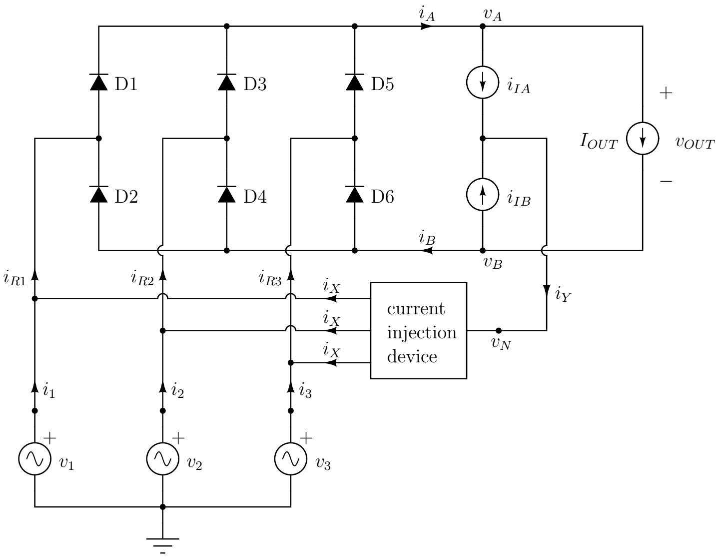
Switching Current Injection Device

aim . . .

- current injection devices inject to all three of the phases . . .
- but only one phase really needs injection!
- is there a way to inject only where needed?
- is there a way to get rid of the current injection device?
- something smaller, lighter, cheaper, . . .

let's get back to basic current injection . . .



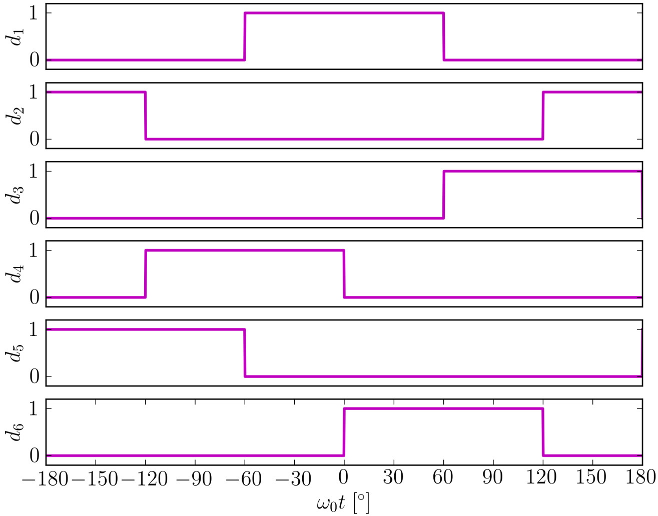
as always, assume . . .

$$m_1 = \cos\left(\omega_0 t\right)$$

$$m_2 = \cos\left(\omega_0 t - \frac{2\pi}{3}\right)$$

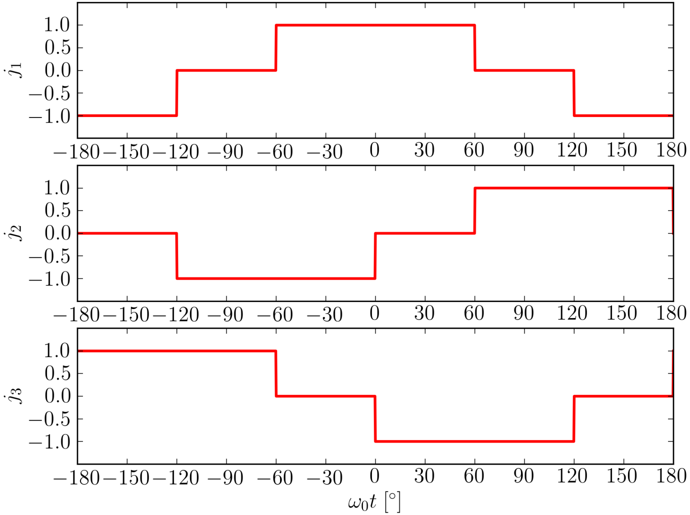
$$m_3 = \cos\left(\omega_0 t - \frac{4\pi}{3}\right)$$

diodes ...



d_1
d_2
d_3
d_4
d_5
d_6
1
0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

currents without injection

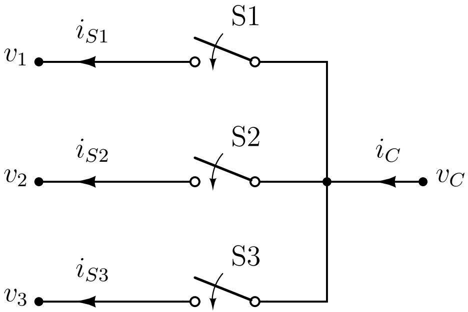


what do we need?

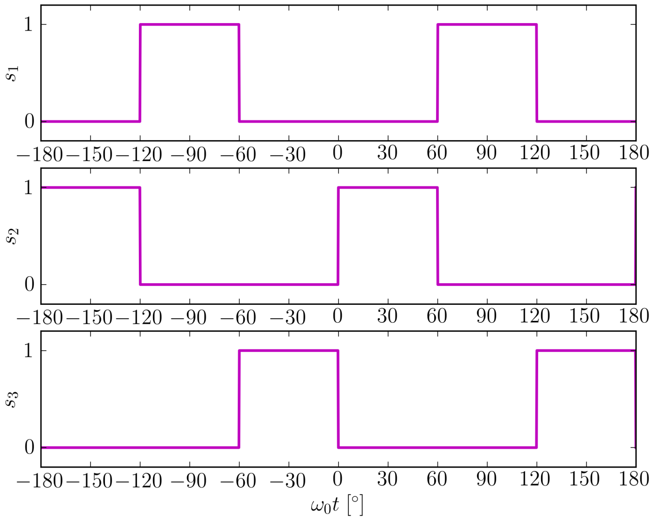
conclusion:

current injection is needed in the phase whose voltage is neither minimal neither maximal in the considered time point

let's do it!



how to operate the switches?



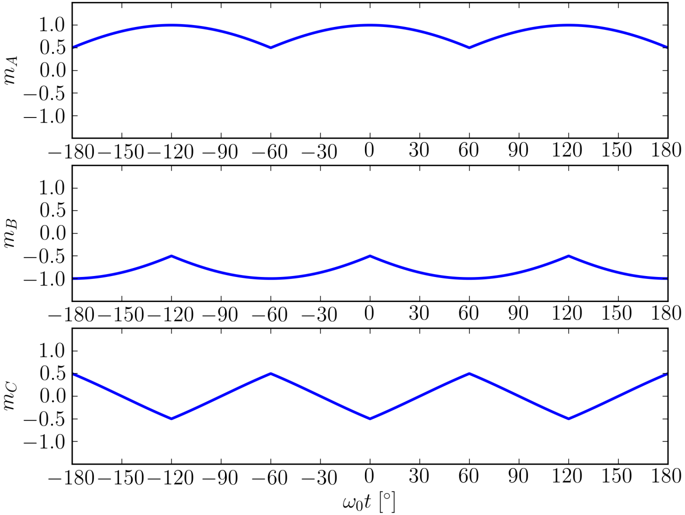
some Boole algebra ...

$$s_1 = \neg d_1 \wedge \neg d_2$$

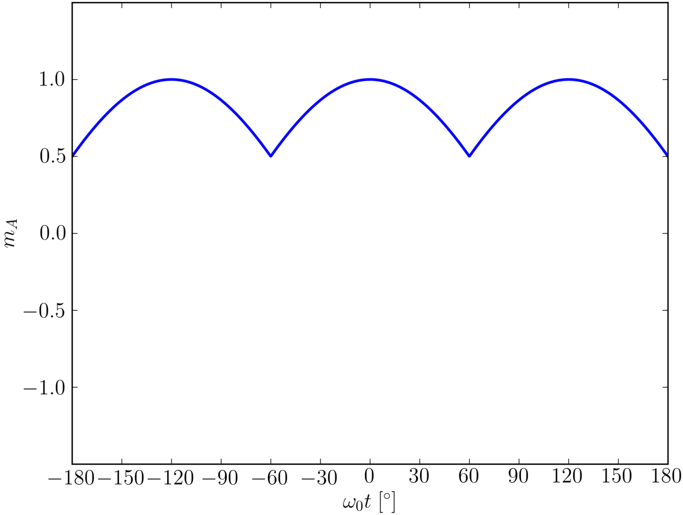
$$s_2 = \neg d_3 \wedge \neg d_4$$

$$s_3 = \neg d_5 \wedge \neg d_6$$

and the voltages are defined ...



m_A, waveform



1.0
0.5
0.0
−0.5
−1.0
m_A
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

m_A, analytical

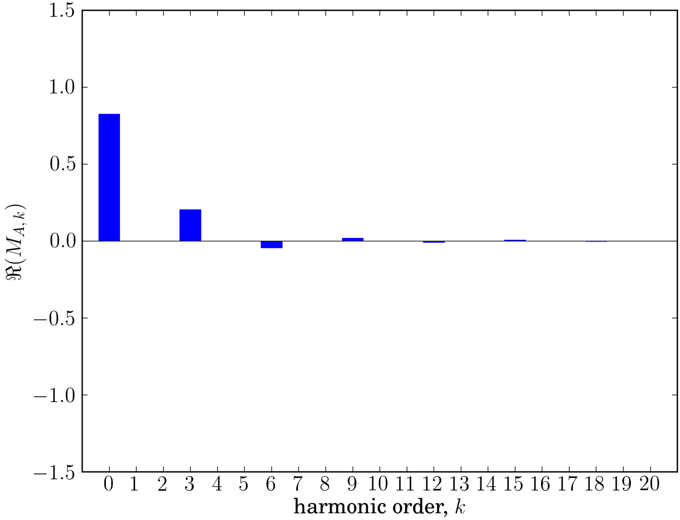
$$m_A = \max\left(m_1,\, m_2,\, m_3\right)$$

$$m_A = M_{A0} + \sum_{k=1}^{\infty} M_{A,\,k}\, \cos\left(3k\omega_0 t\right)$$

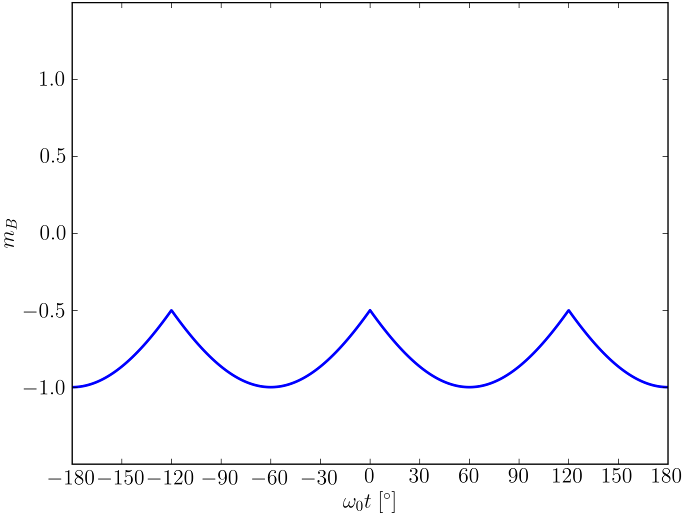
$$M_{A0} = \frac{3\sqrt{3}}{2\pi}$$

$$M_{A,\,k} = \frac{3\sqrt{3}}{\pi}\,\frac{(-1)^{k+1}}{9k^2-1}$$

m_A, spectrum, real part



m_B, waveform



1.0
0.5
0.0
−0.5
−1.0
m_B
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

m_B, analytical

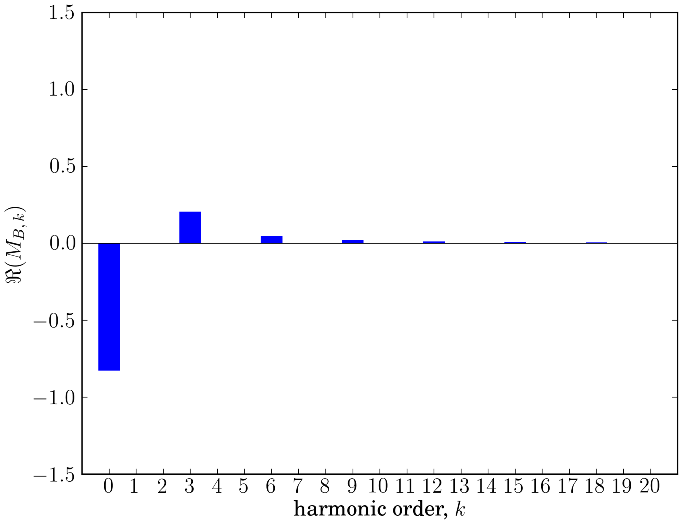
$$m_B = \min\left(m_1,\, m_2,\, m_3\right)$$

$$m_B = M_{B0} + \sum_{k=1}^{\infty} M_{B,\,k}\,\cos\left(3k\omega_0 t\right)$$

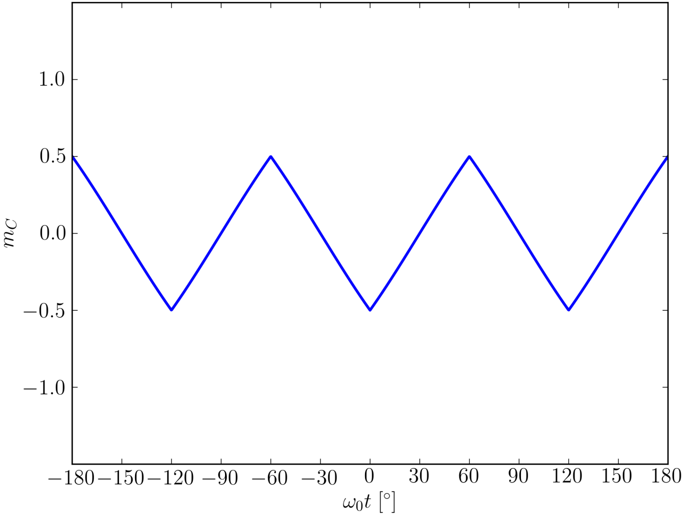
$$M_{B0} = -\frac{3\sqrt{3}}{2\pi}$$

$$M_{B,\,k} = \frac{3\sqrt{3}}{\pi}\,\frac{1}{9k^2 - 1}$$

m_B, spectrum, real part



m_C, waveform, this is a new one ...



m_C, analytical

$$m_C = -m_A - m_B$$

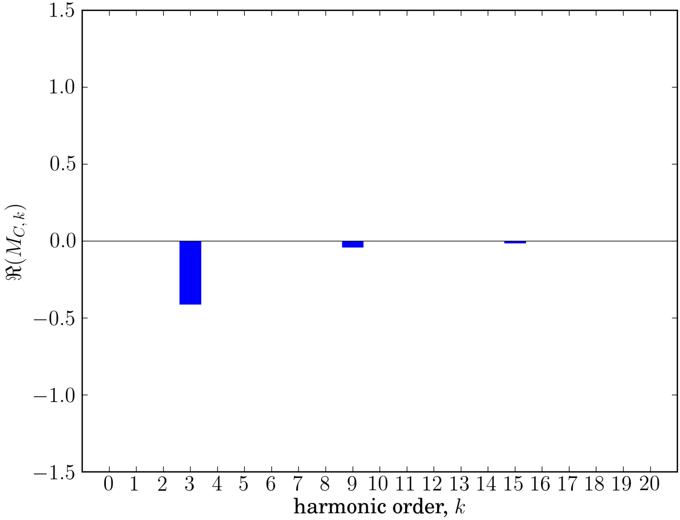
$$m_C = \sum_{k=1,\,3,\,5,\dots}^{\infty} M_{C,\,k} \cos\left(3k\omega_0 t\right)$$

$$M_{C,\,k} = -\frac{6\sqrt{3}}{\pi}\,\frac{1}{9k^2 - 1}$$

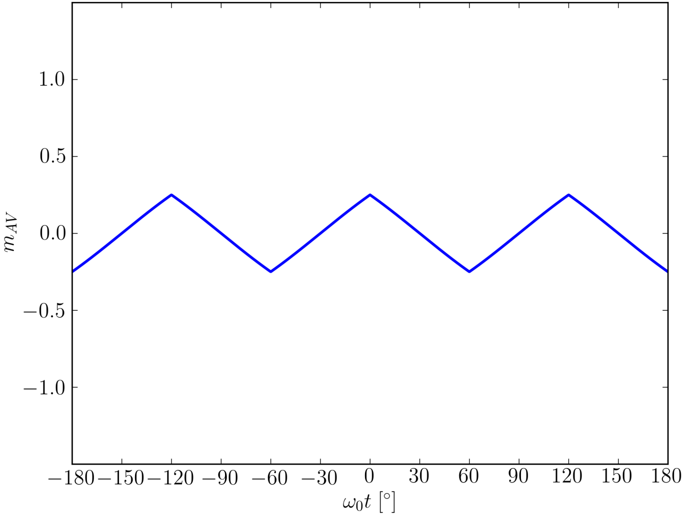
this is a (sort of) new spectrum to deal with ...

and there is no DC component in it ...

m_C, spectrum, real part



since we are already here, m_{AV}, waveform



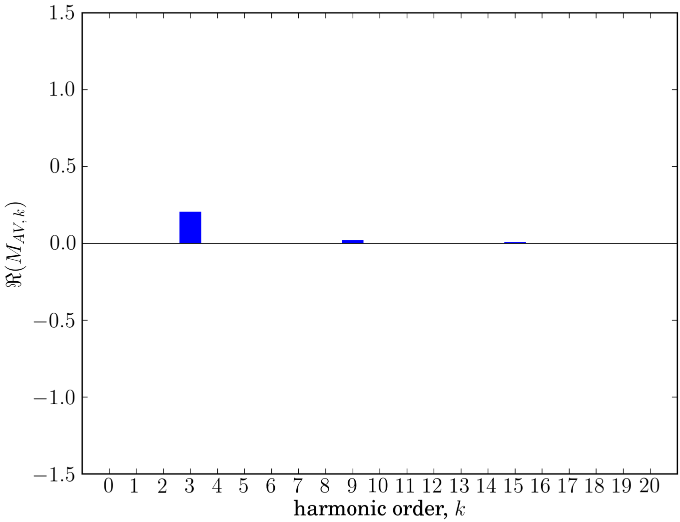
m_{AV}, analytical

$$m_{AV} = \frac{m_A + m_B}{2} = -\frac{m_C}{2}$$

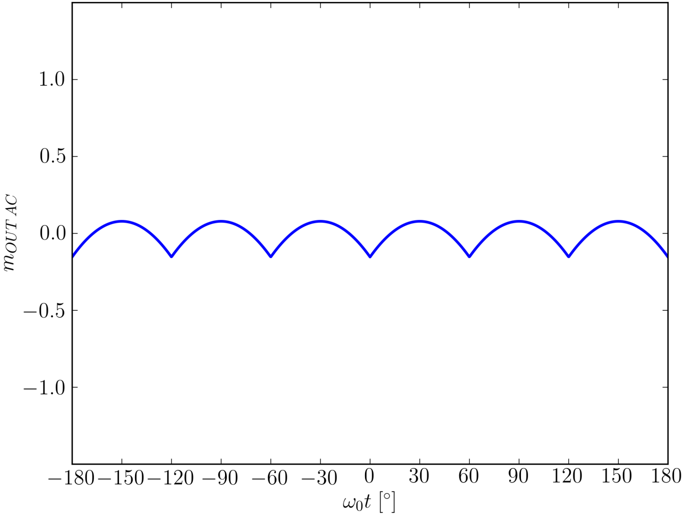
$$m_{AV} = \sum_{k=1,3,5,\ldots}^{\infty} M_{AV,\,k} \cos\left(3k\omega_0 t\right)$$

$$M_{AV,\,k} = \frac{3\sqrt{3}}{\pi} \frac{1}{9k^2 - 1}$$

m_{AV}, spectrum, real part



$m_{OUT\,AC}$, waveform



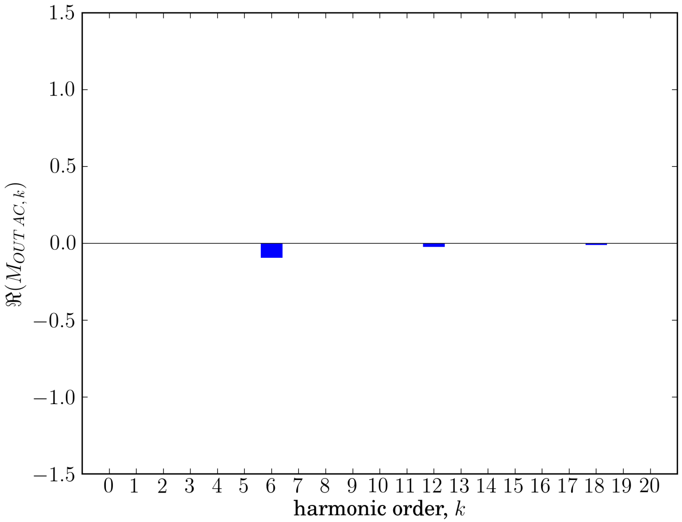
$m_{OUT\,AC}$, analytical

$$m_{OUT\,AC} = m_{OUT} - M_{OUT} = m_A - M_{A,\,0} - m_B + M_{B,\,0}$$

$$m_{OUT\,AC} = \sum_{k=2,\,4,\,6,\ldots}^{\infty} M_{OUT\,AC,\,k} \cos\left(3k\omega_0 t\right)$$

$$M_{OUT\,AC,\,k} = -\frac{6\sqrt{3}}{\pi}\,\frac{1}{9k^2-1}$$

$m_{OUT\,AC}$, spectrum, real part



we would like to have ...

$$j_1 = \cos\left(\omega_0 t\right)$$

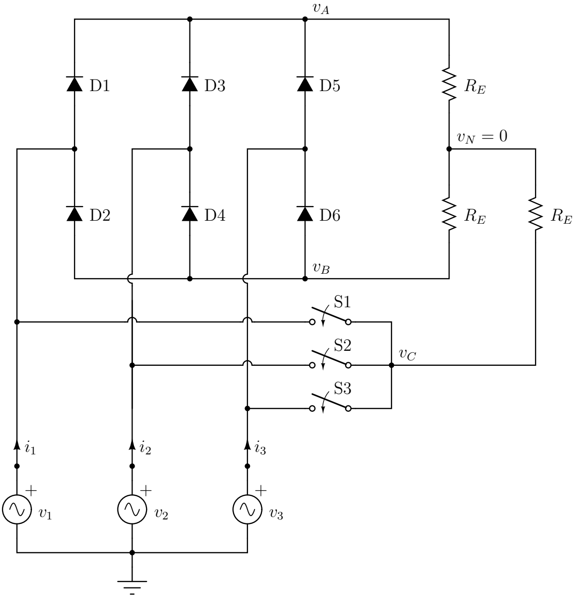
$$j_2 = \cos\left(\omega_0 t - \frac{2\pi}{3}\right)$$

$$j_3 = \cos\left(\omega_0 t - \frac{4\pi}{3}\right)$$

a note, again: normalized amplitude is 1; if actual amplitude is I_m, the normalization is

$$j_X \triangleq \frac{i_X}{I_m}$$

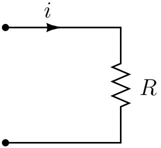
and there is a way to get it . . .

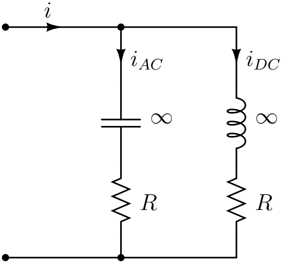


analysis ...

- regarding the inputs, diodes and switches perform useless function
- each phase observes R_E, which is perfect!
- which of the resistors is the hottest one?
- or better to ask, which one is the coldest?
- let's separate AC and DC, you already know the trick ...

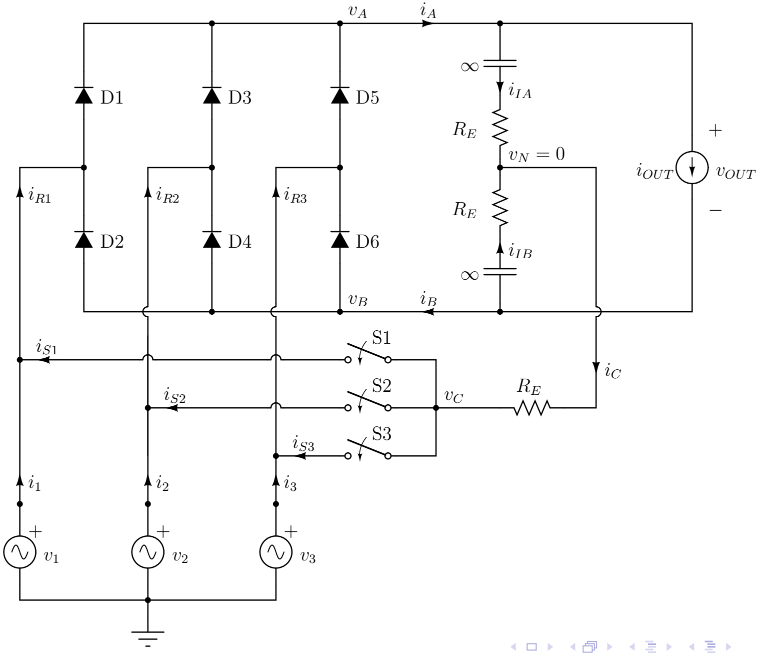
. . . the trick . . .





hint: $L = R^2\,C$, if ∞ is too big

voila!


v_A
i_A
D1
D3
D5
∞
i_{IA}
R_E
$v_N = 0$
$+$
i_{OUT}
v_{OUT}
$-$
i_{R1}
i_{R2}
i_{R3}
R_E
D2
D4
D6
i_{IB}
∞
v_B
i_B
S1
i_{S1}
S2
i_{S2}
v_C
R_E
i_C
S3
i_{S3}
i_1
i_2
i_3
$+$
v_1
$+$
v_2
$+$
v_3

analysis . . .

- . . . and we have the circuit!
- not a long mathematical derivation?
- actually, it's invented right now, while working on this presentation (April 15, 2012, 00:06:53)
- not the first experience of this kind, 1999, . . .

something similar published in . . .

Predrag Pejović

"A Novel Low Harmonic Three Phase Rectifier"

IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications,
vol. 49, no. 7, pp. 955–965, July 2002

after lots of trouble . . .

although, the derivation presented here is much shorter, and the circuit is slightly different . . .

currents . . .

$$j_A = m_A$$

$$j_B = -m_B$$

$$j_C = -m_C$$

analytical description, spectra, waveforms, . . .

$$j_{IA} = j_A - J_{OUT}$$

$$j_{IB} = J_{OUT} - j_B$$

$$J_{OUT} = \frac{3\sqrt{3}}{2\pi}$$

power and efficiency ...

$$P_{IN} = \frac{3}{2}$$

$$P_{OUT} = M_{OUT}\, J_{OUT} = \frac{3\sqrt{3}}{\pi} \times \frac{3\sqrt{3}}{2\pi} = \frac{27}{2\pi^2}$$

$$P_{INJ} = P_{IN} - P_{OUT} = \frac{3\pi^2 - 27}{2\pi^2}$$

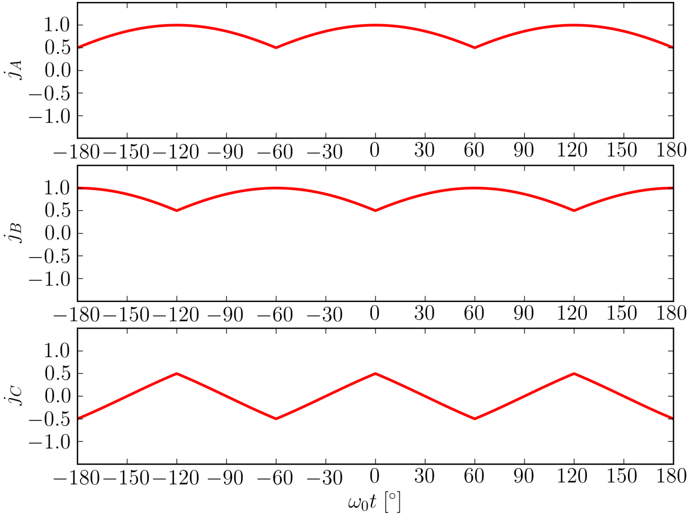
$$\boxed{\eta = \frac{P_{OUT}}{P_{IN}} = \frac{9}{\pi^2} \approx 91.19\,\%}$$

already familiar with the results?

remains to be done . . .

- how hot each resistor is?
- other current injection networks?
- the third harmonic current injection?
- how to build the switching current injection device?
- in the meantime, some waveforms and spectra . . .

j_A, j_B, and j_C



1.0
0.5
0.0
−0.5
−1.0
j_A
j_B
j_C
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

j_A, analytical

$$j_A = \max\left(j_1,\, j_2,\, j_3\right)$$

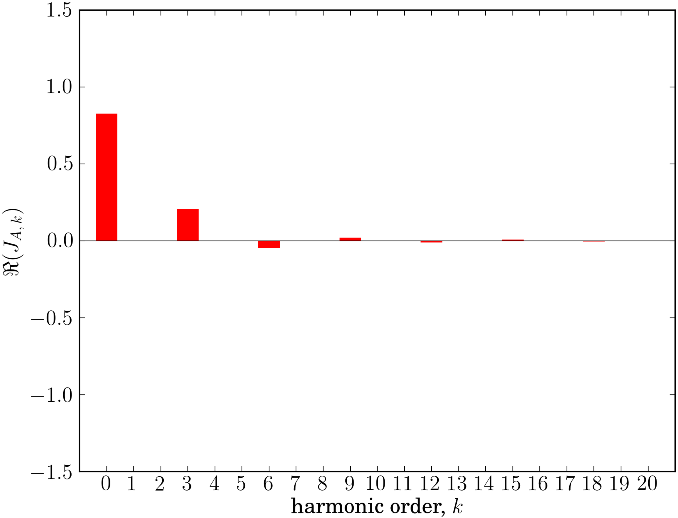
$$j_A = J_{A0} + \sum_{k=1}^{\infty} J_{A,\,k}\, \cos\left(3k\omega_0 t\right)$$

$$J_{A0} = \frac{3\sqrt{3}}{2\pi} = J_{OUT}$$

$$J_{A,\,k} = \frac{3\sqrt{3}}{\pi}\, \frac{\left(-1\right)^{k+1}}{9k^2 - 1}$$

the same as m_A

j_A, spectrum, real part



j_B, analytical

$$j_B = -\min\left(j_1,\, j_2,\, j_3\right)$$

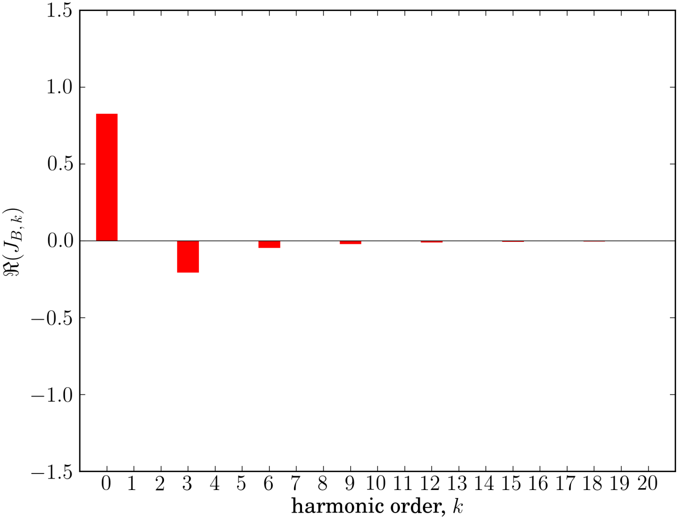
$$j_B = J_{B0} + \sum_{k=1}^{\infty} J_{B,\,k}\, \cos\left(3k\omega_0 t\right)$$

$$J_{B0} = \frac{3\sqrt{3}}{2\pi} = J_{OUT}$$

$$J_{B,\,k} = -\frac{3\sqrt{3}}{\pi}\,\frac{1}{9k^2-1}$$

the same as $-m_B$

j_B, spectrum, real part



j_C, analytical

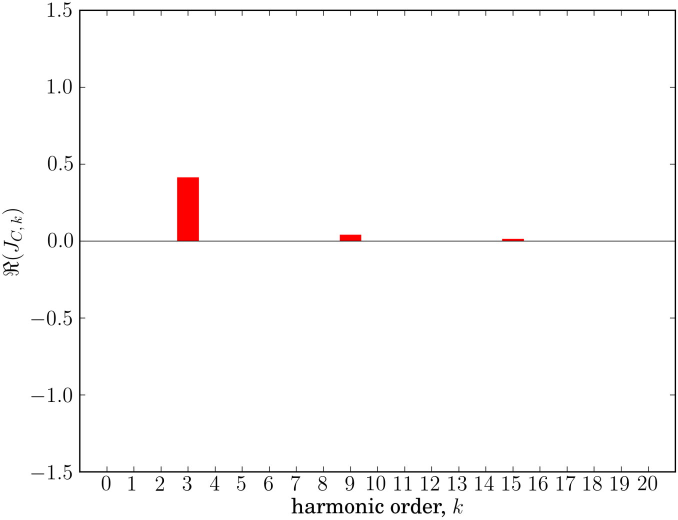
$$j_C = j_A - j_B$$

$$j_C = \sum_{k=1,3,5,\ldots}^{\infty} J_{C,k} \cos\left(3k\omega_0 t\right)$$

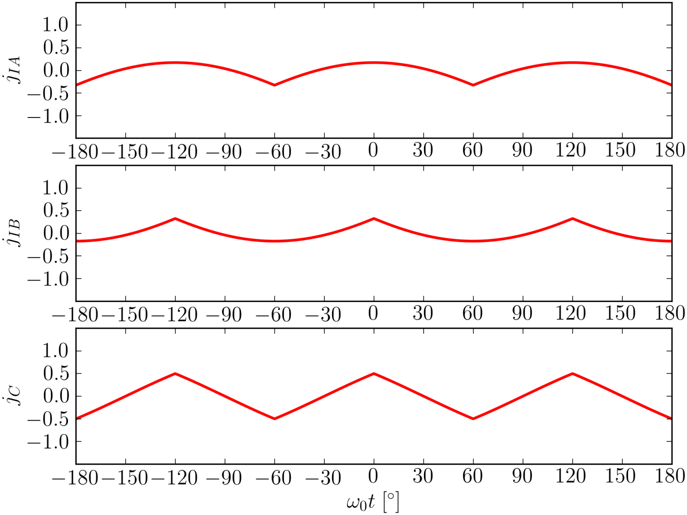
$$J_{C,k} = \frac{6\sqrt{3}}{\pi} \frac{1}{9k^2 - 1}$$

proportional to m_{AV} and $-m_C$; going to be important

j_C, spectrum, real part



j_{IA}, j_{IB}, and j_C



currents . . .

$$j_{IA} = j_A - J_{OUT}$$

$$j_{IB} = J_{OUT} - j_B$$

$$J_{OUT} = \frac{3\sqrt{3}}{2\pi}$$

analytical description, spectra, . . .

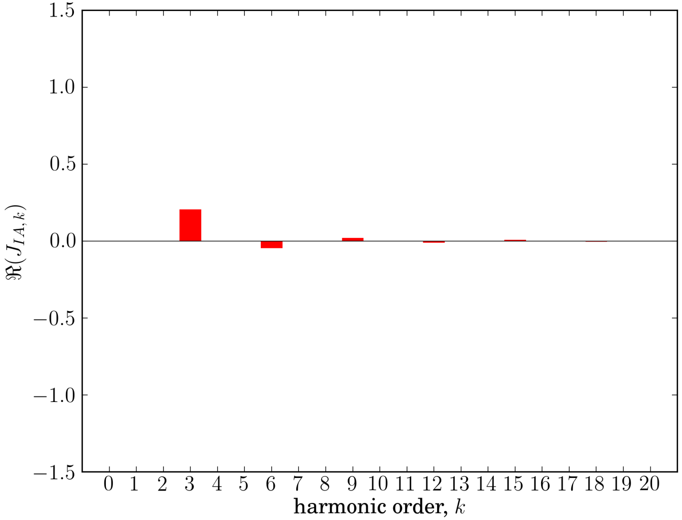
j_{IA}, analytical

$$j_{IA} = \max\left(j_1,\, j_2,\, j_3\right) - \frac{3\sqrt{3}}{\pi}$$

$$j_{IA} = \sum_{k=1}^{\infty} J_{A,\,k}\, \cos\left(3k\omega_0 t\right)$$

$$J_{IA,\,k} = \frac{3\sqrt{3}}{\pi}\, \frac{(-1)^{k+1}}{9k^2 - 1}$$

j_{IA}, spectrum, real part



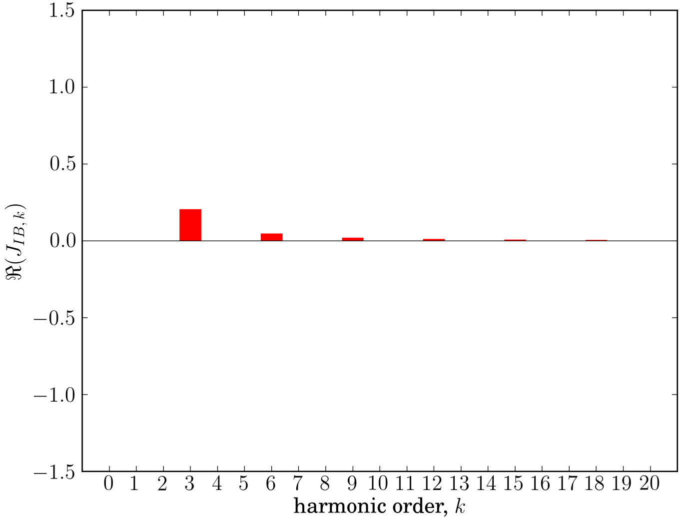
j_{IB}, analytical

$$j_{IB} = \frac{3\sqrt{3}}{2\pi} - \min\left(j_1,\, j_2,\, j_3\right)$$

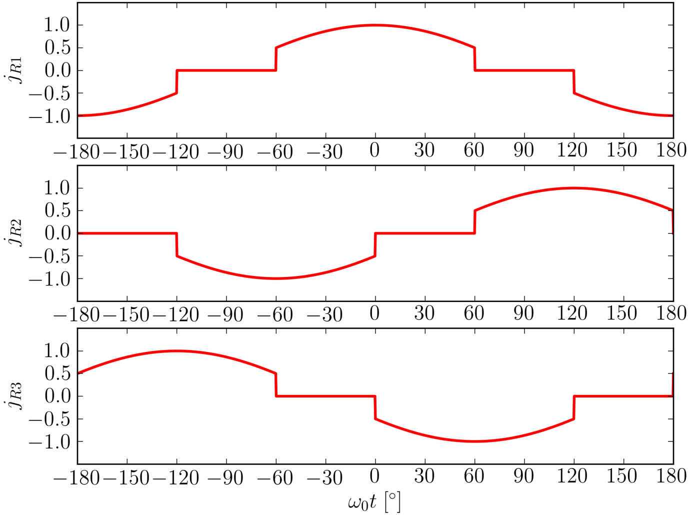
$$j_{IB} = \sum_{k=1}^{\infty} J_{B,\,k}\, \cos\left(3k\omega_0 t\right)$$

$$J_{IB,\,k} = \frac{3\sqrt{3}}{\pi}\, \frac{1}{9k^2 - 1}$$

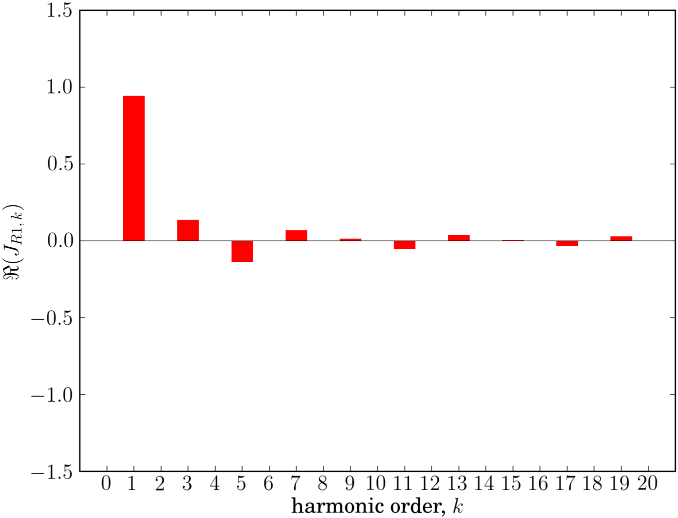
j_{IB}, spectrum, real part



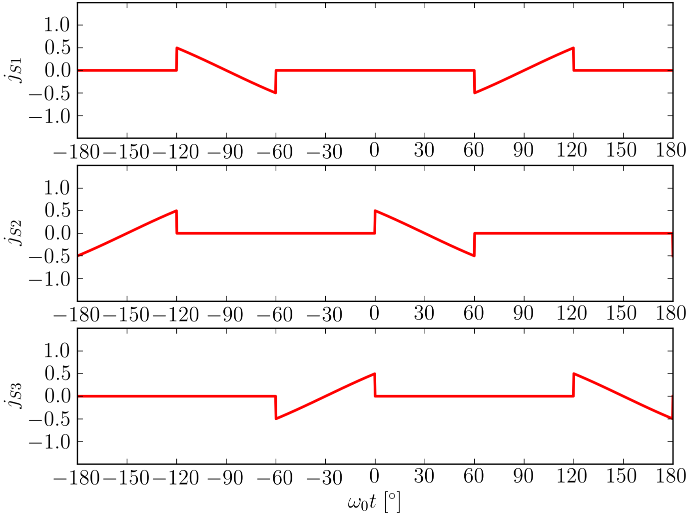
detour: j_{R1}, j_{R2}, and j_{R3}



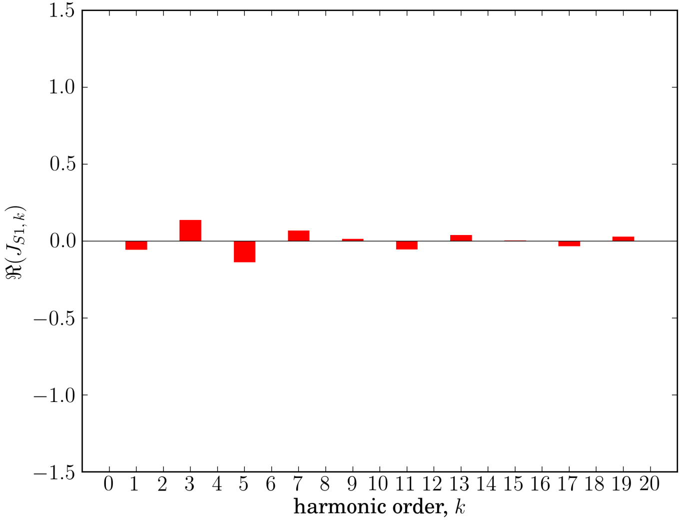
j_{R1}, spectrum, real part



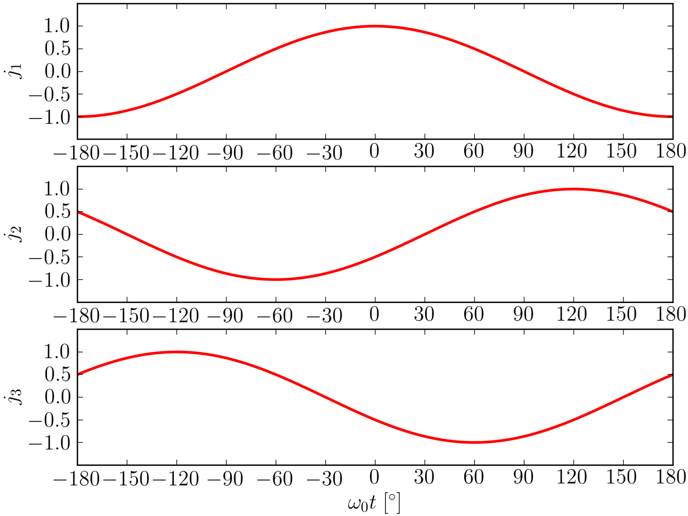
j_{S1}, j_{S2}, and j_{S3}



j_{S1}, spectrum, real part

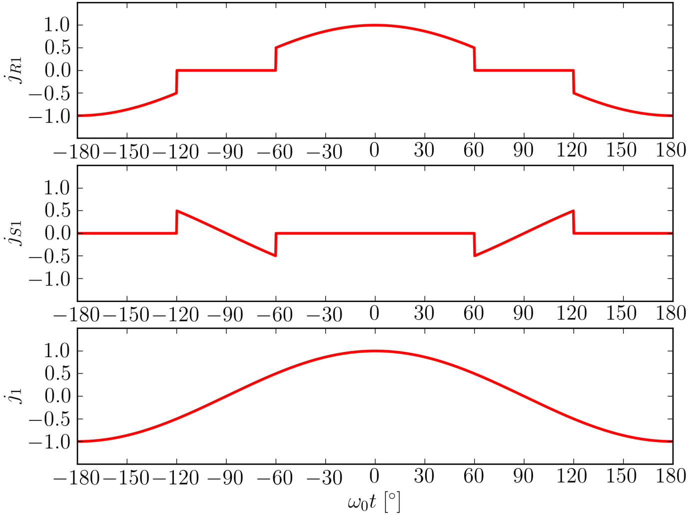


j_1, j_2, and j_3

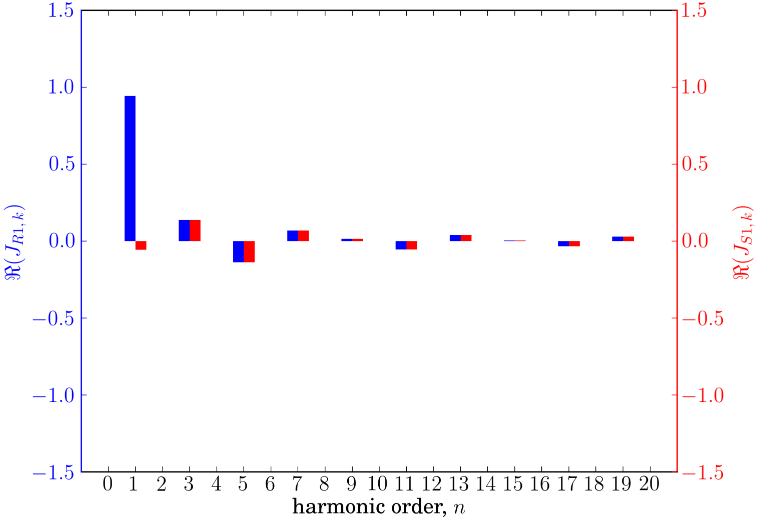


j_1
j_2
j_3
1.0
0.5
0.0
−0.5
−1.0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

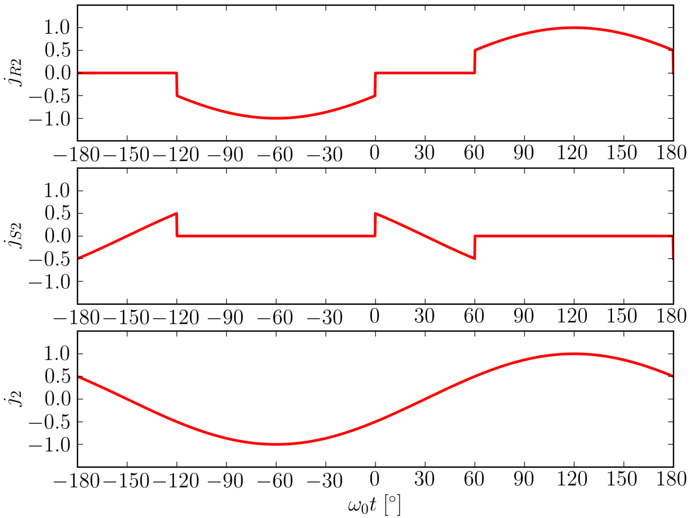
how j_1 is obtained?



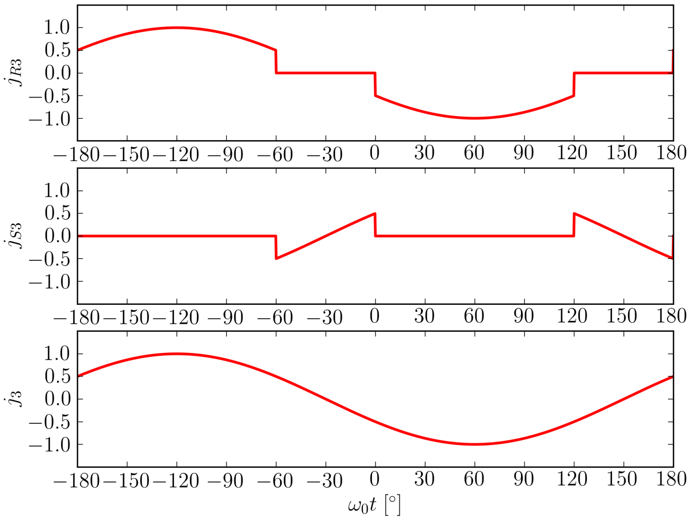
how j_1 is obtained: spectral approach



how j_2 is obtained?



how j_3 is obtained?



j_{odd} and j_{even}

matter of convenience:

$$j_{IA} = j_{odd} + j_{even}$$

$$j_{IB} = j_{odd} - j_{even}$$

$$j_{odd} = \frac{j_{IA} + j_{IB}}{2}$$

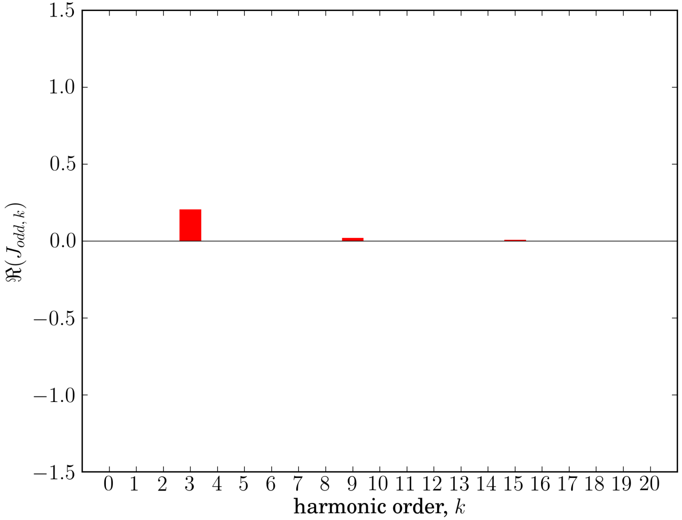
$$j_{even} = \frac{j_{IA} - j_{IB}}{2}$$

j_{odd}, spectrum

$$j_{odd} = \sum_{k=1,3,5...}^{\infty} J_{odd,\,k} \cos\left(3k\omega_0 t\right)$$

$$J_{odd,\,k} = \frac{3\sqrt{3}}{\pi} \frac{1}{9k^2 - 1}$$

j_{odd}, spectrum, real part



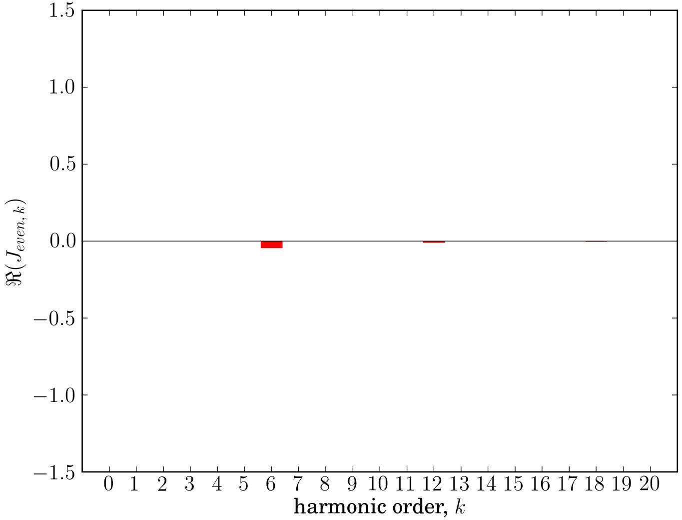
j_{even}, spectrum

$$j_{even} = \sum_{k=2,4,6...}^{\infty} J_{even,\,k} \cos\left(3k\omega_0 t\right)$$

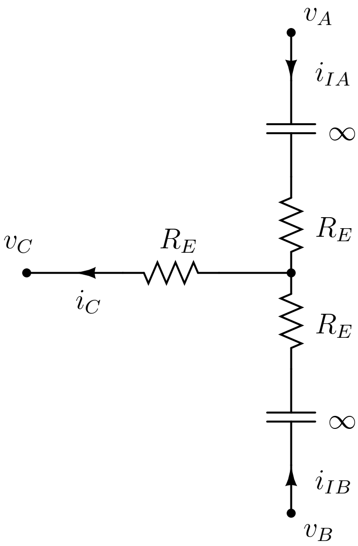
$$J_{even,\,k} = -\frac{3\sqrt{3}}{\pi}\,\frac{1}{9k^2-1}$$

proportional to $m_{OUT\,AC}$; going to be important

j_{even}, spectrum, real part



so, we have SCIN #0



SCIN #0, heat ...

wxMaxima ... I won't be able to complete this job manually, it's too boring ...

$$J_{IA\,RMS} = J_{IB\,RMS} = \frac{\sqrt{4\pi^2 + 3\pi\sqrt{3} - 54}}{2\pi\sqrt{2}}$$

$$P_{vertical\,R_E} = (J_{IA\,RMS})^2 = \frac{4\pi^2 + 3\pi\sqrt{3} - 54}{8\pi^2} \approx 0.0228$$

vertically placed R_E resistors are not so hot

$$J_{C\,RMS} = \sqrt{\frac{2\pi - 3\sqrt{3}}{4\pi}}$$

$$P_{horizontal\,R_E} = (J_{C\,RMS})^2 = \frac{2\pi - 3\sqrt{3}}{4\pi} \approx 0.0865$$

horizontally placed R_E is much hotter, almost 4 times; why 4×?

a few words about SCIN #0

- transformer not required
- too many resistors
- one resistor takes the most of the power

some relations . . .

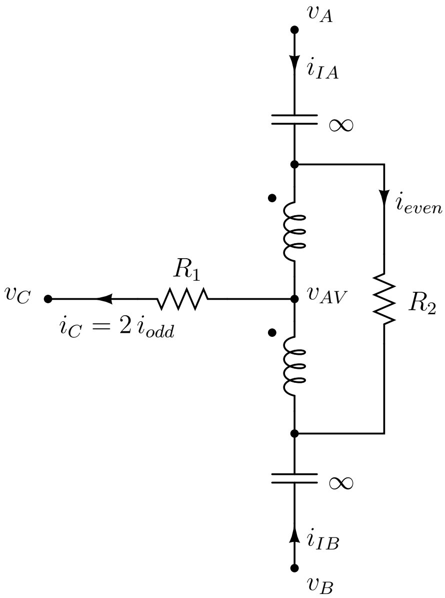
$$\frac{m_{AV}}{j_{odd}} = 1$$

$$\frac{m_C}{j_{odd}} = -2$$

$$\frac{m_{OUT\,AC}}{j_{even}} = 2$$

to be used while creating new current injection networks . . .

SCIN #1, separatism



R_1 and R_2

$$R_1 = \frac{m_{AV} - m_C}{2\, j_{odd}}\, R_E = \frac{3}{2}\, R_E$$

$$R_2 = \frac{m_{OUT\, AC}}{j_{even}} = 2\, R_E$$

and now you know why "some relations" were needed for

some power accounting, again ...

$$J_{odd\,RMS} = \frac{\sqrt{2\pi - 3\sqrt{3}}}{4\sqrt{\pi}}$$

$$P_1 = \frac{3}{2}\left(J_{odd\,RMS}\right)^2 = \frac{3}{8}\left(2 - \frac{3\sqrt{3}}{\pi}\right) \approx 0.1298$$

$$J_{even\,RMS} = \frac{\sqrt{3}}{4\pi}\sqrt{2\pi^2 + 3\pi\sqrt{3} - 36}$$

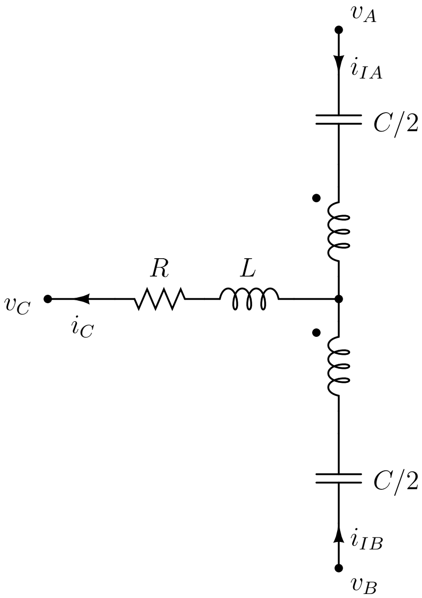
$$P_2 = \frac{3\left(2\pi^2 + 3\pi\sqrt{3} - 36\right)}{8\pi^2} \approx 0.0024$$

dissipation is dominant on R_1

an idea makes a new idea . . .

- power on R_2 is small . . .
- let's get rid of R_2!
- result: the same as the 3^{rd} harmonic CIN #3 for $Q = 0$, $THD \approx 4\,\%$
- could we get $Q \neq 0$?
- definitely!
- do we need it?
- well, maybe for passive resistance emulation, to be talked about later

SCIN #2, the 3rd harmonic one



SCIN #2, parameters

$$3\omega_0 = \frac{1}{\sqrt{LC}}$$

$$j_C = \frac{1}{2}\cos\left(3\omega_0 t\right)$$

$$M_{AV,1} - M_{C,1} = \frac{9\sqrt{3}}{8\pi}$$

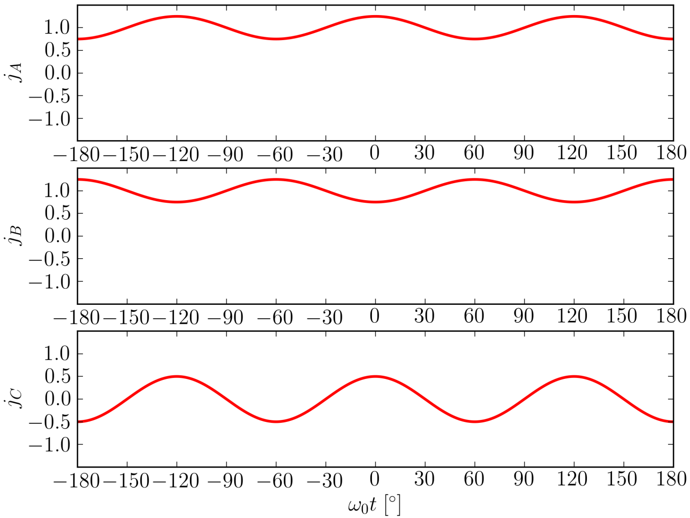
$$R = \frac{9\sqrt{3}}{4\pi}\,\frac{V_m}{I_{OUT}}$$

- $R \quad 9\times\uparrow$
- $i_R \quad 3\times\downarrow$
- $v_R \quad 3\times\uparrow$
- $p_R = v_R\, i_R$ remains the same, no way to save any power

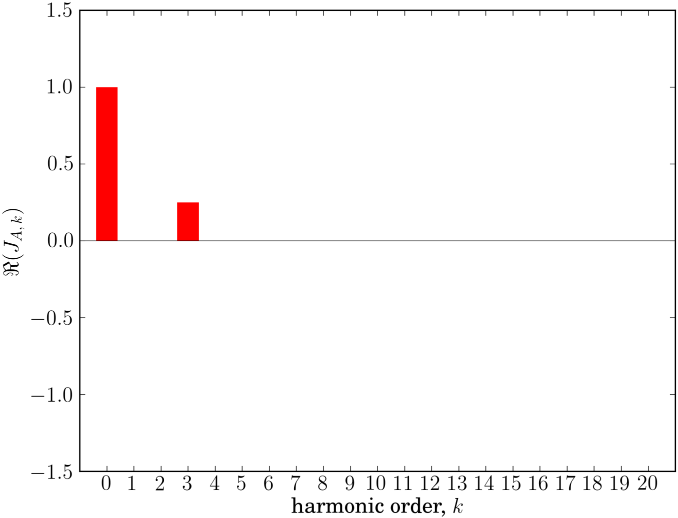
renormalization

- input currents not sinusoidal any more
- convenient to use $I_{base} = I_{OUT}$, instead of $I_{base} = I_m$
- mutual relation?
- $I_{OUT} = \frac{3\sqrt{3}}{2\pi}\, I_m \approx 0.82699\, I_m$, but only when the input currents are sinusoidal

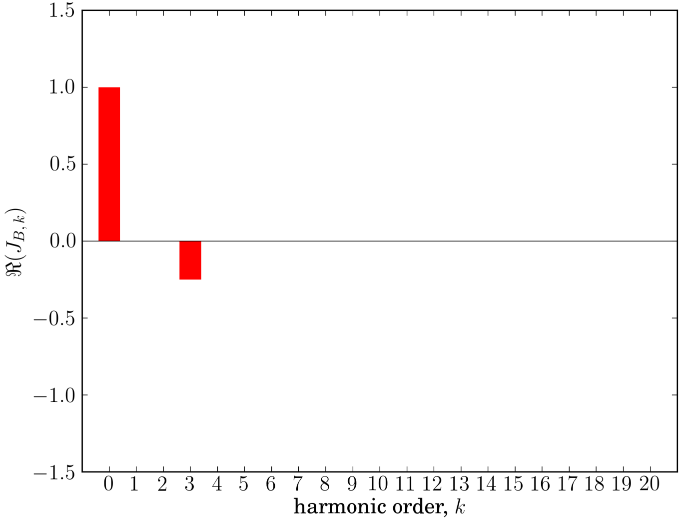
j_A, j_B, and j_C, the 3rd harmonic injection



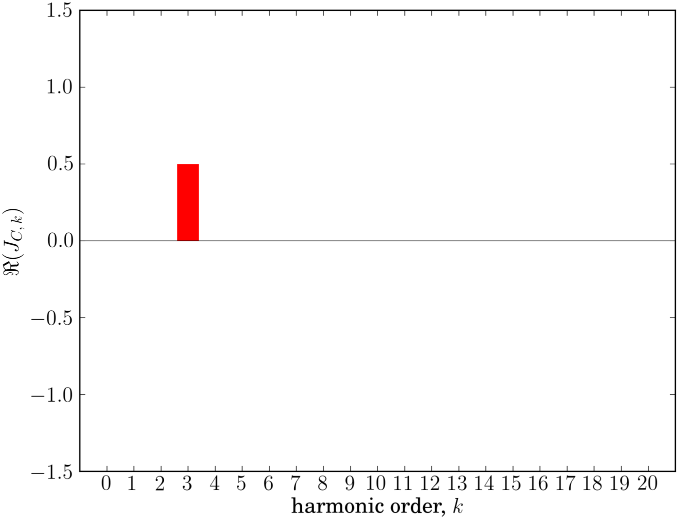
j_A, spectrum, real part, the 3rd harmonic injection



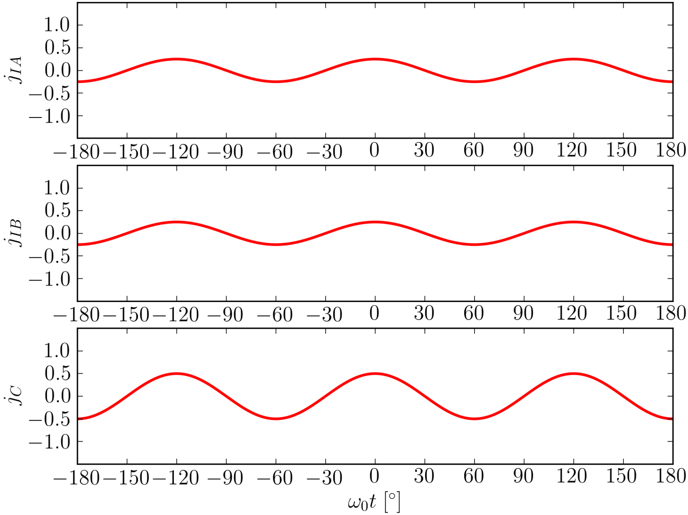
j_B, spectrum, real part, the 3rd harmonic injection



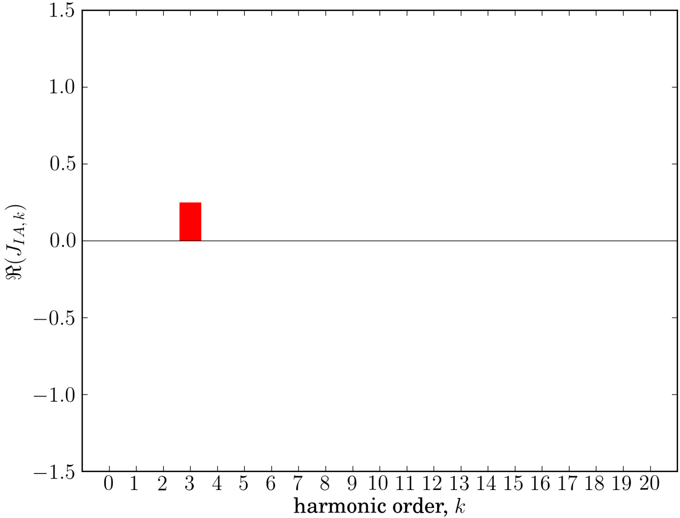
j_C, spectrum, real part, the 3rd harmonic injection



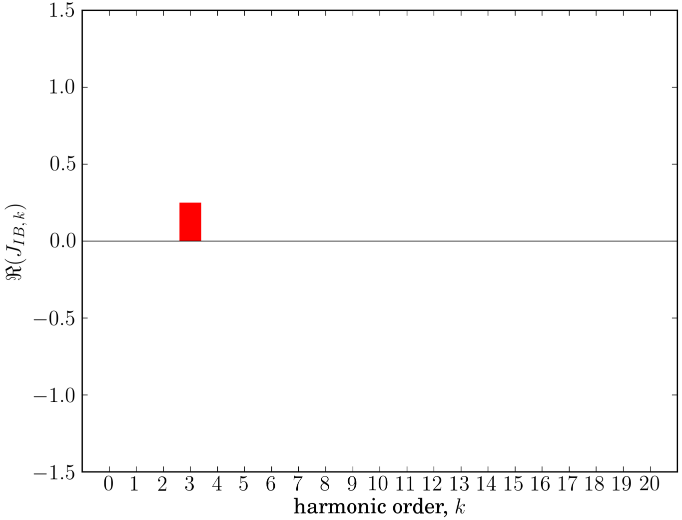
j_{IA}, j_{IB}, and j_C, the 3rd harmonic injection



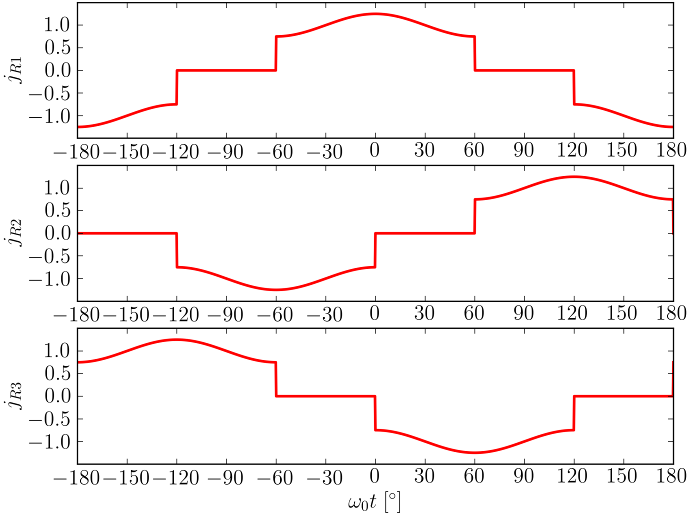
j_{IA}, spectrum, real part, the 3rd harmonic injection



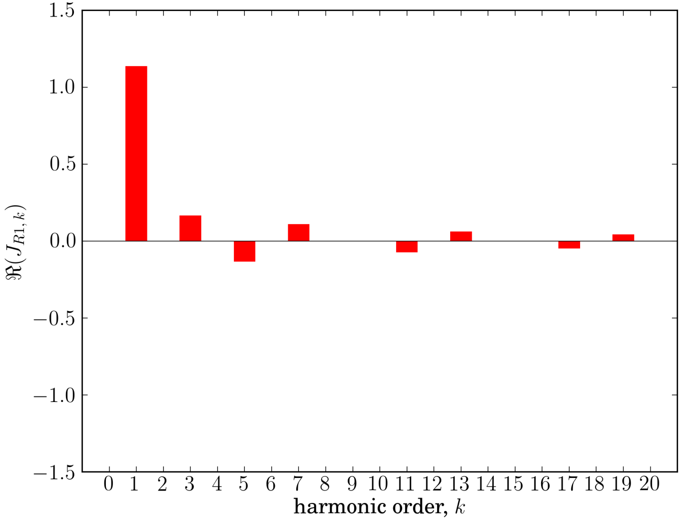
j_{IB}, spectrum, real part, the 3rd harmonic injection



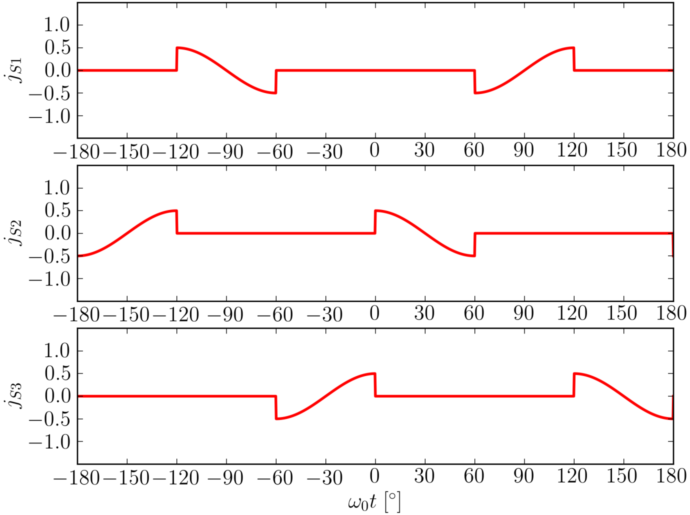
j_{R1}, j_{R2}, and j_{R3}, the 3rd harmonic injection



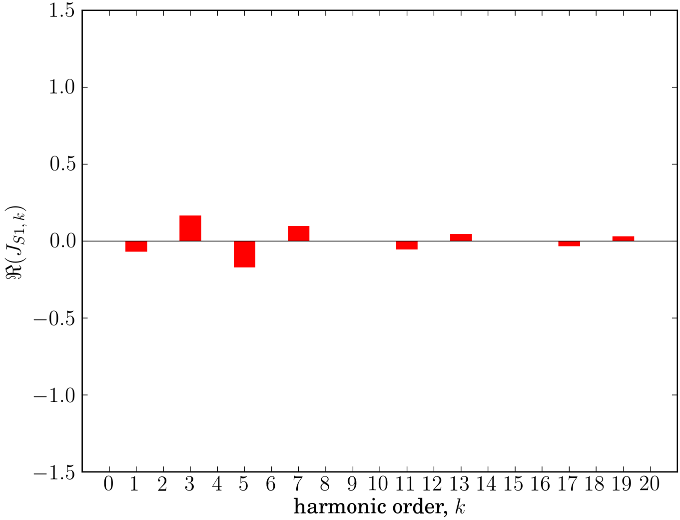
j_{R1}, spectrum, real part, the 3rd harmonic injection



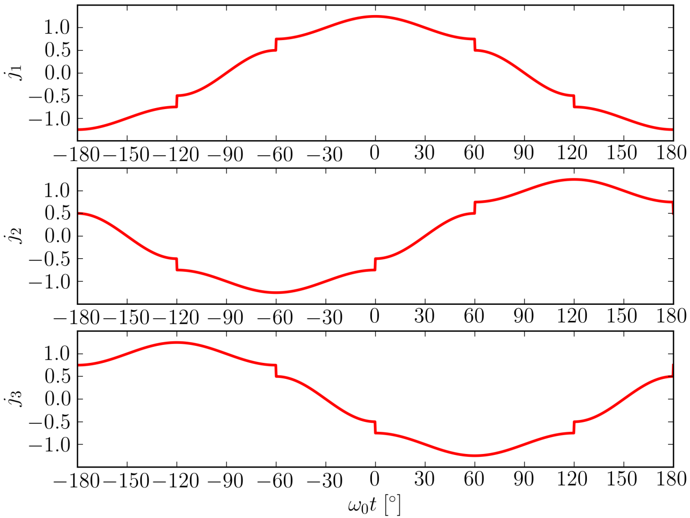
j_{S1}, j_{S2}, and j_{S3}, the 3rd harmonic injection



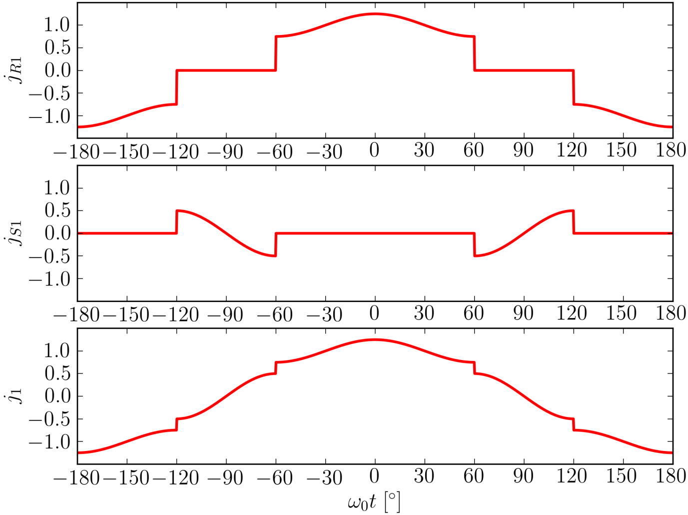
j_{S1}, spectrum, real part, the 3rd harmonic injection



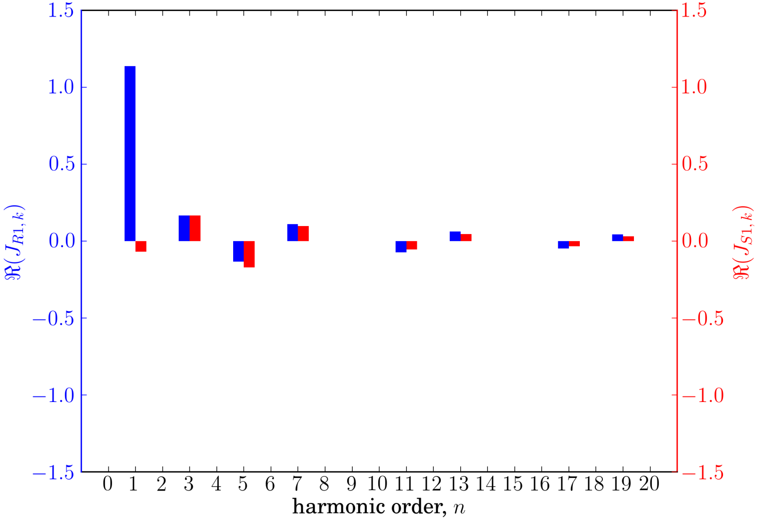
j_1, j_2, and j_3, the 3[rd] harmonic injection



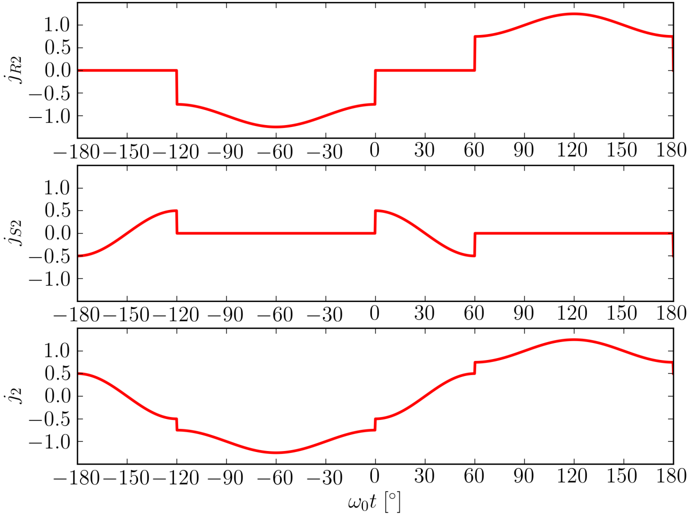
how j_1 is obtained, the 3rd harmonic injection



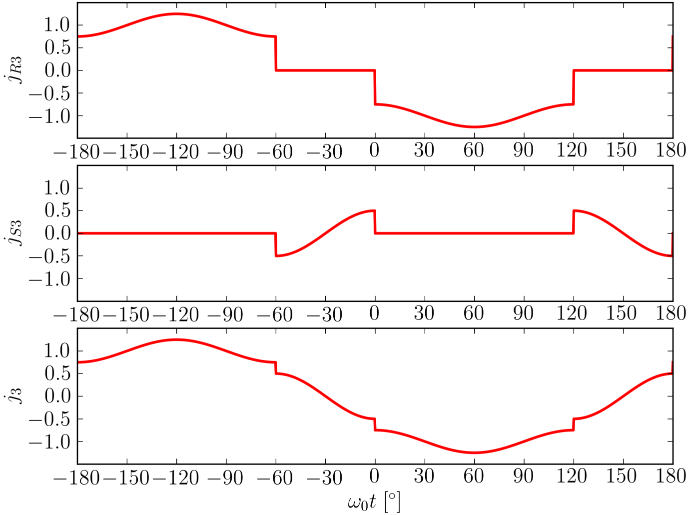
how j_1 is obtained, the 3$^{\text{rd}}$ harmonic injection



how j_2 is obtained, the 3rd harmonic injection



how j_3 is obtained, the 3^{rd} harmonic injection



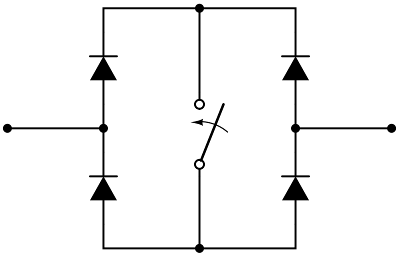
a note about RMSs

$$J_{A,0} = J_{B,0} = 1$$

$$J_{A\,RMS} = J_{B\,RMS} = \sqrt{\frac{33}{32}} \approx 1.0155$$

much better than for magnetic current injection devices (where the increase was about 13%)

a note about bidirectional switches . . .



- turned out to be easier than expected
- control problems, interaction with the diode bridge
- interphase shorts should not be allowed to occur . . .
- primarily in the diode bridge!

conclusions

- switching current injection device
- injection only where needed
- bidirectional switches required
- control of the switches, switching at $2\,f_0$ ...
- three current injection networks proposed, although there are many more
- the optimal and the third harmonic current injection
- "dominant" resistor suitable for resistance emulation
- three times lower currents in comparison to magnetic current injection devices
- lower RMS of the diode bridge load currents ...

“future work”

- how to restore the power taken by the current injection network?