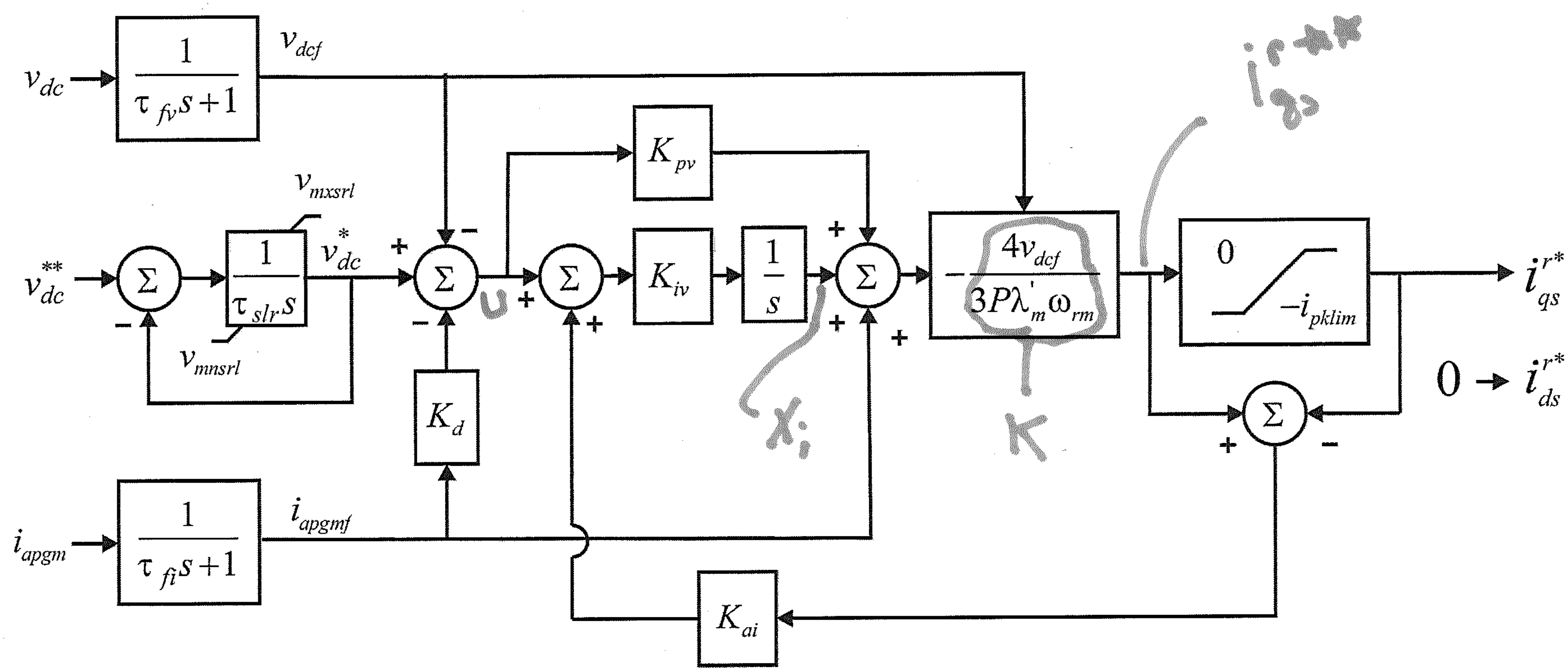
Anti-Windup



Assume U is very large

Assume $i_{qs}^{r*} = -i_{pklim}$

Anti-Windup

$$s\, l_{gs}^{r**} = -K\left[s K_{pv} U + \frac{K_{iv}}{\cancel{s}}\left(U + K_{ai}\left(l_{gs}^{r**} + l_{pklim}\right)\right) + l_{apgm}\, s \right]$$

$$\left[s + K K_{iv} K_{ai}\right] l_{gs}^{r**} = -K\left[(sK_{pv} + K_{iv})U + K_{iv}K_{ai}\, l_{pklim} + l_{apgm}\, s\right]$$

$$l_{gs}^{r**} = \frac{-K\left[(sK_{pv} + K_{iv})U + K_{iv}K_{ai}\, l_{pklim} + l_{apgm}\, s\right]}{s + K K_{iv} K_{ai}}$$

Warning: K is not really a constant

Anti-Windup

"Time Constant"

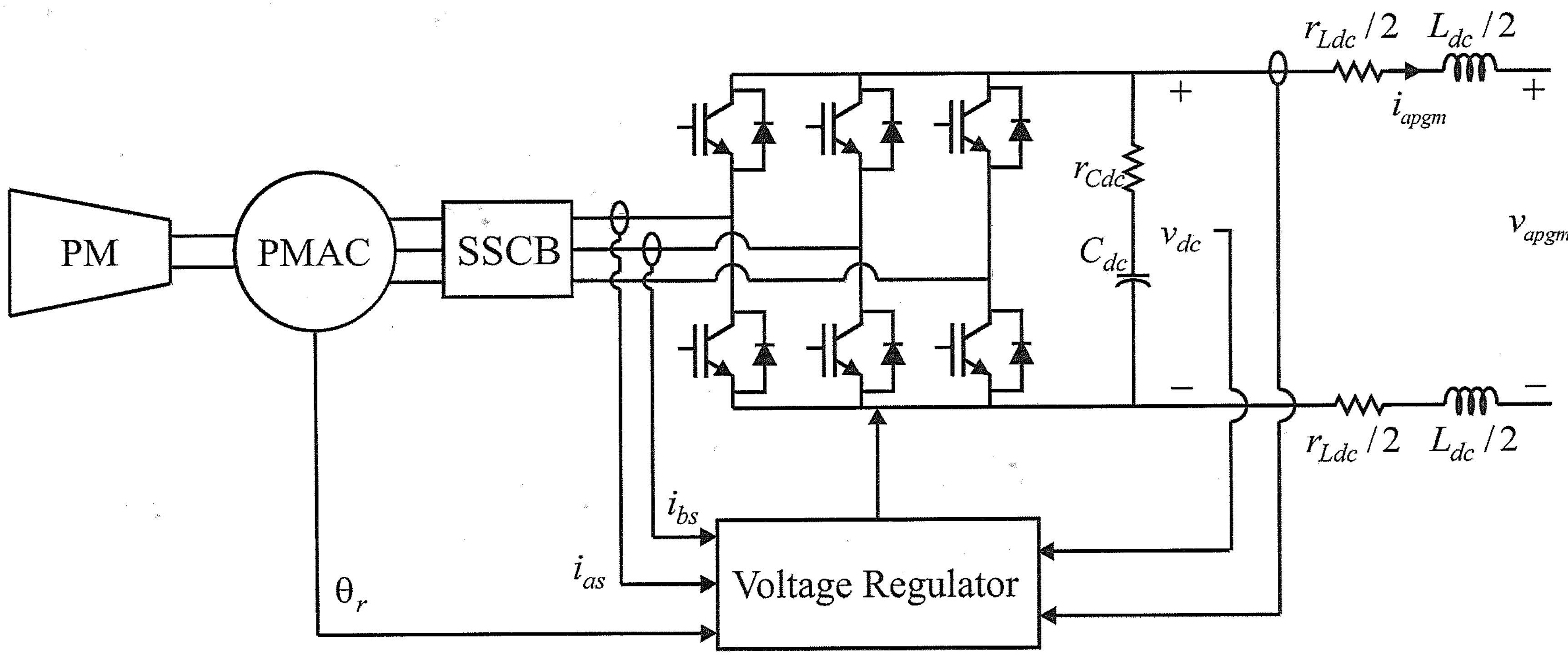
$$\tau = \frac{1}{K K_{iv} K_{ai}}$$

<u>At DC</u>

$$I_{qi}^{r} = \frac{-\cancel{K}\left[\cancel{K_{iv}} U + \cancel{K_{iv}} K_{ai} I_{pk\,lim}\right]}{\cancel{K}\,\cancel{K_{iv}} K_{ai}}$$

$$= -\frac{U}{K_{ai}} - I_{pk\,lim}$$

Operating Considerations



o^* = desired operating status (1 = operate)

cb = circuit breaker status (1 = closed)

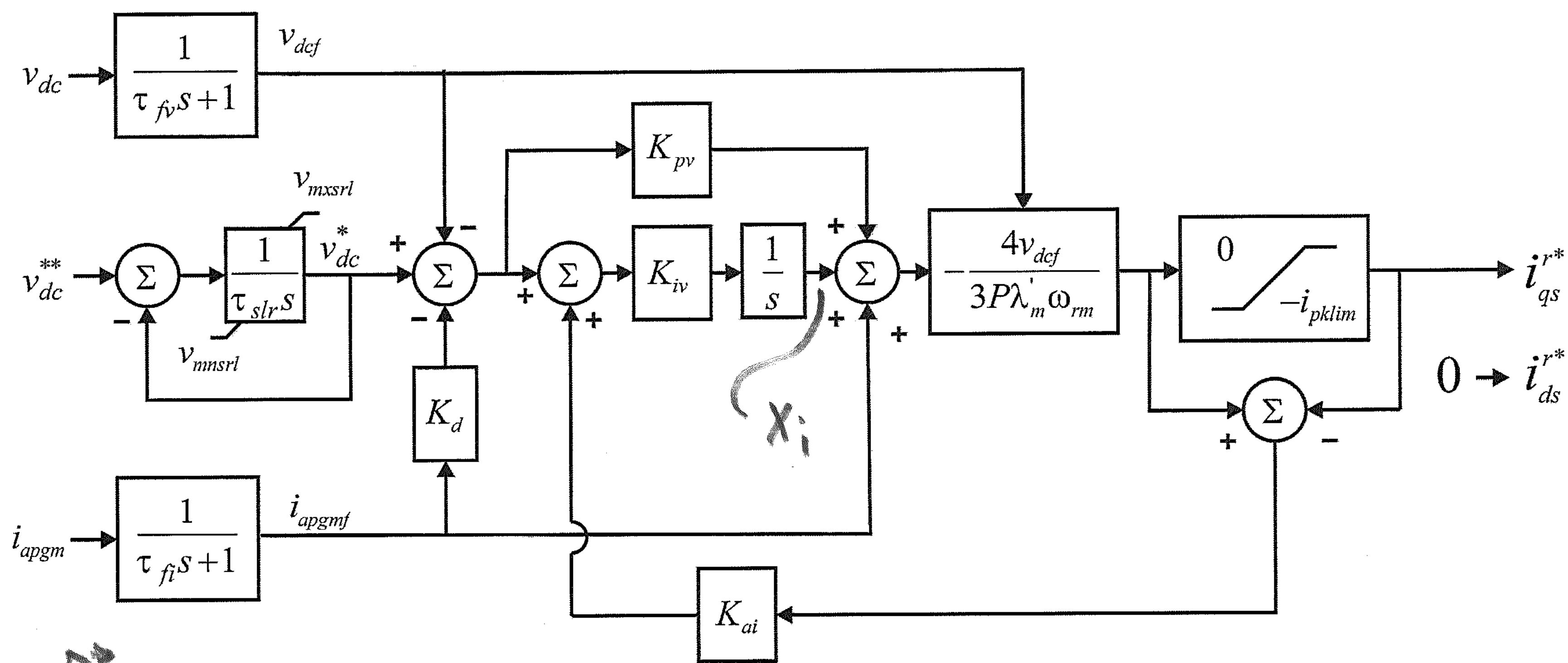
o = operating status

$o = o^* \cdot cb \cdot (\omega_{rm} > \omega_{rm,min})$

better

$o = o^* \cdot cb \cdot [\bar{o} \cdot (\omega_{rm} > \omega_{rm,min,s}) + o(\omega_{rm} > \omega_{rm,min,r})]$

When Not Operating…

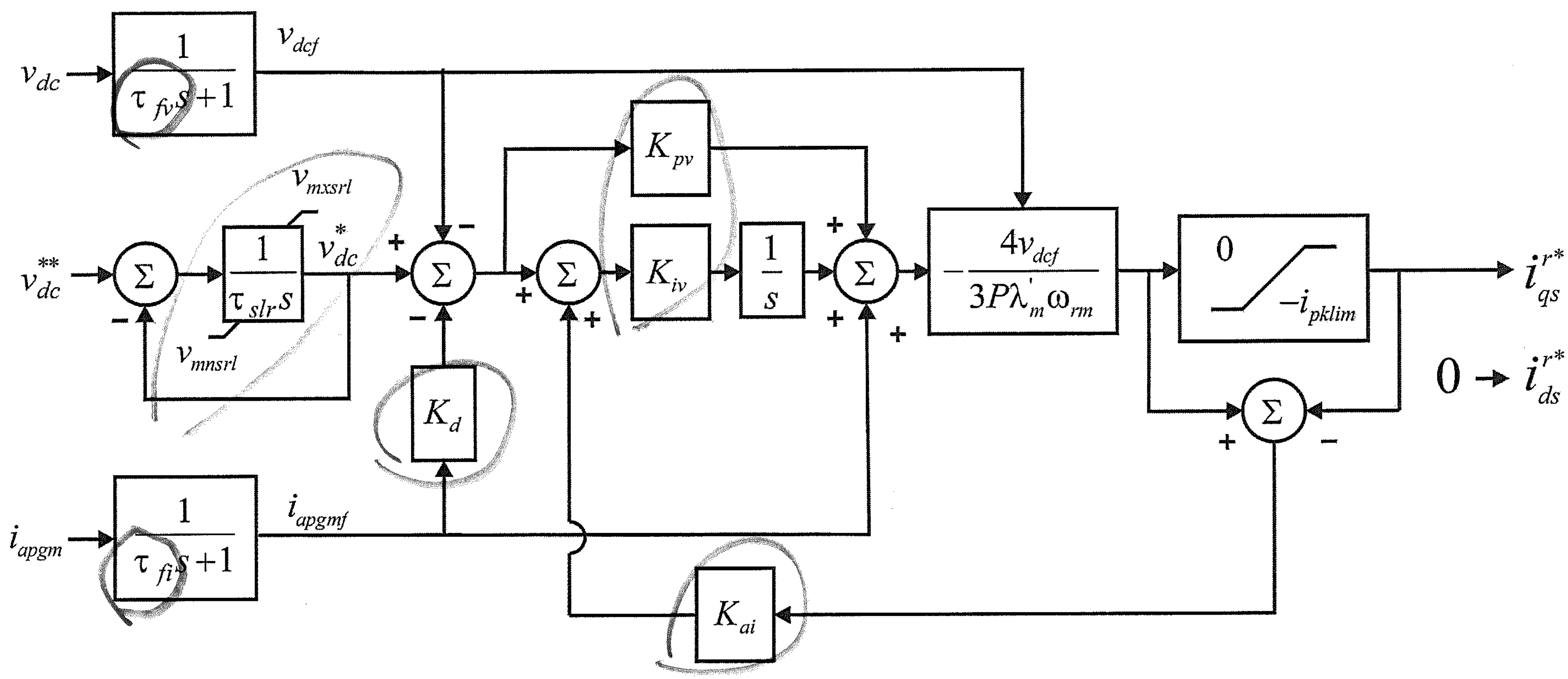


$v_{dc}^{**} = 0$

$i_{qs}^{r*} = i_{ds}^{r*} = 0$

$pX_i = -\frac{X_i}{\tau_r}$

Control Design



Specifications

- System
  - Output Voltage = 750 V (no load) to 725 V (full load)
  - Rated Output Power = 9 kW
- PMAC
  - $r_s = 0.45\ \Omega$, $L_{ss} = 2.6$ mH, $\lambda_m = 0.1723$ Vs, $P = 8$
  - ω_{rm} (nom) = 3600 rpm
- Inverter
  - $v_{sw} = 1$ V, $r_{sw} = 50$ m$\cancel{\text{W}}$ Ω, $v_d = 1$ V, $r_d = 50$ m$\cancel{\text{W}}$ Ω
  - HD Modulated, $h = 1$ A, $f_{smple} = 300$ kHz
  - $C_{in} = 4$ mF, $r_{Cin} = 20$ m$\cancel{\text{W}}$ Ω, $L_{dc} = 300$ uH, $r_{Ldc} = 0.3$ m$\cancel{\text{W}}$ Ω

Slew Rate Limit

- Let's take
  - $v_{mxsrl} = 750/0.1 = 7500$ V/s
  - $v_{mnsrl} = 750/0.01 = 75000$ V/s
  - $\tau_{srl} = 0.1$ ms

Calculation of Droop

- Output voltage should be 750 V at no-load and 725 V at 9 kW rated load

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

At Full load

$$i_{apsm} = \frac{9\,kW}{725\,V} = 12.4 \text{ A}$$

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

$$K_d = \frac{V_{dc}^{*} - V_{dc}\big|_{full\ load}}{i_{apsm}\big|_{full\ load}} = \frac{750 - 725}{12.41}$$

- Thus ✓

$K_d = 2.01$ V/A

Calculation of Current Limit

- Limit on i_b^*

$I_{apsm} = 12.4\ \text{A}$

$I_b = 15\text{A}$

- Next

$$i_{qs}^{r*} = -\frac{4v_{dcf}}{3P\lambda_m\omega_{rm}} i_b^* = -29.3\ \text{A}$$

- Thus

$$i_{pklim} = 30\,\text{A}$$

Input Filter Time Constants

- Lets put cut-off frequency at 2 kHz

$\tau \omega = 1$

$\tau = \frac{1}{2\pi f}$

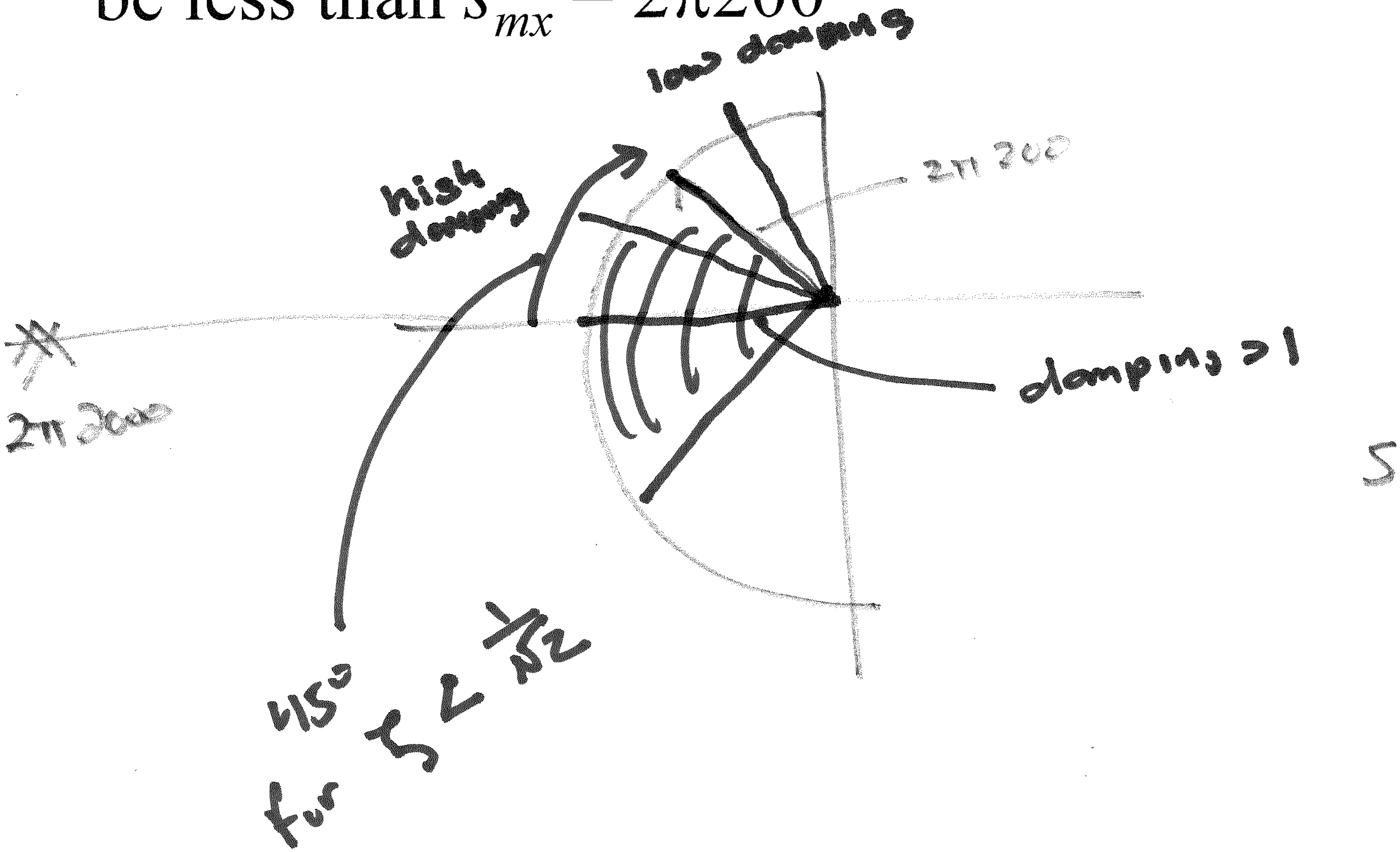
$\frac{1}{\tau s + 1}$

- This yields

$$\tau_{fi} = \tau_{fv} = 79.6\ \mu s$$

Selection of K_{pv} and K_{iv}

- ~~Criteria~~ Criterion 1: The magnitude of the pole locations will be less than $s_{mx} = 2\pi 200$



Selection of K_{pv} and K_{iv}

- ~~Criteria~~ Criterion 2: The damping factor of the poles will be greater than $\cancel{\delta}\,\zeta_{mn}=1/\text{sqrt}(2)$

CP: $s^2 + 2\zeta\omega_o s + \omega_o^2$

$$s = \frac{-\cancel{2}\zeta\omega_o \pm \sqrt{\cancel{4}\zeta^2\omega_o^2 - \cancel{4}\omega_o^2}}{\cancel{2}}$$

$$s = \omega_o\left[-\zeta \pm j\sqrt{1-\zeta^2}\right]$$

Consider $\zeta < 1$

$$|s| = \omega_o\sqrt{\zeta^2 + 1 - \zeta^2} = \omega_o$$

$\cancel{Re(s)}$

- $$\frac{Im(s)}{Re(s)} = \frac{\sqrt{1-\zeta^2}}{\zeta} = \sqrt{\frac{1}{(\zeta)^2} - 1}$$

$$Im(s) = \sqrt{\left(\frac{1}{\zeta}\right)^2 - 1}\quad Re(s)$$

Selection of K_{pv} and K_{iv}

- We wish to minimize the impedance

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

- Thus

$V_{dc} = -Z\, i_{apgm}$

$$Z = r_{Ldc} + sL_{dc} + \frac{(r_{Cdc}C_{dc}s+1)\left[(K_{pv}s+K_{iv})K_d - s(\alpha-1)\right]}{(C_{dc}+K_{pv}r_{Cdc}C_{dc})s^2+(K_{pv}+K_{iv}r_{Cdc}C_{dc})s+K_{iv}}$$

Selection of K_{pv} and K_{iv}

- Some definitions

$$f' = \log f$$

$$Z_{db} = 20\log(|Z|)$$

- Proposition: minimize

$$g = \max_{\alpha \in A} \int_{\log(f_{mn})}^{\log(f_{mx})} Z_{db}(\alpha)\,df'$$

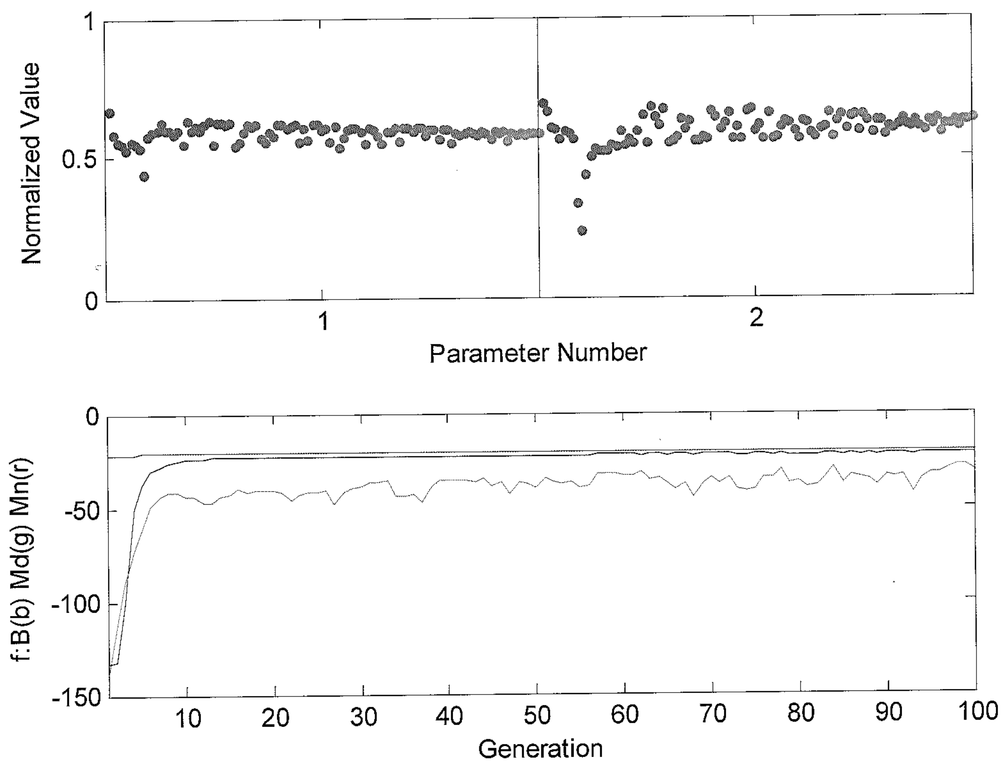
$$A = [\alpha_1 \ \alpha_2 \ \alpha_3 \ldots]$$

subject to constraints being met (minimax optimization)

Selection of K_{pv} and K_{iv}

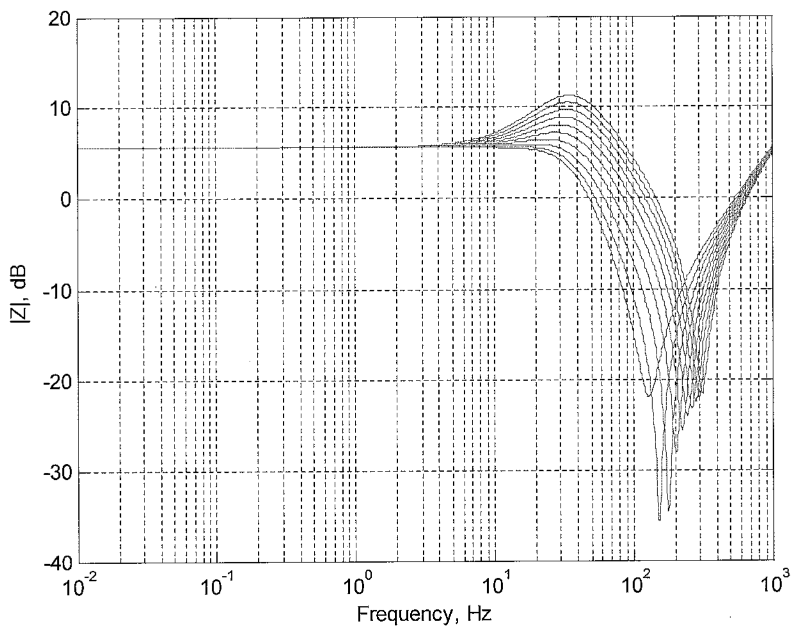
- Let’s vary α from 0.8 to 1.2 in 10 steps
- Lets take $f_{mn} = 0.01$ Hz and $f_{mx} = 1$ kHz
- Range for K_{pv}: 10^{-6} to 10^{3}
- Range for K_{iv}: 10^{-6} to 10^{6}

Gene Distribution and Results

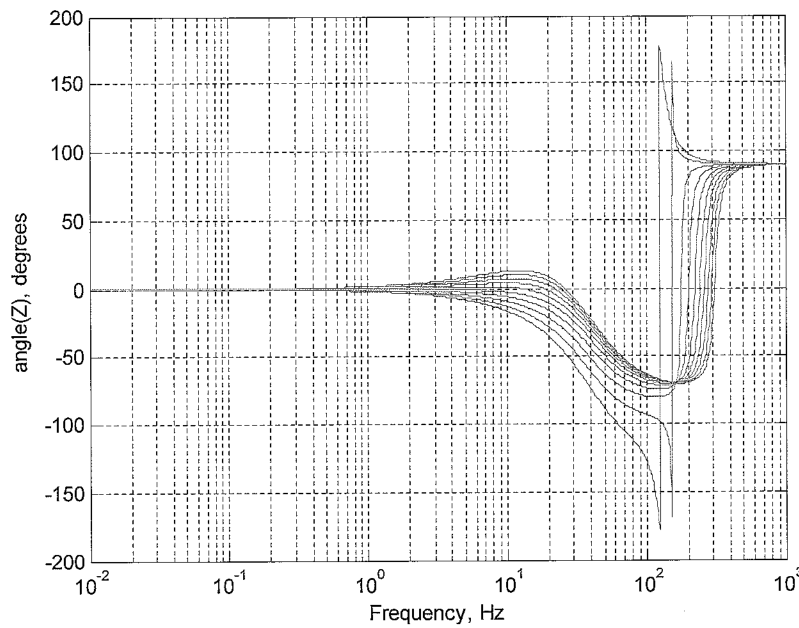


$K_{pv} = 0.136$ A/V
$K_{iv} = 23.2$ A/(Vs)
$s_1 = -170+170i$ 1/s
$s_2 = -170-170i$ 1/s

Impedance



20
10
0
-10
-20
-30
-40
|Z|, dB
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Frequency, Hz



200
150
100
50
0
-50
-100
-150
-200
angle(Z), degrees
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Frequency, Hz

Selecting K_{ai}

- Recall the time constant associated with the anti-windup control is

$$\frac{1}{\tau} = \frac{4v_{dc}}{3P\lambda_m\omega_{rm}} K_{iv} K_{ai}$$

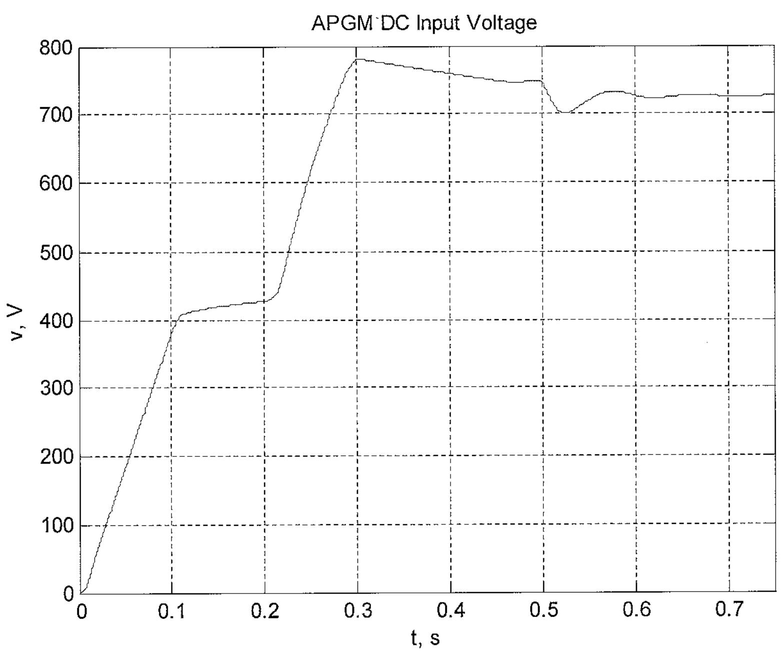
- Putting time constant at 0.1 ms

$$K_{ai} = 5200 \text{ V/A}$$

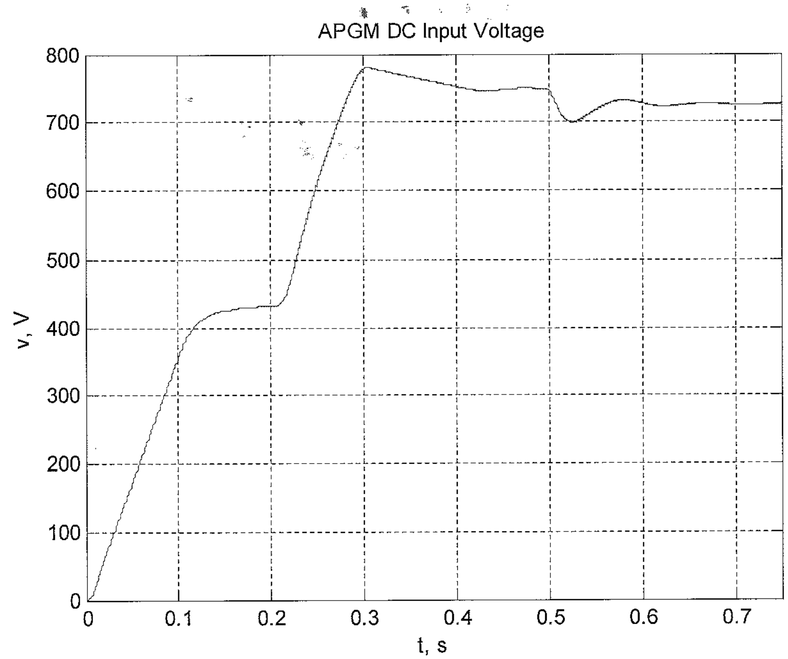
System Performance

- Speed ramps up from 0 to 0.1 s
- Turn on into 625 Ω load at 0.~~15~~ s 0.2 s) (900W)
- Turn on 58.4 Ω load at 0.5 s (9 kW)

Output Voltage



AVM



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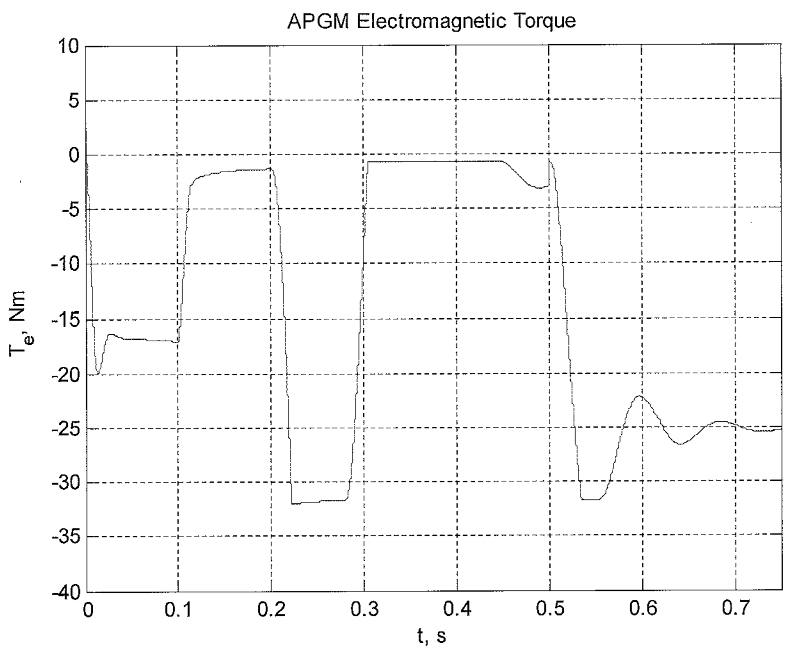
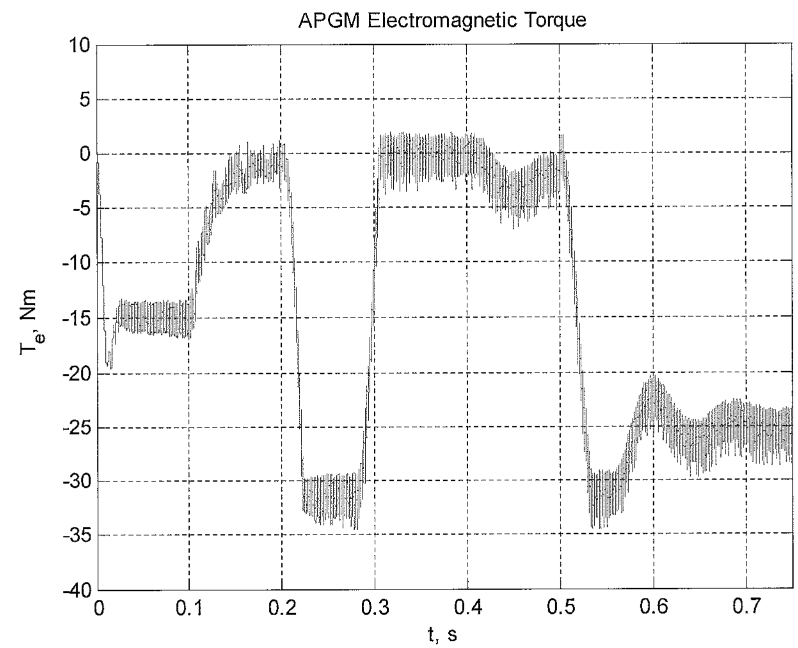
Torque



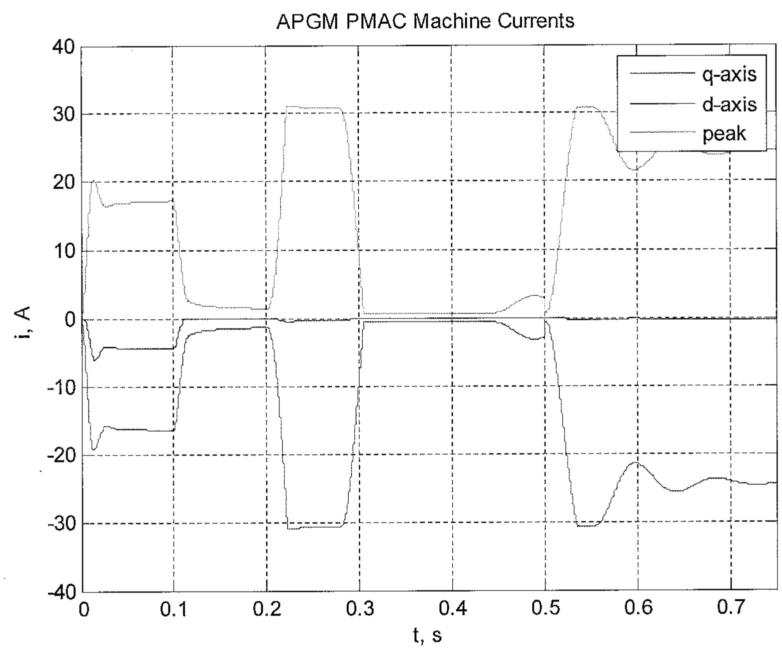


$\hat{V}_{dc} - K_d \hat{i}_{apgm}$

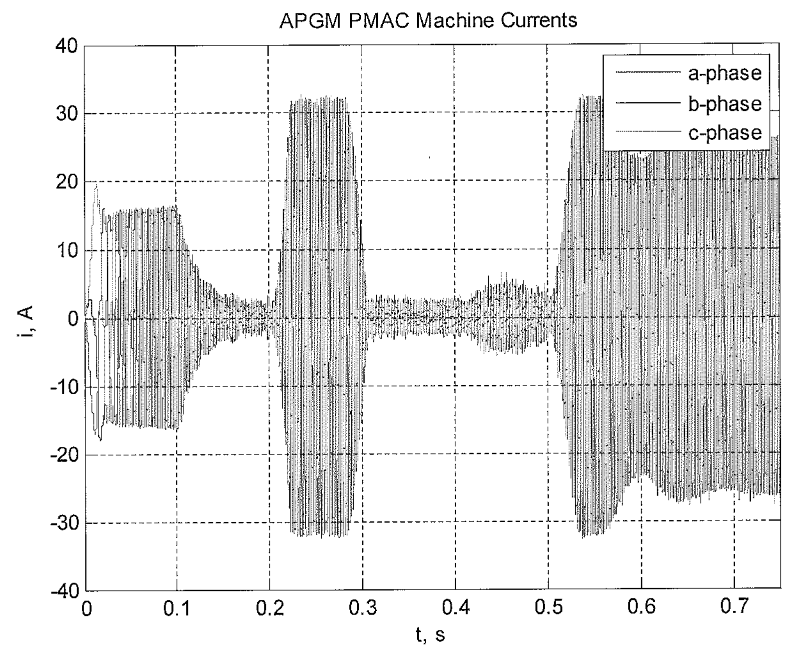
AVM

WLM

Currents



AVM



WLM

ECE61016 Power Electronics Converters and Systems

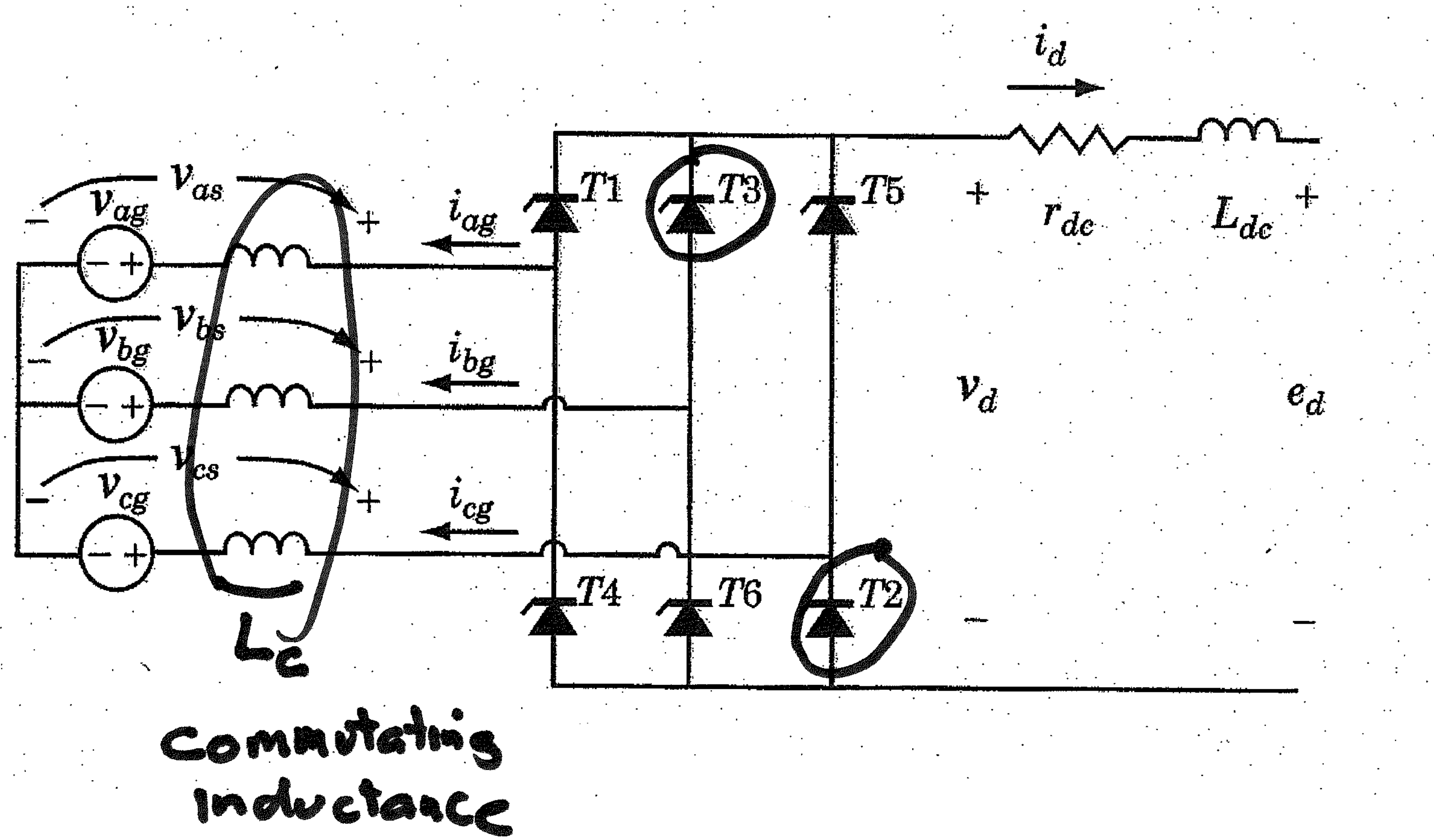
AC/DC Conversion with Passive Rectifiers Lecture Set 7A

S.D. Sudhoff

Fall 2016

Semi-Controlled Bridge Converter

- Topology

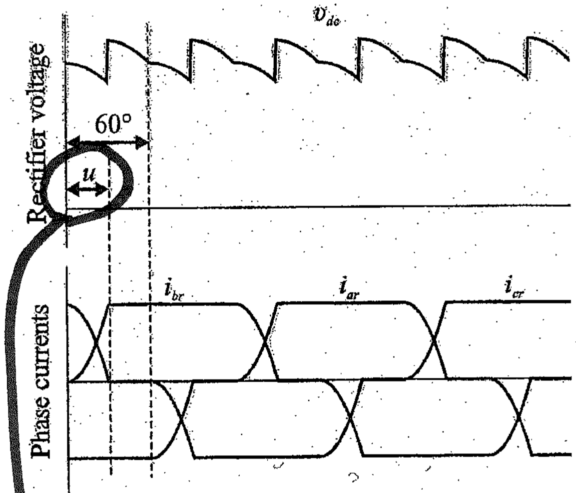


Operating Modes

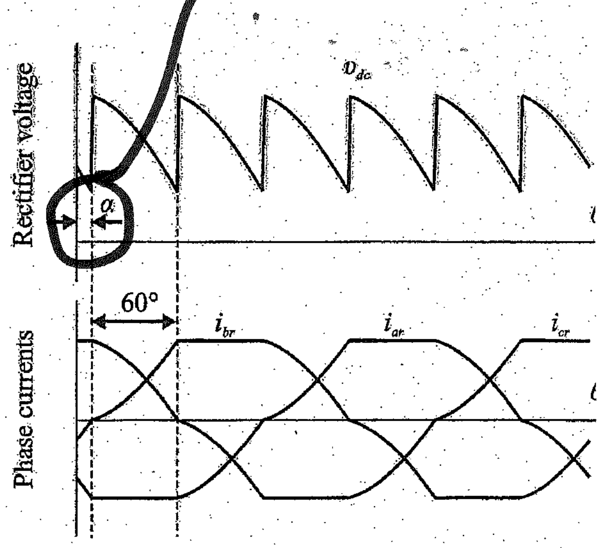
- Mode 0: 2 on / 0 on (discontinuous) 2-0
- **Mode 1: 2 on / 3 on** (normal) 2-3
- Mode 2: 3 on 3-3
- Mode 3: 3 on / 4 on 3-4

Operating Modes

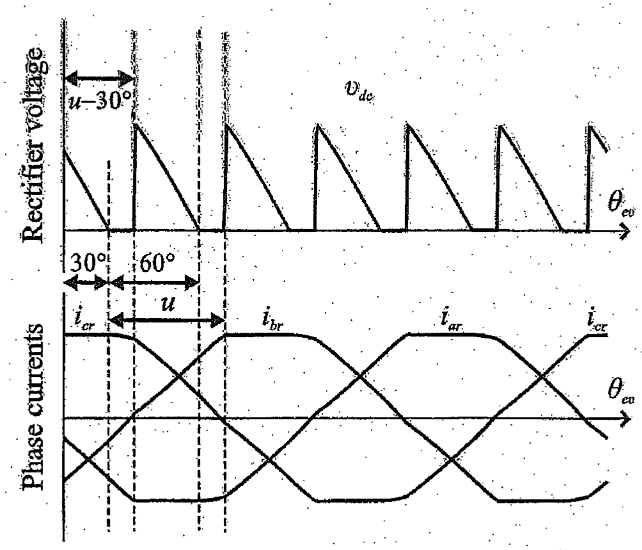
firing delay



Mode 1



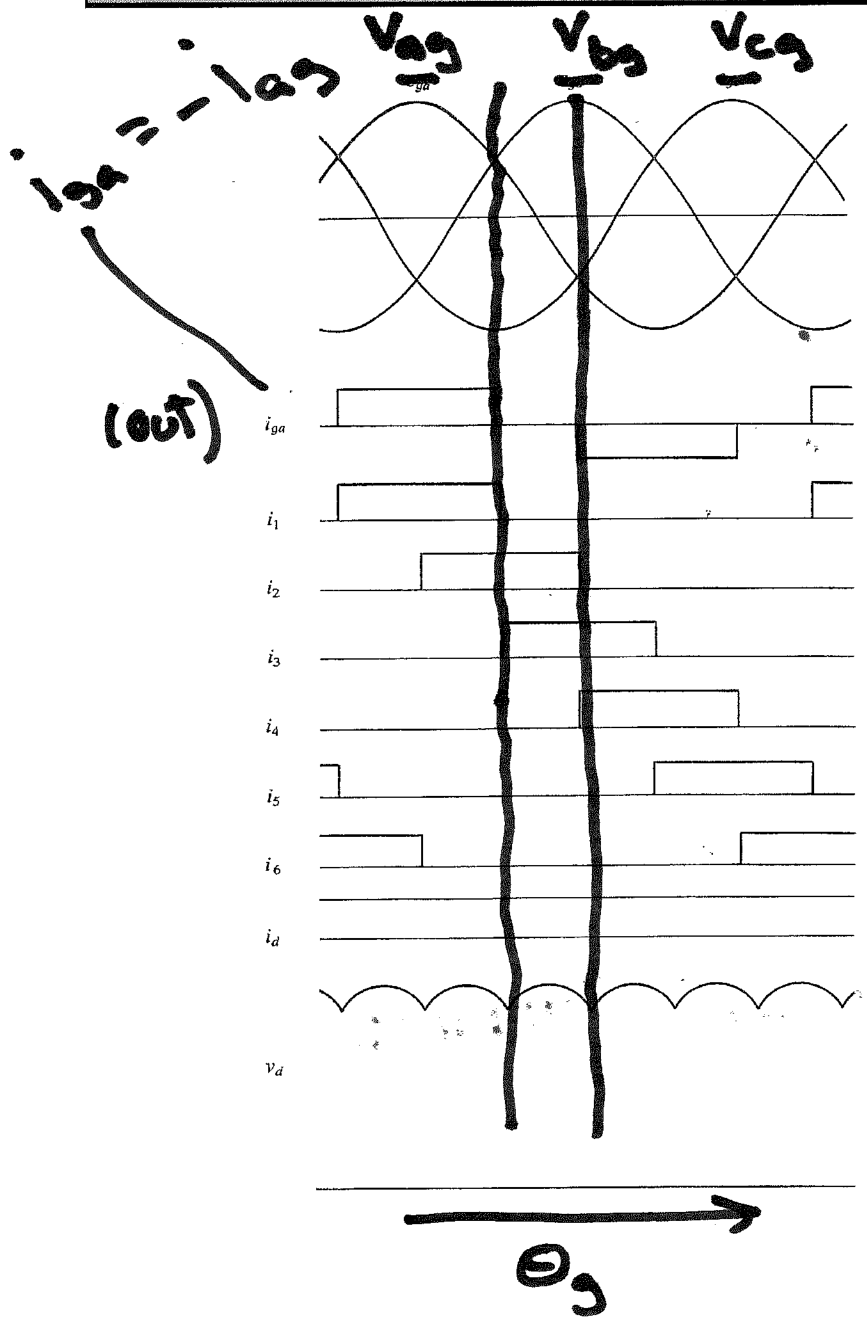
Mode 2



Mode 3

commutation angle (γ)

Idealized Operation



No phase delay $\alpha = 0$
No commutating inductance $L_c = 0$
AC currents out

Value 3 turns on when

$$\theta_g = \frac{\pi}{3} + \cancel{\alpha}^{\,0}$$

Value 4 turns on when

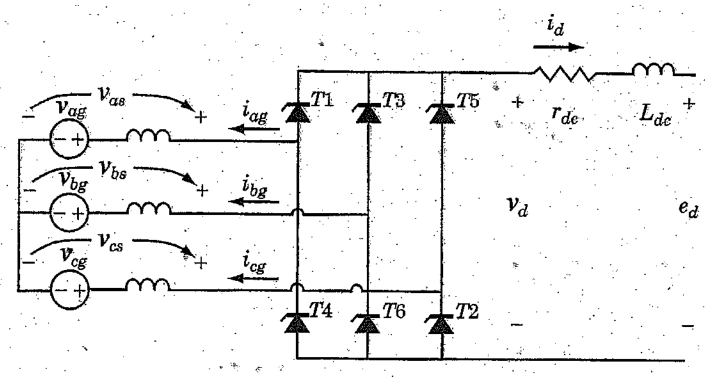
$$\theta_g = \frac{2\pi}{3} + \cancel{\alpha}^{\,0}$$

So we have value 2 & 3 on

$$V_d = V_{bs} - V_{cs}$$
$$= V_{bg} - V_{cg}$$

Idealized Operation

$$v_{abcg} = \sqrt{2}E \begin{bmatrix} \cos(\theta_g) \\ \cos(\theta_g - 2\pi/3) \\ \cos(\theta_g + 2\pi/3) \end{bmatrix}$$

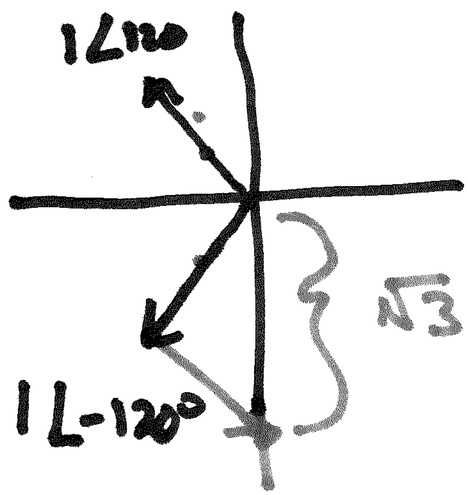


$$\hat{v}_d = \frac{3}{\pi} \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} (v_{bs} - v_{cs})\, d\theta_g \quad = \frac{3}{\pi} \int_{\pi/3}^{2\pi/3} v_{bg} - v_{cg} \, d\theta_g$$

$$= \frac{3}{\pi}\sqrt{2}E \quad 2\pi$$

Idealized Operation

$V_{bs} - V_{cs}$



$\sqrt{3}\angle -90$

$$V_{bs} - V_{cs} = \sqrt{3}\sqrt{2} E \cos(\theta_s - 90°)$$

$$= \sqrt{6} E \sin\theta_s$$

$$\hat{V}_d = \frac{3}{\pi}\sqrt{6} E \int_{\pi/3}^{2\pi/3} \sin\theta_s \, d\theta_s$$

$$C' = -S$$
$$S' = C$$

$$\hat{V}_d = -\frac{3\sqrt{6}}{\pi} E \cos\theta_s \Big|_{\pi/3}^{2\pi/3}$$

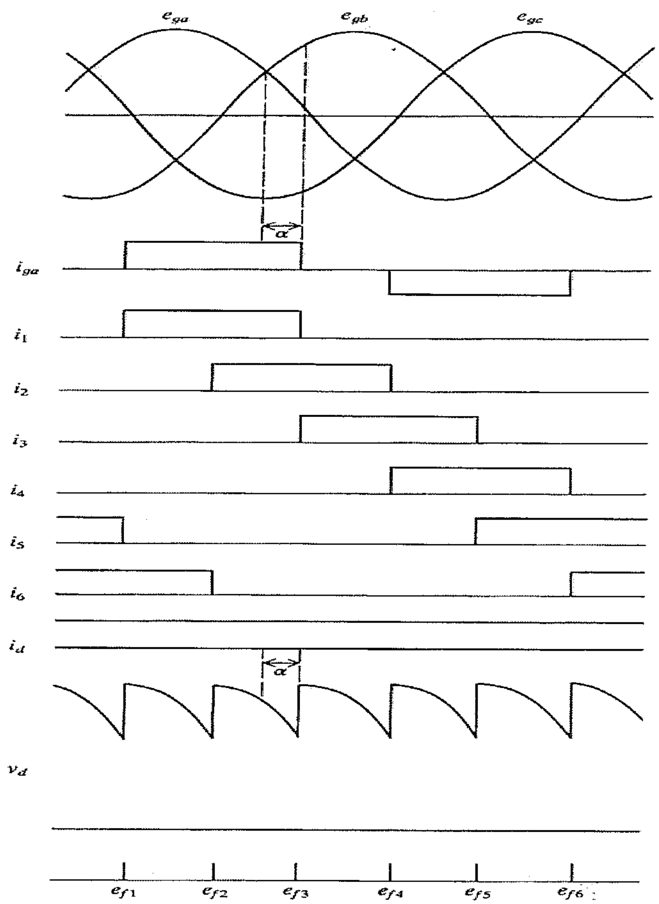
$$= -\frac{3\sqrt{6}}{\pi} E \left[-\frac{1}{2} - \frac{1}{2}\right] = \frac{3\sqrt{6}}{\pi} E$$

Idealized Operation

- Thus

$$\hat{v}_d = \frac{3\sqrt{3}}{\pi}\sqrt{2}E$$

Phase Delay w/o Commutation



$$L_c = 0$$

$$\alpha \neq 0$$

$$\hat{V}_d = \frac{3}{\pi} \int_{\pi/3 + \alpha}^{2\pi/3 + \alpha} V_{bg} - V_{cg} \, d\theta_g$$

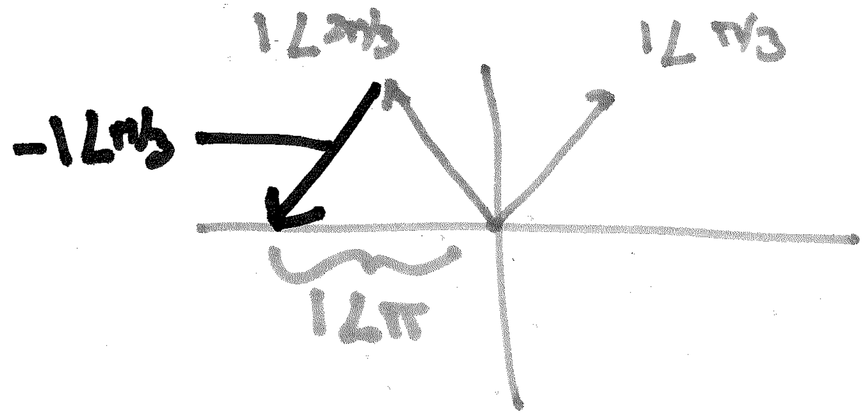
$$\hat{V}_d = \frac{3\sqrt{6}}{\pi} E \int_{\frac{\pi}{3}+\alpha}^{2\pi/3+\alpha} \sin\theta_g \, d\theta_g$$

$$\hat{V}_d = -\frac{3\sqrt{6}}{\pi} E \left[\cos\left(\alpha + \frac{2\pi}{3}\right) - \cos\left(\alpha + \frac{\pi}{3}\right) \right]$$

Warning – ac currents out

Phase Delay w/o Commutation

$$v_{abcg} = \sqrt{2}E \begin{bmatrix} \cos(\theta_g) \\ \cos(\theta_g - 2\pi/3) \\ \cos(\theta_g + 2\pi/3) \end{bmatrix}$$



$$\hat{v}_d = \frac{3}{\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} (v_{bs} - v_{cs})\, d\theta_g$$

$$\hat{V}_d = -\frac{3\sqrt{6}}{\pi} E\,(-\cos\alpha)$$

$$= \frac{3\sqrt{6}}{\pi} E \cos\alpha$$

$$\hat{v}_d = \frac{3\sqrt{3}}{\pi}\sqrt{2}E\cos\alpha$$