CHALMERS

ENM061 - Power Electronic Converters
7.5 ECTS, 2017

Mebtu Beza
mebtu.beza@chalmers.se

Chalmers University of Technology
Department of Electrical Engineering
Division of Electric Power Engineering

CHALMERS

Lecture outline

Converter Control and Improvements

- Control of DC/DC Converters
- Dynamic modeling of a step-down converter
- Controller design for the step-down converter
- Digital Control
- Synchronous rectification in the step-down converter
- Interleaved step-down converters
- Summary

CHALMERS

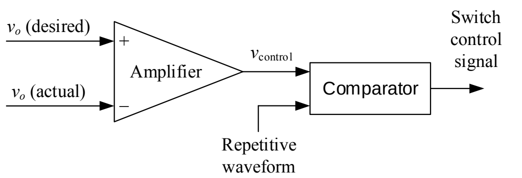
Learning outcomes

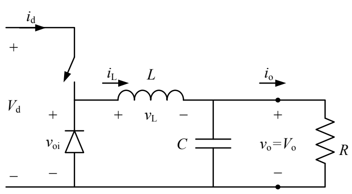
- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the 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.
- 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.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- 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.

CHALMERS

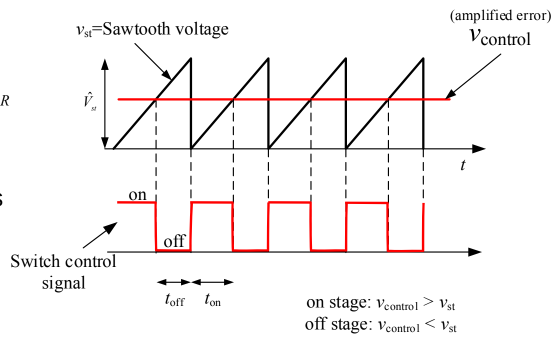
Control of DC/DC Converters

- The buck converter from Lecture 4 with controller circuit





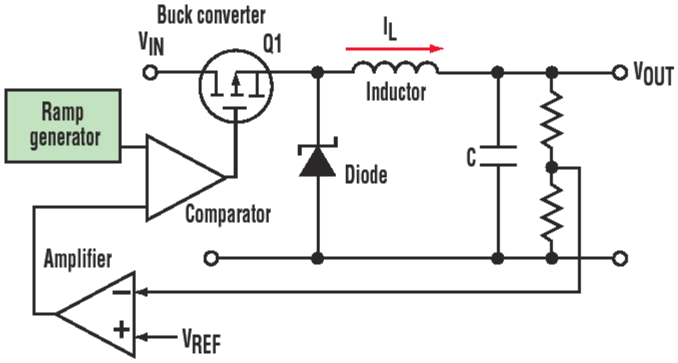
- The PWM pattern to the switch is obtained by comparing a control voltage with a saw tooth carrier



CHALMERS

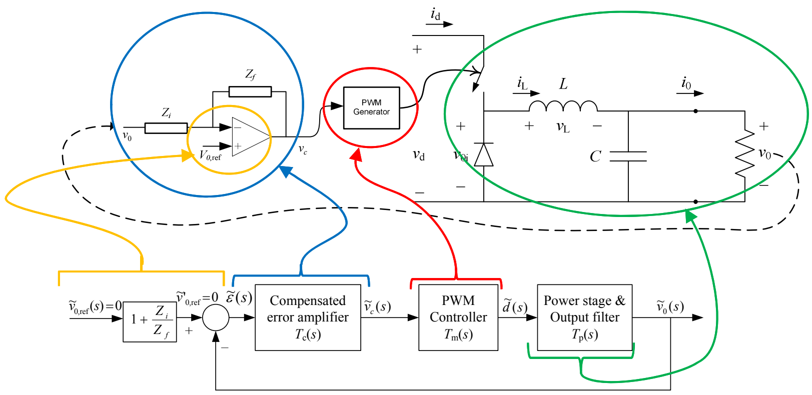
Control of DC/DC Converters

- Voltage mode control – the output voltage is measured and compared to a reference value



CHALMERS

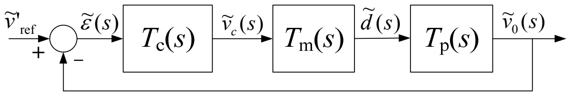
The Dynamic Model



- The behavior or each block is analyzed with its transfer function and corresponding bode plot

Undeland, Power Electronics
Figure 10-19, page 323

The Dynamic Model

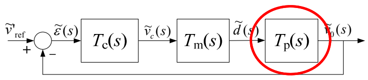


- Once each block is known, the total open-loop transfer function is used to determine the gain and phase margins
- The transfer function of each block depends on e.g. circuit parameters and accounts for the small signal variation around a specific operating point

Small signal perturbation model

$$T_p(s) = \frac{\tilde{v}_0(s)}{\tilde{d}(s)},\quad T_m(s) = \frac{\tilde{d}(s)}{\tilde{v}_c(s)},\quad T_c(s) = \frac{\tilde{v}_c(s)}{\tilde{\varepsilon}(s)} \Rightarrow T_{OL}(s) = T_p(s)T_m(s)T_c(s)$$

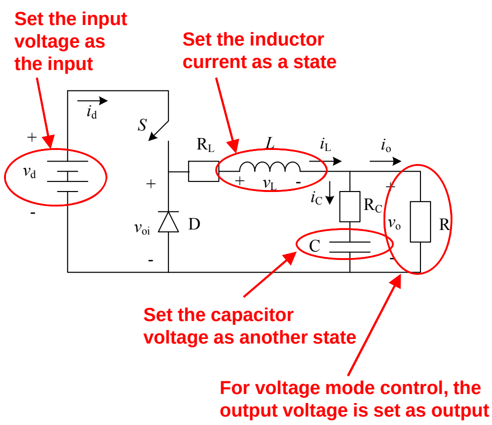
The Power Stage State-Space Modeling



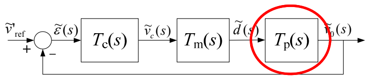
- State-space description of the power stage in a buck converter

$$\dot{x} = \mathbf{A}x(t) + \mathbf{B}u(t)$$
$$y = \mathbf{C}x(t) + \mathbf{D}u(t)$$

- The capacitor voltage and the inductor current are set as states (*x(t)*) since they can be expressed with their time derivatives
- The system input (*u(t)*) is set to V_d and the output (*y*) is the quantity that we want to control (v_o)



The Power Stage State-Space Modeling



1. State variable description of each circuit state

$$\left.\begin{aligned} \dot{x} &= \mathbf{A}x(t)+\mathbf{B}u(t) \\ y &= \mathbf{C}x(t)+\mathbf{D}u(t) \end{aligned}\right\} \left\{\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}_1\mathbf{x}+\mathbf{B}_1 v_\mathrm{d} \quad v_\mathrm{o} = \mathbf{C}_1\mathbf{x} \quad \text{During } d\cdot T_{sw} \\ \dot{\mathbf{x}} &= \mathbf{A}_2\mathbf{x}+\mathbf{B}_2 v_\mathrm{d} \quad v_\mathrm{o} = \mathbf{C}_2\mathbf{x} \quad \text{During } (1-d)\cdot T_{sw} \end{aligned}\right.$$

2. Average the state-variables with d

$$\dot{\mathbf{x}} = [\mathbf{A}_1 d + \mathbf{A}_2(1-d)]\mathbf{x} + [\mathbf{B}_1 d + \mathbf{B}_2(1-d)]v_\mathrm{d}$$
$$v_o = [\mathbf{C}_1 d + \mathbf{C}_2(1-d)]\mathbf{x}$$

then linearize the model around an operating point, i.e. describe,

$$d = D + \tilde{d},\ \mathbf{x} = \mathbf{X} + \tilde{\mathbf{x}},\ v_d = V_d + \tilde{v}_d = V_d,\ v_o = V_o + \tilde{v}_o$$

The Power Stage State-Space Modeling

Define the different matrices using D as

$$\mathbf{A} = \mathbf{A}_1 D + \mathbf{A}_2(1-D) \qquad \mathbf{B} = \mathbf{B}_1 D + \mathbf{B}_2(1-D) \qquad \mathbf{C} = \mathbf{C}_1 D + \mathbf{C}_2(1-D)$$

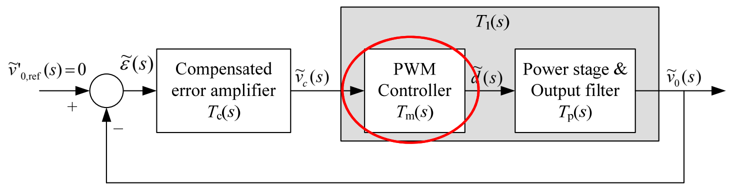
$$\Rightarrow \begin{aligned} \dot{\tilde{\mathbf{x}}} &= \mathbf{A}\tilde{\mathbf{x}} + [(\mathbf{A}_1 - \mathbf{A}_2)\mathbf{X} + (\mathbf{B}_1 - \mathbf{B}_2)V_\mathrm{d}]\tilde{d} \quad \text{where } \dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}V_\mathrm{d} = 0 \\ \tilde{v}_o &= \mathbf{C}\tilde{\mathbf{x}} + [(\mathbf{C}_1 - \mathbf{C}_2)\mathbf{X}]\tilde{d} \quad \text{where } V_o = \mathbf{C}\mathbf{X} = -\mathbf{C}\mathbf{A}^{-1}\mathbf{B}V_\mathrm{d} \end{aligned}$$

3. Transform to the Laplace domain and determine the final transfer function

$$T_p(s) = \frac{\tilde{v}_o(s)}{\tilde{d}(s)} = \mathbf{C}[s\mathbf{I} - \mathbf{A}]^{-1}[(\mathbf{A}_1 - \mathbf{A}_2)\mathbf{X} + (\mathbf{B}_1 - \mathbf{B}_2)V_d] + (\mathbf{C}_1 - \mathbf{C}_2)\mathbf{X}$$

CHALMERS

The Modulator dynamic model

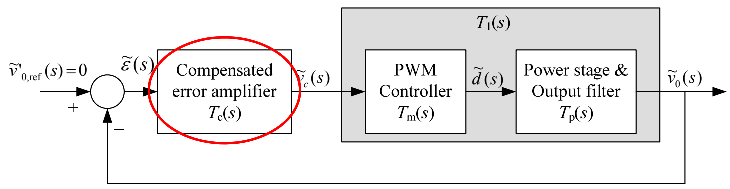


$$T_m(s)=\frac{\tilde{d}(s)}{\tilde{v}_c(s)}=\frac{1}{\hat{V}_r}\Rightarrow T_1(s)=\frac{\tilde{v}_o(s)}{\tilde{v}_c(s)}=\frac{\tilde{v}_o(s)}{\tilde{d}(s)}\frac{\tilde{d}(s)}{\tilde{v}_c(s)}=T_p(s)T_m(s)$$

Undeland, Power Electronics
Figure 10-19, page 323

CHALMERS

The Compensated Error Amplifier



- Once the transfer functions of the PWM controller and the Power stage are known, the error amplifier shall be dimensioned

$$T_c(s)=\frac{\tilde{v}_c(s)}{\tilde{\varepsilon}(s)}$$

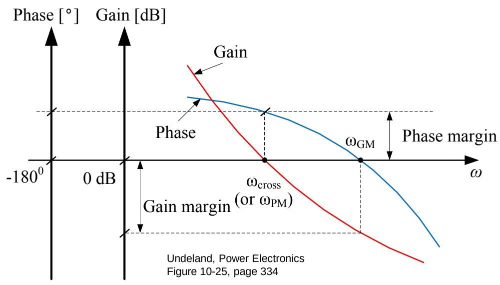
- The total open-loop transfer function (T_{OL}(s)) shall get a suitable behavior.

$$T_{OL}(s)=T_c(s)\cdot T_1(s)$$

  - High gain at low frequencies to minimize steady state errors
  - High cross-over frequency (f_{cross}=0.1f_{sw}) for fast response and high filtering
  - A phase margin in the range of 45º – 60º for good transient response

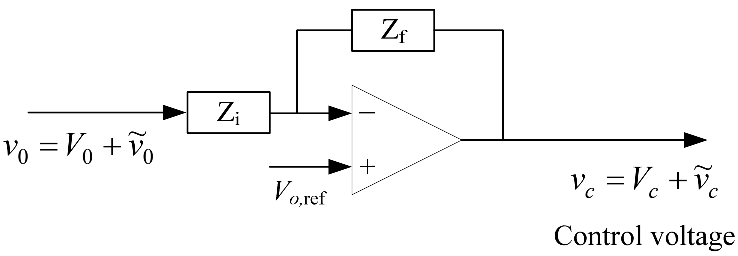
Controller Design
Gain and Phase Margin

- The gain margin and the phase margin (and associated frequencies ω_{GM} and ω_{PM}) indicates the relative stability of the closed-loop system formed by applying unity negative feedback
- The gain margin is the amount of gain increase or decrease required to make the loop gain unity at the frequency ω_{GM} where the phase angle is –180 degrees
- The phase margin is the difference between the phase of the response and –180 degrees when the loop gain is 1. The frequency ω_{PM} at which the magnitude is 1.0 is called the gain crossover frequency.
- Recommendation: gain margins of three or more combined with a phase margin between 30 and 60 degrees for good transient performance and stability.



Undeland, Power Electronics
Figure 10-25, page 334

Controller Design
Circuit Realization

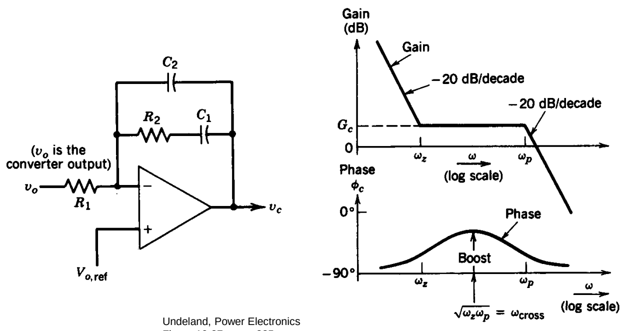


- For small signals: $\frac{\tilde{v}_c(s)}{\tilde{v}_0(s)} = -\frac{Z_f(s)}{Z_i(s)} = -T_c(s)$

CHALMERS

Controller Design Example Integrated-compensation Network

- A zero-pole pair to give a phase boost
- Maximum phase boost of 90 deg can be provided (ω_z and ω_p design parameters)
- Integrator at origin gives high DC gain for good load regulation



Undeland, Power Electronics
Figure 10-27, page 335

$$T_c(s) = \frac{1}{R_1 C_2 s}\,\frac{s+\omega_z}{s+\omega_p}$$

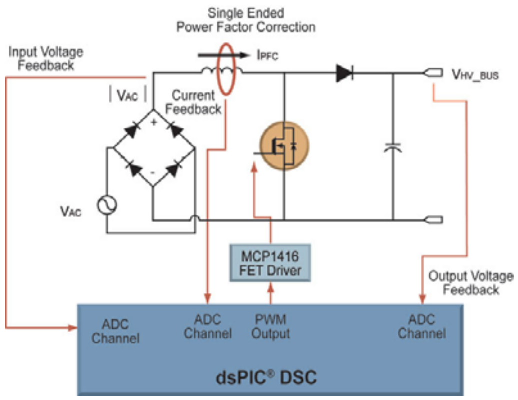
$$\omega_z = \frac{1}{R_2 C_1}$$

$$\omega_p = \frac{C_1 + C_2}{R_2 C_1 C_2}$$

CHALMERS

Digital Control

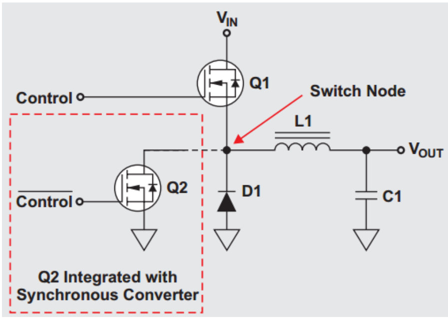
- Can serve as an additional monitoring and control functions to an existing analog controller or as a complete digital control
- Boost converter: Microcontrollers, ADC/DAC, digital input-analog output



© Microchip

Synchronous Step-Down Converters

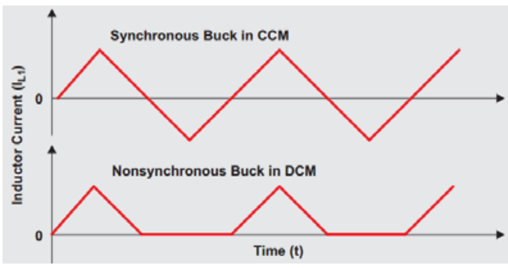
- The freewheeling diode is replaced by a second (low-side) MOSFET that freewheels the current
- Main advantage is lower voltage drop over the low-side MOSFET than a corresponding diode
- Synchronous rectification can also be applied to other topologies as well



© Texas Instruments

Synchronous Step-Down Converters

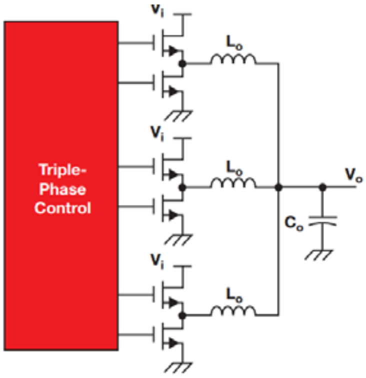
- In a standard buck converter with a free-wheeling diode, the inductor current can only flow in one direction
- In a synchronous buck, the current through the low-side MOSFET can flow in both directions which will increase the losses



© Texas Instruments

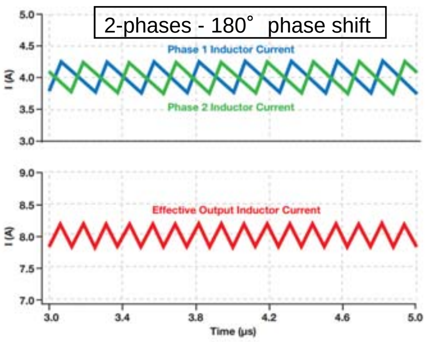
Interleaved Step-Down Converters

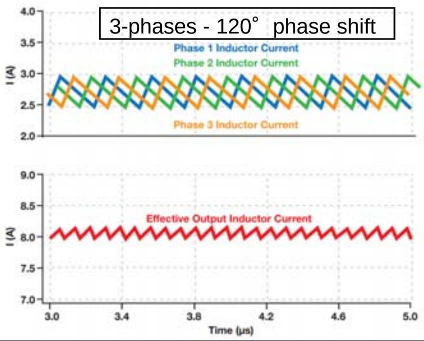
- By connecting several phase shifted converters in parallel, the resulting current and voltage ripple can be decreased
- Typically used in high current and low voltage applications (e.g. processor power supplies)



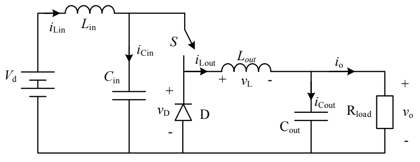
Interleaved Step-Down Converters

- The inductor currents add together which gives a lower effective ripple
- The current ripple determines the resulting output voltage ripple in combination with the output capacitors
- The inductor in each phase can be realized with lower inductance which gives higher saturation current ratings





PSpice 7



Nominal values	
Source voltage (V_d)	15V
Output Inductance (L)	2.2μH
Output Capacitance (C)	150μF
Load Resistance (R_{load})	2Ω
Switching frequency (f_{sw})	300kHz
Duty ratio steady state (D)	0.667

- Buck converter with output voltage controller. How does the controller compensate for changes in the system such as $V_{o,ref}$ and R_{load} changes, both during an increase and a decrease?

$$T_c(s) = \frac{A}{s}\frac{s+\omega_z}{s+\omega_p}$$

Summary

- Why a controller is needed and how it works
- The concept of controller design: bode diagram, phase and gain margins
- Digital Control
- Synchronous rectification in the step-down converter
- Interleaved step-down converters
- Learning outcome:
  - Basics in dynamic modelling and control of power electronic converters