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Current Control with 2 and 4-quadrant converters

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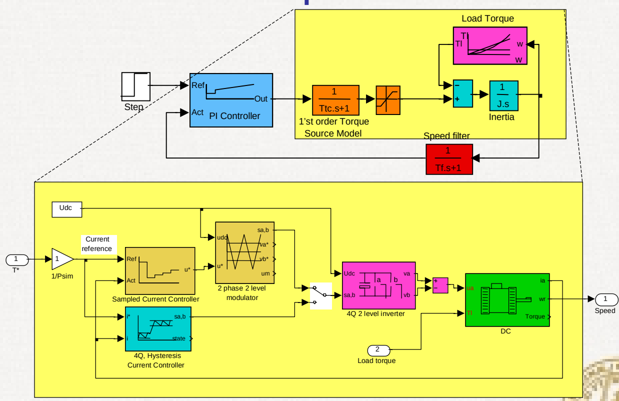
Loops



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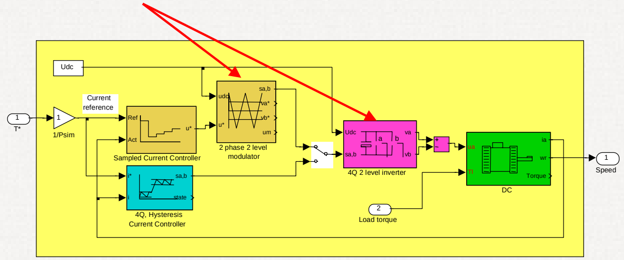
So far

Modulation ...



... or, how to convert a voltage reference into a pulse with modulated voltage

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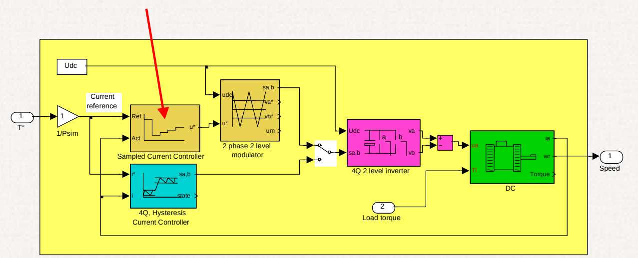
Next step

Current control ...



... or, how to convert a current reference into voltage references, or maybe a PWM pattern directly ...

Problems and means to control current

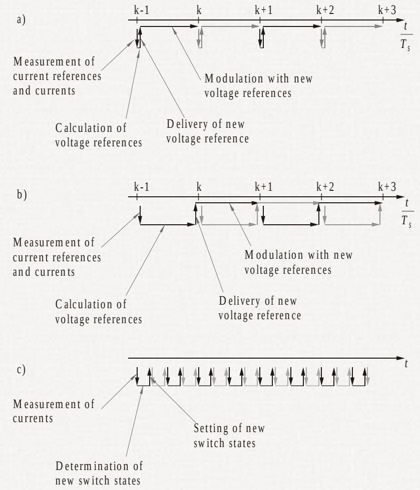
- **Problem:**
  - **Current dynamics are extremely fast**
- **Means**
  - **Analogue controllers**
    - Fast, but prone to drift
    - Difficult to implement non linear control laws
  - **Digital controllers**
    - Not as fast, but exact
    - Easy to implement non linear control laws

Computer speed

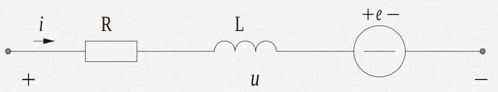
Fast:

Slow:

Continuous:



Generic Load



$$u = R\cdot i + L\cdot\frac{di}{dt} + e$$

Current controller with fast computer - I

$$\frac{\int_{k\cdot T_s}^{(k+1)T_s} u\cdot dt}{T_s} = \frac{R\cdot\int_{k\cdot T_s}^{(k+1)T_s} i\cdot dt + L\cdot\int_{k\cdot T_s}^{(k+1)T_s}\frac{di}{dt}\cdot dt + \int_{k\cdot T_s}^{(k+1)T_s} e\cdot dt}{T_s} =$$

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

$$\bar{u}(k,k+1) = u^*(k) \qquad (a)$$

$$i(k+1) = i^*(k) \qquad (b)$$

$$\bar{i}(k,k+1) = \frac{i^*(k)+i(k)}{2} \qquad (c)$$

$$\bar{e}(k,k+1) = e(k) \qquad (d)$$

$$i(k) = \sum_{n=0}^{n=k-1}\left(i^*(n)-i(n)\right) \qquad (e)$$

Current Controller with a fast computer – II

$$u^*(k) = R\cdot\frac{i^*(k)+i(k)}{2} + L\cdot\frac{i^*(k)-i(k)}{T_s} + e(k) =$$

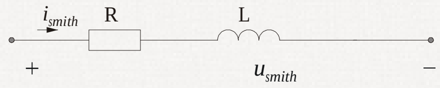
$$= R\cdot\frac{i^*(k)-i(k)}{2} + R\cdot i(k) + L\cdot\frac{i^*(k)-i(k)}{T_s} + e(k) =$$

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

$$= \left(\frac{L}{T_s}+\frac{R}{2}\right)\cdot\left(\underbrace{\left(i^*(k)-i(k)\right)}_{Proportional} + \underbrace{\frac{T_s}{\left(\frac{L}{R}+\frac{T_s}{2}\right)}\cdot\sum_{n=0}^{n=k-1}\left(i^*(n)-i(n)\right)}_{Integral}\right) + \underbrace{e(k)}_{\substack{Feed\\forward}}$$

Compensation for a slow computer - the Smith predictor

- Use a "dummy" system that simulates the current response to voltage references.
- Let the dummy system be purely Resistive-Inductive, i.e. NO EMF!



$$u = R\cdot i_{smith} + L\cdot\frac{di_{smith}}{dt}$$

The Smith Predictor : II

- The SP will have the same dynamics as the real system, but not the same statics.

$$i_{smith,static} = \frac{u}{R} \qquad i_{real,static} = \frac{u-e}{R}$$

$$\frac{di_{smith}}{dt} = \frac{u - R\cdot i_{smith}}{L} \qquad \frac{di_{real}}{dt} = \frac{u-e-R\cdot i_{smith}}{L}$$

- Think like this:
  - Assume stationarity -> nominator of the current derivative = 0
  - A voltage (u) change gives the same derivative in both cases.

The Smith Predictor : III

- Calculate the current of the next sampling instant as the sum of:
  - The current measured at the last sampling instant
  - The change of the current based on the voltage reference at the last sampling instant.
  - i.e.: $\hat{i}(k) = i(k-1) + \Delta i_{smith}(k)$

$$\Delta i_{smith}(k) = i_{smith}(k) - i_{smith}(k-1)$$

$$u^*(k-1) \approx R\cdot i_{smith}(k-1) + L\cdot\frac{i_{smith}(k)-i_{smith}(k-1)}{T_s}$$

$$i_{smith}(k) - i_{smith}(k-1) = u^*(k-1)\cdot\frac{T_s}{L} - R\cdot i_{smith}(k-1)\cdot\frac{T_s}{L}$$

$$i_{smith}(k) = u^*(k-1)\cdot\frac{T_s}{L} + \left(1 - R\cdot\frac{T_s}{L}\right)\cdot i_{smith}(k-1)$$

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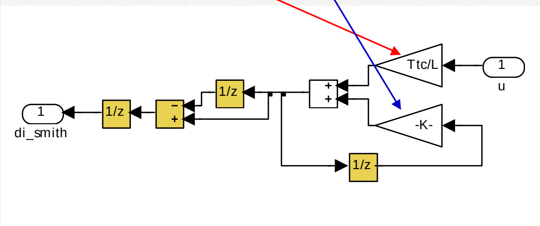
The Smith Predictor : IV

$$i_{smith}(k) = u^*(k-1)\cdot\frac{T_s}{L} + \left(1 - R\cdot\frac{T_s}{L}\right)\cdot i_{smith}(k-1)$$



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Current Control with a slow computer – II

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

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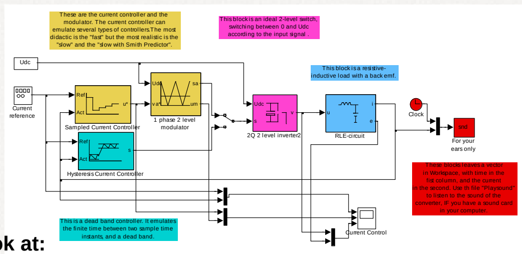
Example – 2-quadrant



- **Look at:**
  - **Step responce fast computer**
  - **Step response slow computer (with "fast" parameters")**
  - **Step response adjusted parameters**
  - **Step response with the Smith Predictor**
  - **Parameter sensitivity**

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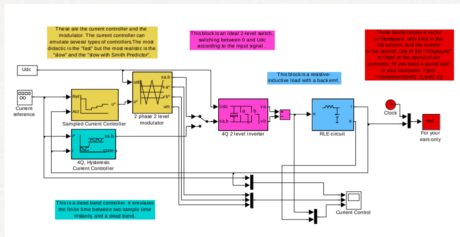
Current control with a 4-quadrant converter

- **Basicly the same situation as with 2-quadrant, BUT negative voltage references are allowed since the amplifier can provide them to the load.**

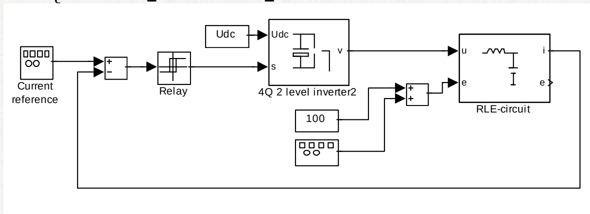


Direct Current Control

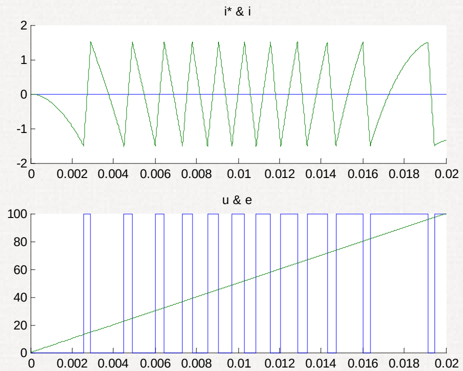
- **Switch state only a function of current error**
- **No intermediate current control or modulation**

2-Quadrant Direct Current Controller

$$s = \begin{cases} 1 \; if \;\; i < i^* - \frac{\Delta i}{2} \\ -1 \; if \;\; i > i^* + \frac{\Delta i}{2} \\ s \; if \;\; i^* - \frac{\Delta i}{2} < i < i^* + \frac{\Delta i}{2} \end{cases}$$

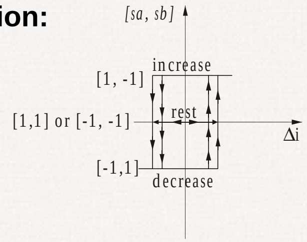


Example



4-Quadrant Direct Current Controller

- **More tricky:**
  - **4 states ([-1,-1] , [1,1] , [1,-1] & [-1,1]), but**
  - **Only 3 output voltages (-Udc, 0, Udc)**
- **One solution:**



$$\Delta i = i^* - i$$

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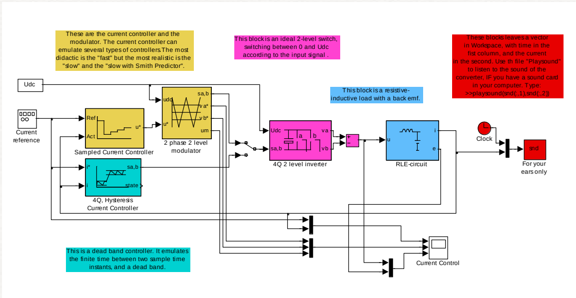
Example



 L3 – Current Control (DC)