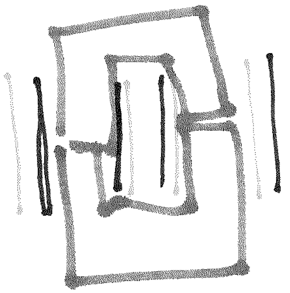
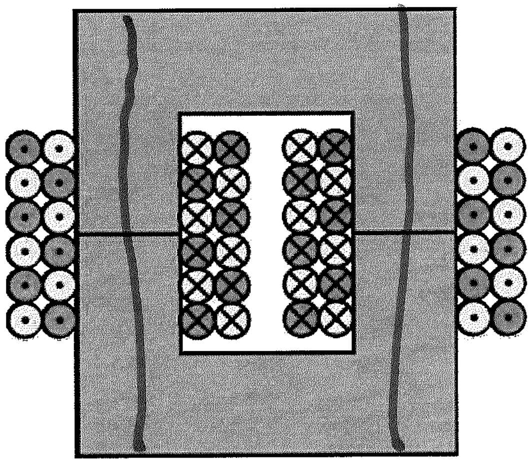
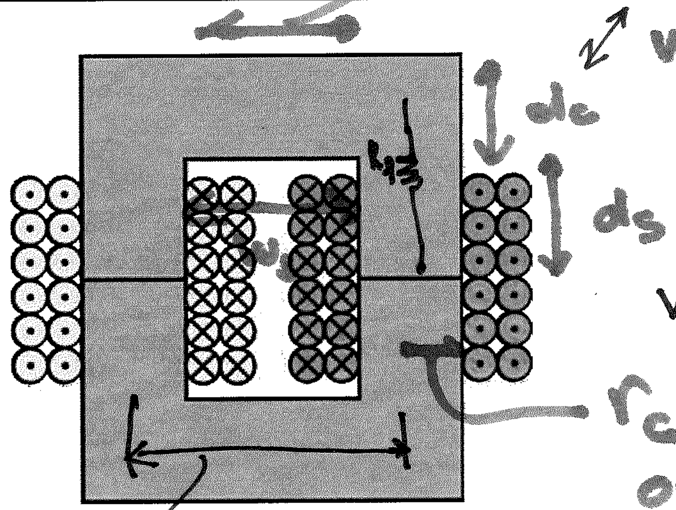
Step 3: CM Inductor Design





Configuration 1



W_c = width of core

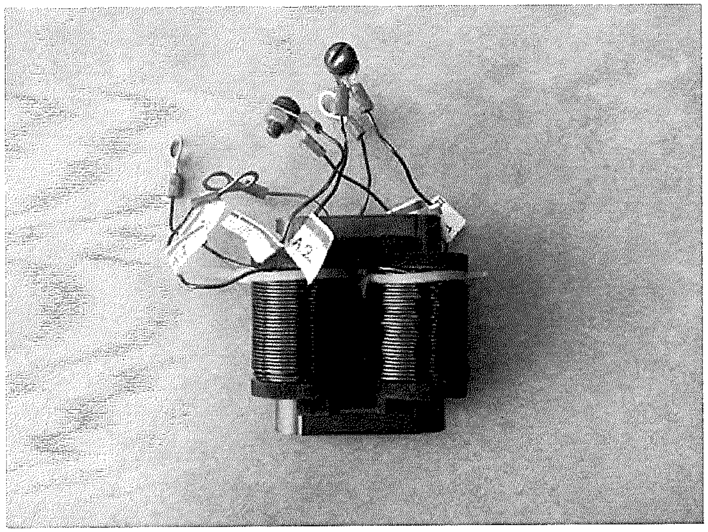
$W_c = 2r_c$

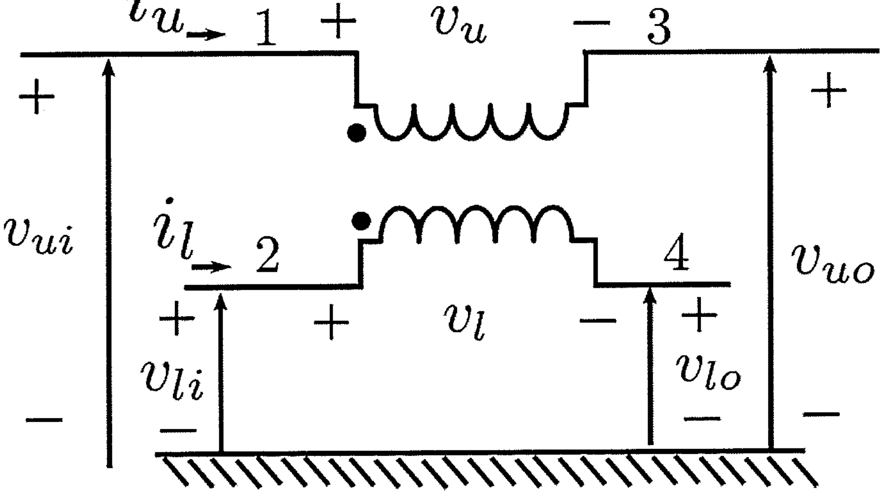
r_c radius of core

Configuration 2

$l_{cc} = 2r_c + w_s$

r_h = radius of the hole

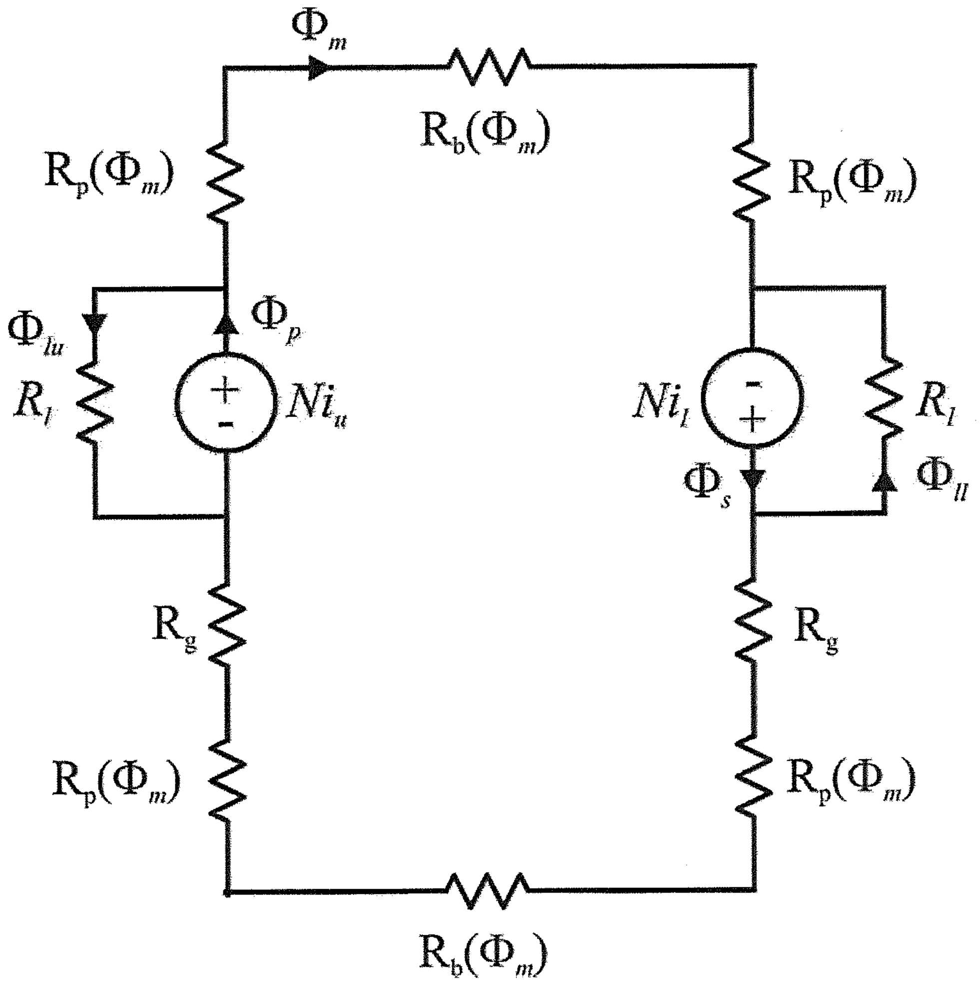


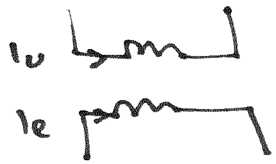


Step 3: DC Common Mode Inductor Design

- Magnetics: MEC
- Losses
  - Conductor
    - DC (high)
    - Skin Effect (high R; low loss)
    - Proximity Effect (high R, low loss)
  - Core
    - Hysteresis (high)
    - Eddy (high)
- Thermal: TEC

Step 3: Magnetic Analysis





$\hat{R}_p$

$$R_p = \frac{d_s + d_c/2}{\pi(r_c^2 - r_h^2)\mu_B(B_p)}$$

$$B_p = \frac{\Phi_m}{\pi(r_c^2 - r_h^2)}$$

$$R_p = \frac{\hat{R}_p}{\mu_B(B_p)}$$

$\hat{R}_b$

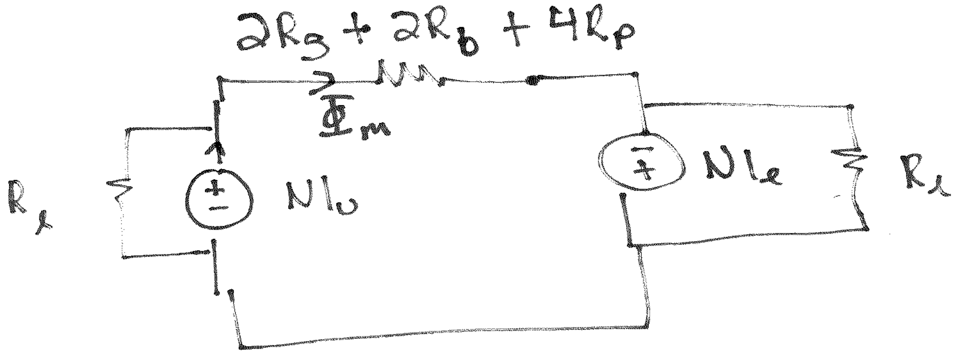
$$R_b = \frac{l_{cc}}{d_c w_c \mu_B(B_b)}$$

$$B_b = \frac{\Phi_m}{d_c w_c}$$

$$R_b = \frac{\hat{R}_b}{\mu_B(B_b)}$$

$$R_g = \frac{g}{\pi(r_c^2 - r_h^2)\mu_0}$$

Step 3: Magnetic Analysis



$$\Phi_m = \frac{N I_u + N I_\ell}{2R_g + 2R_b + 4R_p} = \frac{N I_{cm}}{2R_g + 2R_b + 4R_p}$$

$$\lambda_u = N \Phi_m + \frac{N^2 I_u}{R_\ell}$$

$$\lambda_\ell = N \Phi_m + \frac{N^2 I_\ell}{R_\ell}$$

$$\lambda_{cm} = \frac{1}{2}(\lambda_u + \lambda_u) = N \Phi_m + \frac{1}{2}\frac{N^2}{R_\ell}(\overbrace{I_u + I_\ell}^{I_{cm}})$$

$$R_\ell \lambda_{cm}/N = R_\ell \Phi_m + \frac{1}{2} N I_{cm}$$

$$R_\ell \lambda_{cm}/N = R_\ell \Phi_m + \Phi_m \left[R_g + R_b + 2R_p \right]$$

Step 3: Magnetic Analysis

Define $F_{eq} = R_e \lambda_{cm} / N$

$$f = \Phi_m \left[R_e + R_g + R_b + 2R_p \right] - F_{eq}$$

$$f' = \frac{\partial f}{\partial \Phi_m} = R_e + R_g + R_b \Big|_{B_b} + 2R_p \Big|_{B_p}$$

$$+ \Phi_m \left[- \frac{\hat{R}_b}{\mu_B^2 \left(\frac{\Phi_m}{d_c w_c} \right)} \frac{\partial \mu_B}{\partial B} \Big|_{B_b} \cancel{\frac{\partial B}{\partial \Phi_m}} \rightarrow \frac{1}{d_c w_c} \right.$$

$$\left. - \frac{2\hat{R}_p}{\mu_B^2 \left(\frac{\Phi_m}{\pi (r_c^2 - r_n^2)} \right)} \frac{\partial \mu_B}{\partial B} \Big|_{B_p} \cancel{\frac{\partial B}{\partial \Phi_m}} \rightarrow \frac{1}{\pi (r_c^2 - r_n^2)} \right]$$

Aside

$$R_b = \frac{\hat{R}_b}{\mu_B \left(\frac{\Phi_m}{d_c w_c} \right)}$$

For ~~eve~~ a given Φ_m (an estimate)

$$\Phi_m \Big|_{\text{improved}} = \Phi_m \Big|_{\text{old}} - \frac{f}{f'} \Big|_{\text{old}}$$

} iterate to find Φ_m

Gives us Φ_m waveform

B_p B_b

Step 3: Magnetic Analysis

Find Φ_m

Find B_p

Find B_b

$$I_{cm} = \frac{1}{N}\Phi_m\left[2R_g + 2R_b + 4R_p\right]$$

Step 3: Core Loss – MSE Model

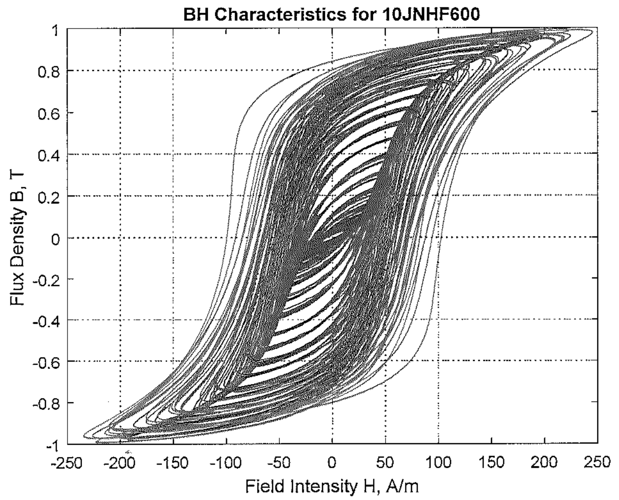
$$B_b = 1\ T$$

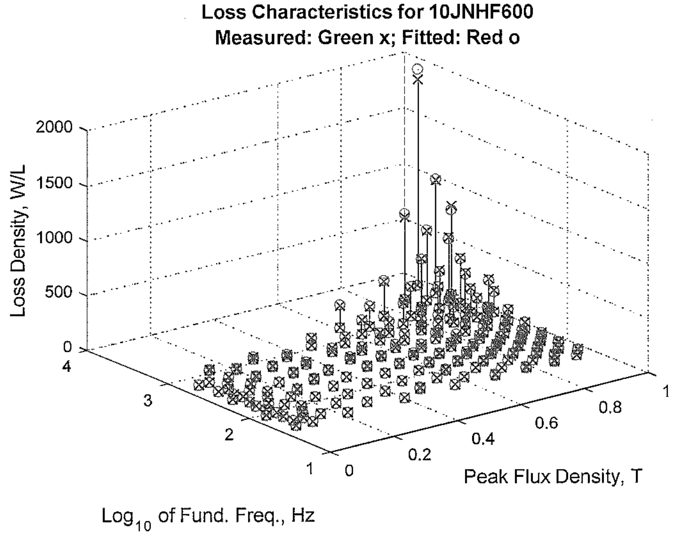
$$f_b = 1\ Hz$$

$$\Delta B = B_{\max} - B_{\min}$$

$$f_{eq} = \frac{2}{\Delta B^2 \pi^2} \int_0^T \left(\frac{dB}{dt} \right)^2 dt$$

$$P_{ld} = \underbrace{k_h \left(\frac{f_{eq}}{f_b} \right)^{\alpha - 1} \left(\frac{B_{\max}}{B_b} \right)^{\beta} f}_{Hysteresis\ Loss} + \underbrace{\frac{k_e f}{B_b^2} \int_0^T \left(\frac{dB}{dt} \right)^2 dt}_{Eddy\ Current\ Loss}$$


BH Characteristics for 10JNHF600

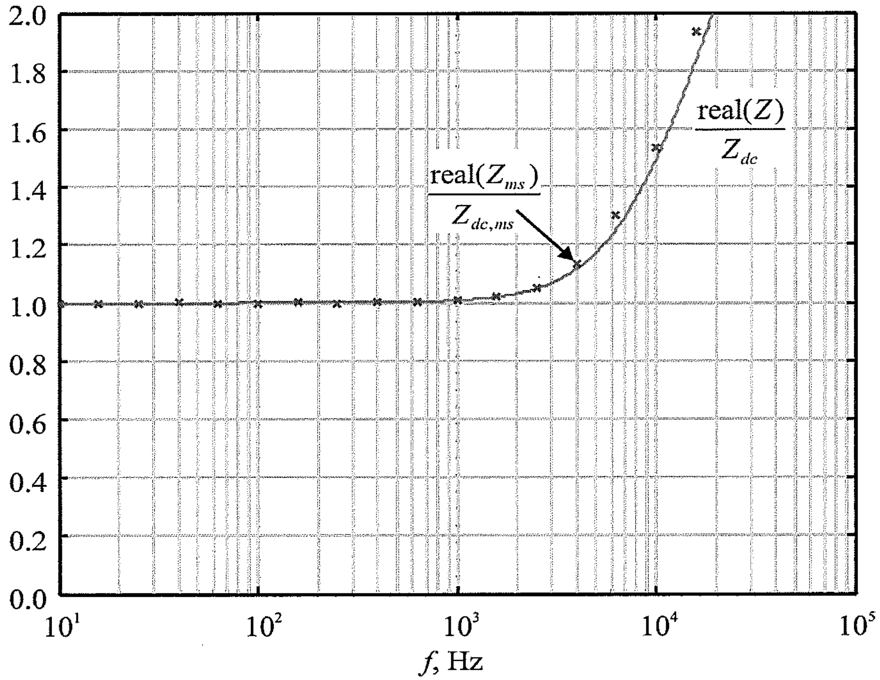

Loss Characteristics for 10JNHF600
Measured: Green x; Fitted: Red o

Step 3: Skin Effect Loss

- Algorithmically

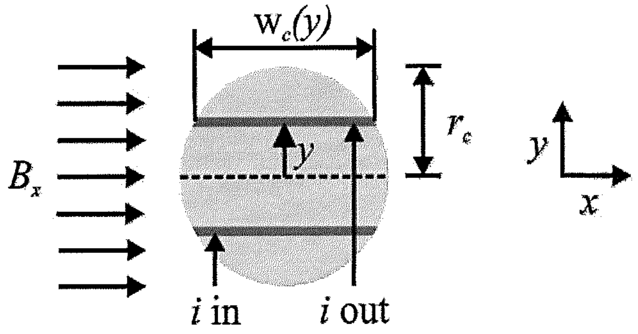
$$\kappa = \sqrt{\frac{j}{\omega\sigma\mu}}$$

$$Z = -\frac{l\,\mathrm{J}_B(R/\kappa)}{2\pi R\kappa\sigma\,\mathrm{J}_B^{'}(R/\kappa)}$$



Step 3: Proximity Effect Loss

$$\overline{p} = \frac{\pi}{4}\sigma r_c^4 l_c \frac{1}{T}\int_0^T \left(\frac{dB_p}{dt}\right)^2 dt$$

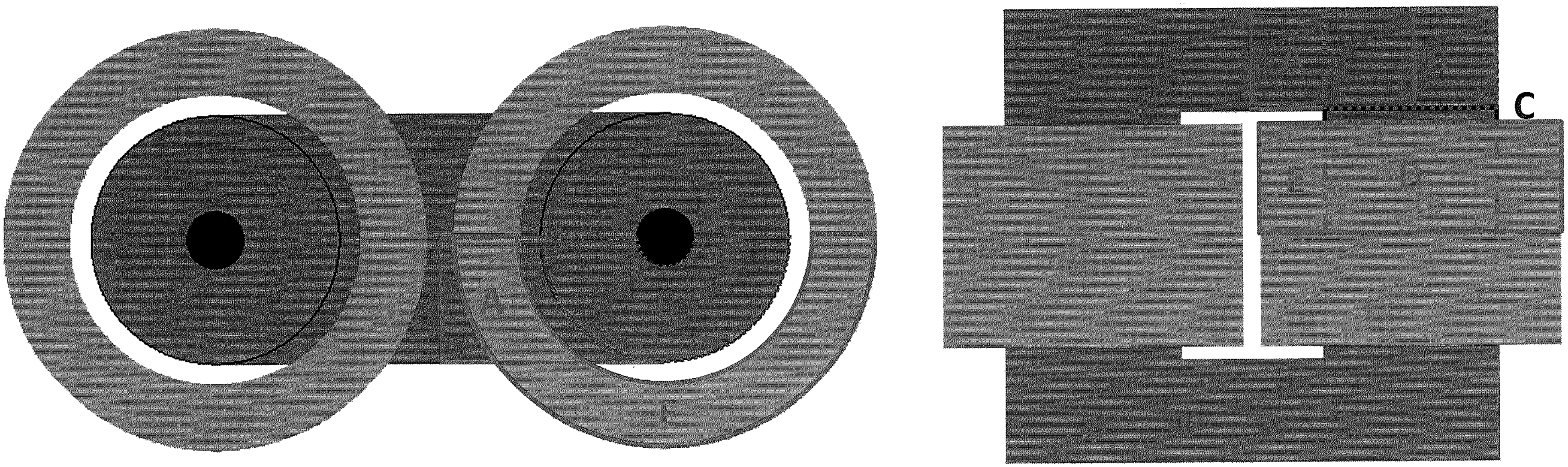


$$c_{xwr} = c_{ywr} = \frac{\pi}{4}\sigma r_{cw}^4 l_{cr}$$

$$\overline{P}_{pwr} = \left|N_w\right|_r c_{xwr} \left\langle \overline{\left(\frac{dB_x}{dt}\right)^2} \right\rangle_r + \left|N_w\right|_r c_{ywr} \left\langle \overline{\left(\frac{dB_y}{dt}\right)^2} \right\rangle_r$$

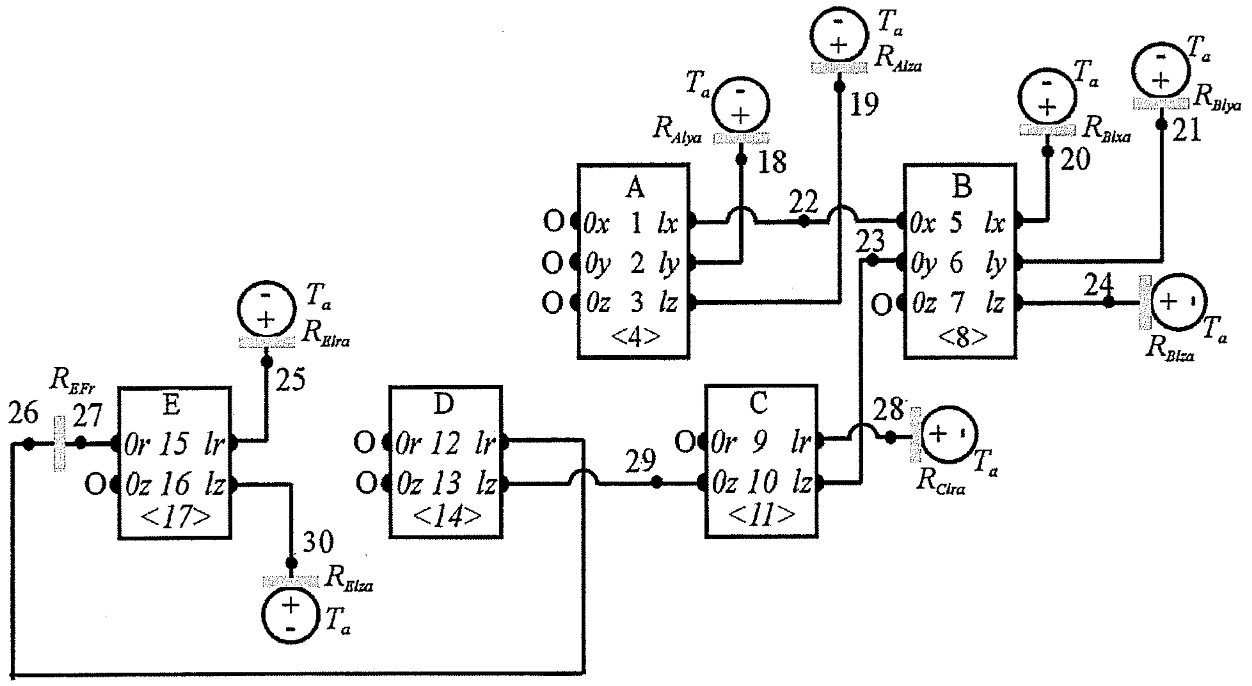
Step 3: DC Inductor Thermal Model

- Regions of thermal equivalent circuit



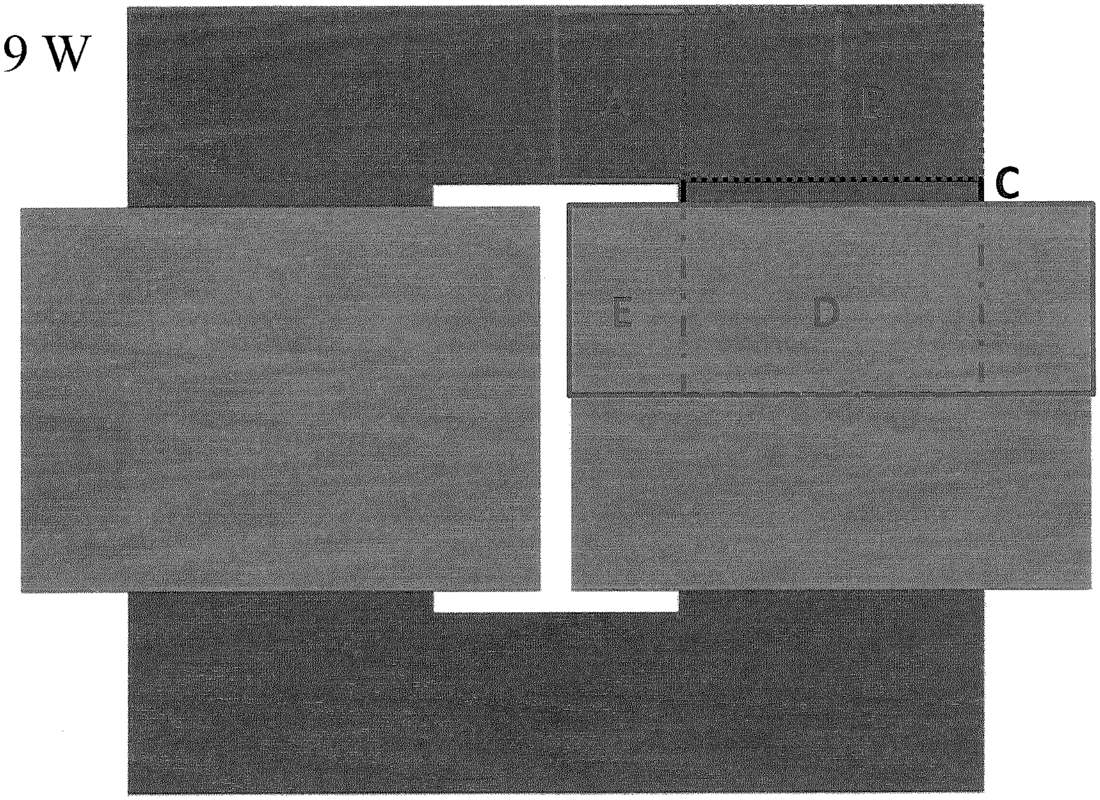
Step 3: DC Inductor Thermal Model

- Construction of thermal equivalent circuit



Step 3: DC Inductor Thermal Model

- Testing with arbitrary design parameters and materials
  - Pcoil = 10.0 W
  - Ppost = 2.7 W
  - Pbase = 3.9 W



‹A›=336.5°K ‹B›=337.5°K

Ambient = 300°K

‹C›=340.1°K

‹D›=340.4°K

‹E›=331.7°K

Step 3: Design Methodology

- Assume proxy flux linkage waveform
- Assume URUR core inductor with ferrite core
- Assume output power of 50 kW; 1 kV bus
- Constraints
  - RMS current density
  - Limit peak common mode current
  - RMS common mode current
  - Limit peak winding temperature
- Minimize mass
- Minimize loss
  - DC resistive loss
  - Skin effect loss
  - Proximity effect loss
  - Core loss

$O \xleftrightarrow{w_p})$ $r_c = r_h + w_p$

Air gap

d_c

desired width of post*

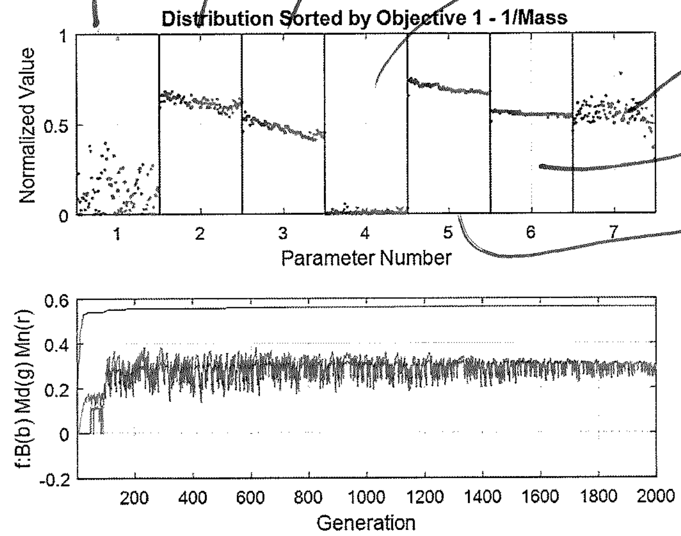
Step 3: URUR Core Pareto Optimal Front

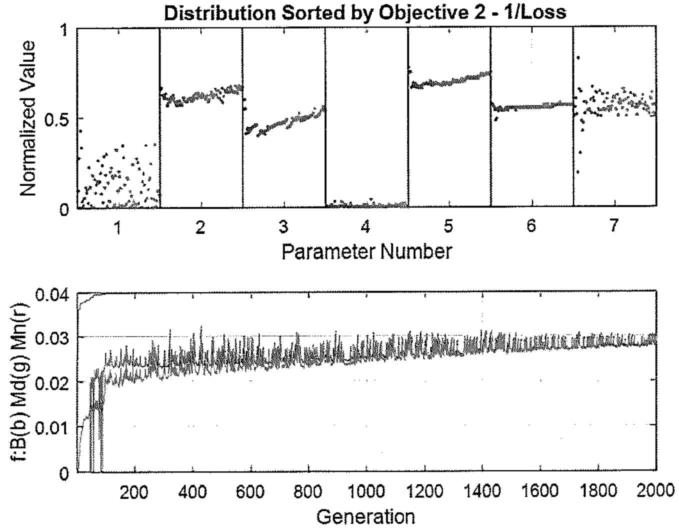
r_h

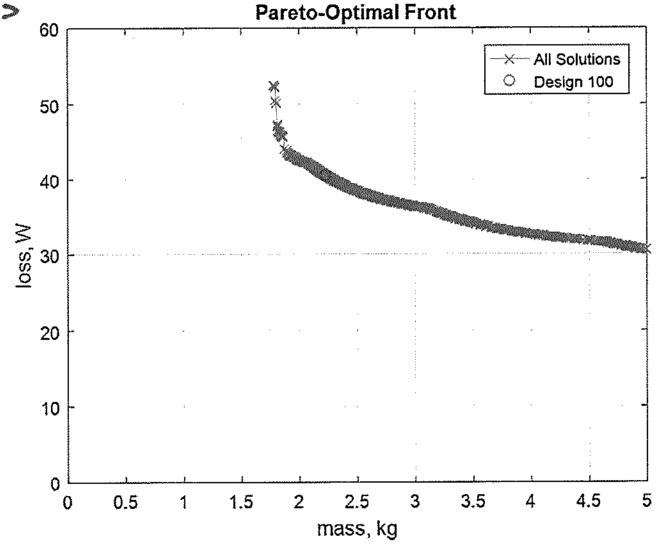
Number of layers

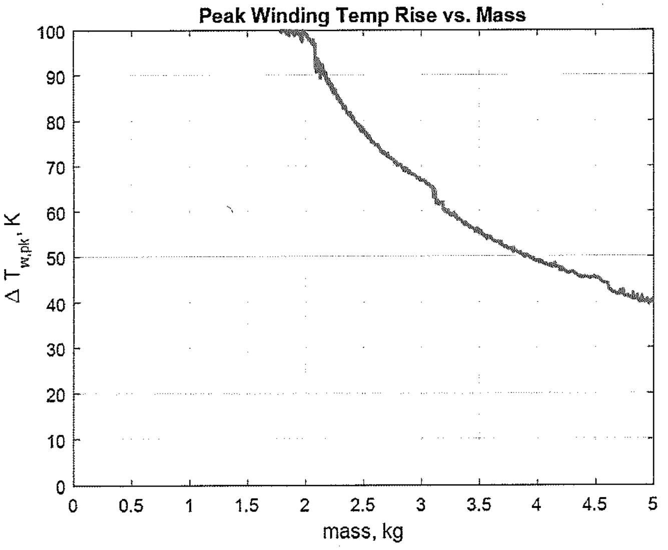
N

a_c



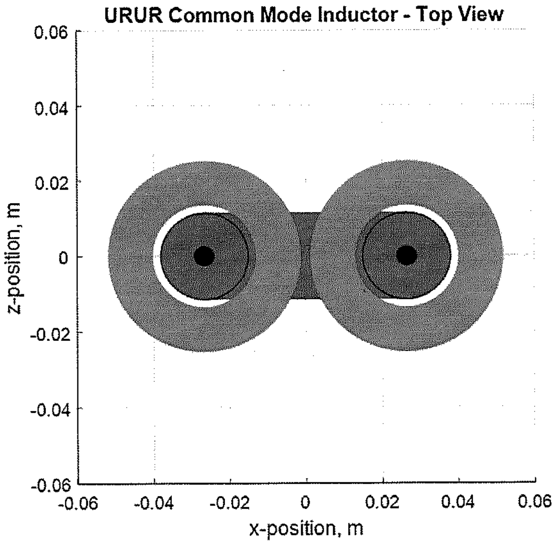


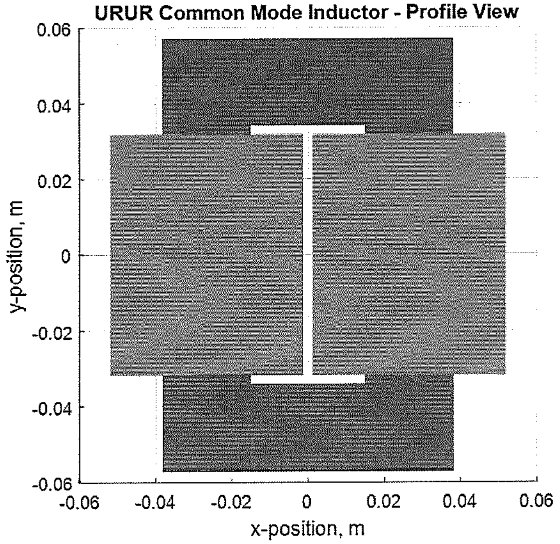




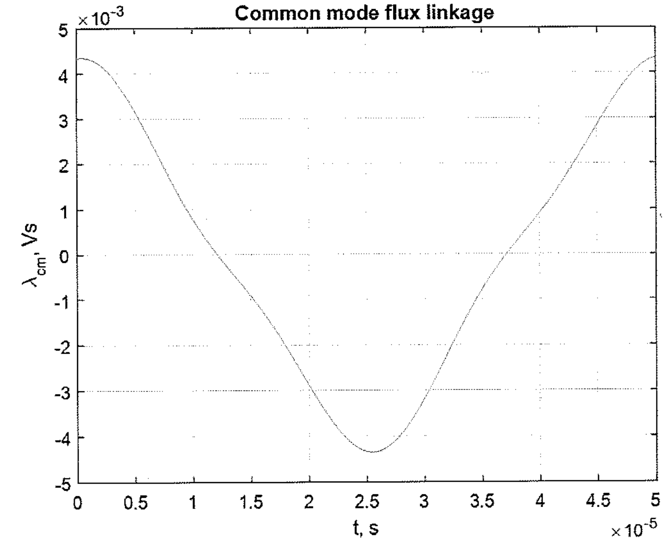
Step 3: Design 100

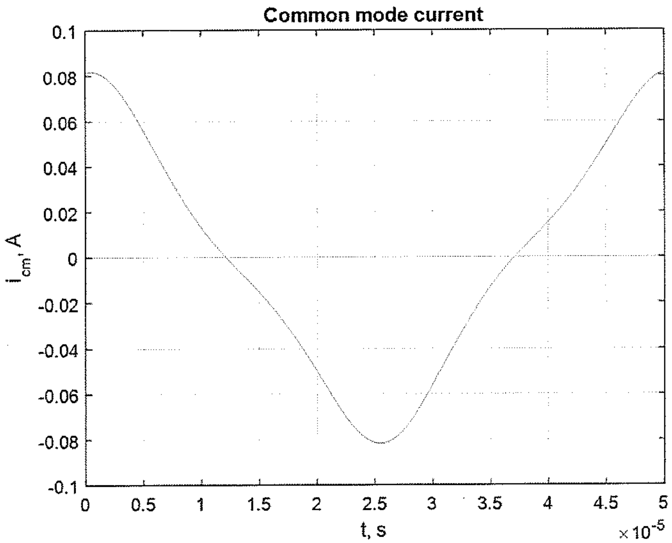
```
Enter design number of solution to report on (0 to skip): 100
Mass--------------------------------------------------
 Total core mass (both cores) (kg) = 0.61214
 Total coil mass (both coils) (kg) = 1.6169
 Total mass (kg) = 2.229
Materials---------------------------------------------
 Core = MN67
 Conductor = Copper
Dimensions--------------------------------------------
 Height (cm) = 11.4163
 Width (cm) = 5.058
 Length (cm) = 10.366
 Circumscribing cuboidal volume (l) = 0.59857
Winding-----------------------------------------------
 Number of turns = 45
 Number of layers = 5
 Number of turns per layer = 9
 Number of strands per conductor = 3
 Strand gauge =  11
 Strand area = (mm^2) = 4.1684
 Strand diameter (mm) = 2.3038
 Current density (rms A/mm^2) = 4.0003
 Winding mean temperature (K) = 380.3725
 Winding peak temperature (K) = 386.6215
Loss--------------------------------------------------
 DC resistive (W) = 16.4854
 Skin effect (W) = 1.8138e-05
 Proximity effect (W) = 0.0060171
 Core loss (W) = 24.0538
 Total loss (W) = 40.5452
Common mode current-----------------------------------
 Peak common mode current (mA) 81.7913
 RMS common mode current (mA) 50.3443
 Absolute CM inductance (H) 0.053149
```

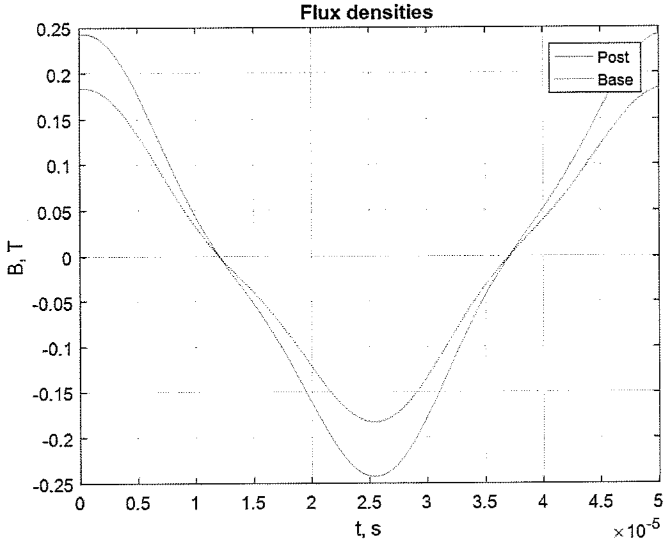




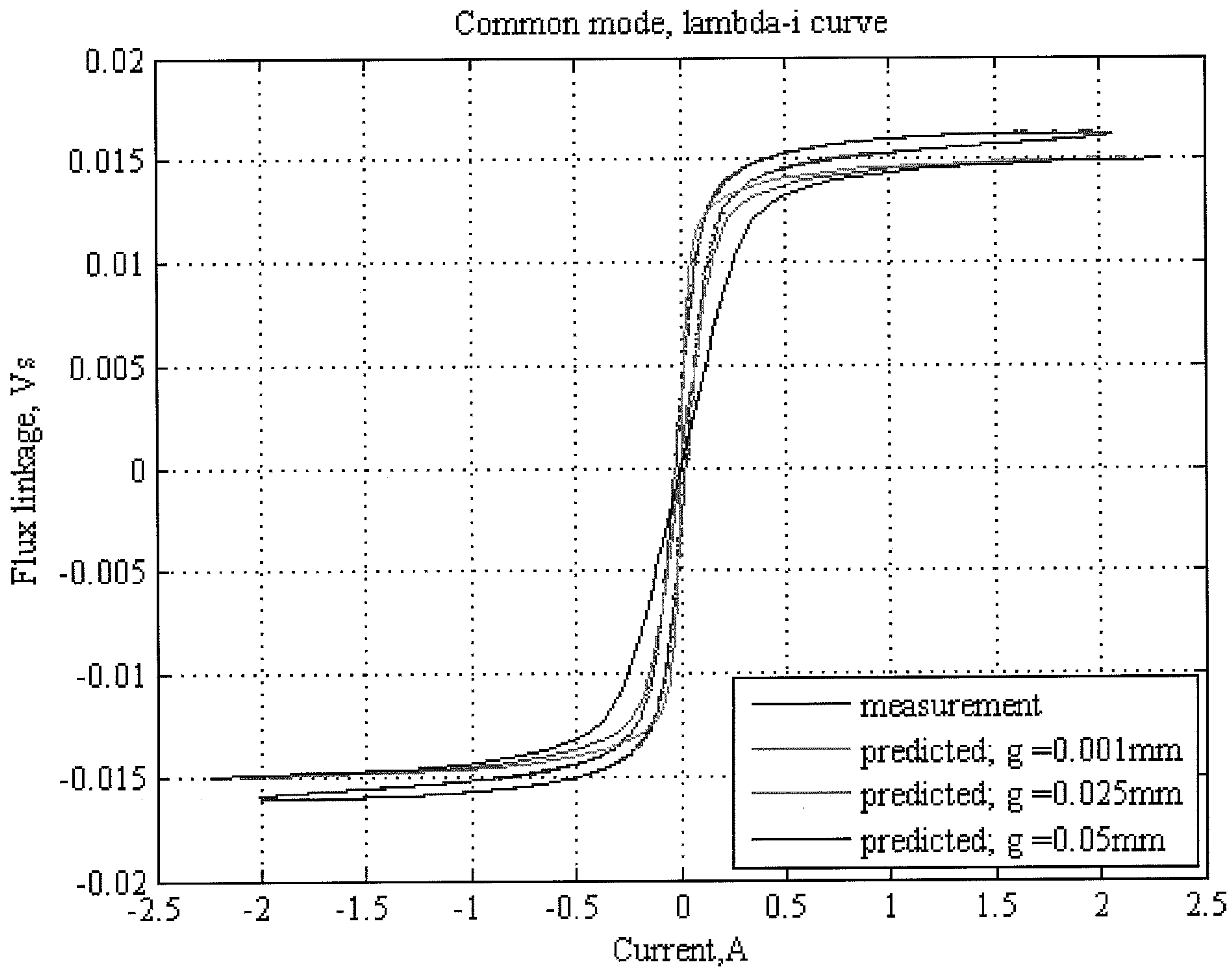
Step 3: Design 100


Common mode flux linkage

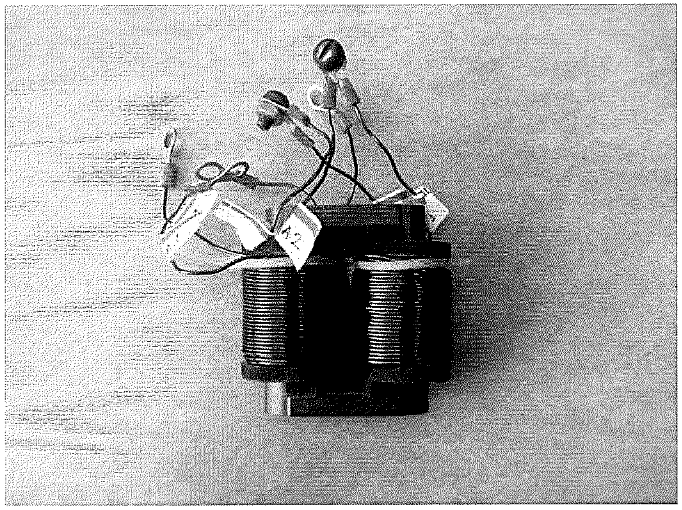

Common mode current

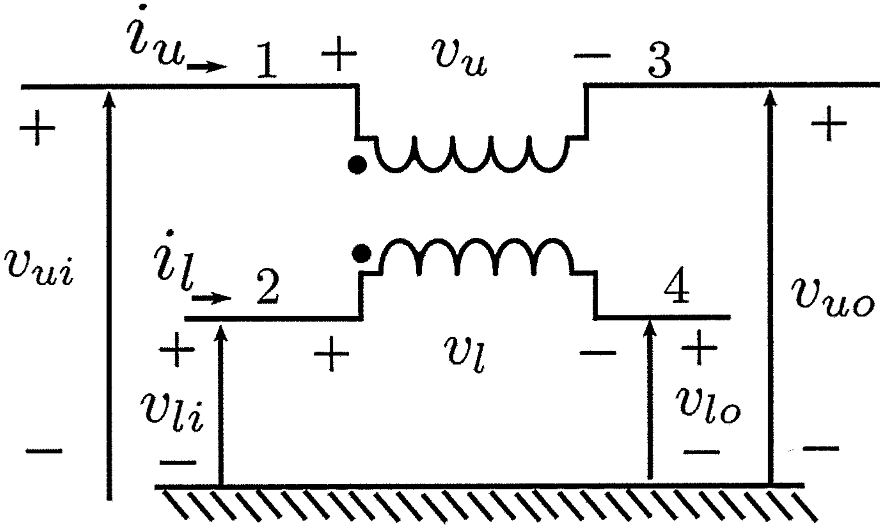

Flux densities

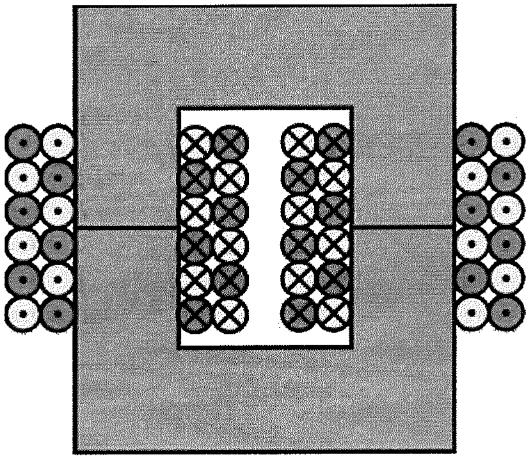
Validation (So Far)



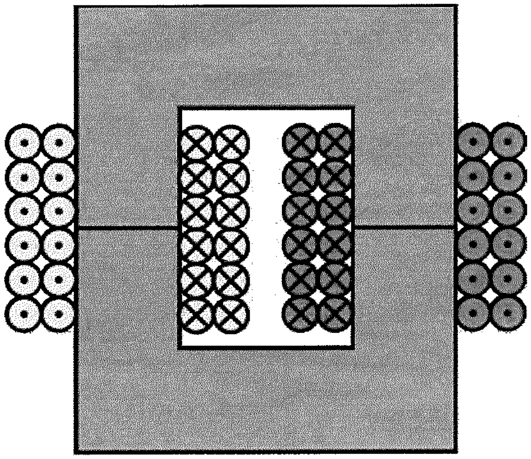
On Configuration



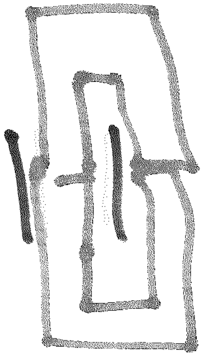




Configuration 1

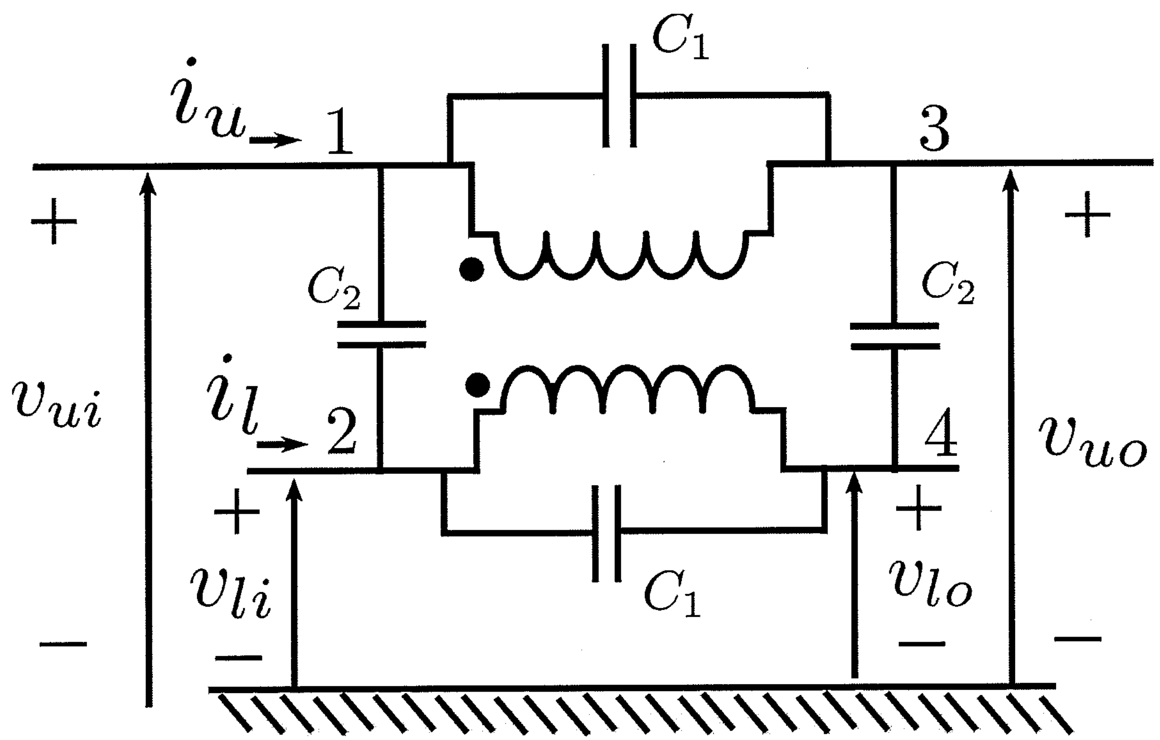


Configuration 2



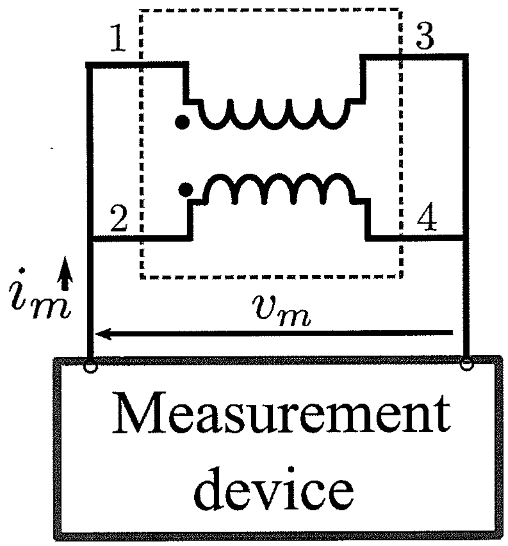
CM Inductor Model with Parasitic Capacitances

- High frequency model

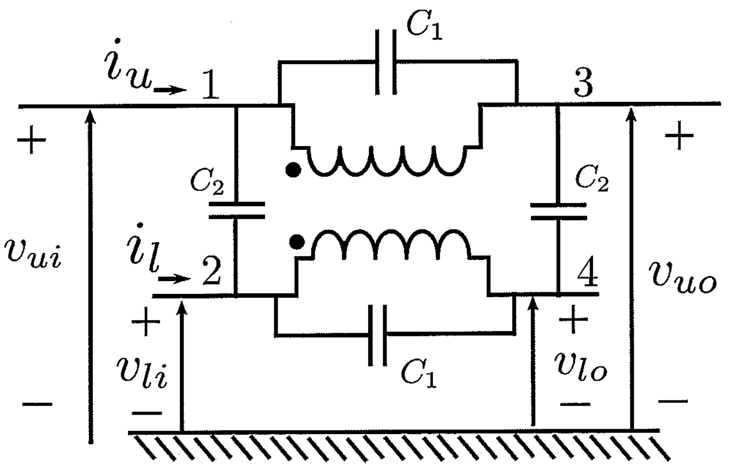


C_1 - Intra-winding capacitance
C_2 - Inter-winding capacitance

Common Mode Measurement



LCR
~~[illegible]~~ Meter



$I_m = I_u + I_l = I_{cm}$

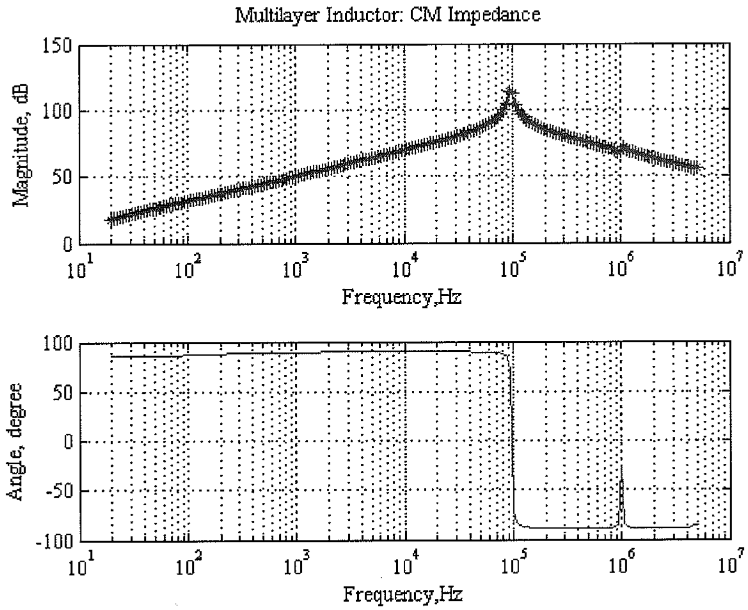
$V_m = V_{ui} - V_{uo} = V_{li} - V_{lo}$

$= \frac{1}{2}(V_{ui} - V_{uo}) + \frac{1}{2}(V_{li} - V_{lo})$

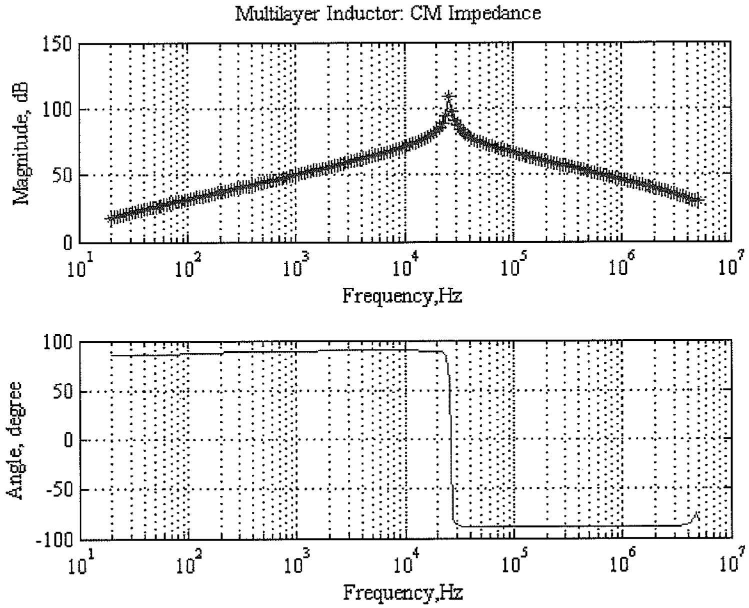
$= \frac{1}{2}(V_{ui} + V_{li})$ ~~[illegible]~~ $- \frac{1}{2}(V_{uo} + V_{lo})$

$= V_{cm}$

Test Inductor Common Mode Impedance

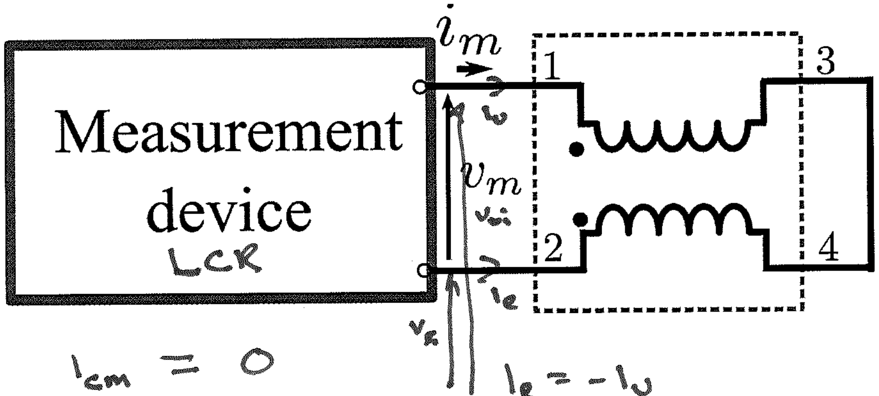


Configuration 1

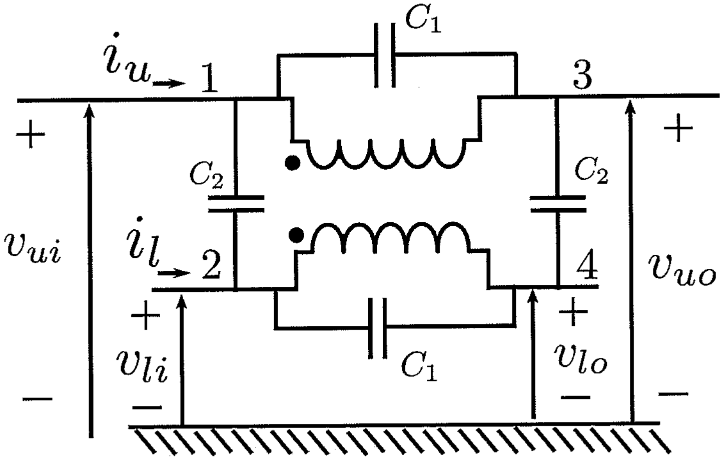


Configuration 2

Differential Mode Measurement



$I_e = -I_u$



$I_{cm} = 0$

$I_{dm} = \frac{1}{2}(I_u - I_e)$

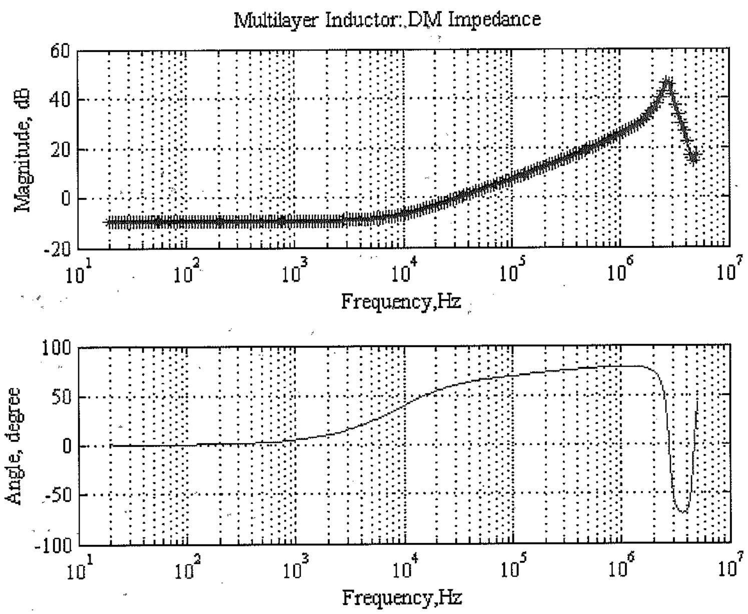
$= I_u$

$V_{di} = V_{ui} - V_{ei} = V_m$

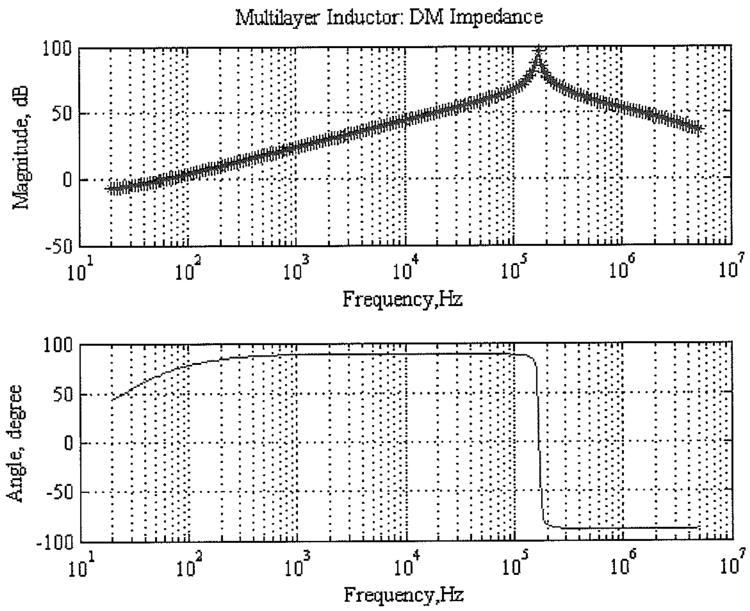
$V_{do} = 0$

$V_d = V_{di} - V_{do} = V_m$

Test Inductor Differential Mode Impedance

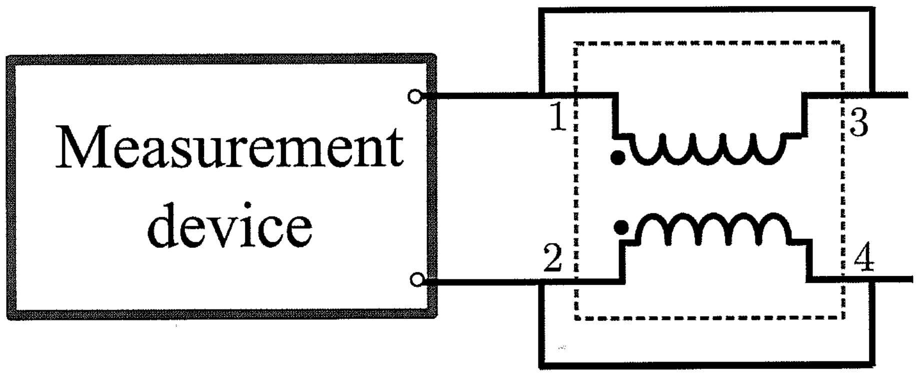


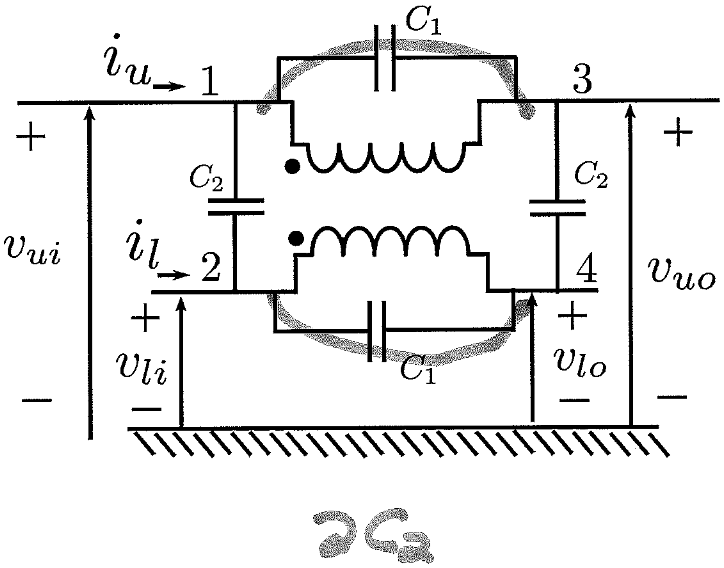
Configuration 1

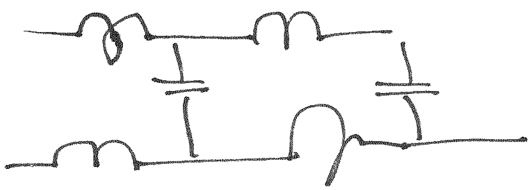


Configuration 2

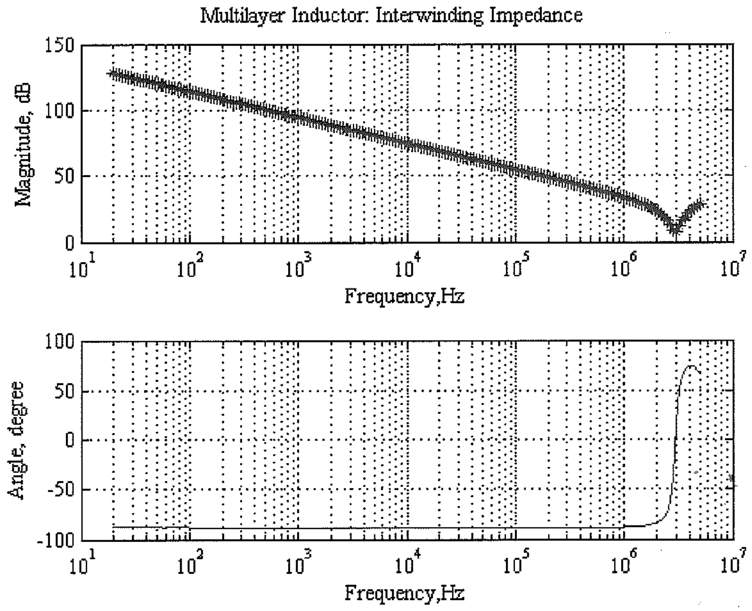
Inter-Winding Capacitance Measurement



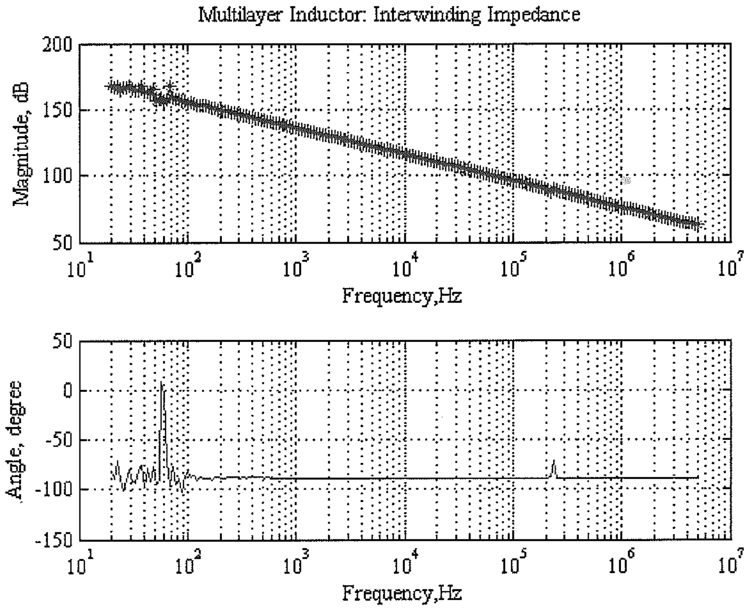




Test Inductor Winding-to-Winding Impedance



Configuration 1

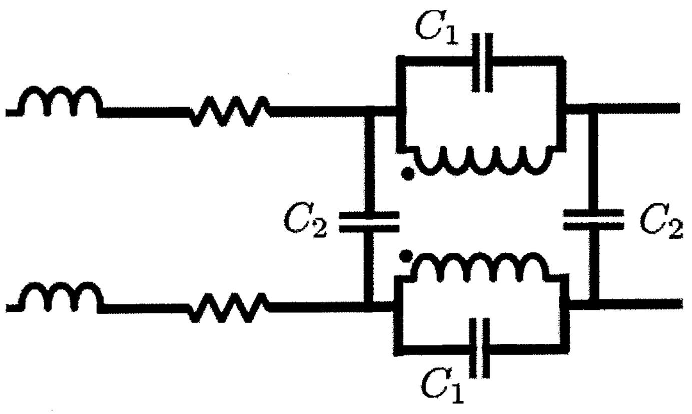


Configuration 2

On Configuration: Inductances (at 2 kHz)

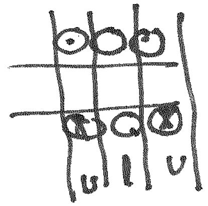
- Configuration 1
  - Common mode inductance = 48.5 mH
  - Differential mode inductance = 4.38 uH (0.09%)

- Configuration 2
  - Common mode inductance = 48.2 mH
  - Differential mode inductance = 2.49 mH (5.2%)

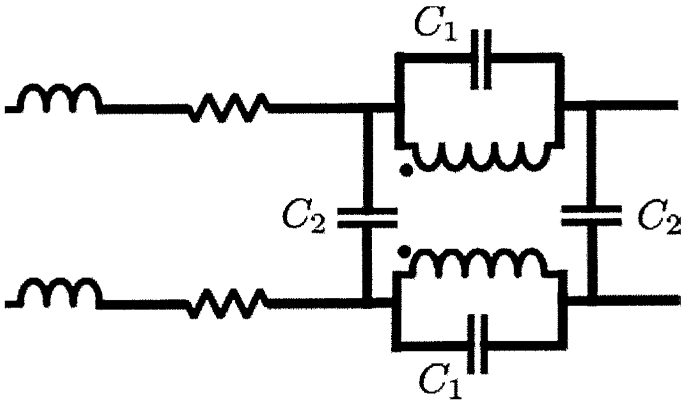


On Configuration: Capacitances

- Configuration 1 (low leakage inductance):
  - – Intrawinding capacitance $C_1 = 27.4$ pF
  - – Interwinding capacitance $C_2 = 1.52$nF



- Configuration 2:
  - – Intrawinding capacitance $C_1 = 390$ pF
  - – Interwinding capacitance $C_2 = 12.3$pF



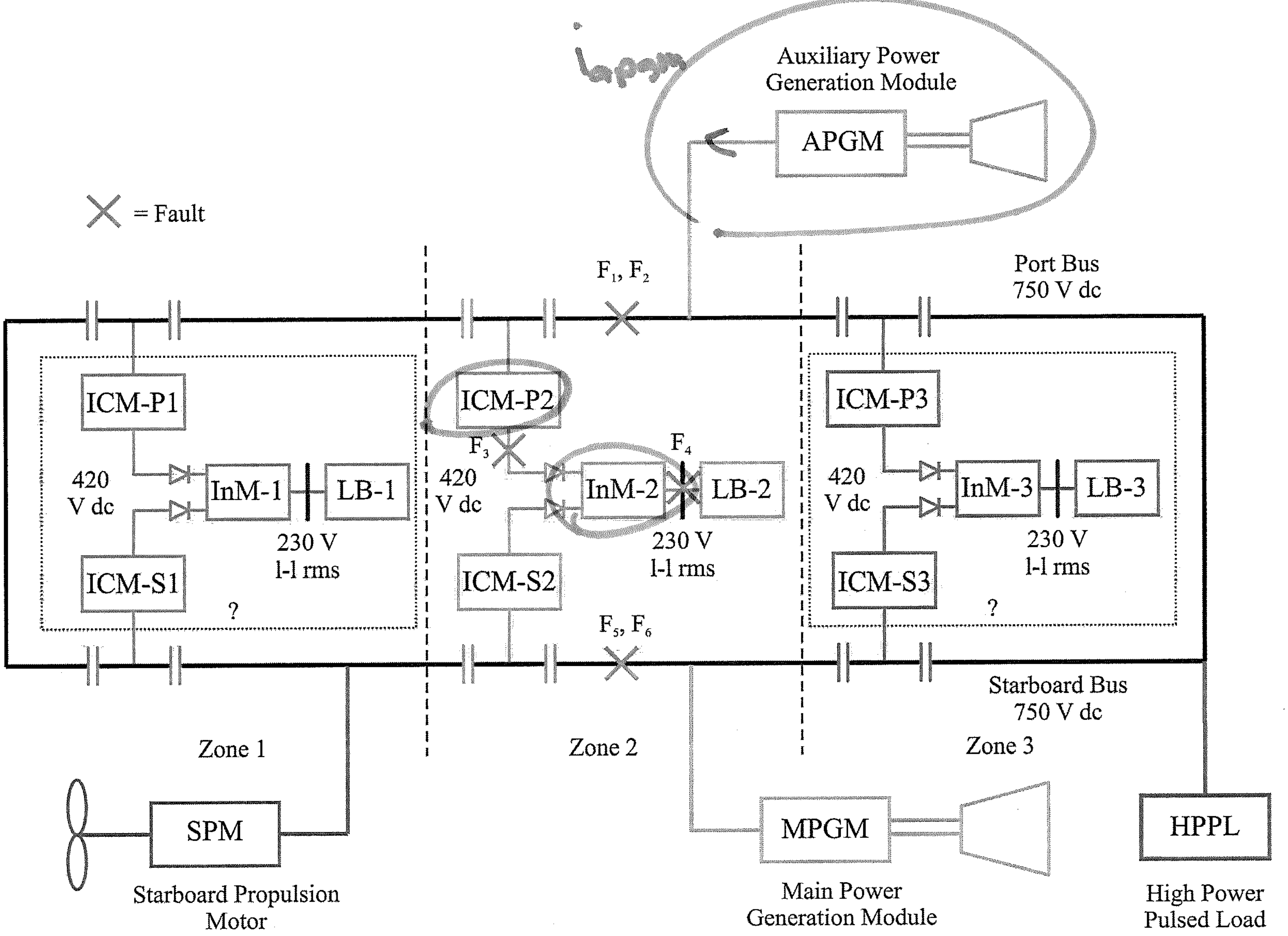
ECE61016 Power Electronics Converters and Systems

Active Bridge PMAC Generation
Lecture Set 6

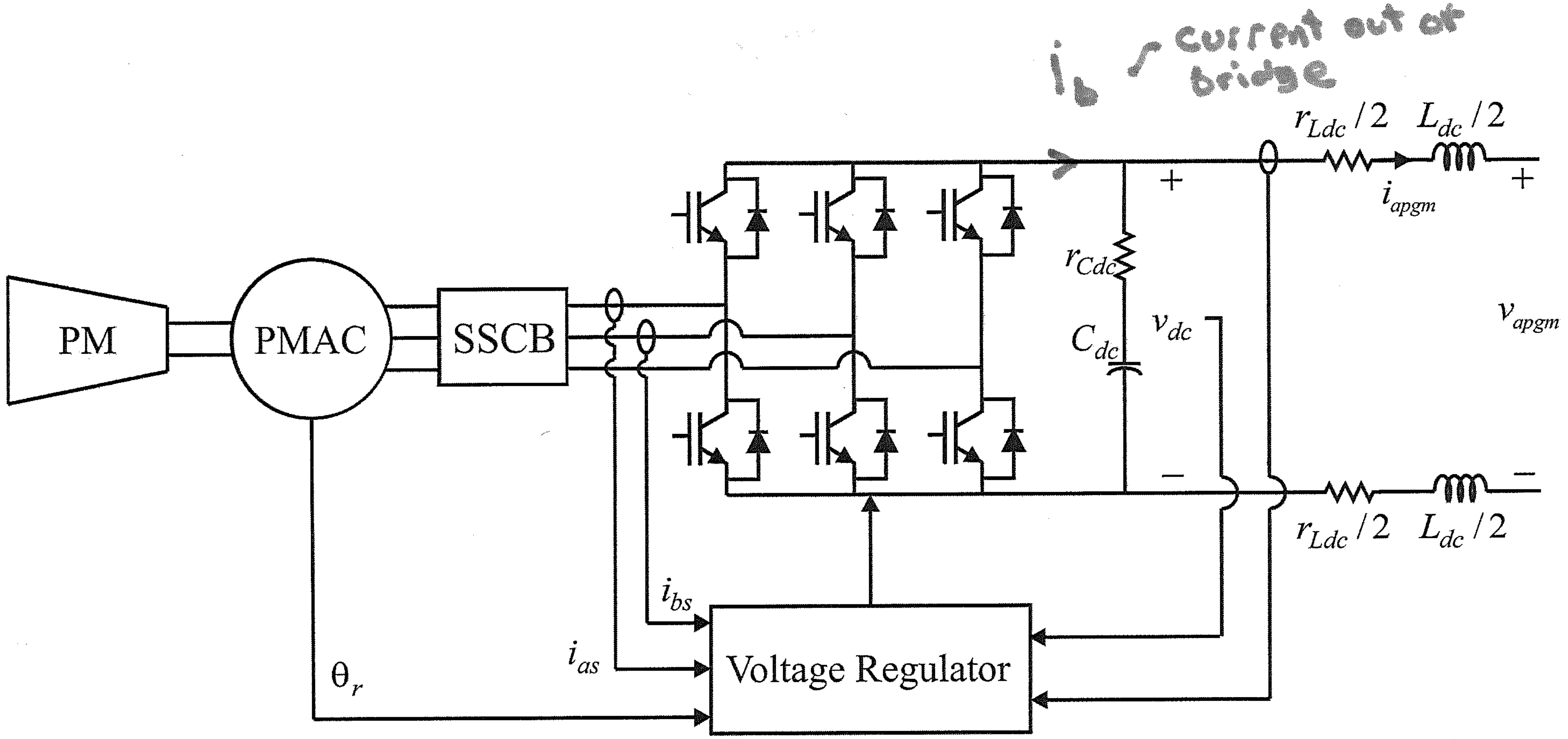
S.D. Sudhoff

Fall 2016

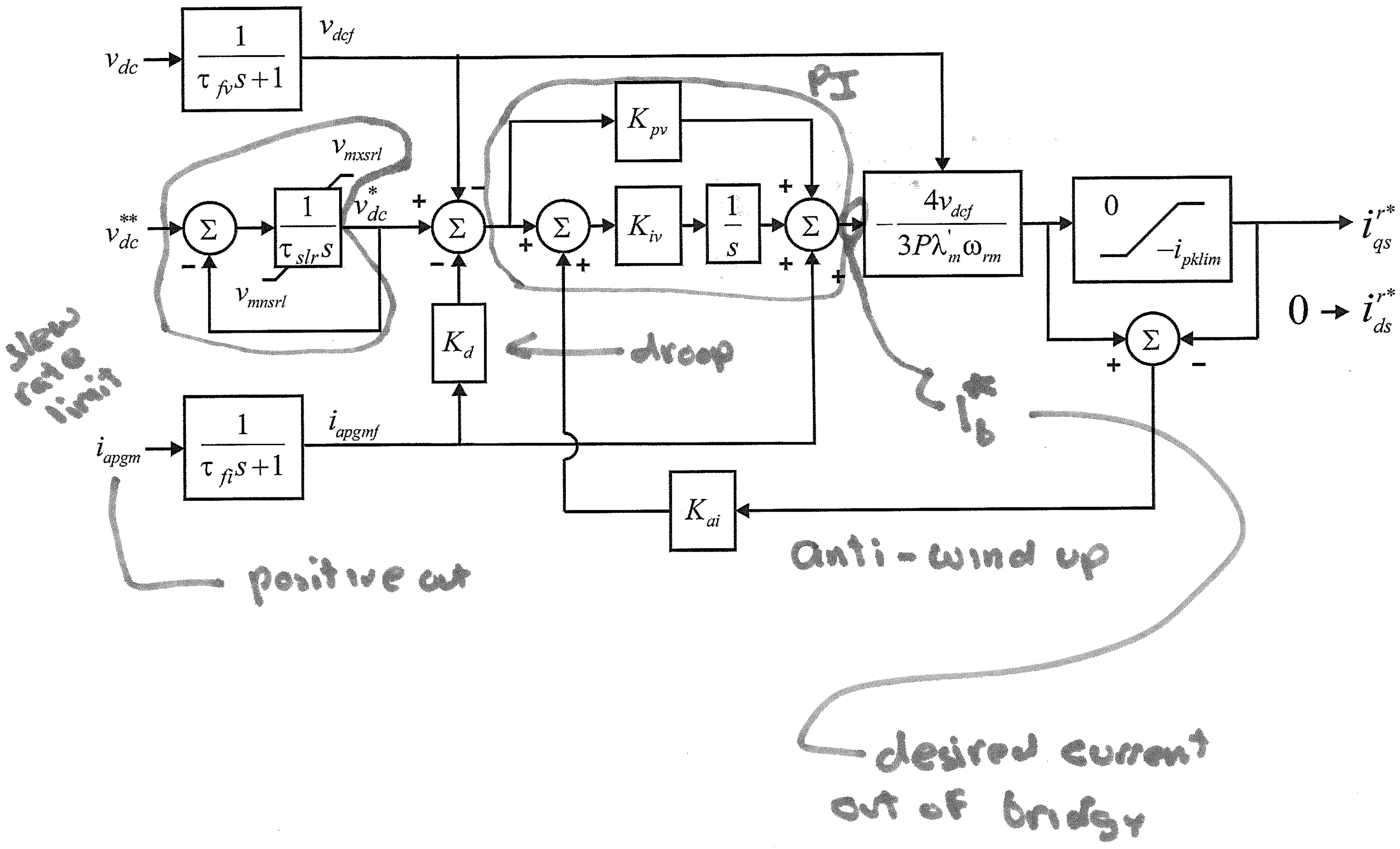
Context


iapgm
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
420 V dc
InM-2
F4
LB-2
230 V l-l rms
ICM-S2
ICM-P3
420 V dc
InM-3
LB-3
230 V l-l rms
ICM-S3
?
F5, F6
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

Active Bridge PMAC Generation



Active Bridge PMAC Control



slew rate limit

PI

droop

i_b^*

positive out

anti-wind up

desired current out of bridge

Review of PMAC Machine

$$\omega_r = \frac{P}{2}\omega_{rm}$$

$$v_{qs}^r = r_s i_{qs}^r + \omega_r \lambda_{ds}^r + p\lambda_{qs}^r$$

$$v_{ds}^r = r_s i_{ds}^r - \omega_r \lambda_{qs}^r + p\lambda_{ds}^r$$

$$\lambda_{qs}^r = L_q i_{qs}^r$$

$$\lambda_{ds}^r = L_d i_{ds}^r + \lambda_m$$

$\underline{\underline{L_q = L_d = L_{ss}}}$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds}^r i_{qs}^r - \lambda_{qs}^r i_{ds}^r\right)$$

$$P_{ine} = \frac{3}{2}\left(v_{qs}^r i_{qs}^r + v_{ds}^r i_{ds}^r\right)$$

$$P_{om} = T_e \omega_{rm}$$

All rotor ref. Frame

Current Command, Non-Salient Machines

$$T_e = \frac{3}{2}\left(\lambda_d i_q - \lambda_q i_d\right)\frac{P}{2}$$

$$= \frac{3}{2}\left(\left(\cancel{L_{ss} i_d} + \lambda_m\right) i_q - \cancel{L_{ss} i_q i_d}\right)\frac{P}{2}$$

$$T_e = \frac{3}{2}\lambda_m i_q \frac{P}{2}$$

$$\boxed{i_q^* = \frac{T_e^*}{\frac{3}{2}\frac{P}{2}\lambda_m}}$$

Current Command, Non-Salient Machines

$$P_{me} = \frac{3}{2}\left(v_q i_q + v_d i_d \right)$$

$$= \frac{3}{2}\Big(\left(r_s i_q + \cancel{\omega_r L_{ss} i_d} + \omega_r \lambda_m \right) i_q$$

$$+ \left(r_s i_d - \cancel{\omega_r L_{ss} i_q} \right) i_d \Big)$$

$$= \frac{3}{2} r_s \left(i_q^2 + i_d^2 \right) + \frac{3}{2} \omega_r \lambda_m i_q$$

$$P_{me} = \underbrace{\frac{3}{2} r_s \left(i_q^2 + i_d^2 \right)}_{\text{Loss}} + \underbrace{\omega_{rm} \underbrace{\frac{3}{2} \frac{P}{2} \lambda_m i_q}_{T_e}}_{P_{mo}}$$

Setting $i_d = 0$ minimizes loss

Voltage Limitations

$$\sqrt{3}\sqrt{V_q^2 + V_d^2} \le V_{dc}$$

$$V_q^2 + V_d^2 \le \frac{1}{3} V_{dc}^2$$

$$(r_s I_q + \omega_r L_{ss} I_d + \omega_r \lambda_m)^2 + (r_s I_d - \omega_r L_{ss} I_q)^2 = \frac{1}{3} V_{dc}^2$$

$$\underline{r_s^2 I_q^2} + \underline{\underline{\omega_r^2 L_{ss}^2 I_d^2}} + \omega_r^2 \lambda_m^2$$

$$+ \xcancel{2 r_s I_q \omega_r L_{ss} I_d} + 2 \omega_r^2 L_{ss} I_d \lambda_m + 2 r_s I_q \omega_r \lambda_m$$

$$+ \underline{\underline{r_s^2 I_d^2}} - \xcancel{2 r_s I_d \omega_r L_{ss} I_q} + \underline{\omega_r^2 L_{ss}^2 I_q^2} = \frac{1}{3} V_{dc}^2$$

$$Z^2 = r_s^2 + \omega_r^2 L_{ss}^2$$

Voltage Limitations

$$Z^2 I_q^2 + \underline{Z^2 I_d^2} + \omega_r^2 \lambda_m^2 + \underline{2\omega_r^2 L_{ss} I_d \lambda_m} + 2 r_s I_q \omega_r \lambda_m = \frac{1}{3} V_{dc}^2$$

$$\underbrace{\left[Z^2\right]}_{A} I_d^2 + \underbrace{\left[2\omega_r^2 L_{ss} \lambda_m\right]}_{B} I_d + \underbrace{\left[Z^2 I_q^2 + \omega_r^2 \lambda_m^2 + 2 r_s I_q \omega_r \lambda_m - \frac{1}{3} V_{dc}^2\right]}_{C} = 0$$

$$I_d = \frac{-B \pm \sqrt{\underbrace{B^2 - 4AC}_{D}}}{2A}$$

if $D < 0$ we are out of luck.

Flux Weakening, Non-Salient Machines

$$D = 4\omega_r^4 L_{ss}^2 \lambda_m^2$$

$$- 4Z^2 \left[\underline{Z^2 I_q^2} + \underline{\underline{\omega_r^2 \lambda_m^2}} + 2 r_s I_q \omega_r \lambda_m - \tfrac{1}{3} V_{dc}^2 \right]$$

$$D = \cancel{4\omega_r^4 L_{ss}^2 \lambda_m^2} \quad \underline{- 4Z^4 I_q^2}$$

$$- 4 r_s^2 \omega_r^2 \lambda_m^2 - \cancel{4\omega_r^2 L_{ss}^2 \omega_r^2 \lambda_m^2}$$

$$- \left(\underline{2 r_s I_q \omega_r \lambda_m} - \underline{\tfrac{1}{3} V_{dc}^2} \right) 4Z^2$$

$$D = \tfrac{1}{3} V_{dc}^2 4Z^2 - \left(4Z^4 I_q^2 + 2 r_s I_q \omega_r \lambda_m 4Z^2 + 4 r_s^2 \omega_r^2 \lambda_m^2 \right)$$

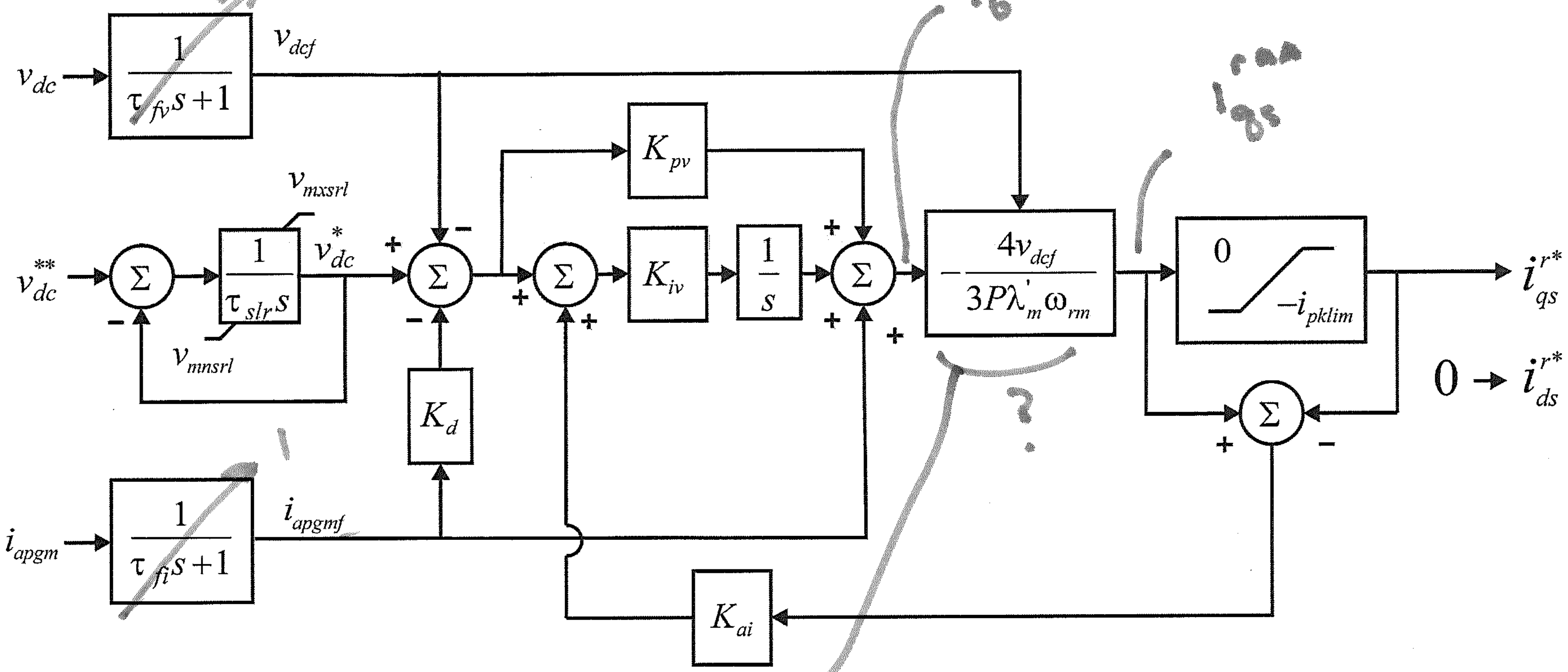
$$= \left[\frac{\cancel{4}\,1}{3} Z^2 V_{dc}^2 - \left(\cancel{2} Z^2 I_q + \cancel{2} r_s \omega_r \lambda_m \right)^2 \right] 4$$

Flux Weakening, Non-Salient Machines

$$i_d = \frac{-\cancel{2}\omega_r^2 L_{ss}\lambda_m \boxed{\pm} \cancel{2}\underbrace{\sqrt{\frac{1}{3}Z^2 V_{dc}^2 - (Z^2 i_q + r_s\omega_r\lambda_m)^2}}_{\text{must test}}}{\cancel{2} Z^2}$$

Flux Weakening, Non-Salient Machines

Control Analysis

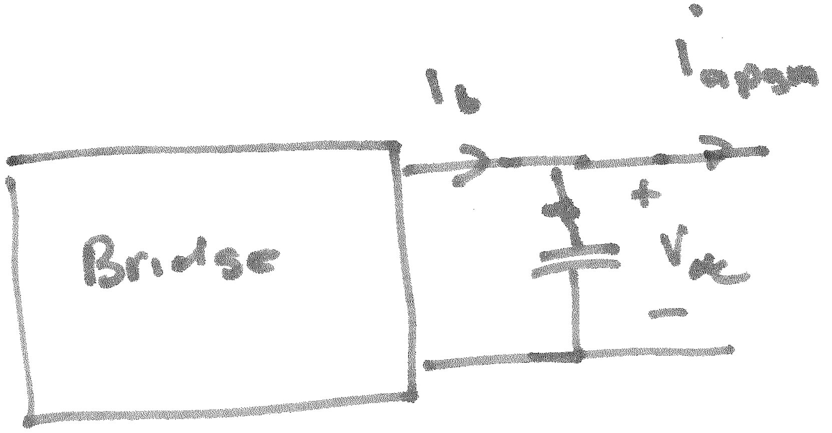


i_b^* = bridge current command

i_{qs}^{r**}

$$-\frac{4V_{dcf}}{3P\lambda_m \max(\omega_{rm,mn}, \omega_{rm})}$$

Control Analysis



$$P_{out} = v_{dc} i_b \approx -T_e \omega_{rm}$$

$$v_{dc} i_b = -\frac{3}{2}\frac{P}{2} \lambda_m i_{qs}^r \omega_{rm}$$

$$i_{qs}^r = -\frac{v_{dc}}{\frac{3}{2}\frac{P}{2} \lambda_m \omega_{rm}} i_b$$

$$= -\frac{4 v_{dc}}{3 P \lambda_m \omega_{rm}} i_b$$

Control Analysis

$$V_{dc} = \left(r_{cdc} + \frac{1}{C_{dc} s}\right)\left(\dot{i}_b - \dot{i}_{apgm}\right)$$

- Neglect Filters
- Assume that $i_b = i_b^*$
- Assume anti-windup is not active

$$\dot{i}_b = \left(K_{pv} + \frac{K_{iv}}{s}\right)\left(V_{dc}^* - K_d \dot{i}_{apgm} - V_{dc}\right) + \underset{\substack{\uparrow \\ \text{Ideally } \alpha = 1}}{\alpha} \dot{i}_{apgm}$$

$$C_{dc} s^2 V_{dc} = \left(C_{dc} r_{cdc} s + 1\right)\Big[\left(K_{pv}s + \frac{K_{iv}}{\cancel{s}}\right)\left(V_{dc}^* - K_d i_{apgm} - V_{dc}\right) + s(\alpha - 1)\, i_{apgm}\Big]$$

Control Analysis

$$\underbrace{\left[C_{dc} S^2 + (C_{dc} r_{cdc} S + 1)(K_{pv} S + K_{iv})\right]}_{CP} V_{dc}$$

$$= \underbrace{(C_{dc} r_{cdc} S + 1)\left[(K_{pv} S + K_{iv})(V_{dc}^* - K_d I_{apgm}) + S(d-1) I_{apgm}\right]}_{N}$$

$$V_{dc} = \frac{N}{CP}$$

where

$$CP = C_{dc}(1 + r_{cdc} K_{pv}) S^2 + (K_{pv} + \cancel{C_{dc} r_{cdc}) S} \; C_{dc} r_{cdc} K_{iv}) S + K_{iv}$$

Control Analysis

At dc

$s \rightarrow 0$

$N = K_{iv}(V_{dc}^{*} - K_d i_{apsm})$

$CP = K_{iv}$

$V_{dc} = V_{dc}^{*} - K_d i_{apsm}$

At high freq

$s \rightarrow \infty$

$CP \rightarrow C_{dc}(1 + r_{cdc} K_{pv}) s^2$

$N \rightarrow C_{dc} r_{cdc} s \left[K_{pv} s (V_{dc}^{*} - K_d i_{apsm}) + s(d-1) i_{apsm} \right]$

$$V_{dc} = \frac{\cancel{C}_{dc} r_{cdc} \left[K_{pv} (V_{dc}^{*} - K_d i_{apsm}) + (d-1) i_{apsm} \right]}{\cancel{C}_{dc}(1 + r_{cdc} K_{pv})}$$

Control Analysis

Control Analysis