Linearization

$$v_c = r_{cin}\,(i_{in} - i_s) + v_{cin}$$

$$\Rightarrow \quad \Delta v_c = r_{cin}\,(\Delta i_{in} - \Delta i_s) + \Delta v_{cin}$$

$$\Rightarrow \quad v_{co} = r_{cin}\,(i_{in0} - i_{s0}) + v_{cin0}$$

$$p\,v_{cin} = \frac{1}{C_{in}}\,(i_{in} - i_s)$$

$$\Rightarrow \quad p\,\Delta v_{cin} = \frac{1}{C_{in}}\,(\Delta i_{in} - \Delta i_s)$$

$$0 = \frac{1}{C_{in}}\,(i_{in0} - i_{s0})$$

Average Value, Small Signal Equivalent Circuit

$$I_s = \frac{P}{V_c}$$

$$I_{so} = \frac{P}{V_{co}}$$

$$\Delta I_s = \left.\frac{\partial I_s}{\partial V_c}\right|_{V_{co}} \Delta V_c = -\frac{P}{V_{co}^2}\,\Delta V_c$$

$$\Delta I_s = \frac{\Delta V_c}{R} \qquad R = -\frac{V_{co}^2}{P}$$

Average Value, Small Signal Equivalent Circuit

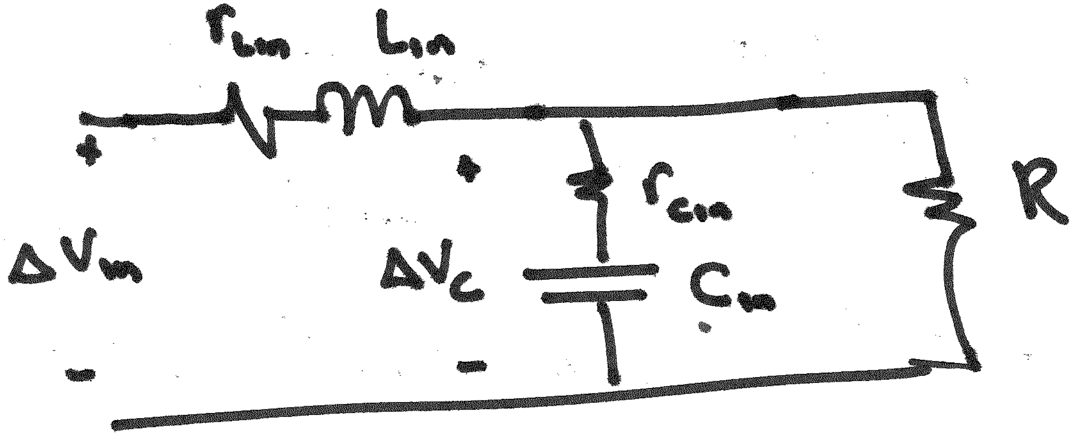
$$\frac{V_{co} - V_{in0}}{r_{Lin}} + \frac{P}{V_{co}} = 0$$

$$V_{co}(V_{co} - V_{in0}) + P r_{Lin} = 0$$

$$V_{co}^2 - V_{co} V_{in0} + P r_{Lin} = 0$$

$$V_{co} = \frac{V_{in0} \pm \sqrt{V_{in0}^2 - 4 P r_{Lin}}}{2}$$

Characteristic Polynomial



$\Delta V_C (CP) - \Delta V_{in}\, stuff = 0$

$$\frac{\Delta V_C - \Delta V_{in}}{r_{Lin} + L_{in} s} + \frac{\Delta V_C \, C_{in} s}{\cancel{r_{Cin} + \frac{1}{C_{in} s}}} + \frac{\Delta V_C}{R} = 0$$

$r_{Cin} C_{in} s + 1$

$$(\Delta V_C - \Delta V_{in})(r_{Cin} C_{in} s + 1) R + \Delta V_C C_{in} s (r_{Lin} + L_{in} s) R$$

$$+ \frac{\Delta V_C}{\cancel{R}} (r_{Lin} + L_{in} s)(r_{Cin} C_{in} s + 1) = 0$$

$$CP: \overbrace{\left[C_{in} L_{in} R + L_{in} C_{in} r_{cin}\right]}^{a} s^2$$

$$\overbrace{\left[r_{cin} C_{in} R + C_{in} r_{Lin} R + L_{in} + r_{Lin} r_{cin} C_{in}\right]}^{b} s$$

$$+ \overbrace{\left[R + r_{Lin}\right]}^{c}$$

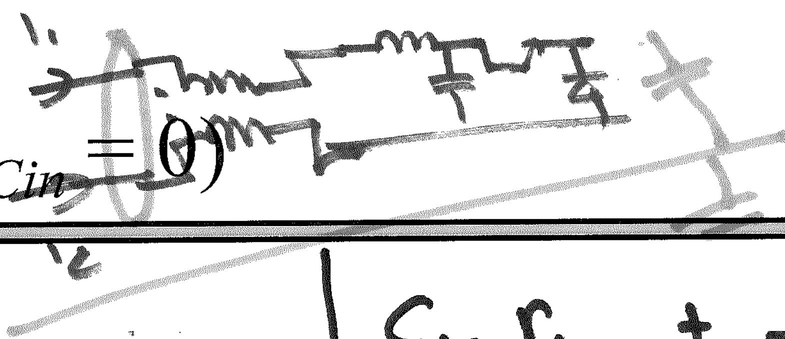
$$s = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Special Case ($r_{Cin} = 0$)

$$CP: \quad [C_{in} L_{in} R]\, s^2 + [C_{in} r_{Lin} R + L_{in}]\, s + [R + r_{Lin}]$$

$$CP: \quad \underbrace{[C_{in} L_{in}]}_{a} s^2 + \underbrace{\left[C_{in} r_{Lin} + \frac{L_{in}}{R}\right]}_{b} s + \underbrace{\left[1 + \frac{r_{Lin}}{R}\right]}_{c}$$

If $a > 0$ then a necessary & sufficient condition for the roots to be in the LHP is $b > 0$, $c > 0$



$i_{dm} = \frac{1}{2}(i_1 - i_2)$

Special Case ($r_{Cin} = 0$)

$$1 + \frac{r_{Lin}}{R} > 0$$

$$1 - \frac{r_{Lin}}{\frac{V_{C0}^2}{P}} > 0$$

$$1 > \frac{r_{Lin} P}{V_{C0}^2}$$

$$P < \frac{V_{C0}^2}{r_{Lin}}$$

$$C_{in} r_{Lin} + \frac{L_{in}}{R} > 0$$

$$C_{in} r_{Lin} - \frac{L_{in}}{\frac{V_{C0}^2}{P}} > 0$$

$$C_{in} r_{Lin} > \frac{L_{in} P}{V_{C0}^2}$$

$$P < \frac{C_{in} r_{Lin} V_{C0}^2}{L_{in}}$$

C is good

L is evil

AVM of Hysteresis Control

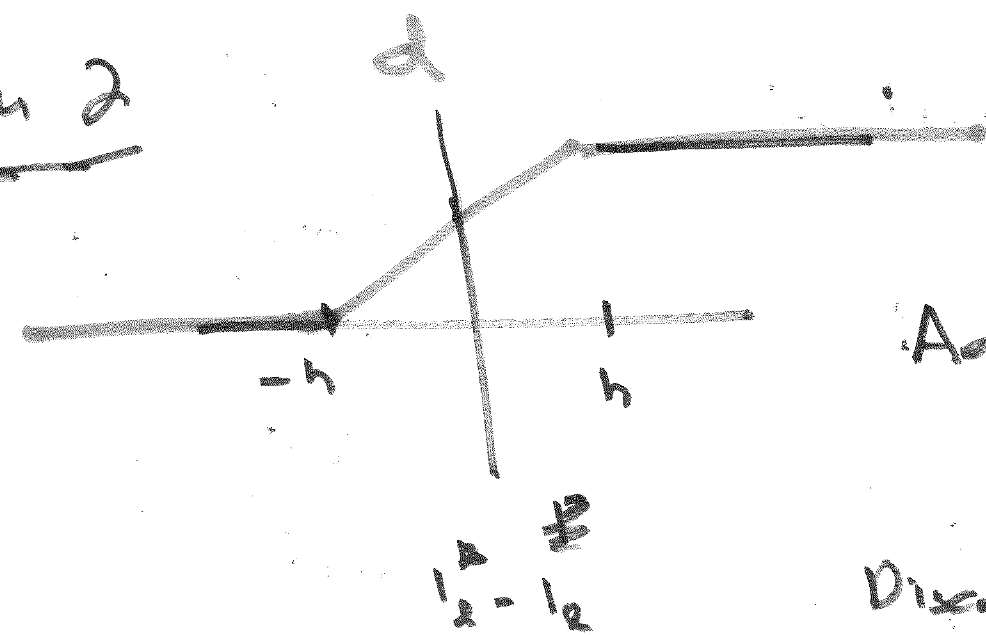
- Consider the following:

Approach 1

Assume $i_e = i_e^*$

Disadvantage: Loss of current tracking

Approach 2



Advantage: Simple
- Voltage limits are recognized

Disadvantage: Stiffness

ECE61016 Power Electronics Converters and Systems

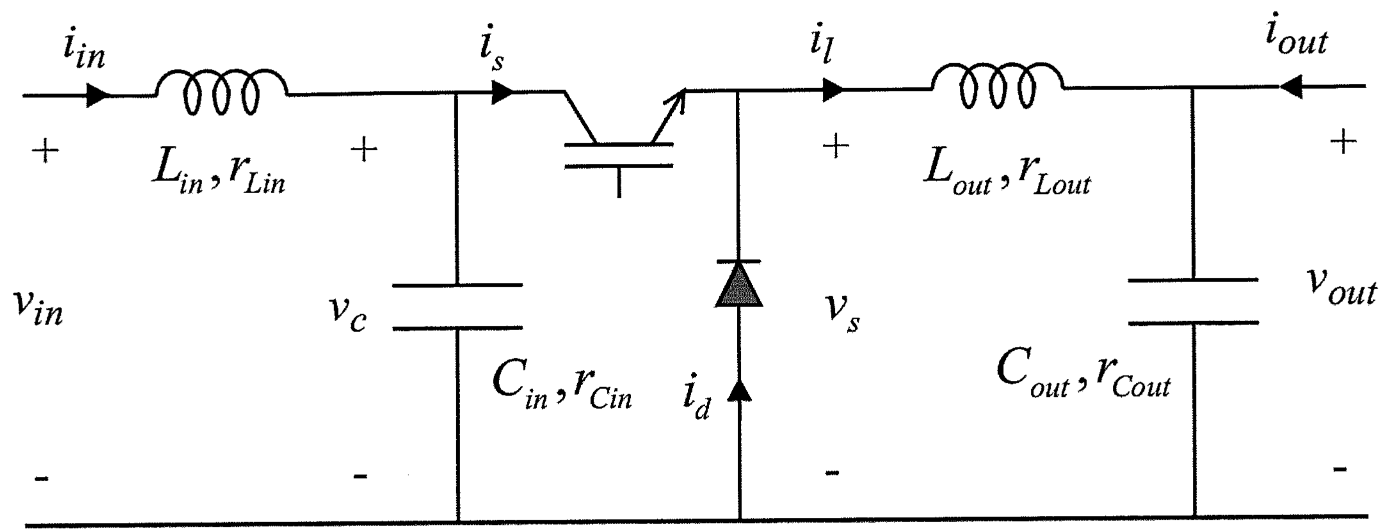
Lecture Set 3E: Control of a Buck Converter (Example)

S.D. Sudhoff

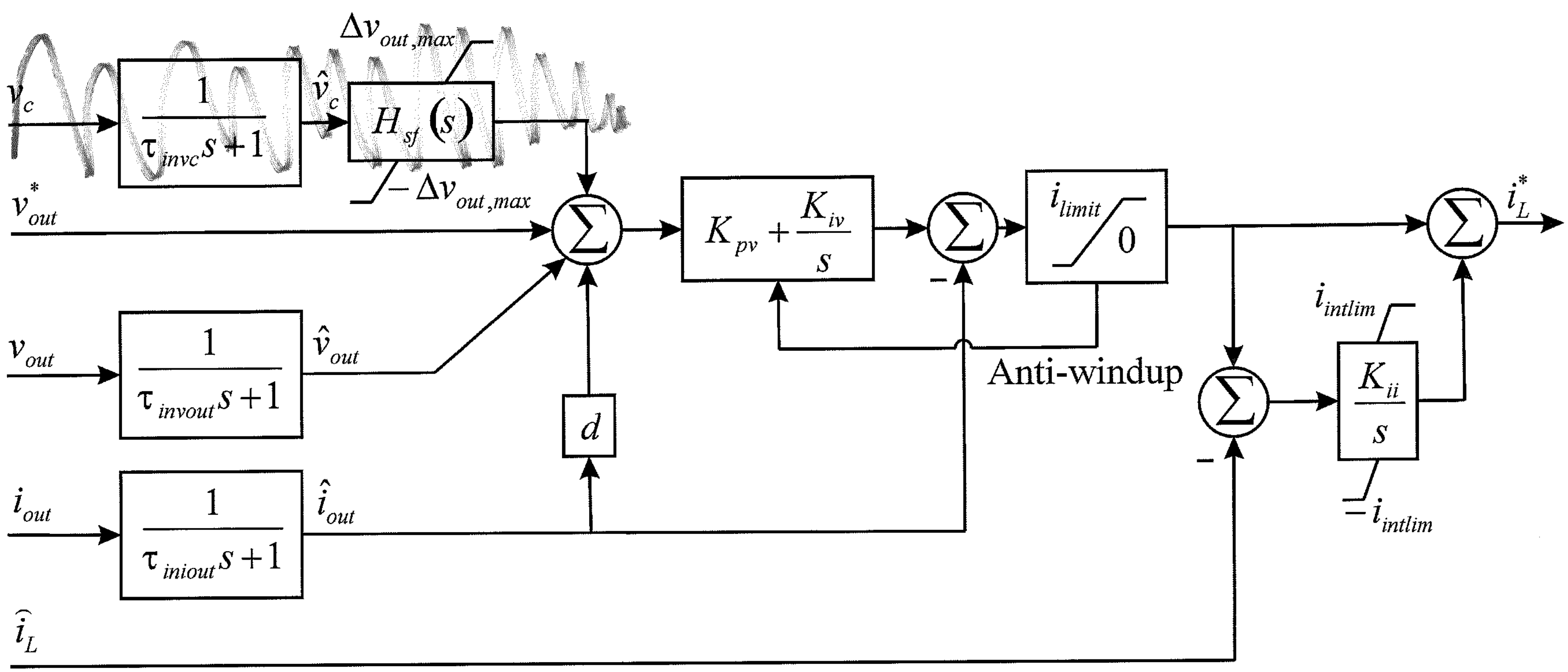
Fall 2016

Buck Converter Control

- Topology



Buck Converter Control



Specifications and Parameters

- Input voltage: 500 V
- Output voltage: 425 V
- Resistive load: steps from 500 W to 5 kW at t=0.1 s
- Input inductor: 0.5 mH, 100 mΩ
- Input capacitor: 450 uF, 130 mΩ
- Output inductor: 3.0 mH, 120 mΩ
- Output capacitor: 450 uF, 130 mΩ
- Reverse biased resistance: 1 kΩ
- Hysteresis level: 0.5 A
- Droop: 0

Switching Frequency

$$t_{on} = \frac{2h\,L_{out}}{V_{in} - V_{fsw} - r_{Lout} I_{\ell} - V_{out}}$$

$$t_{off} = \frac{2h\,L_{out}}{V_{fd} + r_{Lout} I_{\ell} + V_{out}}$$

$$f_{sw} = \frac{1}{t_{on} + t_{off}}$$

Light load : $f_{sw} = 20.9$ KHz

Heavy load : $f_{sw} = 20.6$ KHz

$f_{sw} = 20.8$ KHz

Input and Output Filter

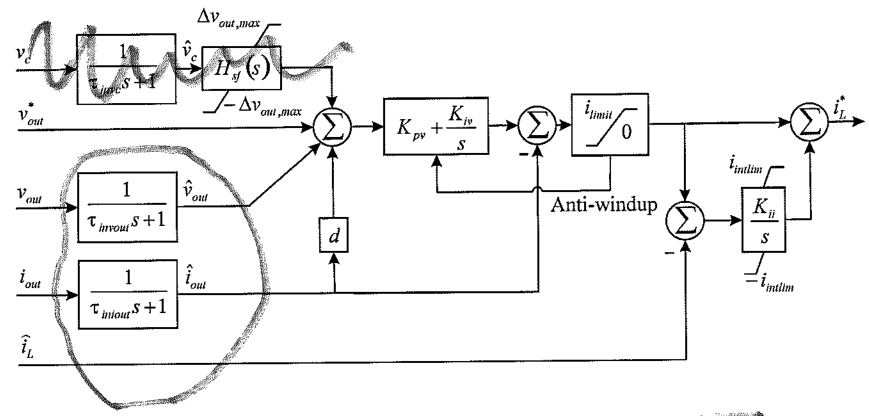
$$H(s) = \frac{1}{\tau s + 1}$$

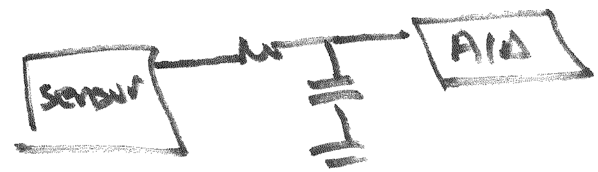
$$\tau \omega = 10$$

$$\tau 2\pi f_{sw} = 10$$

$$\tau = 76.6\ \mu s$$

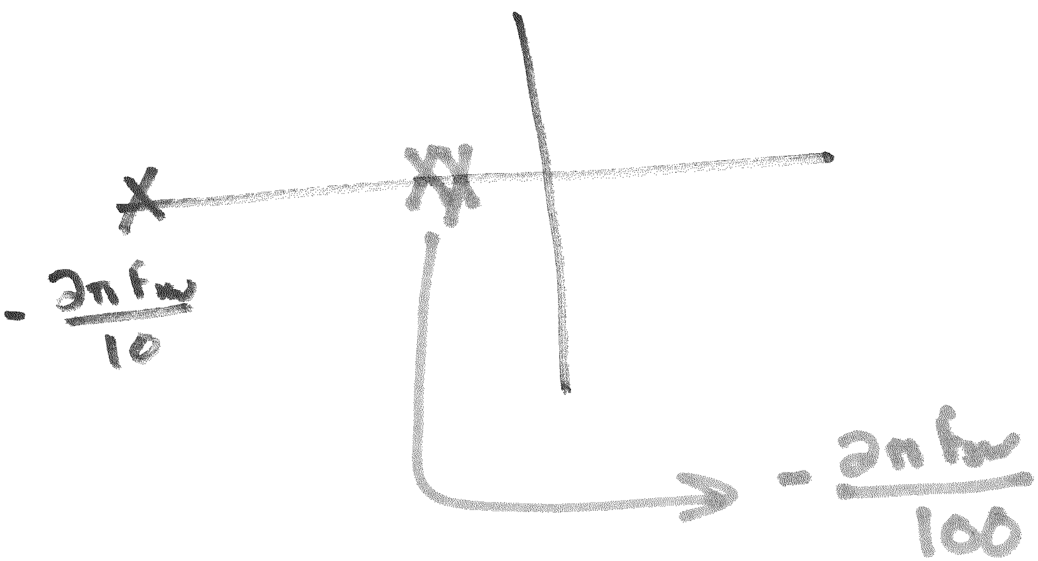
$$= \tau_{invout} = \tau_{iniout}$$

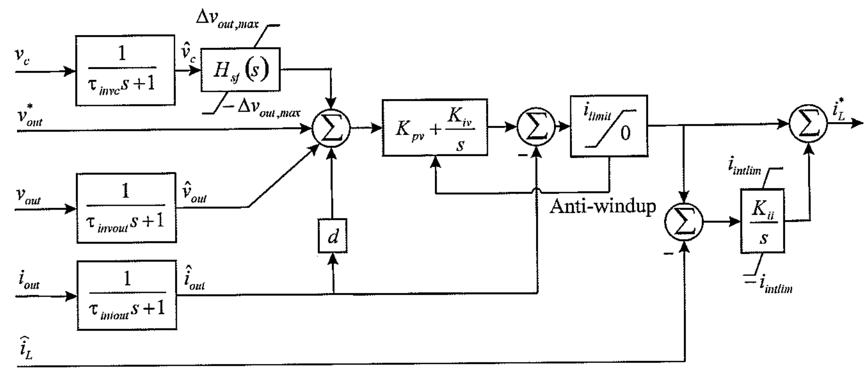




Voltage Control Gains

D.C.P: $(s-s_1)(s-s_2)$





$S_1 = S_2 = -1306$

Analysis of Voltage Control Loop

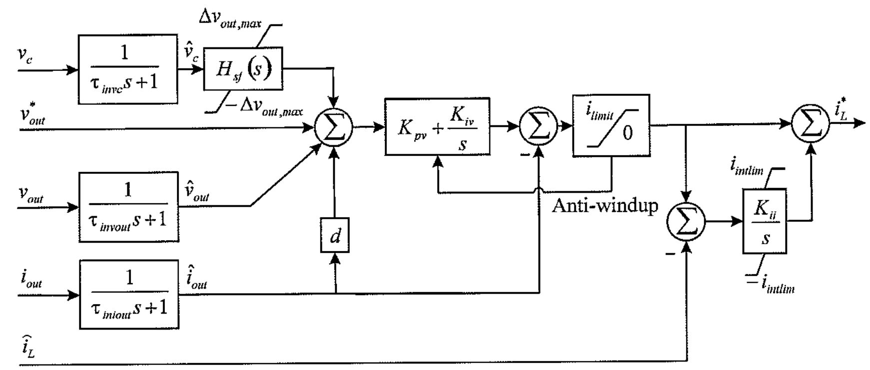
- Thus, in order to get poles at $s = s_1, s_2$
- Set gains to

$$K_{iv} = s_1 s_2 C_{out}(1 + r_{cout} K_{pv}) = 900$$

$$K_{pv} = -\frac{C_{out}}{\dfrac{1}{s_1 + s_2 + s_1 s_2 r_{cout} C_{out}} + C_{out} r_{cout}} = 1.33$$

⇒ check against ccr loop time

Anti-Windup



Recall

$$U = \frac{K_{pv}S + K_{iv}}{S + K_{iv}K_{ai}} e + i_{limit}$$

e'

$$U = \frac{e'}{S + K_{iv}K_{ai}}$$

$$\dot{U} + K_{iv}K_{ai}U = e'$$

$$\dot{U} = -K_{iv}K_{ai}U + e'$$

$$\dot{x} = ax + \text{stuff}$$

$$h < -\frac{2}{a}$$

h is time step of Forward Euler

numerical stability with Forward Euler

$$h < -\frac{2}{-K_{iv}K_{ai}}$$

$$K_{iv}K_{ai} < \frac{2}{h}$$

$$K_{ai} < \frac{2}{hK_{iv}}$$

$$K_{ai} = \frac{1}{hK_{iv}} = 11.1$$

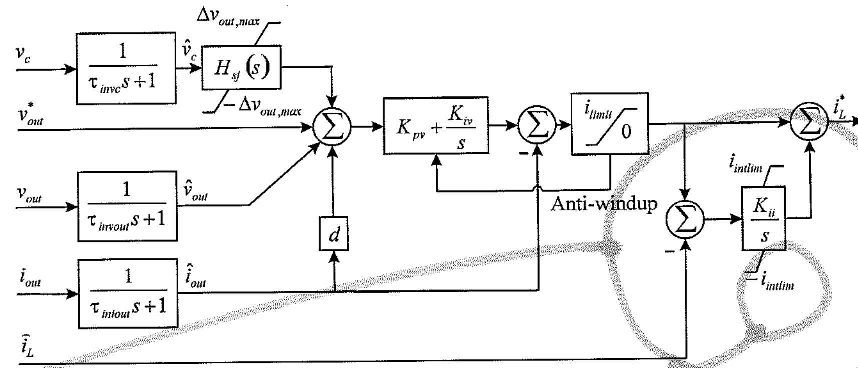
$$\frac{1}{10^4}$$

Current Loop

$$I_e = I_e + \frac{S\Delta}{S+K_{ii}}$$

$$S = -\frac{2\pi f_{sw}}{100}$$

$$K_{ii} = 1306$$



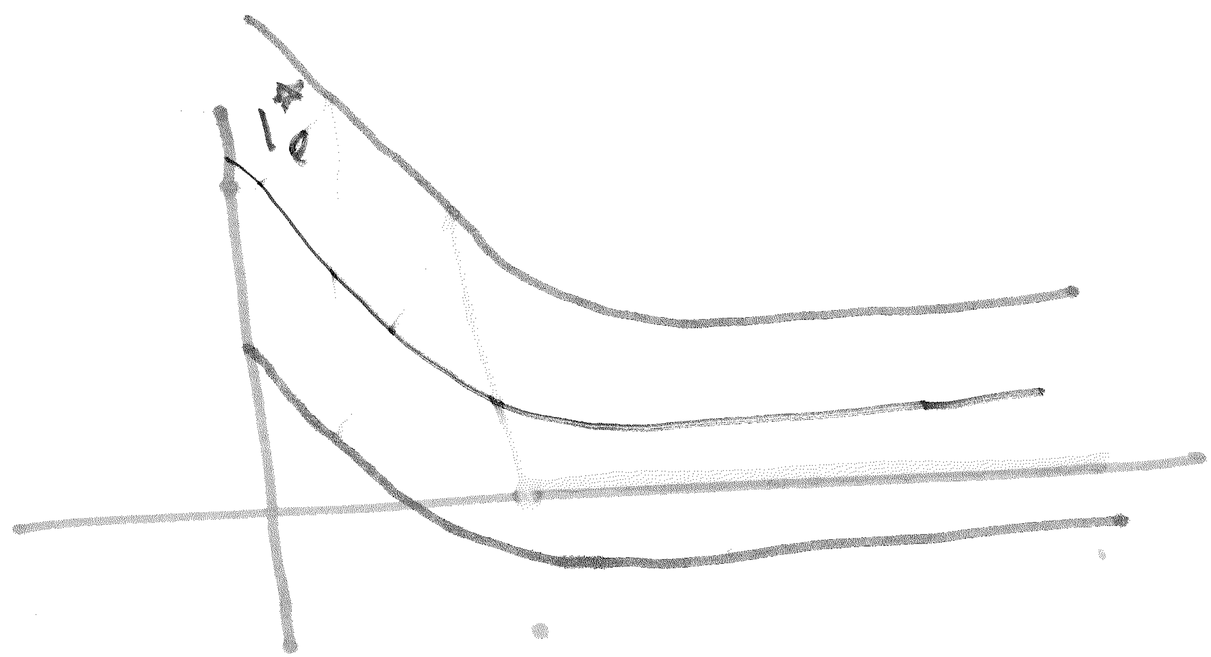
Stop integrating when you hit limit

h(1.25) = 0.625 A

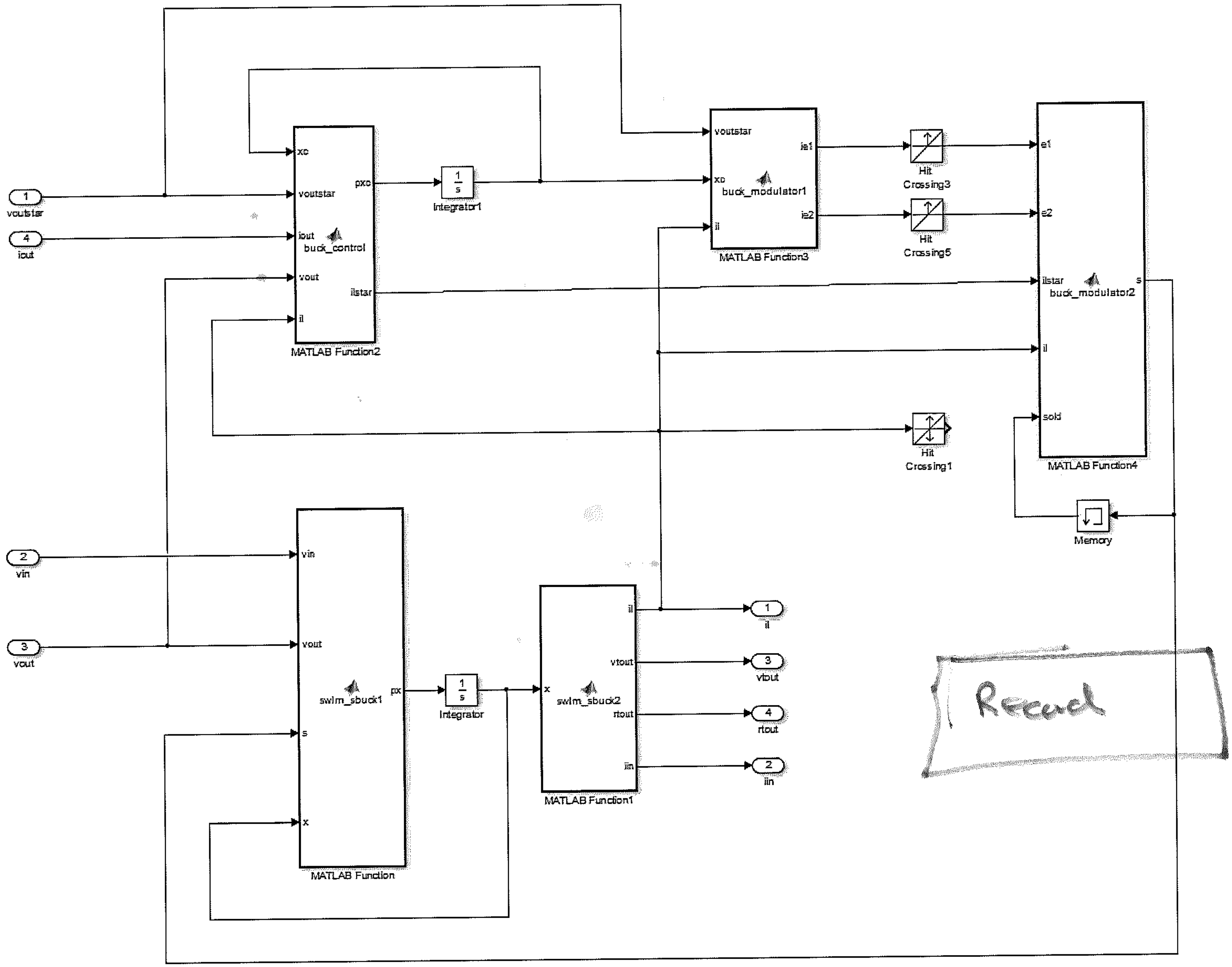
↳ hysteresis level h (0.5A)

Comments on Average Value Model

- Discontinuous mode with hysteresis control



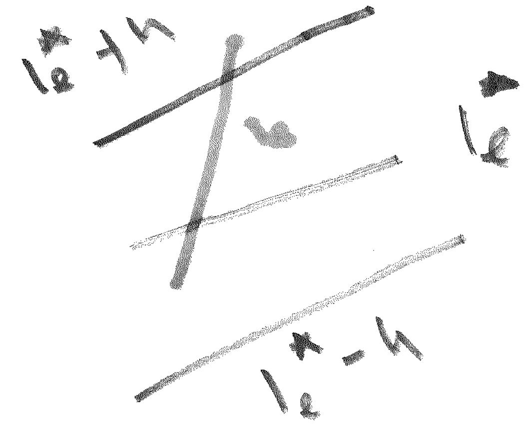
Comments on Waveform Level Model



Recued

Comments on Waveform Level Model

- buck_modulator 1




```
...
ie1=il-(ilstar+P.h);
ie2=(ilstar-P.h)-il;
```

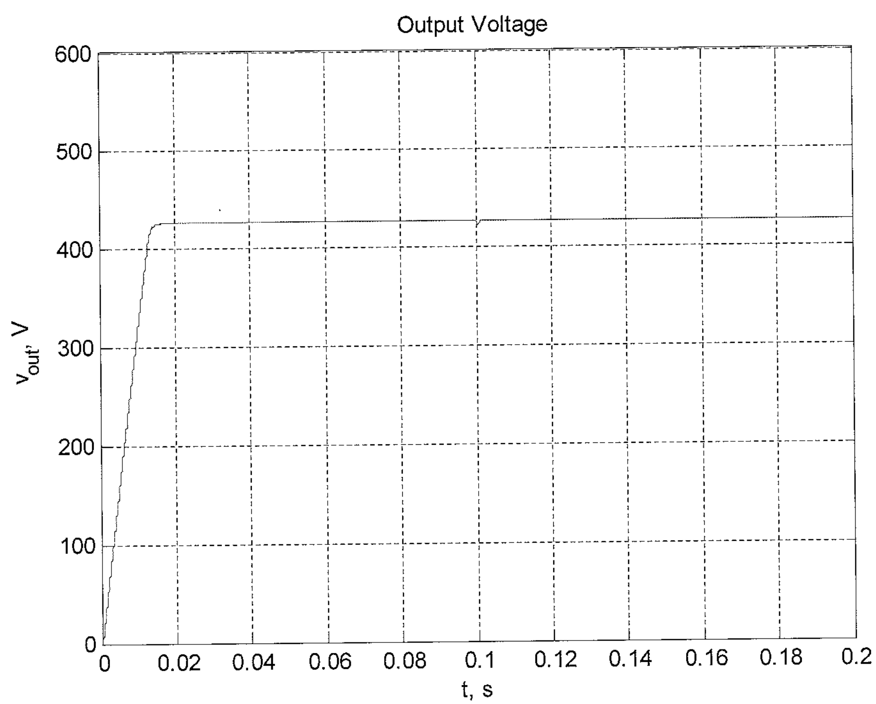
Comments on Waveform Level Model

- buck_modulator 2

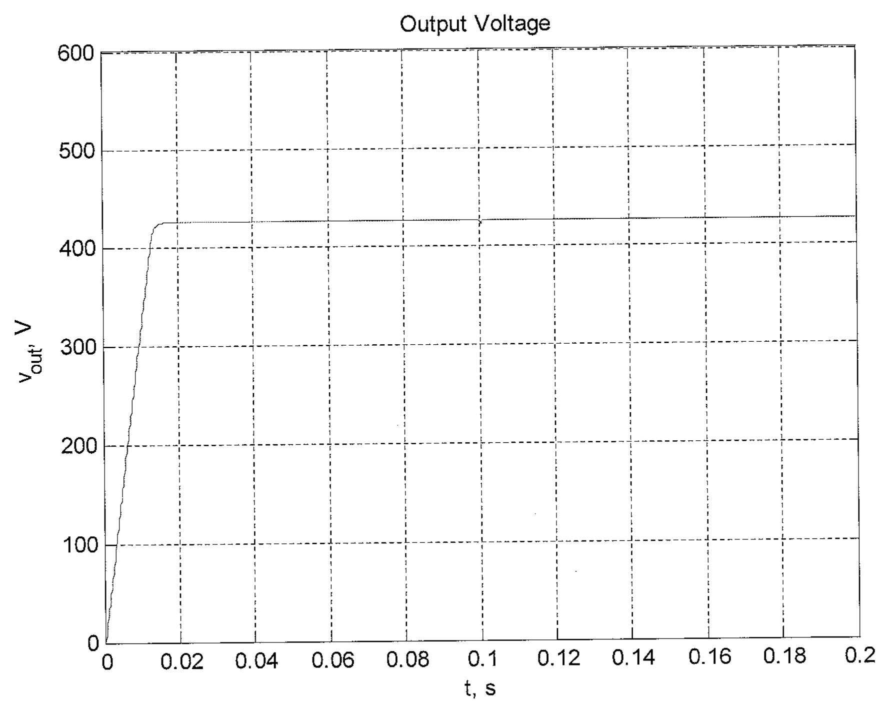
```
% compute current errors relative to hysteresis bands
ie1=il-(ilstar+1.5*P.h);
ie2=(ilstar-1.5*P.h)-il;

% determine the switch state
if (e1||(ie1>0))
   s=0.0;
else
   if (e2||(ie2>0))
      s=1.0;
   else
      s=sold;
   end
end
```

Simulation – Output Voltage

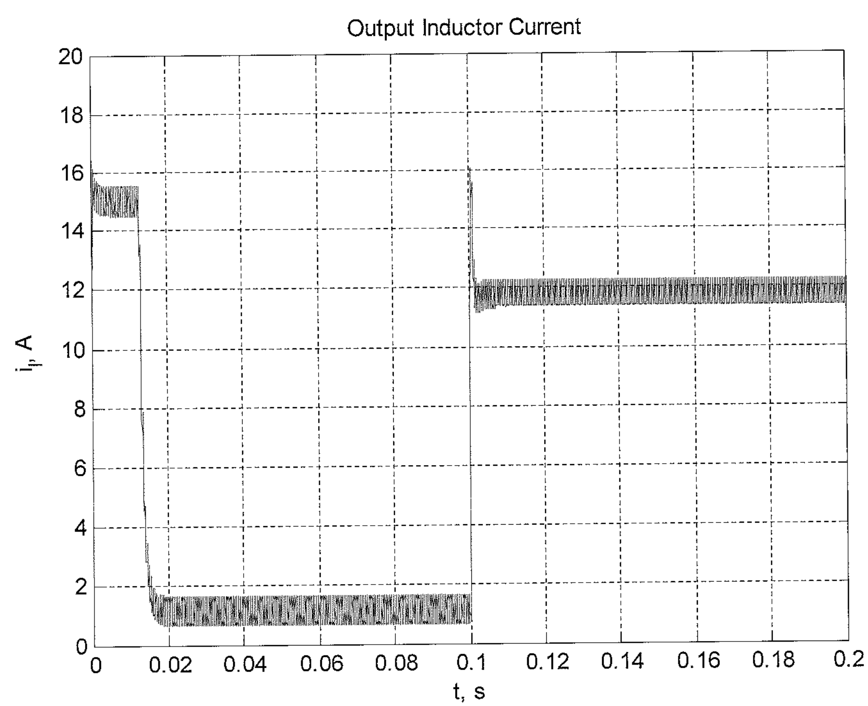


Waveform Level Model

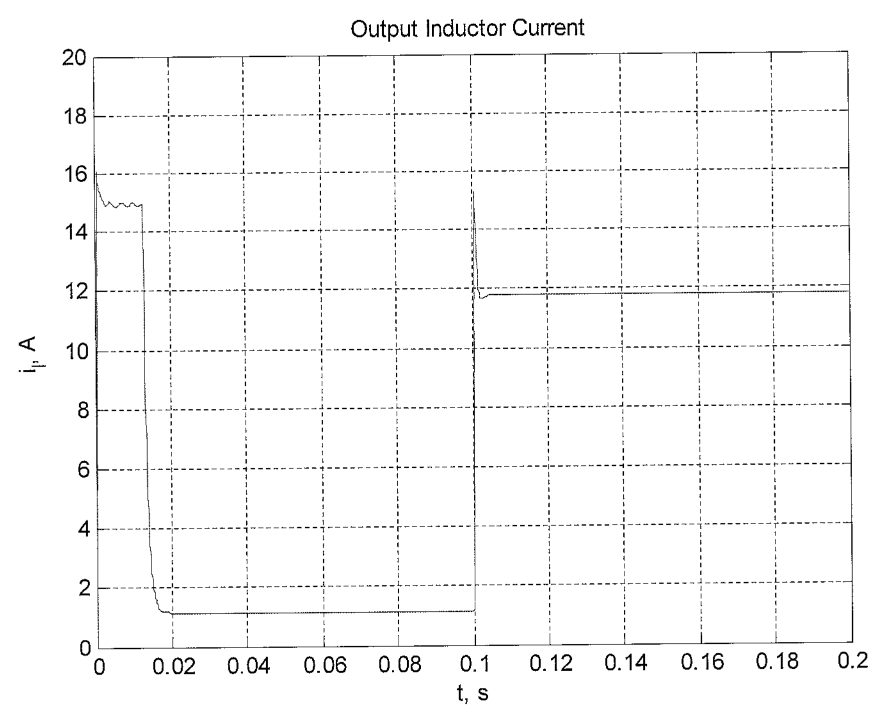


Average Value Model

Simulation – Inductor Current

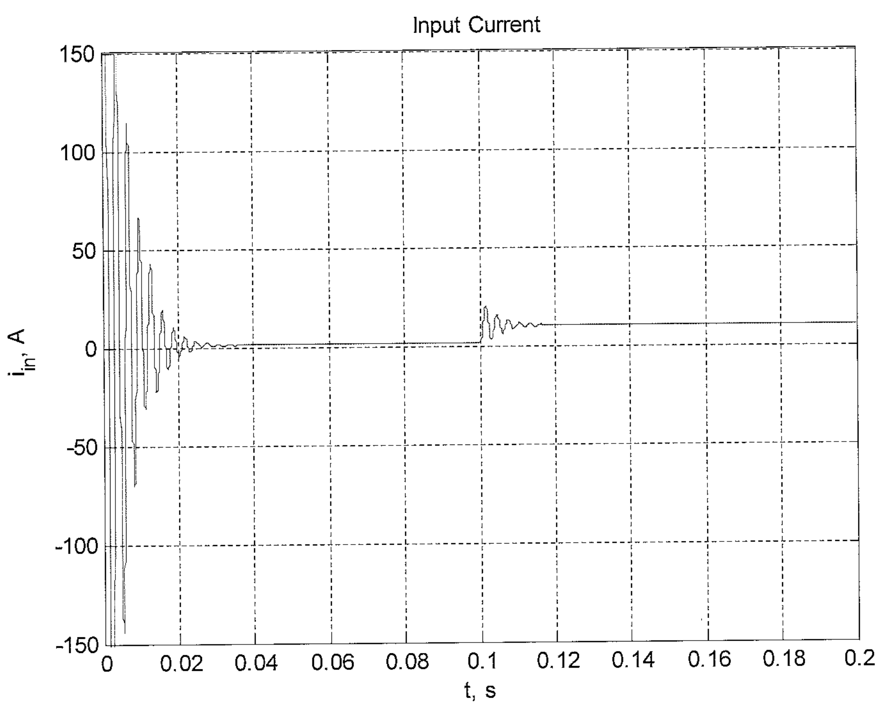


Waveform Level Model

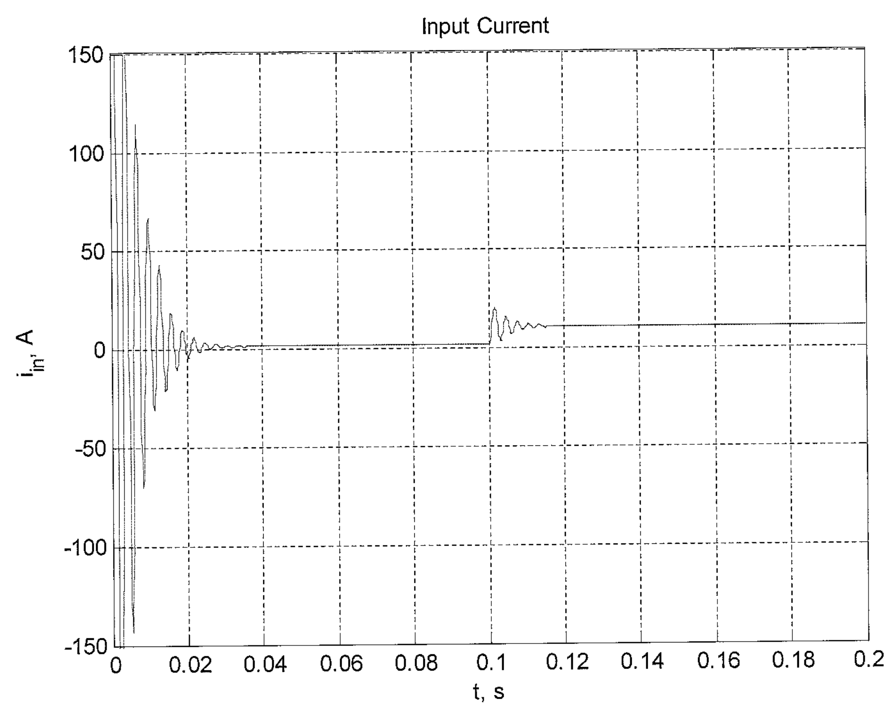


Average Value Model

Simulation – Input Current



Waveform Level Model



Average Value Model

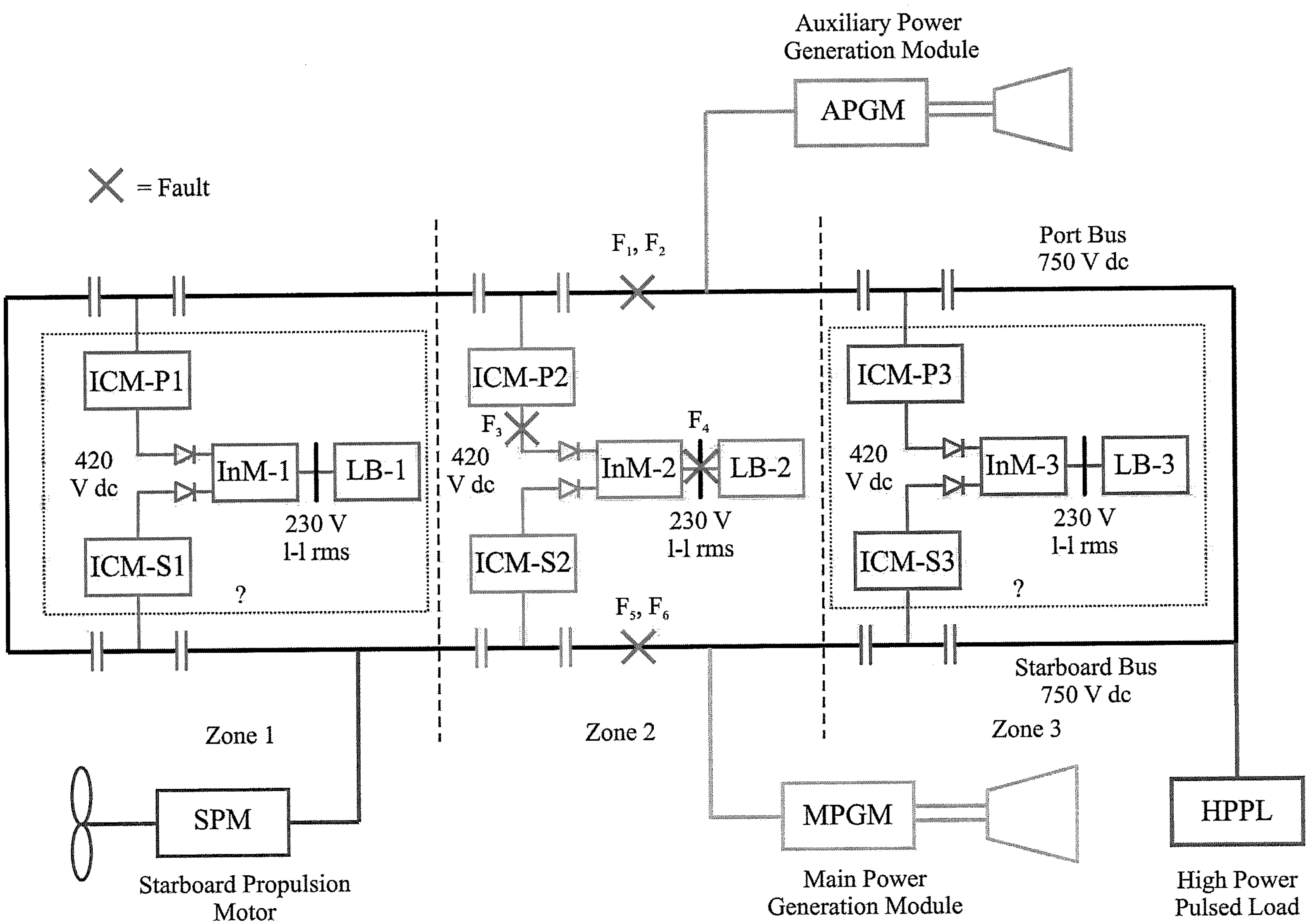
ECE61016 Power Electronics Converters and Systems

DC/AC Conversion Lecture Set 4

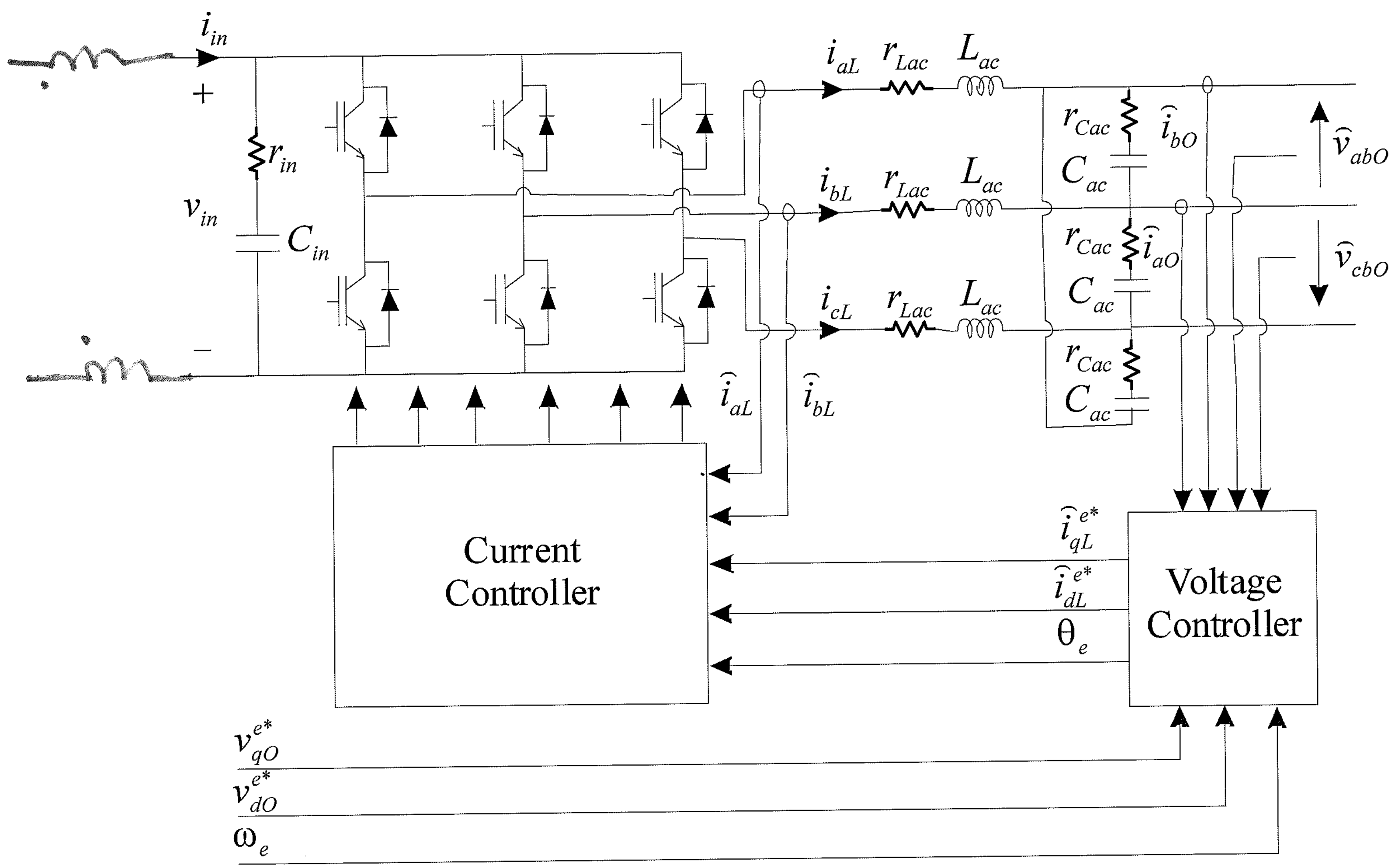
S.D. Sudhoff

Fall 2016

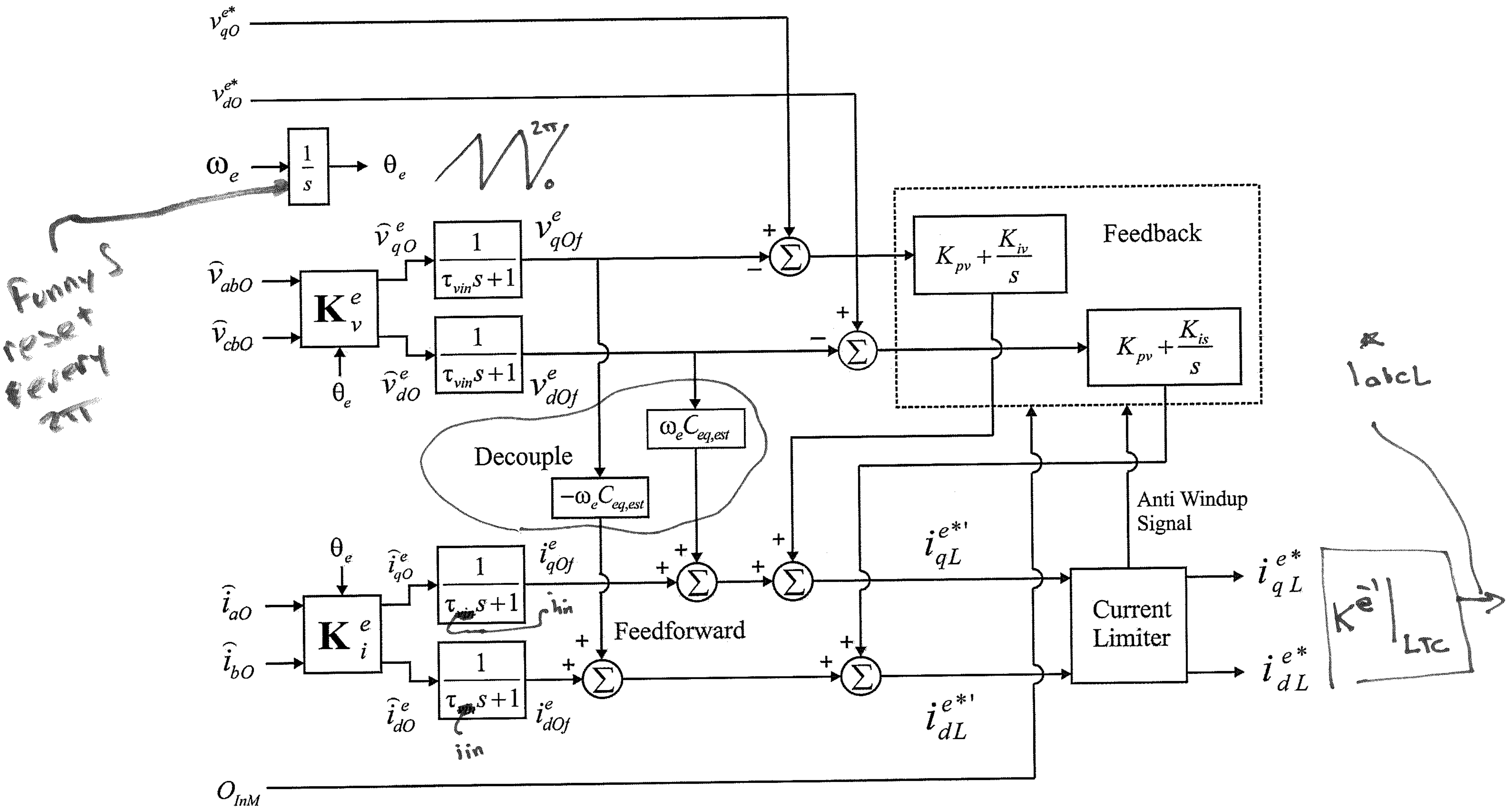
Context


Auxiliary Power Generation Module
APGM
= Fault
F1, F2
Port Bus
750 V dc
ICM-P1
420 V dc
InM-1
LB-1
230 V
l-l rms
ICM-S1
?
ICM-P2
F3
F4
420 V dc
InM-2
LB-2
230 V
l-l rms
ICM-S2
F5, F6
ICM-P3
420 V dc
InM-3
LB-3
230 V
l-l rms
ICM-S3
?
Starboard Bus
750 V dc
Zone 1
Zone 2
Zone 3
SPM
Starboard Propulsion Motor
MPGM
Main Power Generation Module
HPPL
High Power Pulsed Load

Inverter Module (InM) Overview



Voltage Control



Voltage Control

- Why QD Variables?
  - ~~Everything is dc~~
  - Partially decouple system
- Why the Synchronous Reference Frame?
  - Everything is dc
  - control

For modeling → Stationary ref frame

Comment 1: The Voltage Transformation

$$\mathbf{K}_v^e = \frac{2}{3}\begin{bmatrix} \cos(\theta_e) & \cos(\theta_e + 2\pi/3) \\ \sin(\theta_e) & \sin(\theta_e + 2\pi/3) \end{bmatrix}$$

$$V_{qd0}^e = K_v^e \begin{bmatrix} \hat{V}_{ab0} \\ \hat{V}_{cb0} \end{bmatrix}$$

measured

$C = \cos(\theta_e)$

$C^- = \cos(\theta_e - 2\pi/3)$

etc.

Ideally

$$\cancel{V_{qdb0}^e} = K_s^e V_{abc0}$$

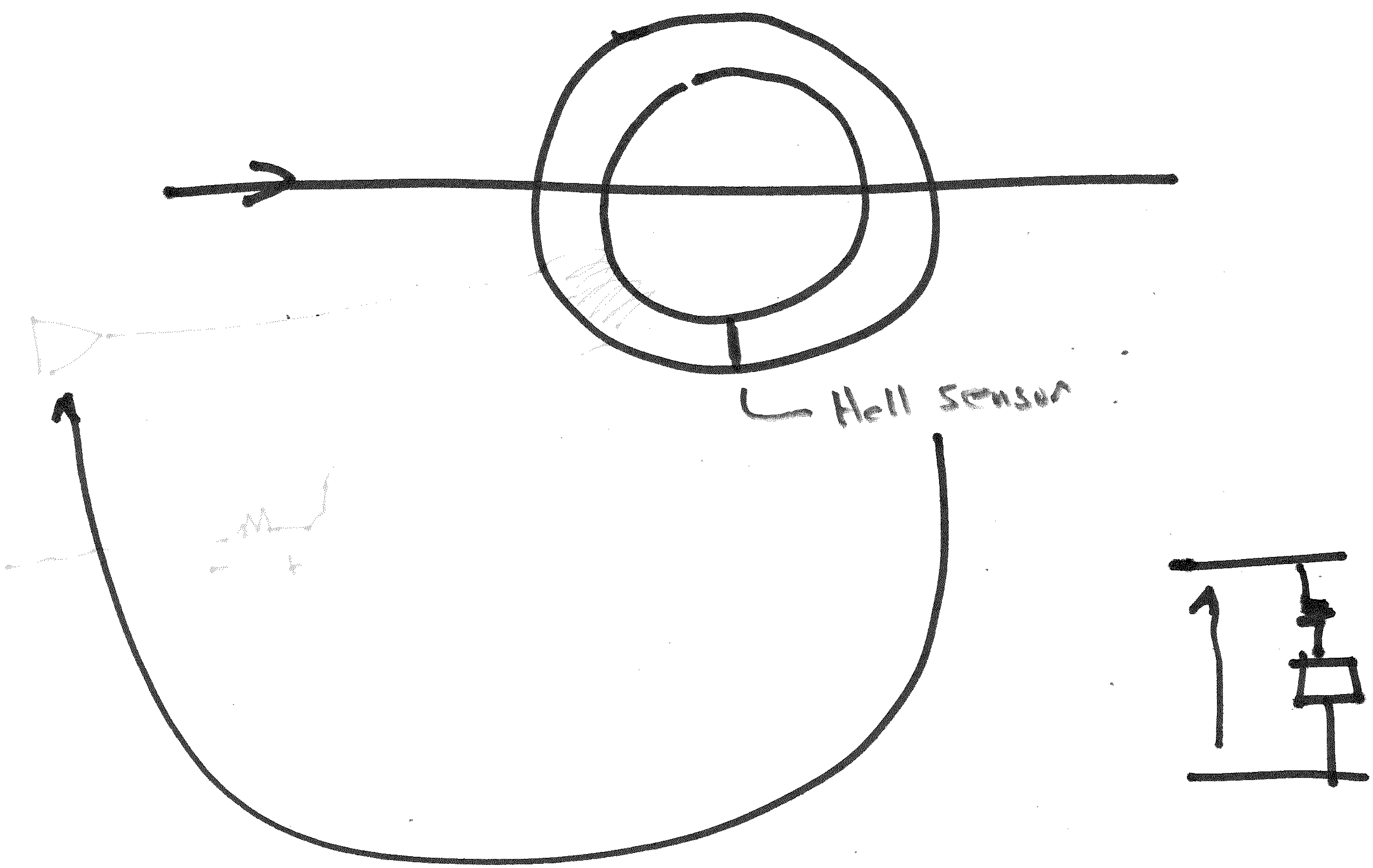
$$= \frac{2}{3}\begin{bmatrix} C & C^- & C^+ \\ S & S^- & S^+ \\ \cancel{\frac{1}{2}} & \cancel{\frac{1}{2}} & \cancel{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} V_{a0} - V_{b0} \\ V_{b0} - V_{b0} \\ V_{c0} - V_{b0} \end{bmatrix}$$

$$C + C^- + C^+ = 0$$

$$V_{qd0}^e = \underbrace{\frac{2}{3}\begin{bmatrix} C & C^+ \\ S & S^+ \end{bmatrix}}_{K_v^e} \begin{bmatrix} V_{ab0} \\ V_{cb0} \end{bmatrix}$$

Current Measurement

~~Voltage Transformation Cont.~~



Comment 2: The Current Transformation

$$\mathbf{K}_i^e = \frac{2}{\sqrt{3}} \begin{bmatrix} \cos(\theta_e - \pi/6) & \sin(\theta_e) \\ \sin(\theta_e - \pi/6) & -\cos(\theta_e) \end{bmatrix}$$

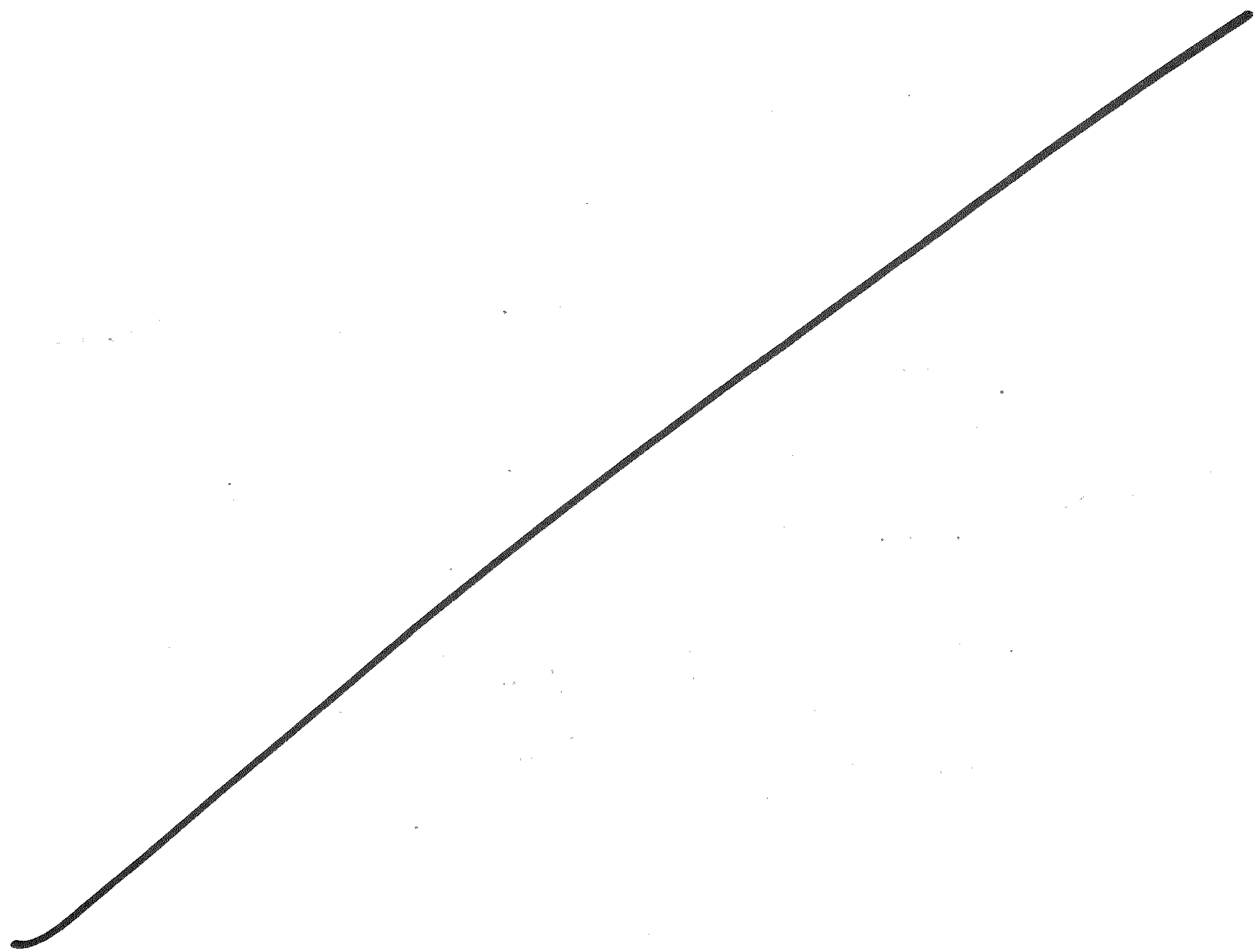
$$i_{qd00} = K_s^e \, i_{abc0}$$

$$= \frac{2}{3} \begin{bmatrix} c & c^- & c^+ \\ s & s^- & s^+ \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{a0} \\ i_{b0} \\ -i_{a0} - i_{b0} \end{bmatrix}$$

$$= \underbrace{\frac{2}{3} \begin{bmatrix} c - c^+ & c^- - c^+ \\ s - s^+ & s^- - s^+ \end{bmatrix}}_{K_i^e} \begin{bmatrix} i_{a0} \\ i_{b0} \end{bmatrix}$$

After we do the trig

Current Transformation Cont.



Current Control

Normally

$$i^*_{abcL} = K_s^{e^{-1}} \begin{bmatrix} i^*_{qL} \\ i^*_{dL} \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} c & s & 1 \\ c^- & s^- & 1 \\ c^+ & s^+ & 1 \end{bmatrix} \begin{bmatrix} \\ \\ 0 \end{bmatrix}$$

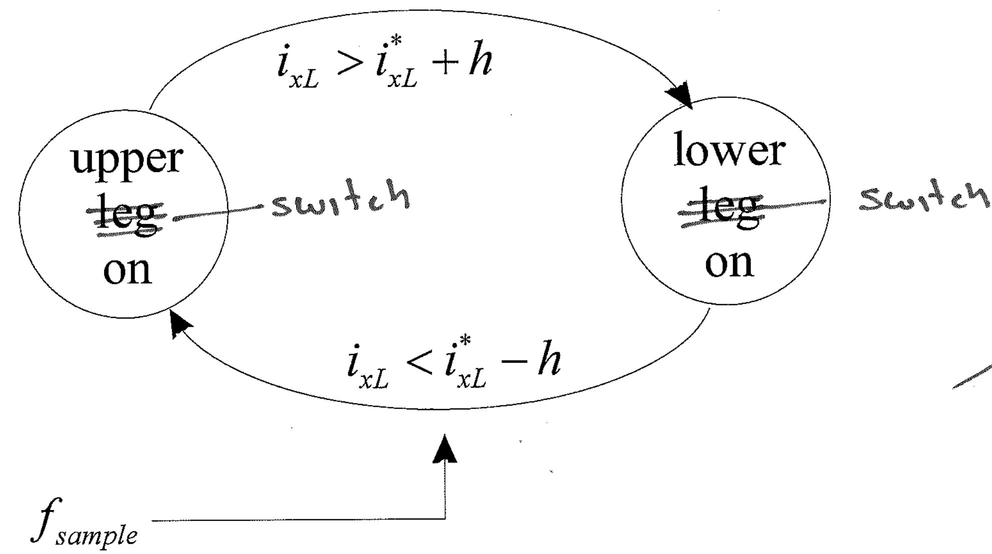
$$= \underbrace{\begin{bmatrix} c & s \\ c^- & s^- \\ c^+ & s^+ \end{bmatrix}}_{K_s^{e^{-1}}\big|_{LTC}} i^*_{qdL}$$

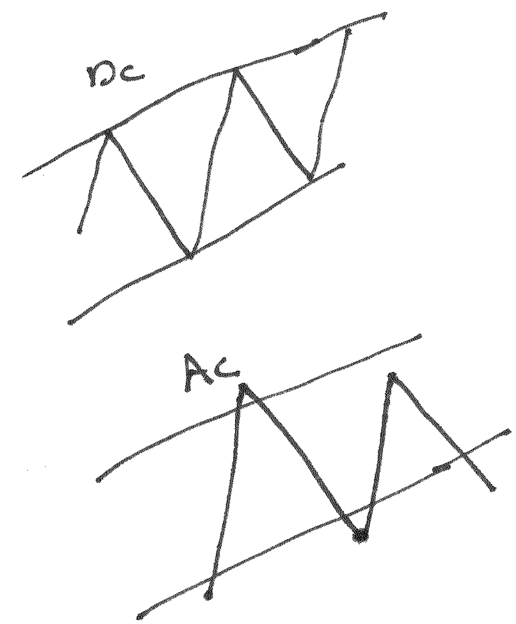
LTC — Left two columns

HD Modulator

Hysteretic - Delta Modulator

$X \in$ ['a', 'b', 'c']





$A \xrightarrow[T_{sample}]{} B \xrightarrow[T_{sample}]{} C \xrightarrow[T_{sample}]{} A$

Fully Controlled 3-Phase Bridge Converter

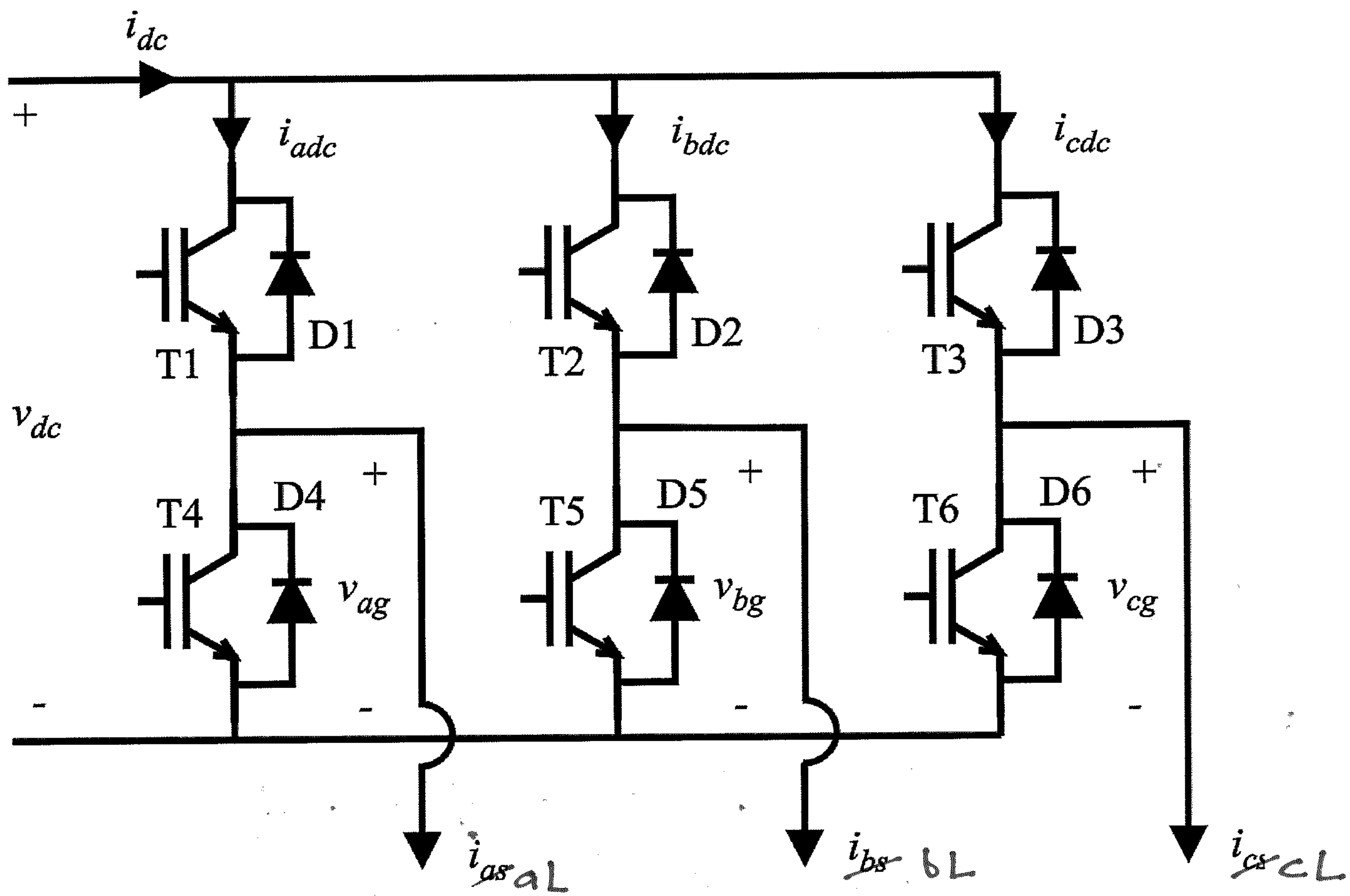


Figure 13.2-1 The three-phase bridge converter toplogy.