EECS 290

Spring 2019

April 15 Lecture

Three Phase VSCs.

Announcements

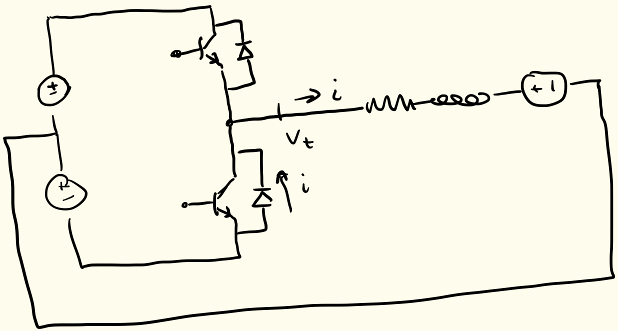
- Next week
  - YI ch 8: dq control
  - Ramasubramanian
- Last week of Class

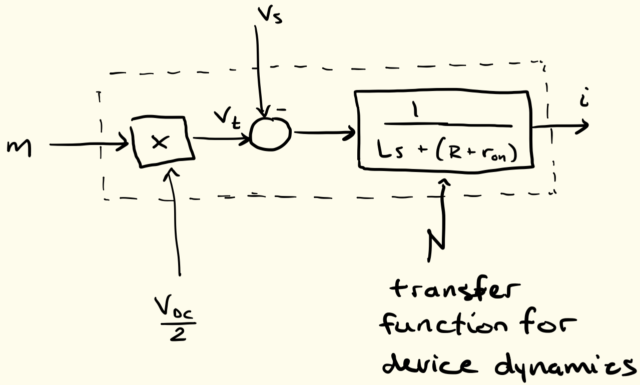
  Cancelled → go to Amber kinetics!
- Reading week
  - Markovic & Lin present
  - Review Rocabert et al.
- Final project
  - I will post guidelines this week.

Today

- Half bridge examples
- Two-level 3ϕ VSC
  - Architecture
  - Switched model
  - Averaged model
  - dq representation
- 3-level "neutral point clamped" 3ϕ VSC
  - Architecture
  - Switched model
  - Averaged model
  - dq representation
- Generic model of both for control representations
- Key takeaways
  - These are very easy to understand at their core
  - In terms of dynamics, not much happening here w/o control

Half Bridge review.





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

$L = 690\,\mu H$

$R = 5\,m\Omega$

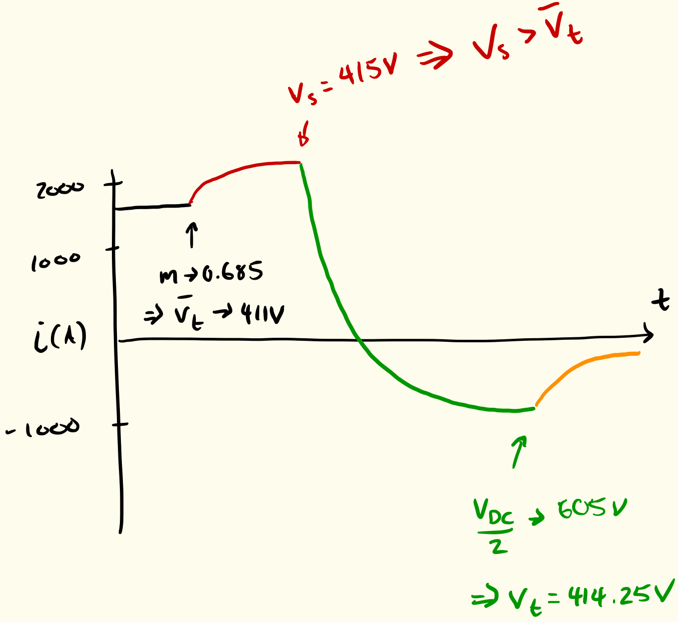
$\frac{V_{DC}}{2} = 600V$, initially

$V_s = 400V$, initially

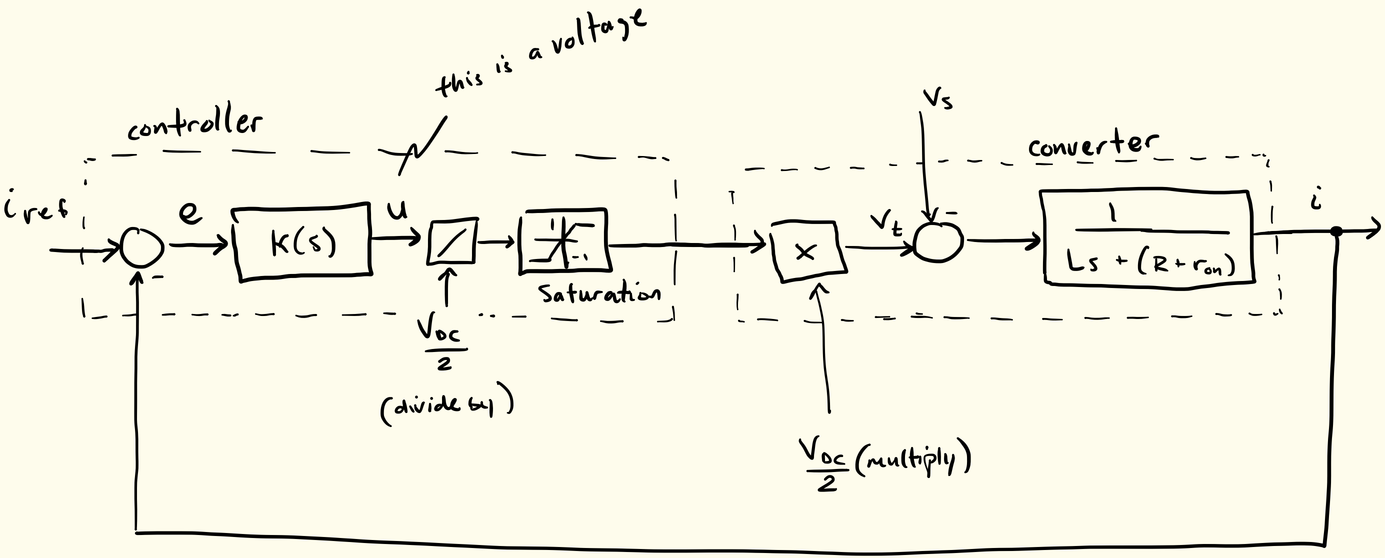
$m = 0.68$, initially

$f_s = 1620Hz$

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



1/2 Bridge control, reminder



- We tune $K(s)$ to quickly reject disturbances to i.

Example

$L = 690\,\mu H$

$R = 5\,m\Omega$

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

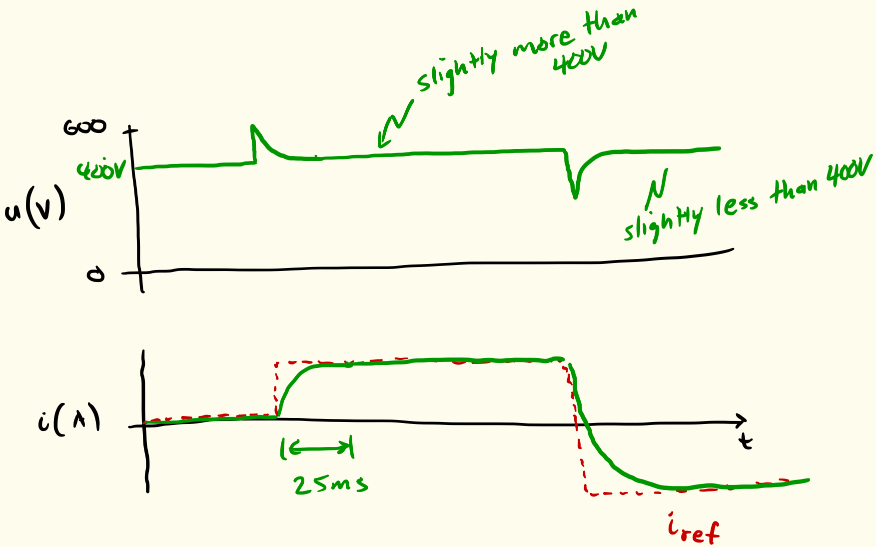
$V_d = 1.0V$

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

$V_s = 400V$ DC

$f_s = 1620\,Hz.$

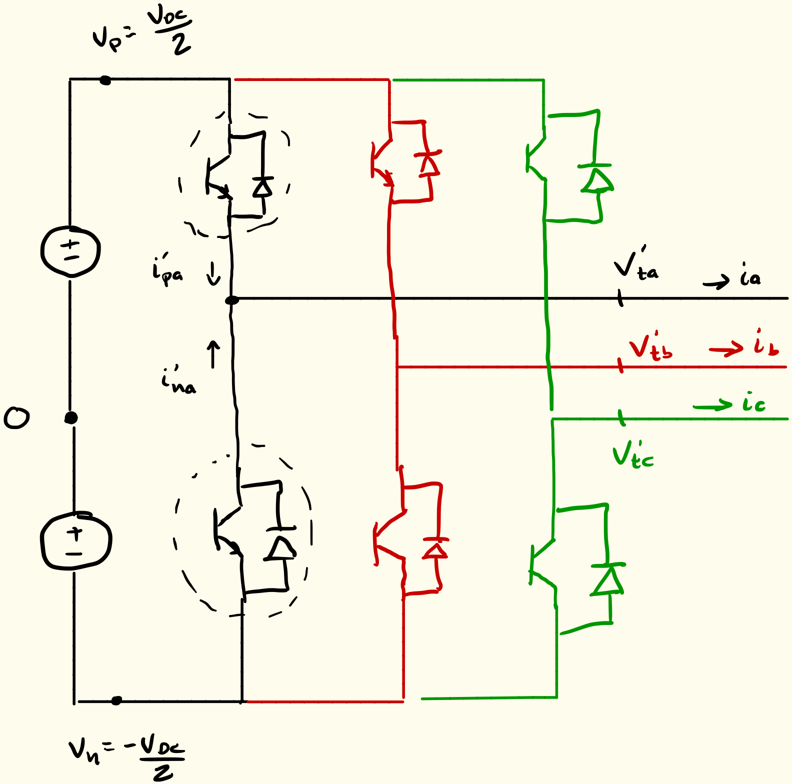
(start with black axes and red i_{ref})



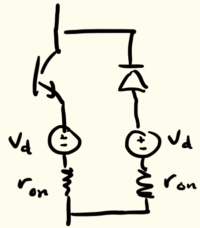
Aim for time const 5ms $\Rightarrow$ $k_p = 0.138\,\Omega$

$k_i = 1.176\,\Omega$

2-Level 3ϕ VSC architecture (sin 5.2.1)



As before, switches are non-ideal



Averaged model from last time

Single half bridge, from last time - averaged, nonideal

$$V_t'(t) = m(t)\,\frac{V_{DC}}{2} - \frac{i(t)}{|i(t)|}V_e - r_e\, i(t)$$

modulating signal

Voltage offset due to semiconductor drop and post-switch dynamics.

Challenge with the voltage offset

- It has a nonlinear effect on the voltage-current relationship when i goes thru zero. $\Rightarrow$ distortion in $V'(t)$
- But $V_e \ll V'(t)$ <u>and</u> controllers remove much of the distortion $\Rightarrow$ ignore

3ϕ model (s'n 5.2.2)

$$V'_{ta}(t) = m_a(t)\frac{V_{DC}}{2} - r_{on}\, i_a(t)$$

$$V'_{tb}(t) = m_b(t)\frac{V_{DC}}{2} - r_{on}\, i_b(t)$$

$$V'_{tc}(t) = m_c(t)\frac{V_{DC}}{2} - r_{on}\, i_b(t)$$

phase currents and phase switching strategy dictate voltage.

Question: If m_a, m_b, m_c are balanced control signals, is current balanced?

Answer: Not if the system the device is connected to is unbalanced.

Losses - one leg (s'n 5.2.3)

charge associated with reverse recovery in diode

charge associated with "tailing current" in recently off transistor

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

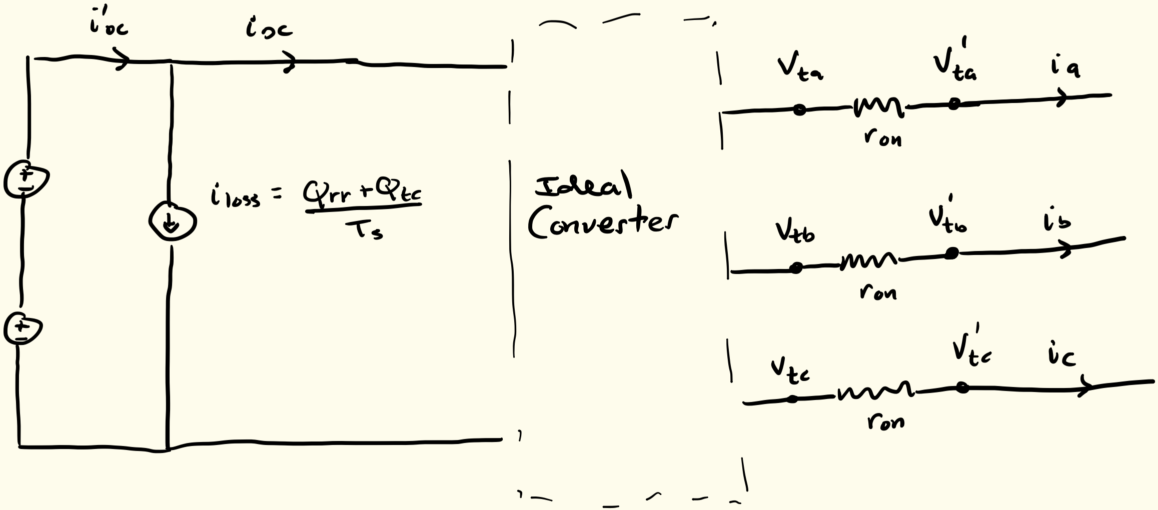
switch period

Q: Which terms matter at low current? Which matter at high current?

A: The second and third terms will go away at zero current, but the first will not. => poor low-load efficiency.

- Losses for 3Φ converter simply 3X this.

Losses - a little more



It's typical to lump i_{loss}, r_{on} in to DC and AC systems, respectively. $\Rightarrow$ leave them out from further model developments.

Working model for 2-level 3ϕ

we'll discuss this soon.

$$V_{ta}(t) = m_a(t)\frac{V_{DC}}{2}, \qquad m_a(t) = \hat{m}(t)\cos(\varepsilon(t))$$

$$V_{tb}(t) = m_b(t)\frac{V_{DC}}{2}, \qquad m_b(t) = \hat{m}(t)\cos(\varepsilon(t) - 2\pi/3)$$

$$V_{tc}(t) = m_c(t)\frac{V_{DC}}{2}, \qquad m_c(t) = \hat{m}(t)\cos(\varepsilon(t) - 4\pi/3)$$

Q: Suppose there is a sharp decline in AC-side voltage. What dynamics will ensue in this model?

A: we don't have enough information...

- The model doesn't describe the control loops that influence $m(t)$
- The model assumes V_{DC} is fixed. In general this is not true...

Non-constant V_{DC}

- The value of V_{DC} need not be constant if it is sensed and passed in to the controller.

- But one needs to at least be aware of
  - * The time constant of the voltage sensor (likely very small)
  - * Any dynamics that might be present on the DC side ⇒ account for those dynamics in controller design.

Space Phasors and $\alpha\beta$ (4.42)

Suppose you have a balanced 3ϕ quantity

$$f_a + f_b + f_c \doteq 0$$

$$\vec{f}(t) = \frac{2}{3}\left(e^{j0} f_a(t) + e^{j2\pi/3} f_b(t) + e^{j4\pi/3} f_c(t)\right)$$

= space phasor.

$\alpha\beta$ coord is simply a decomposition into real and imag. parts

$$\vec{f}(t) = f_\alpha(t) + j f_\beta(t)$$

One can show

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = 2/3\, C \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

Two Level VSC in $\alpha\beta$ (5.3.2)

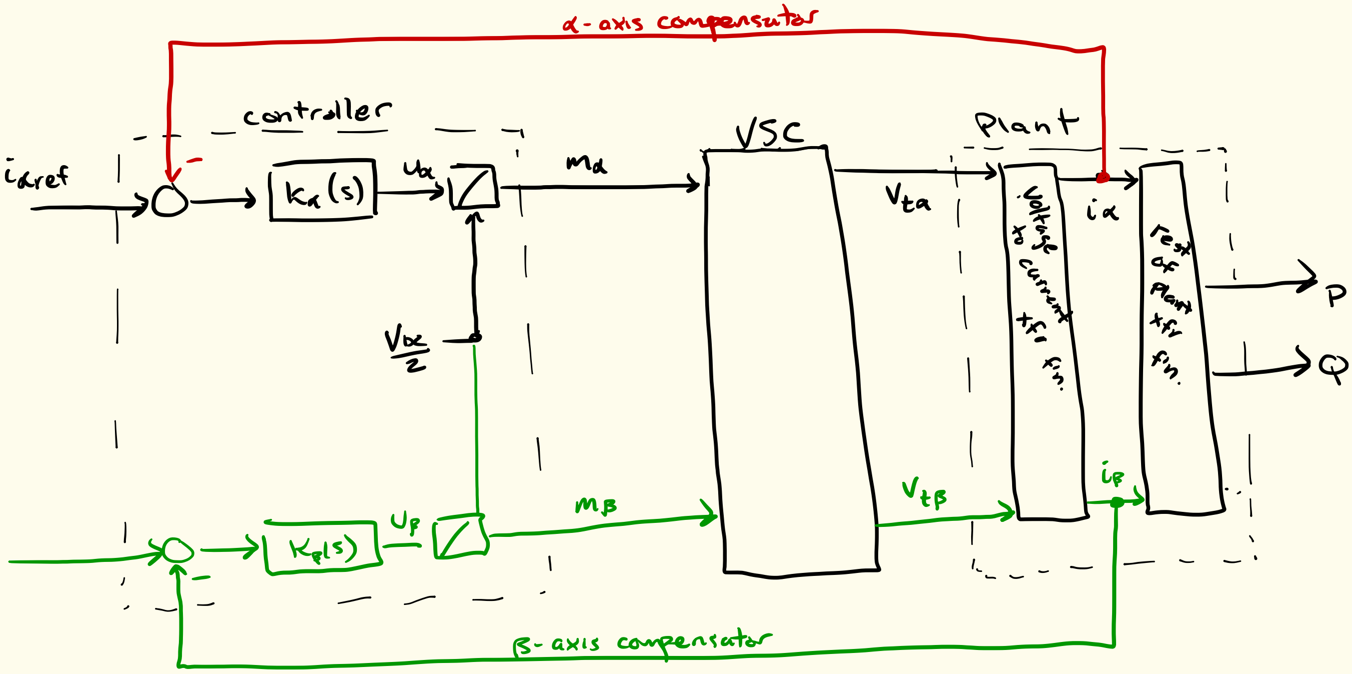
$$\vec{V}_t(t) = \vec{m}(t)\,\frac{V_{DC}}{2} \Rightarrow V_\alpha(t) + jV_\beta(t) = \left[M_\alpha(t) + jM_\beta(t)\right]\frac{V_{DC}}{2}$$

$$\Downarrow$$

In (assumed) balanced conditions, we can represent 3ϕ time varying quantities with just two time-varying.

$\alpha\beta$ control (5.3.2)

Current control is frequently used as a means to another end (real power, frequency, and so on). So it's a good starting block.



Quick note on control

- P and Q might be the ultimate control objectives
- Therefore there would be an "outer control loop" that feeds P+Q errors back in to current references.

dq representation (Sec 5.3.3.)

Remember we had

$$V_{ta}(t) = \hat{m}(t)\cos(\varepsilon(t))\,\frac{V_{DC}}{2} \quad , \text{ and more for phase b \& c.}$$

$$\varepsilon(t) = \underbrace{\omega t}_{\text{frequency}} - \underbrace{\theta_0}_{\text{phase}}$$

dq transform is

$$f_d + j f_q = (f_\alpha + j f_\beta)\, e^{-j\varepsilon(t)} \quad \Rightarrow \quad \vec{f}(t) = (f_d + j f_q)\, e^{j\varepsilon(t)}$$

i.e., we just phase shift by an amount dictated by frequency & phase of the sinusoid.

dq representation continued

As we've discussed a few times already, d- and q- components are

<u>constant</u> if

- system is balanced
- you've got the right representation of $\varepsilon(t)$.

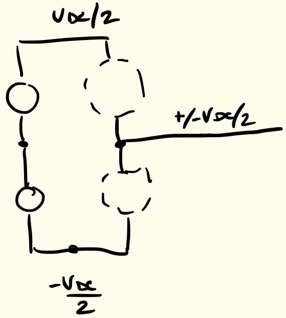
$$\left(V_{td} + jV_{tq}\right) e^{j\varepsilon(t)} = \frac{V_{DC}}{2}\left(m_d + jm_q\right) e^{j\varepsilon(t)}$$

$$\Rightarrow \quad V_{td} = m_d \frac{V_{DC}}{2}$$

$$V_{tq} = m_q \frac{V_{DC}}{2}$$

Issues with the two-level 3ϕ converter

- Each switch cell withstands entire DC-side voltage when off



$\Rightarrow$ need high voltage ratings for high DC-side voltage.

May not be possible for some applications

- Require relatively large LC filters due to high output distortion

- Switching losses high due to relatively fast switch frequency required.

Solving 2-level 3ϕ problems

- Connect multiple switches in series
  - * but might be hard to gate with perfect timing
- 3-level neutral point clamped enables similar benefits without as many series connections

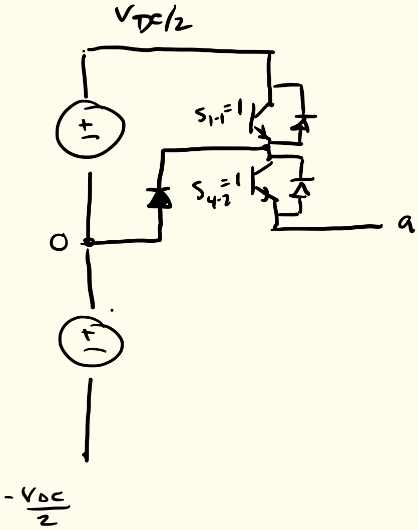
3-level Neutral point clamp (NPC)

3-level: can produce 3 voltage levels

NPC : DC-side neutral point is exposed to the middle of the switched circuit

- In what follows I'll make drawings w/o a return path.
- Don't worry, all we care about now is how to produce different voltages.
- Eventually a 3ϕ circuit will produce return – but that comes later.

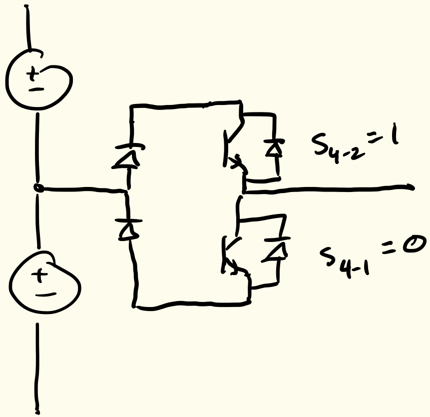
What voltage?



$$\Rightarrow V_{ta} = \frac{V_{DC}}{2}$$

Positive: Neutral clamp diode keeps neutral voltage from appearing

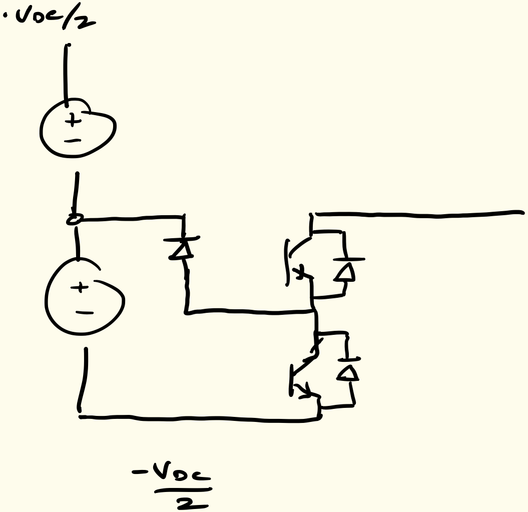
What voltage?



$\Rightarrow V_{ta} = 0$

A: **Zero**

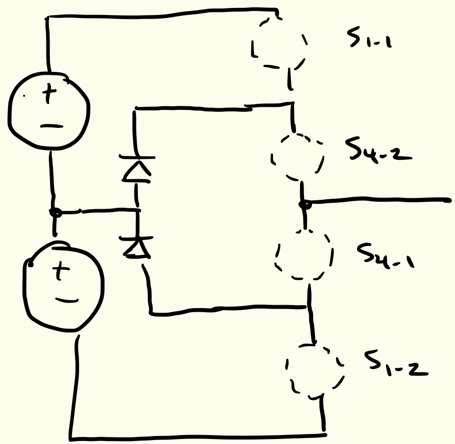
What voltage?

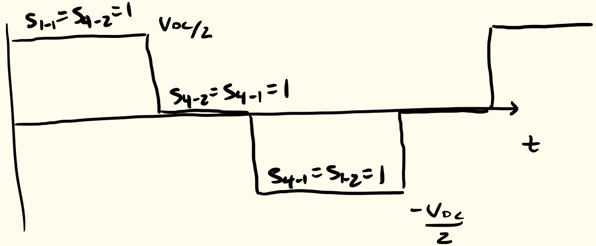


$V_{ta} = -\frac{V_{DC}}{2}$

Negative voltage. Again, neutral clamp diode keeps 0V from appearing.

Full circuit and output voltage trajectory

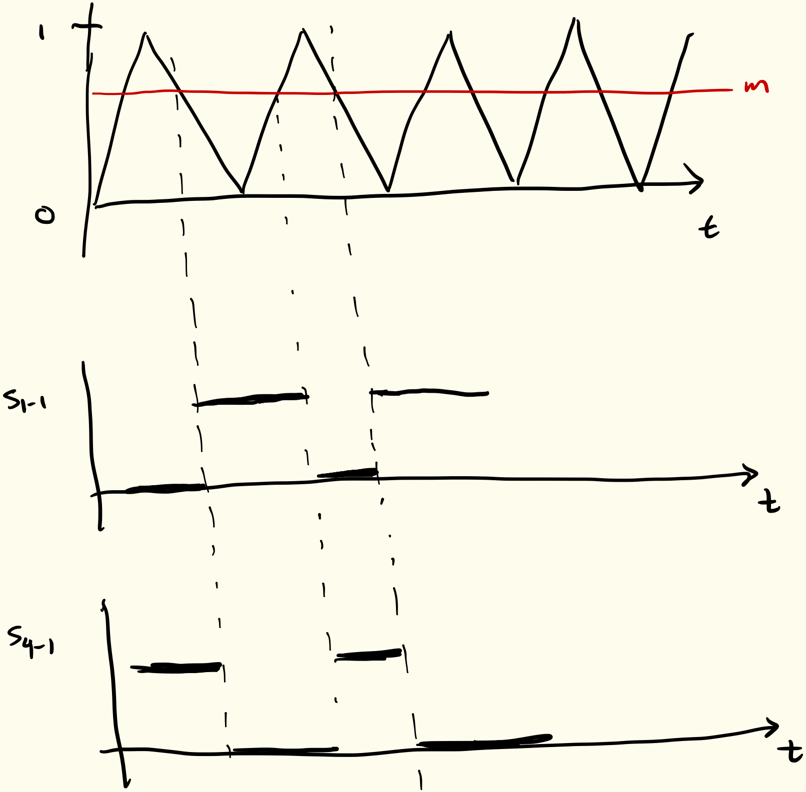




$$S_{1-1}+S_{4-1}\equiv 1$$

$$S_{1-2}+S_{4-2}\equiv 1$$

Switching Strategy for 3-level



$\Rightarrow$ unipolar triangular

$m > \text{carrier} \Rightarrow S_{1-1} = 1$

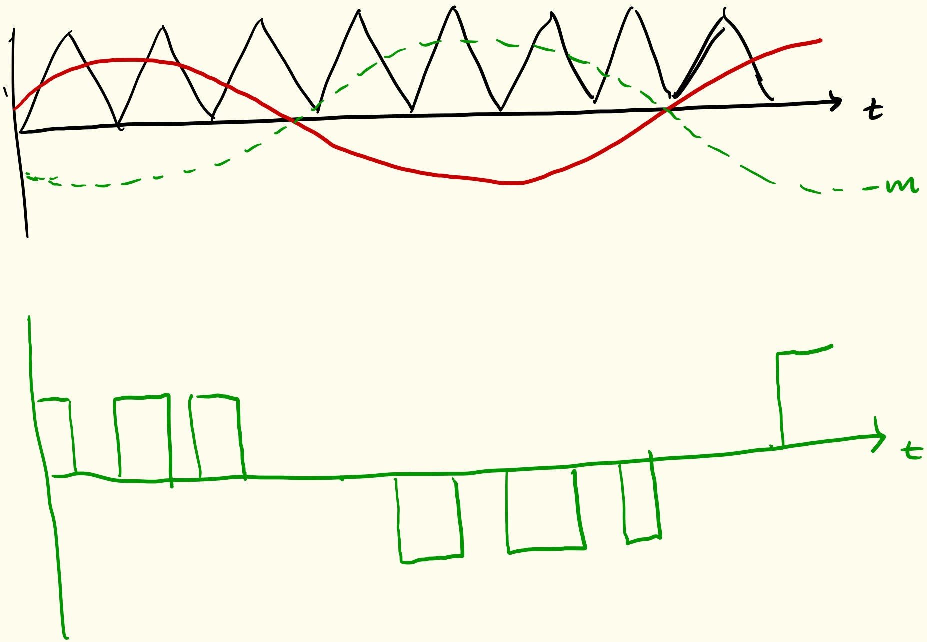
$S_{4-1} = 0$

$m < \text{carrier} \Rightarrow S_{1-1} = 0$

$S_{4-1} = 1$

Switching S_{1-2} and S_{4-2} is identical, except we compare $-m$ to carrier.

What voltage waveform will we get?



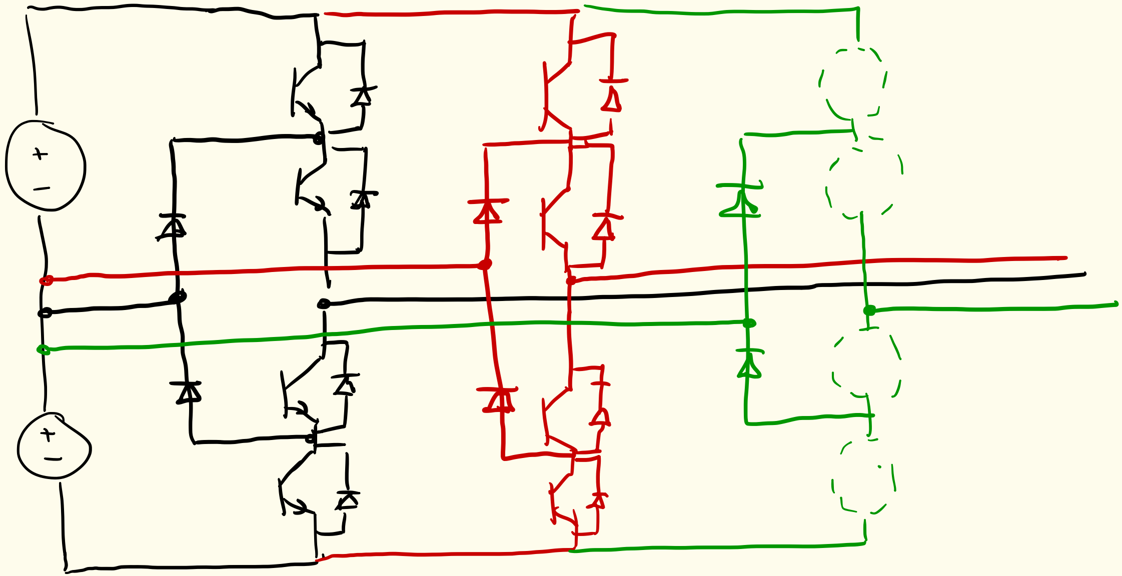
[first draw black and red, then after asking stdts ab't it, draw top green. Then Have class think and draw bot. green.]

Fortunately the averaged model is simple!

$$\bar{v}_t(t) = \frac{V_{DC}}{2} m(t).$$

Same as 2-level!

3 phase architecture



m_a, m_b, m_c are $\frac{2\pi}{3}$ apart.

Comments on Neutral point current

- Three phases drink from this well, so current always is DC plus harmonics in multiples of 3.

- With some work you can show

amplitude of $m(t)$, oscillating @ ω.

$$0.51\,\hat{m}\,\hat{i} \leq \hat{i}_{np} \leq 0.76\,\hat{m}\,\hat{i}$$

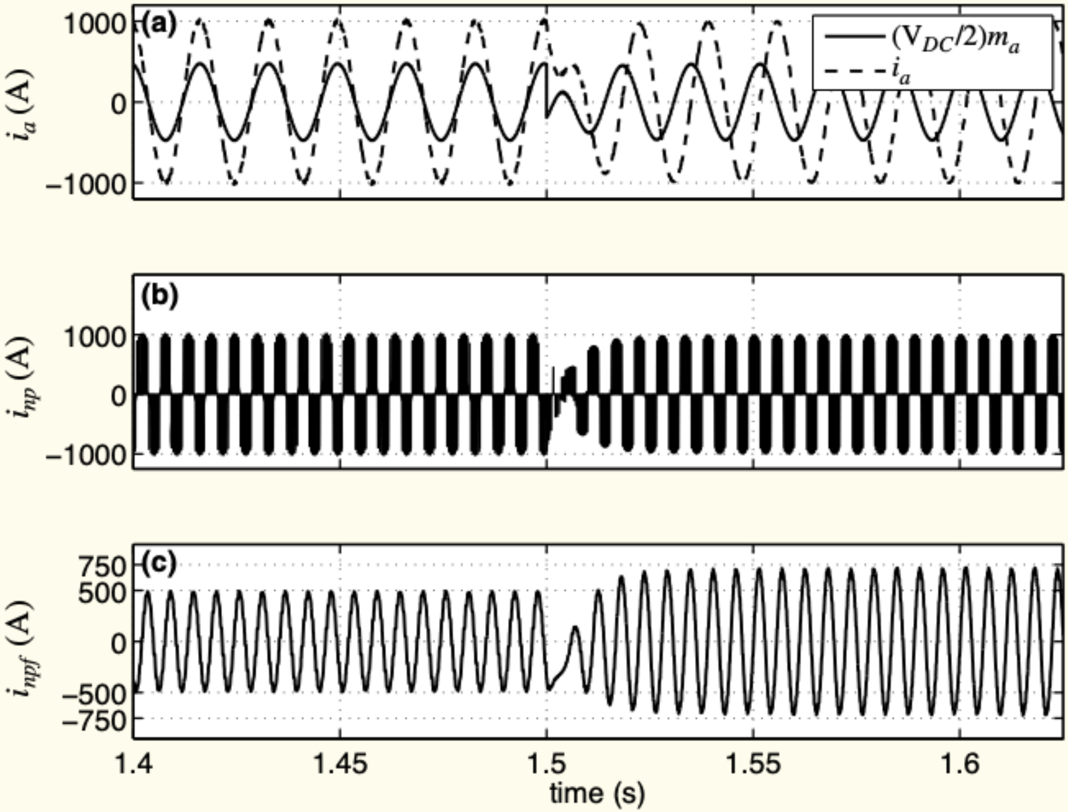
ac current amplitude (per phase)

all real delivery

all reactive delivery

Example 6.1 from text:

→| |← π/2 phase shift



All current

Third harmonic (dominant)

amplitude grows with reactive

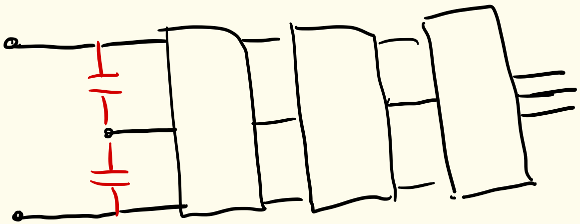
|← all real power to AC →|←— all reactive to AC —→

Unifying 2-level 3ϕ and 3-level NPC 3ϕ.

- Though switching architecture and control sequences differ...

- ... These two architecture produce the same filtered output.

- Furthermore, if we drop in a capacitor on the dc side of a 3-level:



... then one can also show the dc currents are the same for both configurations