EECS 290Ø

Spring 2019

April 8 Lecture

Half Bridge Converter

Outline

Basic Power Converter Components – terminology

Ideal half bridge converter

- basic architecture
- switched model
- averaged model

Non-ideal half bridge

- what's different?
- Averaged model

Half Bridge control

- control model
- basic control design: current tracking
- Feed forward compensation
- Sinusoidal command following

Objectives

1. Understand basic converter architecture design principles

2. Understand averaged models - ideal and non-ideal converter

3. Understand basic control loop design principles

Design factors

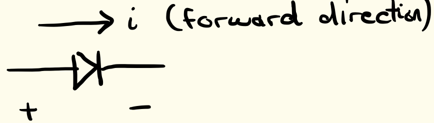
a. Bandwidth /response time

b. Startup current

c. Rejecting AC-side disturbances

Switch types

"**Uncontrollable switch**"   The diode



- Allows current flow in forward direction (voltage drop from + to − terminal)
- Prevents current in reverse direction (but not if voltage exceeds "breakdown voltage"

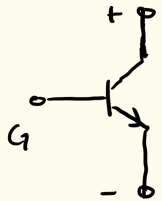
"**Semi-controllable switch**" : Thyristor a.k.a. Semi-controllable Rectifier (SCR
- insulates up to point a signal is applied
- continues conducting until conditions in circuit cause it to stop.
- Most common in high power (transmission scale) applications)

Switch Types, ctd

"Fully controllable switches" : (Transistors)

- Gating command determines both ON and OFF state.

- More common in power applications: Insulated Gate Bipolar transistor: IGBT - (3 layer)



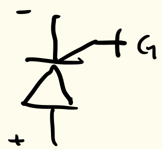
+ low control power

+ high frequency

- high on-state losses

+ high lifetime

- Less common: Insulated Gate Conducting Transistor IGCT (4 layer)



+ high tolerance for overload

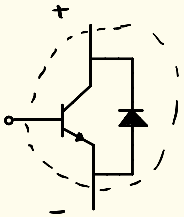
+ low on-state losses

- cooling problems

Switch Classification

In converters, to my knowledge, we focus on

"reverse conducting" switches:



why do this?

- IGBT don't tolerate high reverse voltage
- The diode protects it

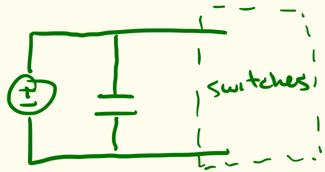
Converter Types : Current Source vs. Voltage Source

This classification refers to operating characteristics of the DC source. [1st Discuss green, then red]

CSC : Typically DC source in series with a large inductor

← commercial switches limited availability, so CSC less common

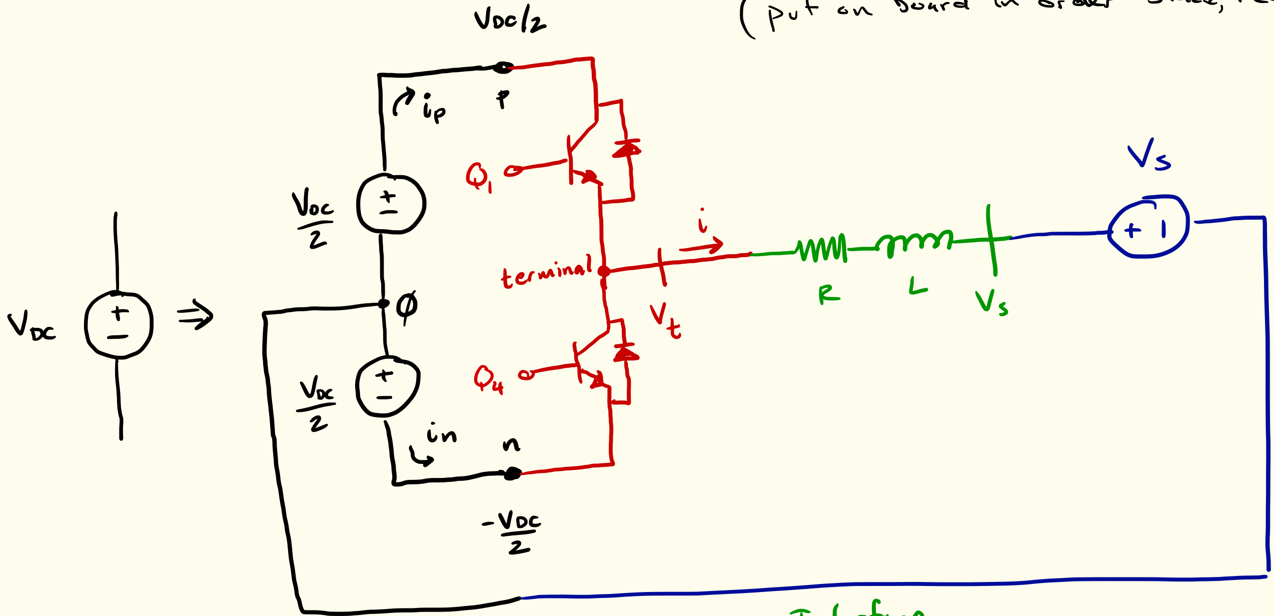
VSC : DC source typically in parallel with a large capacitor



← This is the more common power converter. Based on IGBT.

DC/AC Half Bridge Converter Structure

(put on board in order black, red, green, blue)



DC side

- Terminal ϕ is the "midpoint"

Converter

- V_t, terminal voltage, $\{\frac{V_{DC}}{2}, -\frac{V_{DC}}{2}\}$
- V_t has "ripple"

Interface reactor

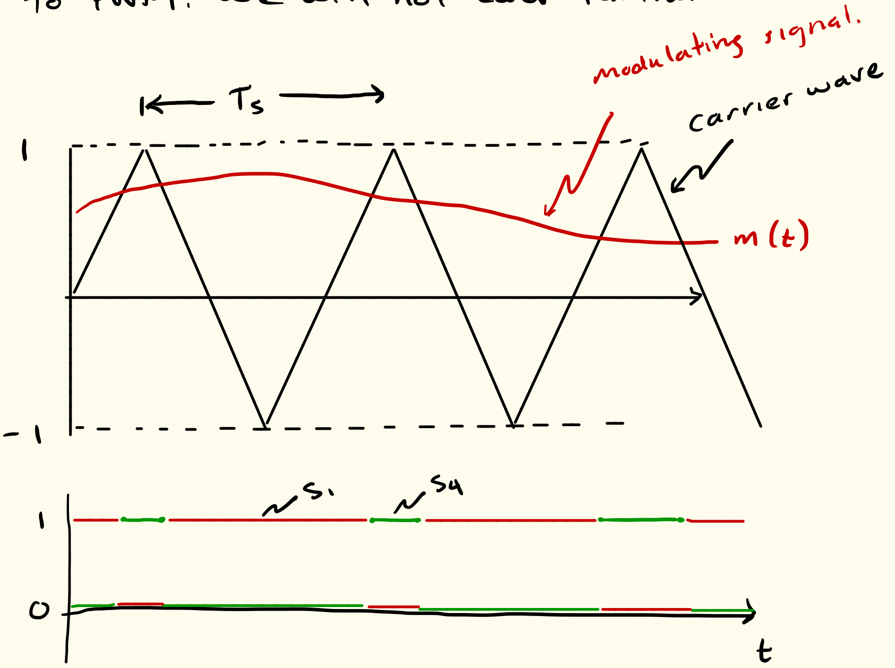
- Acts as filter on V_t ripple
- Also provides $(V_t - V_s)$, which is key control variable

AC side

- V_s is AC voltage source

Switch Control: Pulse Width Modulation

- Note, Seth talked about digital control as an alternative to PWM. We will not cover further.



<u>Important</u>: All signals here are <u>digital</u>

carrier < modulating

$\Rightarrow s_1 = 1$

$s_4 = 0$

carrier > modulating

$\Rightarrow s_1 = 0$

$s_4 = 1$

T_s : Typically $O(100\,\mu s)$

$\sim O(1{,}000\text{ Hz})$

Switch Control analysis

Assumptions

1. Diodes & transistors perfect short circuits when conducting
2. " " " open circuit " blocking
3. No "turn off current"
4. Instant transitions from conducting to blocking
5. AC-side i is "ripple free", and DC over T_s time scale.

Last assumption can be justified on grounds that inductance in between V_t & V_s is sufficiently high to prevent fast current changes.

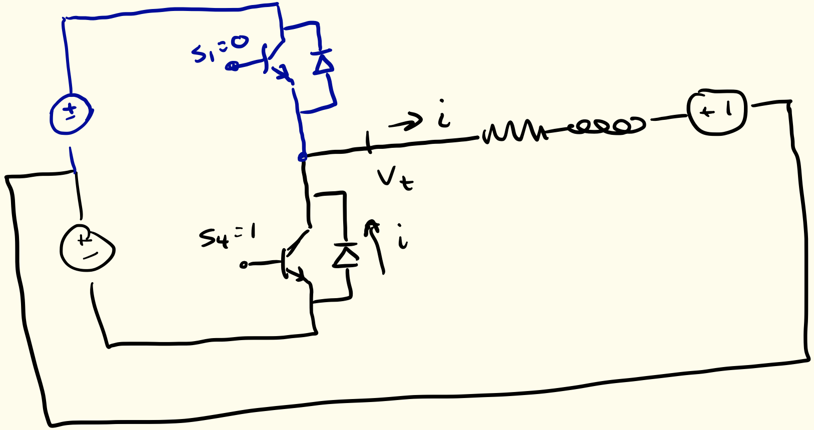
Switch Control Analysis, ctd

Let

$i > 0$ (AC-side current +ive):

$s_1 = 0,\ s_4 = 1$

blue = not active



In this case,

$$V_t = -\frac{V_{DC}}{2}$$

- For $i > 0$, $s_1 = 1$, $s_4 = 0$, $\Rightarrow V_t = +\frac{V_{DC}}{2}$. Current won't flow through S_4, the active leg moves to the top.

Converter Switched Model

Let

$$s_1(t) + s_4(t) \equiv 1$$

$$\Rightarrow \quad v_t(t) = \left(\frac{V_{DC}}{2}\right) s_1(t) + \left(-\frac{V_{DC}}{2}\right) s_4(t)$$

$$i_p(t) = i\, s_1(t)$$

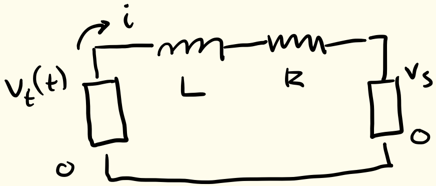
$$i_n(t) = i\, s_4(t)$$

$$P_{DC}(t) = \left(\frac{V_{DC}}{2} s_1(t) - \frac{V_{DC}}{2} s_4(t)\right) i = \frac{V_{DC}}{2} \big(\underbrace{s_1(t) - s_4(t)}_{\text{negative when } s_4 \text{ is on}}\big)\, i$$

(remember we are assuming $i =$ constant)

AC Side Current Dynamics

This will be useful for averaging, up next.



KVL: $$L\frac{di}{dt} + Ri = v_t(t) - v_s$$

For now, assume constant.

Converter Averaged Model

- Why do we average?
  - Simplifies analyses
  - Compensators & filters in control system typically act as low pass

Let

$$V_t(t) = \frac{1}{T_s}\int_{t-T_s}^{t} V_t(\tau)dt + f(t)$$

$\uparrow$ zero mean, high frequency stuff

$$= \bar{V}_t(t) + f(t)$$

$$\Rightarrow \quad L\frac{di}{dt} + Ri = \bar{V}_t(t) + f(t) - V_s$$

Converter Averaged Model, continued

Since the equation is linear,

$$L\frac{d\bar{i}}{dt} + R\bar{i} = \bar{V}_t - V_s \quad ; \quad L\frac{d\tilde{i}}{dt} + R\tilde{i} = f(t)$$

$$i = \bar{i} + \underset{\substack{\uparrow \\ \text{ripple}}}{\tilde{i}}$$

If frequency of $f(t)$ is high relative to $\frac{R}{L}$,

$$\tilde{i} \approx 0 \implies i \approx \bar{i}$$

Converter Averaged Model, continued

Let d = "Duty cycle" for s_1 (fraction of T_s that $s_1 = 1$)

$\Rightarrow$ $\bar{s}_1(t) = d$

$\bar{s}_4(t) = 1 - d$

Assumption: m varies much more slowly than carrier

$\Rightarrow$ $\bar{V}_{DC}$ = constant over T_s.

(Finally) Averaged Quantities

Remember,

$$V_t(t) = \frac{V_{DC}}{2} s_1(t) - \frac{V_{DC}}{2} s_2(t)$$

$$\Rightarrow \bar{V}_t = \frac{V_{DC}}{2} d - \frac{V_{DC}}{2}(1-d) = d V_{DC} - \frac{V_{DC}}{2}$$

$$= \left(d - \tfrac{1}{2}\right) V_{DC}$$

$$= m \frac{V_{DC}}{2}$$ (m is the value of the modulating wave).

also, $\bar{i}_p = \frac{1+m}{2} i$ $\qquad$ $\bar{i}_n = \frac{1-m}{2} i$

+ive side current $\qquad$ -ive side current

Remember, we assume i = constant over T_s time scale.

Example (put on board in order black, red, green, orange)

$L = 690\,\mu H$

$R = 5\,m\Omega$

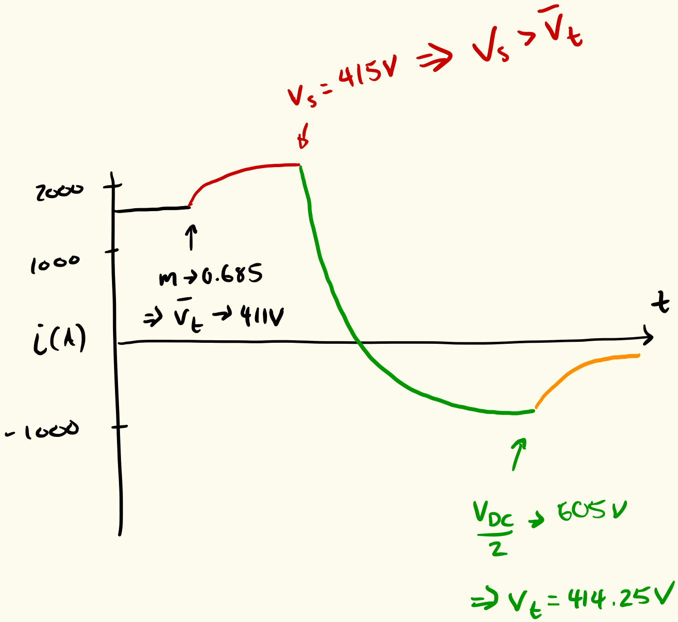
$\frac{V_{DC}}{2} = 600V$, initially

$V_s = 400V$, initially

$m = 0.68$, initially

$f_s = 1620Hz$

$\Rightarrow \bar{V}_t = 408V$, initially



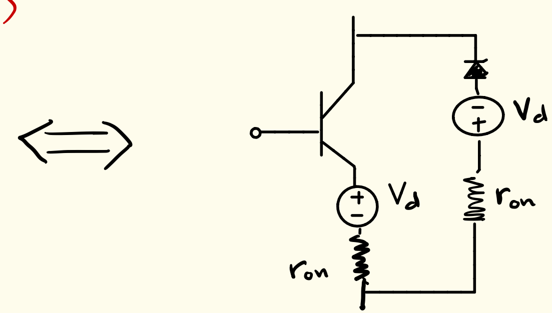
Non-ideal converter

Previous model used "ideal" switch model

Here is a schematic of an alternative:

New assumptions (class to provide)

1. Each switch is modeled by a voltage drop in series w/a resistance



2. Transistors turn on 'immediately', but turn-off experiences a "tailing current"

3. Diodes experience "reverse current recovery"

Voltage model for non-ideal converter

$$\overline{V_t'} = \frac{mV_{DC}}{2} - \frac{i}{|i|} V_e - r_e i$$

charge associated w/ diode reverse recovery

charge associated w/ transistor tailing current

reverse recovery duration

$$V_e = V_d - \left(\frac{Q_{rr} + Q_{tc}}{T_s}\right) r_{on} + V_{DC}\frac{t_{rr}}{T_s}$$

Drop across switch

switch resistance

$$r_e = \left(1 - \frac{t_{rr}}{T_s}\right) r_{on}$$

Power loss for non-ideal converter

Ideal converter had zero loss

Non-ideal, as modeled here, has

$$\overline{P}_{loss} = V_{DC}\left(\frac{Q_{rr} + Q_{tc}}{T_s}\right) + V_e|i| + r_e i^2$$

⇒ zero current still experiences losses, and losses grow with V_{DC}

⇒ But at nonzero currents, increasing V_{DC} (for a given power delivery) will reduce losses by decreasing current.

<u>Half bridge model recap</u>

- Current to AC side assumed constant over switching period due to inductance in "interface reactor" / AC source

- Modulation impacts average voltage. Even if current experiences voltage rise for a fraction of cycle, if it experiences voltage drop for a <u>larger</u> fraction, the average power will be <u>into</u> the device

- Averaging provides simple formulae based on m (carrier wave value) for voltage and current

- Non-ideal converter model introduces no additional dynamics, just different voltages due to losses.

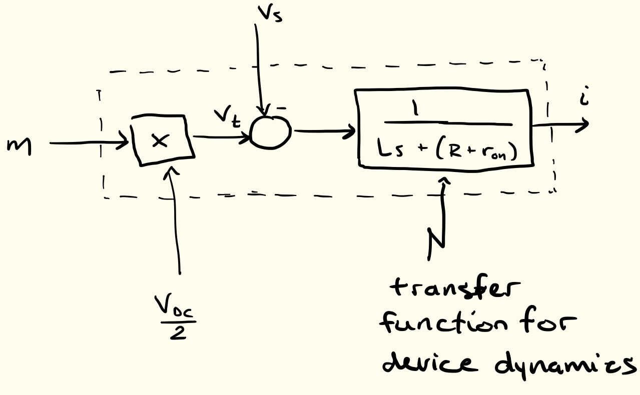
Half Bridge control model

From here on, $\bar{\cdot}$ (overbar) are dropped, but quantities are averaged unless otherwise noted

implicitly includes device voltage drop

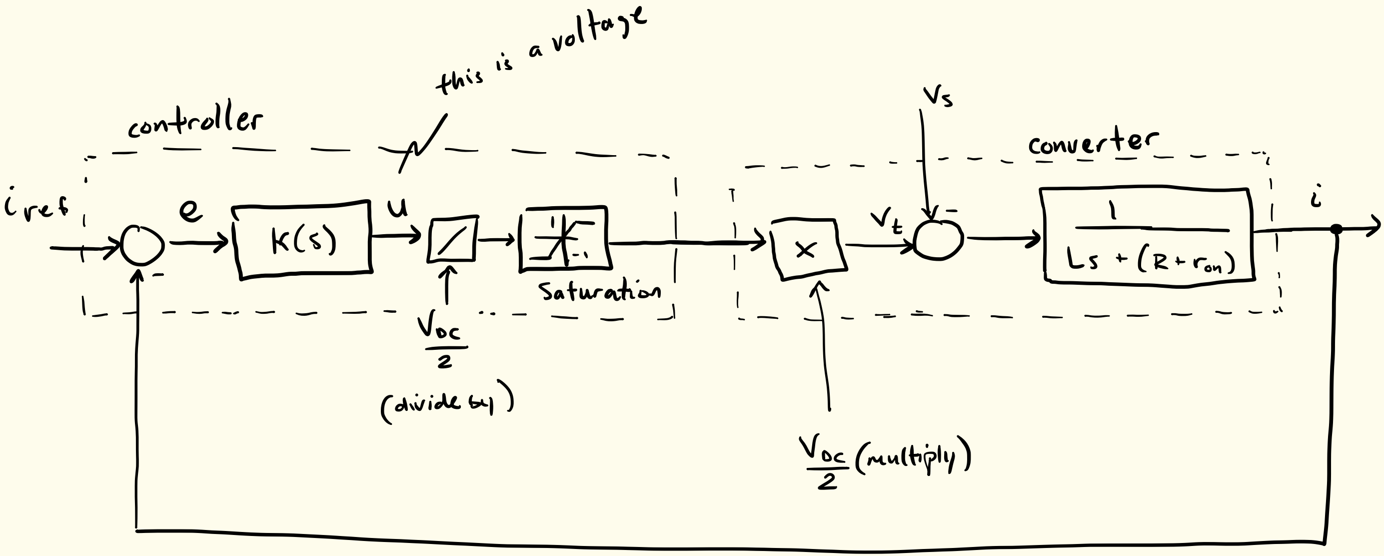
$$L\frac{di}{dt} + (R + r_{on})i = V_t - V_s \quad \Rightarrow$$

device resistance included



The V_d (device voltage drop) is omitted because it is independent of current - but measurement at the actual terminal would need to compensate.

Half Bridge Control - current control



e: current error

$K(s)$: compensator. We're about to talk about what is in here

V_{DC} must be sensed if there are DC-side dynamics.

Control design

PI control works well for some cases (in text, step changes are the initial focus)

$\Rightarrow$ $K(s) = k_p + \dfrac{k_i}{s} = \dfrac{k_p s + k_i}{s}$

↑ ensures zero error tracking

zeros are roots to numerator.

$\Rightarrow$ loop gain $\quad \ell(s) = \dfrac{k_p}{Ls}\left(\dfrac{s + k_i/k_p}{s + \frac{R + r_{on}}{L}}\right)$

poles are roots to denom.

(aside, $= K(s)\,G(s)$ ← closed loop xfr f'n)

Basic control Design

- 1^{st}, note that pole $p = -(R + r_{on})/L$ is stable.

  You can also see this from time domain ODE.

- Second, improve response by setting zero equal to pole

  $$\Rightarrow \frac{k_i}{k_p} = \frac{R + r_{on}}{L}$$

- Third, tune desired time constant of response. How should we think about this?

  $\Rightarrow$ make sure response is significantly slower than switching period

Control Design, ctd.

Closed loop time constant is $\tau_i = \frac{L}{k_p}$. Typical to set this as $10 \times$ switch frequency.

E.g., Switching frequency 1620 Hz $\Rightarrow$ $\tau_i = 6.2\,ms$

Closed-loop transfer function

$$G_i(s) = \frac{i(s)}{i_{ref}(s)} = \frac{1}{\tau_i s + 1}$$

$\Rightarrow$ 1st order current dynamics.

Example

(start with black axes and red iref)

$L = 690\,\mu H$

$R = 5\,m\Omega$

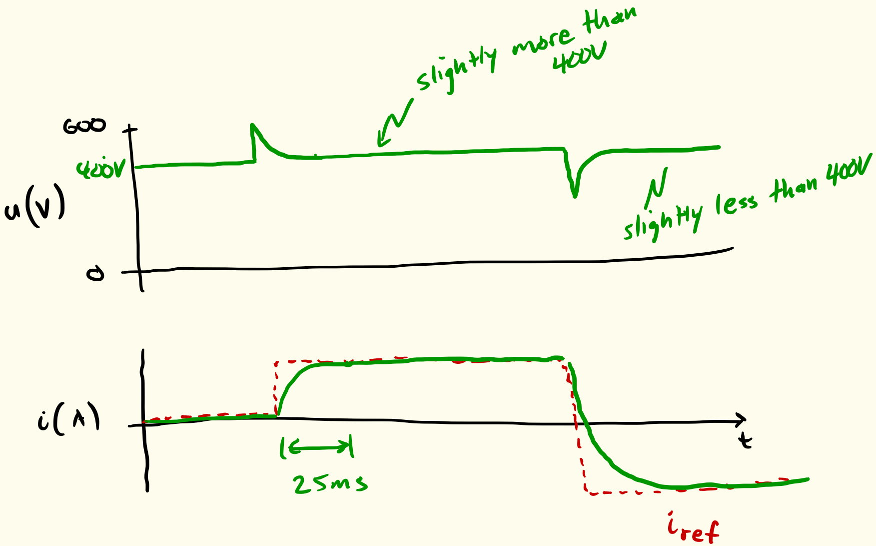
$r_{on} = 0.88\,m\Omega$

$V_d = 1.0V$

$\frac{V_{DC}}{2} = 600V$

$V_s = 400V$ DC

$f_s = 1620\,Hz.$

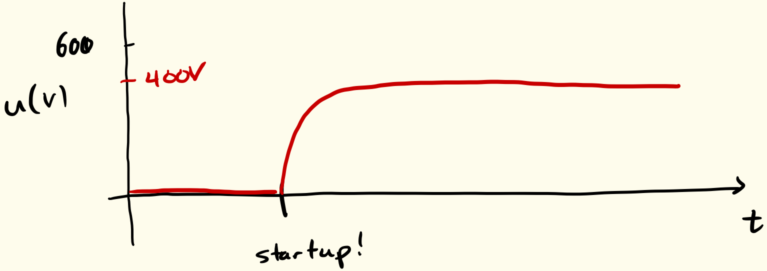


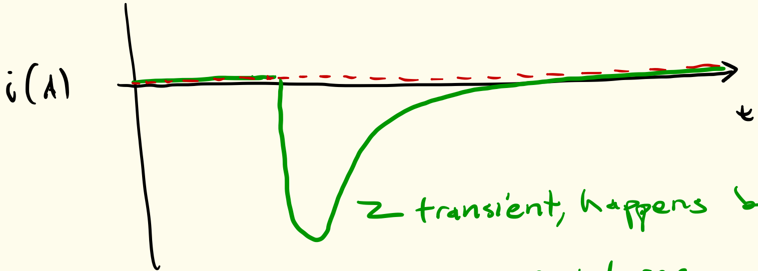
Aim for time const 5ms $\Rightarrow$ $k_p = 0.138\,\Omega$

$k_i = 1.176\,\Omega$

Startup transients

Suppose converter begins zero current operation with $m=0$ and $i_{ref}=0$

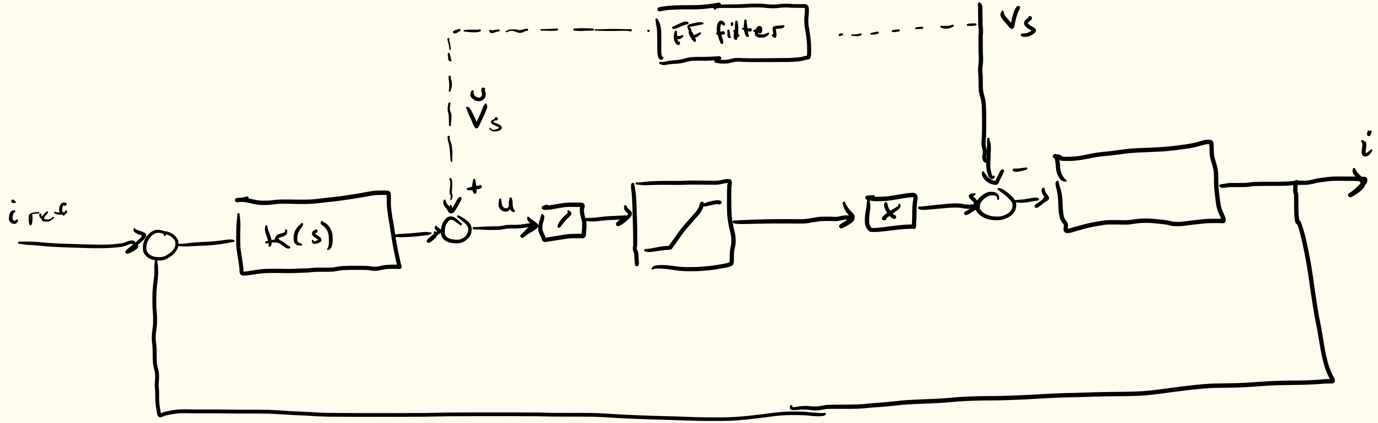




Z transient, happens because $V_s - V_t$ is initially very large

Feed Forward Compensation

Solution to startup transient (and other problems):



- Add (filtered) measure of V_s. ⇒ initial voltage difference is zero

- Compensator now produces deviation from V_s required to reach i_{ref}.

Feed Forward Control etd.

Why else might feed forward compensation be beneficial?

What happens if V_s is time-varying?

$\Rightarrow$ FF compensation also helps to follow time-varying

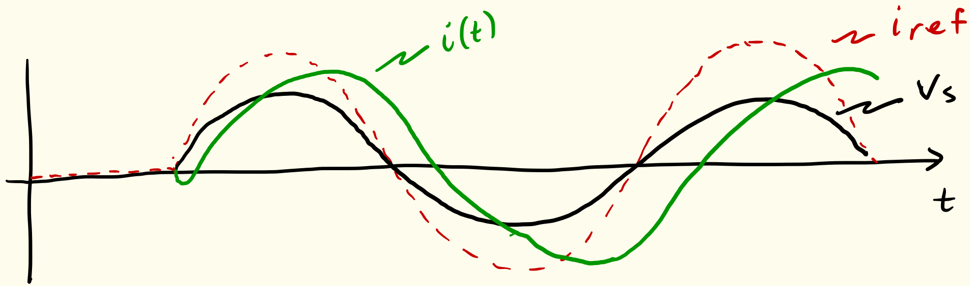
AC dynamics

Sinusoidal Command Following

To this point we have not discussed sinusoidal AC sources. Let's do that now.

$$i_{ref} = \hat{I}\cos(\omega_o t + \phi)$$

with $G_i(s) = \dfrac{i(s)}{i_{ref}(s)} = \dfrac{1}{\tau_i s + 1}$ (from before, no ff comp.)



Sinusoidal, ctd...

So the current out is lower and later:

$$i(t) = \frac{\hat{I}}{\sqrt{1+(\tau_i/\omega_0)^2}} \cos(\omega_0 t + \phi + \delta)$$

$$\delta = -\tan^{-1}(\tau_i \omega_0)$$

$\tau_i = 2\text{ms}$, 60 Hz $\rightarrow$

- Amplitude is 80% of $\hat{I}$, and
- δ is 37°

Sinusoidal, ctd

- There are a few ways to improve tracking, and ~~textbook~~ covers in detail how to design $K(s)$ to do this.
- But for 3ϕ systems we can work in d-q coordinates — a much simpler proposition since control variables become DC quantities.

Takeaways