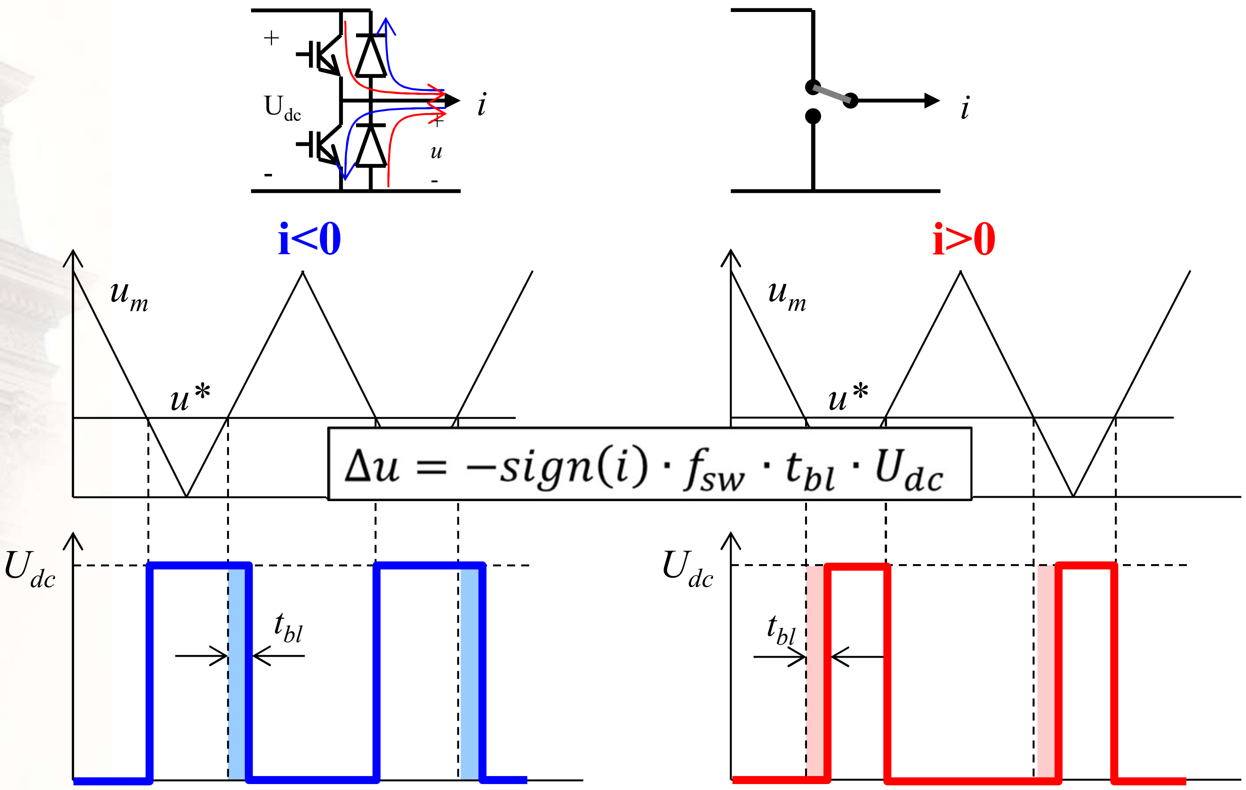
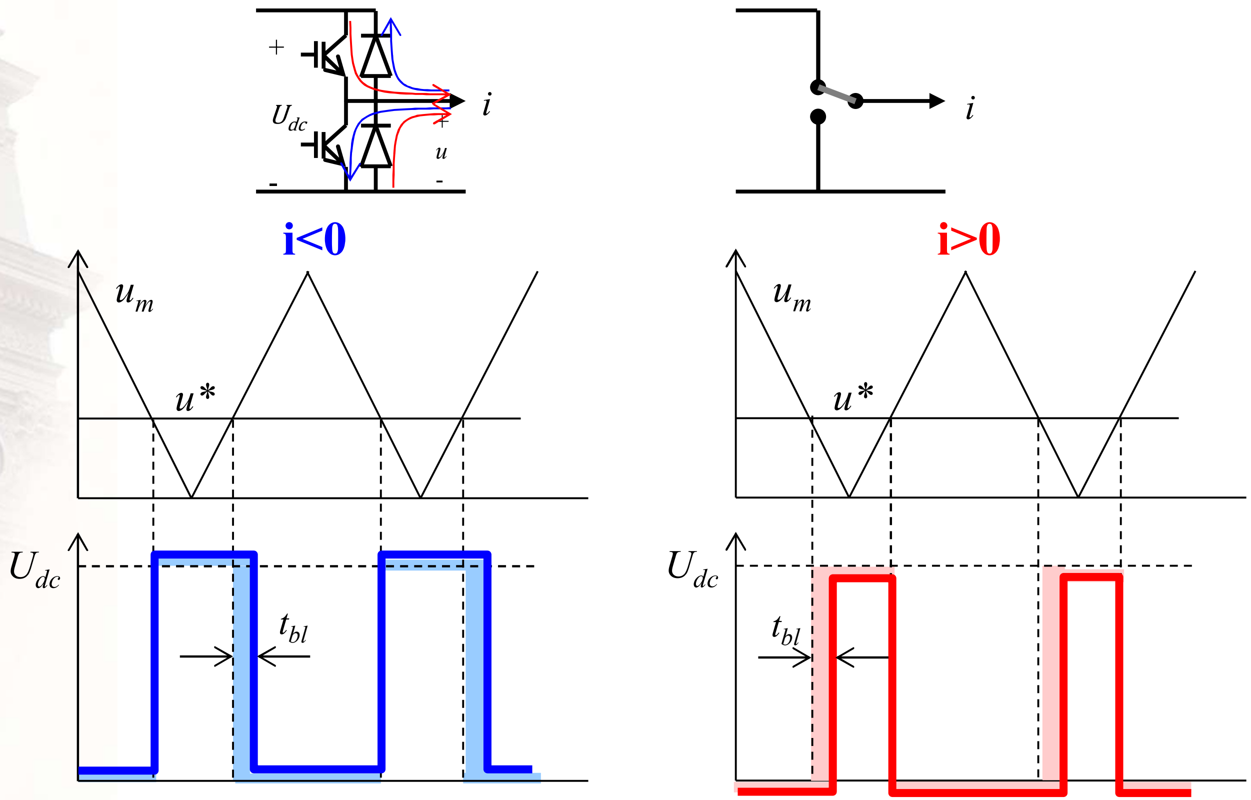
Lecture 4 – 4Q converter and modulation

Blanking Time



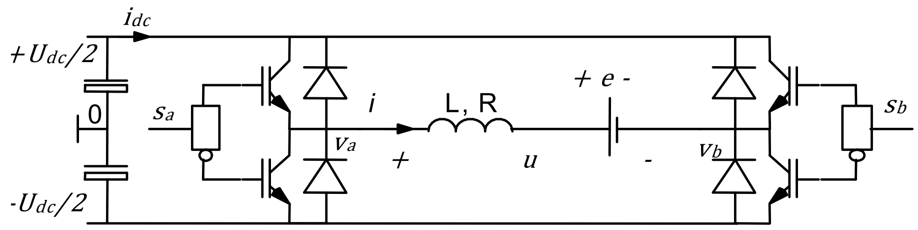
$$\Delta u = -sign(i) \cdot f_{sw} \cdot t_{bl} \cdot U_{dc}$$

Blanking Time + Voltage Drops



Modulation of a 4Q converter

- 1 output voltage, 2 phase potentials ->infinite number of combinations of v_a*och v_b*gives $u = v_a - v_b$.
- 2 clear alternatives:



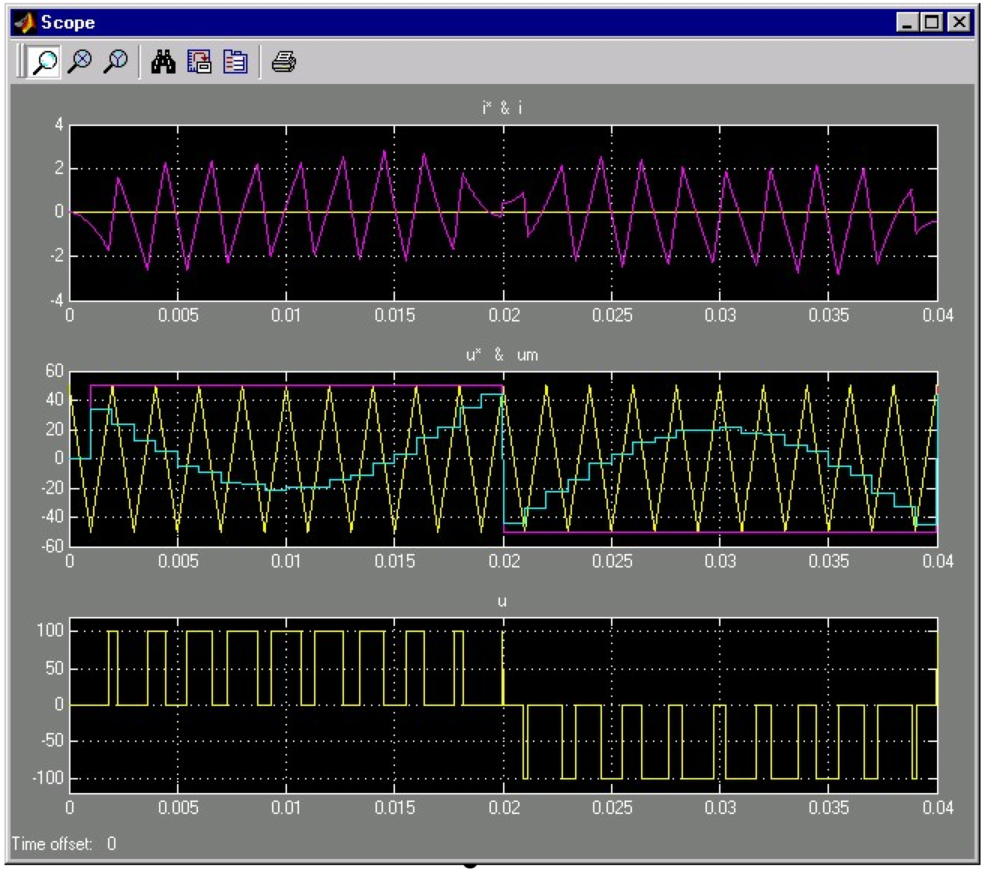
$$u^* = v_a^* - v_b^*$$

$$alt1: v_a^* = sign(u^*) \cdot \frac{U_{dc}}{2} \Rightarrow v_b^* = v_a^* - u *= sign(u^*) \cdot \frac{U_{dc}}{2} - u^*$$

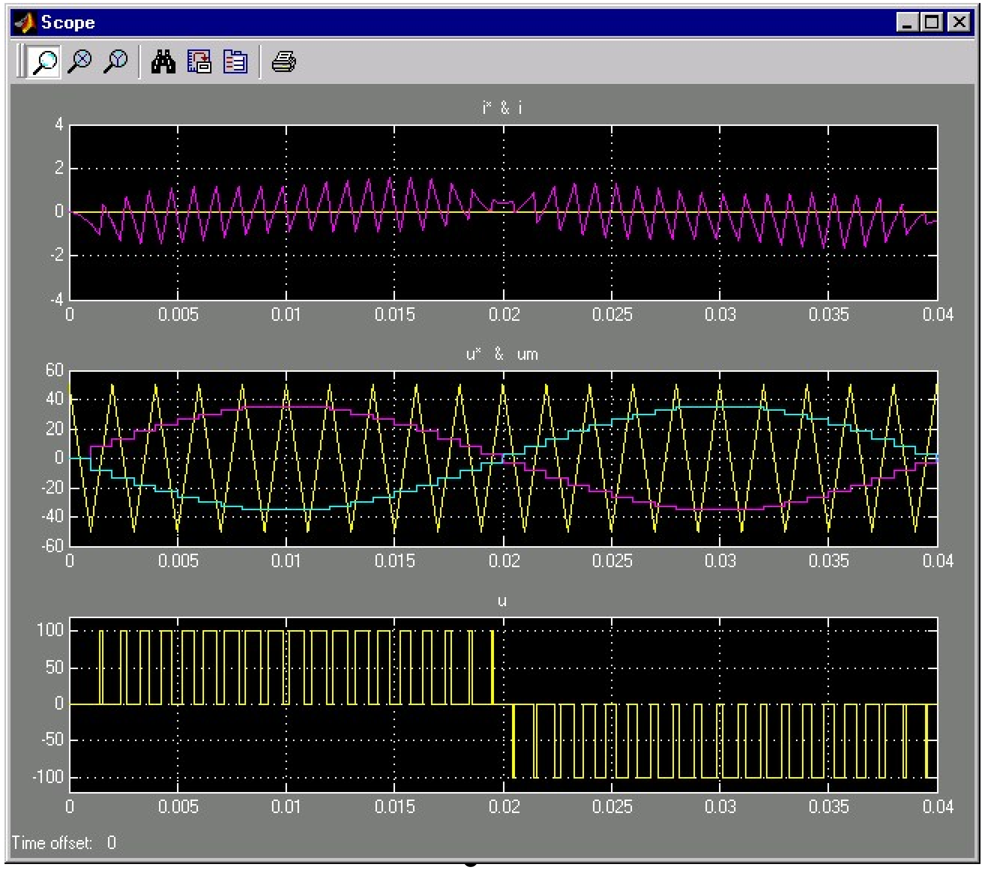
$$alt2: v_a^* = -v_b^* \Rightarrow v_a^* - v_b^* = 2 \cdot v_a^* \Rightarrow \begin{cases} v_a^* = \dfrac{u^*}{2} \\ v_b^* = -\dfrac{u^*}{2} \end{cases}$$

$$\frac{di}{dt} = \frac{(u-e)}{L}$$

4-quadrant DC converters – alt 1



4-quadrant DC converters – alt 2



Modulation of a 4Q converter

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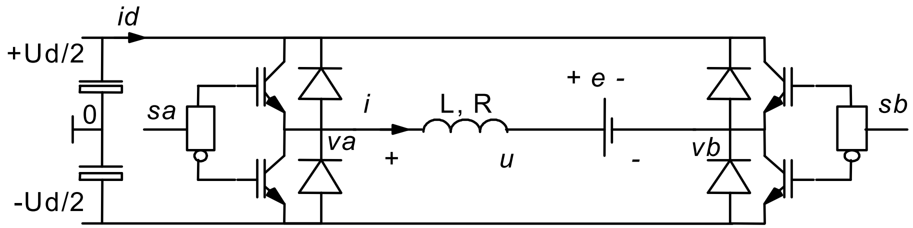

$$u* = v_a^* - v_b^*$$

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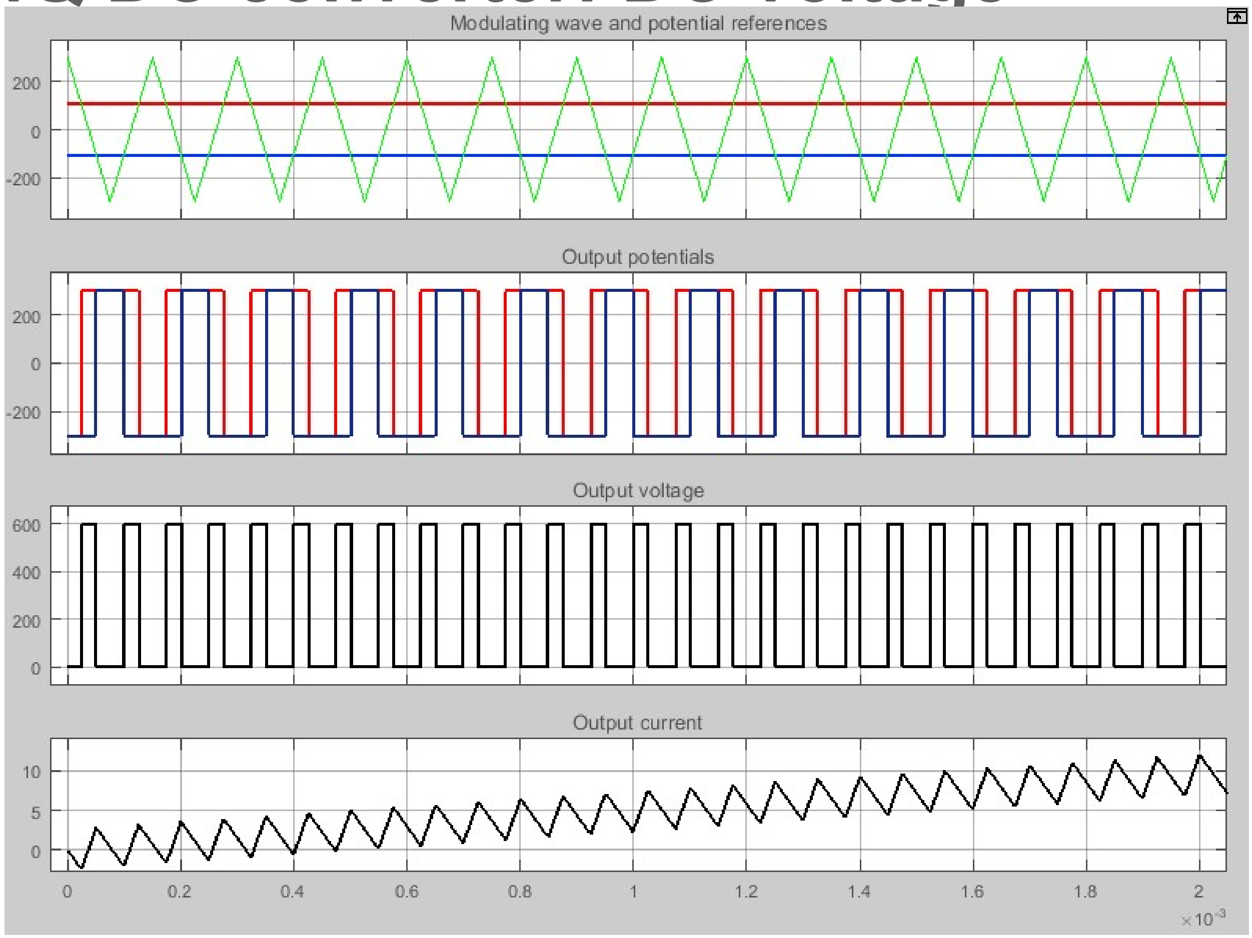
$$\frac{di}{dt} = \frac{(u-e)}{L}$$

Modulation of a 4Q DC converter: DC voltage

- **Example:**
  - *Udc = 600 [V]*
  - *Ra=0.1 [Ohm]*
  - *ea =200 [V]*
  - *L= 2 [mH]*
  - *Switchfrequency: 6.67 [kHz]*
  - *Assume 100 A (20 kW)*
  - *u* = ea + Ra*100*
- *First two millisecond***s:**



Modulation of a 4Q DC converter: DC voltage

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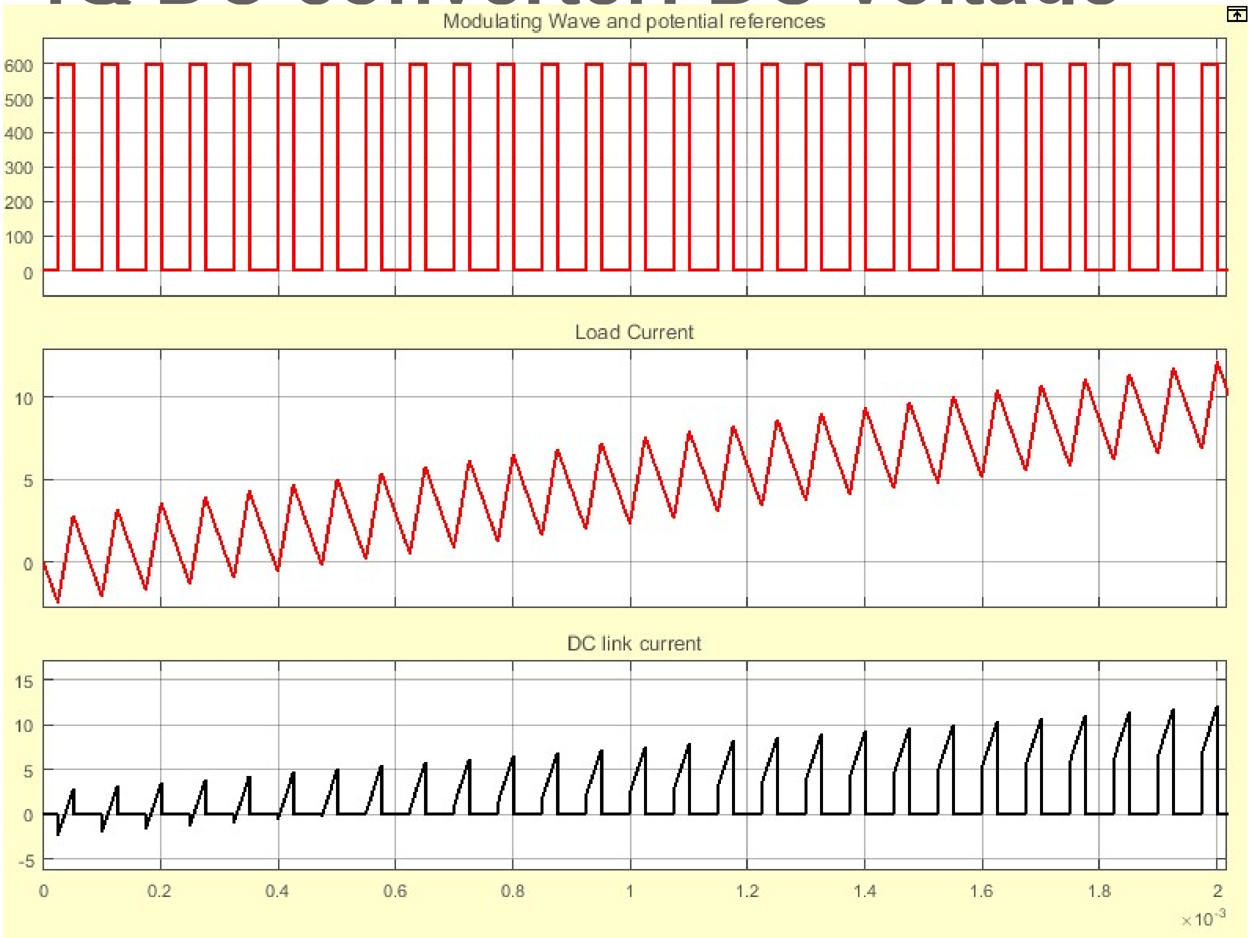
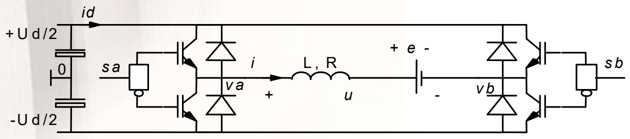
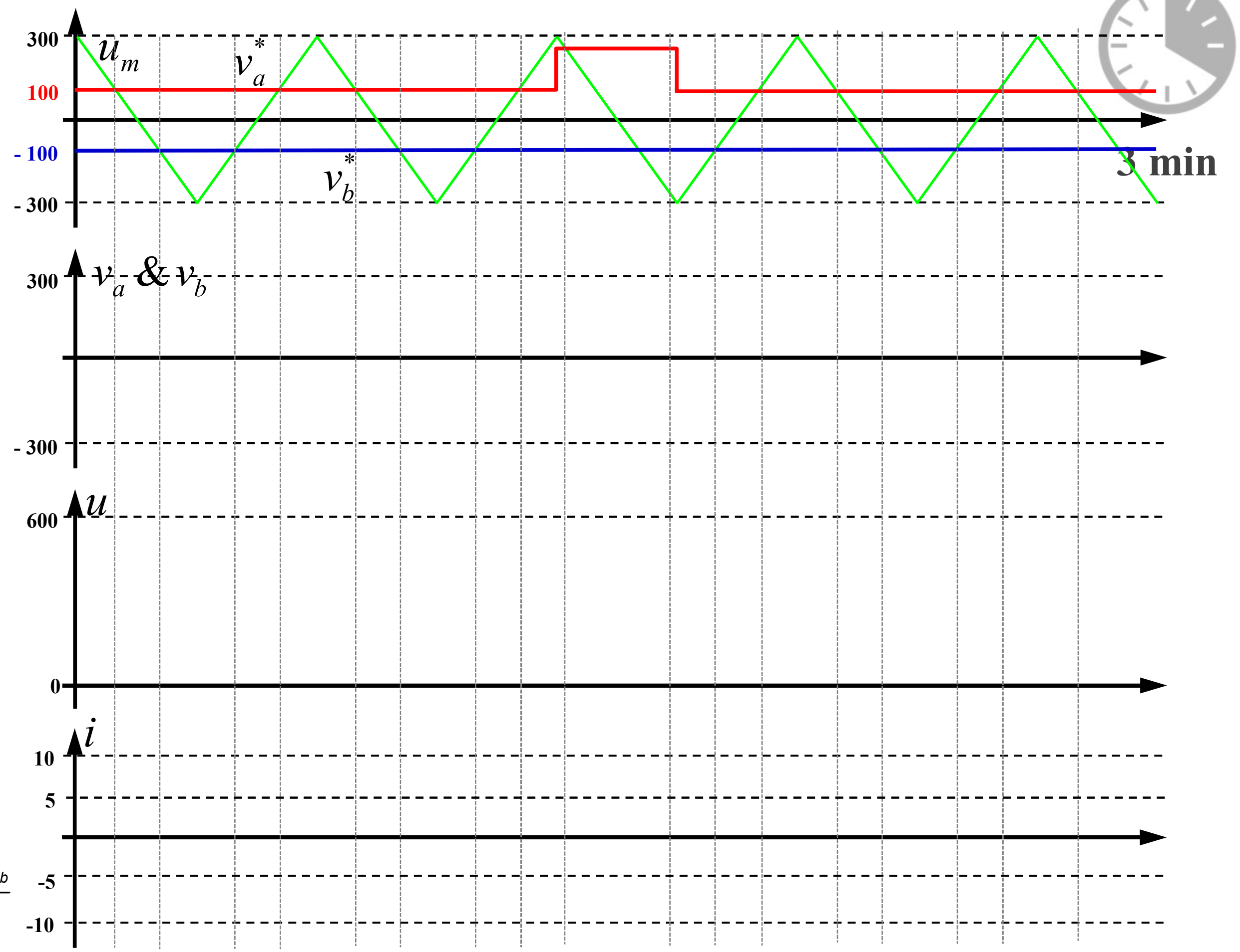
  - *Switchfrequency: 6.67 [kHz]*
  - *Assume 100 A (20 kW)*
  - *u* = ea + Ra*100*
- **First two milliseconds:**
- **Notice:**
  - *DC-side: PWM current*
  - *AC side: PWM voltage*
  - *DC side: instantaneous power, but average (almost) zero, due to mainly reactive load.*
  - **DC side current negative if load current is negative**



Exercise: Modulation of a 4Q converter

- **Given**:
  - *Udc = 600 V*
  - *e=200 V*
  - *i(t=0)=0*
  - *Voltage reference given*
- **Parameters**:
  - *L= 2 [mH]*
  - *Switchfrekvens: 6.67 [kHz]*
- **Draw**:
  - *Potentials v_a and v_b*
  - *Load voltage u*
- **Calculate**
  - *Positive current derivative*
  - *Negative current derivative*
- **Draw**
  - *Load current i*





Exercise: Modulation of a 4Q converter

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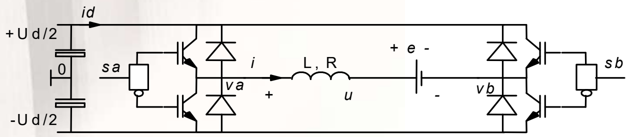
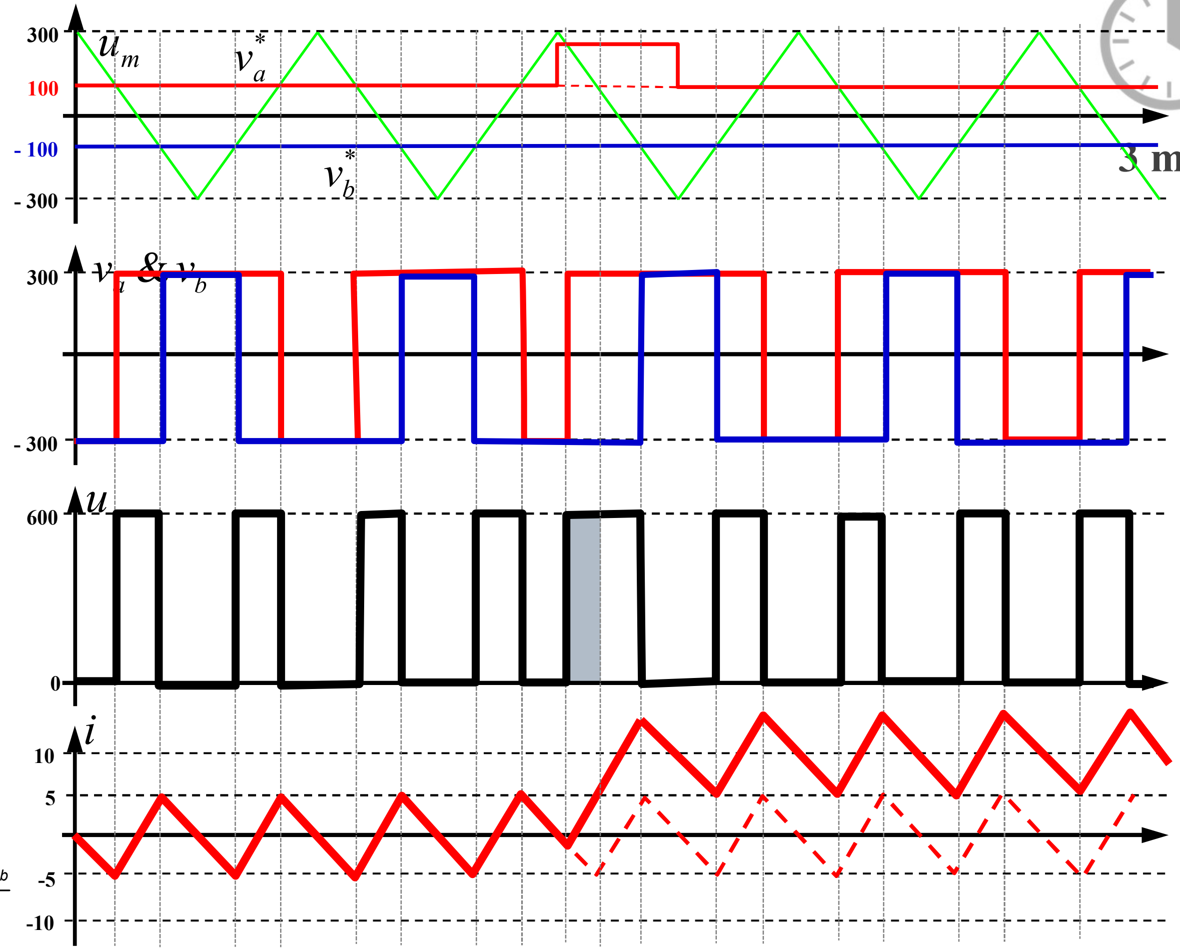
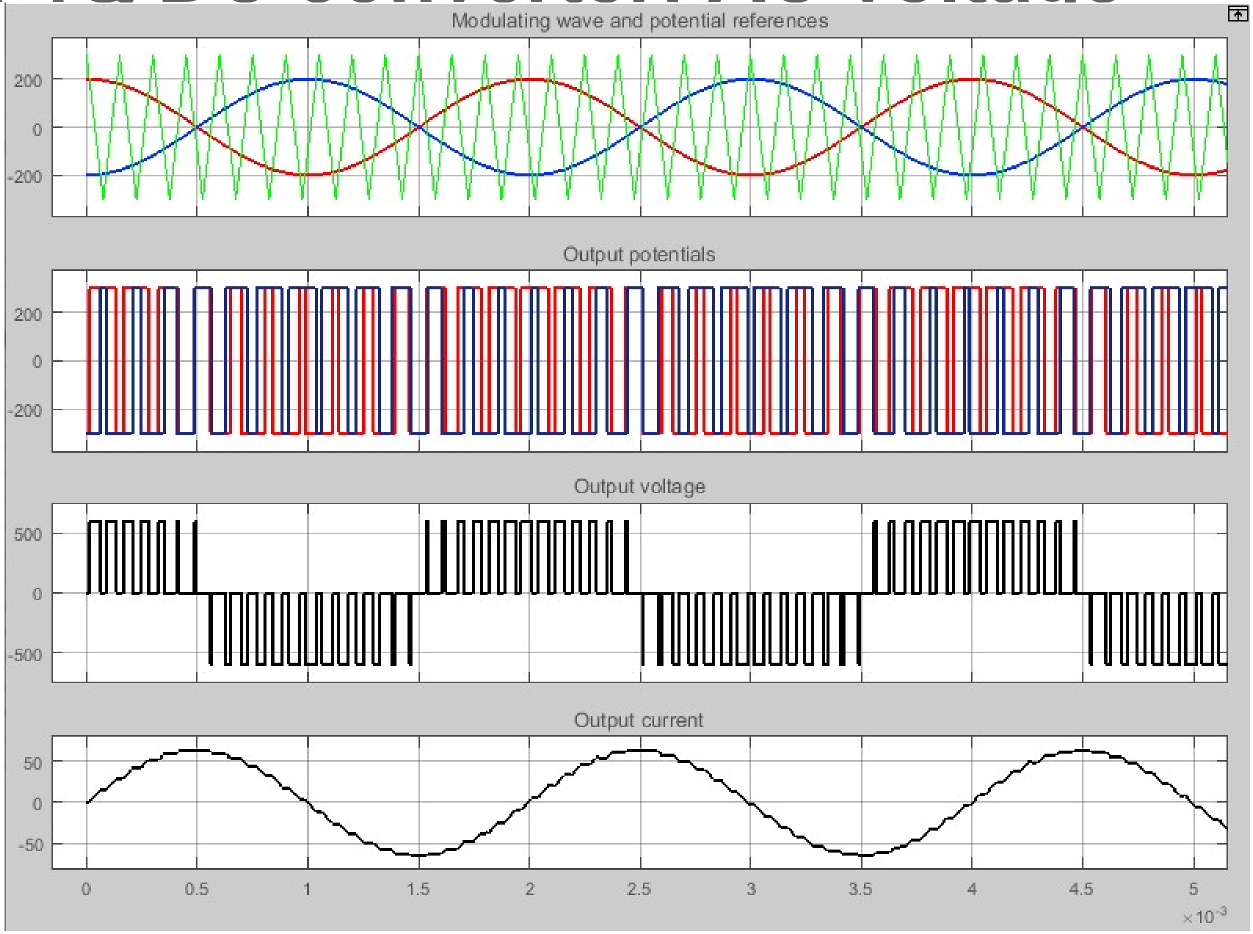




3 min

Modulation of a 4Q DC converter: AC voltage

- **Example:**
  - *Udc = 600 [V]*
  - *ea = 0 [V]*
  - *La = 2 [mH]*
  - *Ra = 0.1 [Ohm]*
  - *Switchfrekvens: 6.67 [kHz]*
  - *Uref=400 [V]; 500 [Hz]*
- **First 5 milliseconds:**



Modulation of a 4Q DC converter: AC voltage

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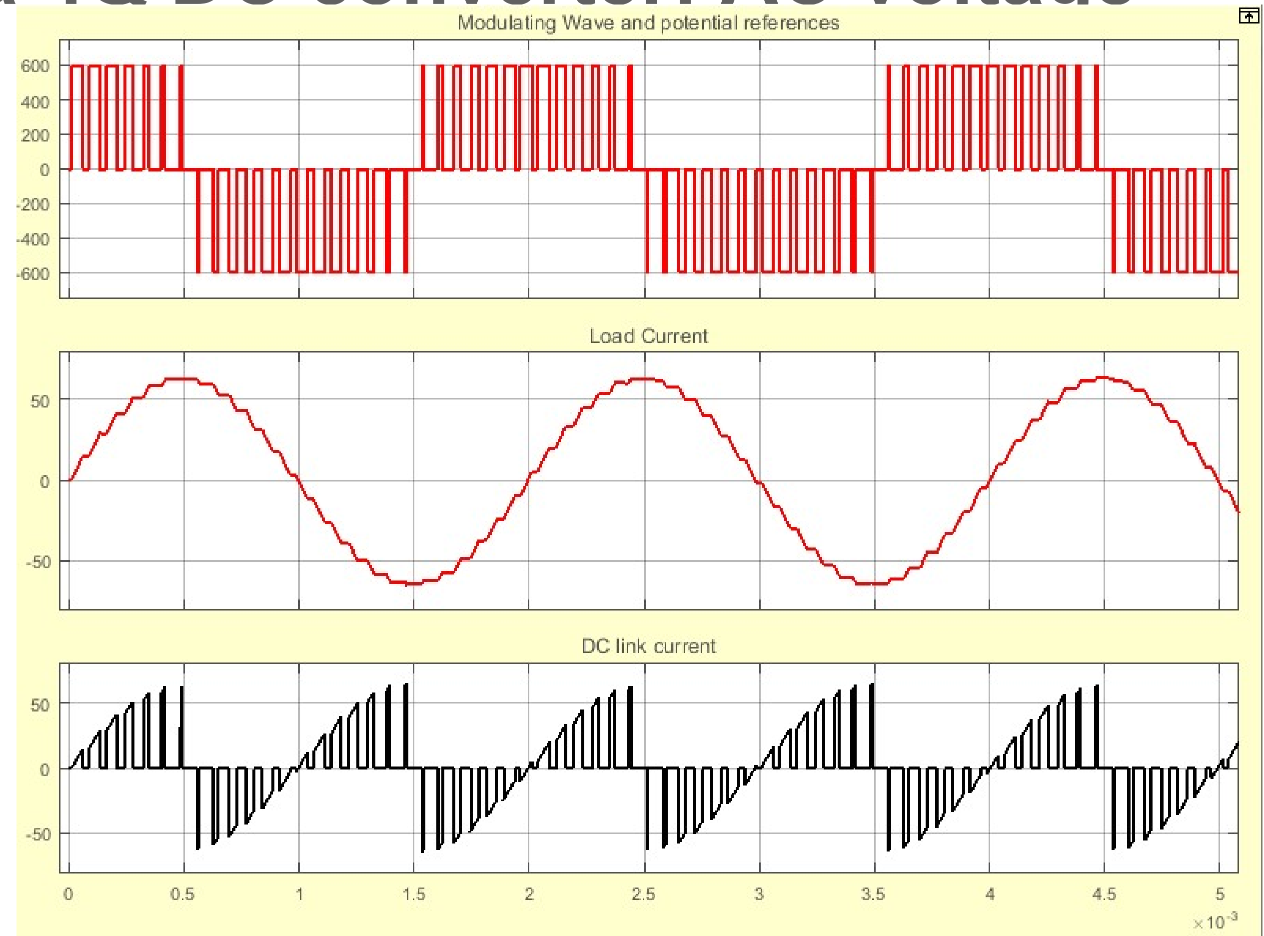
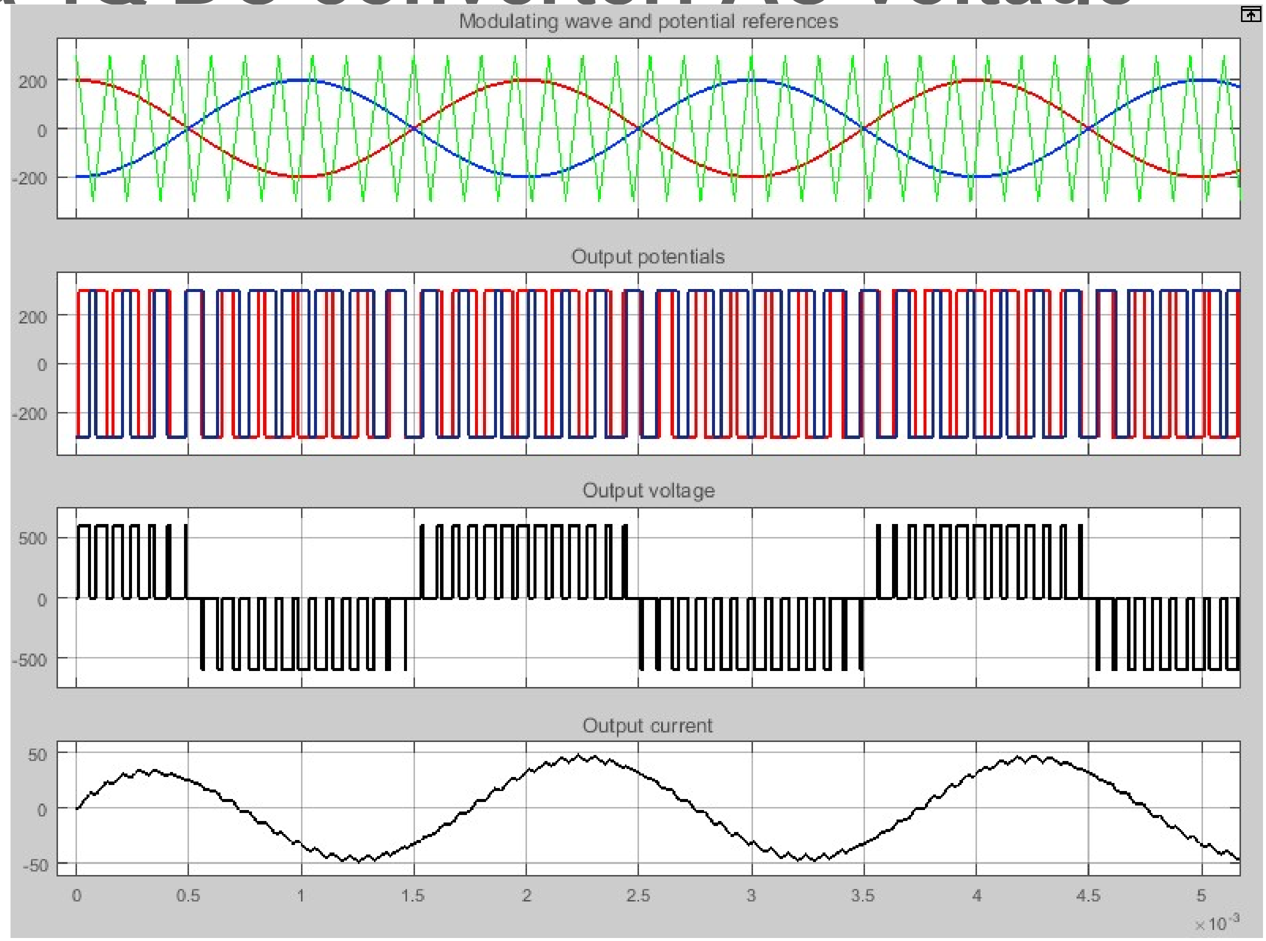


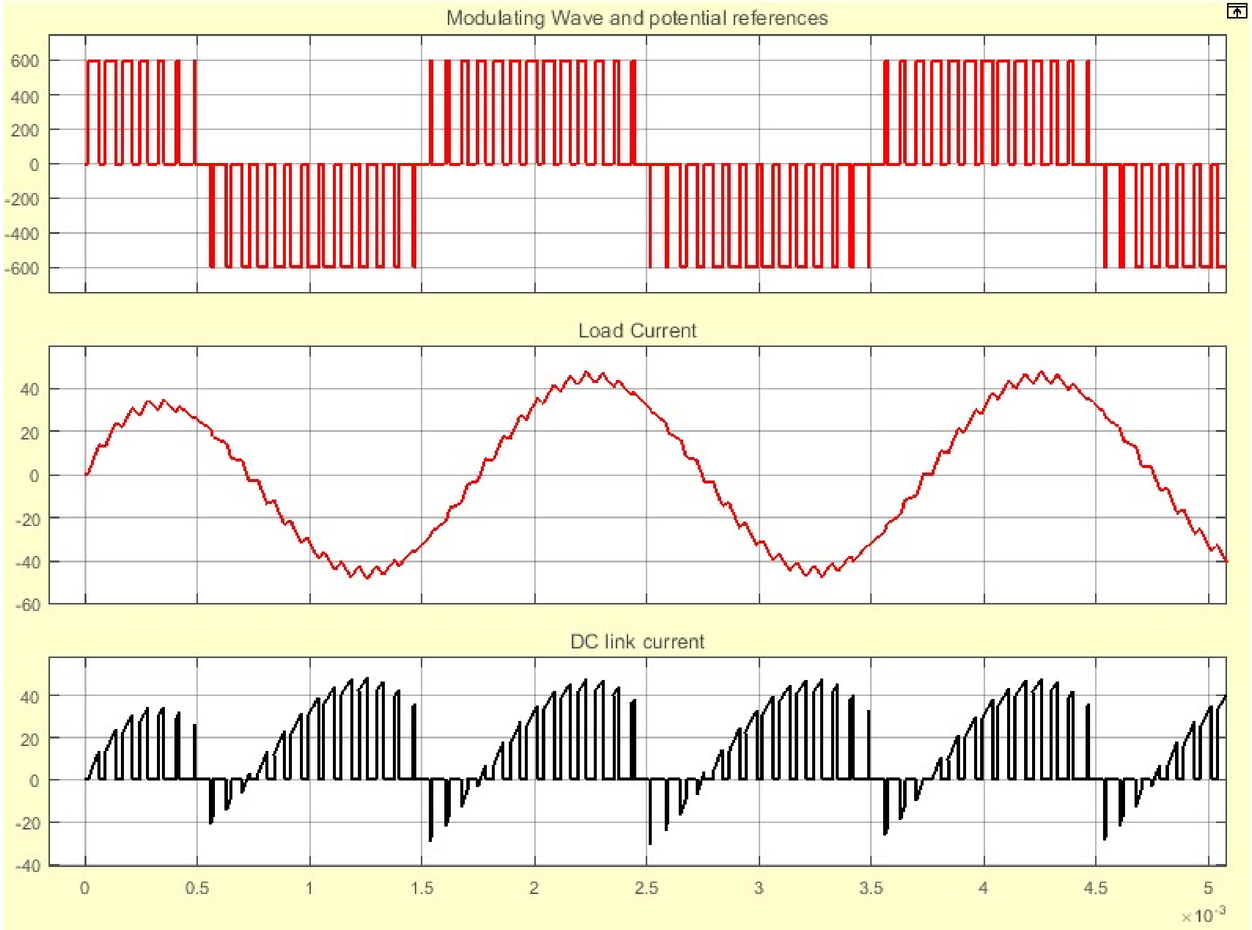
Modulation of a 4Q DC converter: AC voltage

- **Example:**
  - *Udc = 600 [V]*
  - *ea = 0 [V]*
  - *La = 2 [mH]*
  - *Ra = 2*pi*500*La [Ohm]*
  - *Switchfrekvens: 6.67 [kHz]*
  - *Uref=400 [V]; 500 [Hz]*
- **First 5 milliseconds:**

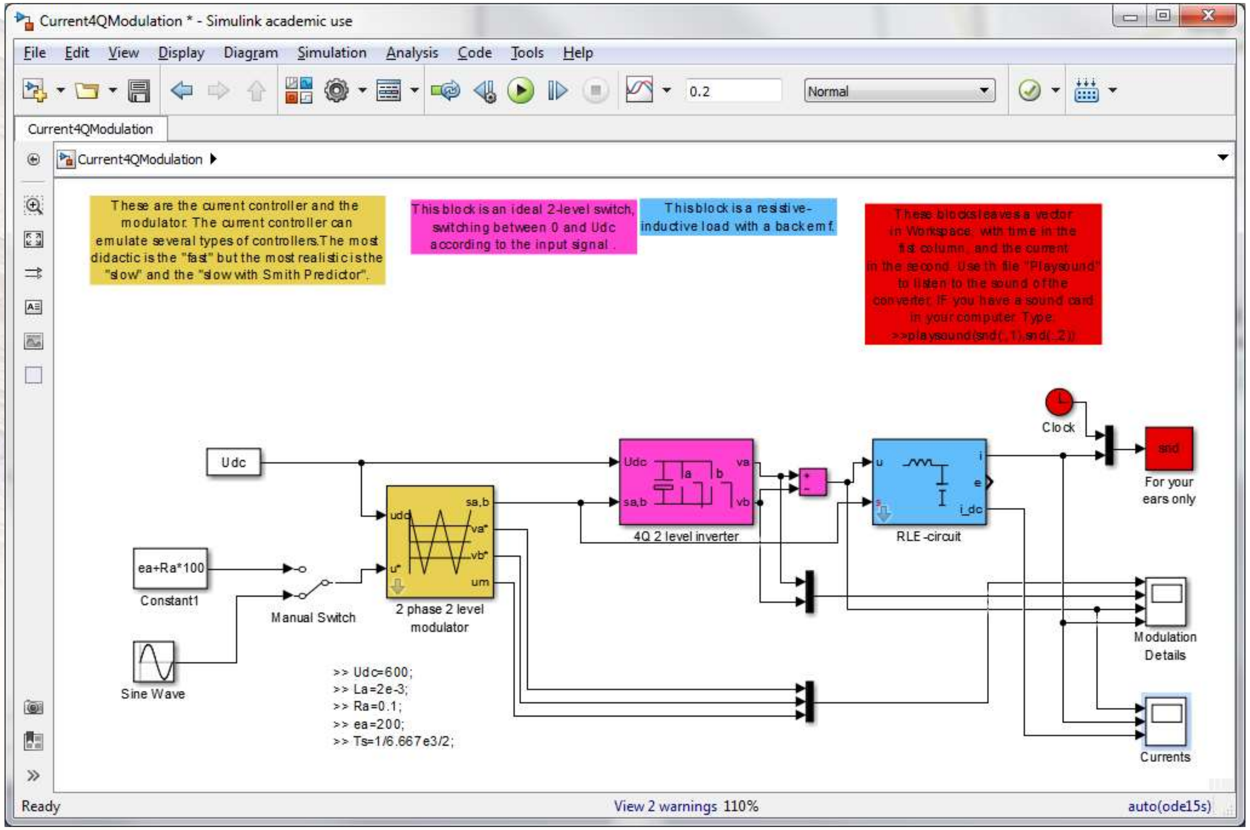


Modulation of a 4Q DC converter: AC voltage

- **Example:**
  - *Udc = 600 [V]*
  - *ea = 0 [V]*
  - *La = 2 [mH]*
  - *Ra = 2*pi*500*La [Ohm]*
  - *Switchfrekvens: 6.67 [kHz]*
  - *Uref=400 [V]; 500 [Hz]*
- **First 5 milliseconds:**
- **Notice:**
  - *DC-side: PWM current*
  - *AC side: PWM voltage*
  - *DC side: Average power positive due to high Ra. p/4 phase shift due to $R_a=\omega L_a$*



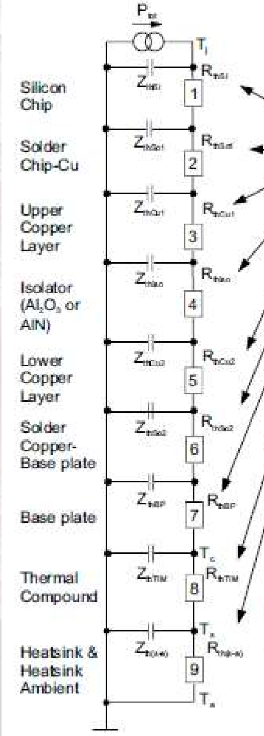
To Simulink

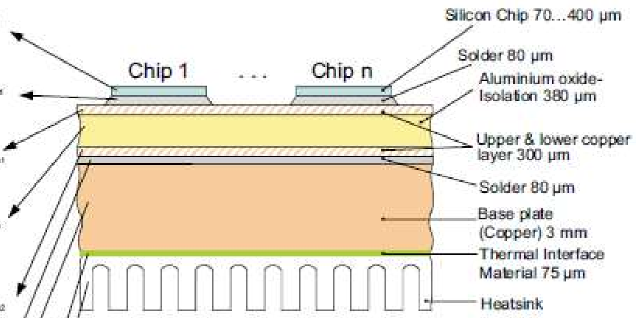


Current4QModulation * - Simulink academic use
File Edit View Display Diagram Simulation Analysis Code Tools Help
0.2
Normal
Current4QModulation
These are the current controller and the modulator. The current controller can emulate several types of controllers.The most didactic is the "fast" but the most 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 .
This block is a resistive-inductive load with a back emf.
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))
Clock
Udc
Udc
sa,b
va
vb
4Q 2 level inverter
u
i
e
i_dc
RLE -circuit
snd
For your ears only
udc
u*
sa,b
va*
vb*
um
2 phase 2 level modulator
ea+Ra*100
Constant1
Manual Switch
Sine Wave
>> Udc=600;
>> La=2e-3;
>> Ra=0.1;
>> ea=200;
>> Ts=1/6.667e3/2;
Modulation Details
Currents
Ready
View 2 warnings 110%
auto(ode15s)

Thermal circuit

Semikron p 82-83





$R_{th(j-s)} = R_{thSi} + R_{thSo1} + R_{thCu1} + R_{thIso} + R_{thCu2} + R_{thSo2} +$

$Z_{th(j-s)} = Z_{thSi} + Z_{thSo1} + Z_{thCu1} + Z_{thIso} + Z_{thCu2} + Z_{thSo2} +$

Material	Heat conductivity λ [W/(m*K)]	Heat storage characteristic s [kJ/(m³*K)]	Thermal expansion coefficient α [10⁻⁶/K]
Silicon	148	1650	4.1
Copper	394	3400	17.5
Aluminium	230	2480	22.5
Silver	407	2450	19
Molybdenum	145	2575	5
Solders	~70	1670	15 – 30
Al_2O_3-DBC	24	3025	8.3
AlN DBC, AlN-AMB	180	2435	5.7
AlSiC (75% SiC)	180	2223	7

- **Chip temperature ϑj**
- **Heat sink temperature ϑ_s**
- **Power losses P**
- **Thermal resistance R_{th}**
- **Thermal capacitance C_{th}**

$$R_{th(j-s)} = \sum R_{th(layers)} \qquad R_{th} = \frac{l}{\lambda A}\left[\frac{K}{W}\right]$$

$$C_{th(j-s)} = \sum C_{th(layers)} \qquad C_{th} = mc\left[\frac{J}{K}\right]$$

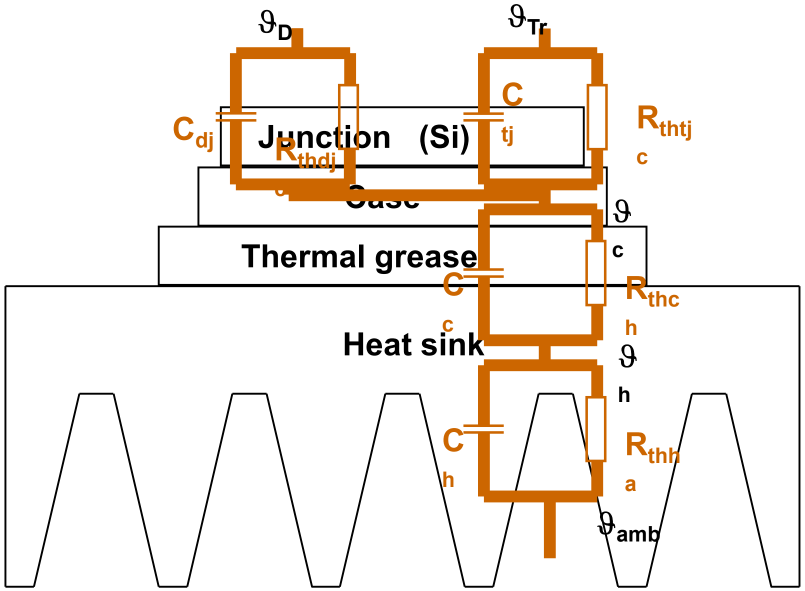
$$R_{conv} = \frac{1}{A_{cool} h}$$

$$\vartheta_j = P_j\left(R_{th} + R_{conv}\right) + \vartheta_{amb}$$

Thermal circuit

6.2 p 233-237

- **Heat flow**
  - *Heat* ***sources****: losses in diodes and transistors*
  - *Heat* ***sink****: natural or forced convection*
  - ***Thermal resistance****: components ant thermal connections between them*
- **Thermal nodes**
  - *Junction*
  - *Case*
  - *Heat sink*
  - *Ambient*
- **Solutions**
  - *Steady state*
  - *Transient*

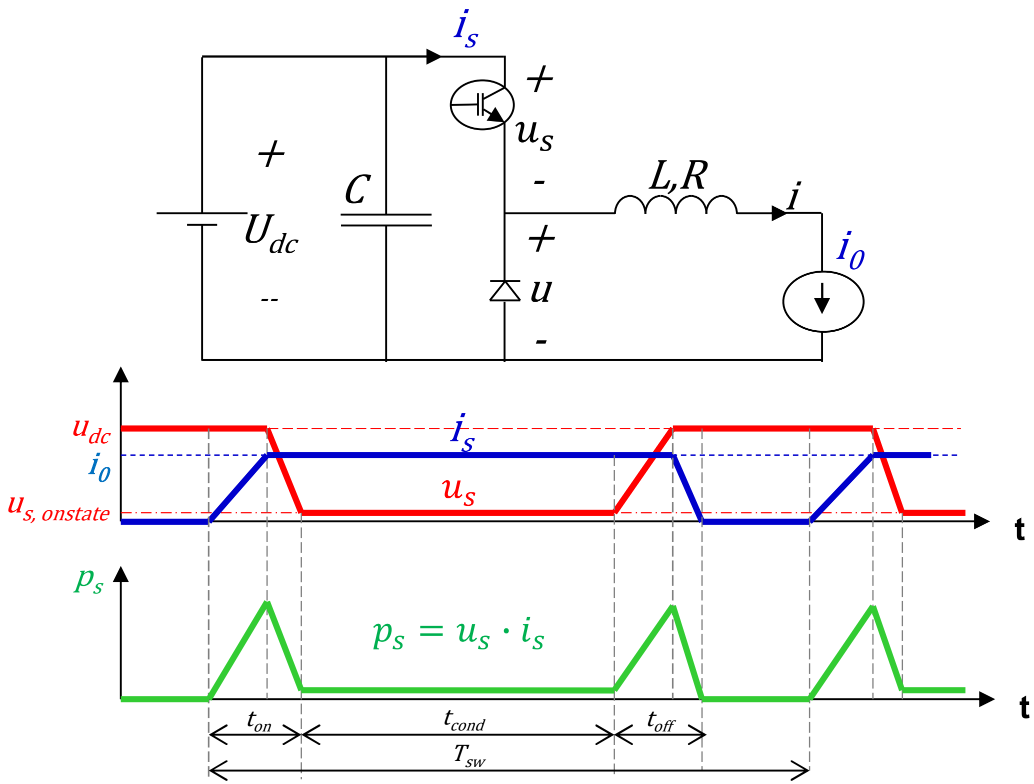


$$\vartheta_{1,end} = (R_{th} \cdot P + \vartheta_{amb}) \cdot (1 - e^{-\frac{t}{\tau}}) + \vartheta_{1,start} \cdot e^{-\frac{t}{\tau}}$$

6.1 p 225-233

Simple converter loss model

- Switching waveforms, looking at turn-on, on-state and turn-off energy losses over switching sequence
- Considering temperature dependence
- Recalculate datasheet values to actual working point
- Pay attention if losses can be separated by components or they are provided as per integrated switch



Switching and conducting losses

Energy losses: $E_S(T_{sw}) = \int_{T_{sw}} p_S(\tau)d\tau = E_{S,on}(T_{sw}) + E_{S,cond}(T_{sw}) + E_{S,off}(T_{sw})$

$$E_{S,on}(T_{sw}) = \int_{t_{on}} p_S(\tau)d\tau = V_{DC} \cdot I_0 \cdot \frac{t_{on}}{2}$$

$$E_{S,cond}(T_{sw}) = \int_{t_{cond}} p_S(\tau)d\tau = V_{S(on)} \cdot I_0 \cdot t_{cond}$$

Note $V_{S(on)} = V_{S0} + R_S \cdot I_0$

$$E_{S,off}(T_{sw}) = \int_{t_{off}} p_S(\tau)d\tau = V_{DC} \cdot I_0 \cdot \frac{t_{off}}{2}$$

Power losses: $P_S(T_{sw}) = \frac{E_S(T_{sw})}{T_{sw}} = P_{S,on}(T_{sw}) + P_{S,cond}(T_{sw}) + P_{S,off}(T_{sw})$

$$P_{S,on}(T_{sw}) = \frac{E_{S,on}(T_{sw})}{T_{sw}} = E_{S,on}(T_{sw}) \cdot f_{sw} = \frac{V_{DC} \cdot I_0 \cdot t_{on}}{2} \cdot f_{sw}$$

$$P_{S,cond}(T_{sw}) = \frac{E_{S,cond}(T_{sw})}{T_{sw}} = V_{S(on)} \cdot I_0 \cdot \frac{t_{cond}}{T_{sw}} = V_{S(on)} \cdot I_0 \cdot D_S$$

$$P_{S,off}(T_{sw}) = \frac{E_{S,off}(T_{sw})}{T_{sw}} = E_{S,off}(T_{sw}) \cdot f_{sw} = \frac{V_{DC} \cdot I_0 \cdot t_{off}}{2} \cdot f_{sw}$$

$$P_{S,sw}(T_{sw}) = P_{S,on}(T_{sw}) + P_{S,off}(T_{sw})$$

Turn on t_{on}
On-state t_{cond}
Turn off t_{off}

Reverse recovery losses

4.2 p 145

If specified, use:

$$E_{S,on}(T_{sw})=\frac{E_{on,n}}{V_{DC,n}\cdot I_{0n}}\cdot V_{DC}\cdot I_0$$

$$E_{S,off}(T_{sw})=\frac{E_{off,n}}{V_{DC,n}\cdot I_{0n}}\cdot V_{DC}\cdot I_0$$

For the freewheeling diode:

$$P_{D,cond}(T_{sw})=V_{D(on)}\cdot I_0\cdot D_D \qquad V_{D(on)}=V_{D0}+R_D\cdot I_0$$

$$D_D\approx 1-D_S$$

$$P_{D,rr}=V_{DC}\cdot Q_f\cdot f_{sw} \qquad Q_f\approx\frac{1}{S+1}\cdot Q_{rr}\ \text{where}\ S=\frac{t_{rr1}}{t_{rr2}}$$

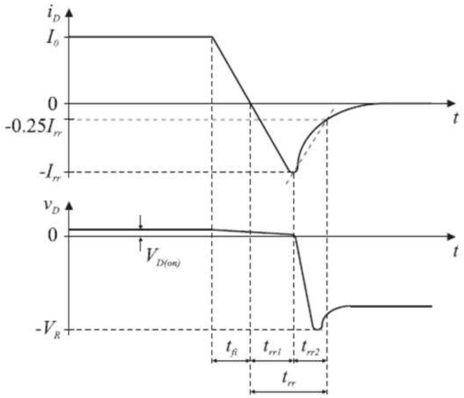


Figure 6.3: Diode turn-off.

If specified, use:

$$P_{D,off}=E_{D,off}(T_{sw})\cdot f_{sw}\ ,\ E_{D,off}(T_{sw})=\frac{E_{off,n}}{V_{DC,n}\cdot I_{0n}}\cdot V_{DC}\cdot I_0 \qquad Q_f=\frac{Q_{f,n}}{I_{0n}}\cdot I_0$$

Fall t_{ft}
di/dt<0 t_{rr1}
di/dt>0 t_{rr2}