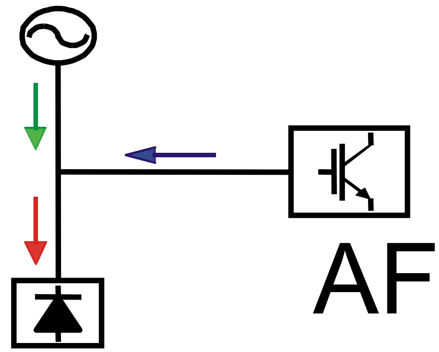
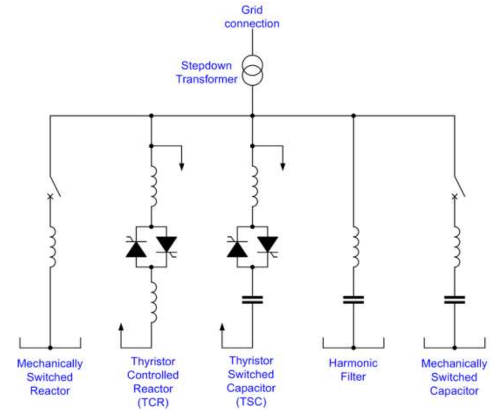
# Grid Connected Power Electronics

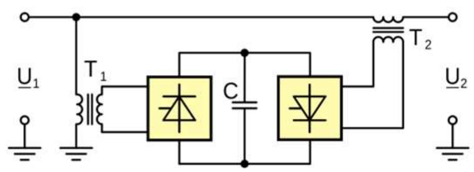
L11 - Static VAr compensation

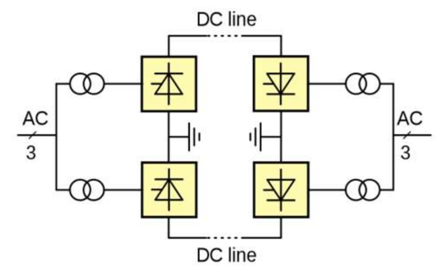
# Acronyms

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




*All made to improve "Power Quality"*

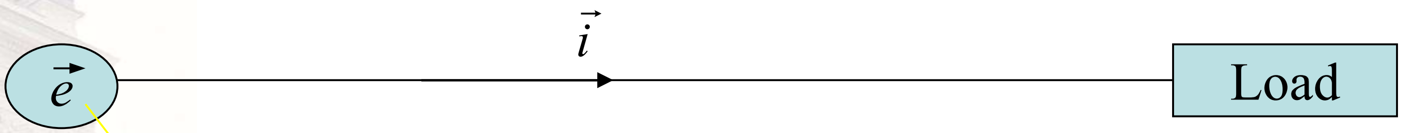
# Non ideal loads

- **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

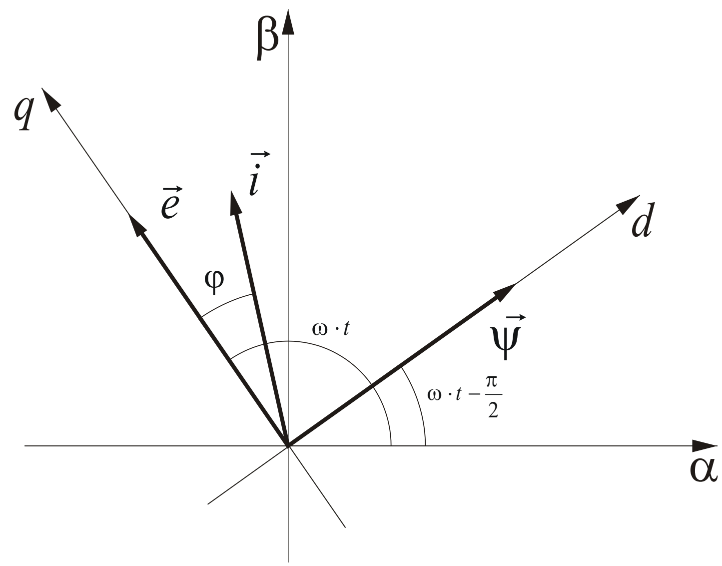
- **Self improvement**
  - ***Solutions that draw as "ideal" current as possible from the grid***
- **Compensation**
  - ***A parallel unit is used to counteract the non ideal currents drawn by the main load***

# Load model




$$\vec{\psi} = \int_0^t \vec{e} \cdot dt = \int_0^t E \cdot e^{j\omega \cdot t} dt = \frac{\vec{e}}{j \cdot \omega} =$$

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



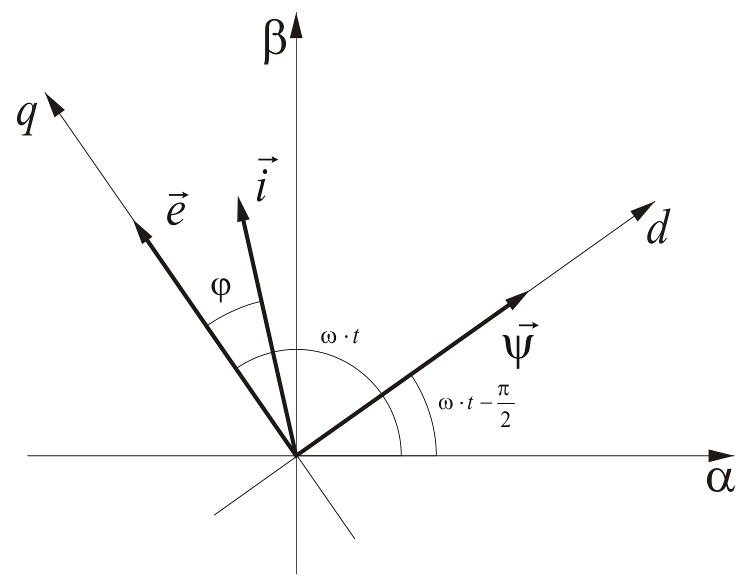
# Reactive power

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

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

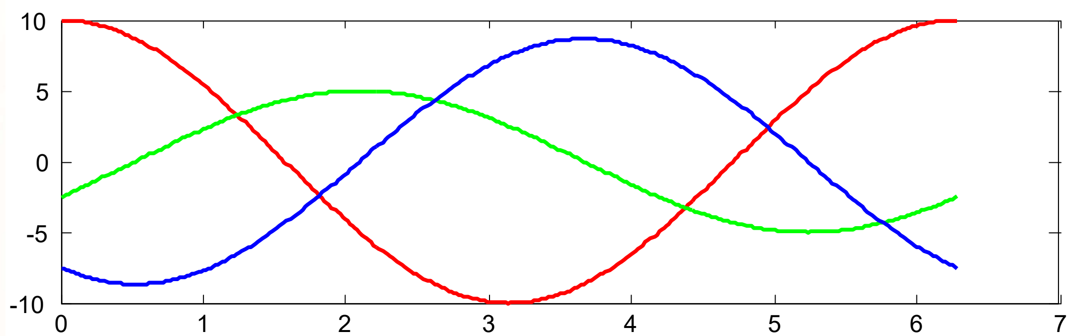
- **In flux coordinates:**

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



# Assymetric load

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



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

$$\vec{\imath} = \sqrt{\frac{2}{3}} \cdot \left( \underbrace{\hat{\imath}_a \cdot \frac{e^{j(\omega t-\phi_a)} + e^{-j(\omega t-\phi_a)}}{2}}_{\hat{\imath}_a \cdot \cos(\omega t-\phi_a)} \cdot 1 + \hat{\imath}_b \cdot \frac{e^{j\left(\omega t-\phi_b-\frac{2\pi}{3}\right)} + e^{-j\left(\omega t- \quad _b-\frac{2\pi}{3}\right)}}{2} \cdot e^{j\frac{2\pi}{3}} + \hat{\imath}_c \cdot \frac{e^{j\left(\omega t-\phi_c-\frac{4\pi}{3}\right)} + e^{-j\left(\omega t-\phi_c-\frac{4\pi}{3}\right)}}{2} \cdot e^{j\frac{4\pi}{3}} \right) =$$

$$= \sqrt{\frac{2}{3}} \cdot \left( \hat{\imath}_a \cdot \frac{e^{j(\omega t-\phi_a)} + e^{-j(\omega t-\phi_a)}}{2} + \hat{\imath}_b \cdot \frac{e^{j(\omega t-\phi_b)} + e^{-j\left(\omega t-\phi_b-\frac{4\pi}{3}\right)}}{2} + \hat{\imath}_c \cdot \frac{e^{j(\omega t-\phi_c)} + e^{-j\left(\omega t-\phi_c-\frac{2\pi}{3}\right)}}{2} \right) =$$

$$= \begin{cases} \hat{\imath}_x = \hat{\imath}, \phi_x = \phi \rightarrow \sqrt{\frac{2}{3}} \cdot \frac{3 \cdot \hat{\imath}}{2} \cdot e^{j(\omega t-\phi)} + \sqrt{\frac{2}{3}} \cdot \frac{3 \cdot \hat{\imath}}{2} \left( \underbrace{e^{-j(\omega t-\phi)} + e^{-j\left(\omega t-\phi-\frac{4\pi}{3}\right)} + e^{-j\left(\omega t-\phi-\frac{2\pi}{3}\right)}}_{=0} \right) = \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot e^{j(\omega t-\phi)} \\ \hat{\imath}_x = \hat{\imath}, \hat{\imath}_c \neq \hat{\imath}, \phi_x = \phi \rightarrow \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot e^{j(\omega t- \quad )} + \sqrt{\frac{2}{3}} \cdot (\hat{\imath}_c - \hat{\imath}) \cdot \frac{e^{j(\omega t-\phi_c)} + e^{-j\left(\omega t-\phi_c-\frac{2\pi}{3}\right)}}{2} \end{cases}$$

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

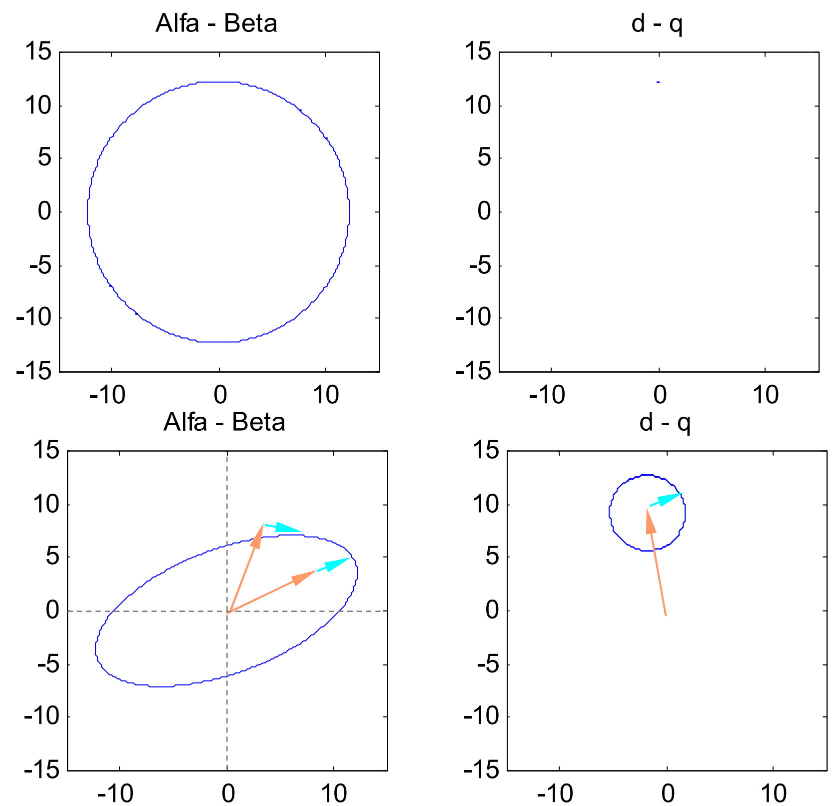
$$\vec{\imath}^{dq} = \vec{\imath}^{\alpha\beta} \cdot e^{-j\left(\omega t \ \frac{\pi}{2}\right)} = \begin{cases} = \\ = \end{cases}$$

$$= \begin{cases} \hat{\imath}_x = \hat{\imath}, \phi_x = \phi \rightarrow \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot e^{j(\omega t - \phi)} \cdot e^{-j\left(\omega t - \frac{\pi}{2}\right)} \\ \hat{\imath}_x = \hat{\imath}, \hat{\imath}_c \neq \hat{\imath}, \phi_x = \phi \rightarrow \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot e^{j(\omega t - \phi)} \cdot e^{-j\left(\omega t - \frac{\pi}{2}\right)} + \sqrt{\frac{2}{3}} \cdot (\hat{\imath}_c - \hat{\imath}) \cdot \frac{e^{j(\omega t - \phi_c)} + e^{-j\left(\omega t - \phi_c - \frac{2\pi}{3}\right)}}{2} \cdot e^{-j\left(\omega t \ \frac{\pi}{2}\right)} \end{cases} =$$

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

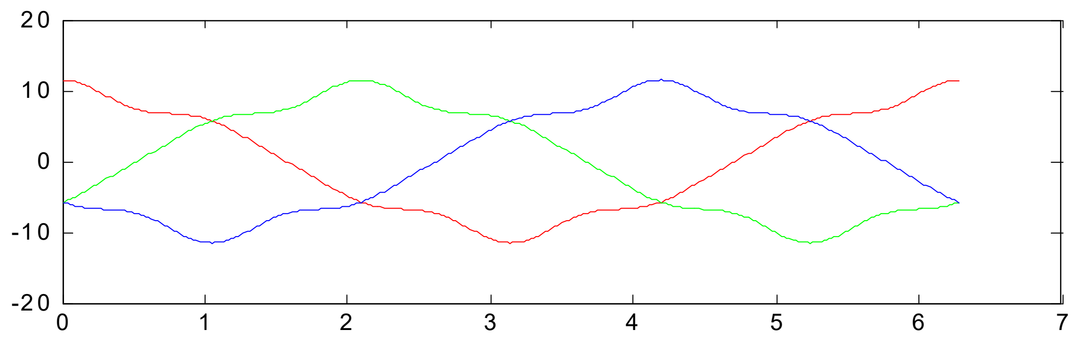
# M-file ”Load current vectors” - demo

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



# Harmonics

- **Non linear load impedance**

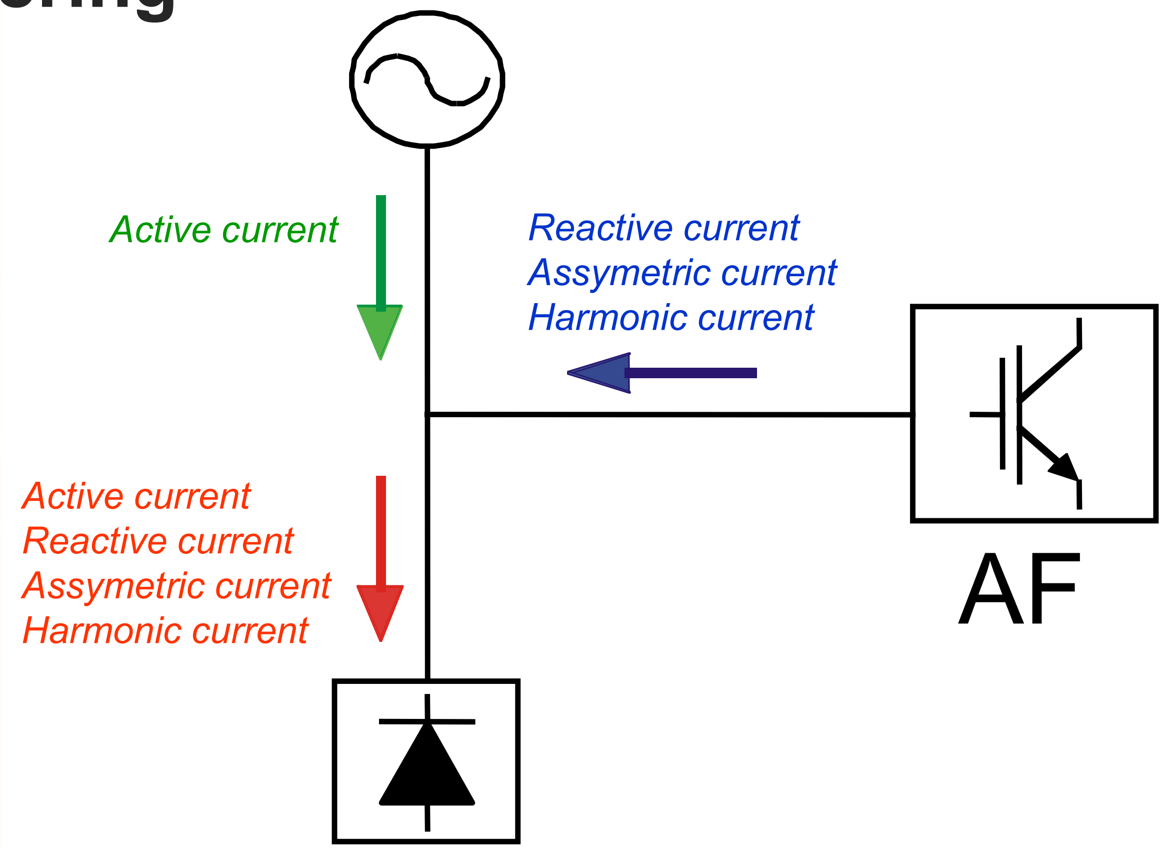


# 5’th and 7’th harmonic example with Simulink

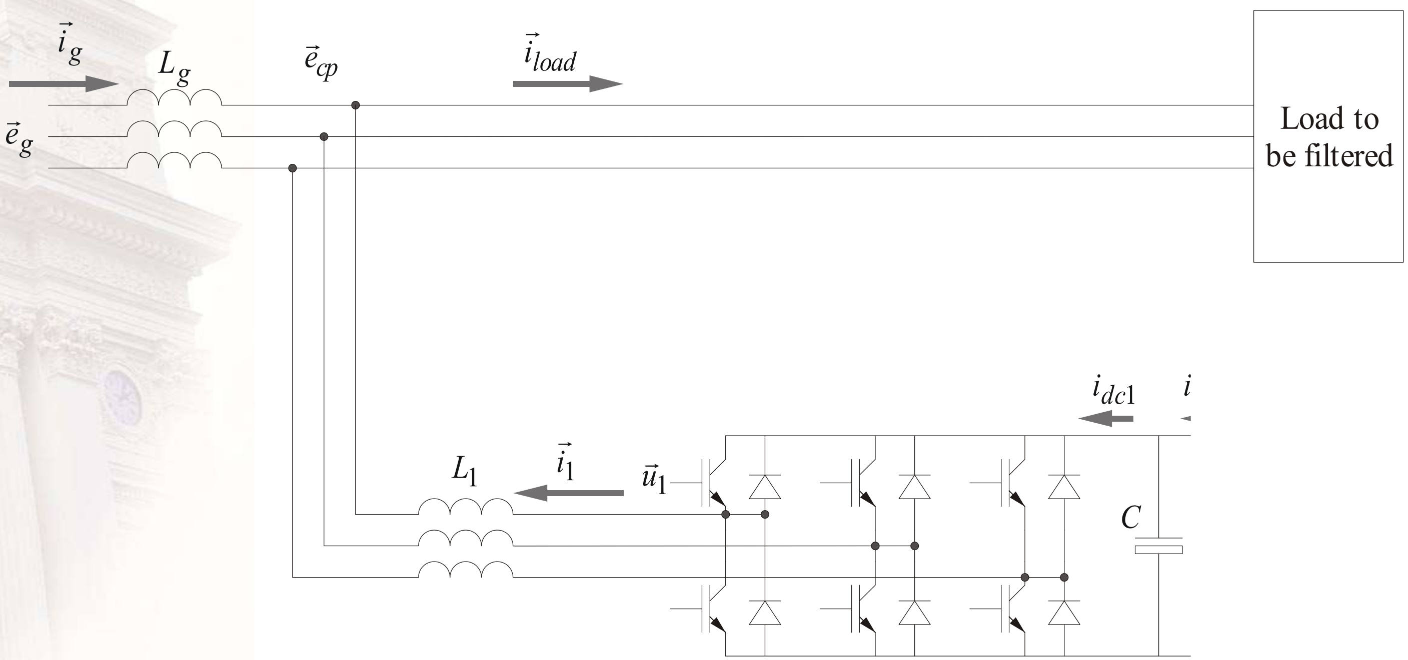
$$\vec{\imath}^{\alpha\beta} = \sqrt{\frac{3}{2}} \cdot \hat{\imath}_1 \cdot e^{j(\omega t - \phi)} + \sqrt{\frac{3}{2}} \cdot \hat{\imath}_5 \cdot e^{j(-5\omega t - \quad)} + \sqrt{\frac{3}{2}} \cdot \hat{\imath}_7 \cdot e^{j(7\omega t - \phi)}$$

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

# Active filtering



# Shunt Active Filter

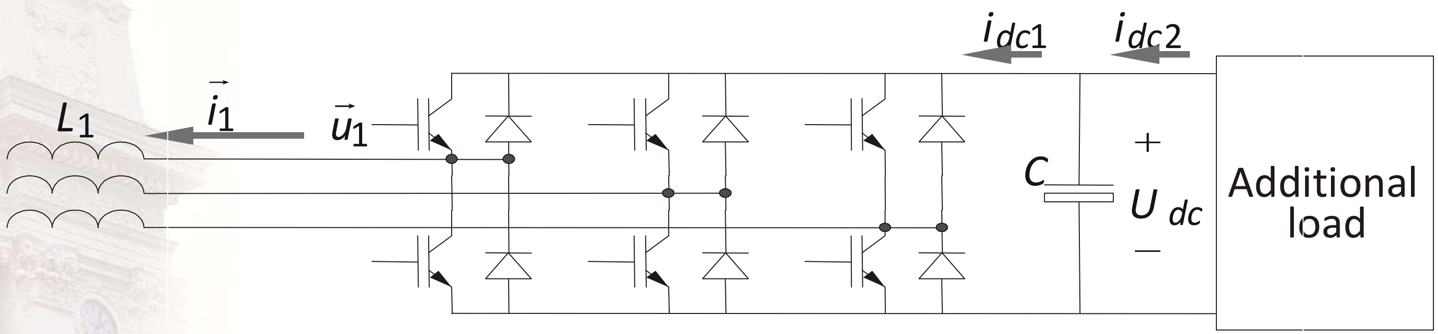


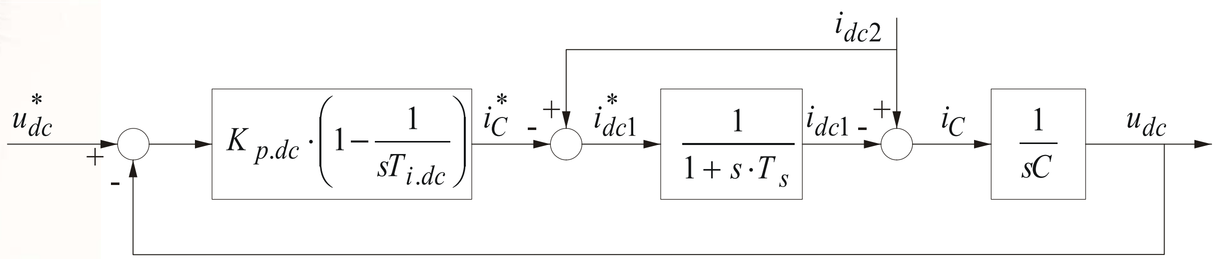
# AC side Current Control

- **Vector Control with Field Orientation**

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

# DC link Voltage Control System



# Controller Parameters ...

- **Use Symmetric Optimum**

$$\zeta = \frac{a-1}{2}$$

$$T_{i.dc} = a^2 \cdot T_s, \text{where} a > 1$$

$$K_{p.dc} = \frac{a \cdot C}{T_{i.dc}}$$

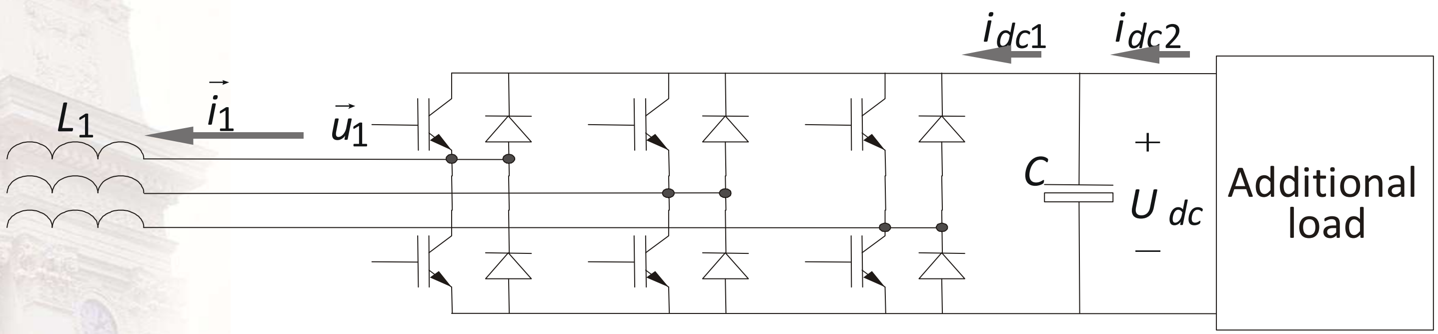
# Convert DC to AC current references

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

$$\Downarrow$$

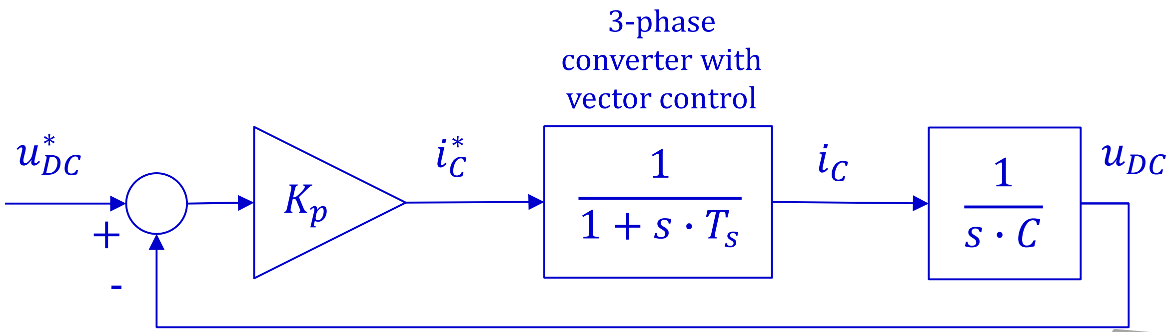
$$i_{dc1} = \frac{e_{cp.q}}{u_{dc}} \cdot i_{1q}$$

# DC link voltage controller




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

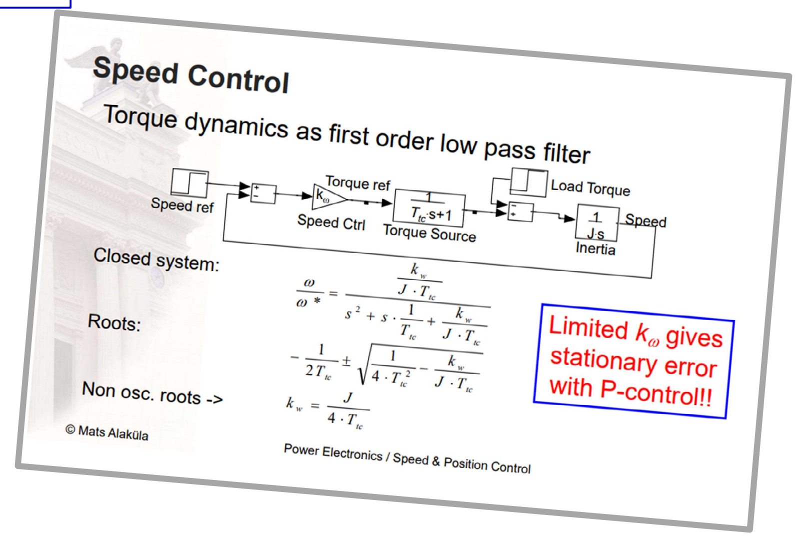
# DC Linc Voltage Control vs Speed Control



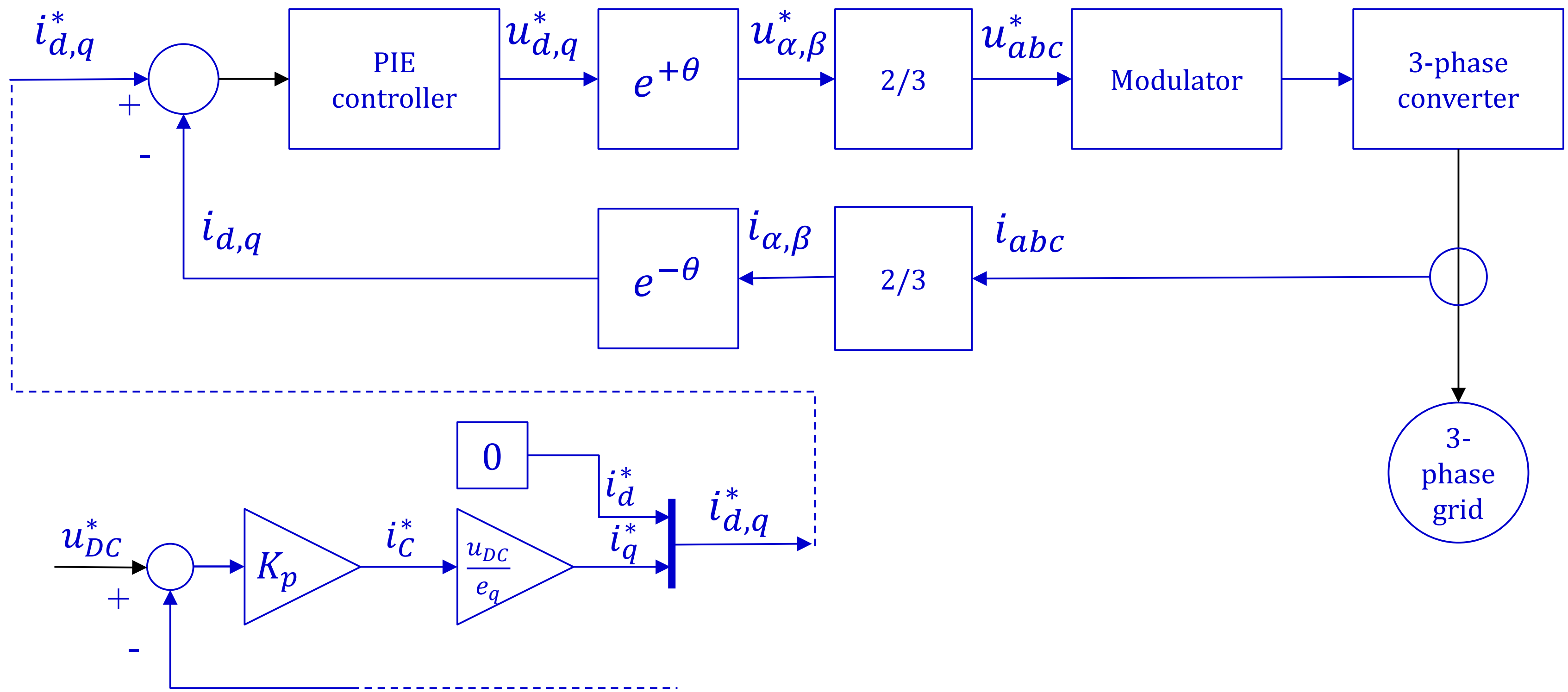

$$\frac{u_{DC}}{u_{DC}^*} = \frac{K_p \cdot \frac{1}{1+s\cdot T_s}\cdot\frac{1}{s\cdot C}}{1+K_p\cdot\frac{1}{1+s\cdot T_s}\cdot\frac{1}{s\cdot C}}$$

$$= \frac{\frac{K_p}{C\cdot T_s}}{s^2+s\cdot\frac{1}{T_s}+\frac{K_p}{C\cdot T_s}}$$

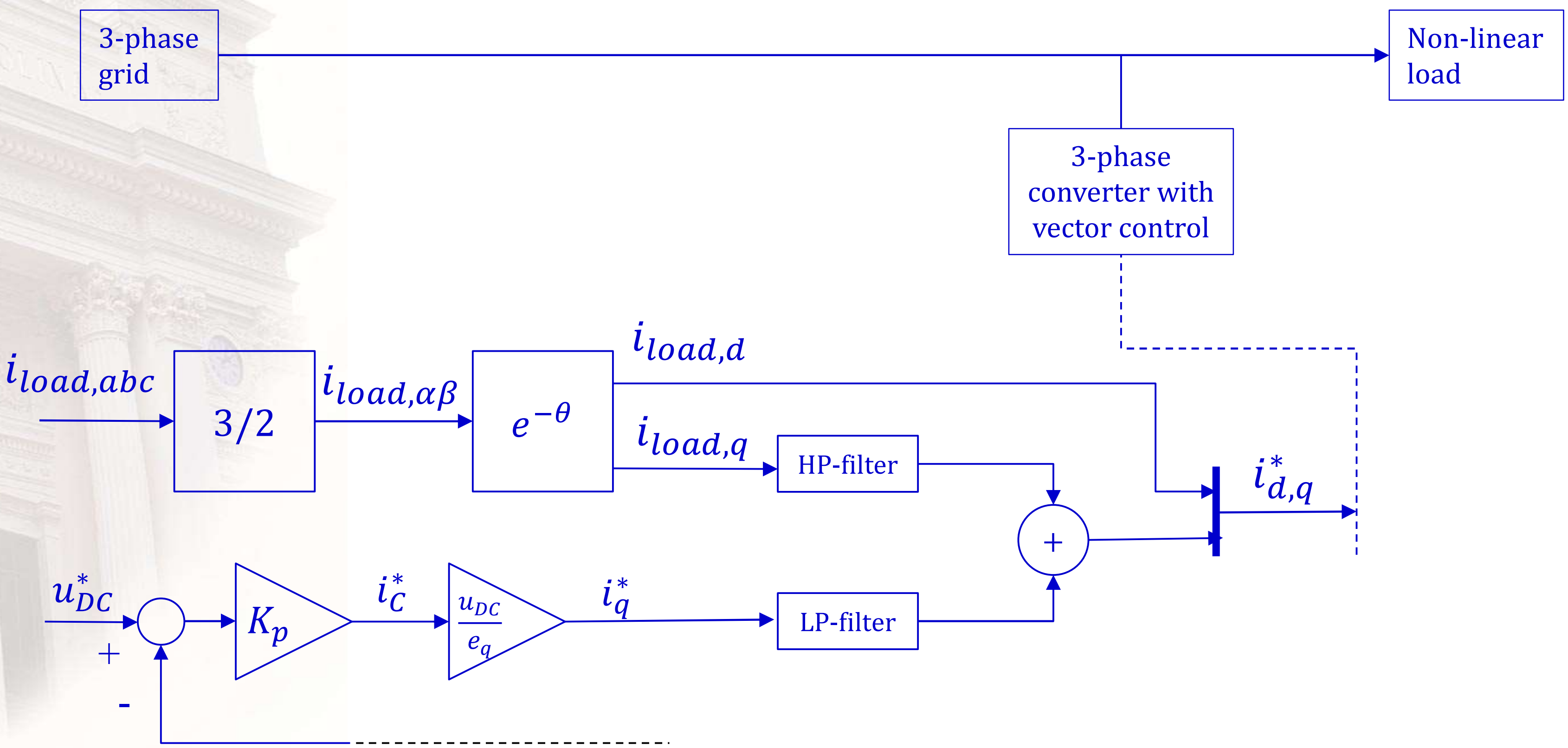
$$s^2 + s\cdot\frac{1}{T_s}+\frac{K_p}{C\cdot T_s}=0 \rightarrow K_p = \frac{C}{4\cdot T_s}$$



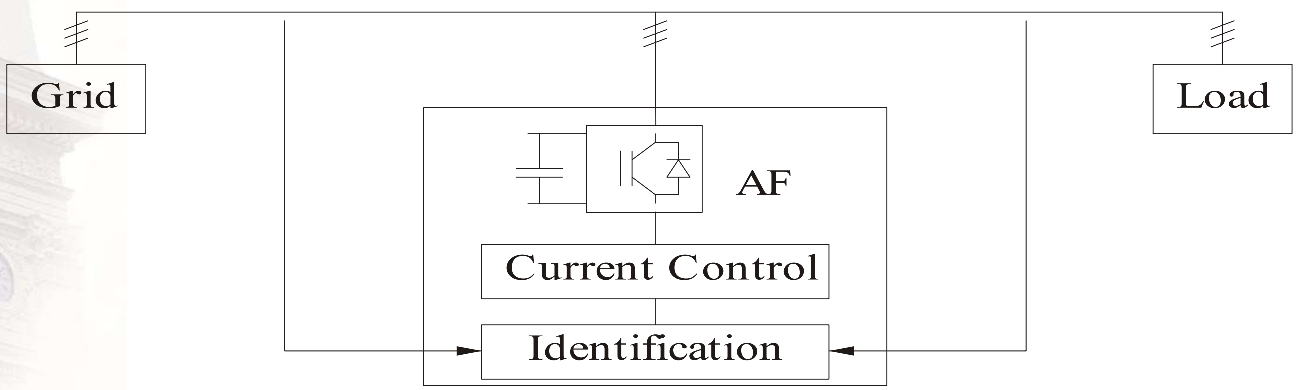
# The 3phase Grid connected converter is the DC link current source



# The full control system

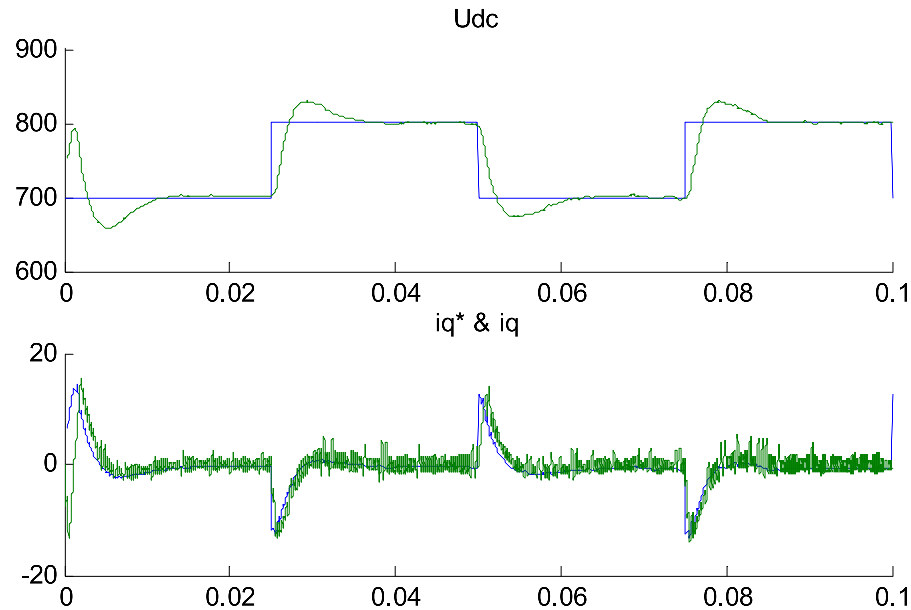


# Active filter control

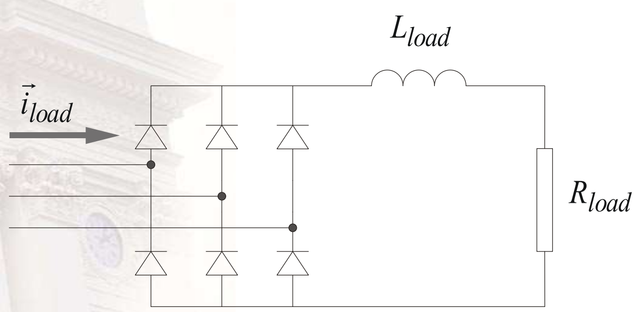


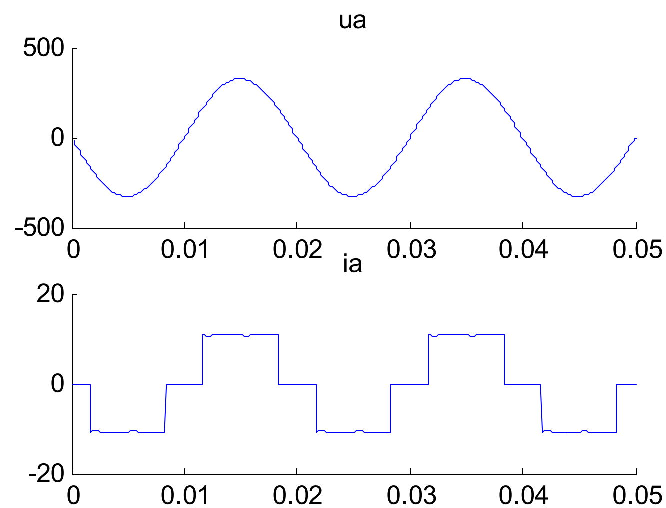
# Example of DC voltage control

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



# Example with active filtering



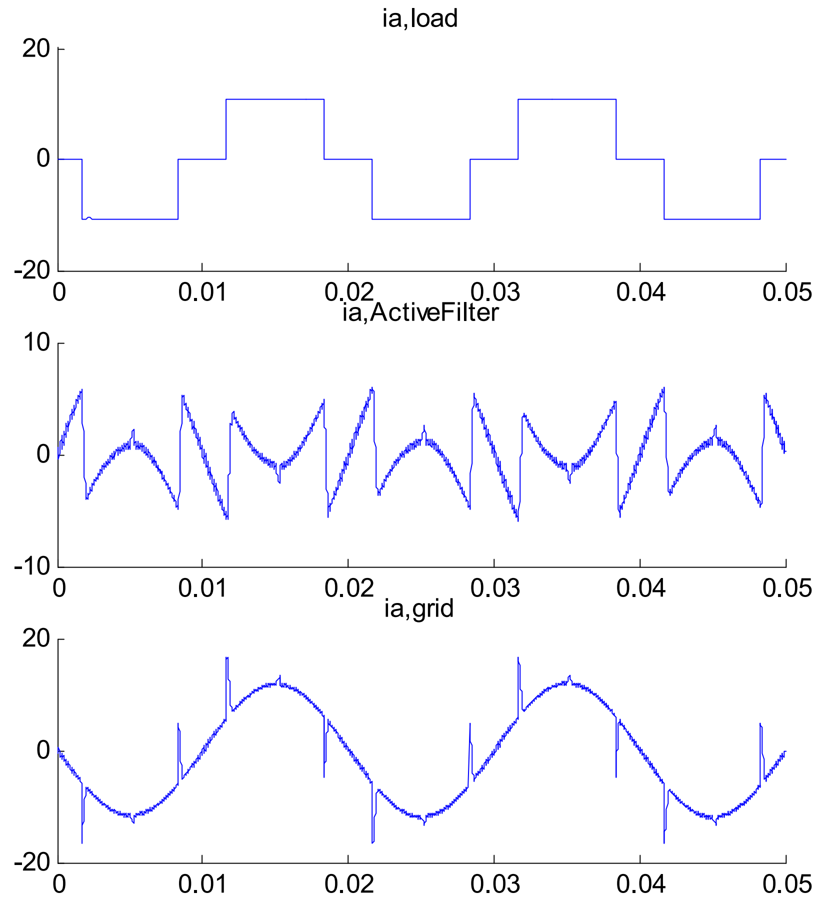
# Filter Current References

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

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

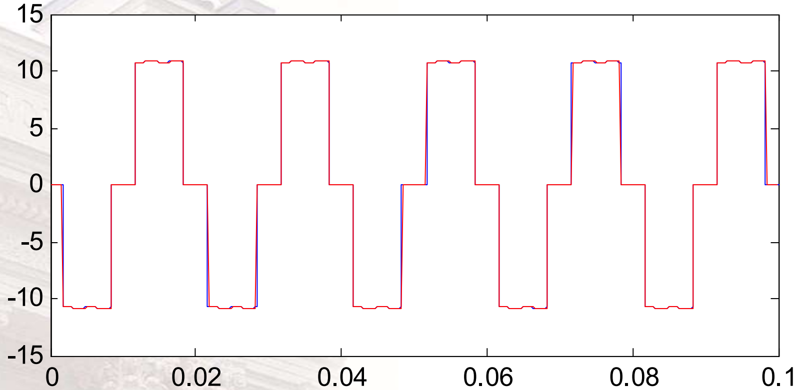
# Filter Currents

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

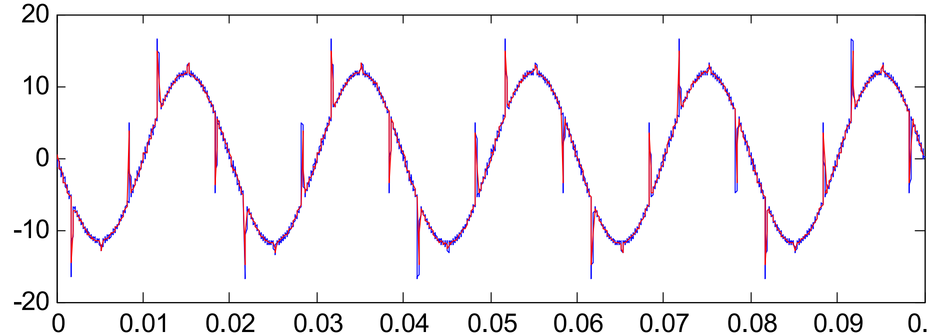


# Spectra

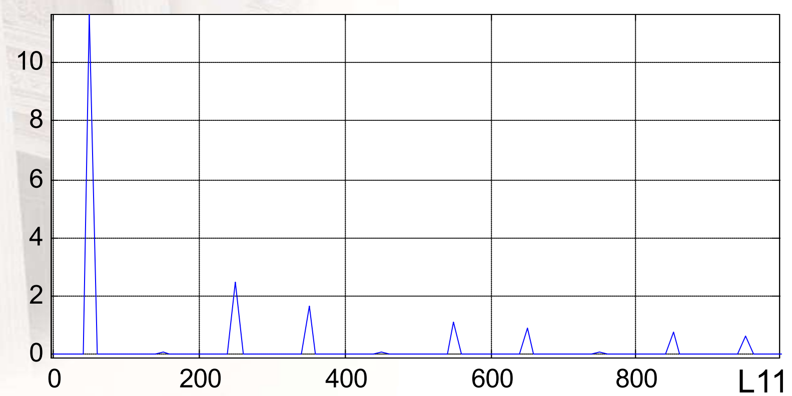
Original signal (Blue) and resampled signal (Red)




Original signal (Blue) and resampled signal (Red)




Frequency spectra with 10 Hz resolution

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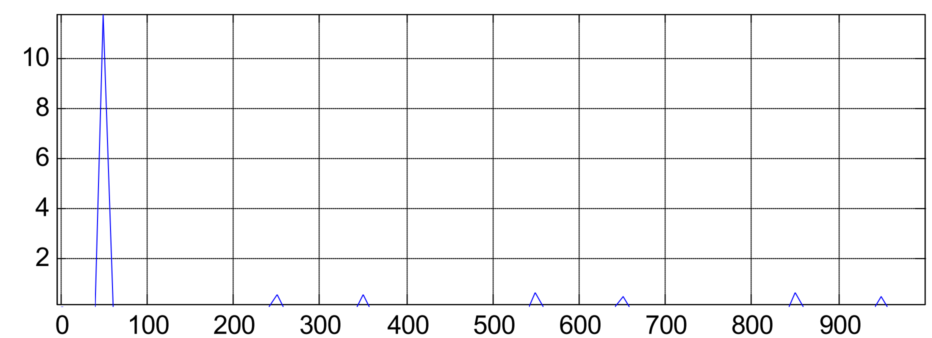

# Exercises

- **3-phase vectors**
  - ***1.11, 1.12, 1.13, 1,14***
- **3-phase current control**
  - ***2.4***