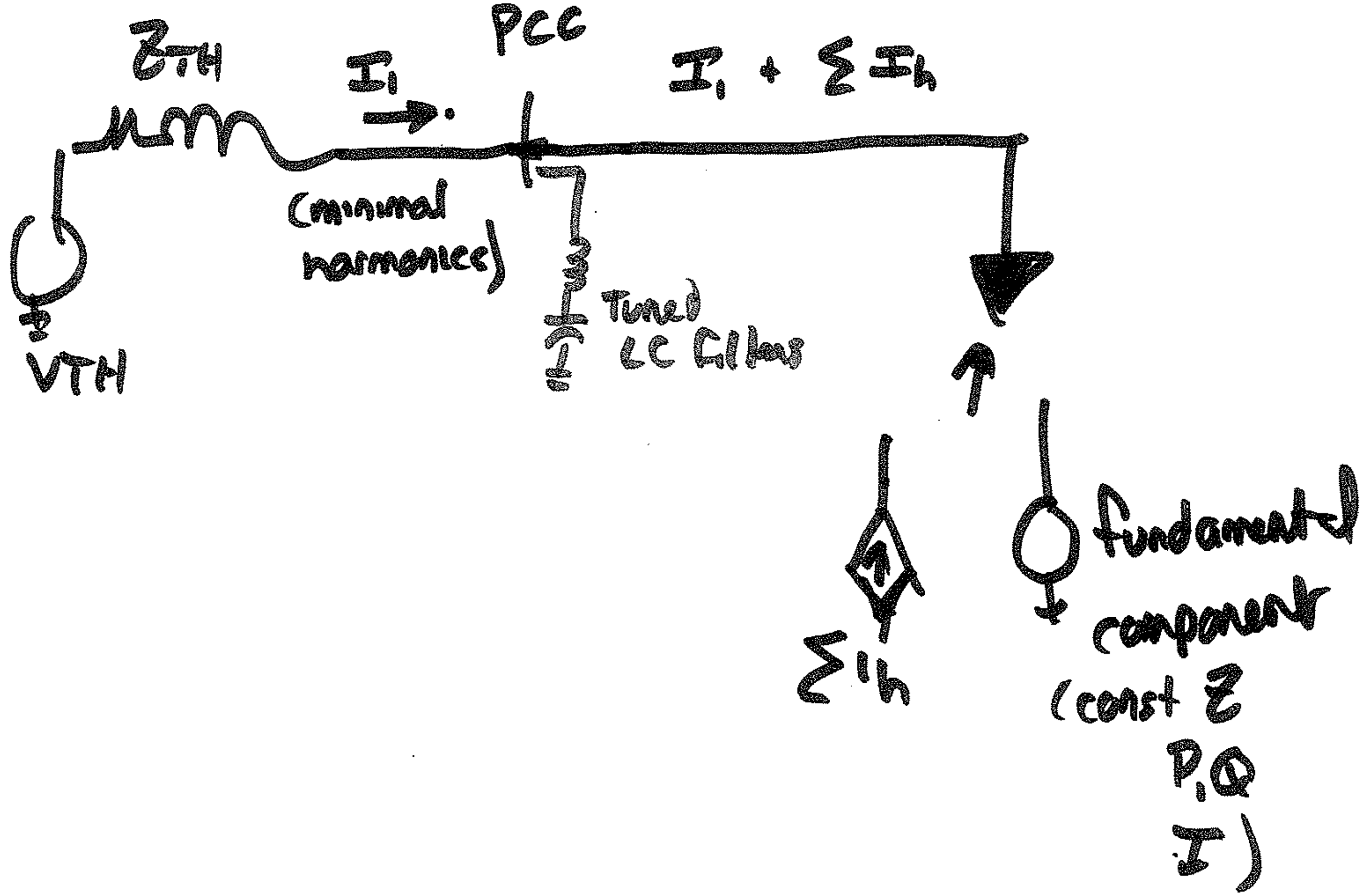
ECE 404-TD / 504-TD

ST: T&D APPLICATIONS OF VOLTAGE SOURCE CONVERTERS

SESSION no. 41

University of Idaho

Harmonic filtering



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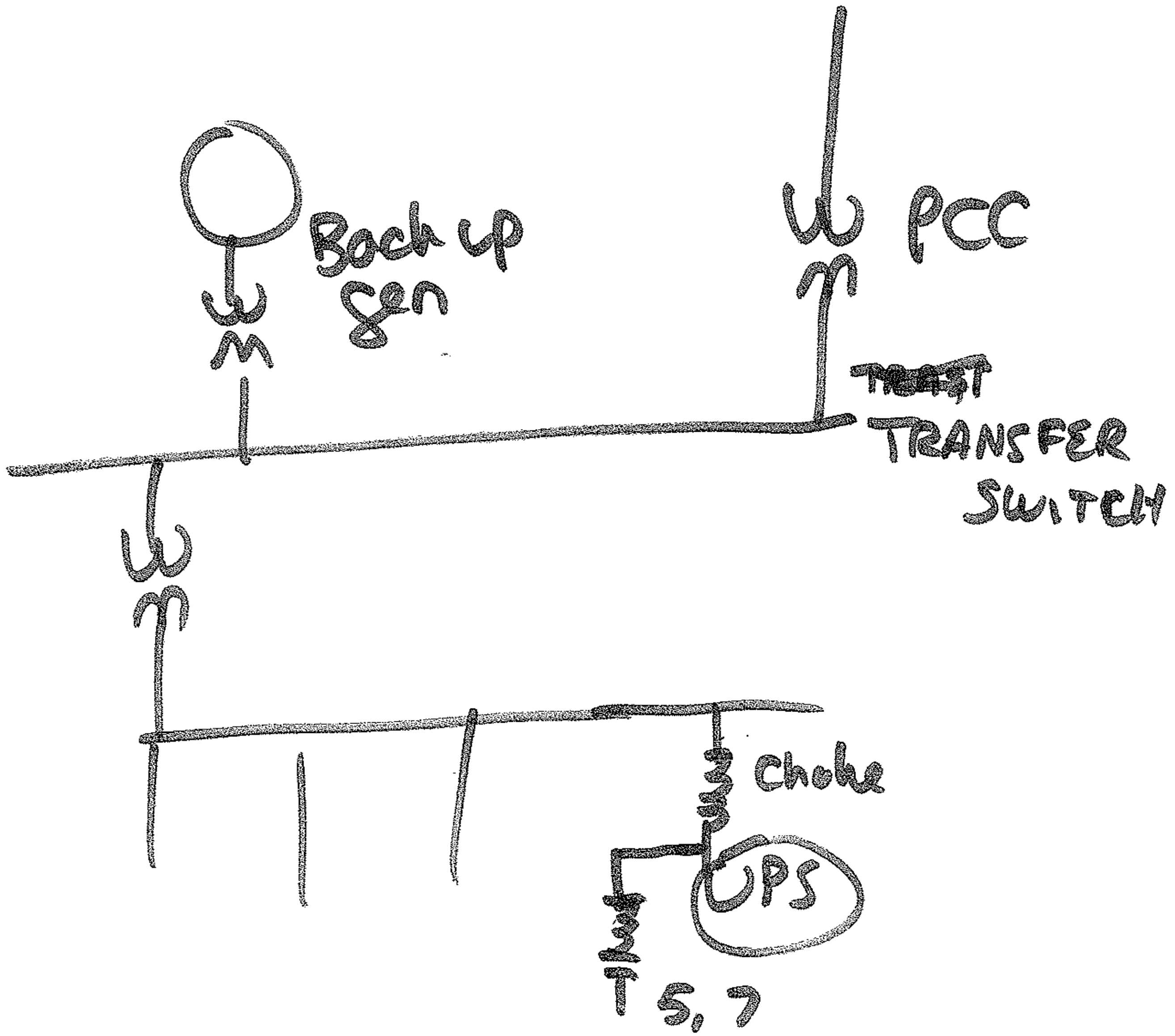

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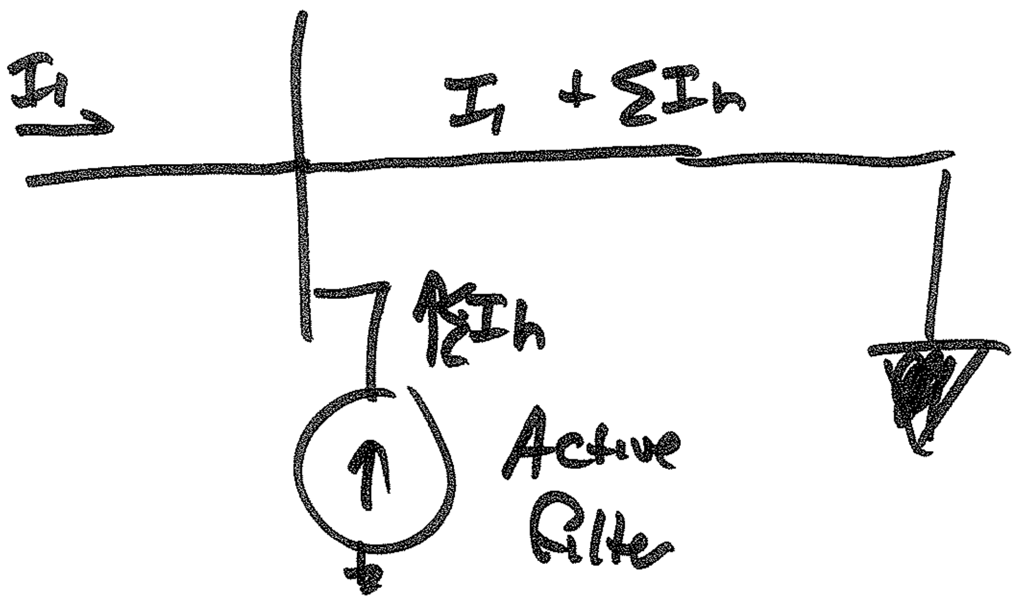
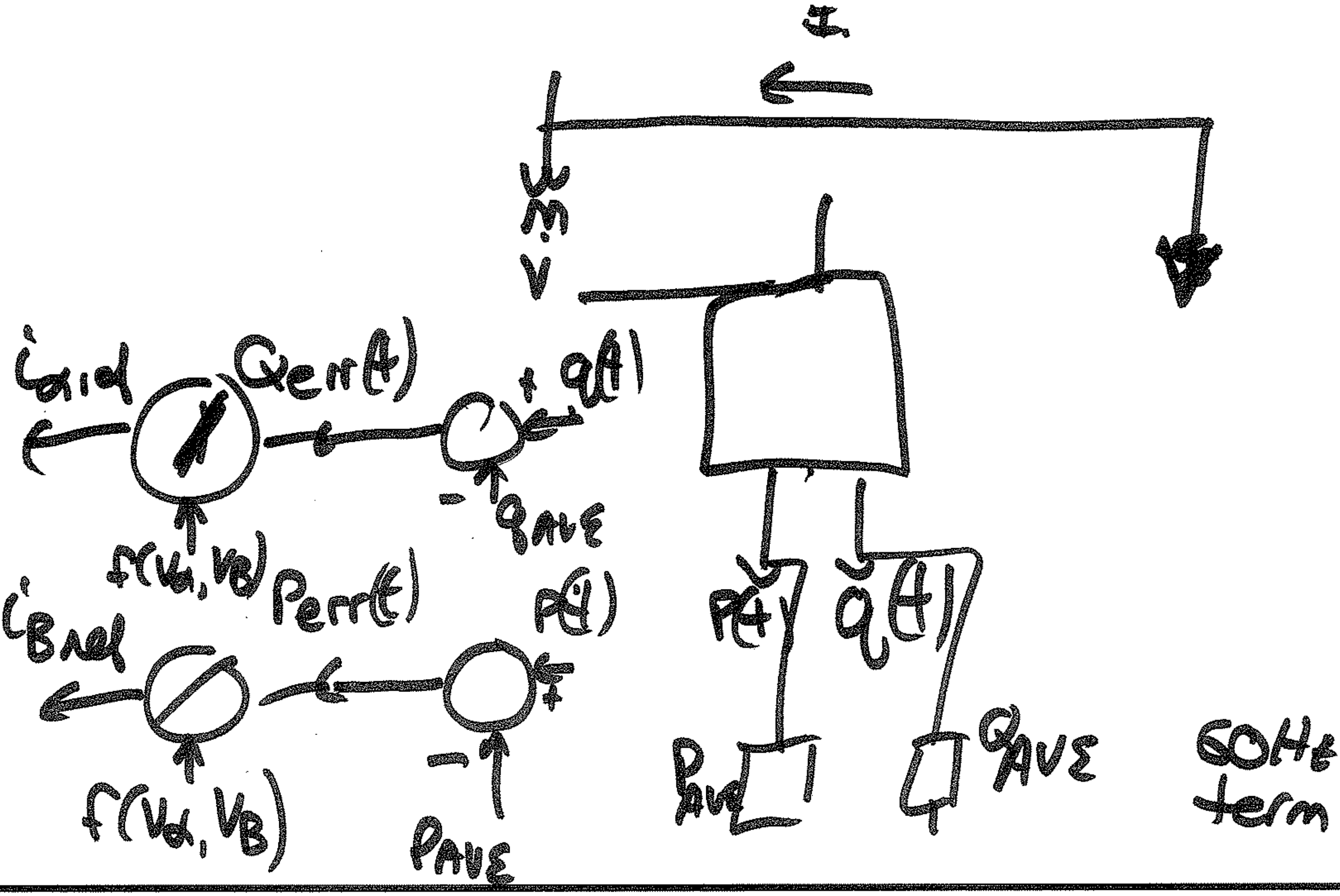
ACTIVE filter



~~Instantaneous~~ Instantaneous $p(t)$ and $q(t)$



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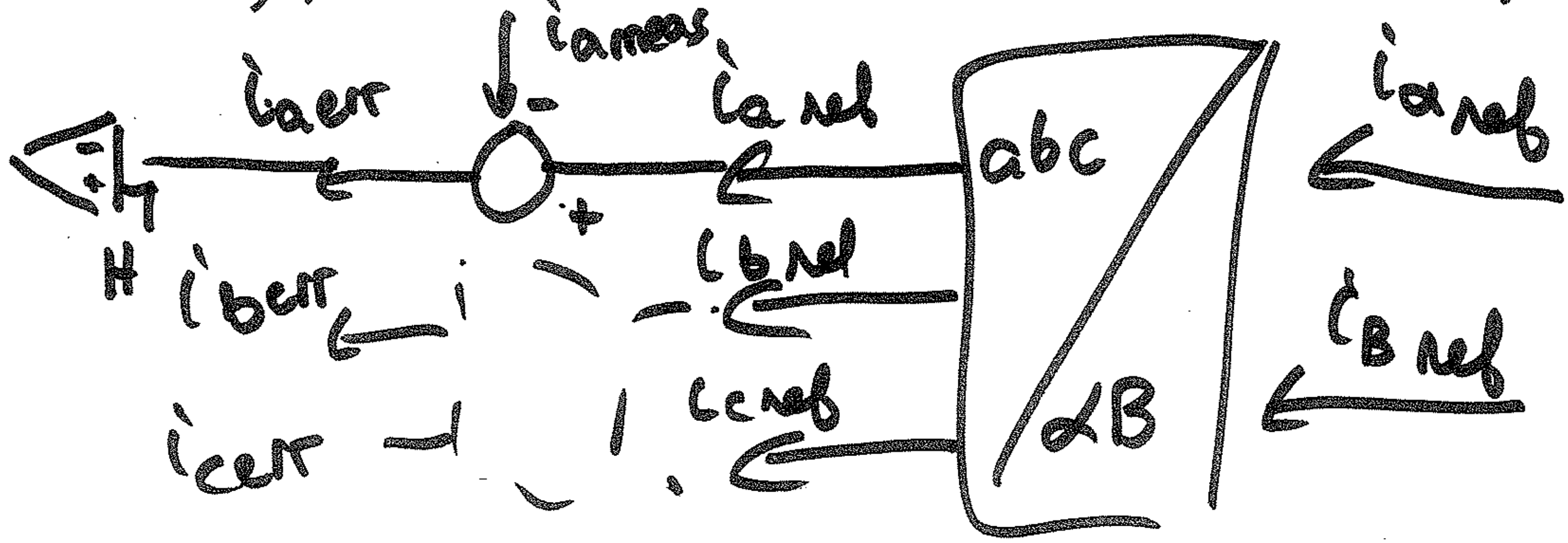
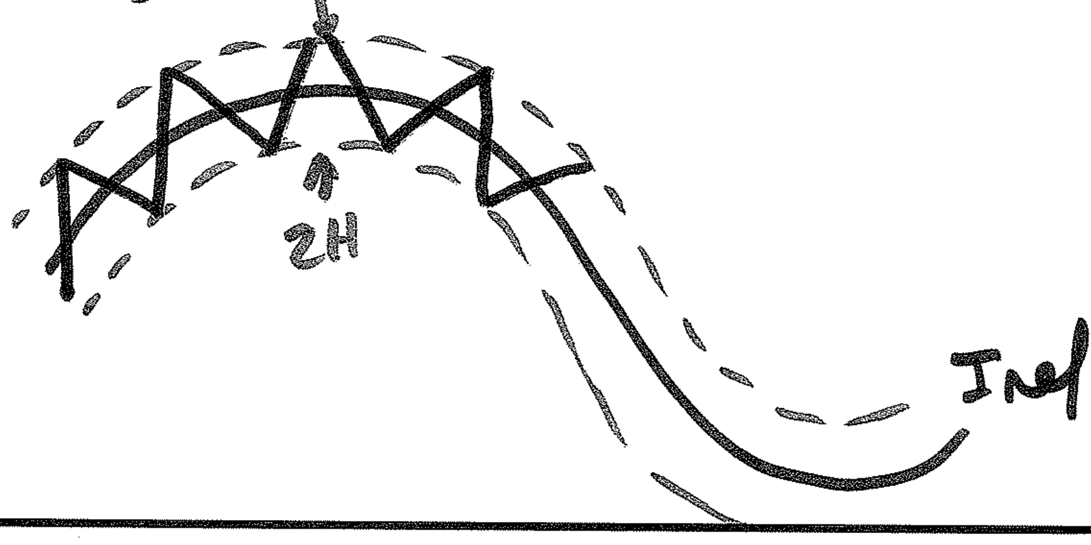


H is hysteresis band



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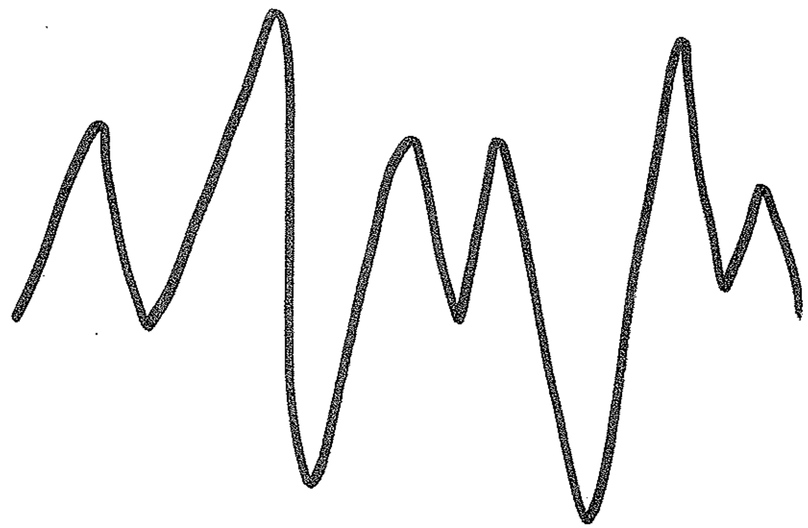

Active Filtering and Reactive Power Control

Imitation Measured Currents:

Define array of time and define angular frequency:

$\Delta t := \dfrac{1}{128 \cdot 60Hz}$ $\qquad \Delta t = 1.302 \times 10^{-4} s$

$t := 0sec, \Delta t .. \dfrac{6}{60Hz}$ $\qquad \omega_0 := 2 \cdot \pi \cdot 60Hz$ $\qquad \omega(t) := \omega_0$

Load current as a function of time

$I_{mag} := 100A$ $\qquad I_{ampl} := \sqrt{2} \cdot I_{mag}$ $\qquad f := 60Hz$

I1

- Sinusoidal harmonic terms for first 15 harmonics of a square wave (magnitude will be added later):

$f_{1A}(t) := \cos(2 \cdot \pi \cdot f \cdot t)$ $\qquad f_{3A}(t) := \cos(2 \cdot \pi \cdot 3 \cdot f \cdot t)$ $\qquad f_{5A}(t) := \cos(2 \cdot \pi \cdot 5 \cdot f \cdot t)$

$f_{7A}(t) := \cos(2 \cdot \pi \cdot 7 \cdot f \cdot t)$ $\qquad f_{9A}(t) := \cos(2 \cdot \pi \cdot 9 \cdot f \cdot t)$ $\qquad f_{11A}(t) := \cos(2 \cdot \pi \cdot 11 \cdot f \cdot t)$

$f_{13A}(t) := \cos(2 \cdot \pi \cdot 13 \cdot f \cdot t)$ $\qquad f_{15A}(t) := \cos(2 \cdot \pi \cdot 15 \cdot f \cdot t)$

- Harmonic amplitudes (assume three phase, thyristor rectifier with stiff dc current source, 3rd harmonic removed). Note the negative signs and 0's:
- Note since functions are cosines, the pattern of the signs changed

$a_1 := I_{ampl}$ $\quad a_3 := 0$ $\quad a_5 := \dfrac{-I_{ampl}}{5}$ $\quad a_7 := \dfrac{I_{ampl}}{7}$ $\quad a_9 := 0$ $\quad a_{11} := \dfrac{-I_{ampl}}{11}$ $\quad a_{13} := \dfrac{I_{ampl}}{13}$ $\quad a_{15} := 0$

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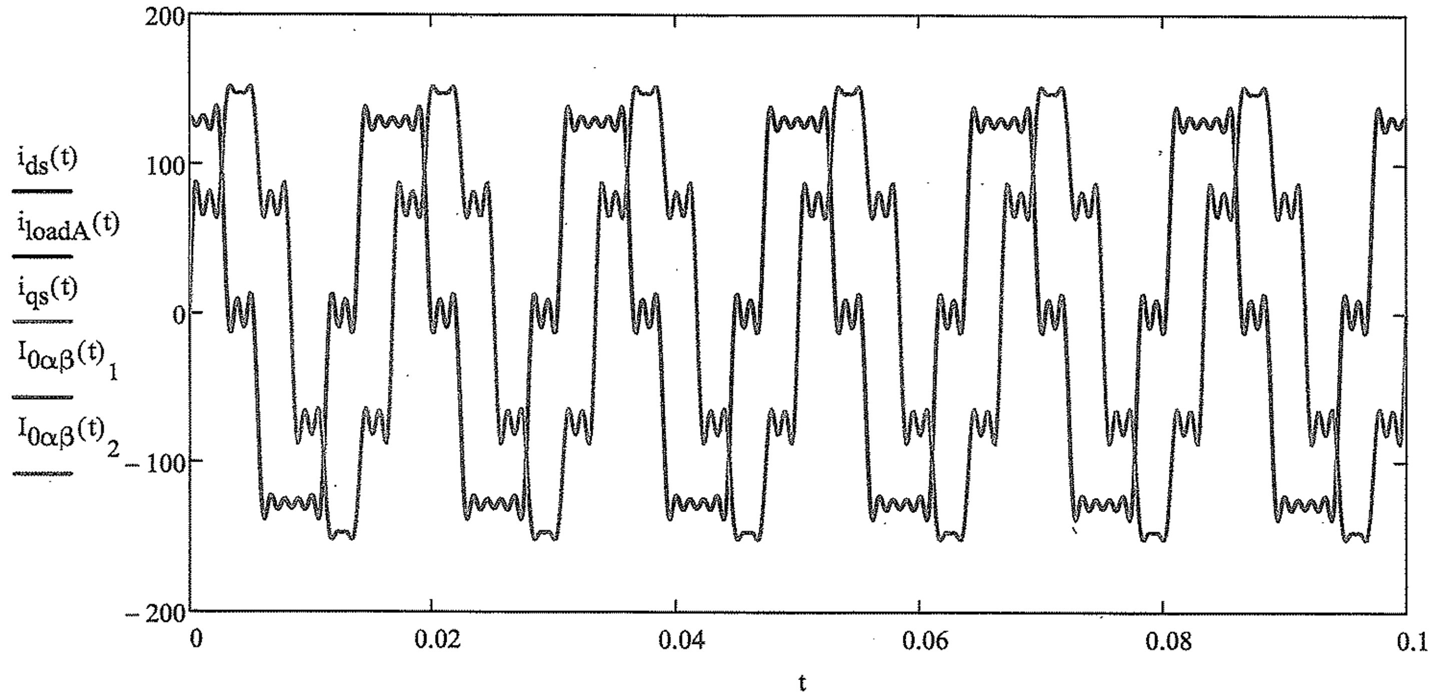
Transformed voltages (not that $i_{ds}(t)$ in phase with $i_a(t)$)



Voltage as a function of time

$V_{mag} := 15kV$ $\quad\quad \phi := 30deg$

$v_a(t) := \sqrt{2}\cdot V_{mag}\cdot\cos(\omega(t)\cdot t + \phi)$

$v_b(t) := \sqrt{2}\cdot V_{mag}\cdot\cos(\omega(t)\cdot t - 120deg + \phi)$

$v_c(t) := \sqrt{2}\cdot V_{mag}\cdot\cos(\omega(t)\cdot t + 120deg + \phi)$

No harmonics in voltage

- Harmonic current equation:

$$i_{loadA}(t) := a_1 \cdot f_{1A}(t) + 1 \cdot \left(a_3 \cdot f_{3A}(t) + a_5 \cdot f_{5A}(t) + a_7 \cdot f_{7A}(t) + a_9 \cdot f_{9A}(t) + a_{11} \cdot f_{11A}(t) + a_{13} \cdot f_{13A}(t) + a_{15} \cdot f_{15A}(t)\right)$$

- Create 120 degree phase shift in units of time.

$$a_{time} := \left(\frac{120}{360}\right) \cdot \frac{1}{60\text{Hz}} \qquad a_{time} = 5.556 \times 10^{-3} \cdot s$$

$$i_{loadB}(t) := i_{loadA}(t - a_{time})$$

$$i_{loadC}(t) := i_{loadA}(t + a_{time})$$

Transform measured currents to the stationary dq0 ($\alpha\beta$) reference frame:

$$\theta r(t) := 2 \cdot \pi \cdot 60.0\text{Hz} \cdot t$$

- Use equations from the Clarke Transformation as equations instead of matrix for now

i_α $$i_{ds}(t) := \frac{2}{3} \cdot \left(i_{loadA}(t) - 0.5 \cdot i_{loadB}(t) - 0.5 \cdot i_{loadC}(t)\right)$$

i_β $$i_{qs}(t) := \frac{i_{loadB}(t) - i_{loadC}(t)}{\sqrt{3}}$$ Q axis 180 out of phase with some definitions

Park's Transformation in Matrix Form

$\theta(t) := \omega_0 \cdot t$ synchronously rotating reference frame, note that this is generally shifted by $\pi/2$ for rotating machines.

- Phasor form first: $V_a := V_{mag} \cdot e^{j \cdot 30deg}$

  $I_a := I_{mag} \cdot e^{j \cdot 0deg}$

$P_{3ph} := 3 \cdot \mathrm{Re}\left(V_a \cdot \overline{I_a}\right)$ $\quad P_{3ph} = 3.897 \cdot MW$

$Q_{3ph} := 3 \cdot \mathrm{Im}\left(V_a \cdot \overline{I_a}\right)$ $\quad Q_{3ph} = 2.25 \cdot MW$

- Note: we need the 3/2 term because of 2/3 constant in transformation matrix.
- This will differ if use SQRT(2/3)

v0 i0 vα iα vβ iβ

$$P_{0\alpha\beta}(t) := \frac{3}{2}\left(V_{0\alpha\beta}(t)_0 \cdot I_{0\alpha\beta}(t)_0 + V_{0\alpha\beta}(t)_1 \cdot I_{0\alpha\beta}(t)_1 + V_{0\alpha\beta}(t)_2 \cdot I_{0\alpha\beta}(t)_2\right)$$

$$Q_{0\alpha\beta}(t) := \frac{3}{2}\left(V_{0\alpha\beta}(t)_2 \cdot I_{0\alpha\beta}(t)_1 - V_{0\alpha\beta}(t)_1 \cdot I_{0\alpha\beta}(t)_2\right)$$

$v_\alpha(t) := V_{0\alpha\beta}(t)_1$ $\quad i_\alpha(t) := I_{0\alpha\beta}(t)_1$

$v_\beta(t) := V_{0\alpha\beta}(t)_2$ $\quad i_\beta(t) := I_{0\alpha\beta}(t)_2$

Since we know $i_0 = 0$ → converter does not have a neutral path

$$PQ_{0\alpha\beta}(t) := \frac{3}{2} \cdot \begin{pmatrix} v_\alpha(t) & v_\beta(t) \\ v_\beta(t) & -v_\alpha(t) \end{pmatrix} \cdot \begin{pmatrix} i_\alpha(t) \\ i_\beta(t) \end{pmatrix}$$

$p(t) := PQ_{0\alpha\beta}(t)_0$ $\quad q(t) := PQ_{0\alpha\beta}(t)_1$

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$RS := 128$

$$LP(t) = \sum_{k=0}^{\frac{RS}{2}-1} \frac{p\left[\left(k - \frac{RS}{2}\right)\cdot\Delta t\right]}{\frac{RS}{2}} \qquad LQ(t) = \sum_{k=0}^{\frac{RS}{2}-1} \frac{q\left[\left(k - \frac{RS}{2}\right)\cdot\Delta t\right]}{\frac{RS}{2}}$$

- For most of this example we will stick with just the 3 phase complex power phasor solutions.

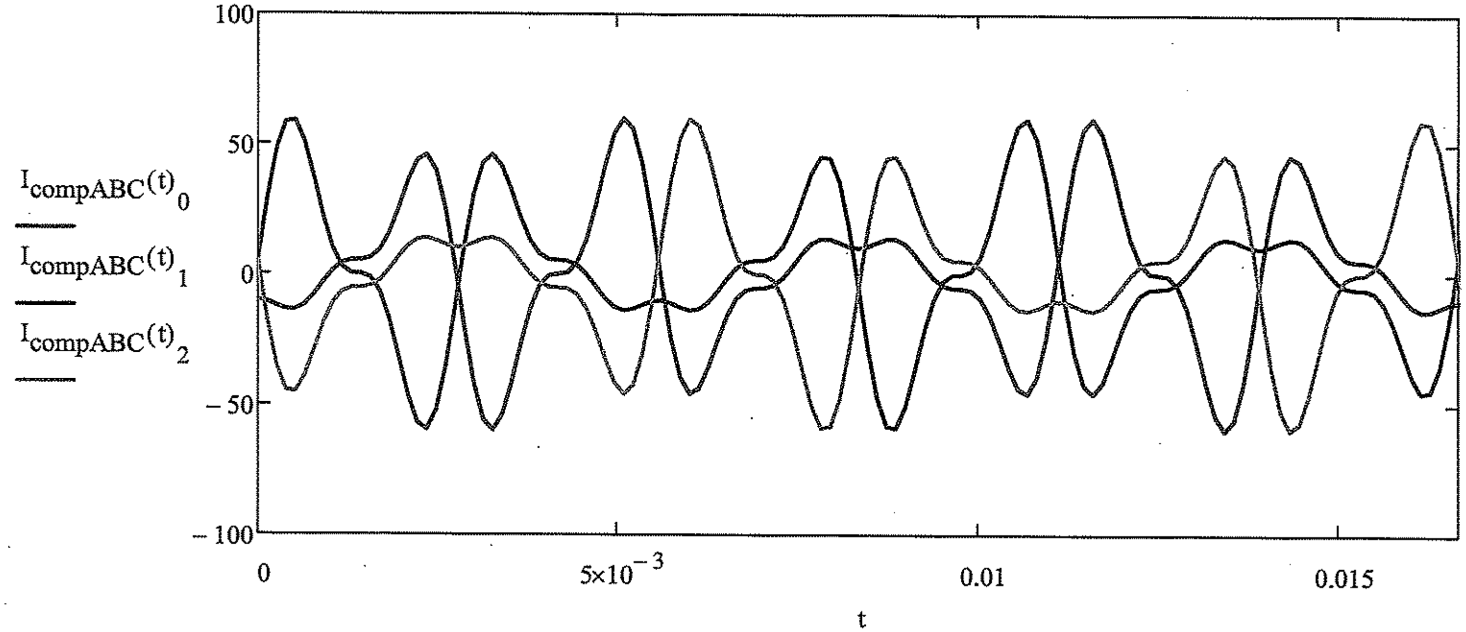
- Compensator Currents:
  Case 1: Just correcting harmonics:

$$i_{comp\alpha\beta}(t) := \frac{\frac{2}{3}}{v_\alpha(t)^2 + v_\beta(t)^2}\begin{pmatrix} v_\alpha(t) & v_\beta(t) \\ v_\beta(t) & -v_\alpha(t) \end{pmatrix}\cdot\begin{pmatrix} p(t) - P_{3ph} \\ q(t) - Q_{3ph} \end{pmatrix}$$

$$i_{comp\alpha}(t) := i_{comp\alpha\beta}(t)_0$$

$$i_{comp\beta}(t) := i_{comp\alpha\beta}(t)_1$$

- By subtracing average P and Q, the error signal for the control group is just the harmonic distortion in "instantaneous P and Q"



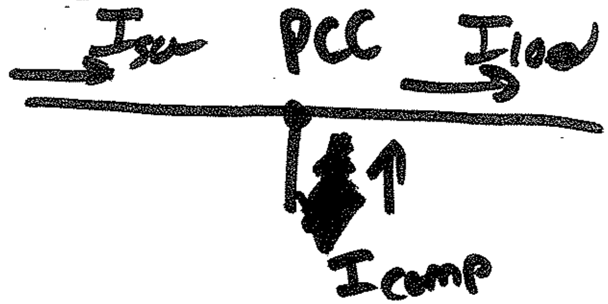
Now find the compensated currents:

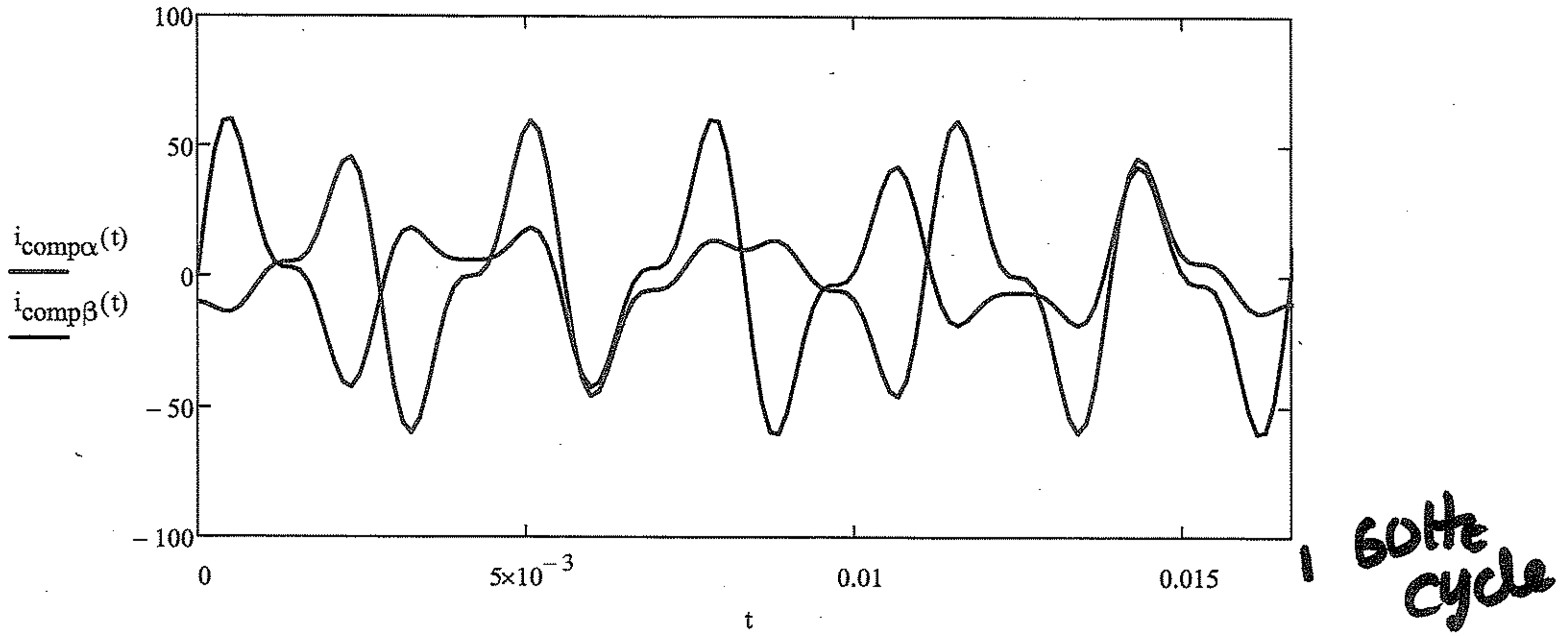
$i_{sourceA}(t) := i_{loadA}(t) - I_{compABC}(t)_0$

$i_{sourceB}(t) := i_{loadB}(t) - I_{compABC}(t)_1$

$i_{sourceC}(t) := i_{loadC}(t) - I_{compABC}(t)_2$

$i_{load} - i_{compensator}$





$$I_{compABC}(t) := P(0)^{-1} \cdot \begin{pmatrix} 0A \\ i_{comp\alpha}(t) \\ i_{comp\beta}(t) \end{pmatrix}$$

Note that the zero sequence part of the compensator current is assumed to be zero. This is due to the assumption that the compensator is a 3 wire device (note that a VSC is inherently ungrounded, so the converter topology needs to change to add a ground return and the ability to compensate zero sequence terms.

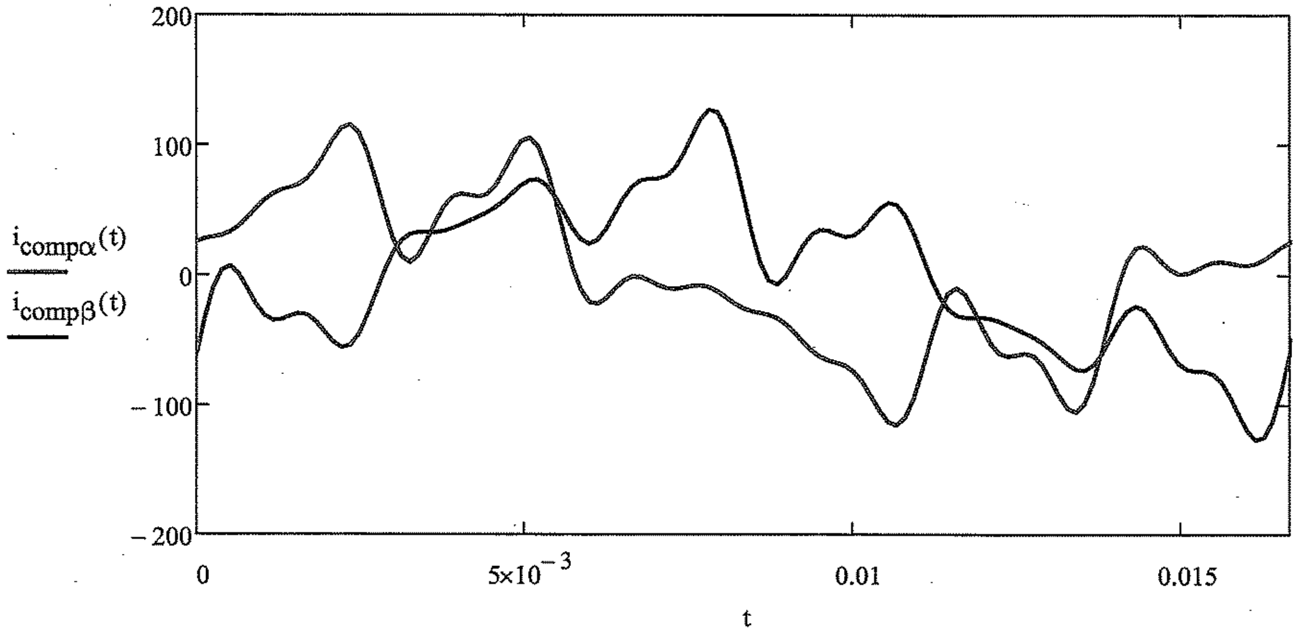
Case 2: This time perform PF correction and harmonic compensation

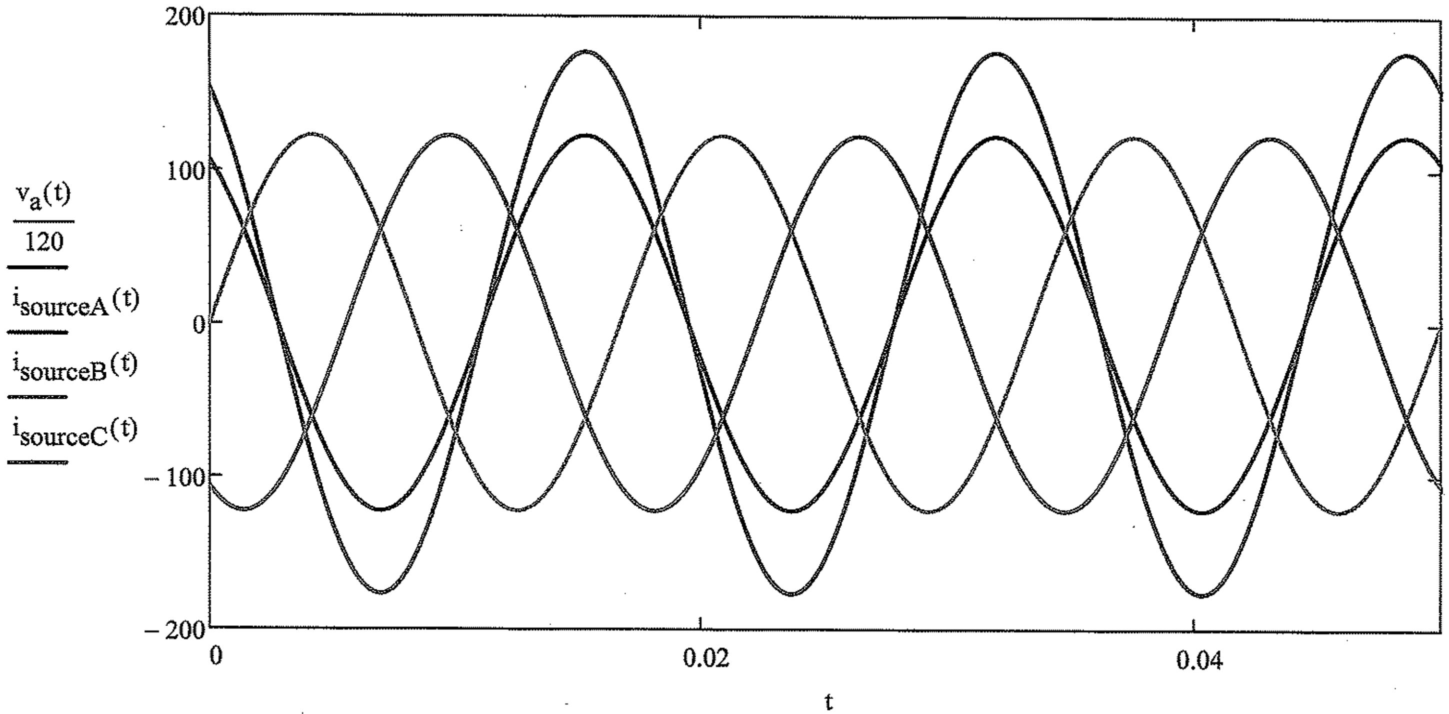
$$i_{comp\alpha\beta}(t) := \frac{\frac{2}{3}}{v_\alpha(t)^2 + v_\beta(t)^2} \cdot \begin{pmatrix} v_\alpha(t) & v_\beta(t) \\ v_\beta(t) & -v_\alpha(t) \end{pmatrix} \cdot \begin{pmatrix} p(t) - P_{3ph} \\ q(t) \end{pmatrix}$$

$$i_{comp\alpha}(t) := i_{comp\alpha\beta}(t)_0$$

$$i_{comp\beta}(t) := i_{comp\alpha\beta}(t)_1$$

- By subtracing average P, but not average Q, the error signal for the control group is both the harmonic distortion in "instantaneous P and Q" and bringing the total reactive power to zero.





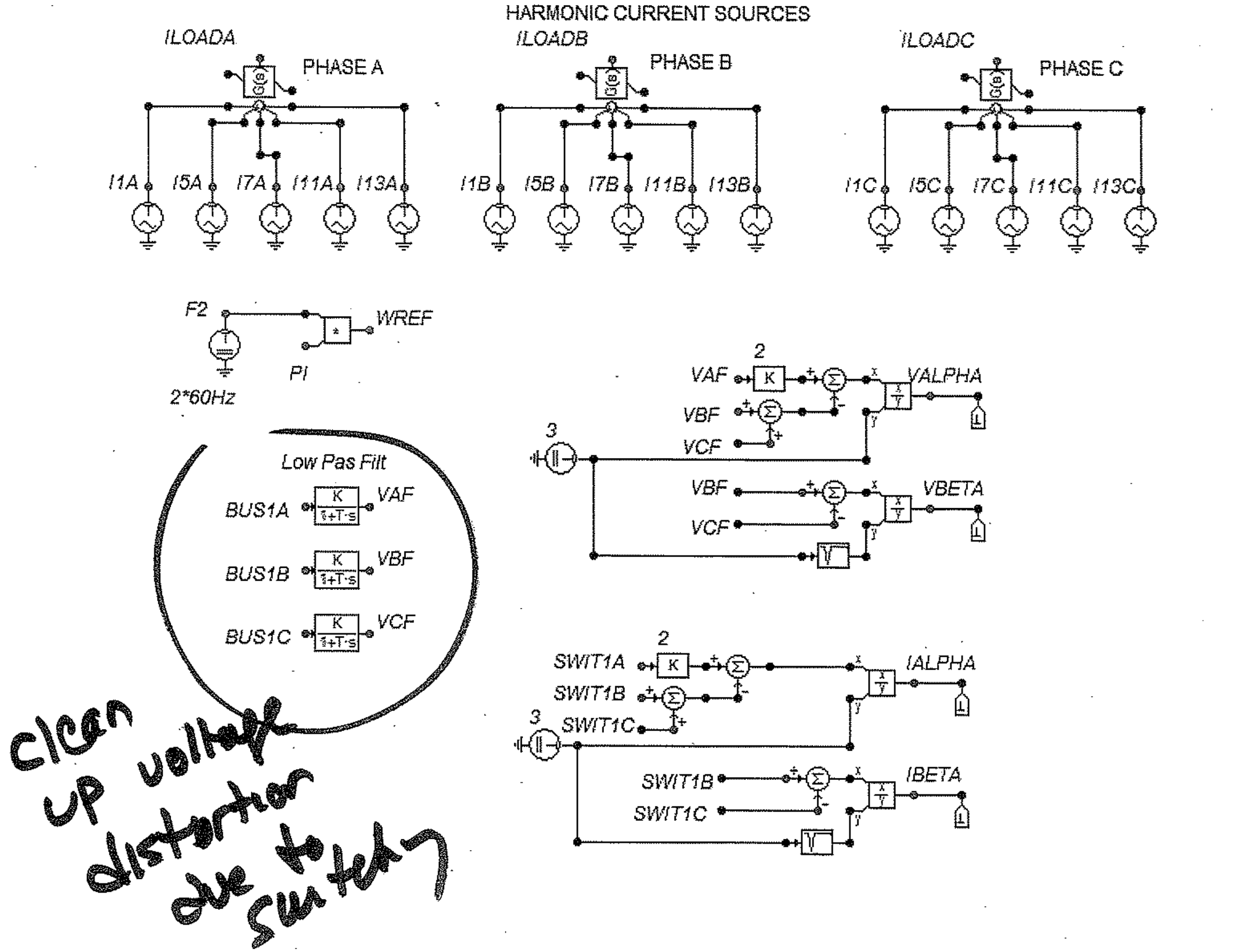
Note that $v_a(t)$ and $i_a(t)$ are in phase now. Unity power factor.

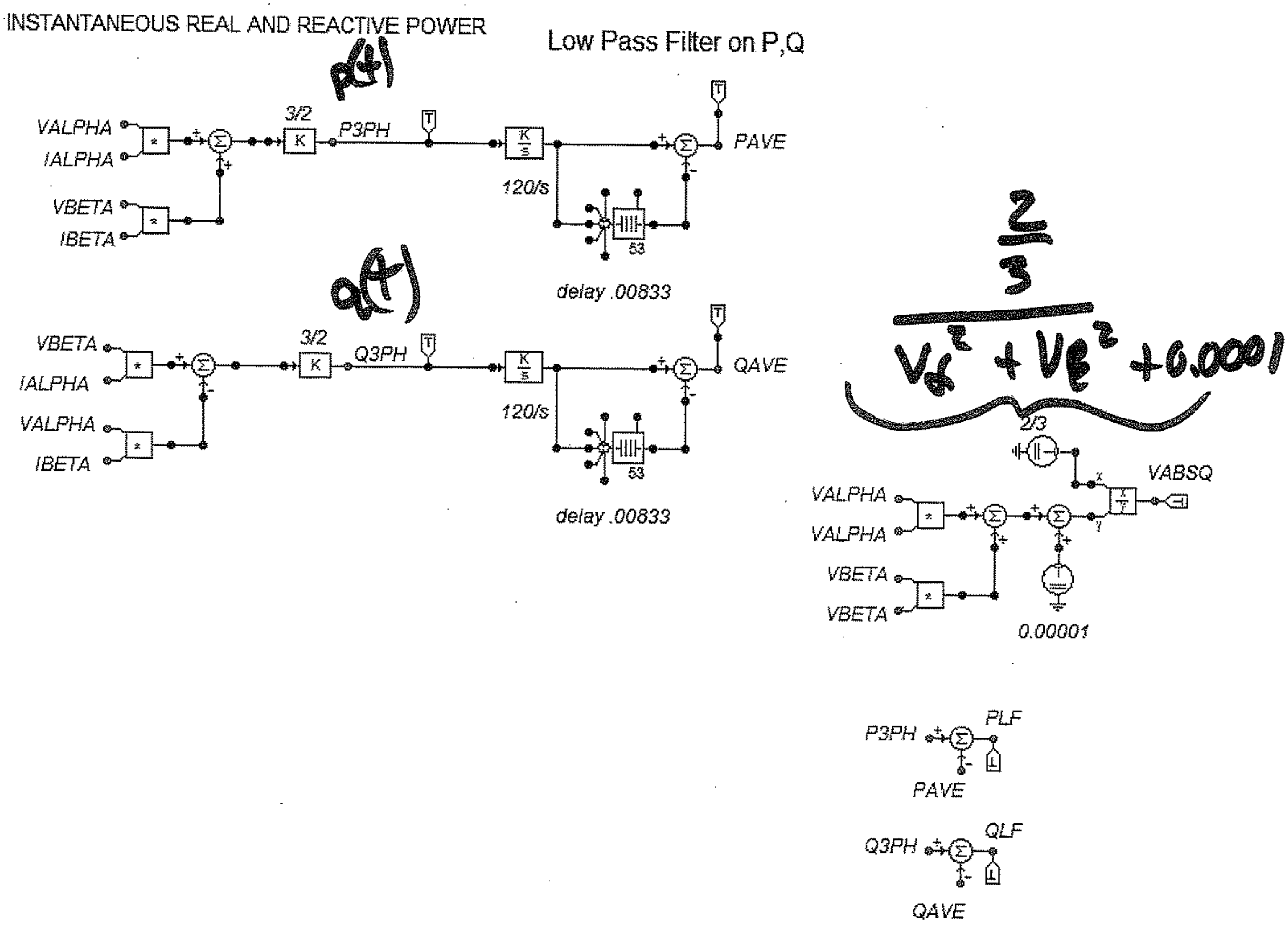
Case 3: PF correction, load balancing and harmonics:

- Keep the same phase A load current and maintain the same voltages across the load as above.

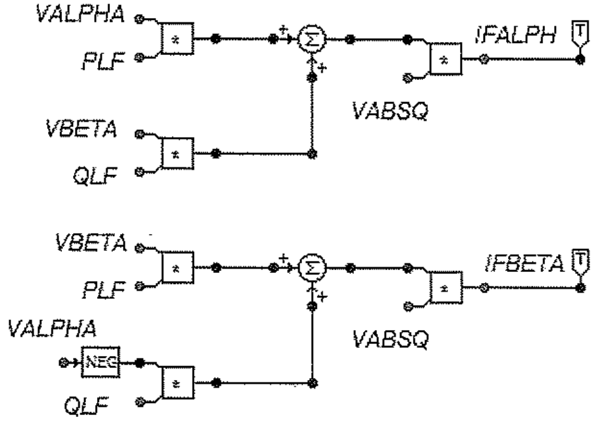
$i_{loadB}(t) := -i_{loadA}(t - 0 \cdot a_{time})$ • Effectively only have a load connected from phase A to phase B

$i_{loadC}(t) := 0A$

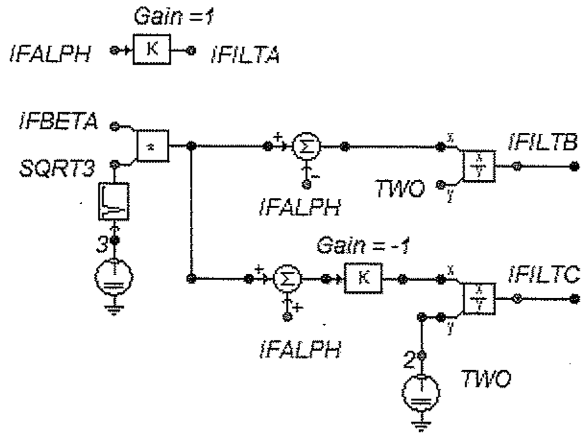

HARMONIC CURRENT SOURCES
ILOADA
PHASE A
ILOADB
PHASE B
ILOADC
PHASE C
I1A
I5A
I7A
I11A
I13A
I1B
I5B
I7B
I11B
I13B
I1C
I5C
I7C
I11C
I13C
F2
WREF
PI
2*60Hz
Low Pas Filt
BUS1A
VAF
BUS1B
VBF
BUS1C
VCF
2
VAF
VBF
VCF
3
VALPHA
VBF
VCF
VBETA
2
SWIT1A
SWIT1B
3
SWIT1C
IALPHA
SWIT1B
SWIT1C
IBETA
clean up voltage distortion due to switching


INSTANTANEOUS REAL AND REACTIVE POWER
Low Pass Filter on P,Q
p(t)
q(t)
VALPHA
IALPHA
VBETA
IBETA
3/2
K
P3PH
T
K/s
120/s
PAVE
53
delay .00833
VBETA
IALPHA
VALPHA
IBETA
3/2
K
Q3PH
120/s
QAVE
53
delay .00833
$\frac{2/3}{V_\alpha^2 + V_\beta^2 + 0.0001}$
2/3
VABSQ
VALPHA
VALPHA
VBETA
VBETA
0.00001
P3PH
PLF
PAVE
Q3PH
QLF
QAVE

Compensator Currents in Alpha-Beta Frame



Transform Filter Currents to ABC Frame



$$\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{pmatrix} p(t) \\ q(t) \end{pmatrix}$$

Hysteresis Regulator