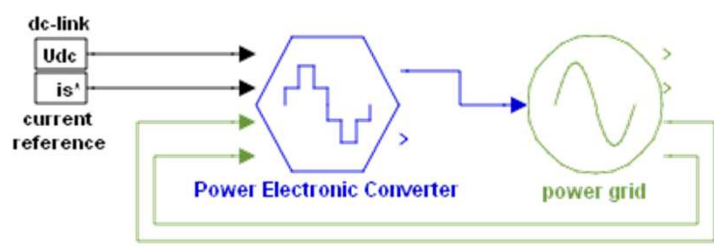
L10 - AC current control



Current vector abc→αβ

- **Symmetric 3-phase**

$$\begin{cases} i_1(t) = \sqrt{2}\cdot\hat{\imath}\cdot\cos(\omega t-\varphi) \\ i_2(t) = \sqrt{2}\cdot\hat{\imath}\cdot\cos\left(\omega t-\frac{2\pi}{3}-\varphi\right) \\ i_3(t) = \sqrt{2}\cdot\hat{\imath}\cdot\cos\left(\omega t-\frac{4\pi}{3}-\varphi\right) \end{cases}$$

- **Transform from abs to αβ**

$$\vec{\imath}^{\alpha\beta} = \sqrt{\frac{2}{3}}\cdot\left(i_a\cdot e^{j\frac{0\pi}{3}} + i_b\cdot e^{j\frac{2\pi}{3}} + i_c\cdot e^{j\frac{4\pi}{3}}\right)$$

$$\vec{\imath}^{\alpha\beta} = \sqrt{\frac{2}{3}}\cdot\left(\hat{\imath}\cdot\cos(\omega t-\varphi) + \hat{\imath}\cdot\cos\left(\omega t-\frac{2\pi}{3}-\varphi\right)\cdot e^{j\frac{2\pi}{3}} + \hat{\imath}\cdot\cos\left(\omega t-\frac{4\pi}{3}-\varphi\right)\cdot e^{j\frac{4\pi}{3}}\right)$$

$$\left\{\cos(\omega t) = \frac{e^{j\omega t}+e^{-j\omega t}}{2}\right\}$$

$$\vec{\imath}^{\alpha\beta} = \sqrt{\frac{2}{3}}\cdot\hat{\imath}\cdot\left(\frac{e^{j(\omega t-\varphi)}+e^{-j(\omega t-\varphi)}}{2} + \frac{e^{j\left(\omega t-\frac{2\pi}{3}-\varphi\right)}+e^{-j\left(\omega t+\frac{2\pi}{3}-\varphi\right)}}{2}\cdot e^{j\frac{2\pi}{3}} + \frac{e^{j\left(\omega t-\frac{4\pi}{3}-\varphi\right)}+e^{-j\left(\omega t+\frac{4\pi}{3}-\varphi\right)}}{2}\cdot e^{j\frac{4\pi}{3}}\right)$$

Current vector αβ

$$\vec{\imath}^{\alpha\beta} = \sqrt{\frac{2}{3}}\cdot\frac{\hat{\imath}}{2}\cdot\begin{pmatrix} e^{j\omega t - j\boldsymbol{\varphi}} + e^{-j\omega t+\ \boldsymbol{\varphi}} + \cdots \\ \cdots + e^{j\omega t - j\frac{2\pi}{3} - j\varphi + j\frac{2\pi}{3}} + e^{-j\omega t + j\frac{2\pi}{3} + j\varphi + j\frac{2\pi}{3}} + \cdots \\ \cdots + e^{j\omega t - j\frac{4\pi}{3} - j\varphi + j\frac{4\pi}{3}} + e^{-j\omega t + j\frac{4\pi}{3} + j\varphi + j\frac{4\pi}{3}} \end{pmatrix} =$$

$$= \sqrt{\frac{2}{3}}\cdot\frac{\hat{\imath}}{2}\cdot\left(e^{j\omega t - j\varphi} + e^{-j\omega t + j\varphi} + e^{j\omega t - j\varphi} + e^{-j\omega + j\varphi + j\frac{4\pi}{3}t} + e^{j\omega t - j\varphi} + e^{-j\omega t + j\varphi + j\frac{8\pi}{3}}\right) =$$

$$= \sqrt{\frac{2}{3}}\cdot\frac{\hat{\imath}}{2}\cdot\left(3\cdot e^{j\omega t - j\varphi} + \frac{3\cdot e^{-j\omega t + j\varphi}}{3}\cdot\left(1 + e^{j\frac{4\pi}{3}} + e^{j\frac{8\pi}{3}}\right)\right) =$$

$$= \sqrt{\frac{3}{2}}\cdot\hat{\imath}\cdot\left(e^{j\omega t - j} \quad + \frac{e^{-j\omega t +}}{3}\cdot\left(1 - \frac{1}{2} - j\frac{\sqrt{3}}{2} - \frac{1}{2} + j\frac{\sqrt{3}}{2}\right)\right) =$$

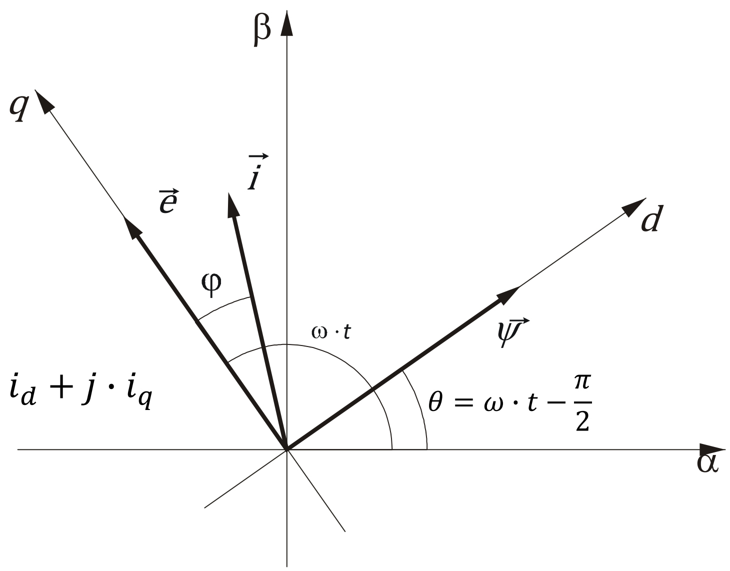
$$= \sqrt{\frac{3}{2}}\cdot\hat{\imath}\cdot e^{j\omega t - j} \quad = \sqrt{\frac{3}{2}}\cdot\hat{\imath}(\cos(\omega t - \varphi) + j\sin(\omega t - \varphi)) = i_\alpha + j\cdot i_\beta$$

Current vector αβ→dq

- **The flux defines d-axis which lags EMF voltage by -90°**

$$\vec{i}_{dq} = \vec{i}_{\alpha\beta} \cdot e^{-j\left(\omega t - \frac{\pi}{2}\right)} = \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot e^{j\omega t - j\varphi} \cdot e^{-j\left(\omega t - \frac{\pi}{2}\right)} =$$

$$= \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot e^{j\left(\frac{\pi}{2} - \varphi\right)} = \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot \left(\cos\left(\frac{\pi}{2} - \varphi\right) + j \cdot \sin\left(\frac{\pi}{2} - \varphi\right)\right) = i_d + j \cdot i_q$$



$$\begin{cases} i_d = \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot \cos\left(\frac{\pi}{2} - \varphi\right) \\ i_q = \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cdot \sin\left(\frac{\pi}{2} - \varphi\right) \end{cases}$$

Power from dq

- **Using dq-frame, dot product**

$$P = e^{dq} \cdot i^{dq} = e_d i_d + e_q i_q$$

- **Grid voltage**

$$\vec{e}^{\alpha\beta} = \sqrt{\frac{3}{2}} \cdot \hat{e} \cdot e^{j\omega t}$$

- **Transform αβ→dq**

$$\vec{e}_{dq} = \vec{e}_{\alpha\beta} \cdot e^{j\left(\omega t\ \ \frac{\pi}{2}-\phi\right)} \rightarrow \sqrt{\frac{3}{2}} \cdot \hat{e} \cdot e^{j\omega t - j\omega t + j\frac{\pi}{2}} =$$

$$= j \cdot \sqrt{\frac{3}{2}} \cdot \hat{e} = \vec{e}_q (\vec{e}_d = 0)$$

- **Active power**

$$P = e_q i_q = \sqrt{\frac{3}{2}} \cdot \hat{e} \cdot \sqrt{\frac{3}{2}} \cdot \hat{\imath} \sin\left(\frac{\pi}{2} - \phi\right) =$$

$$= \frac{3}{2} \hat{e} \cdot \hat{\imath} \cos(\phi) = \sqrt{3} E_L I \cos(\phi)$$

- **Reactive power**

$$Q = e_q i_d = \sqrt{\frac{3}{2}} \cdot \hat{e} \cdot \sqrt{\frac{3}{2}} \cdot \hat{\imath} \cos n \left(\frac{\pi}{2} - \phi\right) =$$

$$= \frac{3}{2} \hat{e} \cdot \hat{\imath} \sin(\phi) = \sqrt{3} E_L I \sin(\phi)$$

Power from αβ

$$P = \mathrm{Re}(\vec{u} \cdot \vec{\imath} *) = \mathrm{Re}\left(\sqrt{\frac{3}{2}}\hat{u} \cdot e^{j\omega} \cdot \sqrt{\frac{3}{2}}\hat{\imath} \cdot e^{-j(\omega t - \phi)}\right)$$

$$= \frac{3}{2}\mathrm{Re}\left(\hat{u} \cdot \hat{\imath} \cdot e^{j\omega - j\omega + \phi}\right) = \frac{3}{2}\hat{u} \cdot \hat{\imath}\cos(\phi) = \sqrt{3} \cdot U \cdot I_{rms,phase} \cdot \cos(\varphi)$$

Relation between U_{dc} and U_{grid}

- **Sinusoidal modulation**

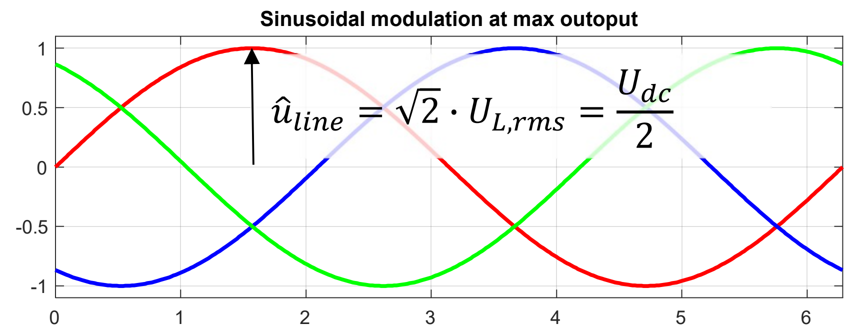
$$U_{LNrms} = \frac{1}{\sqrt{2}}\frac{U_{dc}}{2} \approx 0.35U_{dc}$$

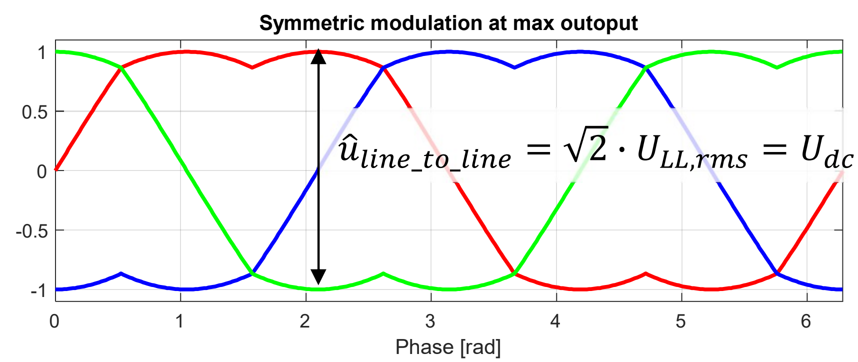
$$U_{LLrms} = \sqrt{\frac{3}{2}}\frac{U_{dc}}{2} \approx 0.61U_{dc}$$

- **Symmetrical modulation**

$$U_{LLrms} = \frac{U_{dc}}{\sqrt{2}} \approx 0.71U_{dc}$$

$$U_{LNrms} = \frac{1}{\sqrt{3}}\frac{U_{dc}}{\sqrt{2}} \approx 0.41U_{dc}$$



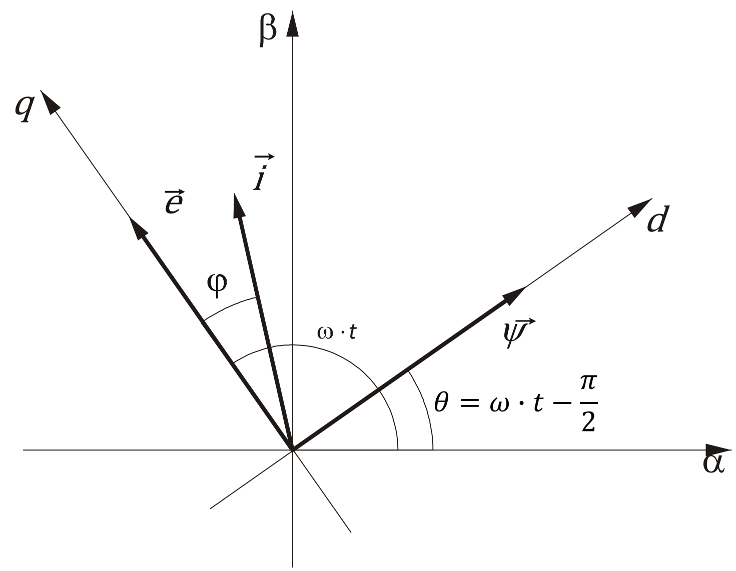


Re-introduce the rotating reference frame

- Use the integral of the grid back emf vector:

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

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



Re-introduce the grid flux reference frame (d,q) …

- **Express the grid voltage equation in the grid flux reference frame**

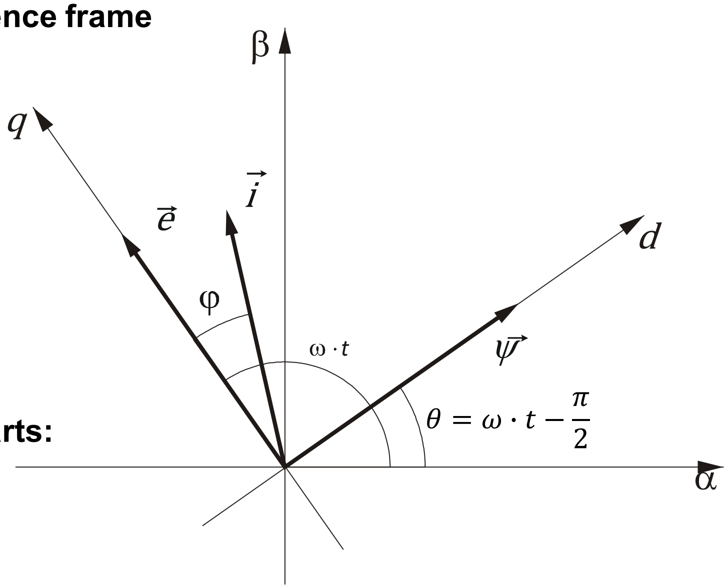
$$\vec{u}^{\alpha\beta} = R\cdot\vec{\imath}^{\alpha\beta} + L\cdot\frac{d\vec{\imath}^{\alpha\beta}}{dt} + \vec{e}^{\alpha\beta}$$

$$\left\{\vec{s}^{\alpha\beta} = \vec{s}^{dq}\cdot e^{j\theta}\right\}$$

$$\vec{u}_s^{dq}\cdot e^{j\theta} = R\cdot\vec{\imath}^{dq}\cdot e^{j\theta} + L\cdot\frac{d}{dt}\left(\vec{\imath}^{dq}\cdot e^{j\theta}\right) + \vec{e}^{dq}\cdot e^{j\theta} =$$

$$= R\cdot\vec{\imath}^{dq}\cdot e^{j\theta} + L\cdot\frac{d\vec{\imath}^{dq}}{dt}\cdot e^{j\theta} + j\cdot\frac{d\theta}{dt}\cdot L\cdot\vec{\imath}^{dq}\cdot e^{j\theta} + \vec{e}^{dq}\cdot e^{j\theta} =$$

$$\vec{u}_s^{dq} = R\cdot\vec{\imath}^{dq} + L\cdot\frac{d\vec{\imath}^{dq}}{dt} + j\cdot\omega\cdot L\cdot\vec{\imath}^{dq} + \vec{e}^{dq}$$



- **Split up the complex equation in real- and imaginary parts:**

$$u_d = R\cdot i_d + L\cdot\frac{di_d}{dt} - \omega\cdot L\cdot i_q$$

$$u_q = R\cdot i_q + L\cdot\frac{di_q}{dt} + \omega\cdot L\cdot i_d + e_q$$

3-phase sampled vector control : 1

- **Assume sampled control @ [..., k, k+1, k+2, ...]Ts**
- **Calculate voltage average over one sample period**

$$\frac{\int_{k\cdot T_s}^{(k+1)T_s} \vec{u} \cdot dt}{T_s} = \frac{R \cdot \int_{k\cdot T_s}^{(k+1)T_s} \vec{\imath} \cdot dt + L \cdot \int_{k\cdot T_s}^{(k+1)T_s} \frac{d\vec{\imath}}{dt} \cdot dt + j \cdot \omega \cdot L \int_{k\cdot T_s}^{(k+1)T_s} \vec{\imath} \cdot dt + \int_{k\cdot T_s}^{(k+1)T_s} \vec{e} \cdot dt}{T_s} =$$

$$= \bar{\vec{u}}(k, k+1) = (R + j \cdot \omega \cdot L) \cdot \bar{\vec{\imath}}(k, k+1) + L \cdot \frac{\vec{\imath}(k+1) - \vec{\imath}(k)}{T_s} + \bar{\vec{e}}(k, k+1)$$

3-phase sampled vector control : 2

Assume:

$$\overline{\vec{u}}(k,k+1) = \vec{u}^*(k)$$
$$\vec{\imath}(k+1) = \vec{\imath}^*(k)$$
$$\bar{\vec{\imath}}(k,k+1) = \frac{\vec{\imath}^*(k) + \vec{\imath}(k)}{2}$$
$$\overline{\vec{e}}(k,k+1) = \vec{e}(k)$$
$$\vec{\imath}(k) = \sum_{n=0}^{n=k-1} (\vec{\imath}^*(n) - \vec{\imath}(n))$$

Gives:

$$\vec{u}^*(k) = (R + j\cdot\omega\cdot L)\cdot\frac{\vec{\imath}^*(k) + \vec{\imath}(k)}{2} + L\cdot\frac{\vec{\imath}^*(k) - \vec{\imath}(k)}{T_s} + \vec{e}(k) =$$
$$= R\cdot\frac{\vec{\imath}*(k) - \vec{\imath}(k)}{2} + R\cdot\vec{\imath}(k) + L\cdot\frac{\vec{\imath}^*(k) - \vec{\imath}(k)}{T_s} + j\cdot\omega\cdot L\cdot\frac{\vec{\imath}^*(k) + \vec{\imath}(k)}{2} + \vec{e}(k) \approx$$
$$\approx \left(\frac{L}{T_s} + \frac{R}{2}\right)(\vec{\imath}^*(k) - \vec{\imath}(k)) + R\cdot\sum_{n=0}^{n=k-1}(\vec{\imath}^*(n) - \vec{\imath}(n)) + j\cdot\omega\cdot L\cdot\vec{\imath}(k) + \vec{e}(k) =$$
$$= \left(\frac{L}{T_s} + \frac{R}{2}\right)\cdot\left(\underbrace{(\vec{\imath}^*(k) - \vec{\imath}(k))}_{\text{Proportional}} + \underbrace{\frac{T_s}{\left(\frac{L}{R} + \frac{T_s}{2}\right)}\cdot\sum_{n=0}^{n=k-1}(\vec{\imath}^*(n) - \vec{\imath}(n))}_{\text{Integral}}\right) + \underbrace{j\cdot\omega\cdot L\cdot\vec{\imath}(k) + \vec{e}(k)}_{Feed\ forward}$$

Current Controllers split on *d*- and *q*-

- **Components**

$$u_d^*(k) = \left(\frac{L}{T_s} + \frac{R}{2}\right) \cdot \left((i_d^*(k) - i_d(k)) + \frac{T_s}{\left(\frac{L}{R} + \frac{T_s}{2}\right)} \cdot \sum_{n=0}^{n=k-1} (i_d^*(n) - i_d(n)) \right) - \omega \cdot L \cdot i_q(k)$$

$$u_q^*(k) = \left(\frac{L}{T_s} + \frac{R}{2}\right) \cdot \left((i_q^*(k) - i_q(k)) + \frac{T_s}{\left(\frac{L}{R} + \frac{T_s}{2}\right)} \cdot \sum_{n=0}^{n=k-1} (i_q^*(n) - i_q(n)) \right) + \omega \cdot L \cdot i_d(k) + e_q(k)$$

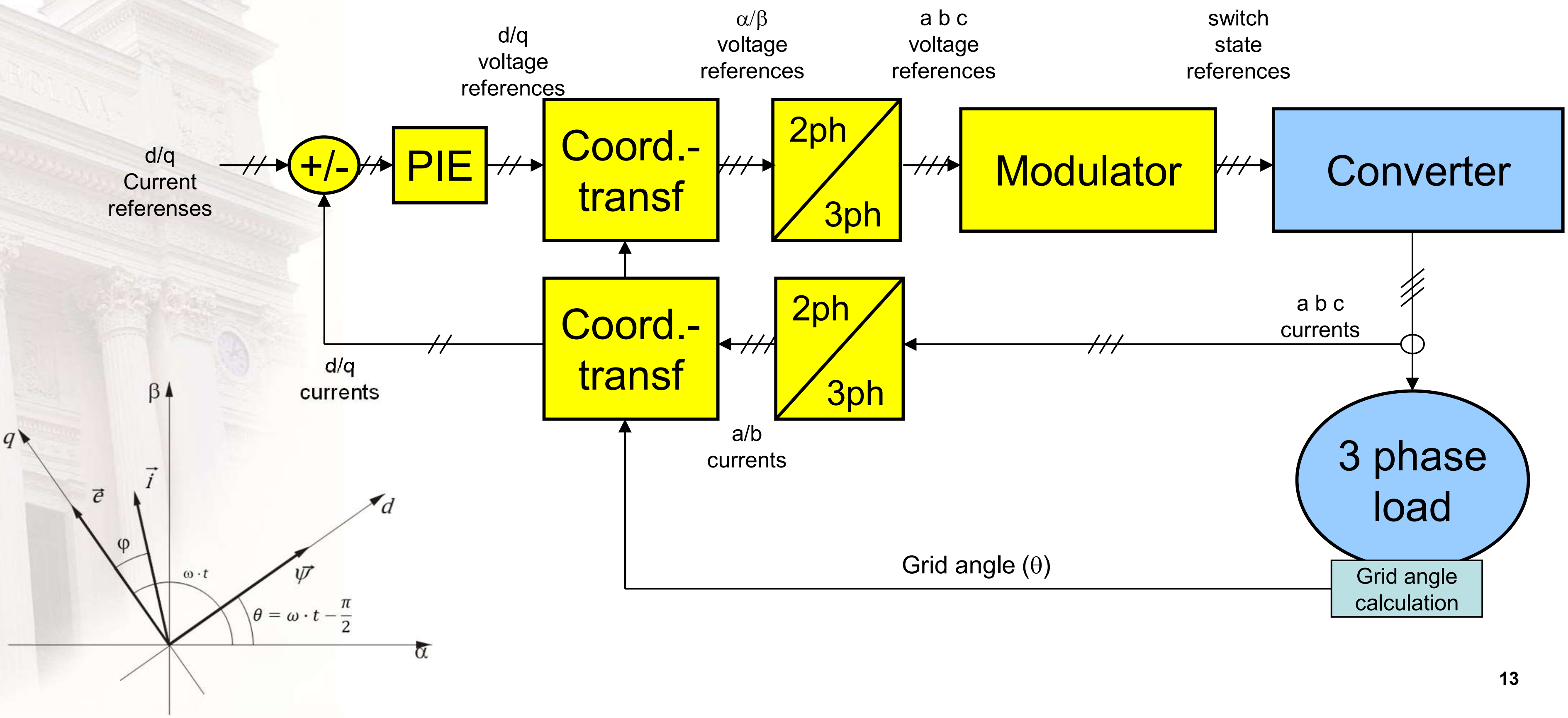
- **Some evaluation of values ...**

  – *>> L=1e-3;*
  – *>> R=0.05;*
  – *>> Ts=100e-6;*
  – *>> [L/Ts R/2] = [10.0000 0.0250]*
  – *>> [L/R Ts/2] = [0.0200 0.00005]*

⇨

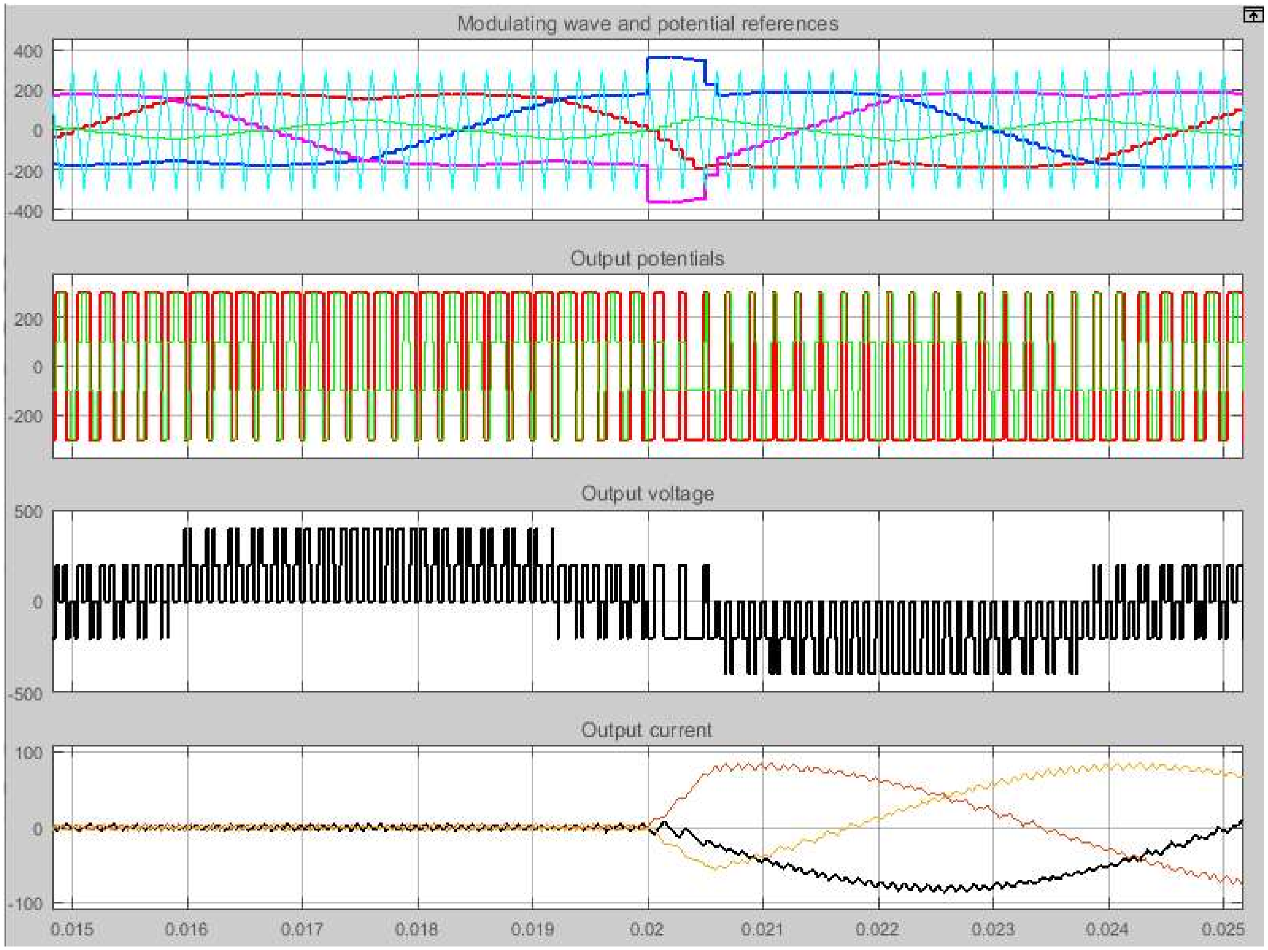
- The inductance defines the gain
- The electric time constant defines the Integral gain

Control in a rotating reference frame



Example

- **Corresponding to a traction machine at 100 Hz_**
  - *La=0.001;*
  - *Ra=0.1;*
  - *Ts=0.1e-3;*
  - *Udc=600;*
  - *Ea=250;*
  - *fel=100;*
  - *IsxREF=0;*
  - *IsyREF=100 [A] @ 20 [ms]*



Example

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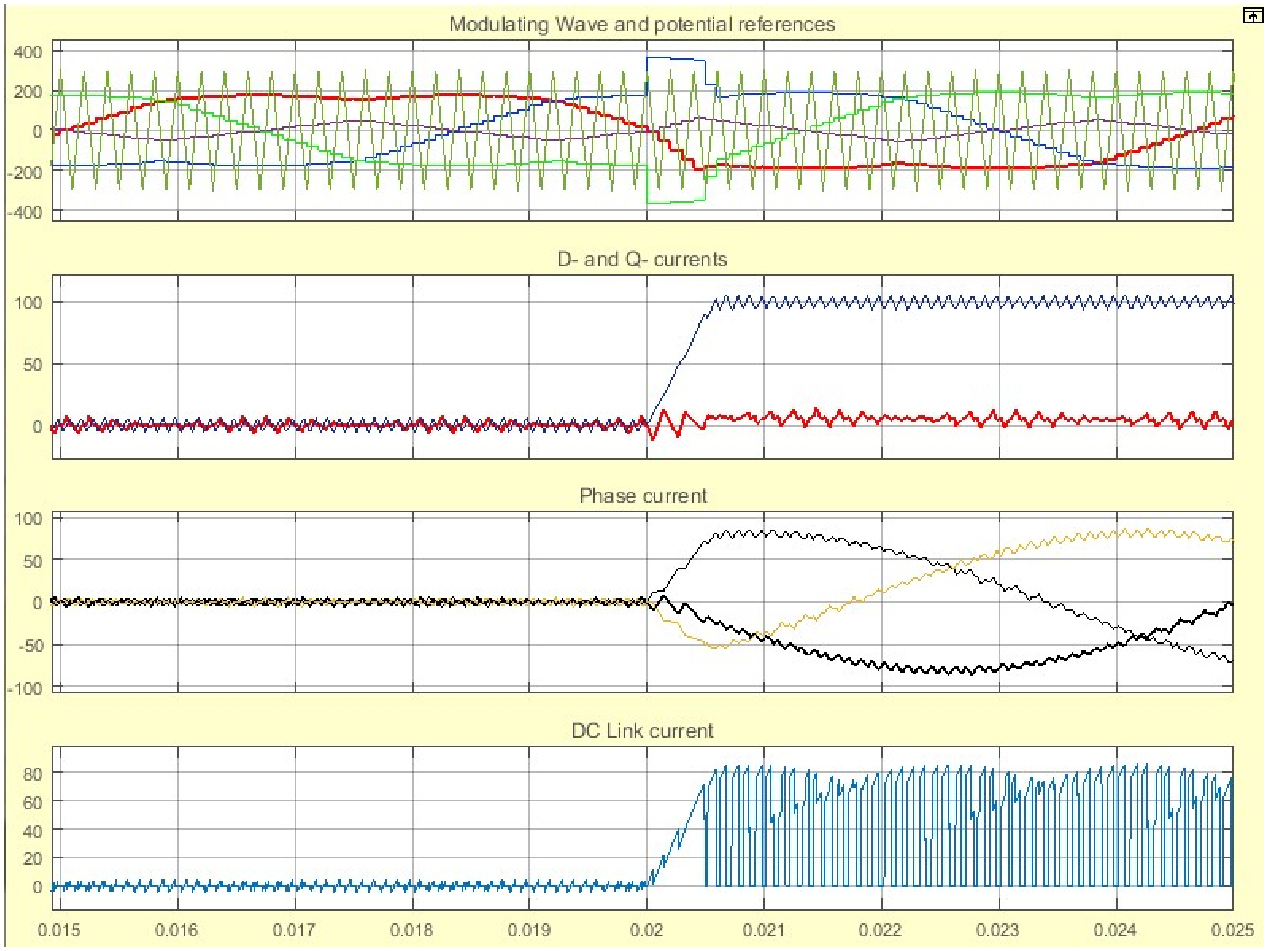
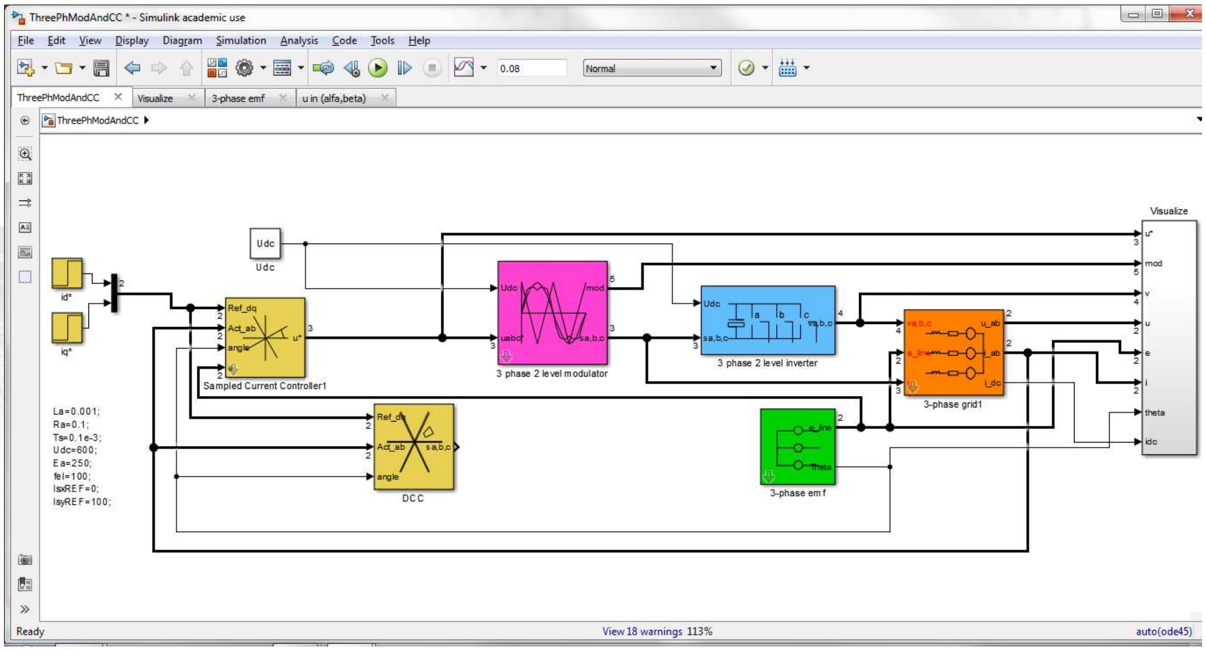
  - *fel=100;*
  - *IsxREF=0;*
  - *IsyREF=100 [A] @ 20 [ms]*
- **Notice:**
  - *DC link ripple current*



To Simulink for more ...



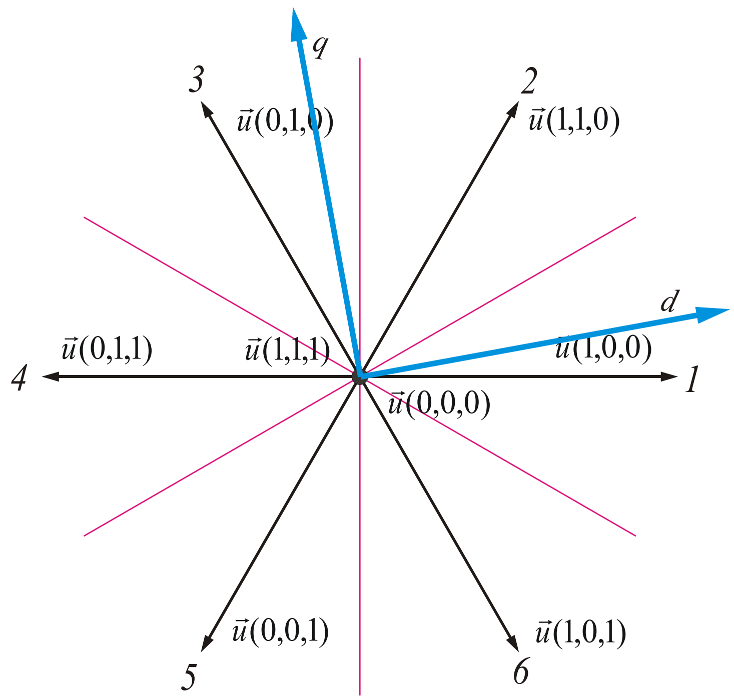
3-phase Direct Current Control

- **Where is the current vector moving?**

$$\vec{u}^{\alpha\beta} = R \cdot \vec{\imath}^{\alpha\beta} + L \cdot \frac{d\vec{\imath}^{\alpha\beta}}{dt} + \vec{e}^{\alpha\beta}$$

$$\frac{d\vec{\imath}^{\alpha\beta}}{dt} = \frac{\vec{u}^{\alpha\beta} - R \cdot \vec{\imath}^{\alpha\beta} - \vec{e}^{\alpha\beta}}{L}$$

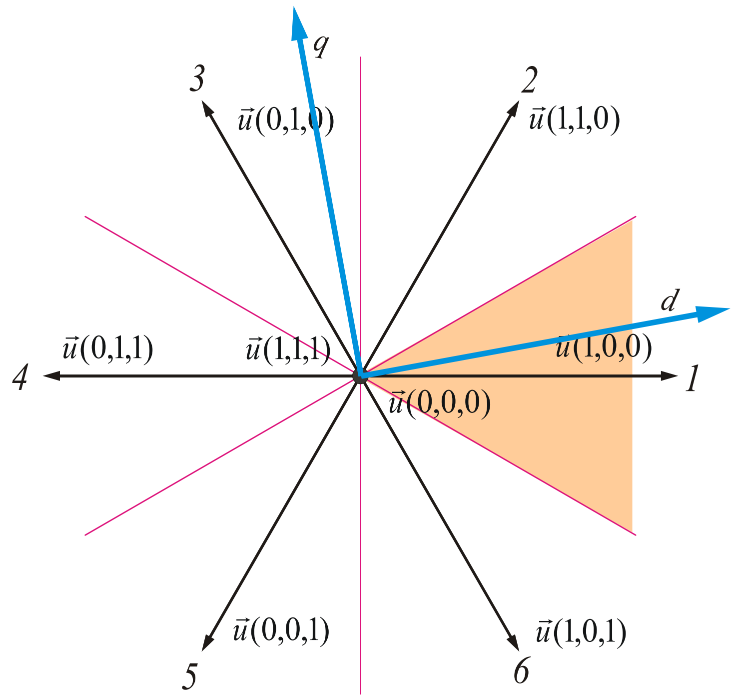
- **The, which vetors have the best chance to move the current in a certain direction?**



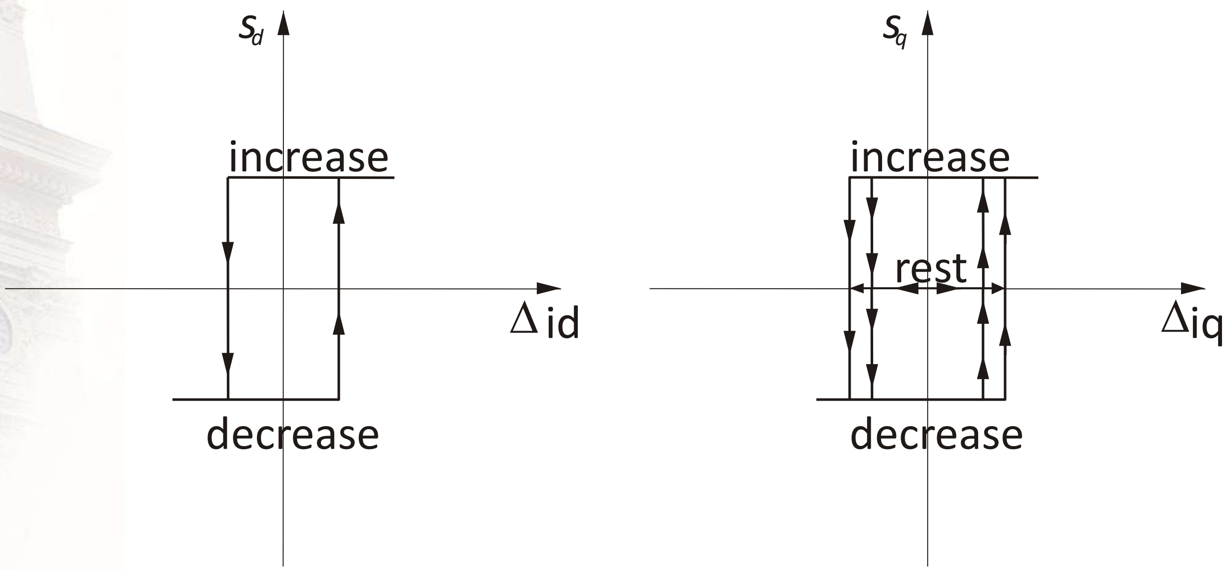
Selecting the right vector

$$vector = sector + s_{offset}$$

s_{offset}	Decrease i_q	Increase i_q
Decrease i_d	4	2
Increase i_d	5	1



Tolerance bands in *d*- and *q*-

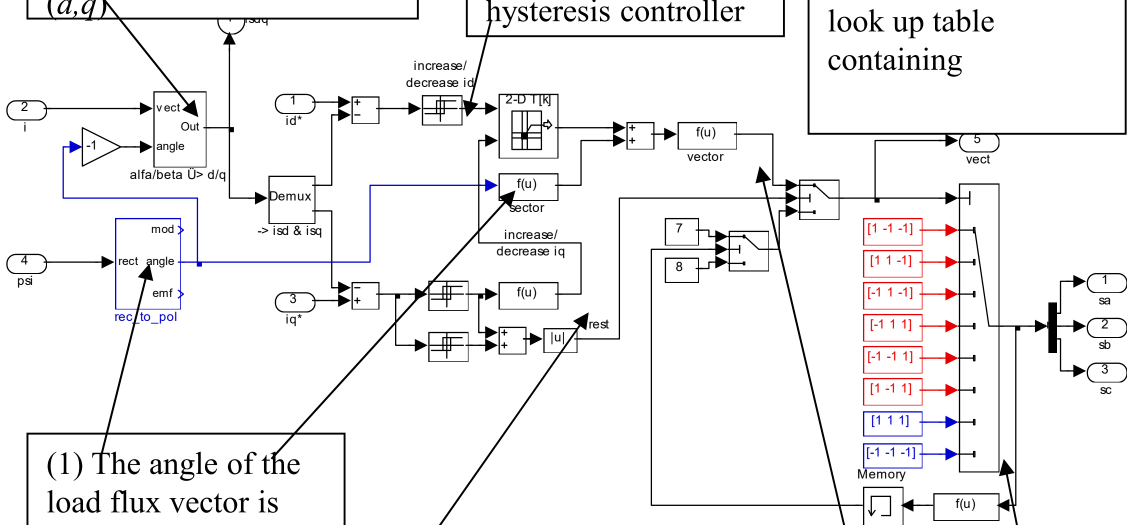


The Direct Current Controller

(2) The load current is transformed from (α,β) to (d,q)

(3) The d-axis current error is evaluated in a hysteresis controller

(5) The correct sector offset is read from a look up table containing



(1) The angle of the load flux vector is calculated and the corresponding sector number is calculated

(4) The q-axis current error is evaluated in a hysteresis controller with zero state calculation

(6) The final vector is calculated and selected.

SCC for slow computer

- **Predict current sample ahead when defining voltage reference**

$$\vec{u} = R \cdot \vec{\imath} + L \cdot \frac{d\vec{\imath}}{dt} + j \cdot \omega \cdot \vec{\imath}$$

$$\vec{u}^{*}(k) = \vec{u}(k, k+1) = R \cdot \vec{\imath}_{sp}(k) + j \cdot \omega \cdot L \cdot \vec{\imath}_{sp}(k) + \frac{L}{T_s} \cdot \left(\vec{\imath}_{sp}(k+1) - \vec{\imath}_{sp}(k)\right)$$

$$\vec{\imath}_{sp}(k+1) = \vec{\imath}_{sp}(k) \cdot \left(1 - \frac{R \cdot T_s}{L} - j \cdot \omega \cdot T_s\right) + \frac{T_s}{L} \cdot \vec{u}^{*}(k)$$

$$\hat{\vec{\imath}}(k+1) = \vec{\imath}(k) + \left(\vec{\imath}_{sp}(k+1) - \vec{\imath}_{sp}(k)\right)$$

SCC PIE parameters

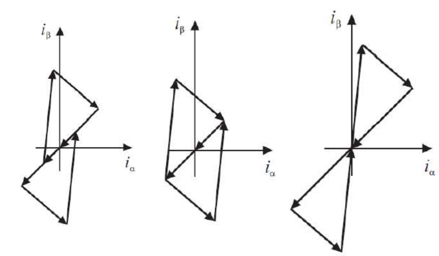
$$\begin{cases} u_{d,ref,k} = K \cdot \left(\left(i_{d,ref,k} - i_{d,k} \right) + \frac{1}{T_i} \cdot \sum_{n=0}^{k-1} \left(i_{d,ref,n} - i_{d,n} \right) \right) - K_c \cdot \frac{i_{q,ref,k} + i_{q,k}}{2} + e_{d,k} \\ u_{q,ref,k} = K \cdot \left(\left(i_{q,ref,k} - i_{q,k} \right) + \frac{1}{T_i} \cdot \sum_{n=0}^{k-1} \left(i_{q,ref,n} - i_{q,n} \right) \right) + K_c \cdot \frac{i_{d,ref,k} + i_{d,k}}{2} + e_{q,k} \end{cases}$$

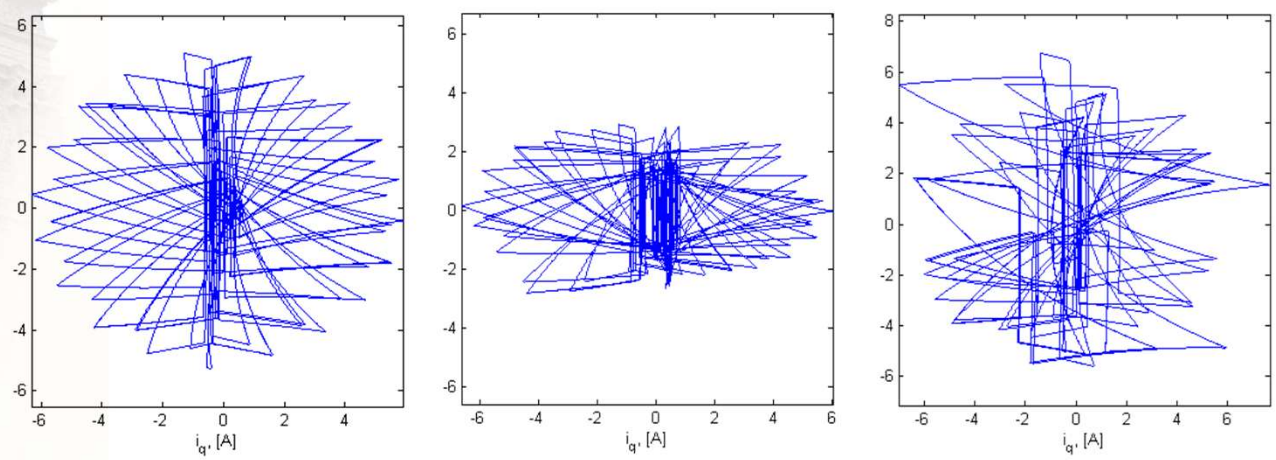
$$\begin{cases} K = \left(\frac{L}{T_s} + \frac{R}{2} \right) \\ T_i = R \Big/ \left(\frac{L}{T_s} + \frac{R}{2} \right) = 1 \Big/ \left(\frac{L}{RT_s} + \frac{1}{2} \right) \\ K_c = \frac{\omega_1 L}{2} \end{cases}$$

SCC current ripple

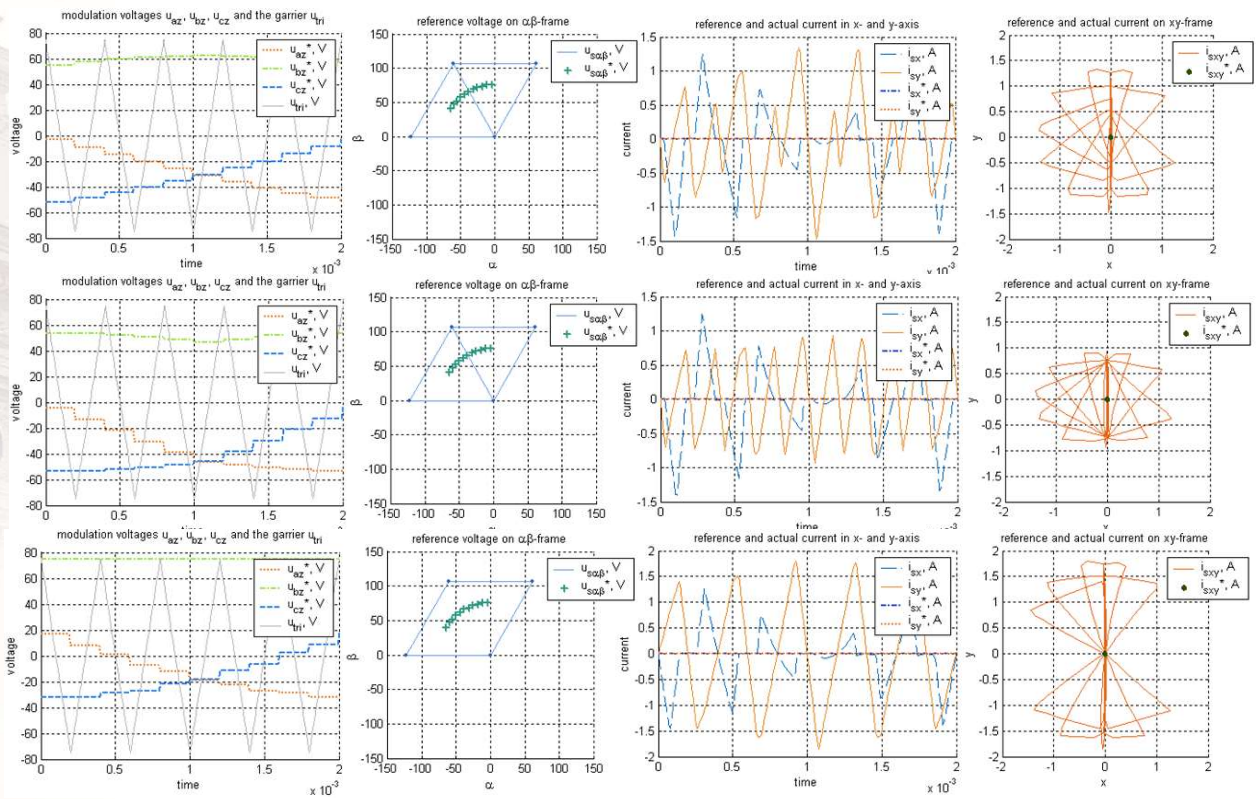
2.7

- **Sine, symmetric and bus clamped**
- **Udc=650V, L=10mH, R=1Ω**

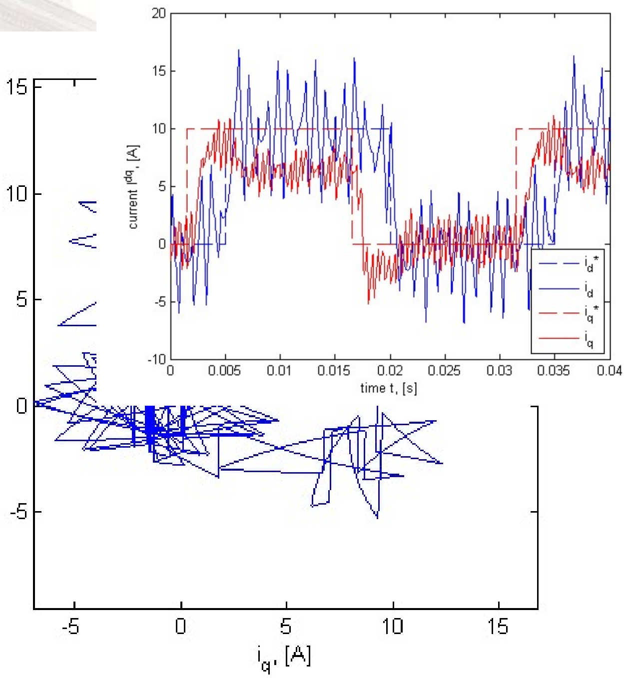


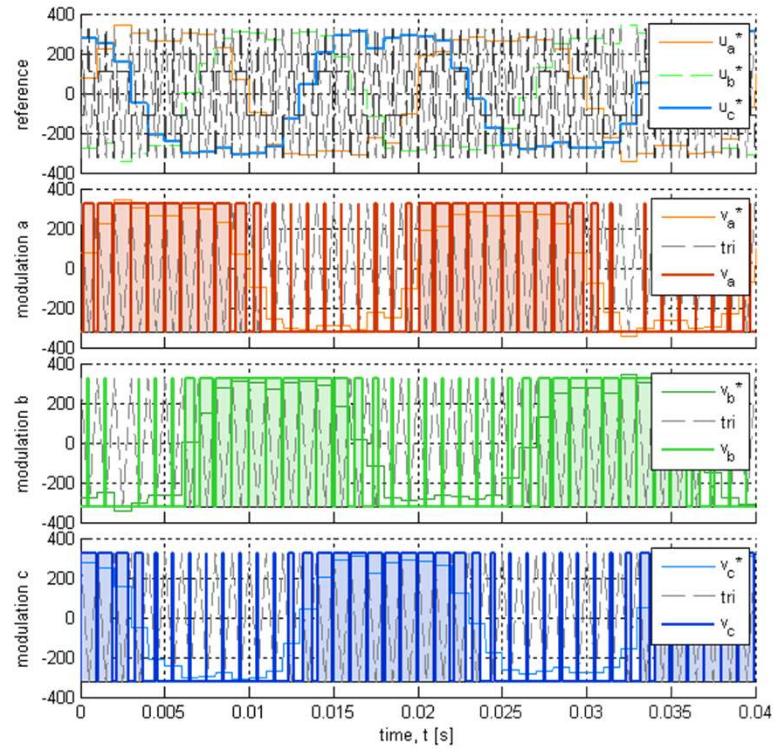


SCC current ripple



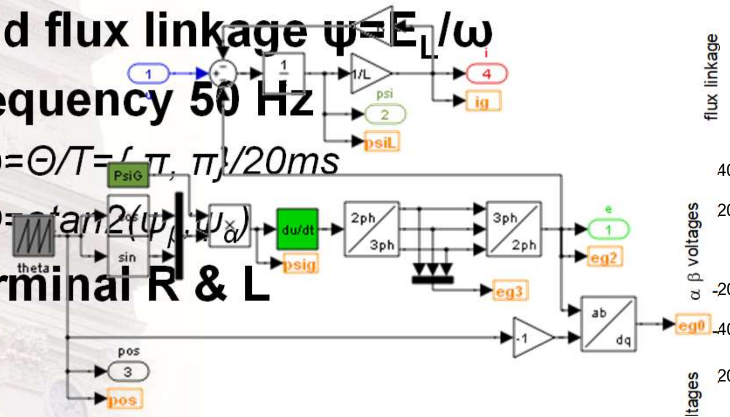
SCC step response

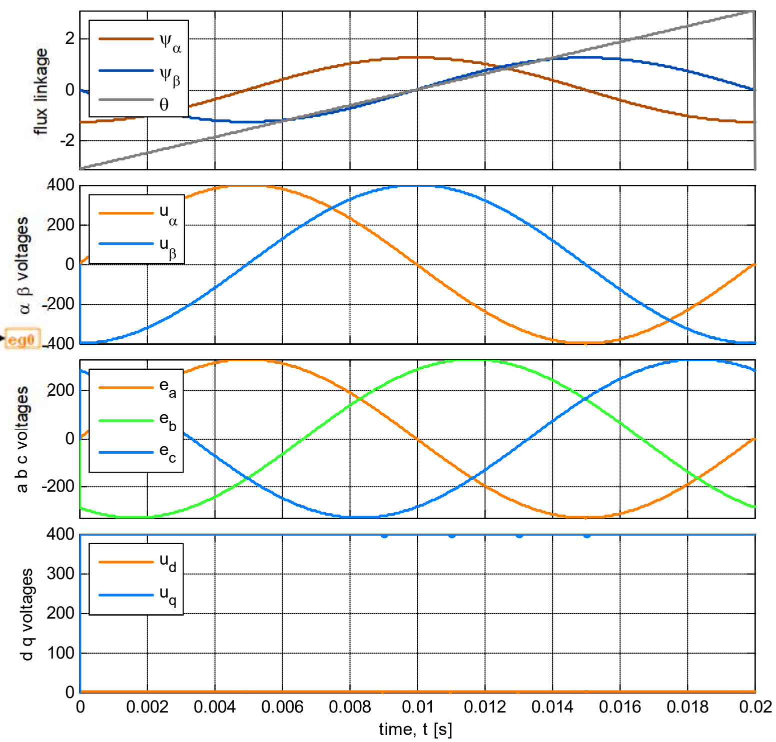




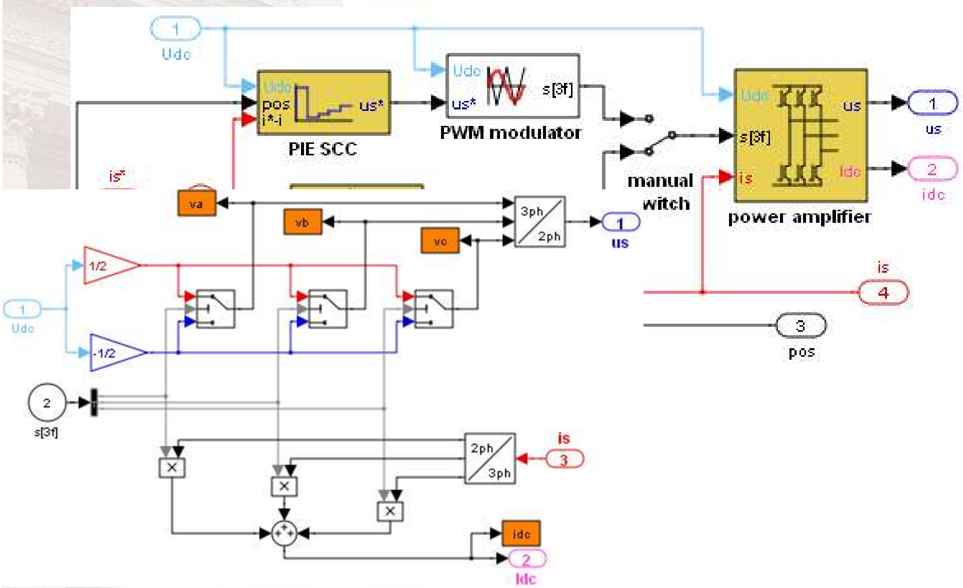
Grid voltage

- **Grid flux linkage $\psi = E_L/\omega$**
- **Frequency 50 Hz**
  - *$\omega = \Theta/T = \{-\pi, \pi\}/20ms$*
  - *$\Theta = atan2(\psi_\beta, \psi_\alpha)$*
- **Terminal R & L**





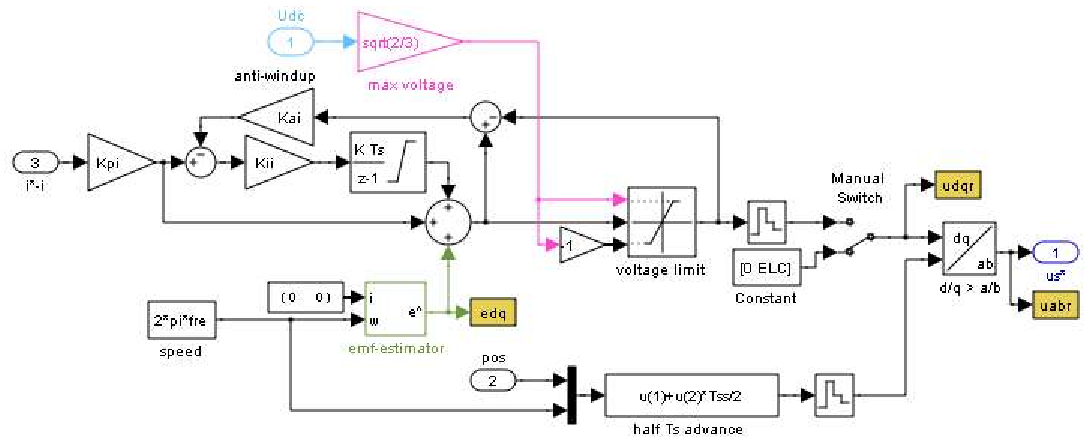
3φ power electronic converter



- Two different current controllers
  - *Sampled current control*
  - *Direct current control*
- Voltages and currents mainly in αβ frame,
- dq used for control
- Field rotation angle used instead of flux vector
  - *Grid flux!*
- Switch states {0,1}

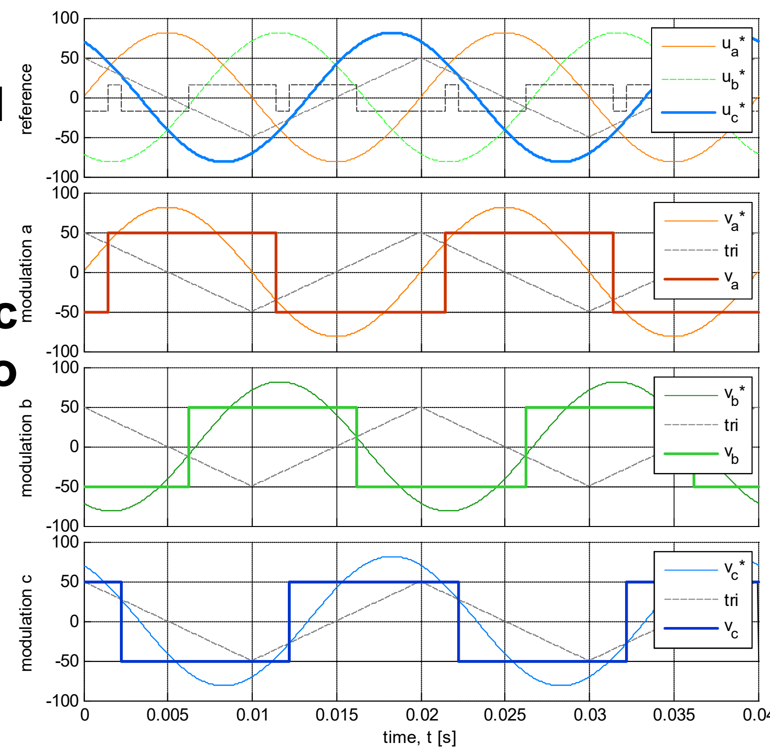
SCC block

- Vector control – dq vector quantities of voltages and currents but same circuit and control parameters
- Feed forward EMF included, cross-coupled ωL excluded
- Current controller calculate voltage references, no current delays and estimators presented
- Advanced angle to compensate rotation
- dq transformed back to αβ



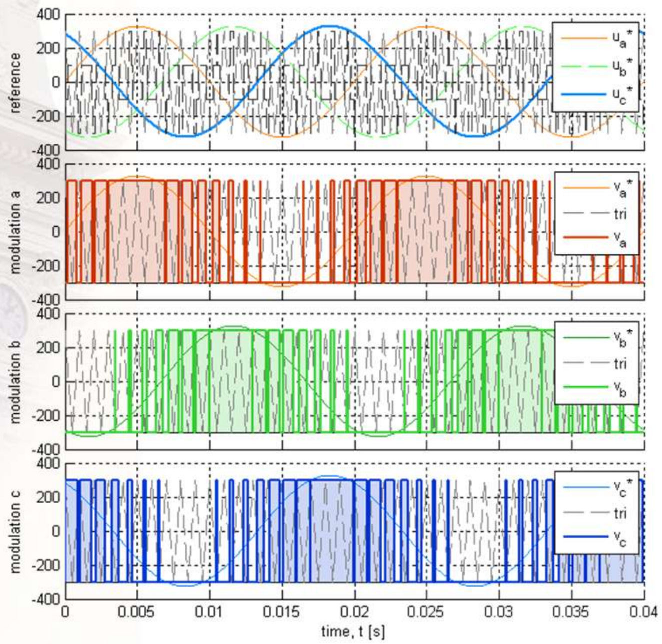
SCC open

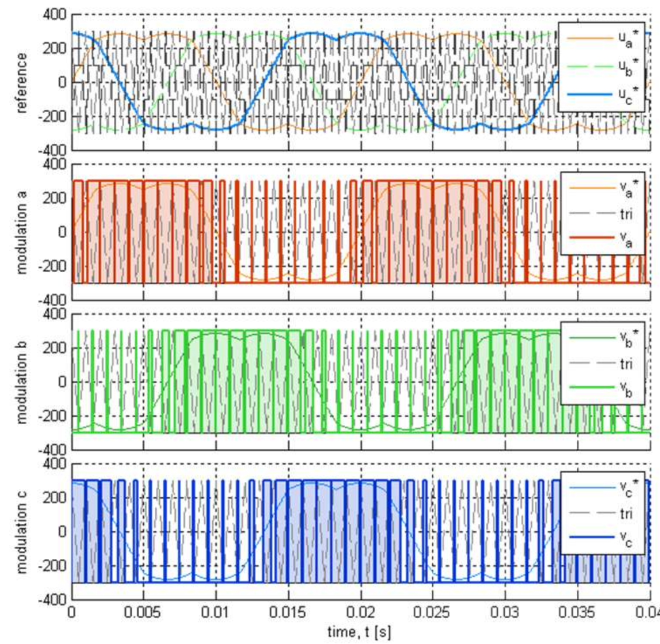
- Current controller gives u_q^*
- Ts equals to fundamental period
- Unsampled references
- 180 voltage pulses
- What sampling frequency and dc link voltage has to be selected to match the grid?



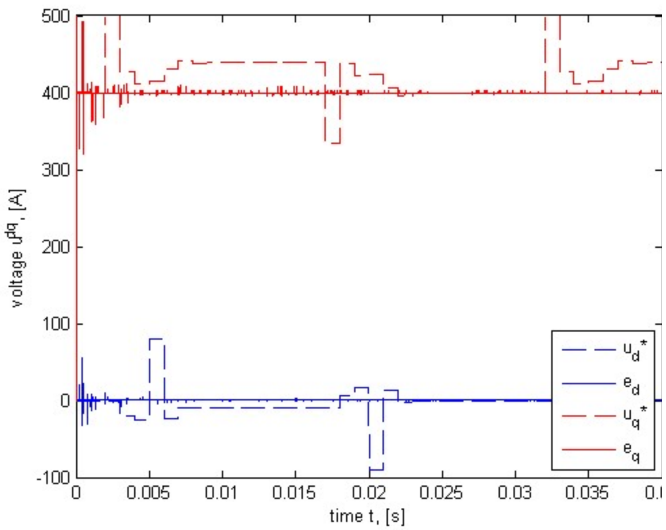
Connecting PEC to Grid?

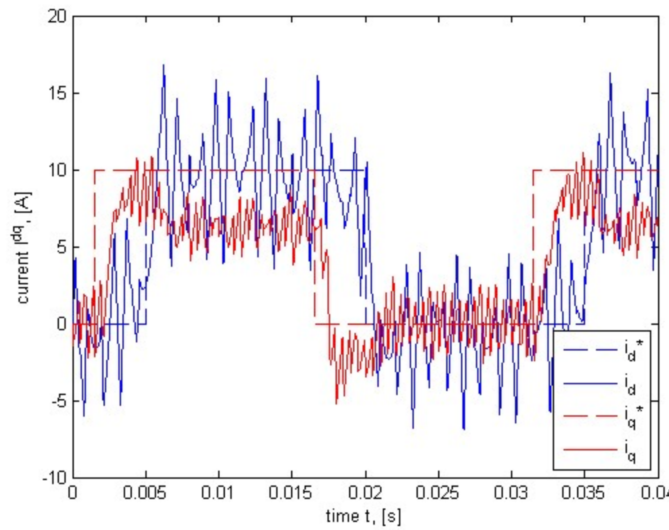
- U_{LL}=400V U_{dc}=600V T_s=1ms





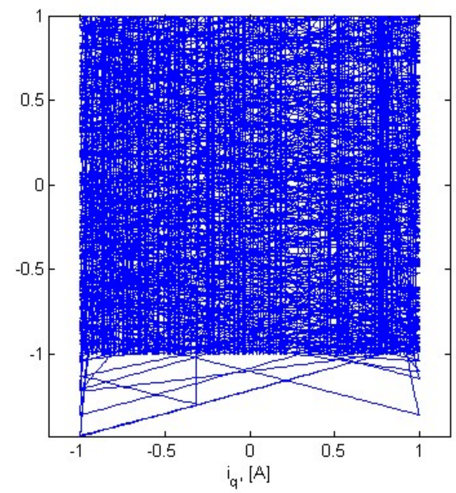
Voltage demand

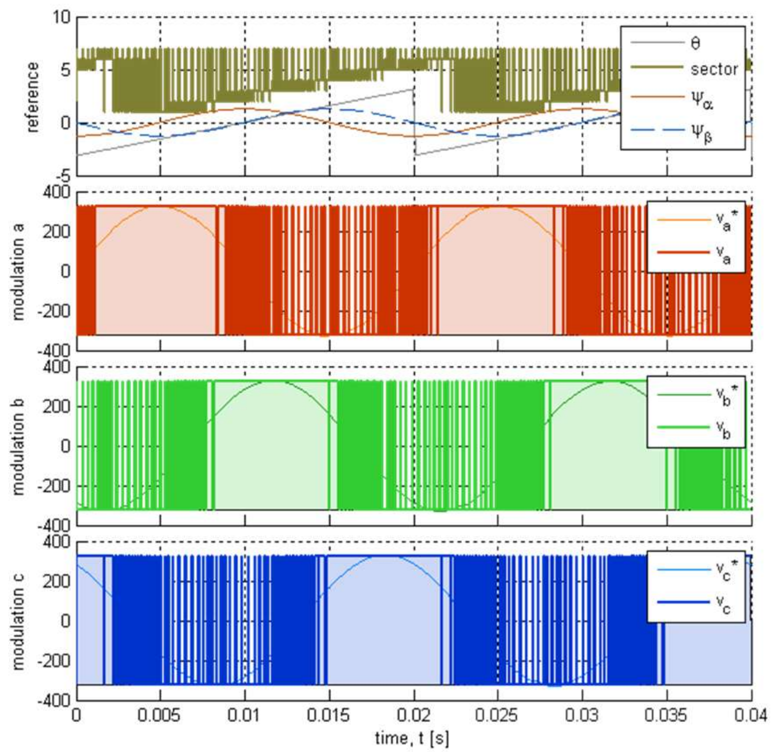




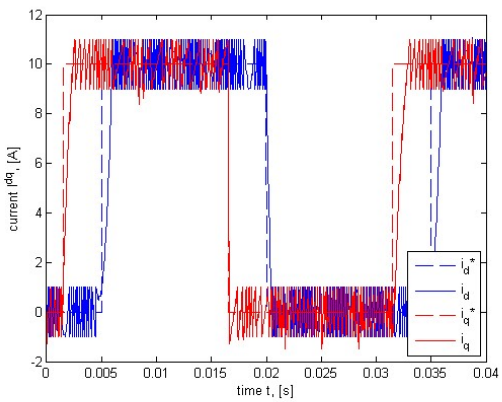
DCC current ripple

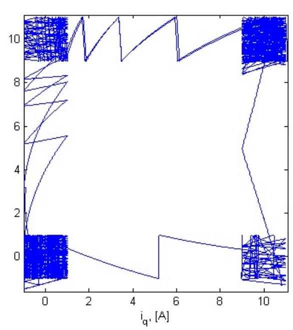
- Select di=2 A
- Switching intensity & frequency?

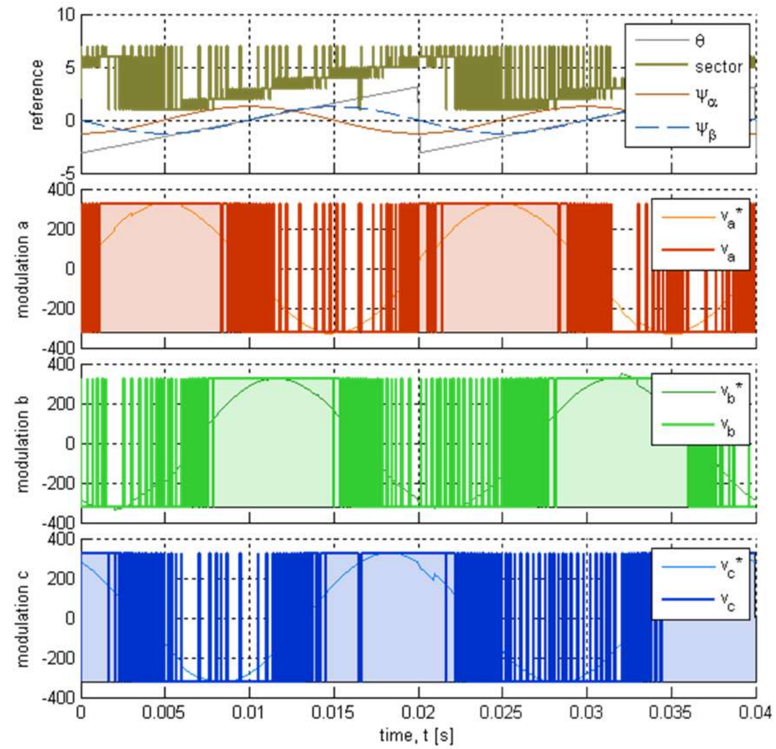




DCC step response







Exercises on 3φ current control (1)

- **PE ExercisesWithSolutions2019b vers 190206**
- **Vector representation of 3φ system**
  - *Relations between quantities*
  - *Coordinate transformation*
- **Control methods principles and schematics**
  - *Sampled current control controller and parameters*
  - *Direct current control controller and parameters*
  - *Waveform presentation of control action over carrier period*