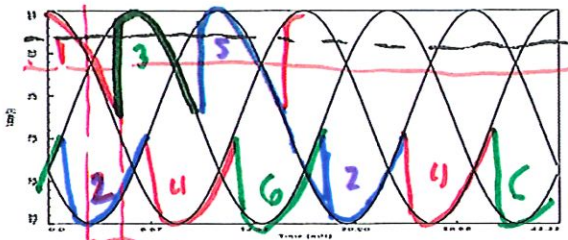
University of Idaho

ECE 529
Utility Applications of Power Electronics

Session 44

Controlled Firing of Thyristors

- Now add a firing delay (α) for the thyristors. Same delay for all 6 switches



$V_{dc\,AVE}$ if $\alpha=0$

$V_{dc\,AVE}$

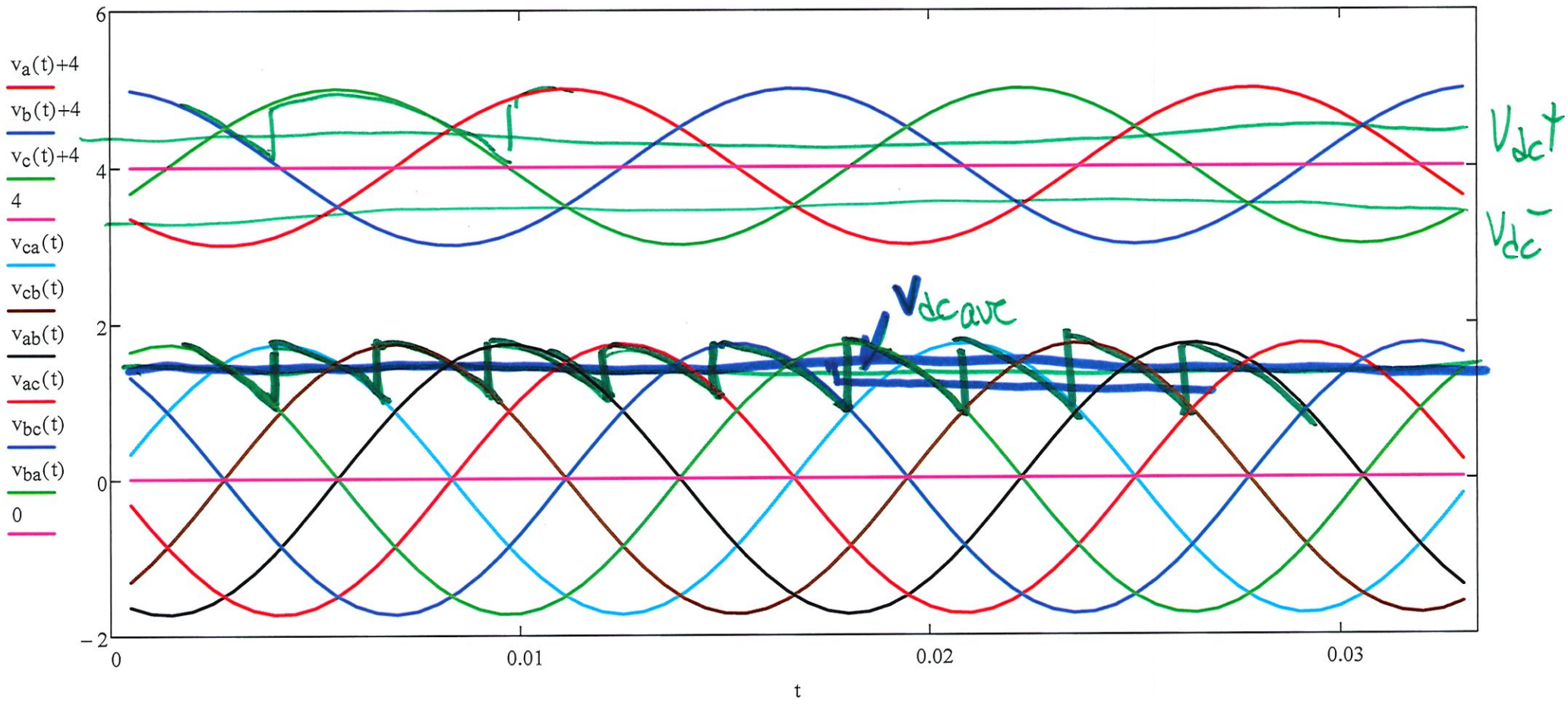
Controlled Firing of Thyristors

- $V_{dc} = \frac{3}{\pi}\int_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} \sqrt{2}|V_{LL}|cos(\theta)d\theta = \frac{3\sqrt{2}}{\pi}|V_{LL}|sin(\theta)\,|_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha}$
- Then $V_{dc} = \frac{3\sqrt{2}}{\pi}|V_{LL}|cos\alpha$
- Define $V_{do} = \frac{3\sqrt{2}}{\pi}|V_{LL}|$
- Therefore $V_{dc} = V_{do}cos\alpha$ (AVE)
- $\alpha = 0 \rightarrow$ diode bridge $V_{dc} = V_{do}$
  $0 \leq \alpha < 90 \rightarrow$ rectifier $V_{dc} > 0$
  $\alpha = 90 \rightarrow$ P =0 $V_{dc} = 0$
  $90 < \alpha \leq 180 \rightarrow$ inverter $V_{dc} < 0$
- Current does not reverse

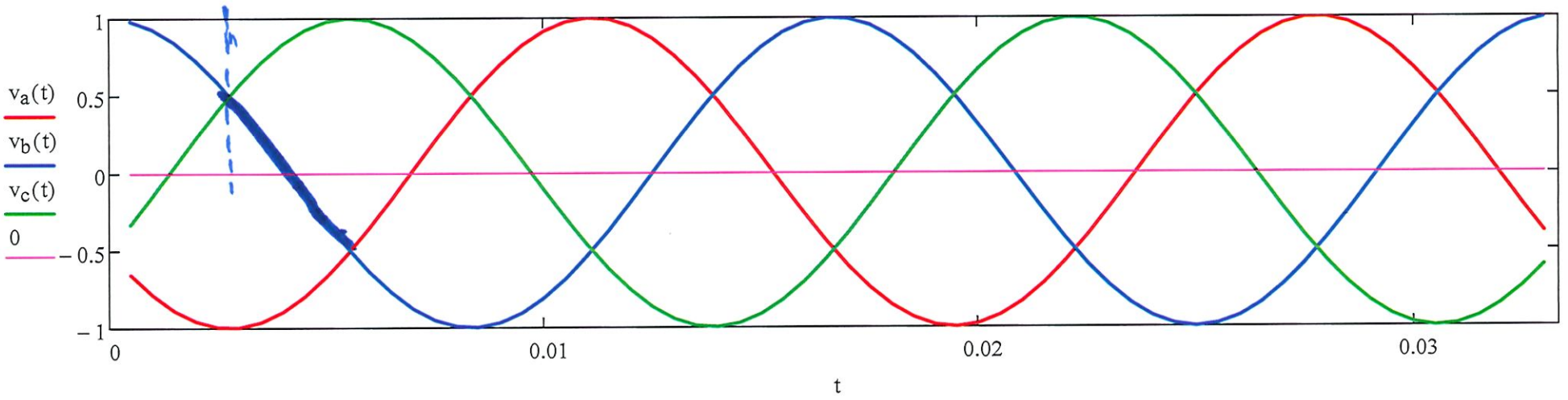
I_{dc} is positive

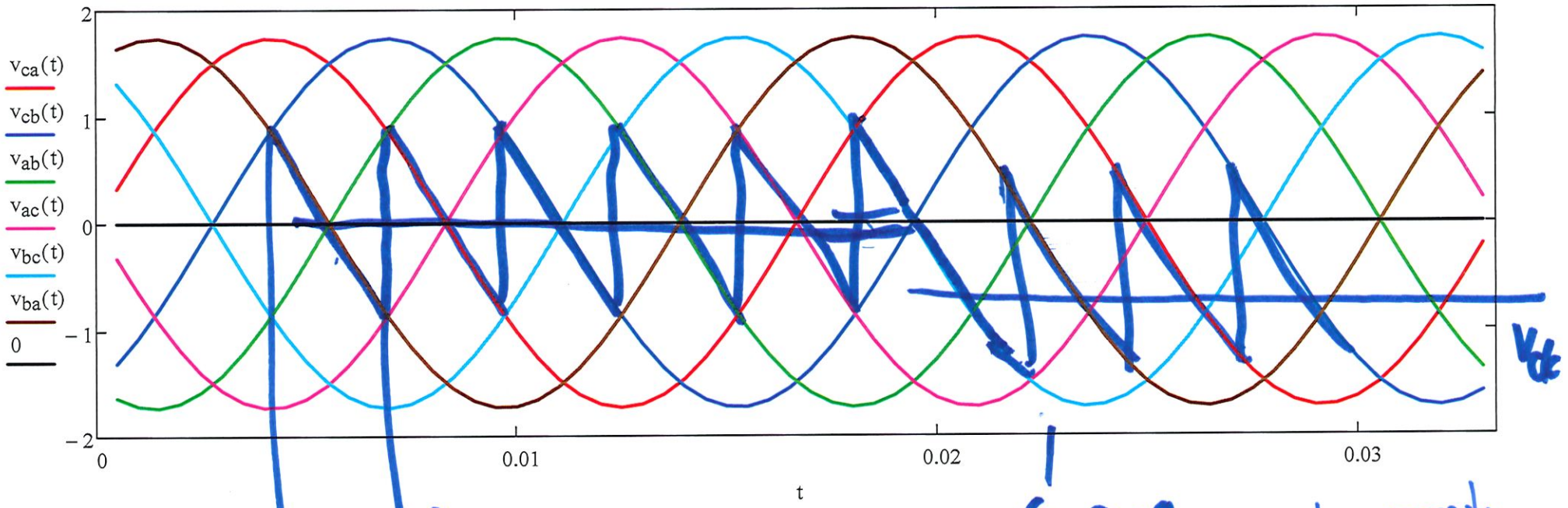
Thyristors Unidirectional

L44 2/12


$v_a(t)+4$
$v_b(t)+4$
$v_c(t)+4$
4
$v_{ca}(t)$
$v_{cb}(t)$
$v_{ab}(t)$
$v_{ac}(t)$
$v_{bc}(t)$
$v_{ba}(t)$
0
6
4
2
0
−2
0
0.01
0.02
0.03
t
V_{dc}
V_{dc}
$V_{dc\,ave}$

L44 3/12



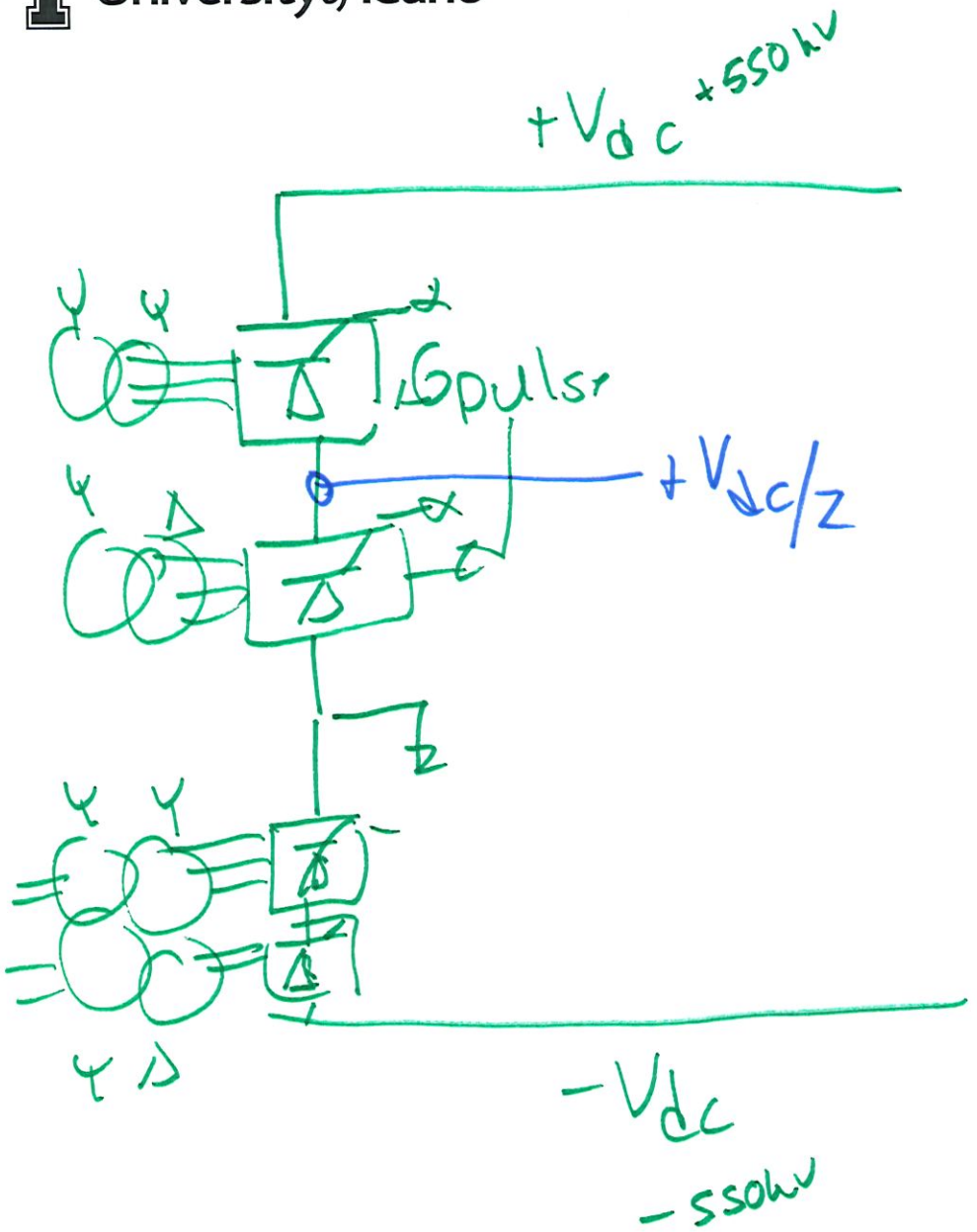


$\alpha = 90°$

$\alpha > 90°$ inverter operation

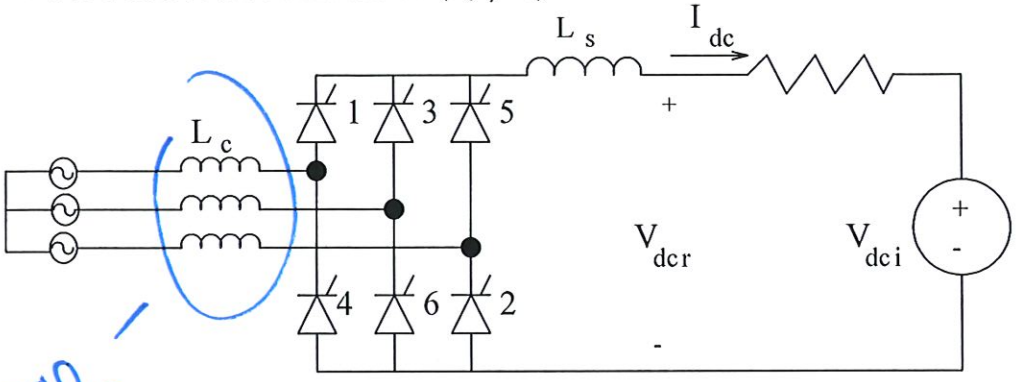
$-V_{dc} \cdot (+I_{dc}) \Rightarrow P_{dc}$ neg

L44 4/12



Commutation Overlap

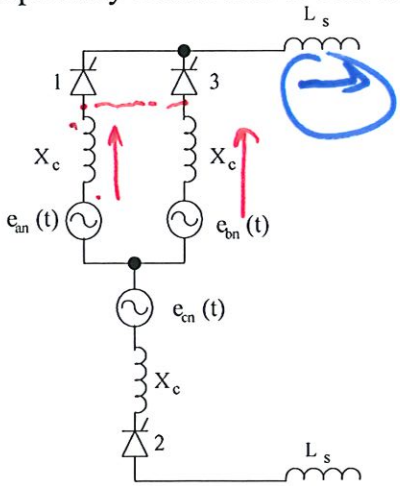
- Now add source inductance ($L_c \neq 0$)

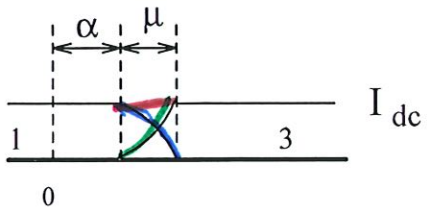


non zero converter transformer $X \approx 0.15$ pu

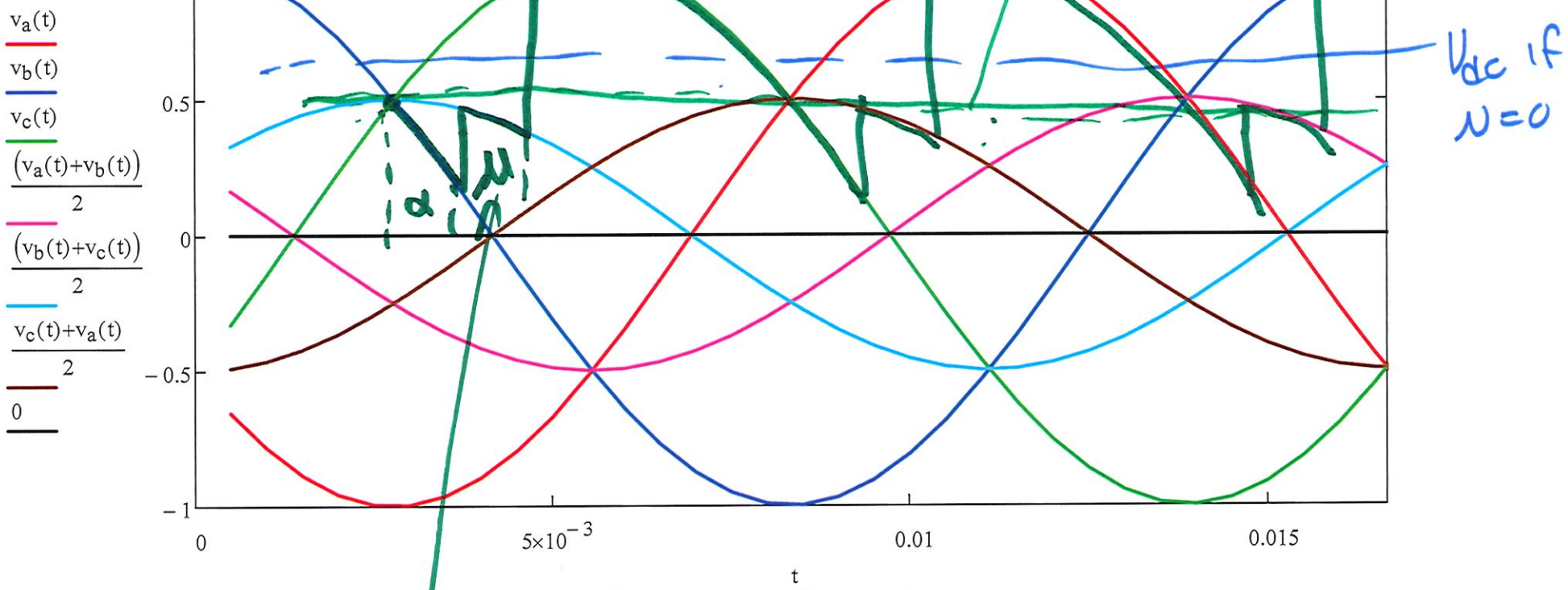
Current Transfer Between Switches

- Current does not fall to zero immediately in ac side inductance
- Temporarily create line to line short



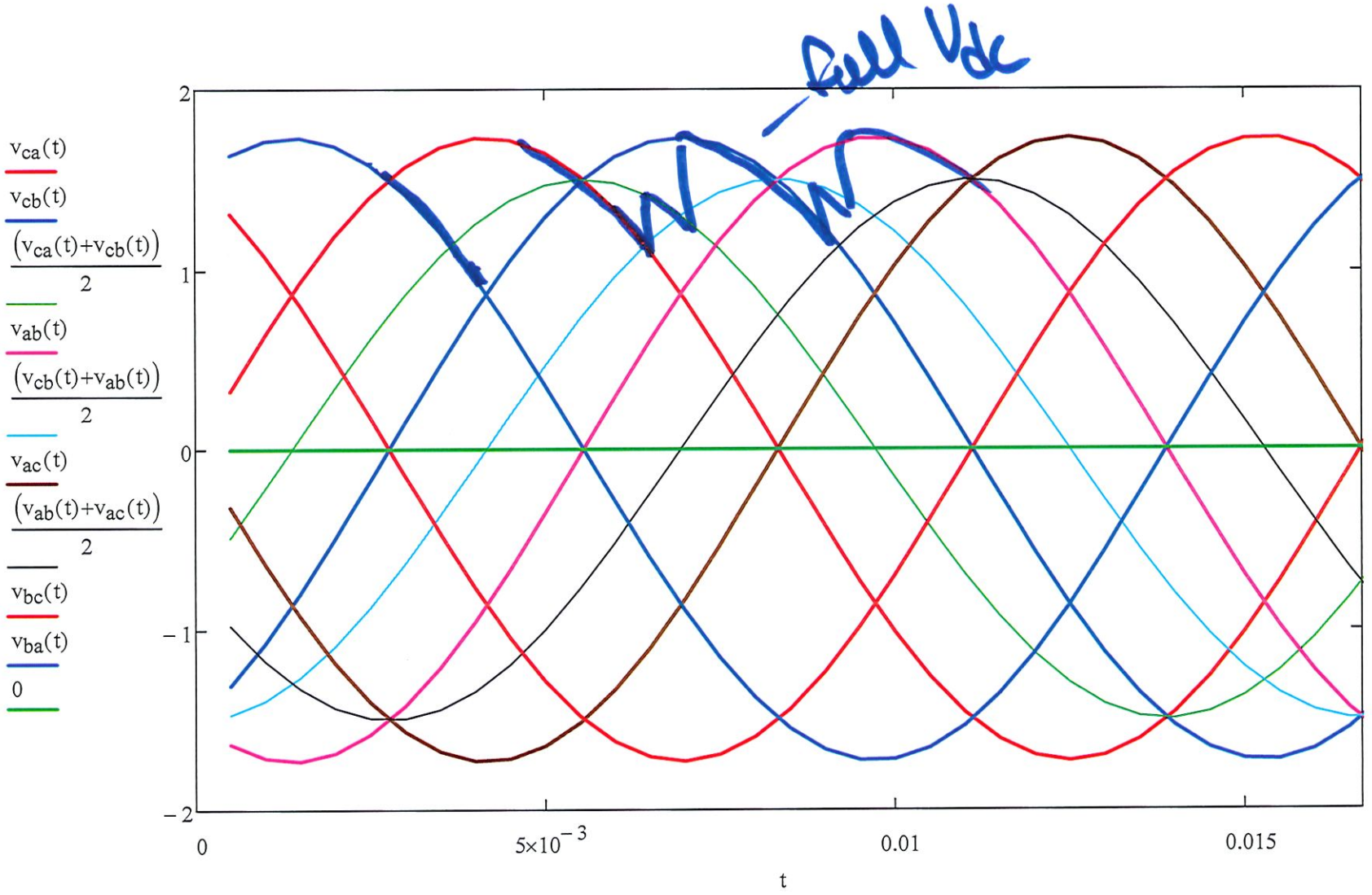


144 6/12



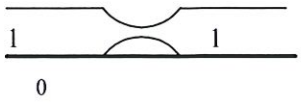
commutation overlap

- fixed value in steady state but varies with steady state operating point


full Vdc
$v_{ca}(t)$
$v_{cb}(t)$
$\frac{(v_{ca}(t)+v_{cb}(t))}{2}$
$v_{ab}(t)$
$\frac{(v_{cb}(t)+v_{ab}(t))}{2}$
$v_{ac}(t)$
$\frac{(v_{ab}(t)+v_{ac}(t))}{2}$
$v_{bc}(t)$
$v_{ba}(t)$
0
2
1
0
−1
−2
0
5×10^{-3}
0.01
0.015
t

Current Transfer Between Switches (cont.)

- What happens if α gets to big (i.e. $\alpha \Rightarrow 180°$)?



This is called a commutation failure

- Thyristor 3 fails to turn on and thyristor 1 fails to turn off
- This is more common if L_c is large, which is the case looking into a "weaker" ac system
- Normally corrects during next interval, although often have a second failure when thyristor 5 turns on, "double commutation failure"

Output Voltage During Commutation

- Switch 1 contribution: $V_{dc1}^{+} = e_{an} - L_c \frac{di_1}{dt}$
- Switch 3 contribution: $V_{dc3}^{+} = e_{bn} - L_c \frac{di_3}{dt}$
- During overlap we see the average between V_{dc1}^{+} & V_{dc3}^{+}
  So $V_{dc}^{+} = \frac{V_{dc1}^{+}+V_{dc3}^{+}}{2} = \frac{e_{an}+e_{bn}}{2} - \frac{L_c}{2}\left(\frac{di_1}{dt} + \frac{di_3}{dt}\right)$
- $i_1 + i_3 = I_{dc}$, so $\frac{di_1+di_3}{dt} = 0$
  But since its a linear network: $\frac{di_1+di_3}{dt} = \left(\frac{di_1}{dt} + \frac{di_3}{dt}\right) = 0$
- So: $V_{dc} = V_{dc}^{+} - e_{cn} = \frac{e_{an}+e_{bn}}{2} - e_{cn} = \frac{e_{ac}+e_{bc}}{2}$

Average DC Voltage with Overlap

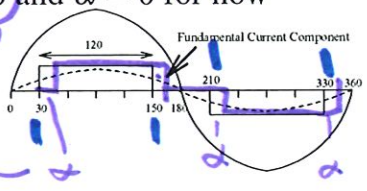
- Recall: $V_{do} = \frac{3\sqrt{2}}{\pi}|V_{LL}| = \frac{3\sqrt{6}}{\pi}|V_{\phi}| = \frac{3\sqrt{3}}{\pi}|E_m|$ where E_m is peak line to neutral voltage
- Then we find:

$$V_{dc} = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\frac{3}{2}E_m cos\theta d\theta + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}\sqrt{3}|E_m|cos(\theta-\frac{\pi}{6})d\theta\right]$$

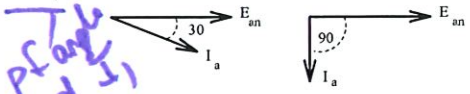
- Leading to: $V_{dc} = \frac{3\sqrt{3}}{2\pi}E_m[cos\alpha + cos(\alpha+\mu)]$
- Or $V_{dc} = \frac{V_{do}}{2}[cos\alpha + cos(\alpha+\mu)]$

Average DC Current

- Start out with $L_c = 0$ and $\alpha = 0$ for now



- Firing delay simply adds a phase shift to the current (always lagging), and $cos\alpha = cos\phi$



- Fundamental Component

$$i_{1pk} = \frac{2}{\pi}\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} i_a cos(\theta)d\theta = \frac{2}{\pi}I_{dc}\int_{\frac{-\pi}{3}}^{\frac{\pi}{3}} cos(\theta)d\theta = \frac{2\sqrt{3}}{\pi}I_{dc}$$

- $|I_{1RMS}| = \frac{\sqrt{6}}{\pi}I_{dc}$

Average DC Current

- Then $i_1(t) = 2\frac{\sqrt{3}}{\pi} I_{dc} cos(\omega t - \alpha)$
- Also: $P = 3I_{1RMS} V_P cos\phi = V_{dc} I_{dc}$
  So: $3I_{1RMS} V_P cos\phi = \frac{3\sqrt{6}}{\pi} V_P cos\alpha I_{dc}$
- So: $|I_{a1RMS}| = \frac{\sqrt{6}}{\pi} I_{dc}$ as expected
- During overlap: $I_{dc} = I_c = \frac{\sqrt{3}E_m}{2\omega L_c} = \frac{e_{LL}}{2X_c}$
- $i_3(t) = I_c(cos\alpha - cos\omega t)$ with $\alpha \leq \omega t \leq \alpha + \mu$
  where $\omega t = \alpha + \mu$ at the end of the commutation interval
- So average current is: $I_{dc} = I_c(cos\alpha - cos(\alpha + \mu))$
- Also: $I_c = \frac{\sqrt{3}E_m}{2\omega L_c} = \sqrt{\frac{3}{2}}\frac{|V_p|}{X_c} = \frac{|V_{LL}|}{\sqrt{2}X_c}$

Average DC Circuit Equations

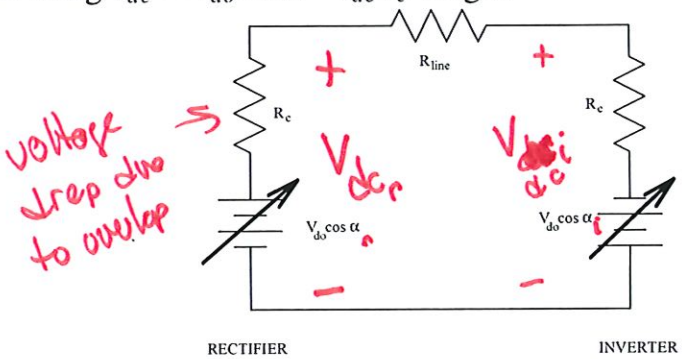
- We have the following equations:

$$\begin{aligned} V_{dc} &= \frac{V_{do}}{2}[cos\alpha + cos(\alpha + \mu)] \\ I_{dc} &= I_c(cos\alpha - cos(\alpha + \mu)) \\ V_{do} &= \frac{3\sqrt{2}}{\pi}|V_{LL}| \\ I_c &= \frac{|V_{LL}|}{\sqrt{2}X_c} = \frac{\pi V_{do}}{6X_c} \end{aligned}$$

- Substitute for the $cos(\alpha + \mu)$ in the V_{dc} equation
- Then $V_{dc} = V_{do}cos\alpha - \frac{V_{do}}{2I_c} I_{dc}$
- Where $\frac{V_{do}}{2I_c} = \frac{V_{do}}{2\frac{\pi V_{do}}{6X_c}} = \frac{3}{\pi}X_c = R_c$ (called the commutating "resistance")
- So $V_{dc} = V_{do}cos\alpha - I_{dc}R_c$

Average DC circuit

- R_c represents a current dependent voltage drop due to overlap
- R_c does not represent any energy dissipation!
- So using $V_{dc} = V_{do}cos\alpha - I_{dc}R_c$ we get:



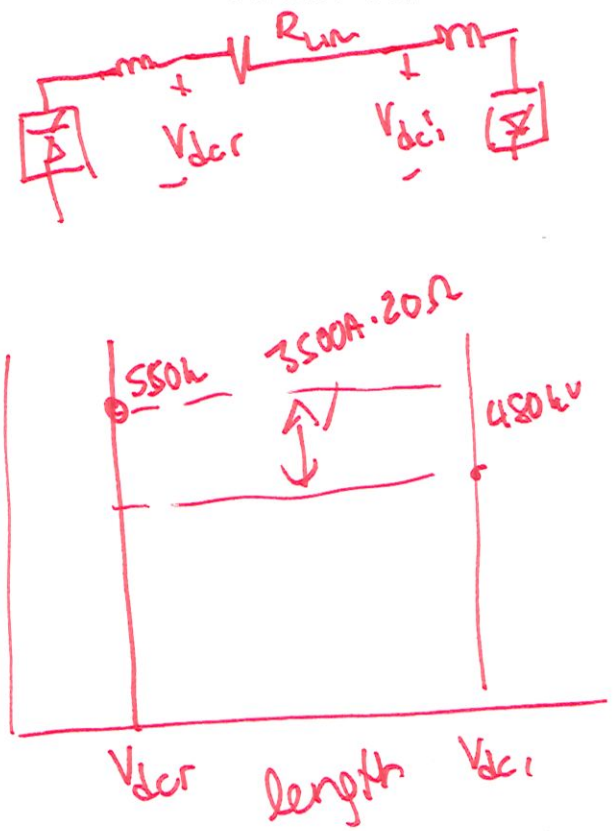
Inverter Operation

- $\alpha + \mu + \gamma = \pi$ Covers positive half cycle of voltage
- γ is defined as the extinction angle
- γ_o is minimum extinction angle for proper turn-off
  Typical values: $15° \rightarrow 20°$
- So $\alpha + \mu \leq 180° - \gamma_o$ gives limits for control settings
- Replace α with $180° - \mu - \gamma$ in averaged equations
  * note: $cos(180° - \theta) = -cos(\theta)$

Example System Calculations

HVDC system with a 12 pulse LCC bridge at each end. The rated dc current is 3500A and the DC line resistance is 20 ohm.

Rectifier	Inverter
$\alpha_{nom} := 15deg$	$\gamma_{nom} := 18deg$
$\alpha_{min} := 5deg$	$\gamma_{min} := 10deg$
$R_{cr} := 6ohm$	$R_{ci} := 6ohm$
$V_{dcr} := 550kV$	$I_{dc} := 3500A$
$R_{line} := 20ohm$	
$V_{dci} := V_{dcr} - I_{dc} \cdot R_{line}$	$V_{dci} = 480 \cdot kV$
$P_{dc_rect} := 2V_{dcr} \cdot I_{dc}$	$P_{dc_rect} = 3850 \cdot MW$
$P_{dc_inv} := 2 \cdot V_{dci} \cdot I_{dc}$	$P_{dc_inv} = 3360 \cdot MW$
$P_{loss} := 2I_{dc}^{2} \cdot R_{line}$	$P_{loss} = 490 \cdot MW$

$P_{dc_rect} - P_{dc_inv} = 490 \cdot MW$

MVAR := MW