,\max} = \frac{T_s V_d}{8L}$$



- Boundary

  $I_o = 4D(1-D)I_{LB,max}$

- CCM

  $\frac{V_o}{V_d} = D$

- DCM

  $\frac{V_o}{V_d} = \frac{D^2}{D^2 + \frac{I_o}{4I_{LB,max}}}$

Ex.: Derive expressions

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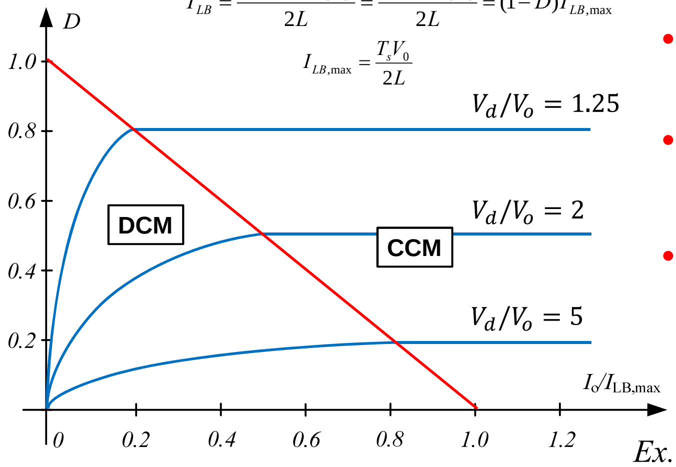
The Step-Down Converter – Boundary Between CCM/DCM with Constant V_o

$$I_{LB} = \frac{D(1-D)T_s V_d}{2L} = \frac{(1-D)T_s V_0}{2L} = (1-D) I_{LB,\max}$$

$$I_{LB,\max} = \frac{T_s V_0}{2L}$$



- Boundary

  $I_{LB} = (1-D) I_{LB,max}$
- CCM

  $\frac{V_o}{V_d} = D$
- DCM

  $D = \frac{V_o}{V_d}\sqrt{\frac{\frac{I_o}{I_{LB,max}}}{1-\frac{V_o}{V_d}}}$

Ex.: Derive expressions

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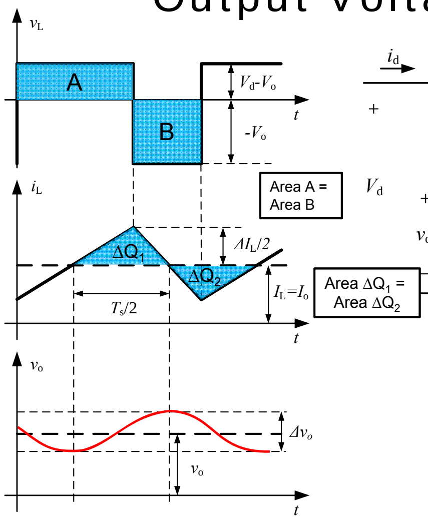
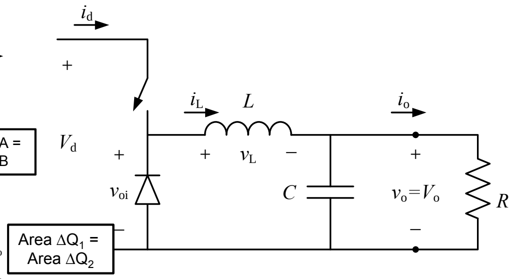
The Step-Down Converter Output Voltage Ripple

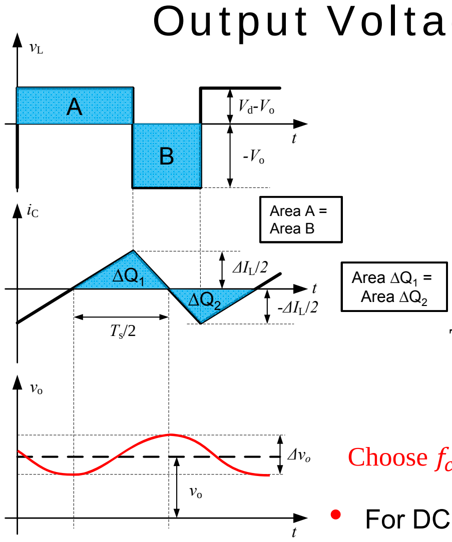




Assumptions:

- All ripple current in i_L flows through the capacitor.
- The output capacitor is ideal (no ESR)

The Step-Down Converter Output Voltage Ripple



- For CCM

$$\Delta v_0 = \frac{\Delta Q_1}{C} = \frac{1}{C}\frac{1}{2}\frac{\Delta I_L}{2}\frac{T_s}{2}$$

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

$$\Rightarrow \frac{\Delta v_0}{V_0} = \frac{\pi^2}{2}(1-D)\left(\frac{f_c}{f_s}\right)^2$$

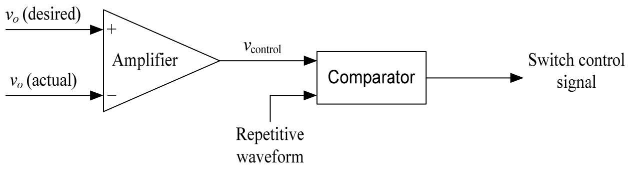
The corner frequency, $f_c = \dfrac{1}{2\pi\sqrt{LC}}$

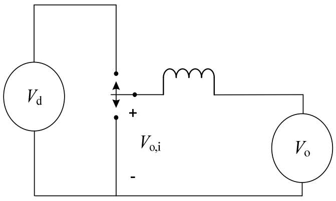
$$f_{cutoff} \approx \frac{\sqrt{1+\sqrt{2}}}{2\pi\sqrt{LC}}$$

Choose $f_c \ll f_s$

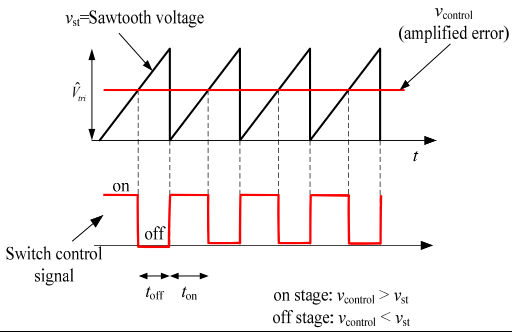
- For DCM: $\dfrac{\Delta v_0}{V_0} = \dfrac{\pi^2}{2}\left[\Delta_1(D+\Delta_1)(2-D-\Delta_1)^2\right]\left(\dfrac{f_c}{f_s}\right)^2$?

The operation of a PWM and its purpose



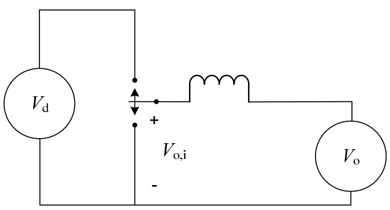


The Buck converter

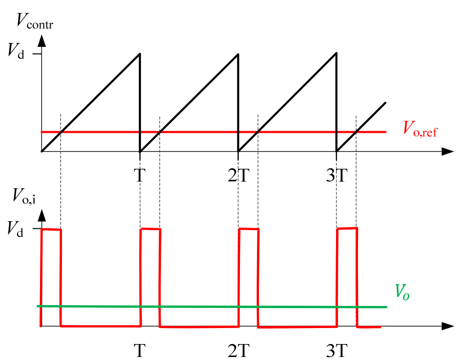


The operation of a PWM and its purpose

- The output voltage is a pulsed voltage with the desired average value
- Steady-state operation gives the same pulse width over all switching cycles



The Buck converter



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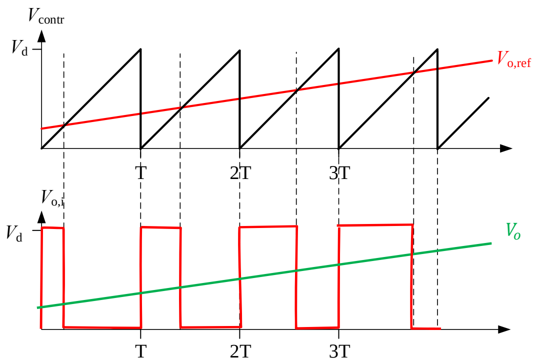
The operation of a PWM and its purpose

- The output voltage is a pulsed voltage with the desired average value
- Non steady-state operation results in a pulse width that increases as the reference value increases



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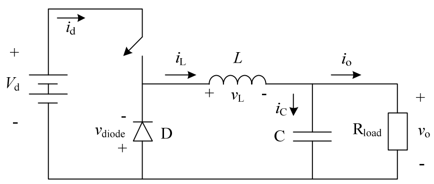
Tutorial 3



V_0=5v (kept constant by controlling D), V_d = 30v, P_o = 40w, L, C and f_{sw} given:

- i_d waveform, $I_{d,AVG}$,
- Voltage ripple, output voltage for a suggen change of power to 2w
- Impact of realistic switch and diode with the corresponding on-state voltage drop on the output voltage for CCM operation

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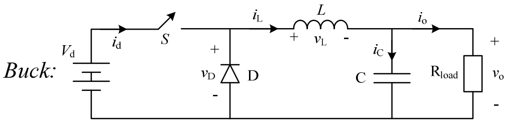
PSpice 2



- Waveforms, CCM or DCM, average and ripple output voltage
- FFT of the output voltage
- Impact of L, C, R_{load}, and R_{ESR}
- Impact of increasing D with parasitic components

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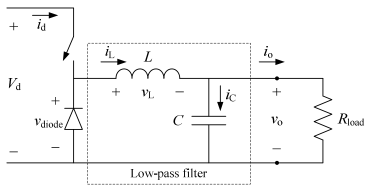
Laboratory 1



- Expressions and waveforms for CCM and DCM operation mode
- Impact of switching frequency on the mode of operation
- Corner frequency of the LPF and its impact on voltage ripple
- Boundary condition expression of D vs R_{Load}

Summary

- Can you list the components of a buck converter and their purposes?
- How can you tell if a Buck converter is operating in CCM, DCM, or the boundary conditions?
- How can you calculate the voltage ripple in a buck converter?
- What is the purpose of a PWM in the buck converter?
- Learning outcome:
  - Operation of a pulse width modulation (PWM) its purpose to control the desired quantity; hence, the need for a controller circuit in the power electronic converter.
  - Analysis of a step-down (buck) DC/DC converter in CCM and DCM operation.