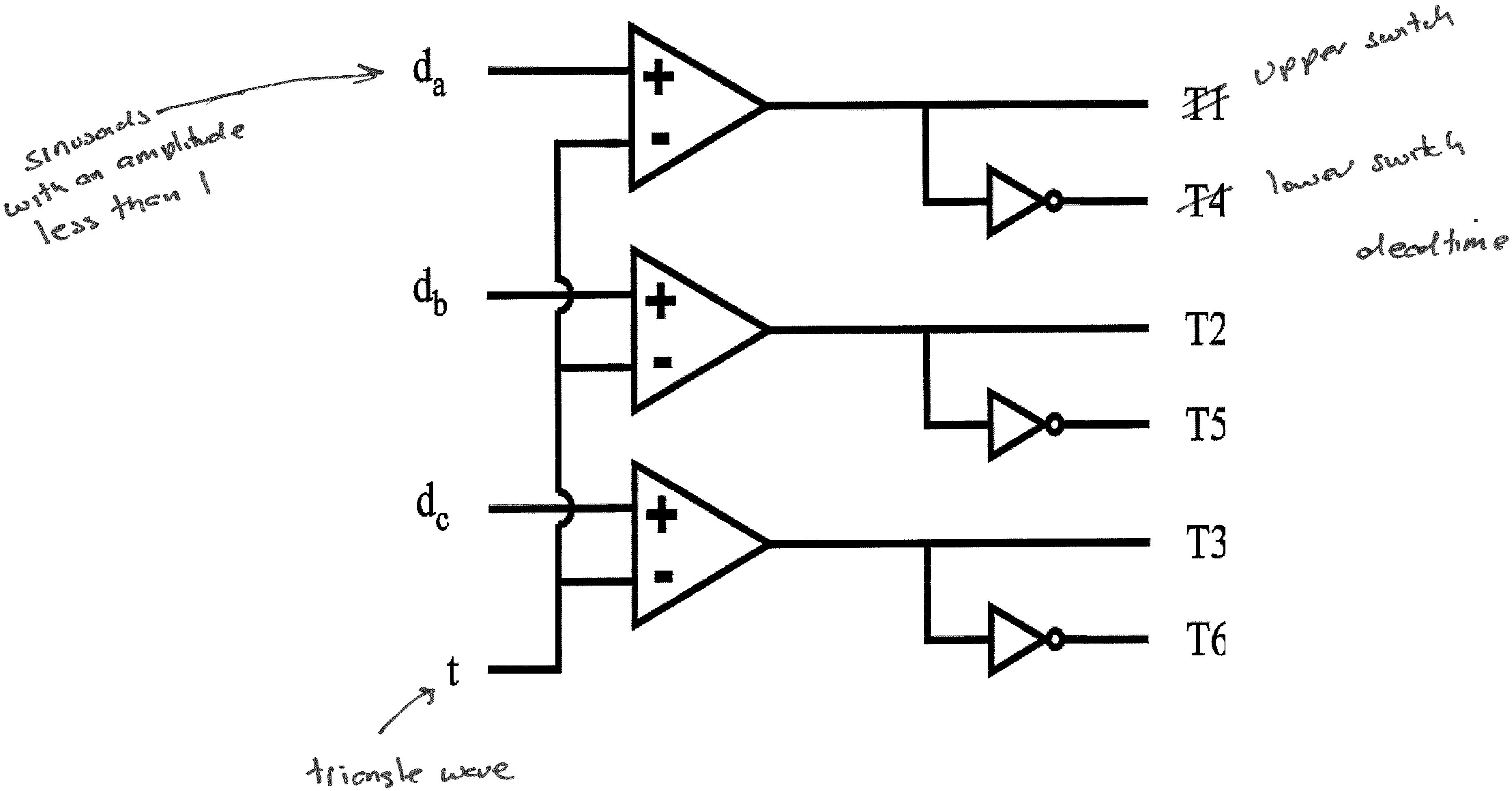
AVM of Inverter Module

- Features
  - Include conduction losses
  - Ignore switching losses
  - Based on sine-triangle with 3rd harmonic modulation

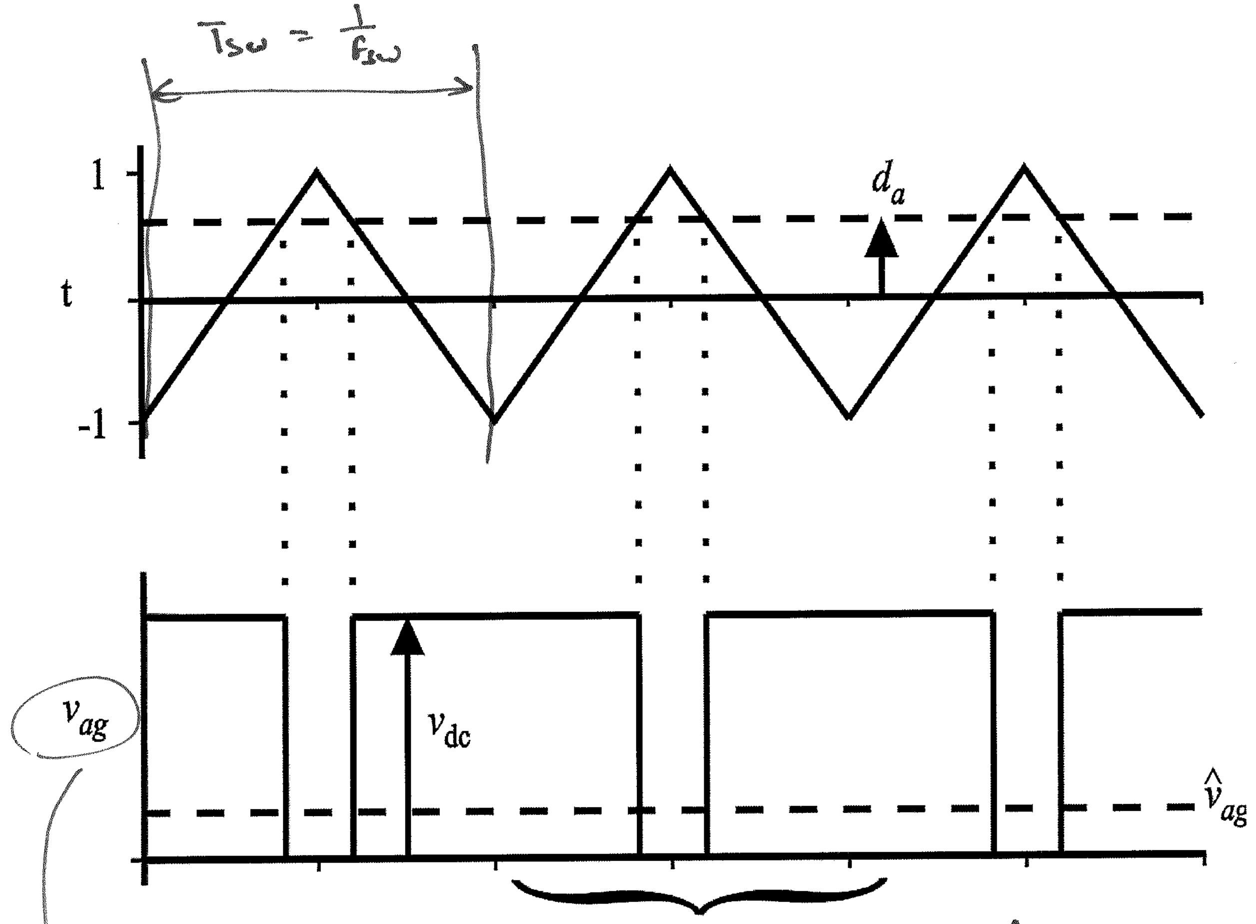
Sine-Triangle Modulation

- Features
  - Adjustable voltage magnitude
  - Adjustable frequency
  - Low low-frequency harmonic content
- Comments
  - Originally meant for analog implementation
  - Digital equivalents exist

Gate Signal Controls



Operation of A-Phase Leg



$V_{as} = V_{dc}\,(d_a > t)$

$\hat{V}_{as} = V_{dc}\underbrace{(1 + d_a)\tfrac{1}{2}}_{d_{as}}$ for $|d_a| \leq 1$

Analysis

- Recall the fast average
  - $$\hat{x}(t) = \frac{1}{T_{sw}} \int_{t-T_{sw}}^{t} x(t)dt \qquad (13.5\text{-}1)$$
- We can show that
  - $$\hat{v}_{ag} = \frac{1}{2}(1+d_a)v_{dc} \qquad (13.5\text{-}2)$$
  - $$\hat{v}_{bg} = \frac{1}{2}(1+d_b)v_{dc} \qquad (13.5\text{-}3)$$
  - $$\hat{v}_{cg} = \frac{1}{2}(1+d_c)v_{dc} \qquad (13.5\text{-}4)$$

Analysis (2)

- Lets specify duty cycles as
  - $d_a = d\cos\theta_c$ (13.5-5)
  - $d_b = d\cos(\theta_c - \frac{2\pi}{3})$ (13.5-6)
  - $d_c = d\cos(\theta_c + \frac{2\pi}{3})$ (13.5-7)

converter angle

If the $\theta = \theta_c$ reference frame, all the commanded voltage is in the q-axis

$V_q^{c*} = \cancel{\ }$

$V_d^{c*} = 0$

Analysis (3)

- Thus
  - $\hat{v}_{qi}^{c} = \frac{1}{2} d v_{dc}$ (13.5-14)
  - $\hat{v}_{di}^{c} = 0$ (13.5-15)

$\cos(\theta_c)$

$$\hat{v}_{qdi}^{c} = \frac{2}{3} \begin{bmatrix} c & c^- & c^+ \\ s & s^- & s^+ \end{bmatrix} \begin{bmatrix} \hat{v}_{as} \\ \hat{v}_{bs} \\ \hat{v}_{cs} \end{bmatrix}$$

$$= \frac{2}{3} \begin{bmatrix} c & c^- & c^+ \\ s & s^- & s^+ \end{bmatrix} \begin{bmatrix} v_{dc} \frac{1}{2}(1 + dc) \\ v_{dc} \frac{1}{2}(1 + dc^-) \\ v_{dc} \frac{1}{2}(1 + dc^+) \end{bmatrix}$$

not including switch drops

$$= \begin{bmatrix} \frac{1}{2} d v_{dc} \\ 0 \end{bmatrix}$$

AVM: Conduction Loss

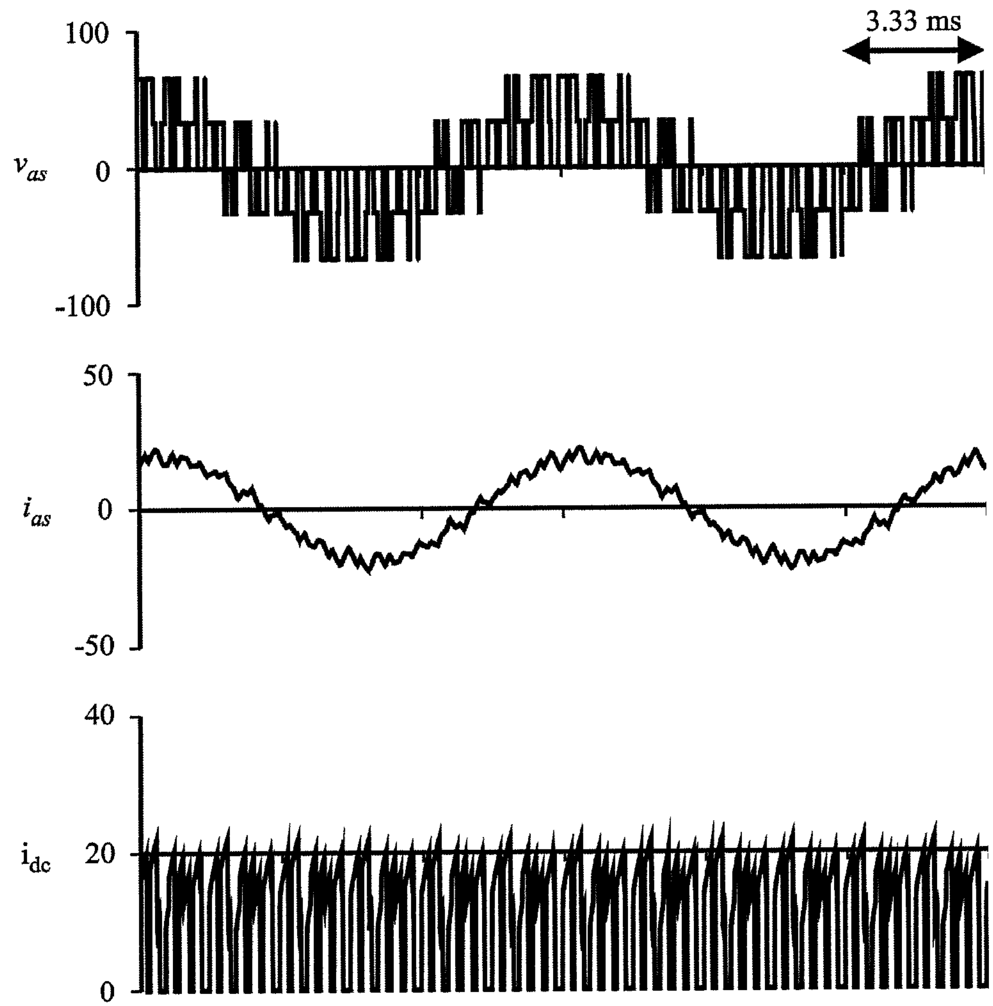
- Develop an Average Value Model for the DC/AC Converter

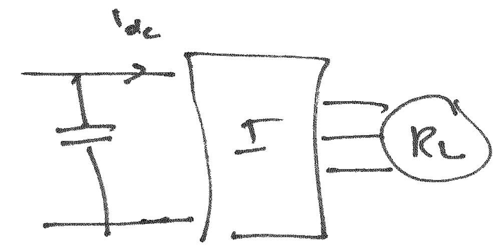
- Features
  - Include conduction losses
  - Ignore switching losses
  - Based on sine-triangle with 3rd harmonic modulation

An Example

- Load: Balanced, wye-connected, series RL
  - R = 2 Ω
  - L = 1 mH
- DC Voltage: 100 V
- Fundamental Frequency: 100 Hz
- Duty Cycle: 0.4 $= \alpha$
- Switching Frequency: 3000 Hz

Sine-Triangle Modulation





Limitations of Sine-Triangle Modulation

- Sine Triangle Modulation
  - Range for duty cycle: $0 \leq d \leq 1$
  - Range for peak voltage (of fund): $\left[0 \quad \tfrac{1}{2}V_{dc}\right]$

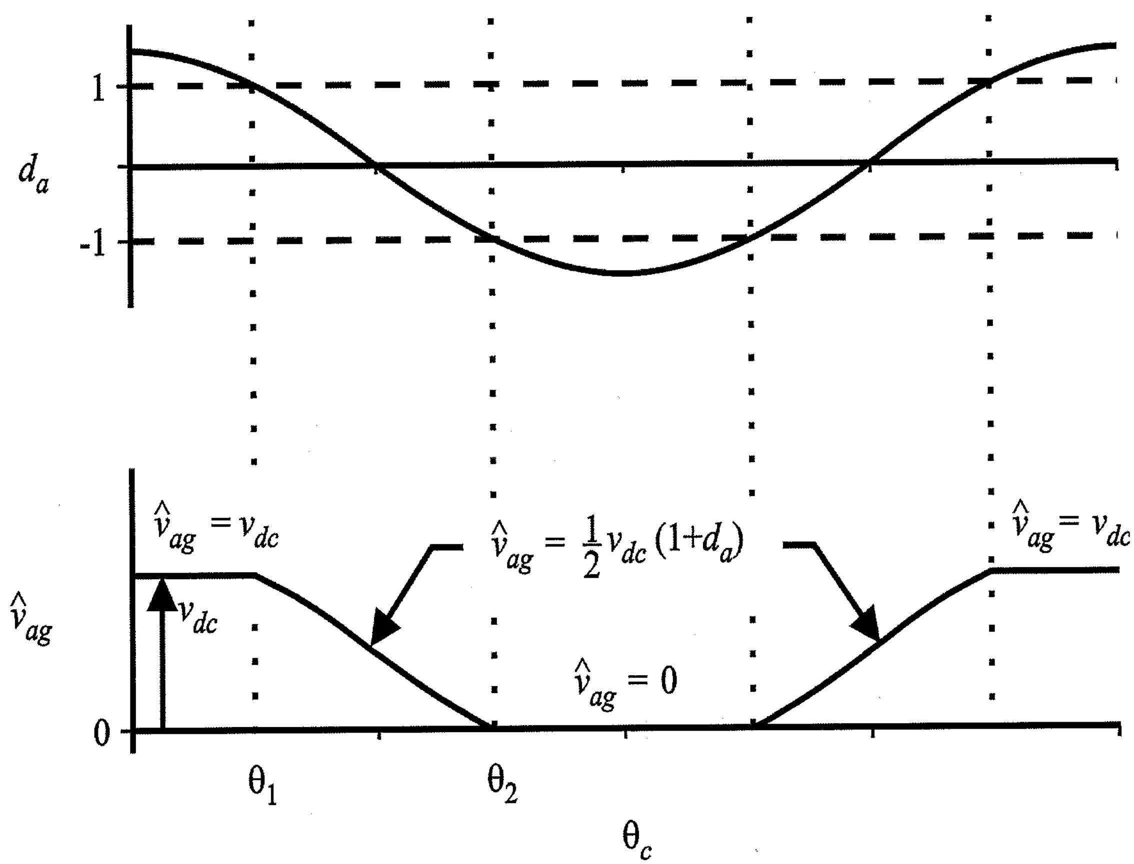
$\underbrace{\left[0 \quad \tfrac{1}{2}V_{dc}\right]}_{\text{peak value of fund.}}$

$$\boxed{V_s \leq \frac{1}{\sqrt{6}} V_{dc}}$$

$$\sqrt{2}\, V_s \leq \frac{1}{\sqrt{3}} V_{dc}$$

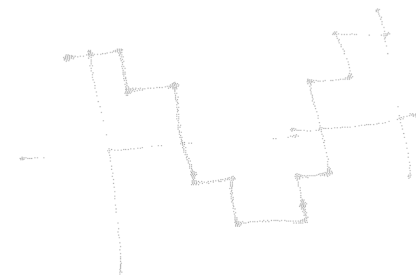
$$\text{peak value of fund} \leq \frac{1}{\sqrt{3}} V_{dc}$$

Overmodulation



Analysis of Overmodulation

- Line-to-ground voltage



  - $$\bar{v}_{ag} = \begin{cases} v_{dc} & d_a > 1 \\ \frac{1}{2}(1+d_a)v_{dc} & -1 < d_a < 1 \\ 0 & d_a < 1 \end{cases} \quad (13.5\text{-}16)$$
  - $$\left|v_{ag}\right|_{avg+fund} = \frac{v_{dc}}{2} + \frac{2v_{dc}}{\pi} f(d)\cos\theta_c \quad (13.5\text{-}17)$$
  - $$f(d) = \frac{1}{2}\sqrt{1-\left(\frac{1}{d}\right)^2} + \frac{1}{4}d\left(\pi - 2\arccos\left(\frac{1}{d}\right)\right) \quad (13.5\text{-}18)$$

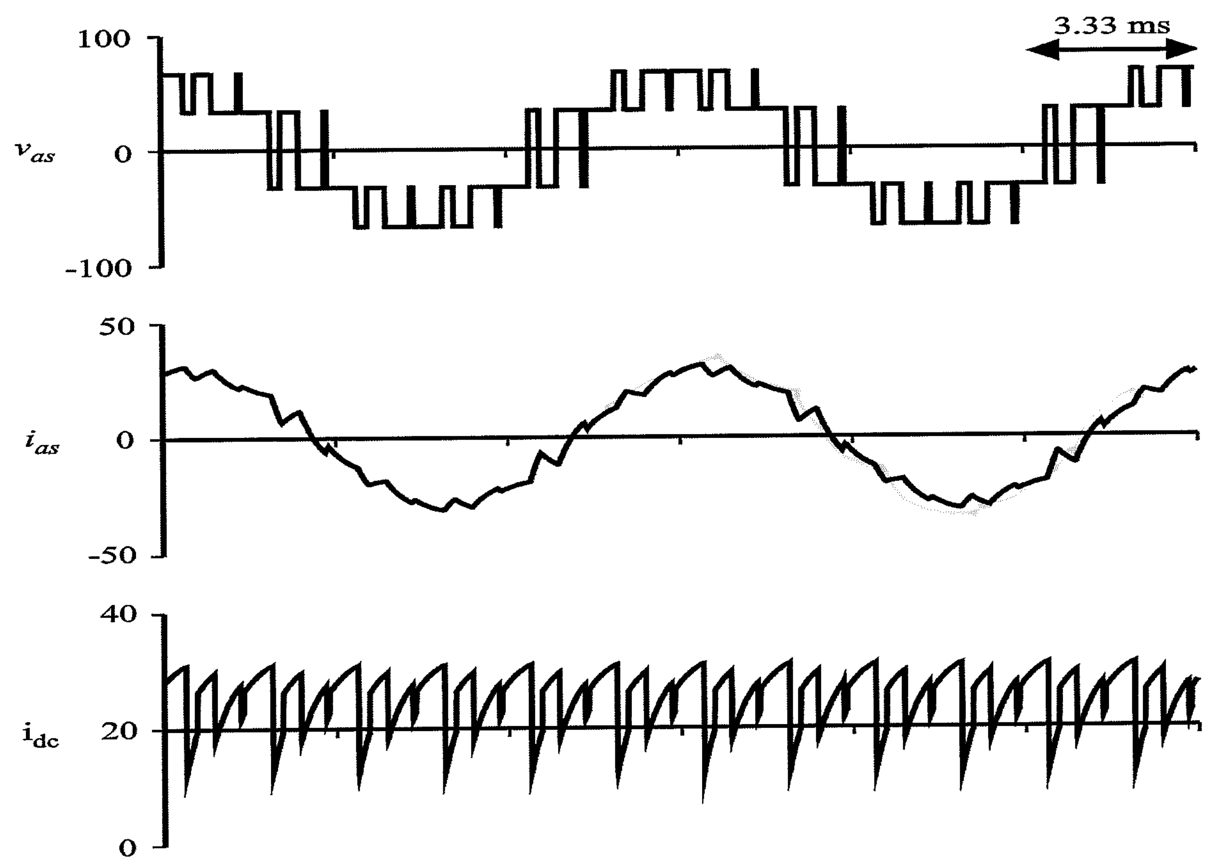
$F(1) = \frac{\pi}{4}$ if $d \to \infty$

$F(\infty) = 1$ $\hat{v}_{ag1}^{c} = \frac{2}{\pi} v_{dc}$

Analysis of Overmodulation (2)

- Thus we have
  - $\bar{v}_{qs}^{c} = \dfrac{2v_{dc}}{\pi} f(d) \;\; d \geq 1$ (13.5-20)
  - $\bar{v}_{ds}^{c} = 0 \;\; d \geq 0$ (13.5-21)

Overmodulation (d=2)



13.6 Third-Harmonic Injection

- Objective …

→ strategy for increasing voltage w/o introducing low-frequency harmonics

The Plan

- Suppose

add to phase duty cycles

  - $d_a = d\cos(\theta_c) - d_3\cos(3\theta_c)$ (13.6-1)
  - $d_b = d\cos(\theta_c - \frac{2\pi}{3}) - d_3\cos(3\theta_c)$ (13.6-2)
  - $d_c = d\cos(\theta_c + \frac{2\pi}{3}) - d_3\cos(3\theta_c)$ (13.6-3)

$$V_{qdi}^{c} = \frac{2}{3}\begin{bmatrix} c & c^- & c^+ \\ s & s^- & s^+ \end{bmatrix}\begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix}$$

$$= \frac{2}{3}\begin{bmatrix} c & c^- & c^+ \\ s & s^- & s^+ \end{bmatrix}\frac{V_{dc}}{2}\begin{bmatrix} 1 + dc - d_3\cos(3\theta_c) \\ 1 + dc^- - d_3\cos(3\theta_c) \\ 1 + dc^+ - d_3\cos(3\theta_c) \end{bmatrix}$$

$$= \frac{1}{2}V_{dc}\begin{bmatrix} d \\ 0 \end{bmatrix}$$

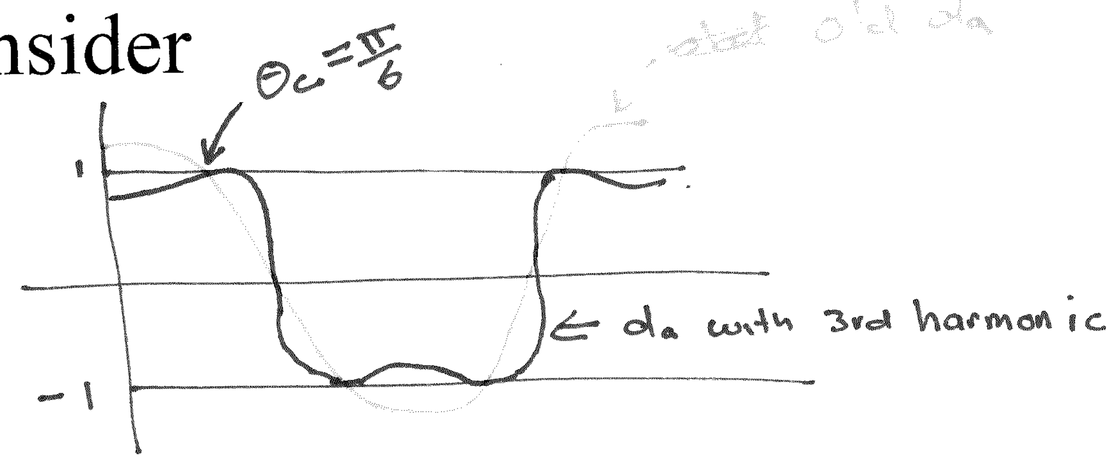
Results

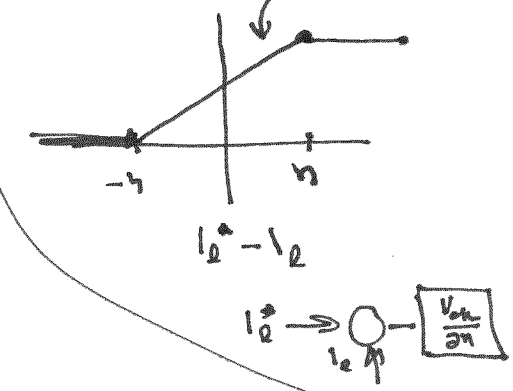
- Working for a little bit …

- Therefore
  - $\hat{v}_{qs}^{c} = \frac{1}{2} d v_{dc}$ (13.5-14)
  - $\hat{v}_{ds}^{c} = 0$ (13.5-15)

So What?

- Consider





$\cos(3\frac{\pi}{6}) = \cos(\frac{\pi}{2}) = 0$

$\Rightarrow$ we need $d\cos(\frac{\pi}{6}) < 1$ $\quad d \leq \frac{1}{\cos(\frac{\pi}{6})}$ $\frac{2}{\sqrt{3}} \simeq 1.15$

$\Rightarrow$ If θ_c is to be the peck then $\frac{dd_a}{d\theta_c} = 0$ at $\pi/6$

$d_a = d\cos\theta_c - d_3\cos 3\theta_c$

$\frac{dd_a}{d\theta_c} = -d\sin\theta_c + 3d_3\sin(3\theta_c) = 0$

$-d\sin(\frac{\pi}{6}) + 3d_3 = 0$

$d_3 = \frac{1}{3}d\sin(\frac{\pi}{6}) = \frac{d}{6}$

So What ?

- Thus
  - $d \le \frac{2}{\sqrt{3}}$
- Result
  - 15% Increase in Available Voltage

AVM2

Semiconductor Model

- Transistor

$$v = v_{sw} + r_{sw}\, i$$

- Diode

$$v = v_d + r_d\, i$$

What we want to do

Given I_q & I_d on ac side we want the dc current

Given V_{dc} on the dc side we want the q- and d-axis voltages

Easy for voltage source strategies

Complications

① saturation of modulation commands

② hysteresis modulator

First Goal: DC current

AVM – DC Current

- Consider the converter current reference frame

reference frame where all the ~~curr~~ ac side current is in the q-axis.

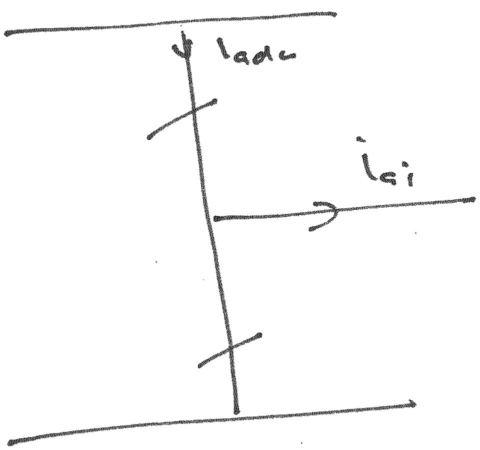
$$i_{ai} = i_{qi}^{ci} \cos\theta_{ci}$$

$$\begin{bmatrix} i_{ai} \\ i_{bi} \\ i_{ci} \end{bmatrix} = \begin{bmatrix} c & s & 1 \\ c^- & s^- & 1 \\ c^+ & s^+ & 1 \end{bmatrix} \begin{bmatrix} i_{qi}^{ci} \\ 0 \\ 0 \end{bmatrix}$$

$$i_{ai} = i_{qi}^{ci} \cos\theta_{ci}$$

AVM – DC Current

- Sine-Triangle Modulation with 3rd Harmonic



upper switch on (d_{as} of time)

$i_{adc} = i_{ai}$

lower switch on $(1-d_{as})$ of the time

$i_{adc} = 0$

$$i_{adc} = i_{ai} d_{as}$$

AVM – DC Current

- We have

$$d_{ag} = \frac{1}{2}(1 + d_{as})$$

$$d_{as} = d\cos(\overbrace{\theta_{ci} - \phi}^{\theta_c}) - d_3 \cos(\overbrace{3(\theta_{ci} - \phi)}^{3\theta_c})$$

$$\theta_c = \theta_{ci} - \phi$$

$$\boxed{\phi = \theta_{ci} - \theta_c}$$

By definition, the angular displacement between the two reference frames.

AVM – DC Current

- We have

$$\hat{i}_{a,dc} = i_{ai} d_{ag}$$

$$\bar{i}_{a,dc} = \frac{1}{2\pi} \int_{-\pi/2}^{3\pi/2} \hat{i}_{a,dc}(\theta_{ci}) d\theta_{ci}$$

$$= \frac{1}{2\pi} \int_{-\pi/2}^{3\pi/2} i_{qi}^{ci} \cos\theta_{ci} \frac{1}{2} \left(1 + d\cos(\theta_{ci} - \phi) - d_3 \cos(3(\theta_{ci} - \phi)\right) d\theta_{ci}$$

$$= \frac{i_{qi}^{ci}}{4\pi} \int_{-\pi/2}^{3\pi/2} \cos\theta_{ci} + \frac{1}{2}\cos(-\phi) + \frac{1}{2}\cos(2\theta_{ci} - \phi) - \frac{d_3}{2}\cos(4\theta_{ci} - 3\phi) - \frac{d_3}{2}\cos(2\theta_{ci} - 2\phi) \, d\theta_{ci}$$

AVM – DC Current

$$\bar{i}_{a,dc} = \frac{i_{g1}^{ci}}{4\cancel{\pi}} \frac{1}{\cancel{2}} \cos(\phi)\, \cancel{2\pi}$$

$$= \frac{1}{4} i_{g1}^{ci} \cos\phi$$

AVM – DC Current

AVM – DC Current

- Thus we have for the a-phase

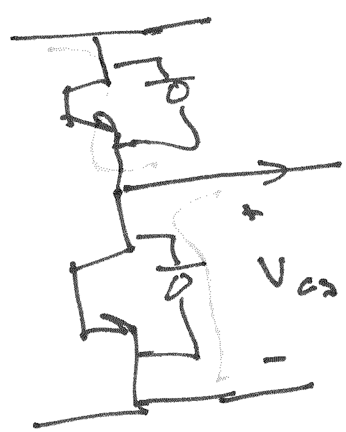
$$\bar{i}_{a,dc} = \frac{1}{4} d\, i_{qi}^{ci} \cos(\phi)$$

- The total dc current must be given by

$$\boxed{\hat{i}_{dc} = \frac{3}{4} d\, i_{qi}^{ci} \cos(\phi)}$$

AVM – Voltage for Positive Current

Assume $i_{ai} \geq 0 \qquad -\frac{\pi}{2} \leq \theta_{ci} \leq \frac{\pi}{2}$



If upper switch on $\underline{(d_{as})}$ of the time

$V_{ag} = V_{dc} - V_{sw} - r_{sw} i_{ai}$

If lower switch on $\underline{(1-d_{as})}$ of the time

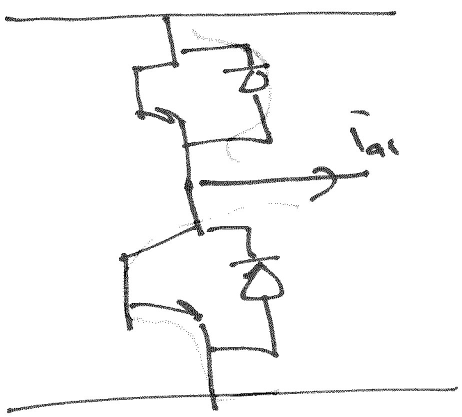
$V_{ag} = -V_{d} - r_{d} i_{ai}$

$$\underline{\hat{V}_{ag+}} = (V_{dc} - V_{FSW} - r_{sw} i_{ai}) d_{as} - (V_{d} + r_{d} i_{ai})(1-d_{as})$$

Fast average of V_{as} when the current is positive or $-\frac{\pi}{2} \leq \theta_{ci} \leq \frac{\pi}{2}$

AVM – Voltage for Positive Current

AVM – Voltage for Negative Current



Assume $i_{ai} < 0$

if upper switch on

$v_{ag} = v_{dc} + v_d - r_d i_{ai}$

if lower switch on

$v_{ag} = v_{sw} - r_{sw} i_{ai}$

$$\therefore \hat{v}_{ag-} = (v_{dc} + v_d - r_d i_{ai}) d_{ag} + (v_{sw} - r_{sw} i_{ai})(1 - d_{ag})$$

fast average of v_{ag} while $i_{ai} < 0$

or $\frac{\pi}{2} \leq \theta_{ci} \leq \frac{3\pi}{2}$

AVM - Voltage

- Thus the fast average voltages may be expressed

$$\hat{v}_{ag} = \begin{cases} \hat{v}_{ag+} & i_{ai} > 0 \\ \hat{v}_{ag-} & i_{ai} < 0 \end{cases}$$

$$\hat{v}_{ag+} = (v_{dc} - v_{sw} - r_{sw} i_{ai}) d_{ag} + (-v_d - r_d i_{ai})(1 - d_{ag})$$

$$\hat{v}_{ag-} = (v_{dc} + v_d - r_d i_{ai}) d_{ag} + (v_{sw} - r_{sw} i_{ai})(1 - d_{ag})$$

AVM - Voltage

- The fundamental component of the line-to-ground voltage may be expressed

$$\hat{v}_{ag}\Big|_{fund} = a_1 \cos\theta_{ci} + b_1 \sin\theta_{ci}$$

$$a_1 = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} \hat{v}_{ag+} \cos(\theta_{ci}) d\theta_{ci} + \frac{1}{\pi}\int_{\pi/2}^{3\pi/2} \hat{v}_{ag-} \cos(\theta_{ci}) d\theta_{ci}$$

$$b_1 = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} \hat{v}_{ag+} \sin(\theta_{ci}) d\theta_{ci} + \frac{1}{\pi}\int_{\pi/2}^{3\pi/2} \hat{v}_{ag-} \sin(\theta_{ci}) d\theta_{ci}$$

AVM - Voltage

- After substantial manipulation

$$a_1 = \frac{1}{2}(v_{dc} - v_{sw} + v_d) d \cos\phi - \frac{2}{\pi}(v_d + v_{sw}) - \cdots$$

$$\left(\frac{1}{2}(r_{sw} + r_d) + \frac{4}{3\pi}\left(d\cos(\phi) - \tfrac{1}{5} d_3 \cos(3\phi) \right)(r_{sw} - r_d) \right) i_{qc}^{ci}$$

$$b_1 = \frac{1}{2}(v_{dc} + v_d - v_{sw}) d \sin(\phi) - \cdots$$

$$\frac{2(r_{sw} - r_d)}{3\pi}\left(d\sin(\phi) - \frac{3}{5} d_3 \sin(3\phi) \right) i_{qc}^{ci}$$

AVM - Voltage

- After a little more work, we have

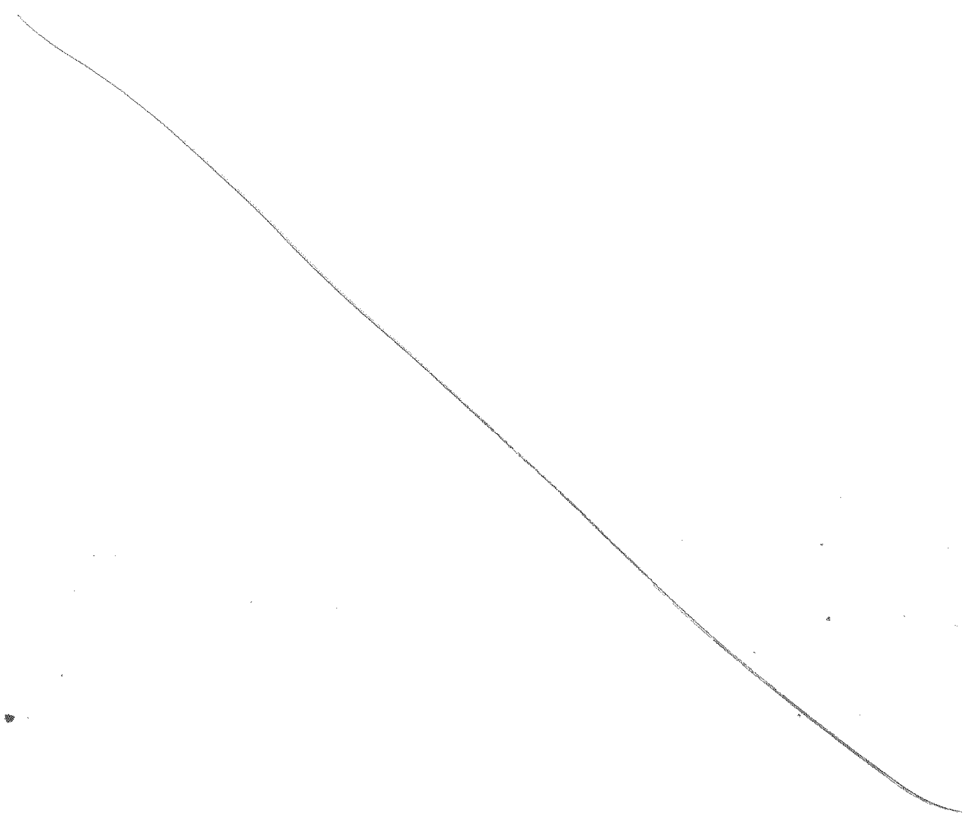
$$\overline{v}_{qi}^{ci} = a_1$$

$$\overline{v}_{di}^{ci} = b_1$$

- To show this

$$\begin{bmatrix} v_{qi}^{ci} \\ v_{di}^{ci} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \overset{\cos(\theta_{ci})}{c} & c^- & c^+ \\ s & s^- & s^+ \end{bmatrix} \begin{bmatrix} a_1 c + b_1 s \\ a_1 c^- + b_1 s^- \\ a_1 c^+ + c_1 s^+ \end{bmatrix} = \begin{bmatrix} a_1 \\ b_1 \end{bmatrix}$$

AVM - Voltage



AVM - Voltage

AVM – Modulation Signal

- Problem: we need to know d, d_3, ϕ
- Starting point: modulation indices

$$m_q^* = \frac{v_q^*}{v_{dc}}$$

$$m_d^* = \frac{v_d^*}{v_{dc}}$$

AVM – Modulation Signal

- We will need the modulation signal in the current reference frame

$$\begin{bmatrix} m_q^{ci*} \\ m_d^{ci*} \end{bmatrix} = \overbrace{\begin{bmatrix} \cos(\theta_{ci}-\theta) & -\sin(\theta_{ci}-\theta) \\ \sin(\theta_{ci}-\theta) & \cos(\theta_{ci}-\theta) \end{bmatrix}}^{{}^{a}K^{ci}} \begin{bmatrix} m_q^{*} \\ m_d^{*} \end{bmatrix}$$

AVM – Modulation Signal

- It can be shown that

$$\theta_{ci} - \theta = \text{angle}(i_{qi} - j i_{di})$$

- To show this

cos ($\theta_{ci} - \theta$)

$$\begin{bmatrix} i_{qi}^{ci} \\ 0 \end{bmatrix} = \underbrace{\begin{bmatrix} c & -s \\ s & c \end{bmatrix}}_{{}^{a}K^{ci}} \begin{bmatrix} i_{qi} \\ i_{di} \end{bmatrix}$$

$$\begin{bmatrix} i_{qi} \\ i_{di} \end{bmatrix} = \underbrace{\begin{bmatrix} c & s \\ -s & c \end{bmatrix}}_{{}^{ci}K^{a}} \begin{bmatrix} i_{qi}^{ci} \\ 0 \end{bmatrix}$$

AVM – Modulation Signal

$$\dot{i}_{qi} = I_{qi}^{ci} \cos(\theta_{ci} - \theta)$$

$$\dot{i}_{di} = - I_{qi}^{ci} \sin(\theta_{ci} - \theta)$$

$$\dot{i}_{qi} - j\dot{i}_{di} = I_{qi}^{ci} e^{j(\theta_{ci} - \theta)}$$

$$\boxed{\begin{aligned} \theta_{ci} - \theta &= \text{angle}\left(\dot{i}_{qi} - j\,\dot{i}_{di}\right) \\ I_{qi}^{ci} &= \sqrt{(i_{qi})^2 + (i_{di}^2)} \end{aligned}}$$

AVM – Modulation Signal

AVM – Modulation Signal

- In converter voltage reference frame

$$d_{as} = d^{*} \cos(\theta_c) - d_3^{*} \cos(3\theta_c)$$

- In this frame

$$\theta_c - \theta = angle(m_q^{*} - j m_d^{*})$$

$$m_q^{c*} = \sqrt{m_q^{*2} + m_d^{*2}}$$

$$m_d^{c*} = 0$$

AVM – Modulation Signal

- To show this

$$\begin{bmatrix} m_q^{cv*} \\ 0 \end{bmatrix} = \overbrace{\begin{bmatrix} \cos(\theta_{cv}-\theta) & -S(\ ) \\ S(\ ) & \cos(\theta_{cv}-\theta) \end{bmatrix}}^{{}^{a}K^{cv}} \begin{bmatrix} m_q^{*} \\ m_d^{*} \end{bmatrix}$$

$$\begin{bmatrix} m_q^{*} \\ m_d^{*} \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(\theta_{cv}-\theta) & S(\ ) \\ -\sin(\ ) & \cos(\theta) \end{bmatrix}}_{{}^{cv}K^{a}} \begin{bmatrix} m_q^{cv*} \\ 0 \end{bmatrix}$$

'c' = 'cv'

$$m_q^{*} = m_q^{cv*} \cos(\theta_{c*}-\theta)$$

same as m_q^{c*}

$$m_d^{*} = -m_q^{cv*} \sin(\theta_{c*}-\theta)$$

$$m_q^{*} - j m_d^{*} = m_q^{cv*} e^{j(\theta_{cv}-\theta)}$$

$$\theta_{cv}-\theta = \mathrm{angle}(m_q^{*} - j m_d^{*})$$

$$m_q^{cv*} = \sqrt{(m_q^{*})^2 + (m_d^{*})^2}$$

AVM – Modulation Signal

- Since we have

$$\theta_{ci} - \theta = \text{angle}(i_{qi} - j i_{di}) \qquad d_{as} = d\cos(\theta_{ci} - \phi) - d_3\cos(3(\theta_{ci} - \phi))$$

$$\theta_{cv} - \theta = \text{angle}(m_q^* - j m_d^*) \qquad d_{as} = d^*\cos(\theta_c) - d_3^*\cos(3\theta_c)$$

$$\phi = \theta_{ci} - \theta_{cv} = (\theta_{ci} - \theta) - (\theta_{cv} - \theta)$$

- We therefore have

$$\boxed{\phi = \text{angle}(i_{qi} - j i_{di}) - \text{angle}(m_q^* - j m_d^*)}$$

ϕ d, d_3

AVM Modulation Signal

- Desired magnitudes

$V_q^{cv} = \frac{1}{2} d V_{dc}$

$V_q^{cv} = \cancel{2} m_q^{cv} V_{dc}$

$\frac{1}{2} d = m_q^{cv*}$

$$d^* = 2m_q^{cv*}$$

$$d_3^* = \frac{1}{6} d^*$$

- For unsaturated operation $d^* < \frac{2}{\sqrt{3}}$

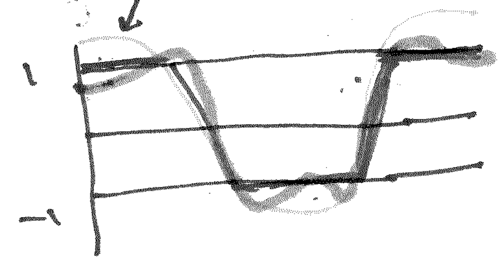
$$d = d^*$$

$$d_3 = d_3^*$$

AVM - Modulation

- Analysis plan for saturated operation

based on d^* d_3^*



a.

b.

$$d_{a,aprx} = d\cos(\theta_{cv}) - d_3\cos(3\theta_{cv})$$

$$f(d, d_3) =$$
$$\int_0^{\pi/2} \left(\text{bound}(-1,1,d_a(\theta_{cv})) - d_{a,aprx}(\theta_{cv})\right)^2 d\theta_{cv}$$

find d & d_3
that minimize f

$$\text{bound}(a,b,x) \equiv \begin{cases} a & x < a \\ x & a \le x \le b \\ b & x > b \end{cases}$$

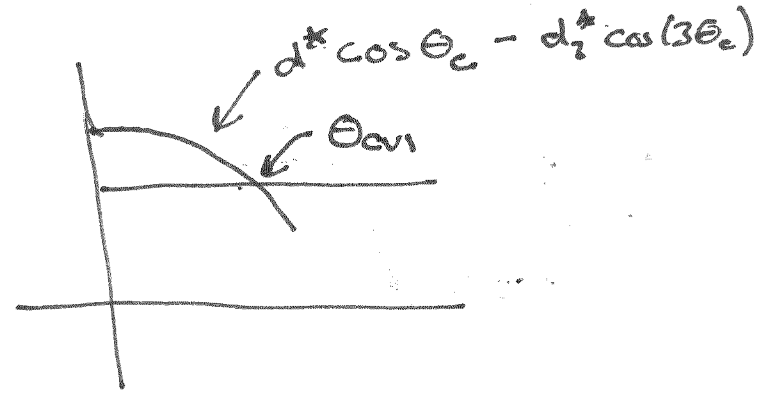
AVM Modulation

- Results

$$d = d^* + \frac{4}{\pi}\sin\theta_{cv1} + \frac{1}{\pi}\sin(2\theta_{cv1})(d_3^* - d^*) +$$
$$\frac{1}{2\pi}d_3^*\sin(4\theta_{cv1}) - \frac{2}{\pi}d^*\theta_{cv1}$$

$$d_3 = d_3^* - \frac{2}{\pi}d_3^*\theta_{cv1} + \ldots$$
$$\frac{1}{3\pi}\begin{pmatrix}(9d^* - 2d_3^*)\cos\theta_{cv1} + (3d^* - 2d_3^*)\cos(3\theta_{cv1}) - \ldots \\ 2d_3^*\cos(5\theta_{cv1}) - 4 - 8\cos(2\theta_{cv1})\end{pmatrix}\sin\theta_{cv1}$$

$$d^*\cos(\theta_{cv1}) - d_3^*\cos(3\theta_{cv1}) = 1$$



$$f = 1 - d^*\cos(\theta_{cv1}) + d_3^*\cos(3\theta_{cv1})$$

$$\frac{df}{d\theta_{cv1}} = d^*\sin\theta_{cv1} - 3d_3^*\sin(3\theta_{cv1})$$

To get θ_{cv1}

① Initialize

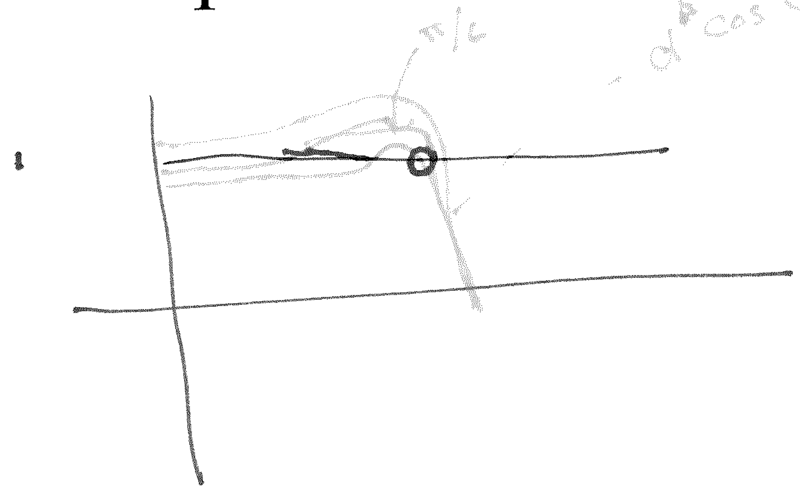
$\cancel{\theta_{cv1}}$ $\theta_{cv1} = \mathrm{acos}\left(\frac{1}{d^*}\right)$

② Iterate using Newton's method

$$\theta_{cv1} = \theta_{cv1} - \frac{F}{\frac{\partial F}{\partial \theta_{cv1}}}$$

AVM Modulation

- A subtle point



$- d^* \cos\theta_c - d_3^* \cos(3\theta_c)$

- This occurs when $\frac{2}{\sqrt{3}} < d < \frac{6}{5}$

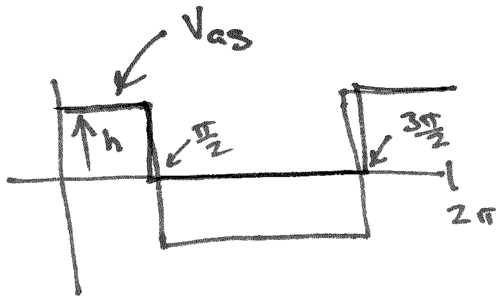
1.15 1.2

AVM – Hysteresis Modulator

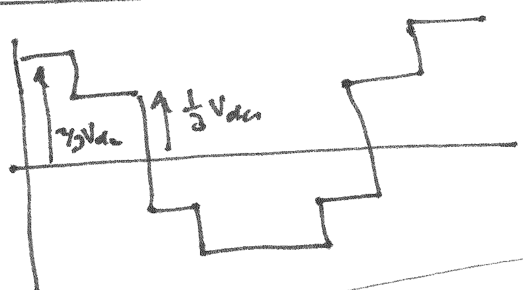
$$\dot{i}_{qde} = \bar{i}^*_{qdL} - i_{qdL}$$

$$m^*_{qd} = K\, \dot{i}_{qde}$$ → Unsaturated voltage is in phase with the current error

i_{ae}
a-phase current error



fundamental $= \frac{4}{\pi} h$ $\quad \dot{i}_{qe} = \frac{4}{\pi} h$



Fundamental $= \frac{2}{\pi} V_{dc}$ $\quad V_q = \frac{2}{\pi} V_{dc}$

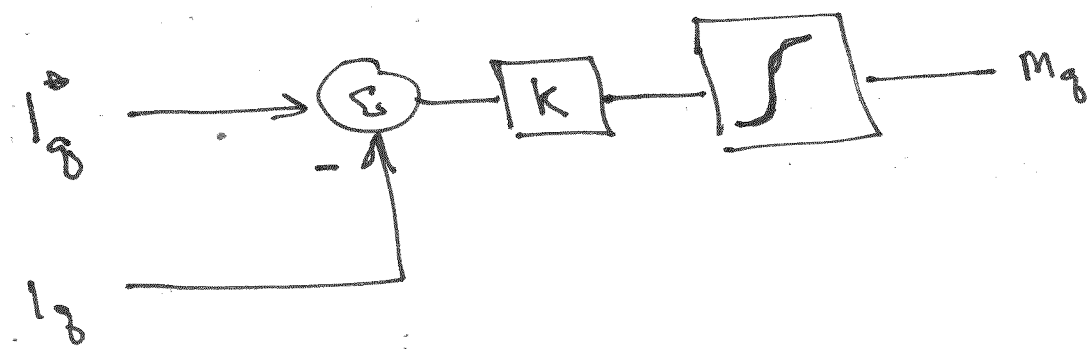
$m_q = \frac{2}{\pi}$

$$m_q = K\, i_{qe}$$

$$\frac{2}{\cancel{\pi}} = K \frac{4}{\cancel{\pi}} h$$

$$\boxed{K = \frac{1}{2h}}$$

AVM – Hysteresis Modulator

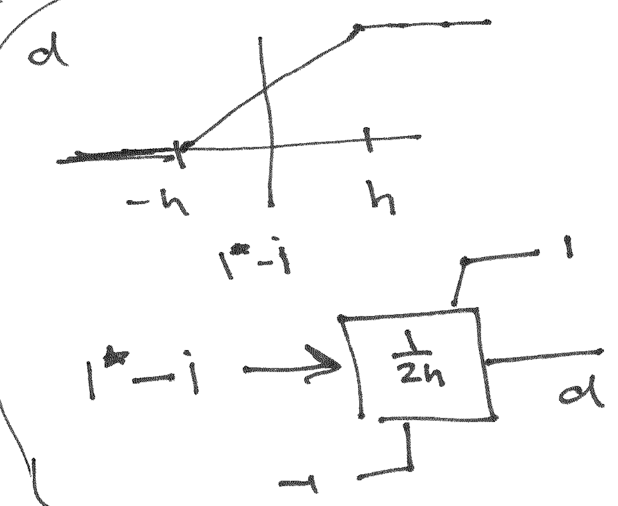


AVM – Summary

① $i_{qde} = i_{qdL}^{*} - i_{qdL}$

② $m_{qd}^{*} = \frac{1}{2h} i_{qd}^{e}$

$\Big\}$ representation of hysteresis



③ $m_q^{cv*} = \sqrt{(m_q^*)^2 + (m_d^*)^2}$

④ $d^* = 2\, m_q^{cv*}$

$d_3^* = d^*/6$

⑤ if $d^* < 2/\sqrt{3}$

$d = d^*$

$d_3 = d_3^*$

else

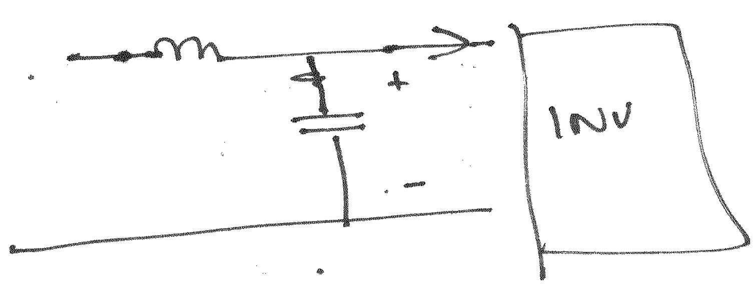
solve for θ_{cv}, d, d_3

⑥ $\phi = \text{angle}(\dot{i}_{qi} - j\dot{i}_{di}) - \text{angle}(m_q^* - j m_d^*)$

AVM – Summary

7 $I_{q1}^{ci} = \sqrt{(I_{q1})^2 + (I_{d1})^2}$

8 $I_{dc} = \frac{3}{4} I_{q1}^{ci} \cos\phi$

9 

find V_{dc}

10 find a_1, b_1

11 $V_q^{ci} = a_1$

$V_d^{ci} = b_1$