Power Quality Enhancing Systems

Industrial Electrical Engineering and Automation
Lund University, Sweden

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1. Objectives

Discuss the problems related to harmonics in the power system and present some methods to reduce the problems.

- Single-phase diode rectifiers and power factor correctors
- Three-phase diode rectifiers
- Controlled three-phase diode rectifiers: Minnesota and Vienna
- The voltage source converter
- Series and shunt active filters, the unified power flow controller
- Detection and identification of harmonic currents
- Effect of blanking time and forward voltage drop
- Multiple rotating coordinate systems
- Simulation and measurement results

Acronyms

- **APF – Active Power Filter**
- **UPFC – Unified Power Flow Controller**
- **SVC – Static Var Converter**
- **HVDC – High Voltage Direct Current**
- **...**

All made to improve "Power Quality"

Non-ideal loads

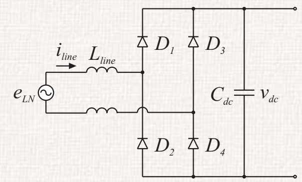
- **are loads that:**
  - **are non-resistive -> consume reactive power**
  - **vary with time or phase -> consume harmonic current components.**
  - **are different in different phases -> consume negative sequence currents**

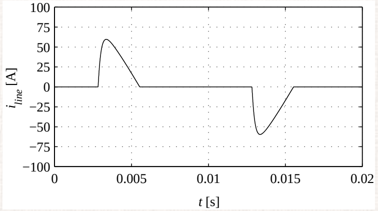
Ways to improve the loads

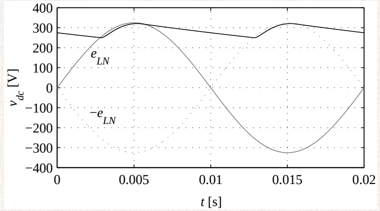
- **Self improvement**
  - **Solutions that draw as "ideal" current as possible from the grid**
- **Compensation**
  - **A parallel unit is used to counteract the non ideal currents drawn by the main load**

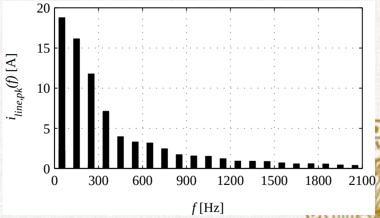
2. Single-phase diode rectifiers (I)

A single-phase diode rectifier draws a line current with a large harmonic content since the diodes must be forward biased to conduct.



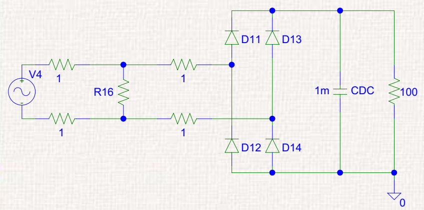


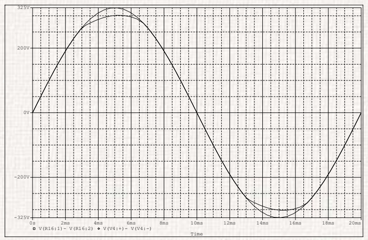




2. Single-phase diode rectifiers (II)

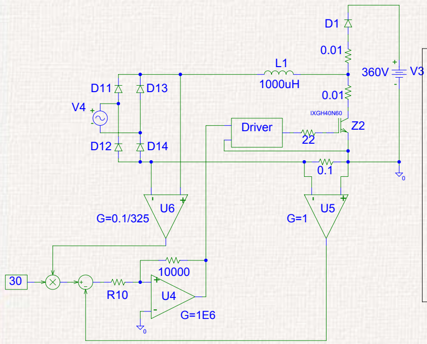
The current harmonics create voltage harmonics at the point of common coupling (PCC), i.e. at the point where other loads are connected. Note that all single phase diode rectifiers draws current in the vicinity of the peak voltage.

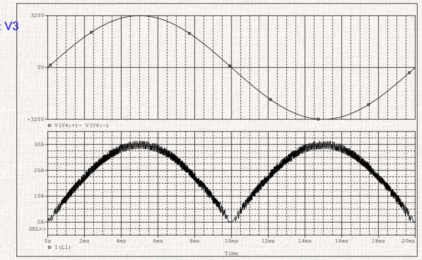




2. Power Factor Corrector (PFC)

Implemented with tolerance-band (or hysteresis) current controller.





3. Three-Phase diode rectifiers

Note that for three-phase diode rectifiers, only two phases carry current simultaneously. This means that each diode has a maximum conduction interval equal to 120° for each half period. Therefore a three-phase PFC is not possible to implement. However there are two types of controllable diode rectifiers derived from three single-phase diode rectifiers (which is also possible to implement):

- The Minnesota rectifier invented by Ned Mohan
- The Vienna rectifier invented by Johann Kolar

3. The Minnesota Rectifier

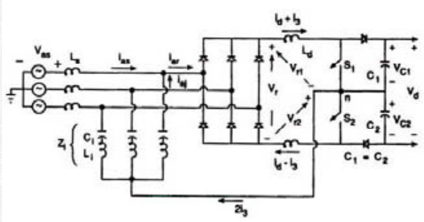


Fig. 3 Proposed Rectification Approach. Capacitors for ripple-current component are not shown.

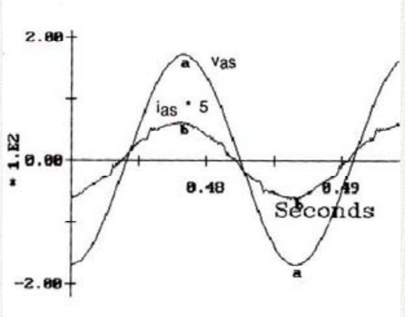
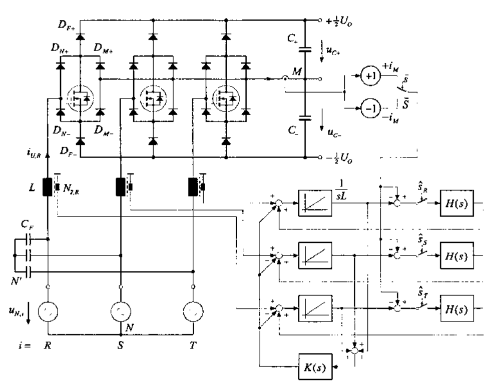


Fig. 8. Utility-Side Waveforms in the proposed rectifier.

3. The Vienna Rectifier



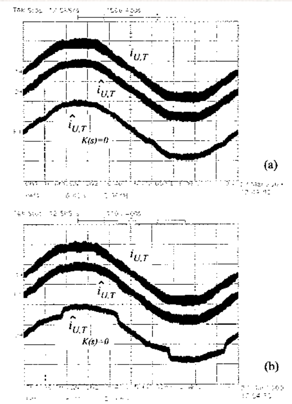
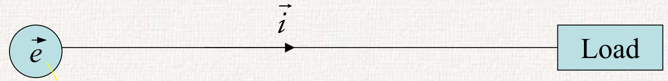
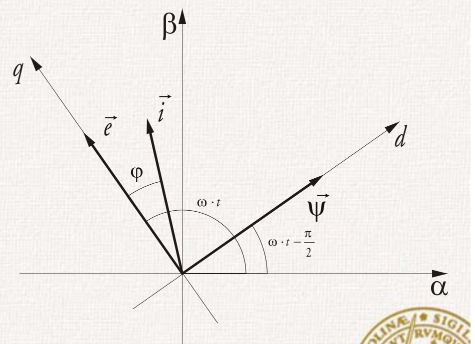


Fig.11: Sensitivity of the phase current reconstruction concerning inaccuracies of the inductance value on which the integration of the voltages $u_{L,i,m}$ is based. **(a)**: zero sequence current correction activated, **(b)**: no zero sequence current correction, i.e. $K(s) = 0$.

Load model



$$\vec{\psi} = \int_0^t \vec{e}\cdot dt = \int_0^t E\cdot e^{j\omega\cdot t}\,dt = \frac{\vec{e}}{j\cdot\omega} = \frac{E}{\omega} e^{j\left(\omega\cdot t-\frac{\pi}{2}\right)}$$



Reactive power

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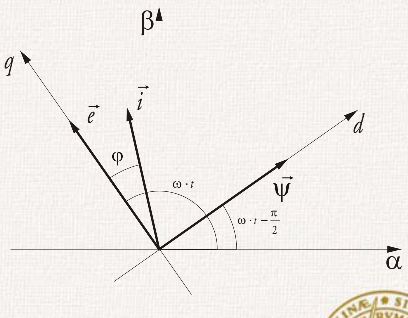
- **A phase lag between the voltage and the current:**

$$\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j(\omega t-\varphi)}$$

- **In flux coordinates:**

$$\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j\left(\frac{\pi}{2}-\varphi\right)}$$



Assymetric load

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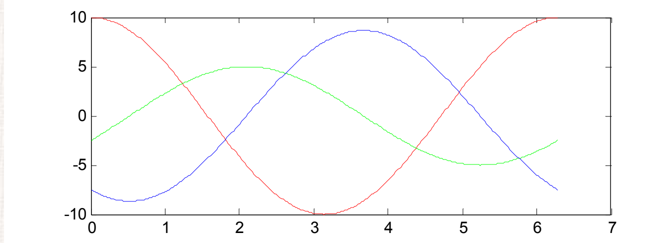
- **The phase currents are not equal in amplitude or phase lag ...**



An assymetric load current vector in the (α,β)-frame

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$$\vec{i}=\sqrt{\frac{2}{3}}\cdot\left(\underbrace{\hat{i}_a\cdot\frac{e^{j(\omega t-\varphi_a)}+e^{-j(\omega t-\varphi_a)}}{2}}_{\hat{i}_a\cdot\cos(\omega t-\varphi_a)}\cdot 1+\hat{i}_b\cdot\frac{e^{j\left(\omega t-\varphi_b-\frac{2\pi}{3}\right)}+e^{-j\left(\omega t-\varphi_b-\frac{2\pi}{3}\right)}}{2}\cdot e^{j\frac{2\pi}{3}}+\hat{i}_c\cdot\frac{e^{j\left(\omega t-\varphi_c-\frac{4\pi}{3}\right)}+e^{-j\left(\omega t-\varphi_c-\frac{4\pi}{3}\right)}}{2}\cdot e^{j\frac{4\pi}{3}}\right)=$$

$$=\sqrt{\frac{2}{3}}\cdot\left(\hat{i}_a\cdot\frac{e^{j(\omega t-\varphi_a)}+e^{-j(\omega t-\varphi_a)}}{2}+\hat{i}_b\cdot\frac{e^{j(\omega t-\varphi_b)}+e^{-j\left(\omega t-\varphi_b-\frac{4\pi}{3}\right)}}{2}+\hat{i}_c\cdot\frac{e^{j(\omega t-\varphi_c)}+e^{-j\left(\omega t-\varphi_c-\frac{2\pi}{3}\right)}}{2}\right)=$$

$$=\begin{cases}\hat{i}_x=\hat{i},\ \varphi_x=\varphi & \rightarrow\sqrt{\frac{2}{3}}\cdot\frac{3\cdot\hat{i}}{2}\cdot e^{j(\omega t-\varphi)}+\sqrt{\frac{2}{3}}\cdot\frac{3\cdot\hat{i}}{2}\left(\underbrace{e^{-j(\omega t-\varphi)}+e^{-j\left(\omega t-\varphi-\frac{4\pi}{3}\right)}+e^{-j\left(\omega t-\varphi-\frac{2\pi}{3}\right)}}_{=0}\right)=\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j(\omega t-\varphi)}\\ \hat{i}_x=\hat{i},\hat{i}_c\neq\hat{i},\varphi_x=\varphi & \rightarrow\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j(\omega t-\varphi)}+\sqrt{\frac{2}{3}}\cdot\left(\hat{i}_c-\hat{i}\right)\cdot\frac{e^{j(\omega t-\varphi_c)}+e^{-j\left(\omega t-\varphi_c-\frac{2\pi}{3}\right)}}{2}\end{cases}$$

An assymetric load current vector in the (d,q)-frame

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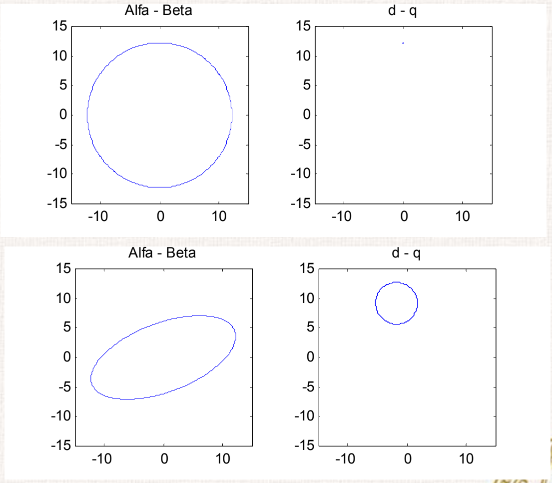
$$\vec{i}^{dq}=\vec{i}^{\alpha\beta}\cdot e^{-j\left(\omega t-\frac{\pi}{2}\right)}=$$

$$=\begin{cases}\hat{i}_x=\hat{i},\varphi_x=\varphi\rightarrow\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j(\omega t-\varphi)}\cdot e^{-j\left(\omega t-\frac{\pi}{2}\right)}\\ \hat{i}_x=\hat{i},\hat{i}_c\neq\hat{i},\varphi_x=\varphi\rightarrow\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j(\omega t-\varphi)}\cdot e^{-j\left(\omega t-\frac{\pi}{2}\right)}+\sqrt{\frac{2}{3}}\cdot\left(\hat{i}_c-\hat{i}\right)\cdot\frac{e^{j(\omega t-\varphi_c)}+e^{-j\left(\omega t-\varphi_c-\frac{2\pi}{3}\right)}}{2}\cdot e^{-j\left(\omega t-\frac{\pi}{2}\right)}\end{cases}=$$

$$=\begin{cases}\sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j\left(\frac{\pi}{2}-\varphi\right)}\\ \sqrt{\frac{3}{2}}\cdot\hat{i}\cdot e^{j\left(\frac{\pi}{2}-\varphi\right)}+\frac{1}{\sqrt{6}}\cdot\left(\hat{i}_c-\hat{i}\right)\cdot\left(\underbrace{e^{j\left(\frac{\pi}{2}-\varphi_c\right)}}_{\substack{\text{Not}\\ \text{moving!}}}+\underbrace{e^{-j\left(2\omega t-\varphi_c-\frac{2\pi}{3}-\frac{\pi}{2}\right)}}_{\substack{\text{Rotating}\\ \text{backwards}\\ \text{with}2\omega\,!}}\right)\end{cases}$$

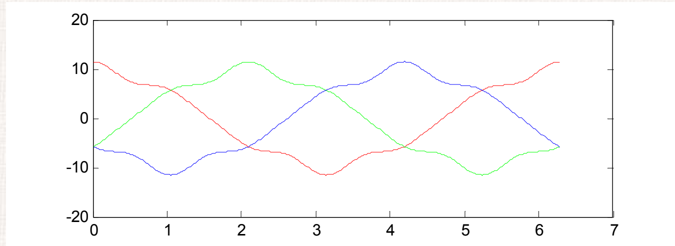
M-file ”Load current vectors” - demo

- **Symmetric load**
- **Assymetric**



Harmonics

- **Non-linear load impedance**

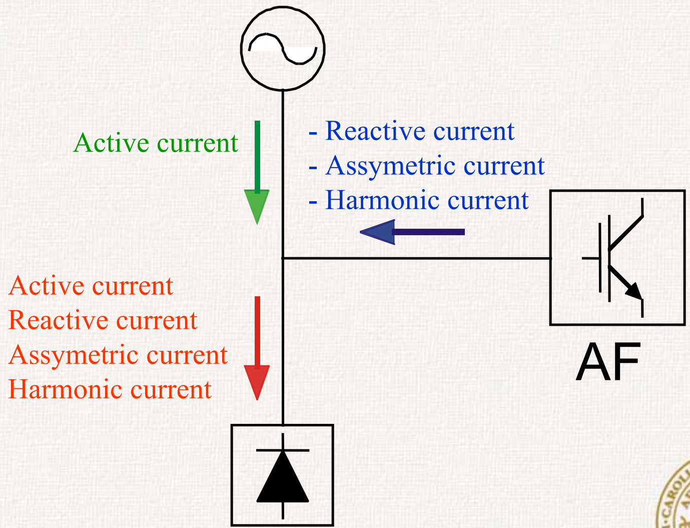


5’th and 7’th harmonic example with Simulink

$$\vec{i}^{\alpha\beta} = \sqrt{\frac{3}{2}}\cdot\hat{i}_1\cdot e^{j(\omega t-\varphi)} + \sqrt{\frac{3}{2}}\cdot\hat{i}_5\cdot e^{j(-5\omega t-\varphi)} + \sqrt{\frac{3}{2}}\cdot\hat{i}_7\cdot e^{j(7\omega t-\varphi)}$$

$$\vec{i}^{dq} = \sqrt{\frac{3}{2}}\cdot\hat{i}_1\cdot e^{j\left(\frac{\pi}{2}-\varphi\right)} + \sqrt{\frac{3}{2}}\cdot\hat{i}_5\cdot e^{j(-6\omega t-\varphi)} + \sqrt{\frac{3}{2}}\cdot\hat{i}_7\cdot e^{j(6\omega t-\varphi)}$$

Active filtering



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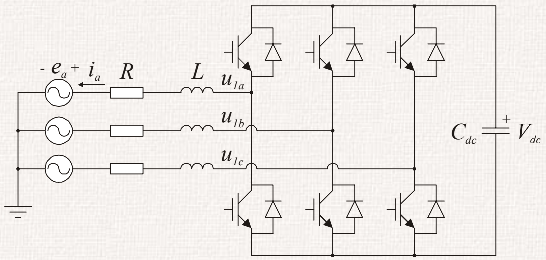
Voltage Source Converters



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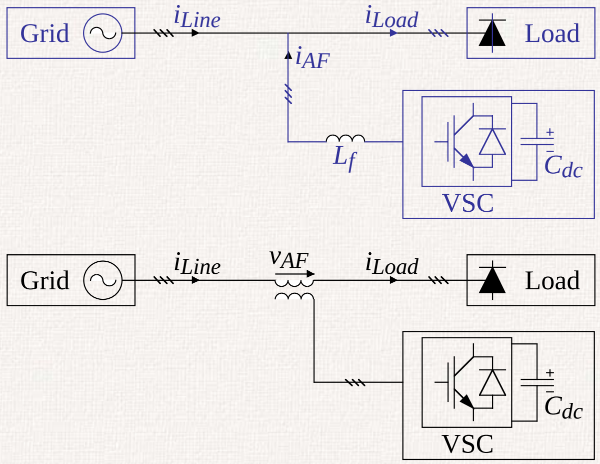
Types of Active Filters



Shunt (top) and series (bottom) active filters.

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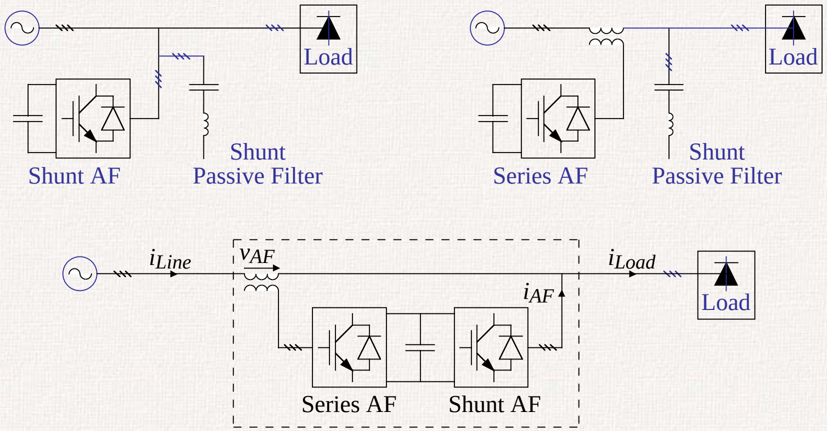
Active Filter Combinations



Shunt and series hybrid active filters (top) and Unified Power Flow Controller, UPFC (bottom).

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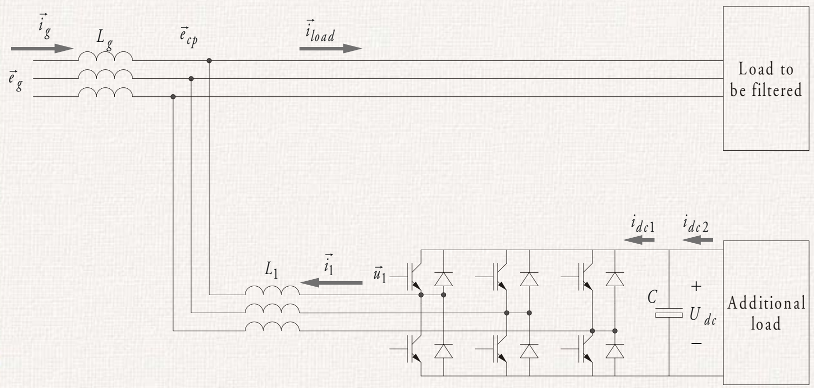
Shunt Active Filter



AC side Current Control (I)

- **Vector Control with Field Orientation**

$$\vec{u}_1^*(k)=\left(\frac{L_1}{T_s}+\frac{R_1}{2}\right)\cdot\left(\left(\vec{i}_1^*(k)-\hat{\vec{i}}_1(k)\right)+\frac{T_s}{\left(\frac{L}{R}+\frac{T_s}{2}\right)}\cdot\sum_{n=0}^{n=k-1}\left(\vec{i}_1^*(n)-\hat{\vec{i}}_1(n)\right)\right)+\hat{\vec{e}}_{cp}(k)$$

AC side Current Control (II)

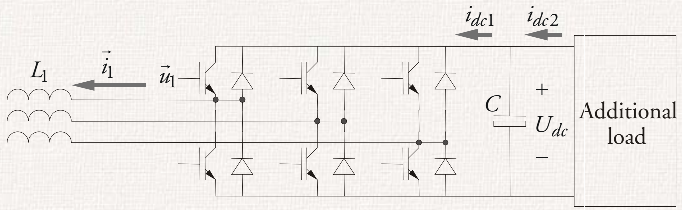
- **Note the cross-coupling in the line model**

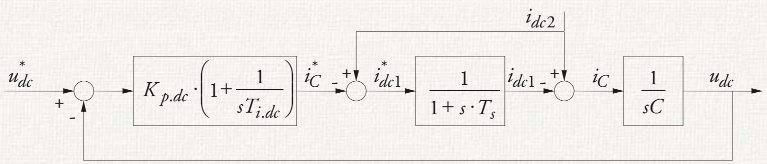
$$\vec{u}_1^{dq}=L_1\frac{d}{dt}\vec{i}_1^{dq}+j\omega_1L_1\vec{i}_1^{dq}+R_1\vec{i}_1^{dq}+\vec{e}_{cp}^{dq}\Leftrightarrow\begin{cases}u_{1d}=L_1\frac{d}{dt}i_{1d}+R_1i_{1d}-\omega_1L_1i_{1q}+e_{cpd}\\ u_{1q}=L_1\frac{d}{dt}i_{1q}+R_1i_{1d}+\omega_1L_1i_{1d}+e_{cpq}\end{cases}$$

- **This cross-coupling should be incorporated in the current controller**

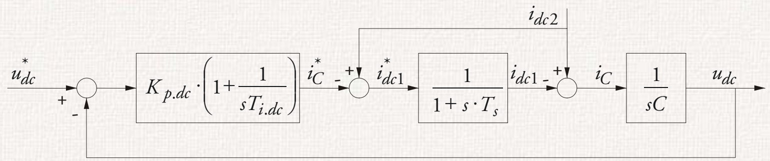
$$\vec{u}_1^*(k)=\left(\frac{L_1}{T_s}+\frac{R_1}{2}\right)\cdot\left(\left(\vec{i}_1^*(k)-\hat{\vec{i}}_1(k)\right)+\frac{T_s}{\left(\frac{L}{R}+\frac{T_s}{2}\right)}\cdot\sum_{n=0}^{n=k-1}\left(\vec{i}_1^*(n)-\hat{\vec{i}}_1(n)\right)\right)+\frac{j\omega L}{2}\cdot\left(\vec{i}_1^*(k)+\hat{\vec{i}}_1(k)\right)+\hat{\vec{e}}_{cp}(k)$$

DC link Voltage Control System (I)





DC link Voltage Control System (II)



- **Transfer function from reference to actual DC link voltage**

$$\left(U_{dc}^*(s)-U_{dc}(s)\right)\cdot K_{p,dc}\cdot\left(1+\frac{1}{sT_{i,dc}}\right)\cdot\frac{1}{1+sT_s}\cdot\frac{1}{sC}=U_{dc}(s)\Leftrightarrow$$

$$G_{Udc}(s)=\frac{U_{dc}(s)}{U_{dc}^*(s)}=\frac{s^3+(1/T_s)s^2}{s^3+(1/T_s)s^2+\left(K_{p,dc}/T_sC\right)s+\left(K_{p,dc}/T_{i,dc}T_sC\right)}$$

- **Desired denominator polynomial**

$$A(s)=(s+\omega_n)\cdot\left(s^2+2\zeta_n\omega_ns+\omega_n^2\right)$$

Controller Parameters ...

- **Use Symmetric Optimum**

$$\zeta_n = \frac{a-1}{2} \quad , \quad \omega_n = \frac{a}{T_s} \quad \text{(Note } a > 1 \text{ for stable system)} \quad \Rightarrow$$

$$K_{p.dc} = \frac{a \cdot C}{T_{i.dc}} \quad , \quad T_{i.dc} = a^2 \cdot T_s$$

- **Note that for $a = 2$ the poles are placed as for a Butterworth filter, i.e. maximum flat pass-band. However, the bandwidth is by far to high for practical operation.**

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Convert DC to AC current references

$$p(t) = Ri_{1d}^2 + Ri_{1q}^2 + L\frac{di_{1d}}{dt}i_{1d} + L\frac{di_{1q}}{dt}i_{1q} + e_{cp.q}i_{1q} = u_{dc} \cdot i_{dc1} \approx e_{cp.q}i_{1q} \quad \Rightarrow$$

$$i_{dc1} = \frac{e_{cp.q}}{u_{dc}} \cdot i_{1q} \quad \Rightarrow \quad i_{1q}^* = \frac{u_{dc}}{e_{cp.q}} \cdot i_{dc1}^* = \frac{u_{dc}}{e_{cp.q}} \cdot \left(i_{dc2} - i_{Cdc}^*\right)$$

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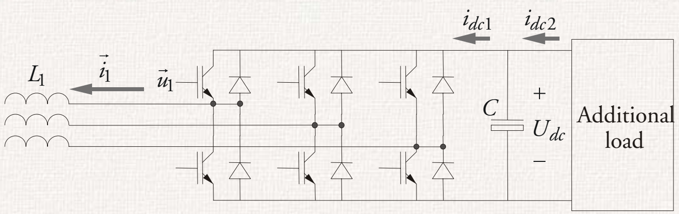
DC link voltage controller



$$i_{1q}^* = \frac{u_{dc}}{e_{cp}}\left(i_{dc2} - \underbrace{K_{p.dc} \cdot \left(1 + \frac{1}{sT_{i.dc}}\right) \cdot \left(u_{dc}^* - u_{dc}\right)}_{i_{Cdc}^*}\right)$$

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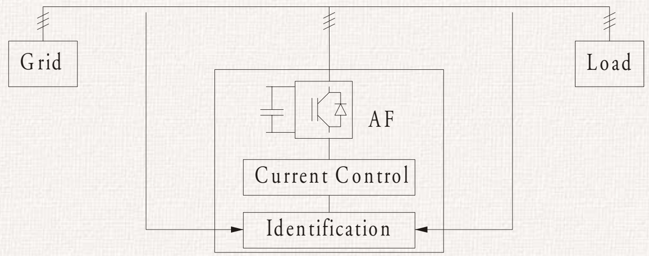
Active filter control



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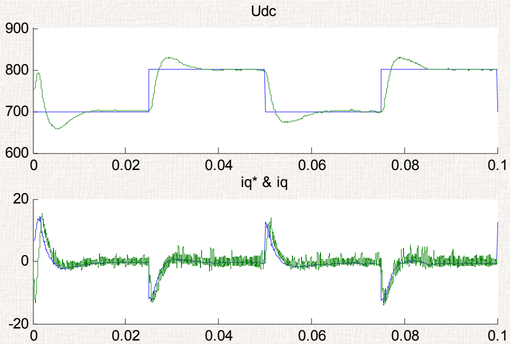
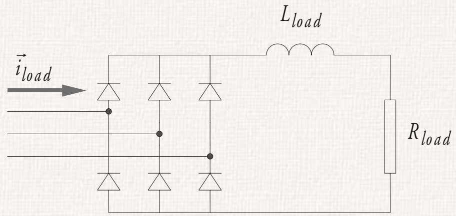
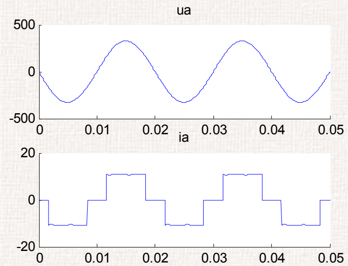
Example of DC voltage control

```
>> L=0.01;
>> R=1;
>> Ts=0.0005;
>> Tidc=9*Ts;
>> Kpdc=3*Cdc/Tidc;
>> Cdc=1e-4;
```



Example with active filtering





Filter Current References (I)

$$i^*_{d,ActiveFilter} = i_{d,load}$$

$$i^*_{q,ActiveFilter} = i_{q,load} \cdot \frac{s \cdot T_f}{1 + s \cdot T_f} + \frac{u_{dc}}{e_{cp}} \left(i_{dc2} - K_{p.dc} \cdot \left(1 + \frac{1}{sT_{i.dc}} \right) \cdot \left(u^*_{dc} - u_{dc} \right) \right) \cdot \frac{1}{1 + s \cdot T_f}$$

- **Note that the q-direction current reference based on the load current is high-pass filtered since the active filter should not provide active power to the load**
- **Note that the DC link current reference is low- pass filtered since it is important that it does not contain any 100 Hz (twice fundamental) component which would result in a negative sequence component consumed by the active filter**

Filter Current References (II)

- **To avoid that the DC link current reference contains a negative sequence component $T_f \leq 10$ ms is a proper choice.**
- **To assure that the negative sequence current consumed by the load is provided by the active filter $T_f \geq 10$ ms is a proper choice.**
- **Use $T_f = 10$ ms**

Filter Current References (III)

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- Since $T_f = 10$ ms >> $T_s \approx 100$ µs (typically) the converter dynamics do not have to be included in the selection of the DC link voltage controller parameters, i.e. $G_i(s) \equiv 1$.
- However a new low-pass filter shows up in the transfer function, e.g. the one with time constant T_f.
- This means that the transfer function looks exactly the same but T_s is replaced by T_f.
- In this case $a = 2$ is a proper choice for the DC link voltage controller parameters.
- Note that $a = 3$ gives real poles since the closed loop damping of all poles is equal to 1.

Filter Current References (IV)

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- The rather long time constant of the low-pass filter (T_f) results in the need of a comparably large DC link capacitor (C) for converters used for active filters.
- In this case the DC side load current (i_{dc2}) is also filtered with T_f which increases the need of a large DC link capacitor. The DC side load current (i_{dc2}) should be fed forward without any low-pass filtering for proper operation.

Filter Currents

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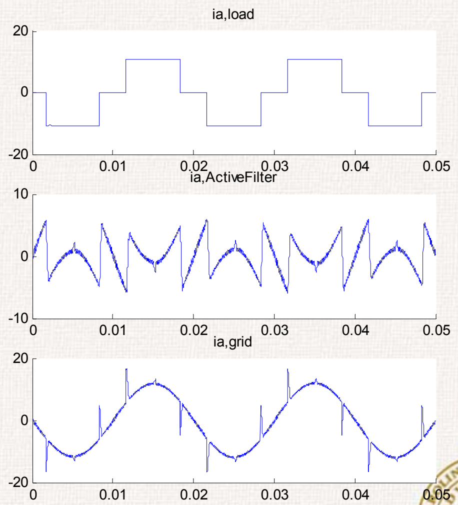
```
>> L=0.01;
>> R=1;
>> Ts=0.00005;
>> Rload=50;
>> Lload=0.1;
>> Tf=10e-3;
>> Tidc=9*Tf;
>> Kpdc=3*Cdc/Tidc;
```



Spectra

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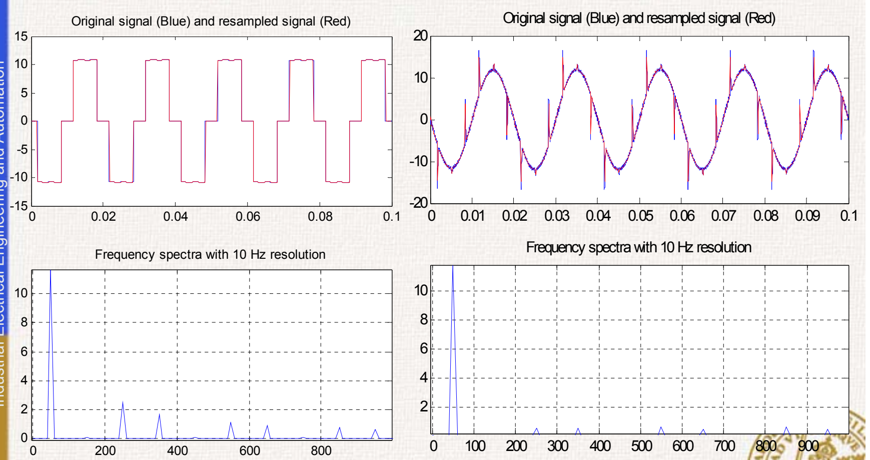
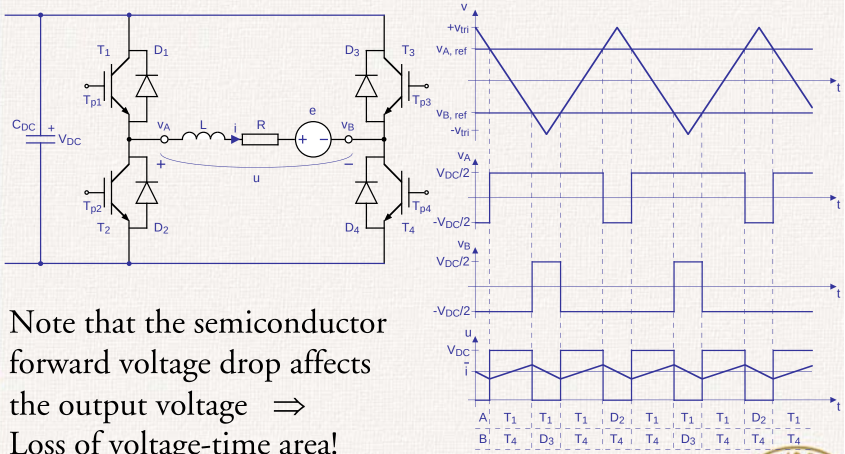


X. Effects of non-idealities (I)



Note that the semiconductor forward voltage drop affects the output voltage $\Rightarrow$
Loss of voltage-time area!

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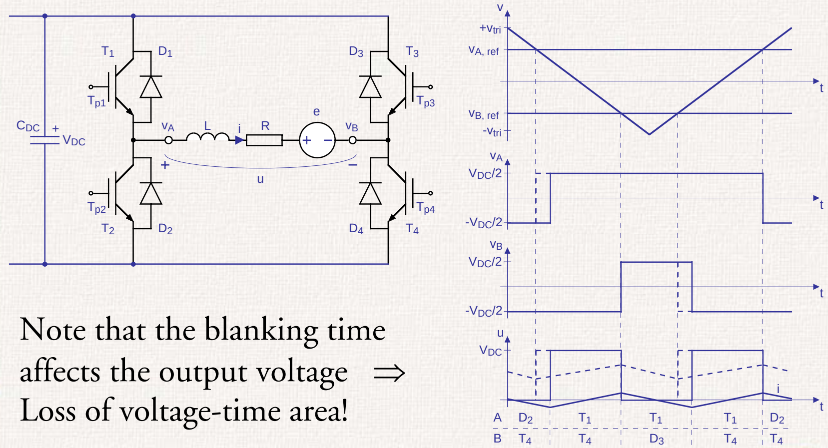
X. Effects of non-idealities (II)



Note that the blanking time affects the output voltage $\Rightarrow$
Loss of voltage-time area!

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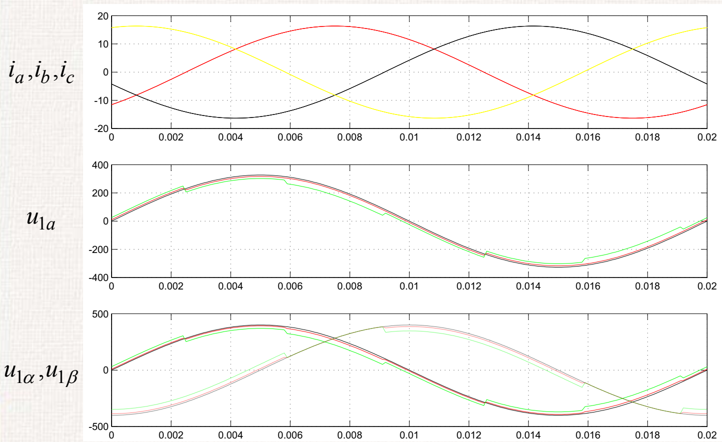
X. Effects of non-idealities (III)



Forward Voltage drop: red
Blanking Time: green

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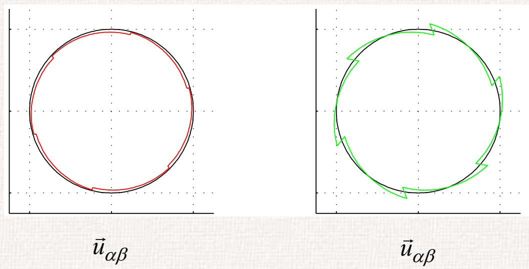
X. Effects of non-idealities (IV)



Forward Voltage drop: red
Blanking Time: green

X. Effects of non-idealities (V)

The three-phase converter controller can not fully compensate for these non-idealities for two reasons:

- The proportional part of the controller is too "weak" to compensate. The only possible way to make it less weak is to increase the gain which would give an oscillatory behaviour
- The integral part act properly only on dc-components and not on *dq*-reference frame harmonics. To circumvent the last problem, rotating coordinate systems are included also for the frequencies where the harmonics appear.

More Information

Active Power Line Conditioners are in most cases not covered in books on power electronics, however:

On the home page of power electronics course:

- The Power Electronics Handbook", edited by Timothy L Skvarenina, *CRC-press*, 2002, ISBN 0-8493-7336-0. http://www.engnetbase.com/books/447/7336_pdf_toc.pdf

On Per Karlsson's homepage:

- M. Bojrup, (1999), "Advanced Control of Active Filters in a Battery Charger Application", *Licentiate thesis, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology*, Lund, Sweden, December 1999, ISBN 91-88934-13-6. http://www.iea.lth.se/~ielper/charger/MB-thesis.pdf

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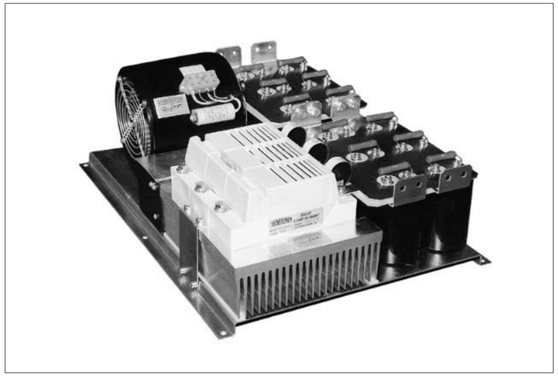
Y. Conclusions

Commercial Semikron three-phase inverter
Suitable also for active power line conditioning!



73 kVA PWM three phase inverter with a long-life DC-link for motor drives

$V_{DC\text{-}link}$ = 600 V ± 10 %
V_{output} = 3 x 420 V (0,05 Hz ... 60 Hz)
$I_{nominal}$ = 100 A_{RMS}, $I_{overload}$ = 165 A_{RMS}
$f_{switching}$ = 1,5 kHz

SKiiP 342GD120 - 314 CTV
P 16/280 F
9 900 µF / 800 V at DC-link

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