AVM – Summary

(12) $\Theta_{ci} - \Theta = \text{angle}\,(i_{qi} - j\,i_{di})$

(13)
$$\begin{bmatrix} V_{qi} \\ V_{di} \end{bmatrix} = \begin{bmatrix} \cos(\Theta_{ci}-\Theta) & -s(\ ) \\ s(\ ) & c(\ ) \end{bmatrix} \begin{bmatrix} V_q^{ci} \\ V_d^{ci} \end{bmatrix}$$

Sample Study

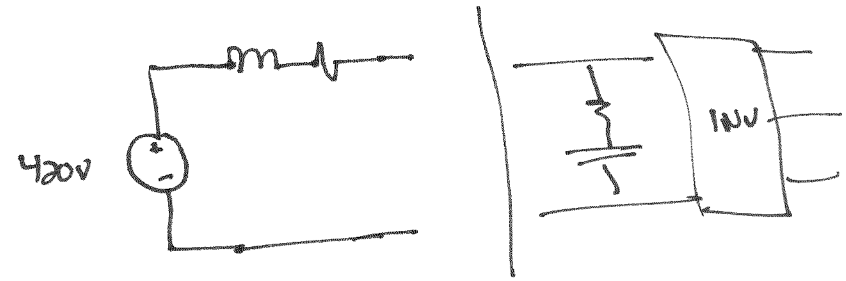
- Commanded voltage: 230 V l-l rms
- Commanded frequency: 60 Hz
- Peak current limit: 30 A
- Minimum voltage to run: 350
- Maximum voltage to run: 450
- Minimum voltage to start: 400
- Maximum voltage to start: 430
- Estimated l-n capacitance: 160 uF
- Sampling frequency: 450 kHz
- Hysteresis level: 1 A

Sample Study

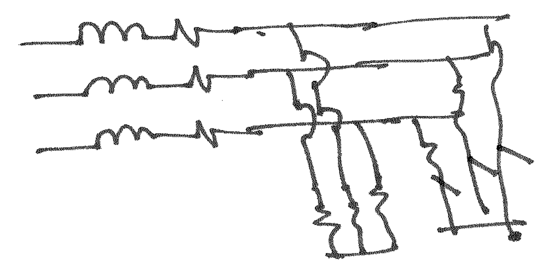
- Forward switch drop: 1 V
- Forward switch resistance: 100 mΩ
- Forward diode drop 2 V
- Forward diode resistance 50 mΩ
- Input capacitor capacitance 590 uF
- Input capacitor resistance 127 uΩ
- Equivalent l-n output capacitance: 150 uF
- Equivalent l-n output capacitor resistance: 2.67 mΩ
- AC inductor inductance: 550 uH
- AC inductor resistance: 38 mW

Sample Study

- DC Source
  - 420 V with 50 uH and 50 mΩ



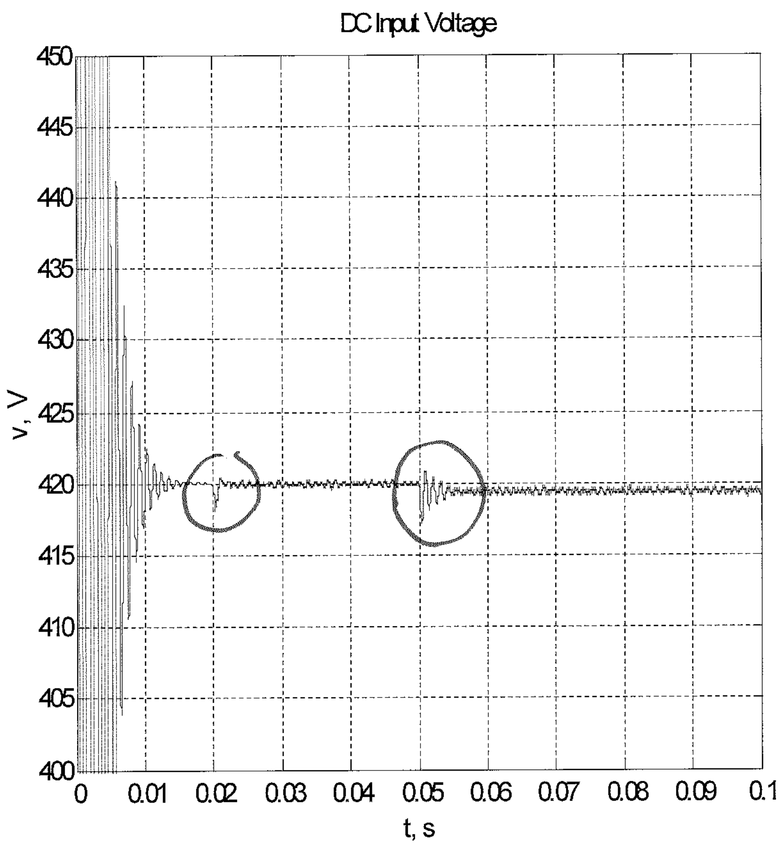
- Loads
  - Cable: 100 mΩ and 0.1 mH impedance
  - Load 1: 105.8 Ω line-to-neutral
  - Load 2: 10.58 Ω line-to-neutral



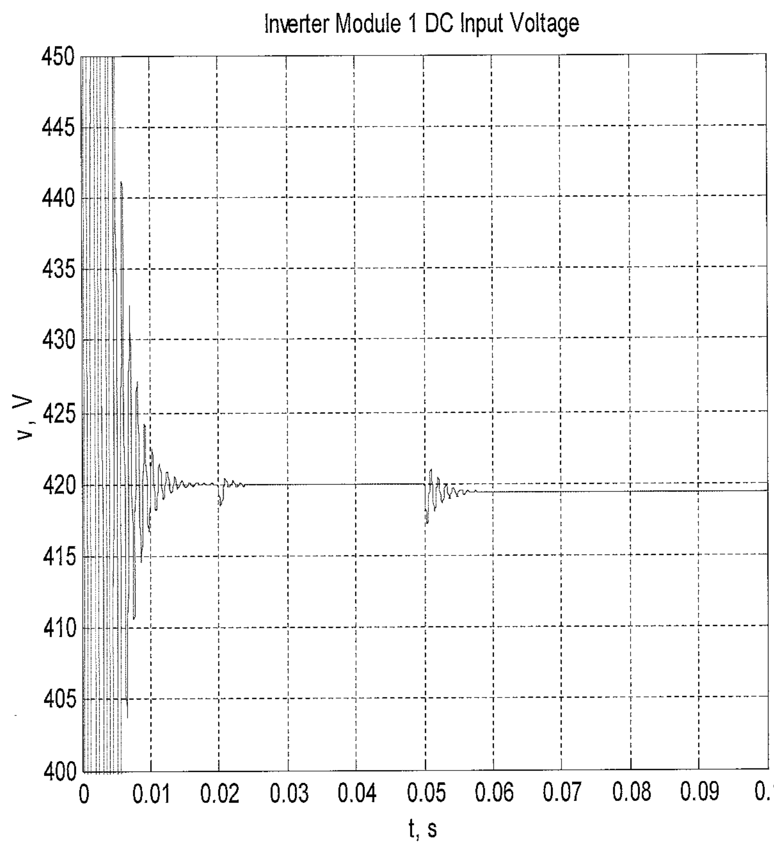
Scenario

- Power connected at t=0
  - Load 1 is initial present
  - Initially device is commanded off
  - Turned on at t=0.02 s
- Load 2 replaces load 1 at t=0.05 s

Input Voltage

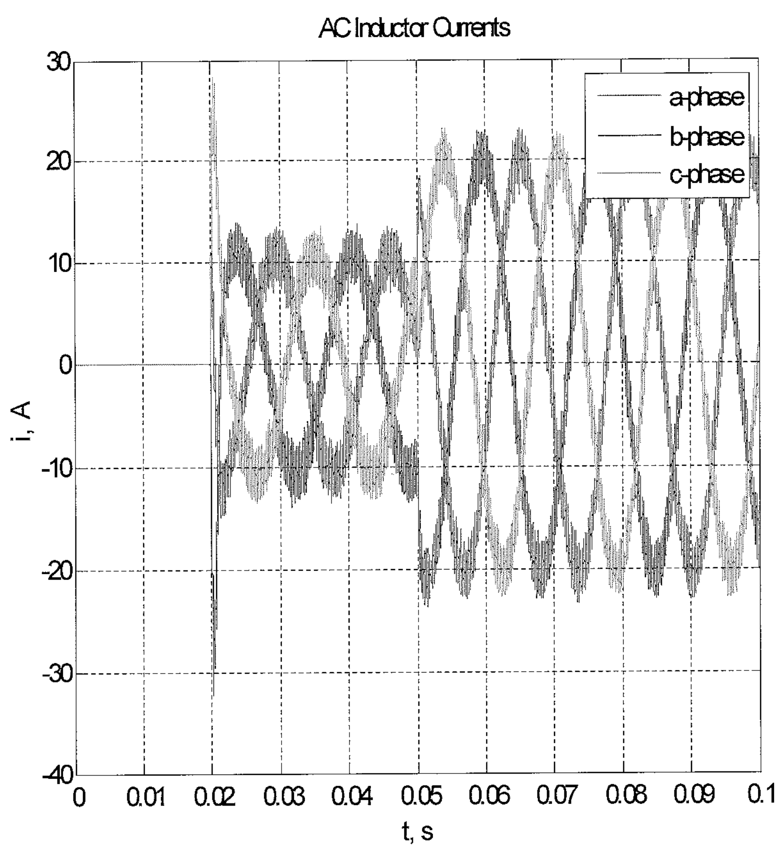


WLM

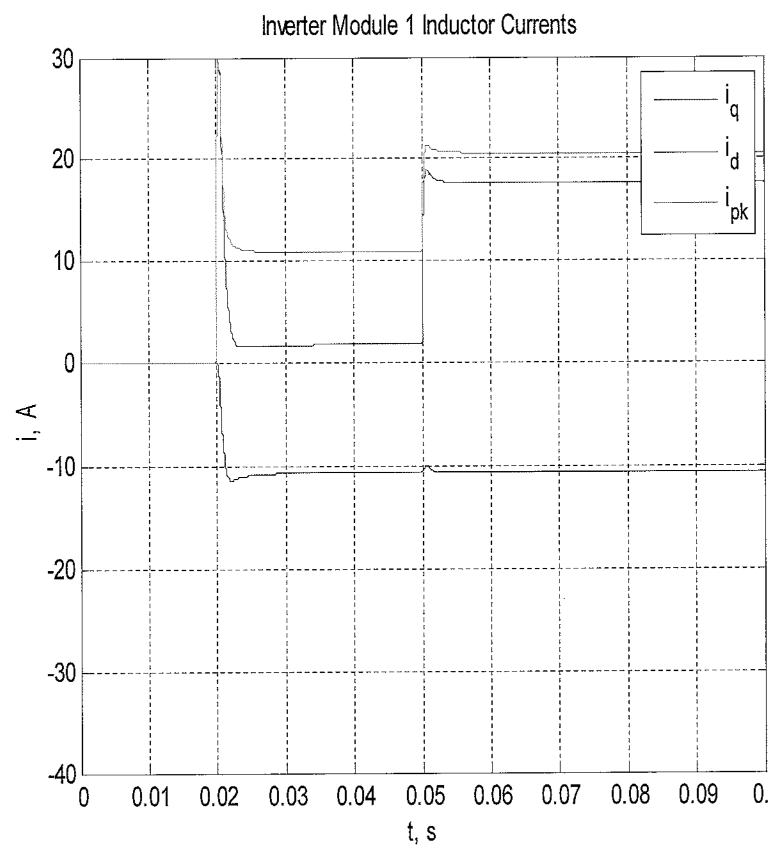


AVM

Inductor Current



WLM



AVM

ECE61016 Power Electronics Converters and Systems

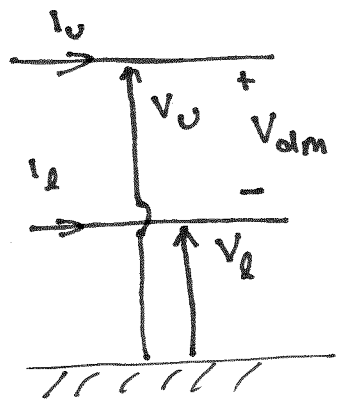
Common Mode Concerns Lecture Set 5

S.D. Sudhoff

Fall 2016

CM and DM Voltages and Currents

- Consider a bus



- Definitions

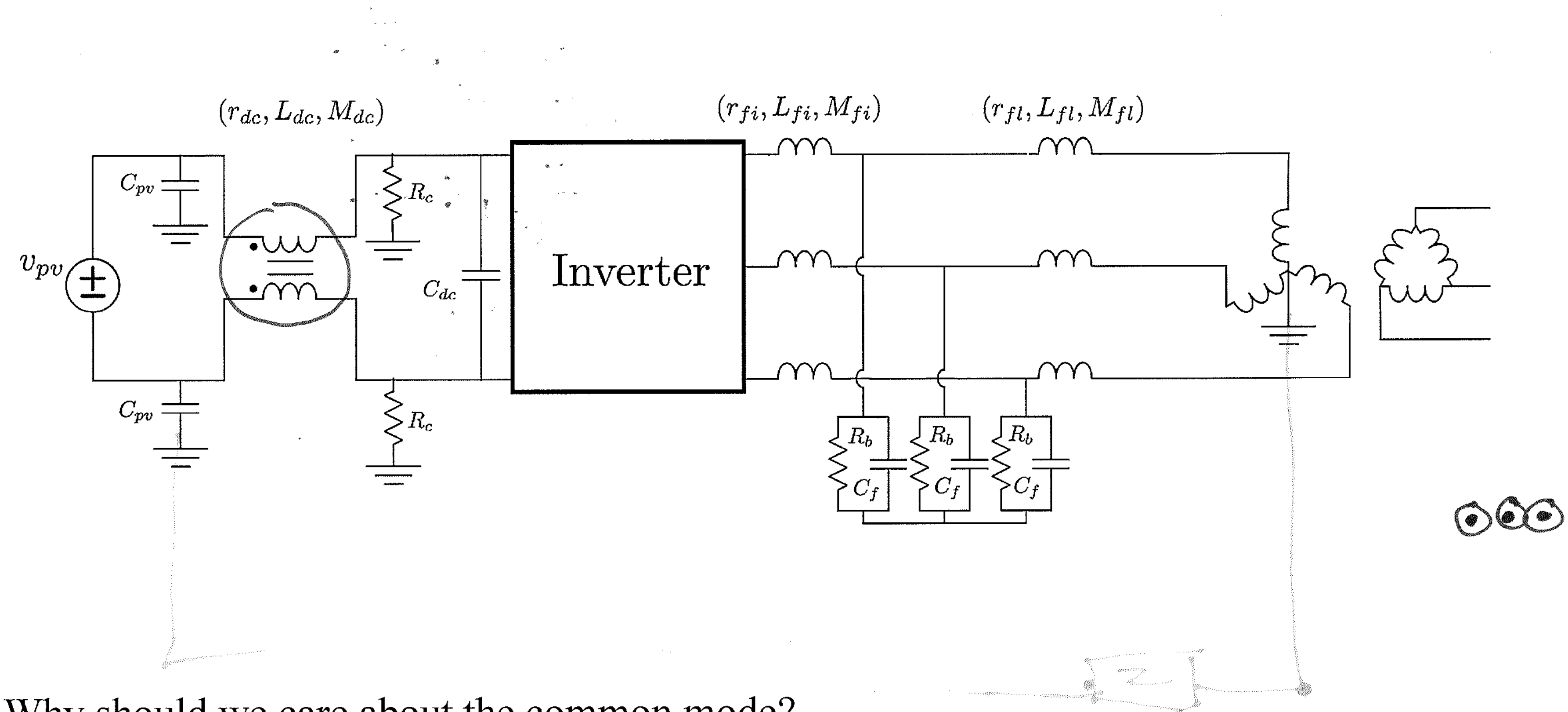
$$i_{dm} = \frac{1}{2}(i_u - i_l)$$

$$i_{cm} = i_u + i_l$$

$$v_{dm} = v_u - v_l$$

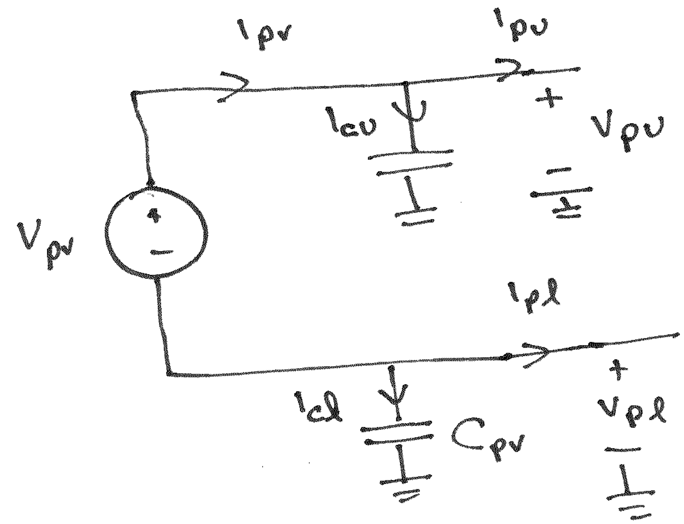
$$v_{cm} = \frac{1}{2}(v_u + v_l)$$

Example: PV Inverter System



Why should we care about the common mode?

Modeling of PV Array



$$I_{cu} = C_{pv} \frac{dV_{pu}}{dt}$$

$$I_{cl} = C_{pv} \frac{dV_{pl}}{dt}$$

$$-V_{pl} - V_{pv} + V_{pu} = 0$$

$$I_{cu} + I_{pv} + I_{cl} + I_{pl} = 0$$

DM Analysis of the PV Array

$$V_{pd} = V_{pu} - V_{pl} = V_{pv}$$

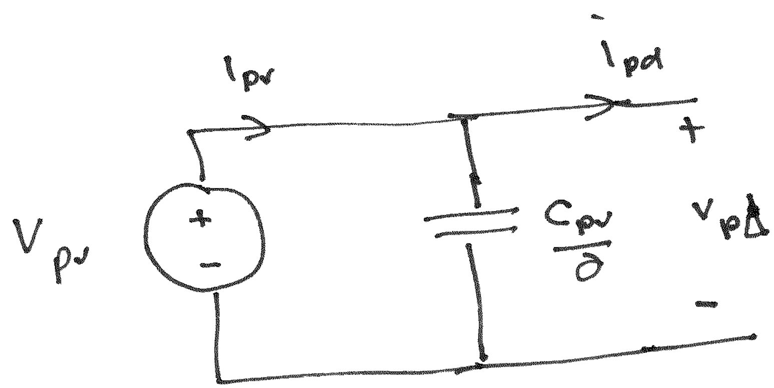
$$I_{pu} = -I_{cu} + I_{pv} = I_{pv} - C_{pv}\, p V_{pu}$$

$$I_{pl} = -I_{cl} - I_{pv} = -I_{pv} - C_{pv}\, p V_{pl}$$

$$I_{pd} = \frac{1}{2}(I_{pu} - I_{pl})$$

$$= \frac{1}{2}\left(I_{pv} - C_{pv}\, p V_{pu} + I_{pv} + C_{pv}\, p V_{pl} \right)$$

$$= I_{pv} - \frac{C_{pv}}{2}\, p\,\underbrace{(V_{pu} - V_{pl})}_{V_{pv}}$$



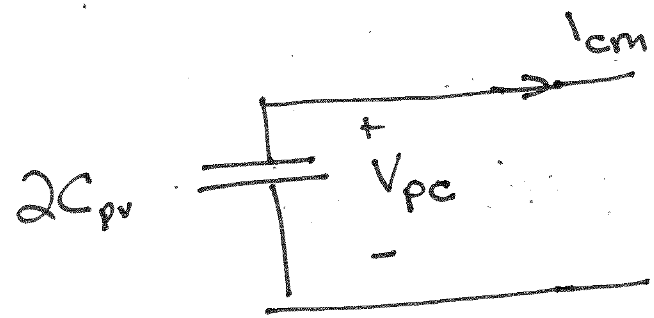
CM Analysis of PV Array

$$i_{cu} = C_{pv}\, p\, V_{pu}$$

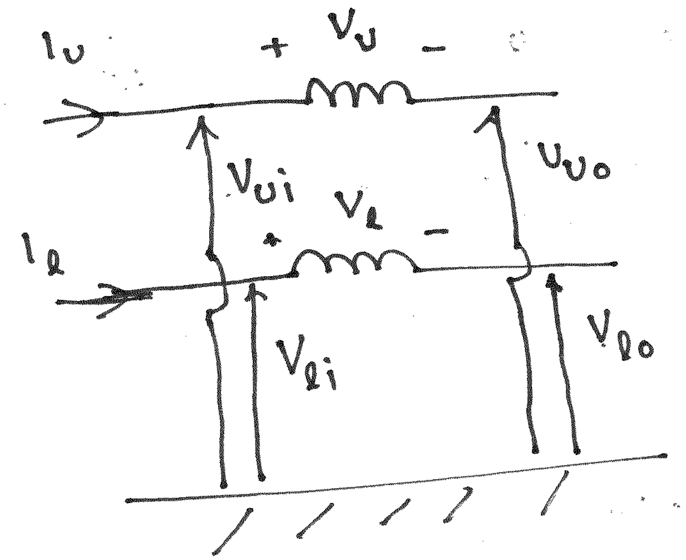
$$V_{pc} = \frac{1}{2}\left(V_{pu} + V_{pl}\right)$$

$$= \frac{1}{2}\left(\frac{i_{cu}}{C_{pv}p} + \frac{i_{cl}}{C_{pv}p}\right)$$

$$2C_{pv}\, p\, V_{pc} = i_{cu} + i_{cl} = -\left(i_{pu} + i_{pl}\right) = -i_{cm}$$



Modeling of DC Side Inductor



$$\begin{bmatrix} \lambda_u \\ \lambda_l \end{bmatrix} = \begin{bmatrix} L & M \\ M & L \end{bmatrix} \begin{bmatrix} i_u \\ i_l \end{bmatrix}$$

$L > 0 \quad M > 0$

M slightly less than L

$$-v_{ui} + v_u + v_{uo} = 0$$

$$-v_{li} + v_l + v_{lo} = 0$$

$$v_u = r\, i_u + p\lambda_u$$

$$v_l = r\, i_l + p\lambda_l$$

DM Analysis of DC Side Inductor

V_{di} = DM voltage on input = $V_{ui} - V_{li}$

V_{do} = DM voltage on output = $V_{uo} - V_{lo}$

$i_d = \frac{1}{2}(i_u - i_l)$

V_d = DM voltage drop across Ind = $V_{di} - V_{do}$

$= V_{ui} - V_{li} - (V_{uo} - V_{lo})$

$= (V_{ui} - V_{uo}) - (V_{li} - V_{lo}) = V_u - V_l$

$= r i_u + p\lambda_u - r i_l - p\lambda_l$

$= r \underbrace{(i_u - i_l)}_{2 i_d} + p(\lambda_u - \lambda_l)$

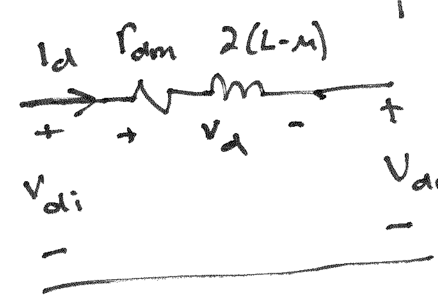
$= \underbrace{2r}_{r_{dm}} i_d + \underbrace{2(L-M)}_{L_{dm}} p\, i_d$

$\lambda_u - \lambda_l$

$= (L-M) i_u + (M-L) i_l$

$= (L-M)(i_u - i_l)$

$= 2(L-M) i_d$



DM Analysis of DC Side Inductor

CM Analysis of DC Side Inductor

CM Analysis of DC Side Inductor

$$V_{ci} = \frac{1}{2}(V_{ui} + V_{li})$$

$$V_{co} = \frac{1}{2}(V_{uo} + V_{lo})$$

$$V_{cm} = V_{ci} - V_{co} = \frac{1}{2}(V_{ui} - V_{uo}) + \frac{1}{2}(V_{li} - V_{lo}) = \frac{1}{2}(V_u + V_l)$$

$$V_u = r\,i_u + p\lambda_u$$

$$V_l = r\,i_l + p\lambda_l$$

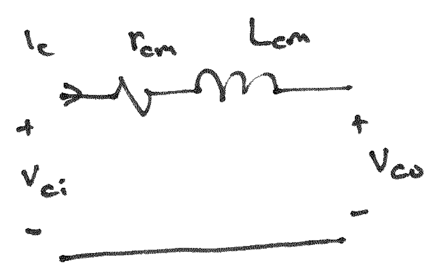
Looking at slide 7

$$\lambda_u + \lambda_l = (L+M)(i_u + i_l) = (L+M)\,i_c$$

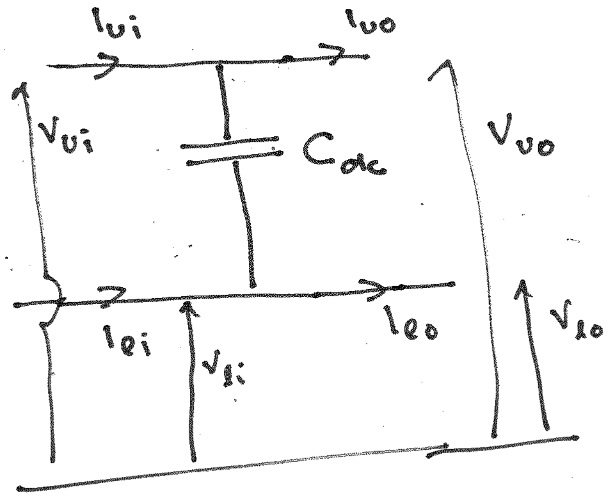
$$V_{cm} = \frac{1}{2}r(i_u + i_l) + \frac{1}{2}p(\lambda_u + \lambda_l)$$

$$= \frac{1}{2}r\,i_c + \frac{1}{2}p(\lambda_u + \lambda_l)$$

$$= \underbrace{\frac{1}{2}r}_{r_{cm}}\,i_c + \underbrace{\frac{1}{2}(L+M)}_{L_{cm}}\,p\,i_c$$



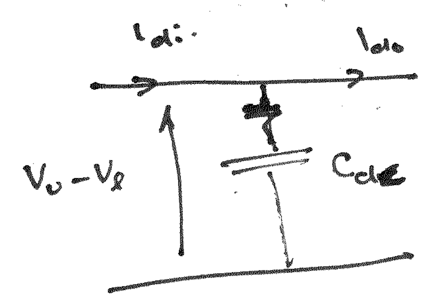
Modeling of DC Side Capacitor



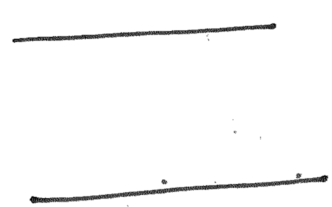
$$V_u = V_{ui} = V_{uo}$$
$$V_l = V_{li} = V_{lo}$$

<u>DM</u>

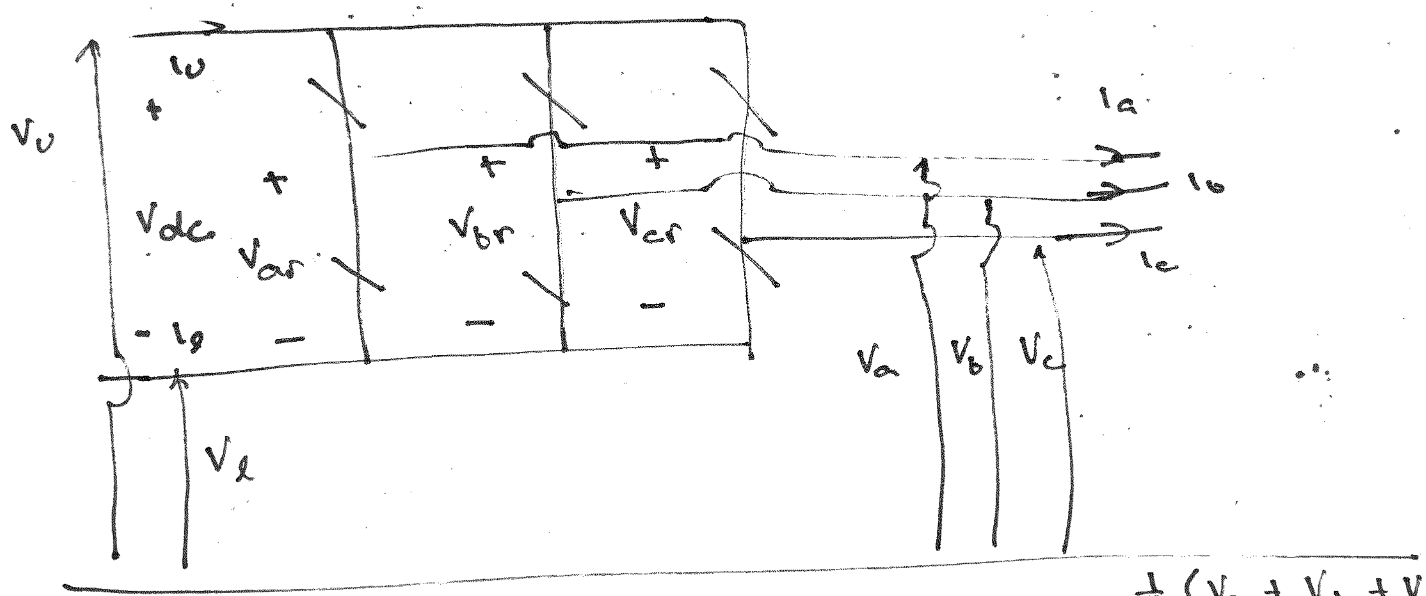
$$C_{dc}\, p\,(V_u - V_l) = i_{ui} - i_{uo} = i_{lo} - i_{li}$$
$$= \tfrac{1}{2}(i_{ui} - i_{uo}) + \tfrac{1}{2}(i_{lo} - i_{li})$$
$$= i_{di} - i_{do}$$



<u>CM</u>



CM Inverter Model



$$V_{cmi} = \frac{1}{2}(V_u + V_\ell)$$

$$i_{cmi} = i_u + i_\ell$$

$$V_{cmo} = \frac{1}{3}(V_a + V_b + V_c)$$

$$i_{cmo} = i_a + i_b + i_c$$

$$i_{cmi} = i_{cmo}$$

CM Inverter Model

$$-V_\ell - V_{ar} + V_a = 0$$

$$-V_\ell - V_{br} + V_b = 0$$

$$-V_\ell - V_{cr} + V_c = 0$$

$$-3V_\ell - (V_{ar} + V_{br} + V_{cr}) + (V_a + V_b + V_c) = 0$$

$$V_{dc} = V_U - V_\ell$$

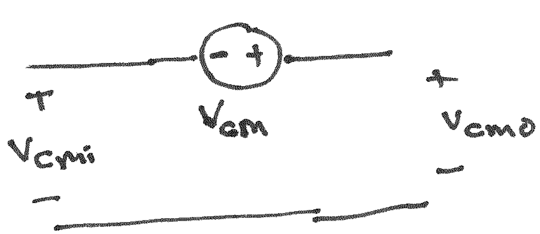
$$V_{dc} + 2V_\ell = V_U + V_\ell = 2V_{ci}$$

$$V_\ell = V_{cmi} - \tfrac{1}{2}V_{dc}$$

$$-3\left(V_{cmi} - \tfrac{1}{2}V_{dc}\right) - (V_{ar} + V_{br} + V_{cr}) + 3V_{cmo} = 0$$

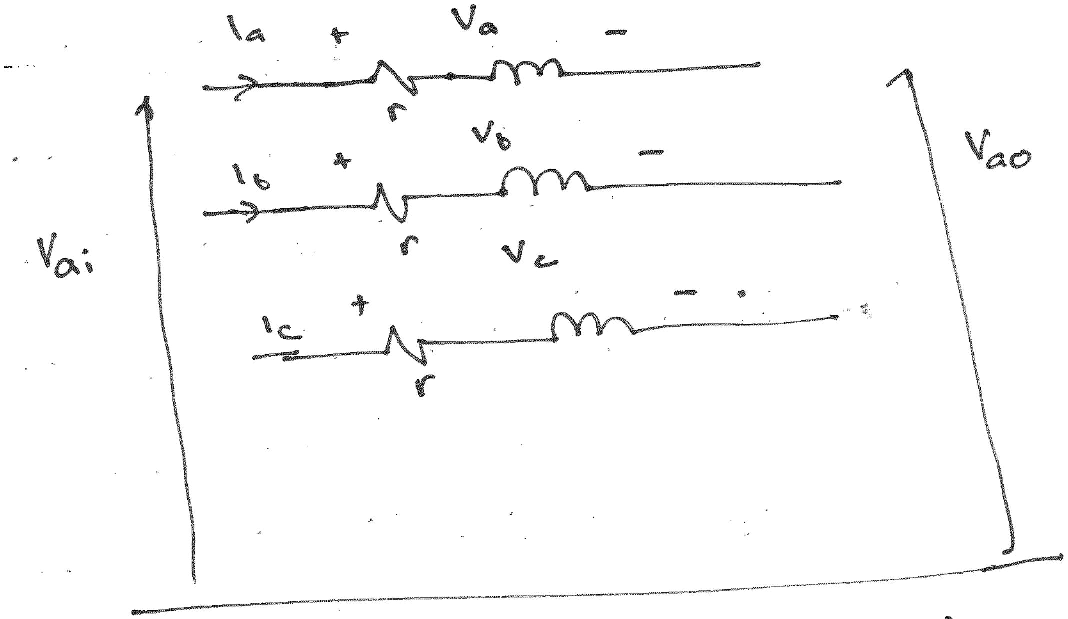
$$-V_{cmi} + \tfrac{1}{2}V_{dc} - \tfrac{1}{3}(V_{ar} + V_{br} + V_{cr}) + V_{cmo} = 0$$

$$V_{cmi} - V_{cmo} = \tfrac{1}{2}V_{dc} - \tfrac{1}{3}(V_{ar} + V_{br} + V_{cr})$$



$$V_{cm} = \tfrac{1}{3}(V_{ar} + V_{br} + V_{cr}) - \tfrac{1}{2}V_{dc}$$

Modeling of a Three-Phase Inductor



$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} = \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\lambda_a + \lambda_b + \lambda_c = (L+2M)(i_a + i_b + i_c)$$

$$= (L+2M)\, i_{cm}$$

$$V_{cmi} = \frac{1}{3}(V_{ai} + V_{bi} + V_{ci})$$

$$V_{cmo} = \frac{1}{3}(V_{ao} + V_{bo} + V_{co})$$

$$V_{cm} = V_{cmi} - V_{cmo}$$

$$= \frac{1}{3}(V_{ai} - V_{ao}) + \frac{1}{3}(V_{bi} - V_{bo}) + \frac{1}{3}(V_{ci} - V_{co})$$

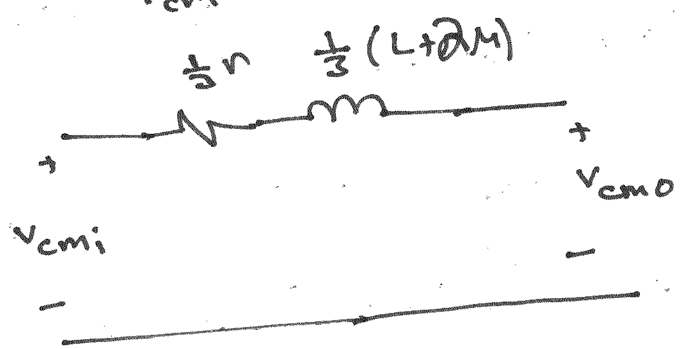
$$= \frac{1}{3}(V_a + V_b + V_c)$$

Modeling of a Three-Phase Inductor

$$V_a = r\, i_a + p\lambda_a$$
$$V_b = r\, i_b + p\lambda_b$$
$$V_c = r\, i_c + p\lambda_c$$

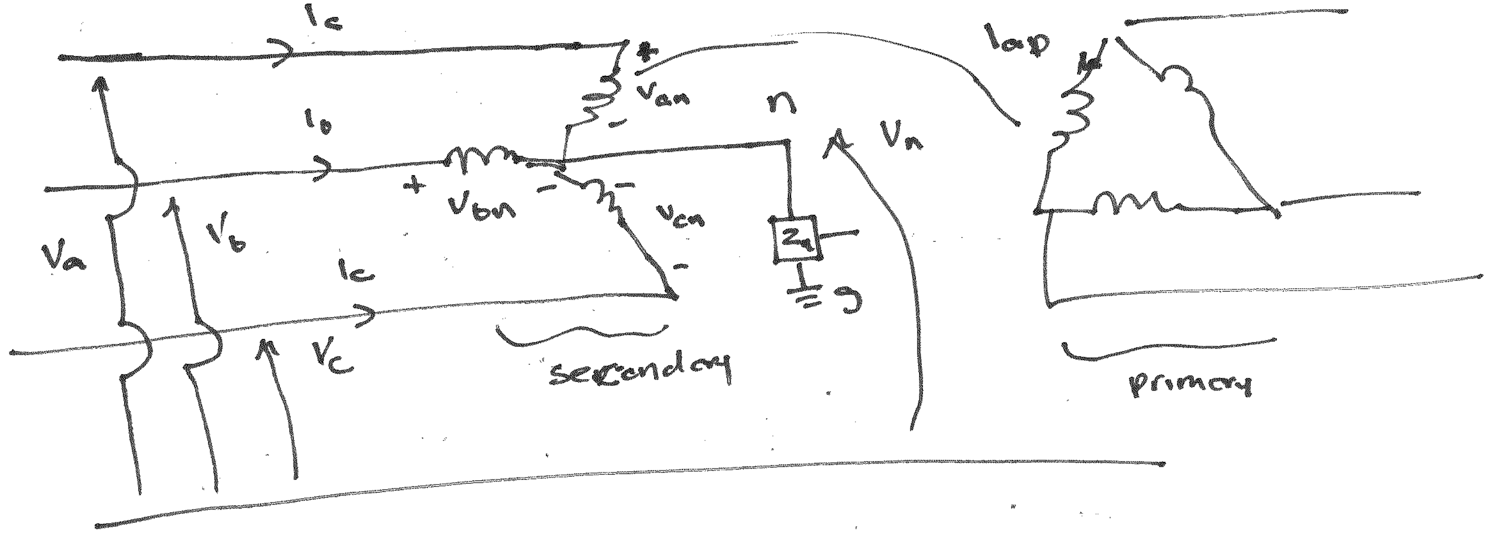
$$3V_{cm} = V_a + V_b + V_c = r\underbrace{(i_a + i_b + i_c)}_{i_{cm}} + p(\lambda_a + \lambda_b + \lambda_c)$$

$$V_{cm} = \frac{1}{3} r\, i_{cm} + \frac{1}{3} p(\lambda_a + \lambda_b + \lambda_c)$$
$$= \underbrace{\frac{1}{3} r}_{r_{cm}}\, i_{cm} + \underbrace{\frac{1}{3}(L + 2M)}_{L_{cm}}\, p\, i_{cm}$$



$$L = L_{\ell s} + L_m$$
$$M = -\frac{1}{2} L_m$$
$$\frac{1}{3}(L + 2M) = \frac{1}{3} L_{\ell s}$$

Modeling the Utility Connection



$$-V_a + V_{an} + V_n = 0$$

$$-V_b + V_{bn} + V_n = 0$$

$$-V_c + V_{cn} + V_n = 0$$

$$-(V_a + V_b + V_c) + (V_{an} + V_{bn} + V_{cn}) + 3V_n = 0$$

$$-3V_{cmi} + (V_{an} + V_{bn} + V_{cn}) + 3V_n = 0$$

Modeling the Utility Connection

$$V_{an} = r\, i_a + p\lambda_{as} \quad \text{— secondary}$$

$$V_{bn} = r\, i_b + p\lambda_{bs}$$

$$V_{cn} = r\, i_c + p\lambda_{cs}$$

$$V_{an} + V_{bn} + V_{cn} = r\, i_{cm} + p(\lambda_{as} + \lambda_{bs} + \lambda_{cs})$$

$$\lambda_{abcs} = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} i_{abc}$$

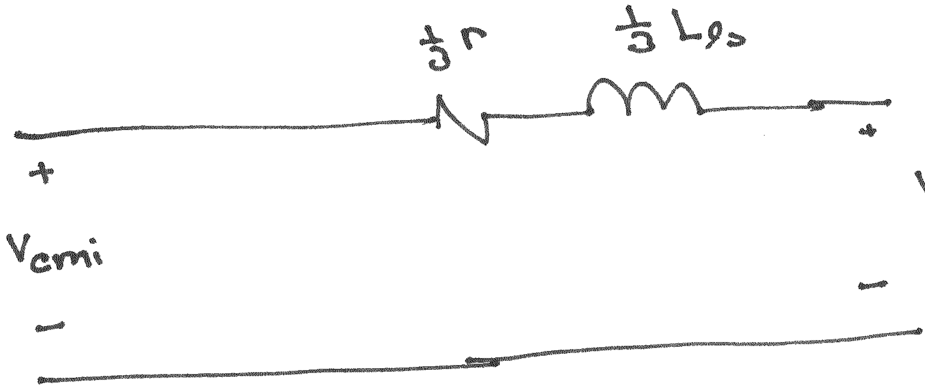
$$+ \begin{bmatrix} L_{ps} & -\frac{1}{2}L_{ps} & -\frac{1}{2}L_{ps} \\ -\frac{1}{2}L_{ps} & L_{ps} & -\frac{1}{2}L_{ps} \\ -\frac{1}{2}L_{ps} & -\frac{1}{2}L_{ps} & L_{ps} \end{bmatrix} i_{abcp}$$

$$\lambda_{as} + \lambda_{bs} + \lambda_{cs} = L_{ls}(i_a + i_b + i_c) = L_{ls}\, i_{cm}$$

$$V_{an} + V_{bn} + V_{cn} = r\, i_{cm} + L_{ls}\, p\, i_{cm}$$

$$-3V_{cmi} + r i_{cm} + L_{ls} p i_{cm} + 3v_n$$

$$V_{cmi} = \tfrac{1}{3} r i_{cm} + \tfrac{1}{3} L_{ls} p i_{cm} + V_n$$

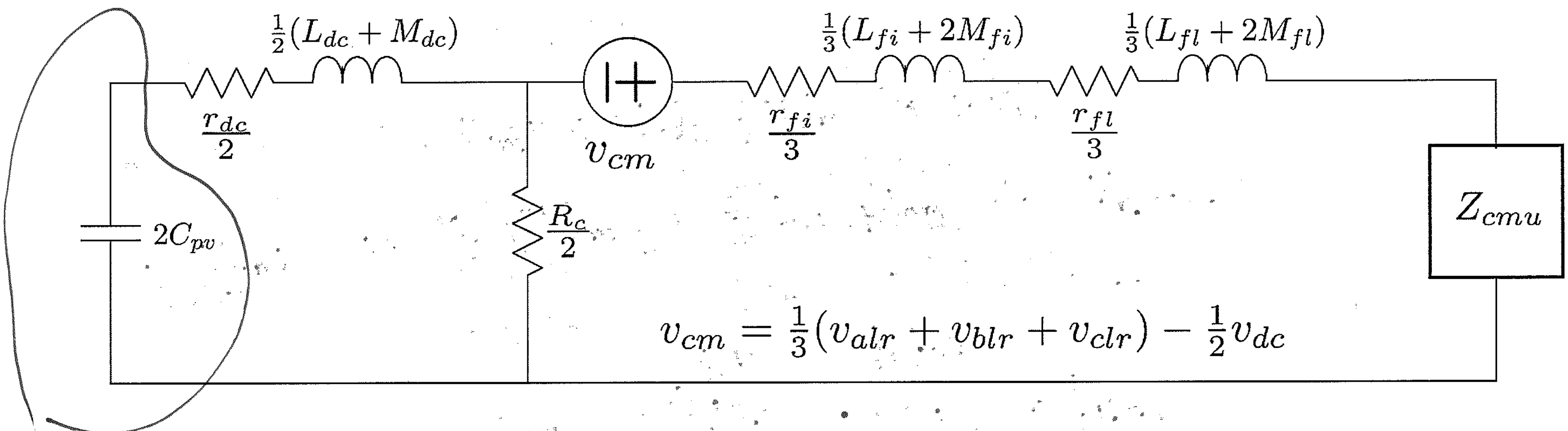


V_n → relative to my point of ref.

If I pick my reference to be the ground at PP array

$$V_n = Z_n i_{cm}$$

PV Inverter Equivalent Circuit



$$v_{cm} = \frac{1}{3}\left(v_{alr} + v_{blr} + v_{clr}\right) - \frac{1}{2}v_{dc}$$

The common mode load impedance is unknown. The quantity is C_{pv} is also unknown, but we can guarantee a minimum value by adding some.

Simplifying the CM equiv. circuit

- Assumptions:
  - Ignore R_c
  - Common mode ~~load~~ utility impedance is RL (neutral of transformer directly connected to ground)
- Define

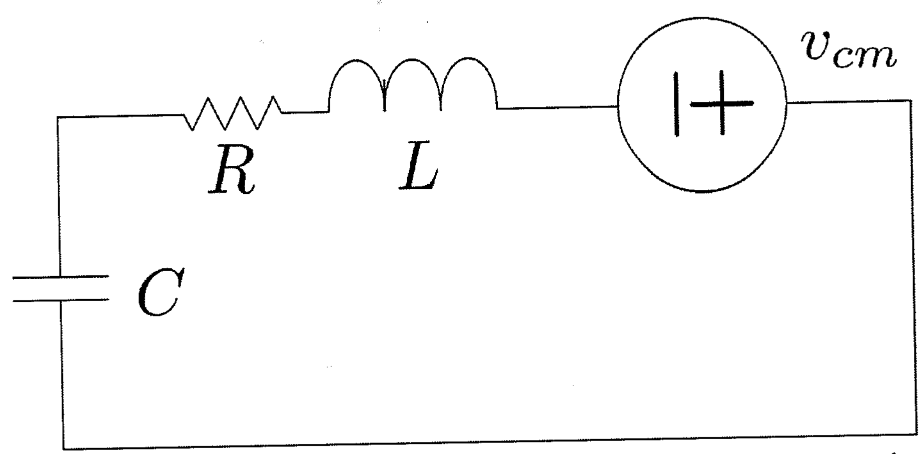
$$Z_{cmu} = r_{cmu} + j\omega L_{cmu}$$

$$L = \frac{1}{2}(L_{dc} + M_{dc}) + \frac{1}{3}(L_{fi} + 2M_{fi}) + \frac{1}{3}(L_{fl} + 2M_{fl}) + L_{cmu}$$

$$R = \frac{1}{2} r_{dc} + \frac{1}{3} r_{fi} + \frac{1}{3} r_{fl} + r_{cmu}$$

$$C = 2C_{pv}$$

Simplified Common Mode Equivalent Circuit



$$v_{cm} = \frac{1}{3}\left(v_{alr} + v_{blr} + v_{clr}\right) - \frac{1}{2}v_{dc}$$

DC Side Common Mode Inductor

- Step 1: Strategy for common mode current mitigation
- Step 2: Develop common mode inductor design specifications
- Step 3: Design methodology for inductor

Step 1: Common Mode Current

- The common mode current at a given frequency is given by

$$Z = R + j\omega L + \frac{1}{j\omega C}$$

$$\tilde{i}_{cm} = \frac{\tilde{v}_{cm}}{Z}$$

- So

$$\left|\tilde{i}_{cm}\right| = \frac{\left|\tilde{v}_{cm}\right|}{\sqrt{R^2 + \left|\omega L - \frac{1}{\omega C}\right|^2}} \le \frac{\left|\tilde{v}_{cm}\right|}{\left|\omega L - \frac{1}{\omega C}\right|}$$

$$\omega L \gg \frac{1}{\omega C}$$

$$C \gg \frac{1}{\omega^2 L}$$

Step 1: Strategy

- We must avoid resonances. Therefore we require

$$C >> \frac{1}{\omega_{sw}^2 L}$$

- This can be assured if

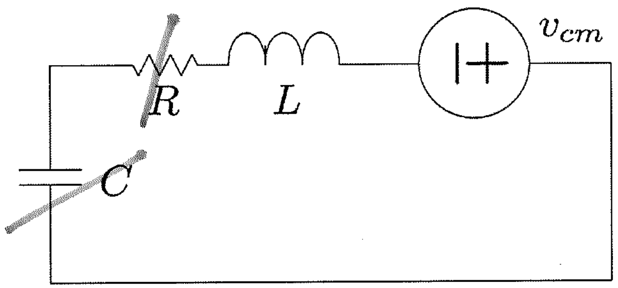
$$C_{pv} >> \frac{1}{2\omega_{sw}^2 L}$$

- Thus we will take (for example)

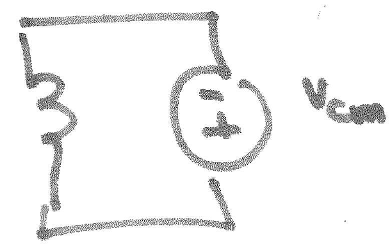
$$L = \frac{1}{2}(L_{dc} + M_{dc}) = L_{cm}$$

$$C_{pv} = \frac{5}{\omega_{sw}^2 L_{cm}}$$

Further Reduced CM Equivalent Circuit



$$v_{cm} = \frac{1}{3}(v_{alr} + v_{blr} + v_{clr}) - \frac{1}{2}v_{dc}$$



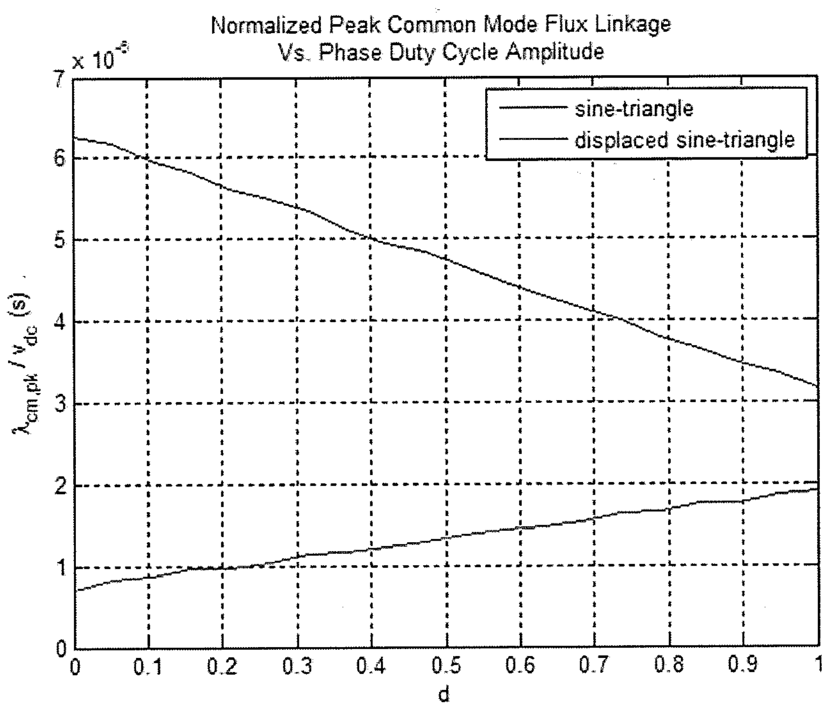
Common Mode Flux Linkage

$$p\,\lambda_{cm} = v_{cm} - r\,i_{cm}$$

$$\lambda_{cm} = L\,i_{cm}$$

Step 1: Common Mode Flux Linkage

Peak common mode flux linkage / V_{dc}



amplitude of the phase duty cycle

- For sine-triangle modulation, the peak flux linkage goes down with duty cycle.
- Let's assume a duty cycle amplitude of d=0.627, which is 80% of the value corresponding to 480 V at the terminals

Step 1: Numbers Check

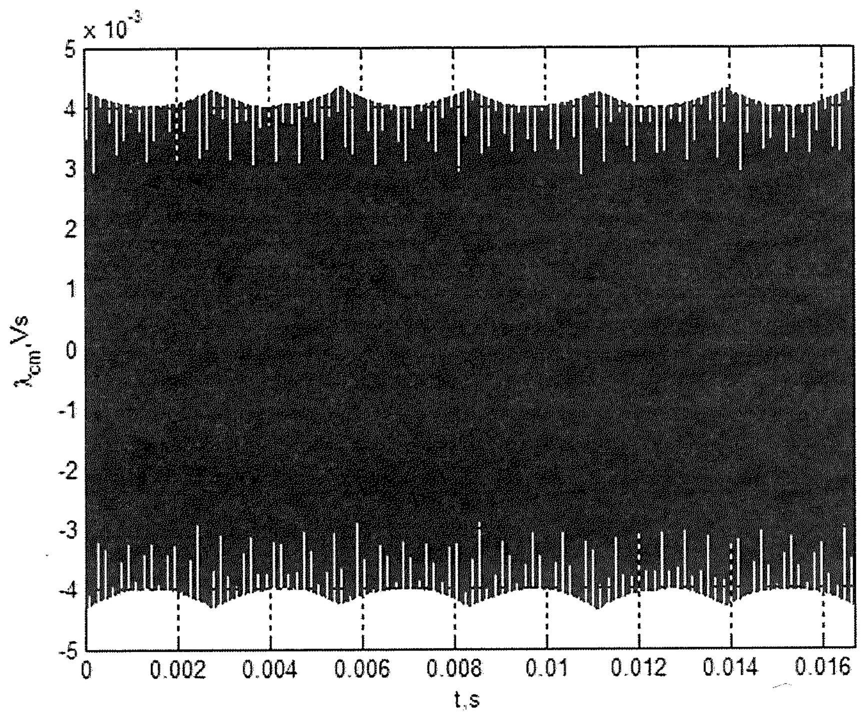
- Case 1
  - Peak common mode current = 120 mA
  - Switching at 20 kHz
  - $L_{cm} = (L_{dc} + M_{dc}) / 2 = 36$ mH
  - Required $C_{pv} = 8.8$ nF

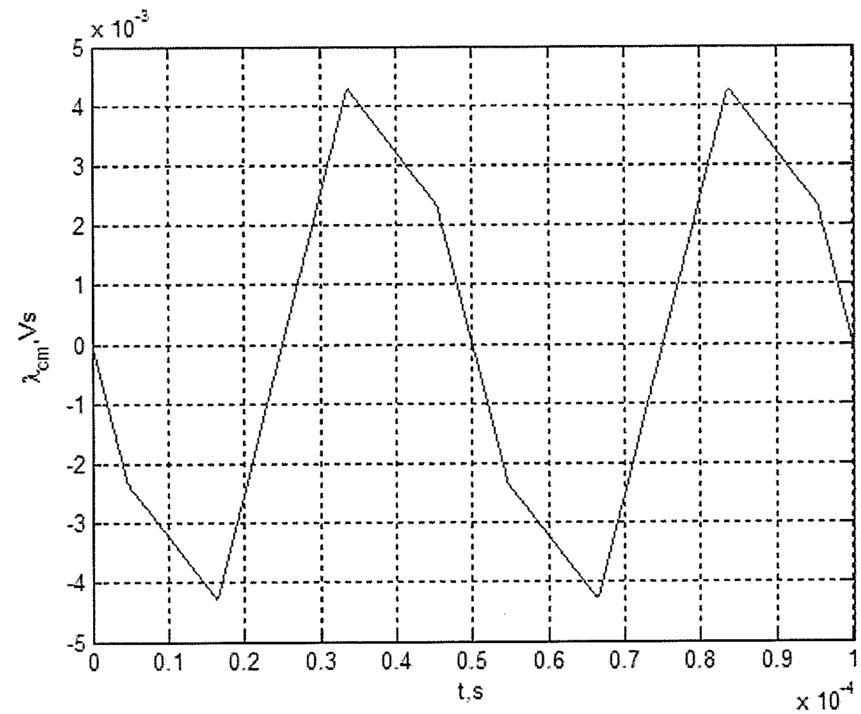
- Case 2
  - Peak common mode current = 120 mA
  - Switching at 50 kHz
  - $L_{cm} = (L_{dc} + M_{dc}) / 2 = 14$ mH
  - Required $C_{pv} = 3.6$ nF

- Conclusion: it won't take much C to make approach valid

- Suggestion: we will add the required capacitance and not rely on parasitics

Step 1: Common Mode Flux Linkage at d = 0.627





Step 2: Setting Up Design Problem

- Problem
  - Waveforms are quasi a-periodic
  - Slowly vary amplitude and shape

- Solution – Define a proxy flux linkage waveform
  - Same peak value (saturation)
  - Same rms value (resistive loss)
  - Time derivative has same rms value as the original waveform (proximity effect loss)

Approach to Fitting

$$\lambda_p = a_1 \cos(\omega_{sw} t) + a_3 \cos(3\omega_{sw} t) + b_3 \sin(3\omega_{sw} t)$$

Find

$\lambda_{p,pk}$

$\lambda_{p,rms}$

$\left(\left(\frac{d\lambda_p}{dt}\right)^2\right)_{rms}$

$$\omega_{sw} = 2\pi f_{sw}$$

$$Error = \sqrt{(\lambda_{p,pk} - \lambda_{cm,pk})^2 + (\lambda_{p,rms} - \lambda_{cm,rms})^2 + \frac{1}{\omega_{sw}^4}\left(\left(\left(\frac{d\lambda_p}{dt}\right)^2\right)_{rms} - \left(\left(\frac{d\lambda_{cm}}{dt}\right)^2\right)_{rms}\right)^2}$$

$$fit = \frac{1}{Error + \_\_}$$

Approach to Fitting

Step 2: Proxy CM Flux Linkage Waveform