ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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

Lecture outline

Review of power electronics and Fourier series

- Course information
- The purpose of power electronics
- Alternating current (AC) representation
- The steady-state condition
- Fourier analysis
- Harmonics, displacement power factor (DPF) and power factor (PF)
- Average (AVG) vs Root Mean Square (RMS) value
- Brief description of the Tutorial and PSpice exercises
- Summary

Course staff

Lectures: Mebtu Beza
(18, HC1)

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(13, HC1)
Consultations:
(4, ML2, ML11, or Fredrik Lamm - Room 2503)

Practical Labs: Alessandro Acquaviva
(2, Room 3502) Anton Kersten
1.5 ECTS Qian Xun, and Robert Karlsson

Computer Labs: Georgios Mademlis
(7, E-Studion) Alessandro Acquaviva
Anton Kersten
Qian Xun
Zeyang Geng, and Mebtu Beza

Staff page: https://www.chalmers.se/en/departments/e2/contact/Pages/Personnel.aspx

Course Information

Course book: Mohan, Undeland, Robbins, *Power Electronics - Converters, applications and design*, Wiley 2003, 3rd ed.

Extra handouts will be given during the course.

Lectures and tutorials mainly from the book

Written examination (U, 3, 4 or 5)

4 hrs final exam– Jan 13, 2018 at 14:00 (**Registration compulsory – last 22 Nov.**)

2 hrs midterm exam (0, 1, 2, 3 or 4) – Nov 20, 2017 at 8:00

Approved laboratory (U or G) – Registration necessary

7 Pspice exercises each 2 hrs – 2 students per group (random)

2 practical labs each 4 hrs - 3 students per group (random)
https://pingpong.chalmers.se/courseId/8806/courseDocsAndFiles.do

Course representatives

TIELL Norbert Batiuk (batiuk@student.chalmers.se)
MPEPO Sebastian Bergman (sebaber@student.chalmers.se)
TIELL Philip Hoang (hoangp@student.chalmers.se)
MPEPO Duo Xu (xduo@student.chalmers.se)

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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.

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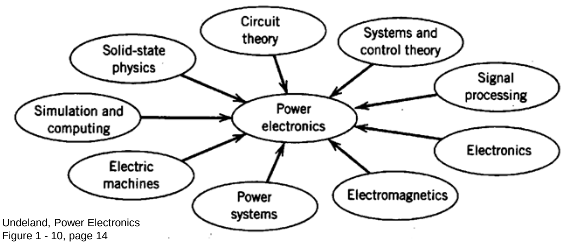
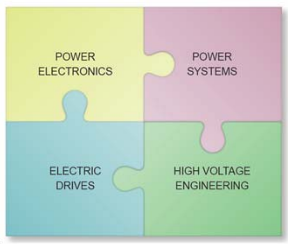
Why Power Electronics?

- Power electronics is the application of solid-state electronics for the control and conversion of electric power.
- The course discusses the different circuits used to convert and control electrical energy. Examples include designing converters, selection of suitable converter topologies, power semiconductors and passive components.
- The main goal of the course is to study the operating principles of the most common power electronic converter topologies, basic converter design and analysis of the different wave-shapes.

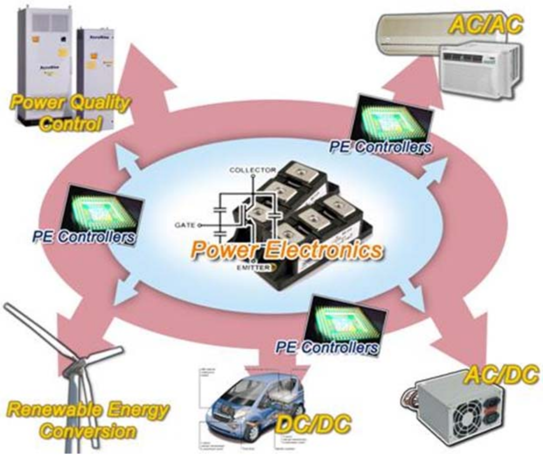


Undeland, Power Electronics
Figure 1 - 10, page 14

MPEPO Chalmers main courses



Why Power Electronics?



- ❖ Chargers (mobile phones, computers, tvs, battries…)
- ❖ Household appliances
- ❖ Pumps and fans
- ❖ Traction applications
- ❖ Power transmission
- ❖ FACTS devices
- ❖ HVDC systems

Advanced Power Electronics

Wide range of application

- Mobile charger ~ 5 W/5 V

- HVDC Light ~ 500 MW/500 kV

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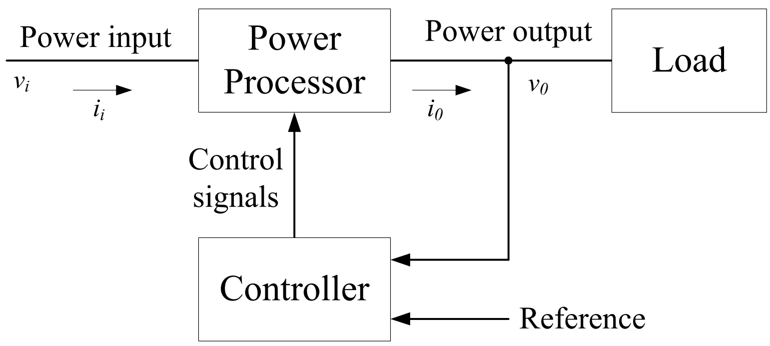
Application of power electronics increased with

- Improved semiconductors (faster, lower loss, better cooling)
- Improved magnetic materials and capacitors
- Advanced converter control

The Purpose of Power Electronics

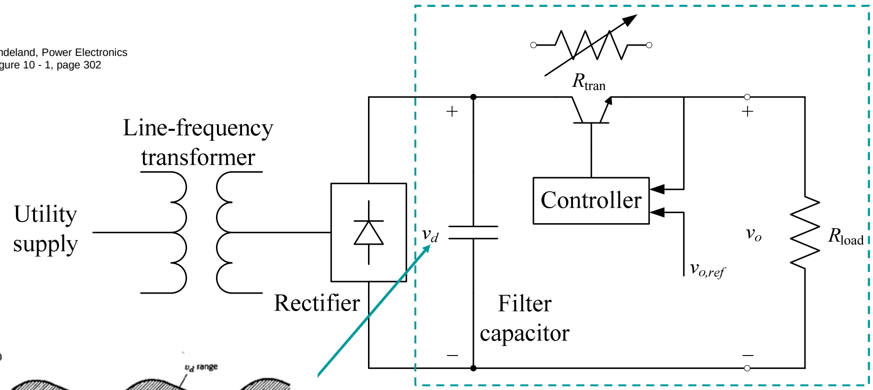


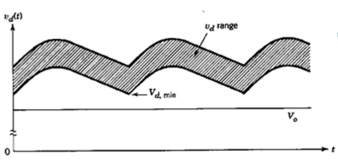
Undeland, Power Electronics
Figure 1 - 1, page 3

Linear power supply

$$V_{CE} = V_d - V_0$$

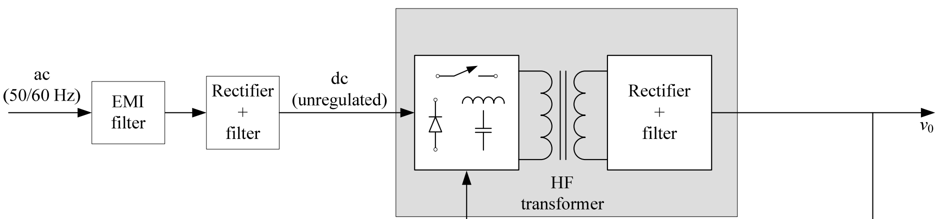
Undeland, Power Electronics
Figure 10 - 1, page 302





With v_d assumed constant, $V_o = \frac{R_{load}}{R_{load} + R_{tran}} V_d$

Switch-mode power supply

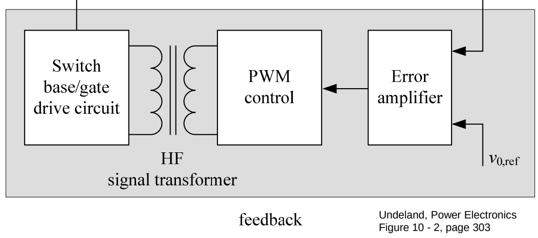


Advantages:

- Higher efficiency
- Smaller size converter

Challenges:

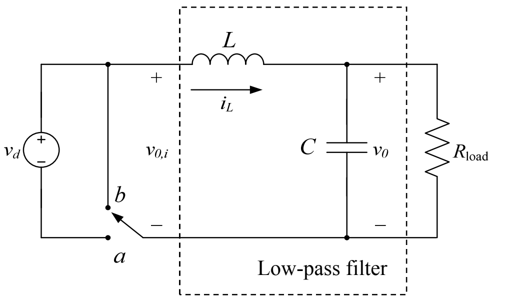
- Complicated control
- More Components

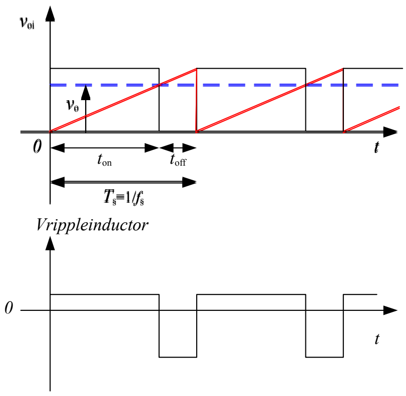


Undeland, Power Electronics
Figure 10 - 2, page 303

Switch-mode power supply

Equivalent circuit





Average load voltage

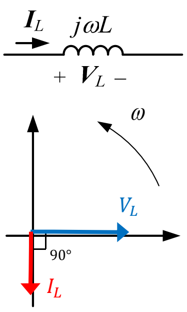
$$V_0 = \frac{1}{T_s}\int_0^{T_s} v_{0,i}dt = \frac{t_{on}}{T_s}V_d = DV_d = \frac{R_{load}}{R_{load}+R_{tran}}V_d$$

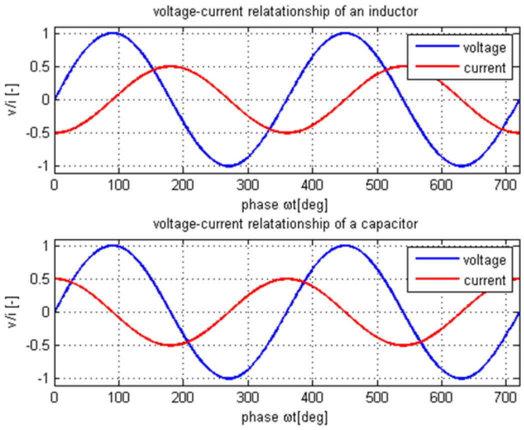
Choice of T_s how?

AC-Representation – Basic Components and Phasors

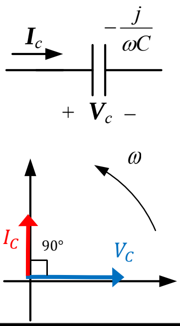
- Phasors rotate counterclockwise and represent the RMS-values
- For an inductor/capacitor, the current lags/leads the voltage by 90 degrees.

$$v_L = L\frac{di_L}{dt}$$



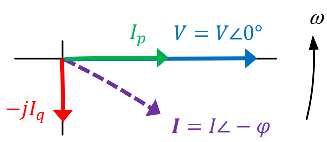


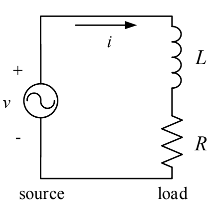
$$i_C = C\frac{dv_C}{dt}$$



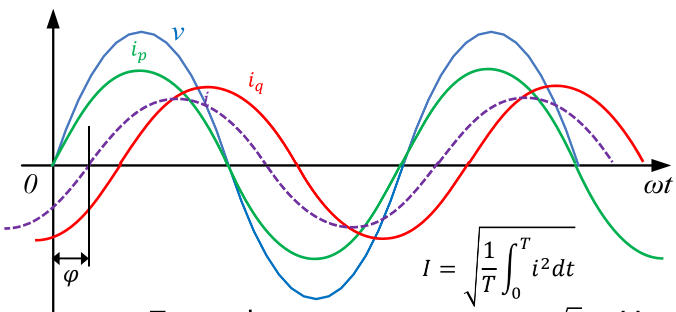
AC-Representation – Basic Components and Phasors

- The phase angle is the phase difference between the total current and the source voltage
- Ex: *Time and phasor plots for currents?*





$$I = \frac{V}{Z} = \frac{V}{R + j\omega L}$$

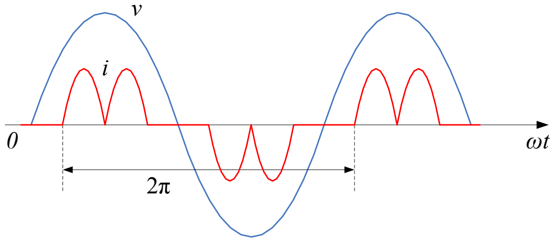


$$I = \sqrt{\frac{1}{T}\int_0^T i^2 dt}$$

For a sine wave: $I_{RMS} = I_{peak}/\sqrt{2}$ How?

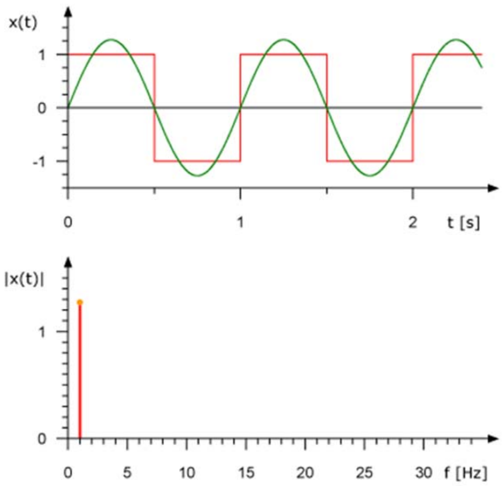
The Steady State Condition

- Power Electronic circuits often generate non-sinusoidal waveforms



- Steady state is when everything is repeated with a time period (T) and a corresponding frequency f $(= 1/T)$.

Fourier Analysis



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For any periodic signal,
eg. $f(t) = x(t)$

$$f(t) = \frac{1}{2}a_0 + \sum_{h=1}^{\infty}\{a_h \cos(h\omega t) + b_h \sin(h\omega t)\}$$

$$\begin{cases} a_h = \dfrac{1}{\pi}\displaystyle\int_0^{2\pi} f(t)\cos(h\omega t)d(\omega t) \\ b_h = \dfrac{1}{\pi}\displaystyle\int_0^{2\pi} f(t)\sin(h\omega t)d(\omega t) \end{cases}$$

$F_0 = 1/2a_0$ average value

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Fourier Analysis – Phasors and RMS

The Fourier coefficients can also be expressed as complex RMS phasors:

$$\boldsymbol{F}_h = F_h e^{j\varphi_h} \quad \left\{ \begin{array}{l} F_h = \dfrac{\sqrt{a_h^2 + b_h^2}}{\sqrt{2}} \\ \tan(\varphi_h) = \dfrac{(-b_h)}{a_h} \end{array} \right\} \quad f(t) = F_0 + \sum_{h=1}^{\infty} \sqrt{2} F_h \sin(h\omega t + \varphi_h)$$

RMS expressed in terms of Fourier coefficients: $F = \sqrt{F_0^2 + \sum_{h=1}^{\infty} F_h^2}$

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Fourier Analysis – Symmetry

Symmetry	Condition required		a_h and b_h
Even	$f(-t) = f(t)$		$b_h = 0, \quad a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)d(\omega t)$
Odd	$f(-t) = -f(t)$		$a_h = 0, \quad b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)d(\omega t)$
Half-wave	$f(t) = -f(t+1/2T)$	$a_h = b_h = 0, \quad \text{for even } h$	$a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)d(\omega t), \ \text{for odd } h$ $b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)d(\omega t), \ \text{for odd } h$
Even quarter-wave	Even and half-wave	$b_h = 0, \ \text{for all } h$	$a_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\cos(h\omega t)d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$
Odd quarter-wave	Odd and half-wave	$a_h = 0, \ \text{for all } h$	$b_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\sin(h\omega t)d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$

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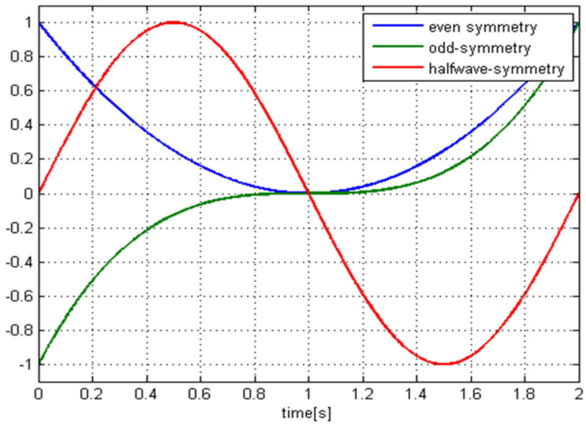
Fourier Analysis – Symmetry



Even quarter-wave and Odd quarter wave?

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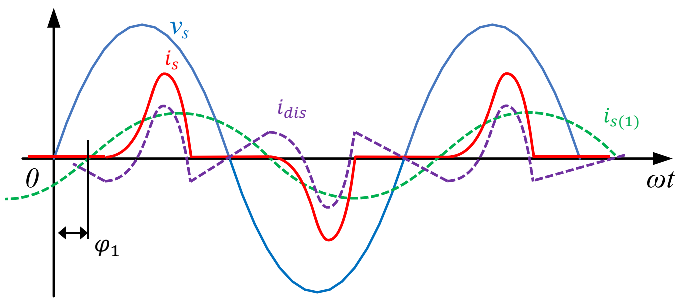
Harmonics and Power Factor



$$I_s = \sqrt{\frac{1}{T_1}\int_0^{T_1} i_s^2 dt} = \sqrt{I_{s(1)}^2 + \sum_{h\neq 1} I_{s(h)}^2} \rightarrow I_{dis} = \sqrt{I_s^2 - I_{s(1)}^2}$$

$$\%THD_i = 100\frac{\sqrt{I_s^2 - I_{s(1)}^2}}{I_{s(1)}} \rightarrow \%THD_i = 100\frac{I_{dis}}{I_{s(1)}}$$

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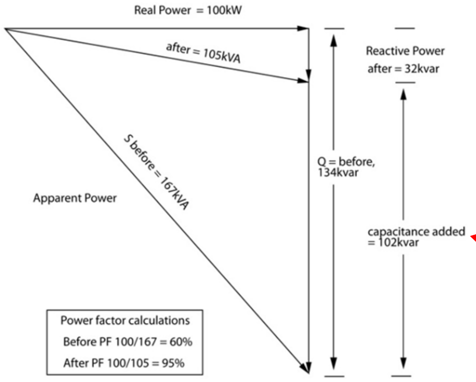
Harmonics and Power Factor

- Two different power factors are defined (PF and DPF) which are the same for sinusoidal quantities.



$$DPF = \cos(\varphi_1)$$

$$PF = \frac{I_{S(1)}}{I_S}\cos(\varphi_1)$$

Increasing the power factor using traditional VAr compensation, e.g. adding a capacitor bank.

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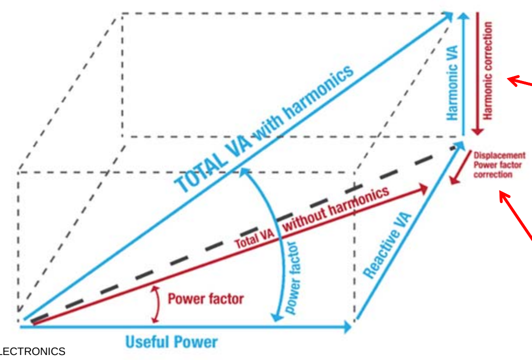
Harmonics and Power Factor

- For non-sinusoidal quantities, DPF and PF will differ depending on the harmonic content.
- DPF only takes the angle between the fundamental components into consideration
- PF accounts for the angle between the fundamental components as well as the ratio between the fundamental current component and the total RMS-current (including harmonics)



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A large distortion in the current waveform will result in a low PF. By reducing the harmonic content in the current, the PF will also be improved.

$$PF = \frac{I_{S(1)}}{I_S}\cos(\varphi_1) = \frac{DPF}{\sqrt{1+THD_i^2}}$$

Increasing the displacement power factor (traditional VAr compensation).

$$DPF = \cos(\varphi_1)$$

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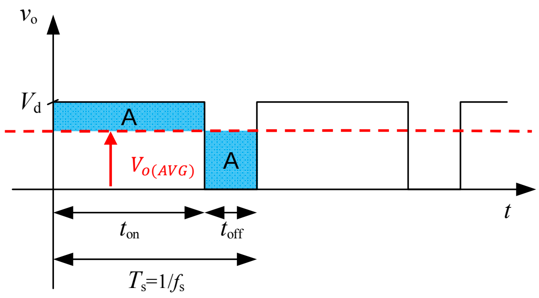
Average vs RMS value



Ex.: *Average voltage?*

$$V_{o(AVG)} = \frac{1}{T_s}\int_0^{T_s} v_o dt = \frac{t_{on}}{T_s}V_d = DV_d$$

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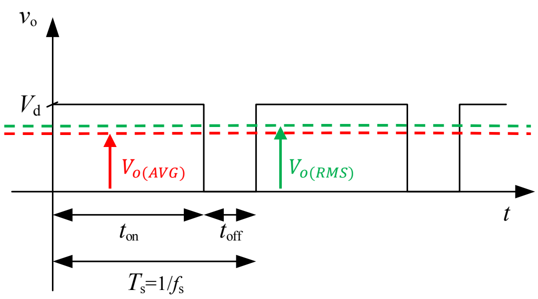
Average vs RMS-Value

- The RMS-value of a current is equal to the value of the direct current that would produce the same power dissipation in a resistive load.



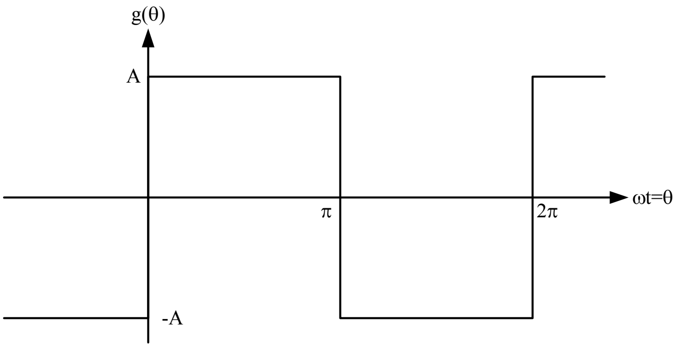
For a sine wave,
AVG vs RMS?

$$V_{RMS} = V_{peak}/\sqrt{2}$$
$$V_{AVG} = 0$$

Ex.: *RMS voltage?* $V_{o(RMS)} = \sqrt{\frac{1}{T_s}\int_0^{T_s} v_o^2 dt} = \sqrt{\frac{t_{on}}{T_s}}V_d = \sqrt{D}V_d$

Tutorial 1

- AVG and RMS value of the fundamental and the harmonic components
  Fourier calculations, any symmetry?



Tutorial 1

- AVG and RMS value of the fundamental and the harmonic components
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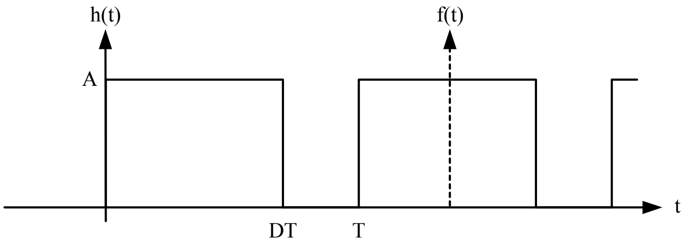
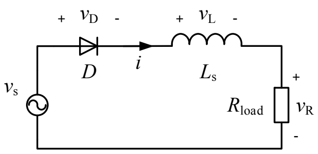
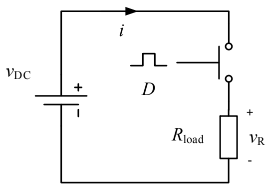


- Current in three-phase RL-load using phasor calculation

PSpice 1

Power electronc circuits and Fourier analysis in Cadence PSpice





- Waveforms
- Phasor methods
- AVG vs RMS values
- Fourier calculation
- AVG vs RMS values
- Harmonic components

Summary

- What is power electronics and what is its purpose?
- What are the pros and cons of switch-mode and linear power supplies?
- What is the purpose of using phasors for AC signals?
- What is the phasor representation of an inductor and a capacitor?
- Why do we need to calculate the Fourier components of a signal?
- What are harmonic components and what does a DPF and a PF tell us?
- What is the difference between average and RMS values?
- Learning outcome:
  - Calculation of Fourier components, THD, PF and DPF for basic waveforms