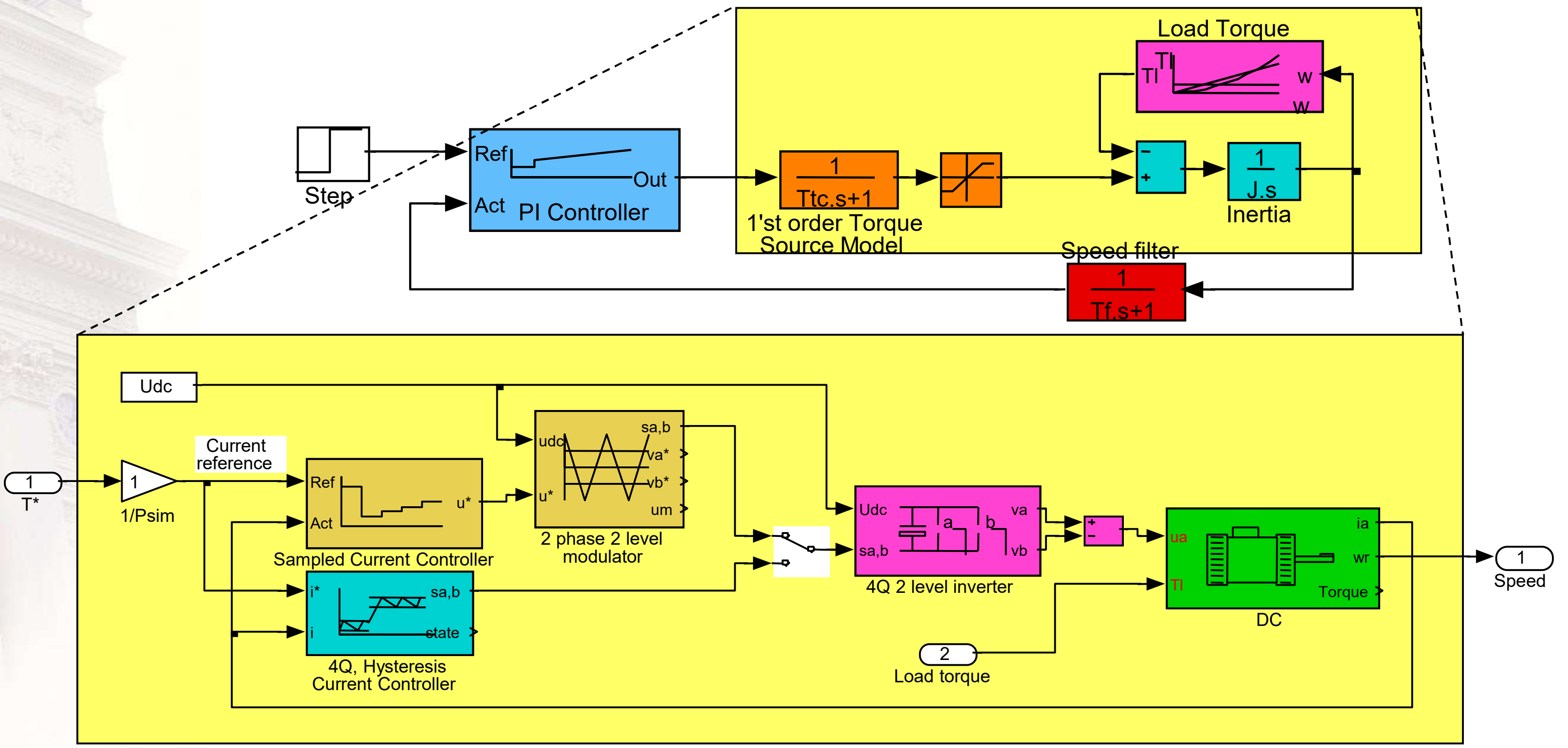
Current Control with 2 and 4-quadrant converters

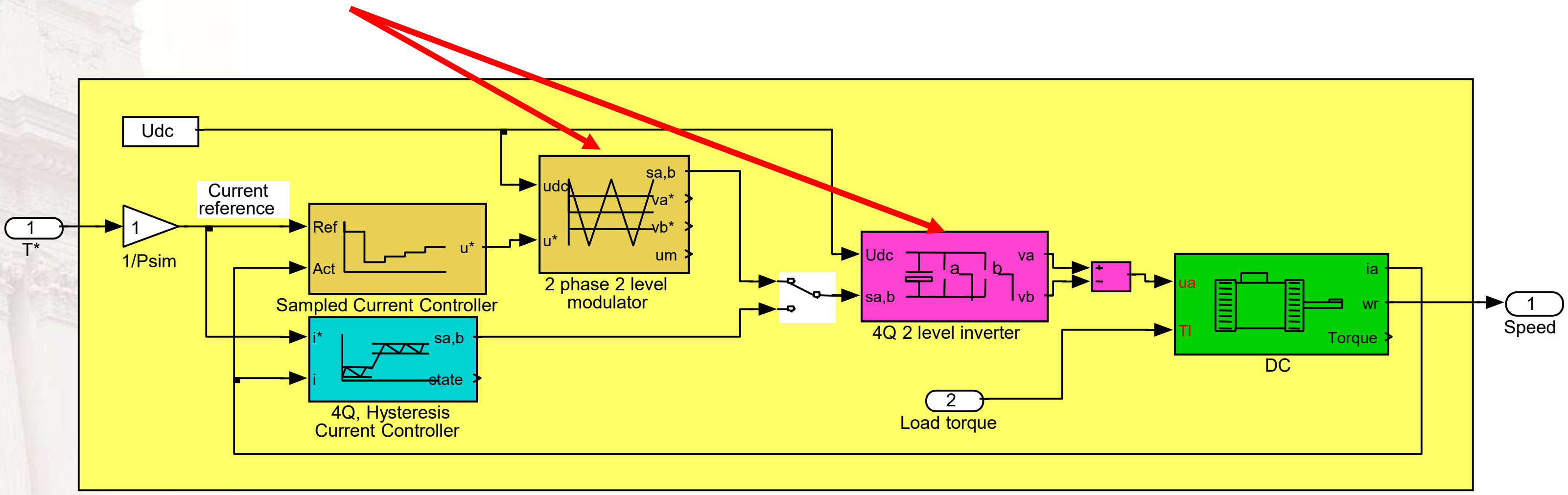
Loops



L6 – Current Control (DC)

So far

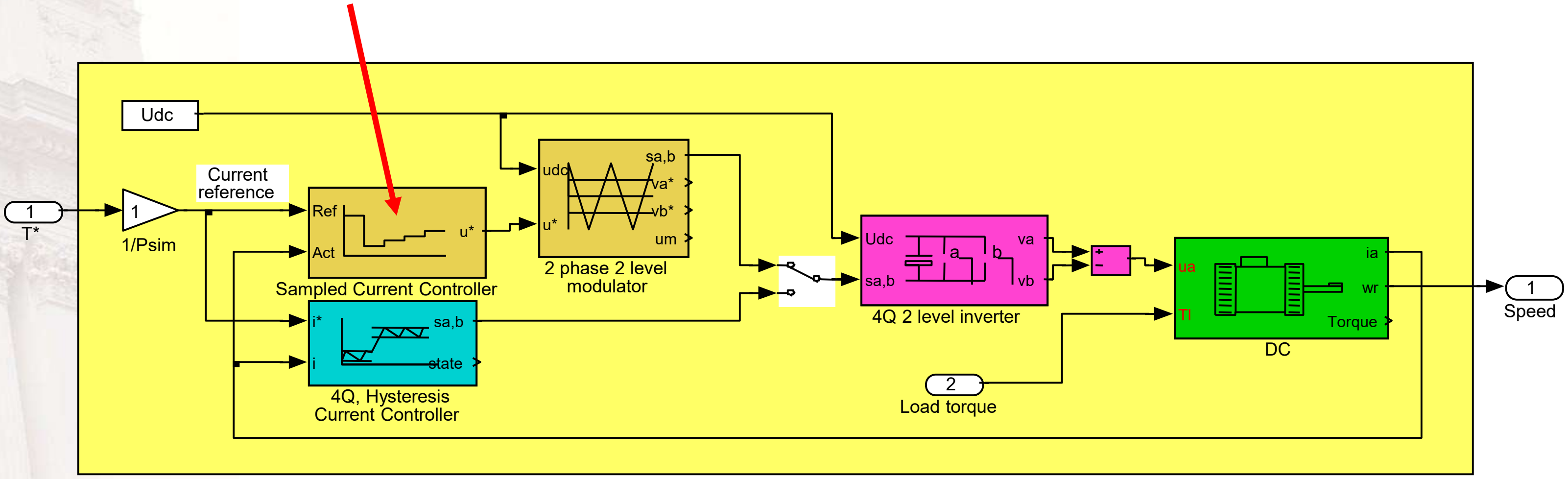
Modulation ...



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

Next step

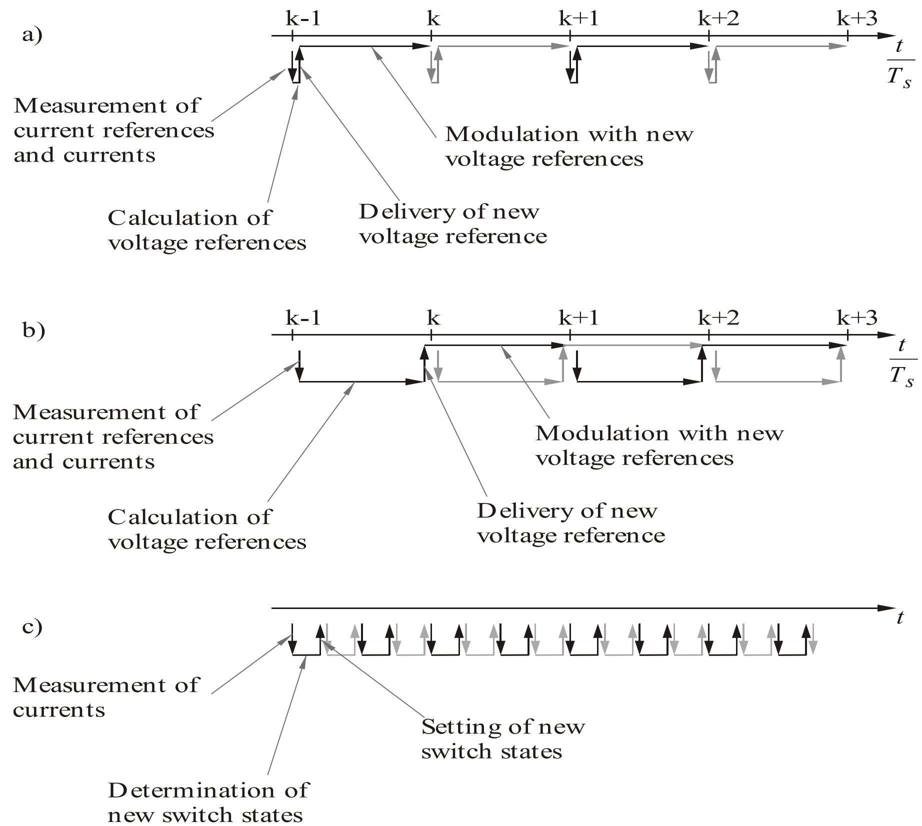
Current control ...



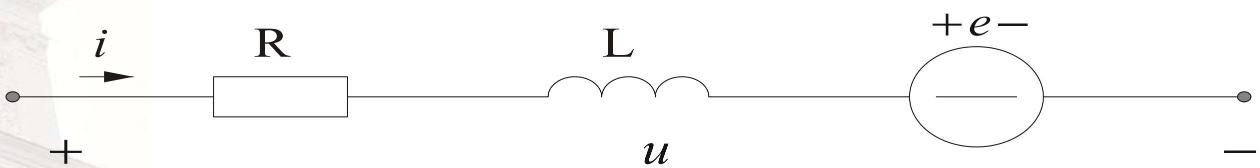
... or, how to convert a current reference into voltage references, or maybe a PWM pattern directly ...

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
    - Speed matters!



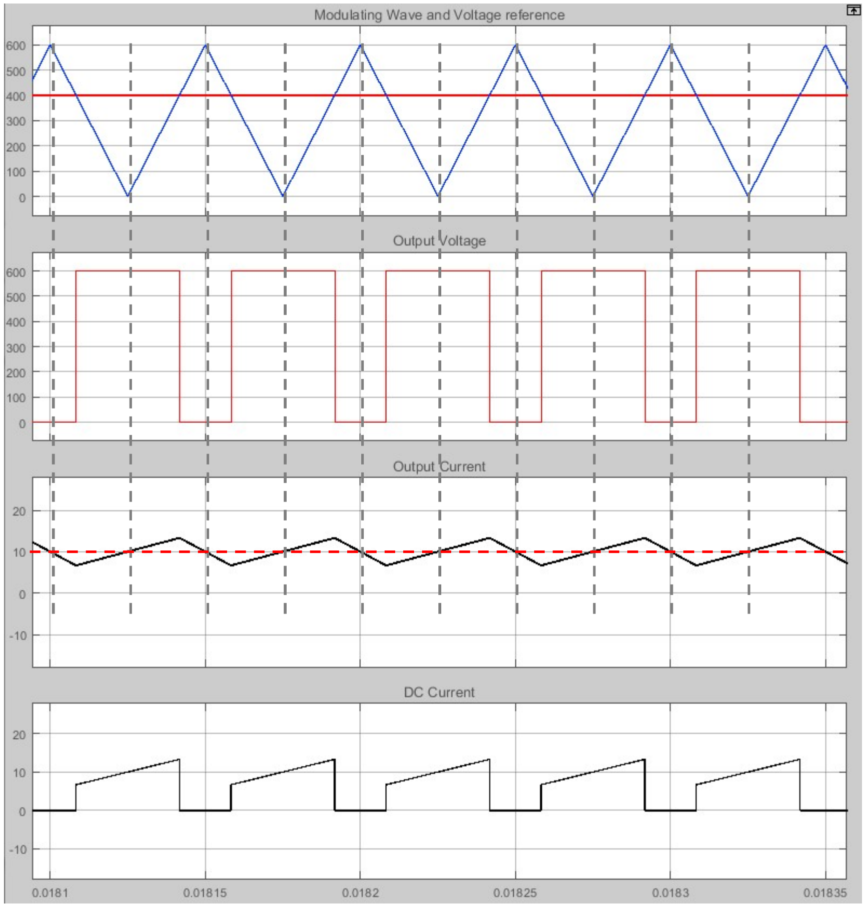
Generic Load



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

Sampling of the current?

- Controllers are usually digital, with a fixed sampling frequency
- The current has a large ripple
- How to measure the current?
  - *Let's recapitulate the 2Q Modulations examples ...*
  - *Notice that the current passes through its average value every time the carrier wave turns ...*
- The solution is to sample the current when the carrier wave turns, in the 2 quadrant case, i.e. A twice the switching frequency.
- So, we go on with a sampled current controller



Current controller, derived from the voltage equation

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

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

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

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

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

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

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

Current Controller continued

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

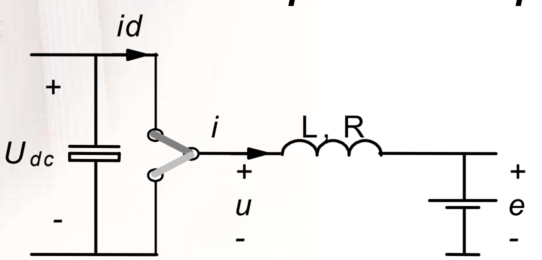
$$= R \cdot \frac{i*(k)-i(k)}{2} + R \cdot i(k) + L \cdot \frac{i*(k)-i(k)}{T_s} + e(k) =$$

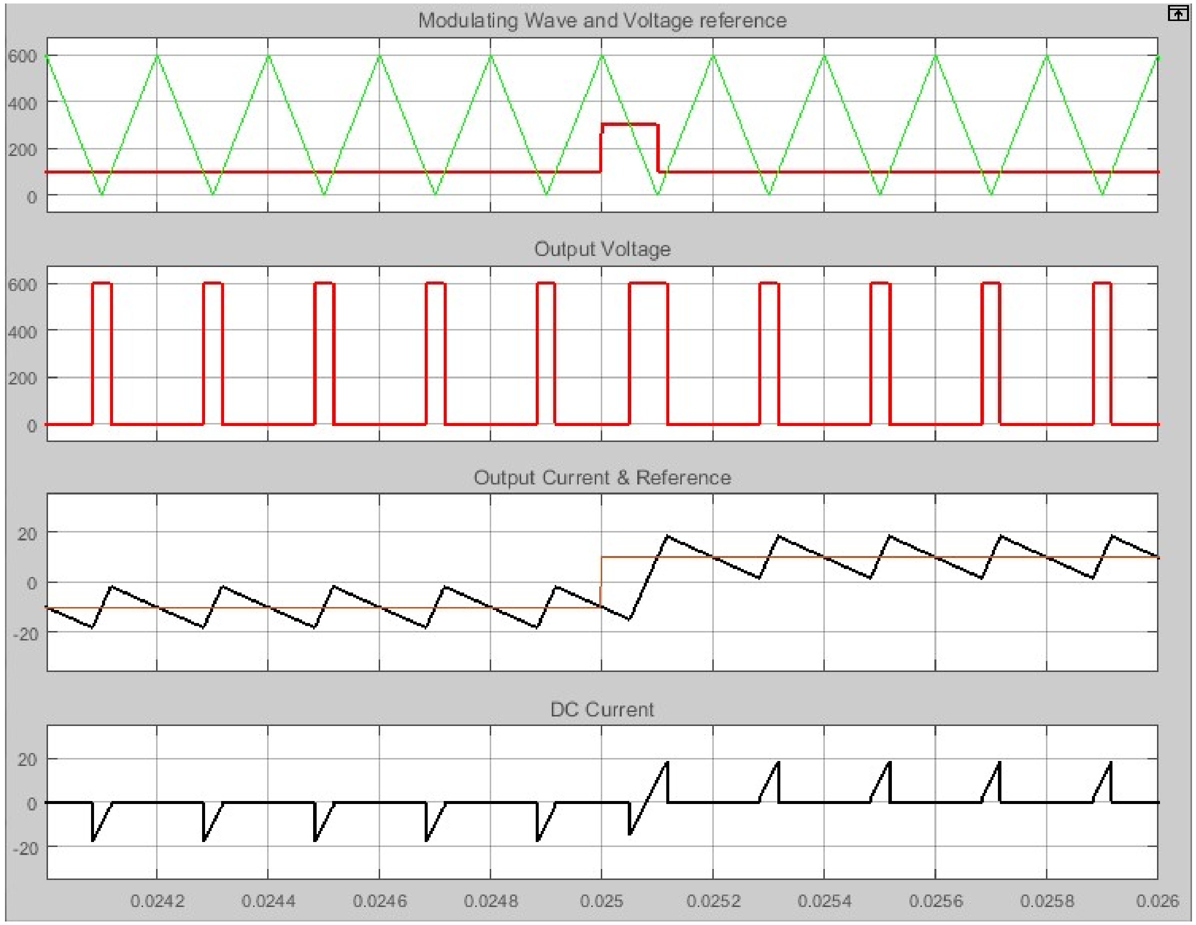
$$= \left(\frac{L}{T_s} + \frac{R}{2}\right)(i*(k)-i(k)) + R \cdot \sum_{n=0}^{n=k-1} (i*(n)-i(n)) + e(k) =$$

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

Current Control of a 2Q DC converter

- **Example:**
  - *Udc=600;*
  - *La=1e-3;*
  - *Ra=0.1;*
  - *ea=100;*
  - *Ts=100e-6*
  - *i* = +/- 10 A square wave @ 20 Hz*
- **1 millisecond around step**
- **Notice:**
  - ***Positive step in one sample***





Current Controller continued

- **Example:**
  - *Udc=600;*
  - *La=1e-3;*
  - *Ra=0.1;*
  - *ea=100;*
  - *Ts=100e-6*

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

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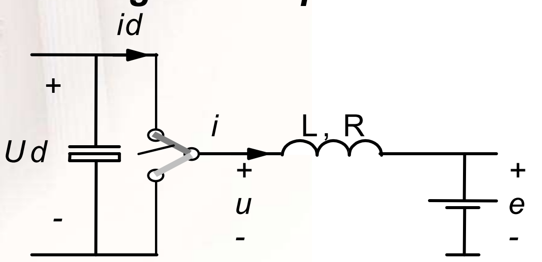
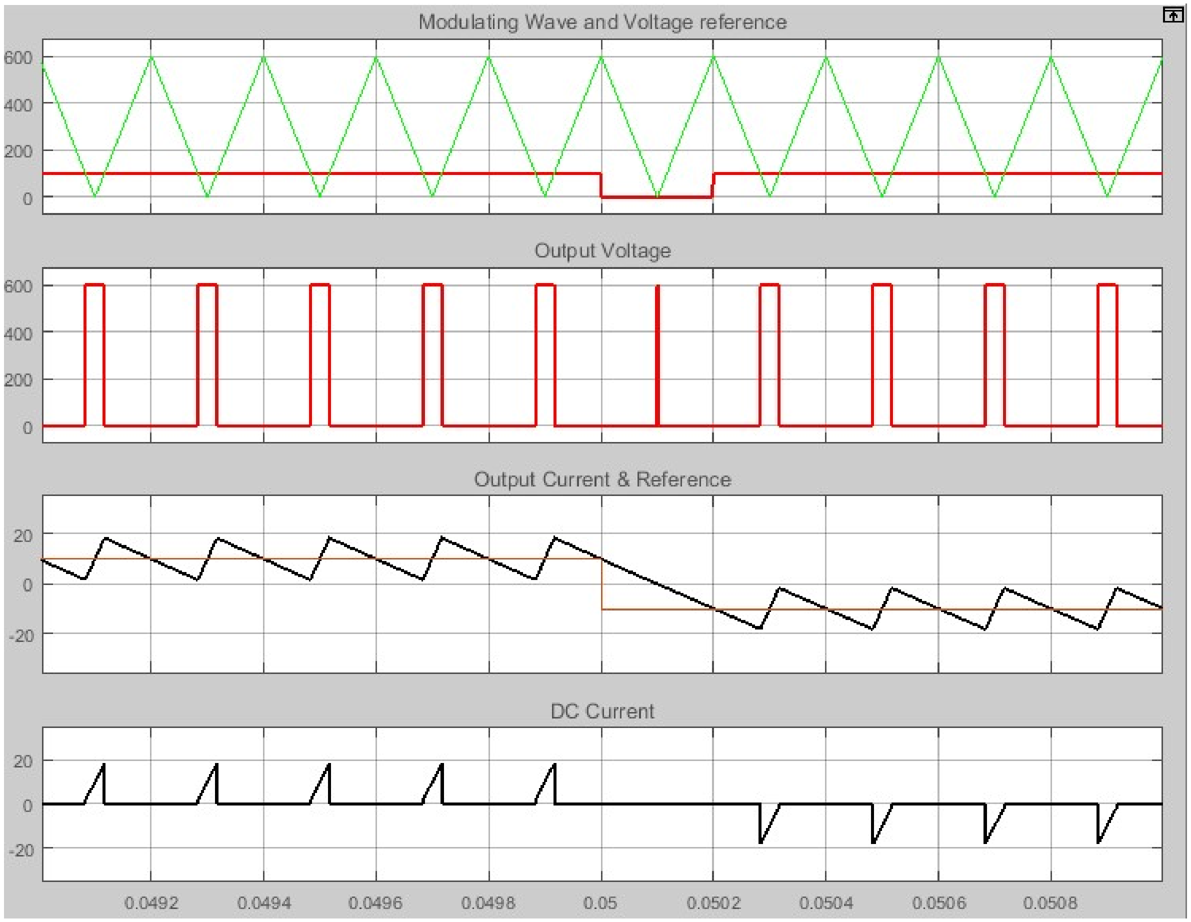
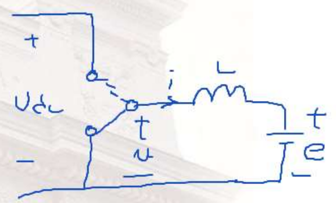
  - *ea=100;*
  - *Ts=100e-6*
  - *i* = +/- 10 A square wave @ 20 Hz*
- **1 millisecond around step**
- **Notice:**
  - ***Negative step SLOW!***

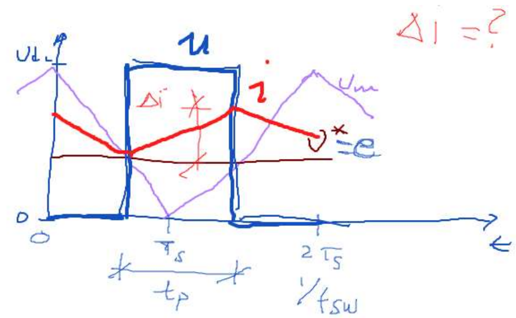




Current ripple



$$\frac{di}{dt} = \begin{cases} \frac{U_{dc} - e}{L} & \text{if } u = U_{dc} \\ \frac{-e}{L} & \text{if } u = 0 \end{cases}$$



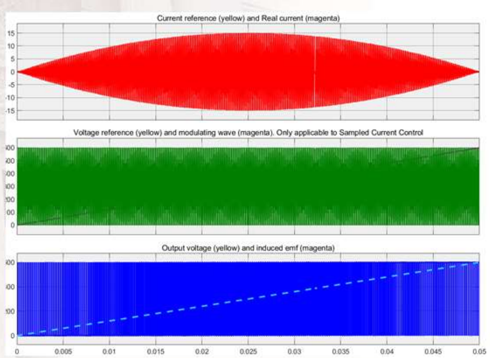
$$\Delta i = \frac{U_{dc} - e}{L} \cdot t_p$$

Stationary $\longrightarrow$ $t_p = \frac{e}{U_{dc}} \cdot 2 T_s$

$$\Delta i = \frac{U_{dc} - e}{L} \cdot \frac{e}{U_{dc}} \cdot 2T_s = e \cdot \frac{U_{dc} \cdot 2 T_s}{L \cdot U_{dc}} - e^2 \cdot \frac{2T_s}{U_{dc} L}$$

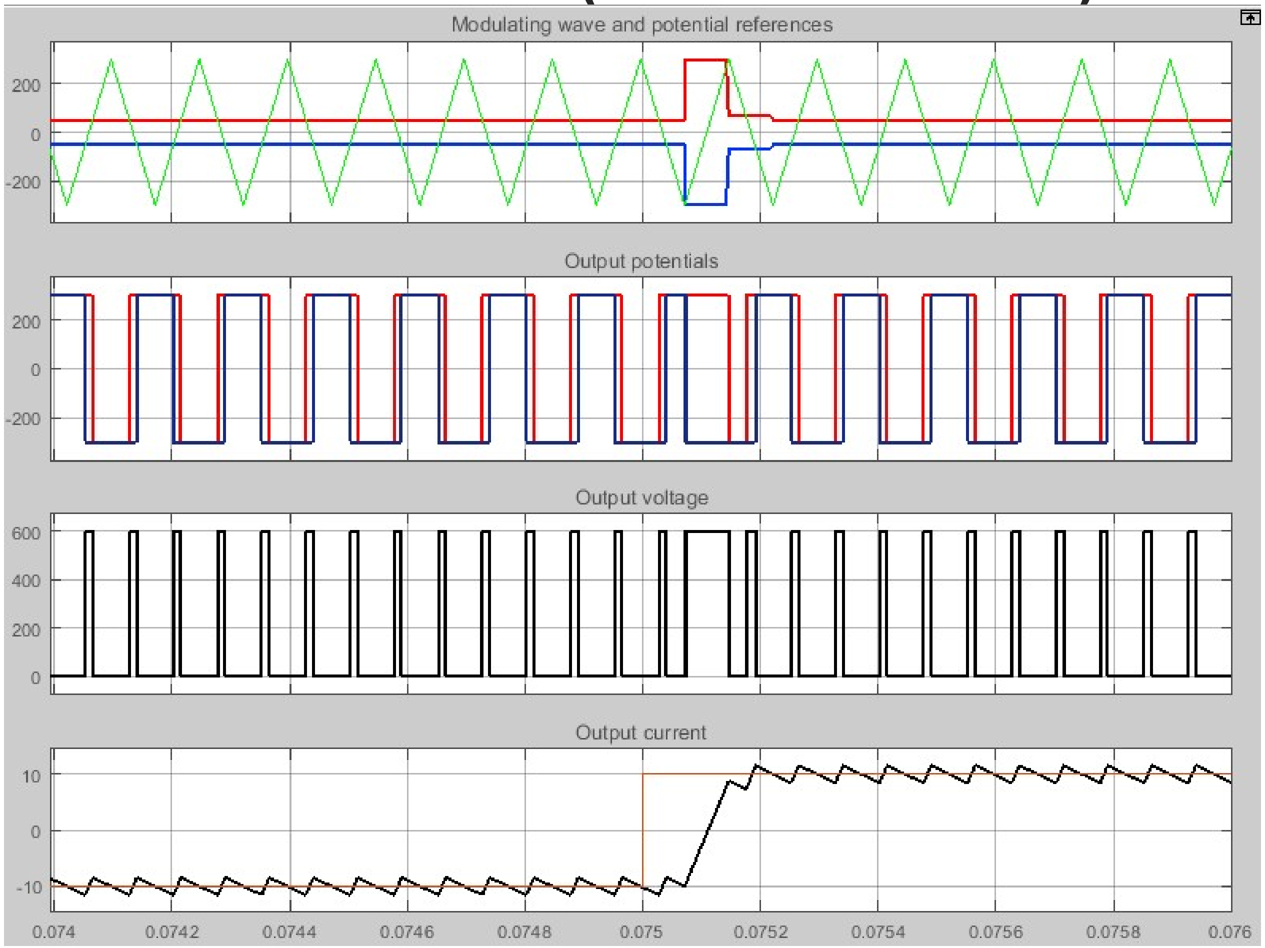
$$\frac{d\Delta i}{de} = \frac{2 T_s}{L} - 2 \cdot e \cdot \frac{2 \cdot T_s}{L \cdot U_{dc}} = 0 \rightarrow \frac{2 T_s}{L} = 2 \cdot e \cdot \frac{2 T_s}{U_{dc} L} \qquad e = \frac{U_{dc}}{2}$$

$$\Delta i_{max} = \frac{U_{dc}}{2} \cdot \frac{2 \cdot T_s}{L} - \frac{U_{dc}^2 \cdot 2 T_s}{4 \cdot U_{dc} \cdot L} = \frac{U_{dc} \cdot T_s}{L} - \frac{U_{dc} \cdot 2 T_s}{4 \cdot L} = \frac{U_{dc}}{L} \cdot T_s$$



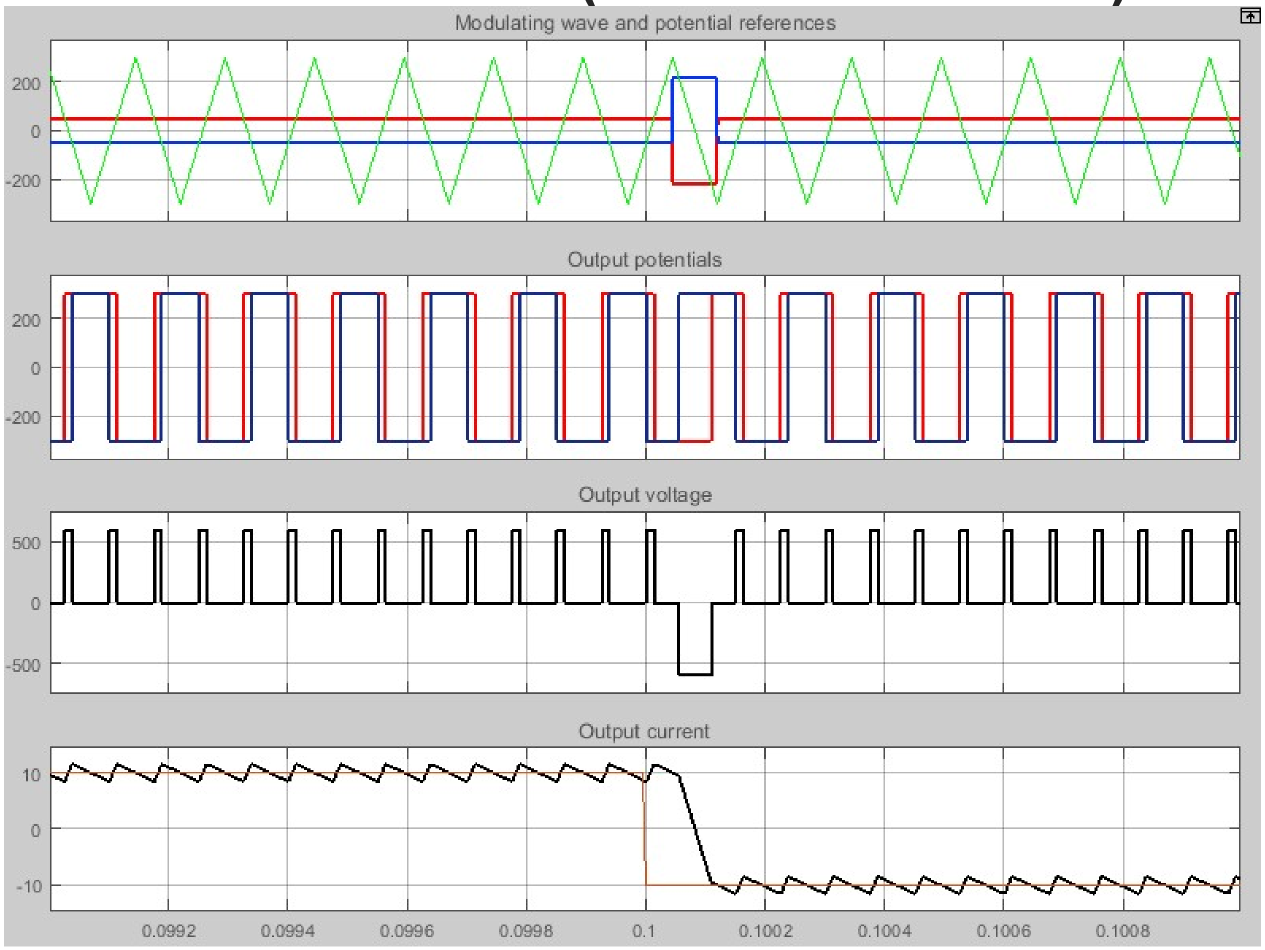
Current Control of a 4Q DC converter (POSITIVE STEP)

- **Example**:
  - Udc = 600 [V]
  - Ra=0.1 [Ohm]
  - ea =100 [V]
  - L= 2 [mH]
  - Switchfrequency: 6.67 [kHz]
  - i* = +/- 10 A square wave at 20 Hz.
- **1 millisecond around step**
- **Notice:**
  - One sample interval ALMOST enough for **positive step**



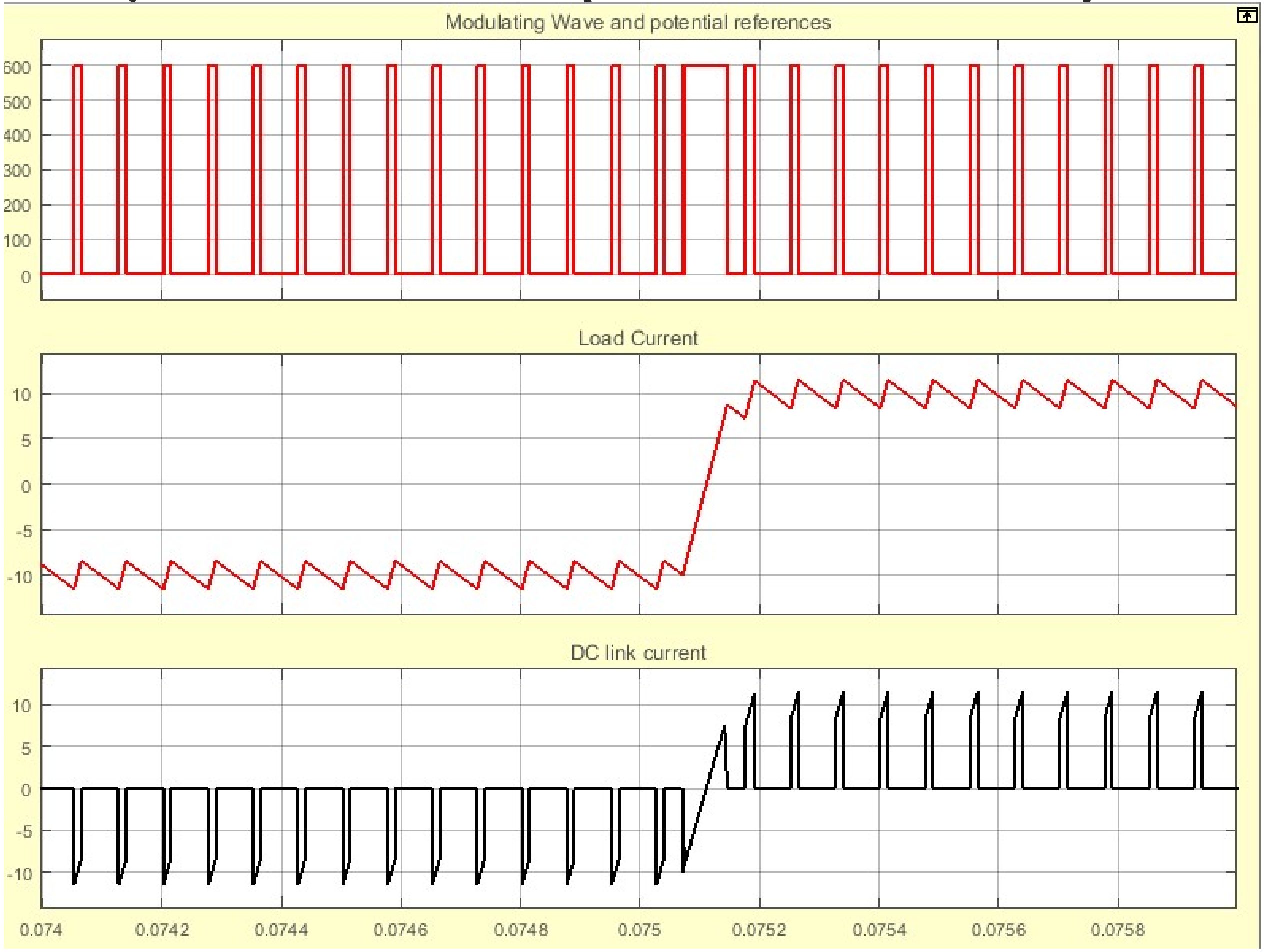
Current Control of a 4Q DC converter (NEGATIVE STEP)

- **Example**:
  - Udc = 600 [V]
  - Ra=0.1 [Ohm]
  - ea =100 [V]
  - L= 2 [mH]
  - Switchfrequency: 6.67 [kHz]
  - i* = +/- 10 A square wave at 20 Hz.
- **1 millisecond around step**
- **Notice:**
  - One sample interval enough for **negative step**



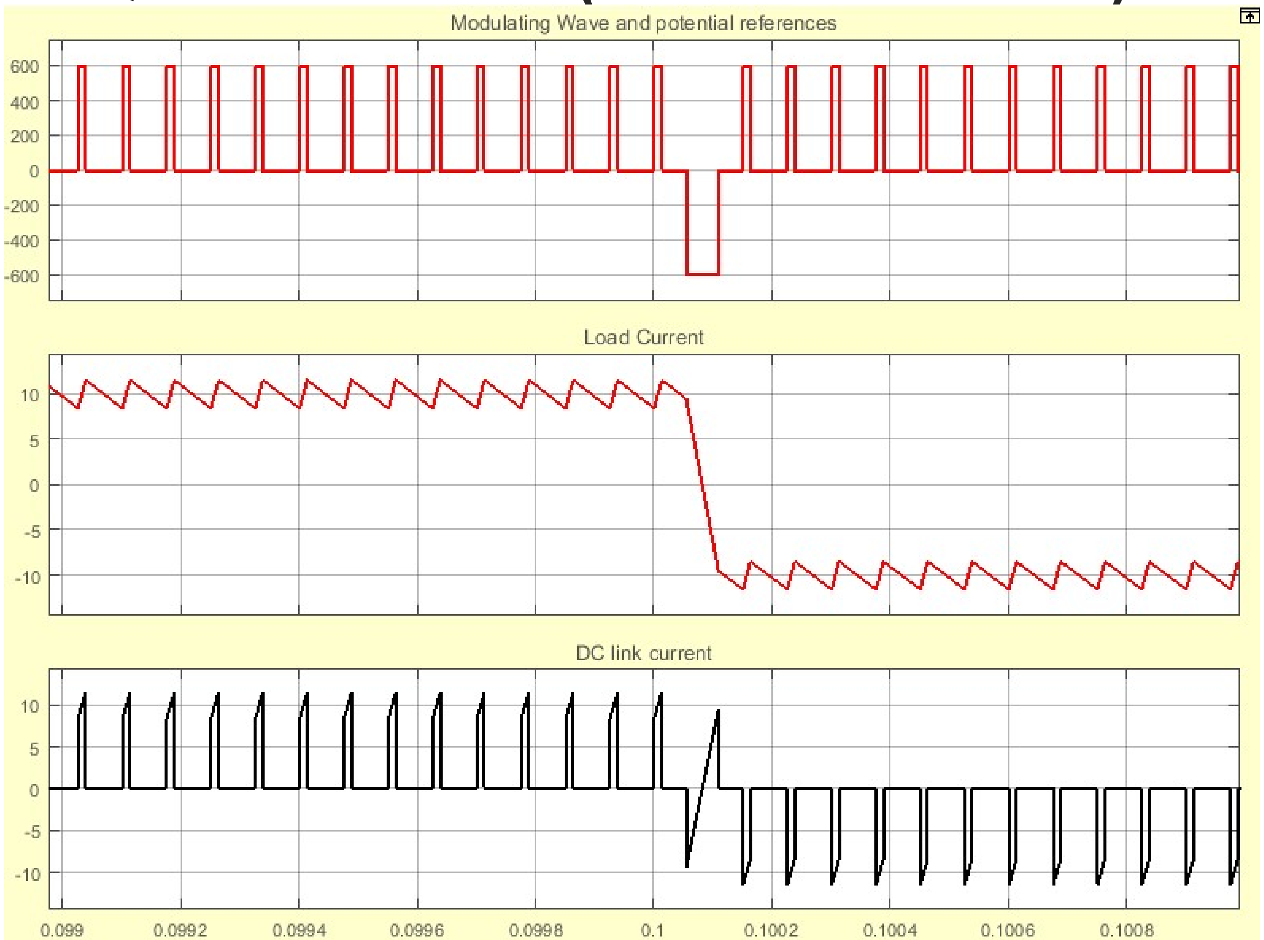
Current Control of a 4Q DC converter (POSITIVE STEP)

- **Example**:
  - Udc = 600 [V]
  - Ra=0.1 [Ohm]
  - ea =100 [V]
  - L= 2 [mH]
  - Switchfrequency: 6.67 [kHz]
  - i* = +/- 10 A square wave at 20 Hz
- **First two milliseconds:**
- **Notice:**

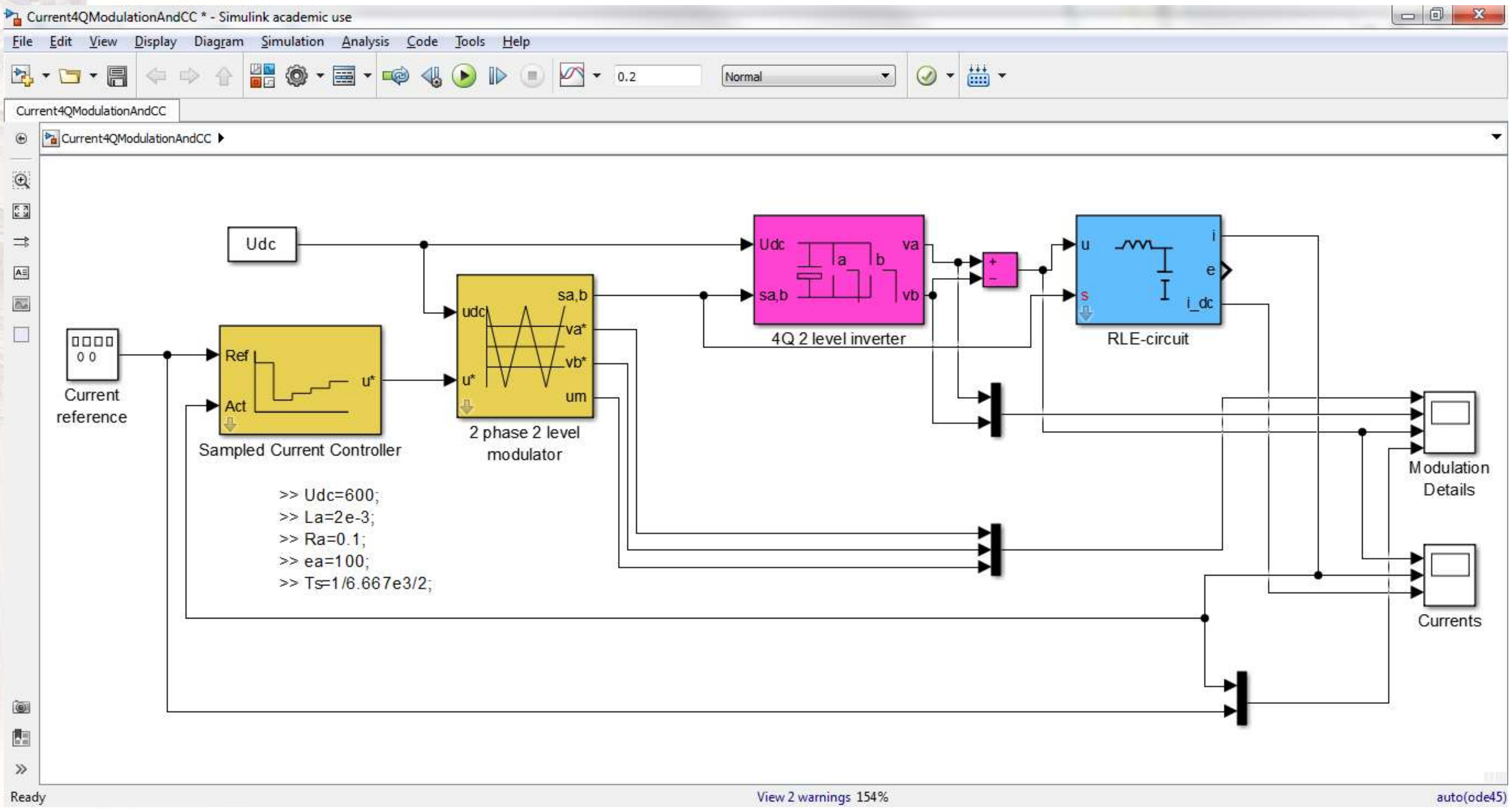


Current Control of a 4Q DC converter (NEGATIVE STEP)

- **Example**:
  - Udc = 600 [V]
  - Ra=0.1 [Ohm]
  - ea =100 [V]
  - L= 2 [mH]
  - Switchfrequency: 6.67 [kHz]
  - i* = +/- 10 A square wave at 20 Hz
- **First two milliseconds:**
- **Notice:**



Go to Simulation

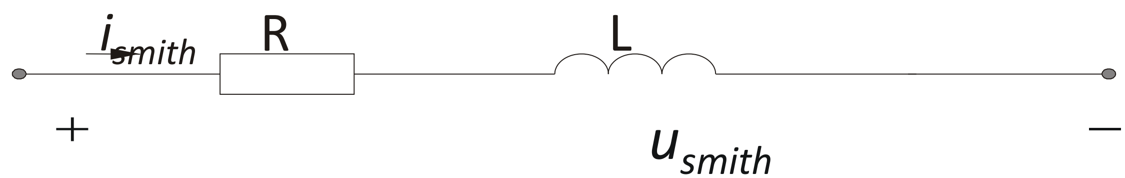


If the computer is to slow .... ?

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.*

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

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

- *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.:*

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

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

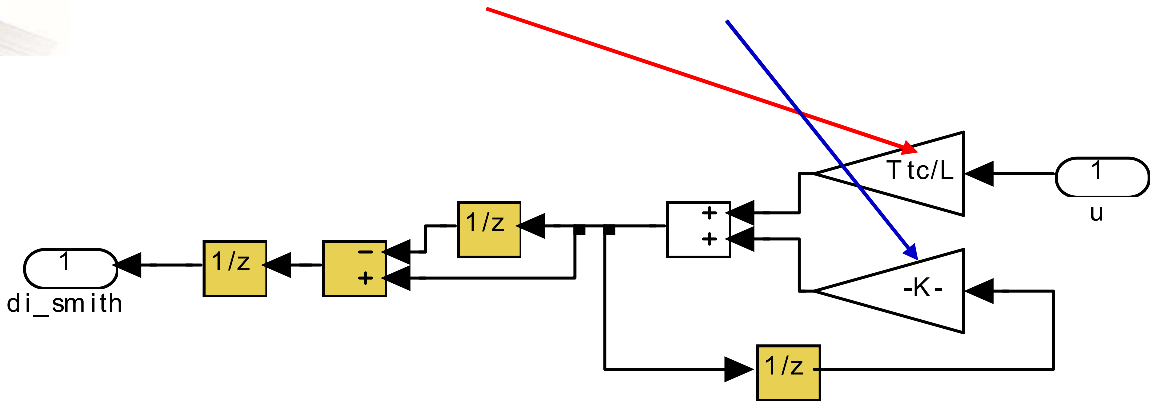
$$u^*(k-1) \approx R \cdot i_{smith}(k-1) + L \cdot \frac{i_{smith}(k) - i_{smith}(k-1)}{T_s}$$

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

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

The Smith Predictor : IV

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



Current Control with a slow computer – II

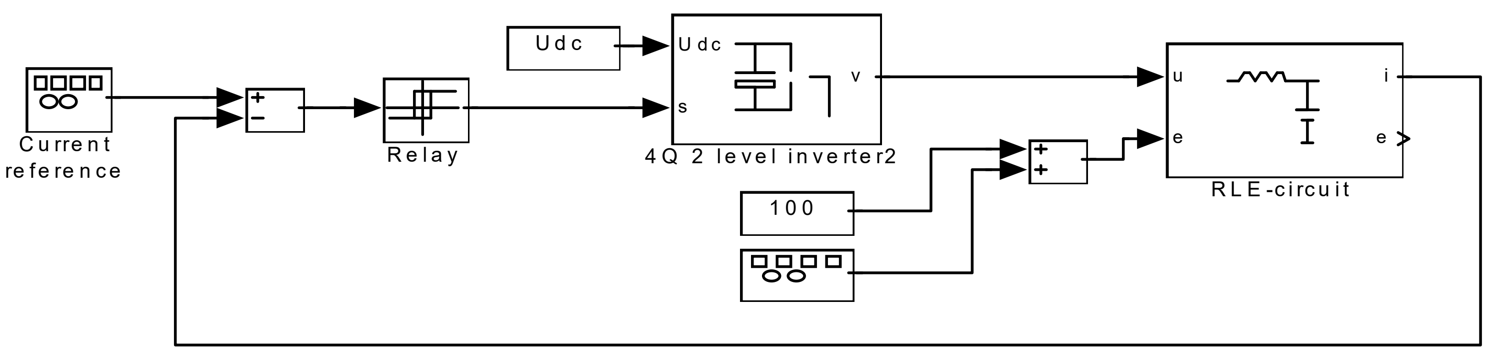
$$u^*(k) = \left(\frac{L}{T_s} + \frac{R}{2}\right) \cdot \left(\left(i^*(k) - \hat{i}(k)\right) + \frac{T_s}{\left(\frac{L}{R} + \frac{T_s}{2}\right)} \cdot \sum_{n=0}^{n=k-1} \left(i^*(n) - \hat{i}(n)\right) \right) + \hat{e}(k)$$

Direct Current Control

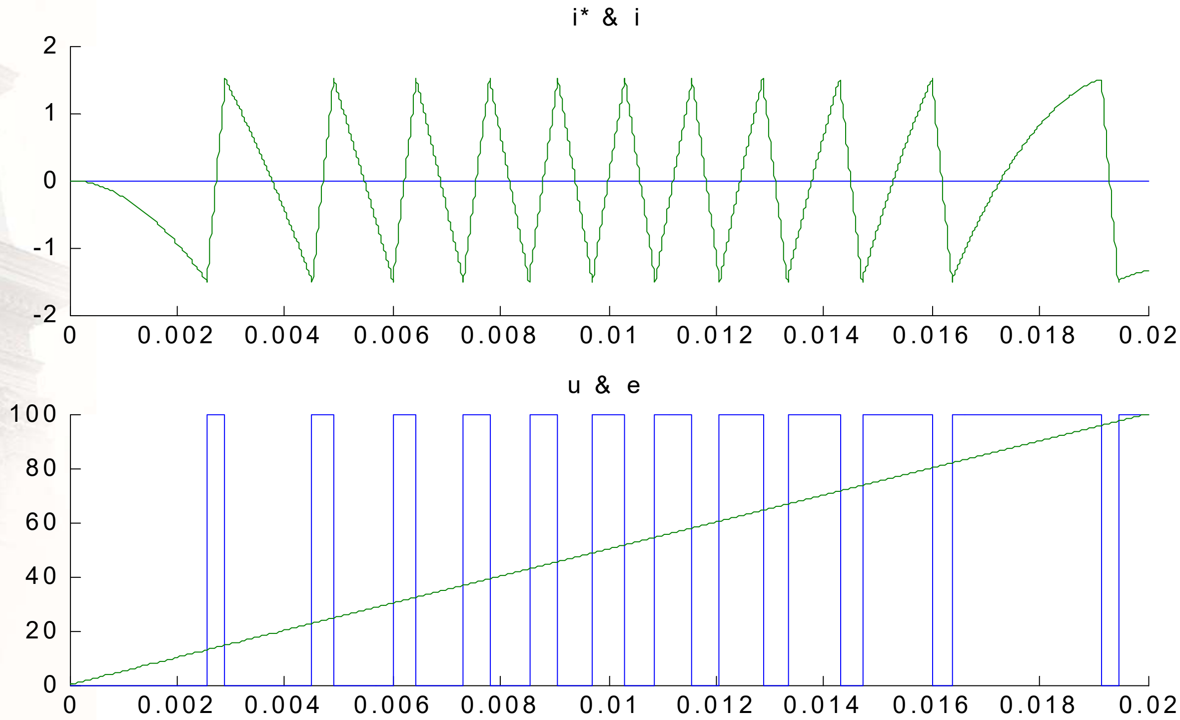
- **Switch state only a function of current error**
- **No intermediate current control or modulation**

2-Quadrant Direct Current Controller

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



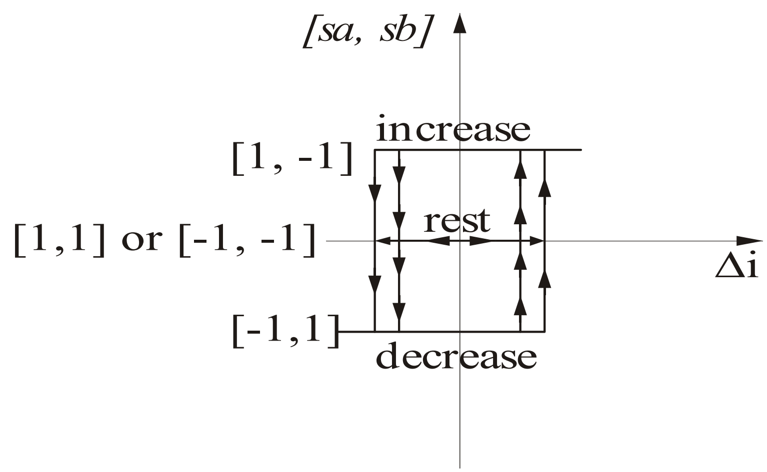
Example



i* & i
2
1
0
-1
-2
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
u & e
100
80
60
40
20
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02

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:**

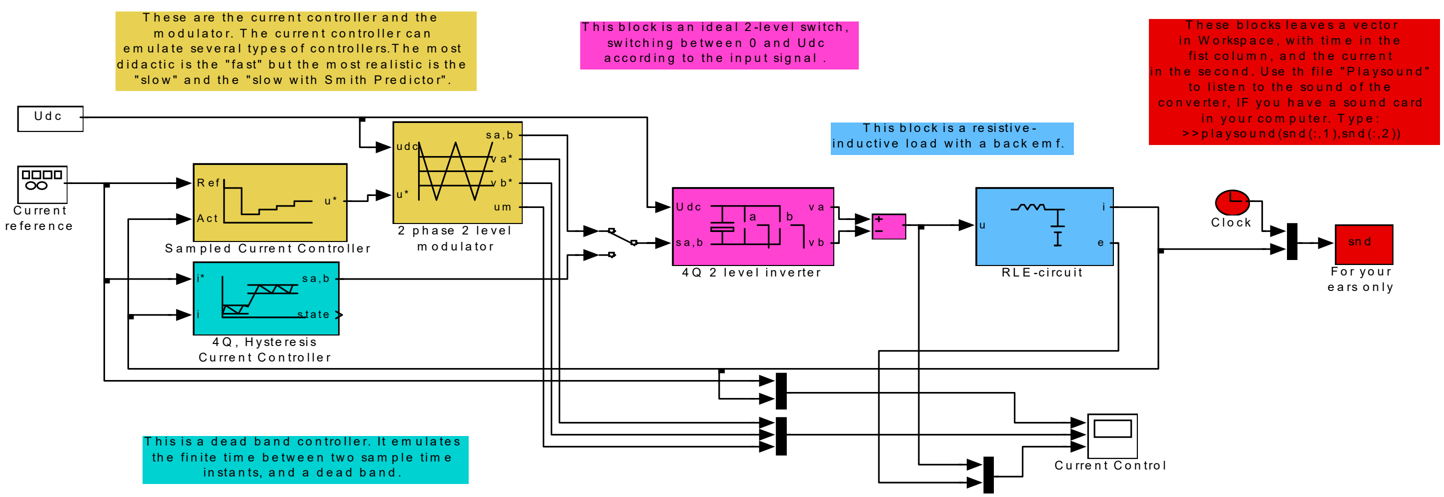


$$\Delta i = i^* - i$$

Q hysteresis control in detail

State	u	di/dt	
[-1,-1]	0	-e/L	
[1,-1]	Udc	(Udc-e)/L	
[-1,1]	-Udc	(-Udc-e)/L	
[1,1]	0	-e/L	

Example


These are the current controller and the modulator. The current controller can emulate several types of controllers.The most didactic is the "fast" but the most realistic is the "slow" and the "slow with Smith Predictor".
This block is an ideal 2-level switch, switching between 0 and Udc according to the input signal .
These blocks leaves a vector in Workspace, with time in the fist column, and the current in the second. Use th file "Playsound" to listen to the sound of the converter, IF you have a sound card in your computer. Type: >>playsound(snd(:,1),snd(:,2))
This block is a resistive-inductive load with a back emf.
Udc
Current reference
Ref
Act
u*
Sampled Current Controller
udc
sa,b
va*
vb*
um
2 phase 2 level modulator
Udc
sa,b
va
vb
a
b
4Q 2 level inverter
u
i
e
RLE-circuit
Clock
snd
For your ears only
i*
i
sa,b
state
4Q, Hysteresis Current Controller
Current Control
This is a dead band controller. It emulates the finite time between two sample time instants, and a dead band.