Passive Resistance Emulation

how to restore the power taken by the CIN?

- resistance emulation . . . since all we need are resistors . . .
- switching converter?
- possible, something done, something in progress . . .
- requires: auxiliary power supply, control logic, sensors . . .
- causes EMI . . . which requires filtering . . .
- reliability? maintainability?
- is there a simpler way?
- at least, to have some fun . . .
- passive resistance emulation!
- "passive" means that there are no controlled switches . . .
- neither any control logic . . .
- so all the thinking should be done in advance

solved before we started ...

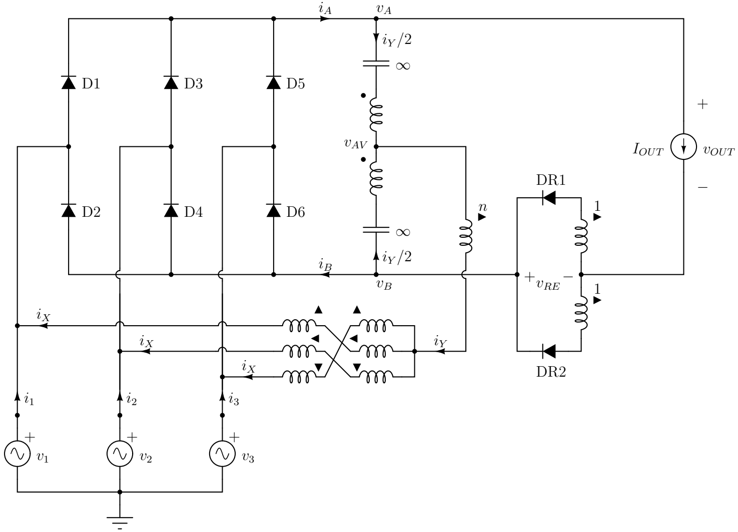
Shigeo Masukawa, Shoji Iida

"An Improved Three-Phase Diode Rectifier for Reducing AC Line Current Harmonics"

7^{th} *European Conference on Power Electronics and Applications*, EPE'97

pp. 4.227–4.232, Trondheim, Norway, September 1997

and they proposed . . .



initial thoughts . . . for a long time . . .

- just another multipulse rectifier . . .
- from a different (multipulse) world
- which for multi $= 12$ provides $THD = 15.22\,\%$
- all of this is true . . .
- but there is more . . .
- let's study it, first!

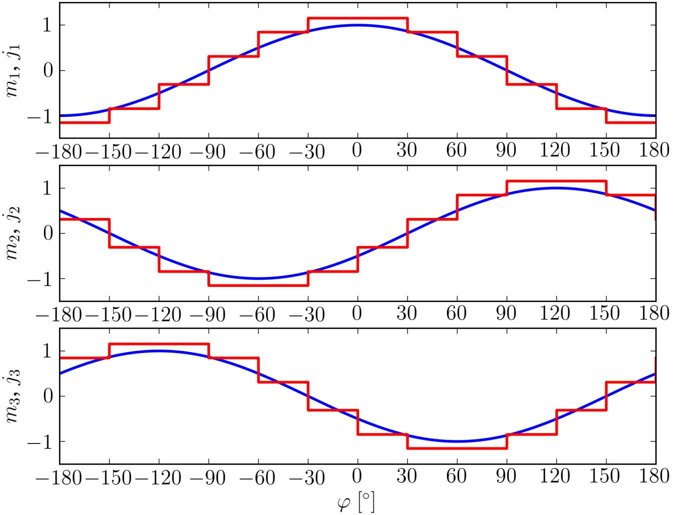
some equations . . .

$$i_Y = \frac{1}{n} I_{OUT} \operatorname{sgn}(v_{AV})$$

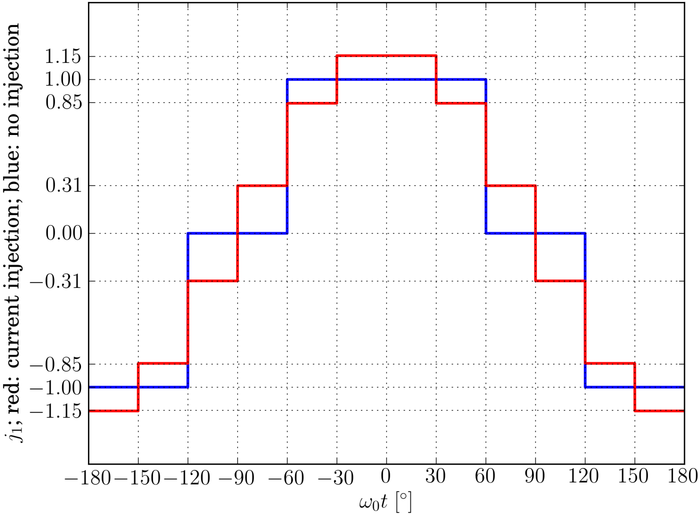
$$v_{RE} = \frac{1}{n} |v_{AV}|$$

$$n_{OPT} = \frac{1}{4\sqrt{3} - 6} \approx 1.0774$$

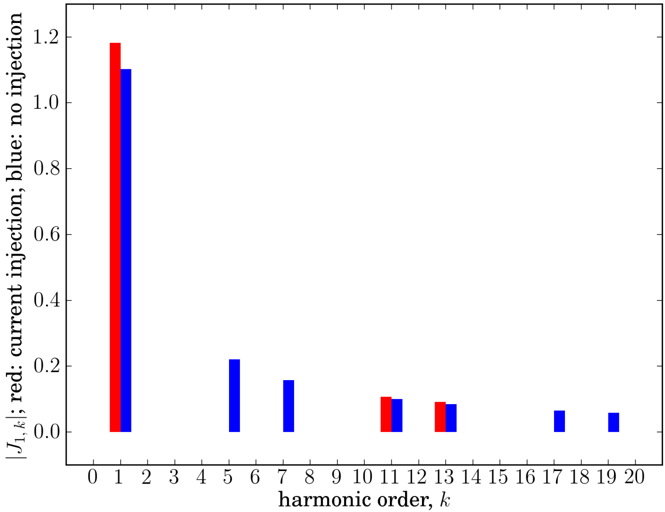
m_k and j_k, $k \in \{1, 2, 3\}$



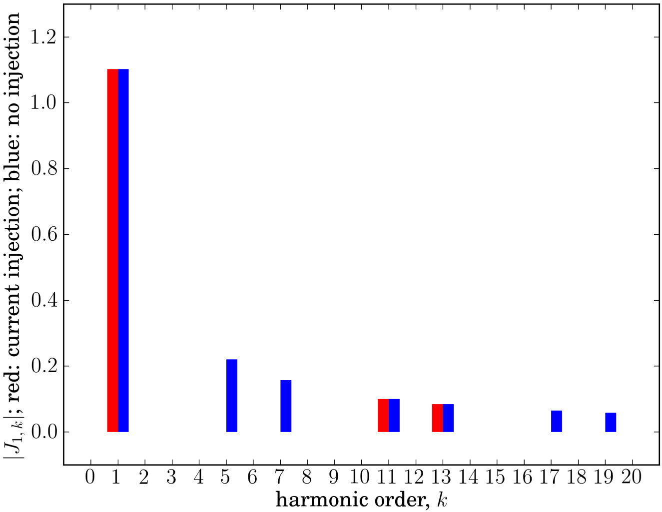
a closer look at j_1



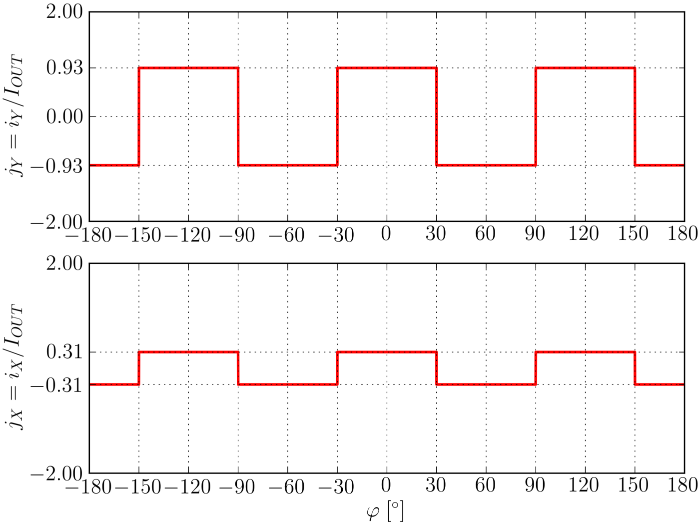
a closer look at j_1, spectrum



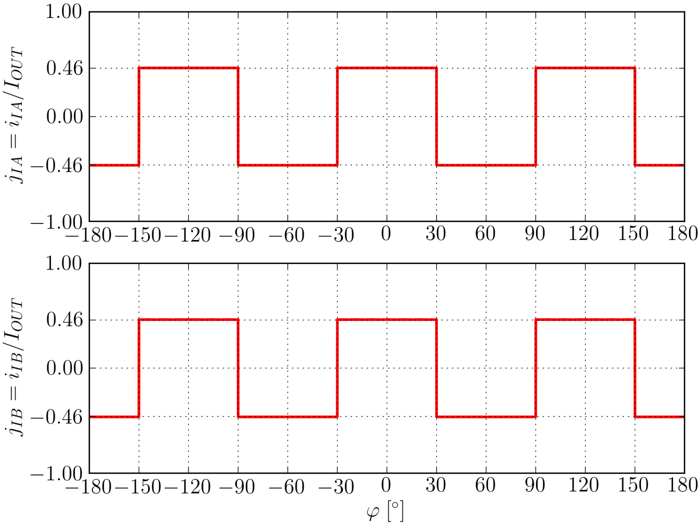
j_1, spectrum renormalized



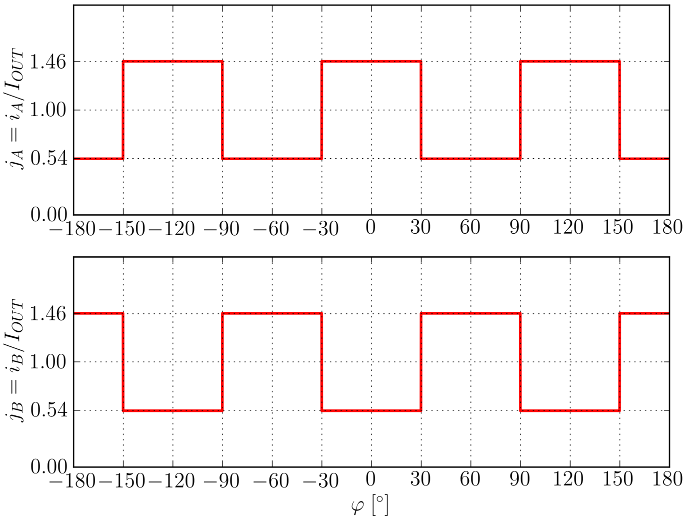
how does it work: j_Y and j_X



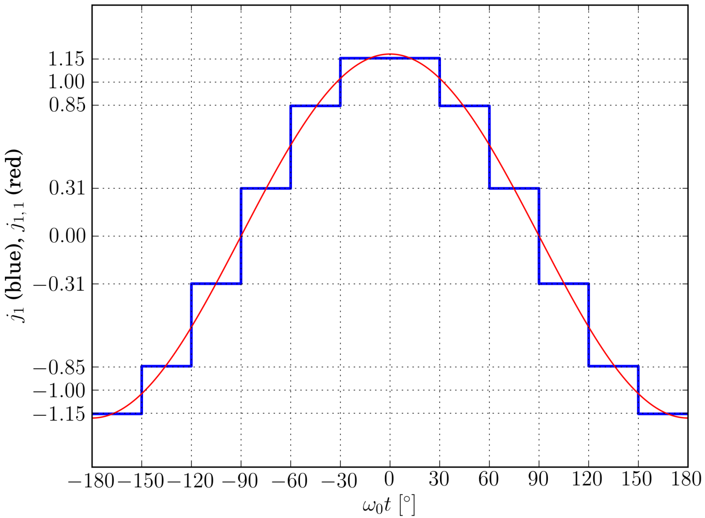
how does it work: j_{IA} and j_{IB}



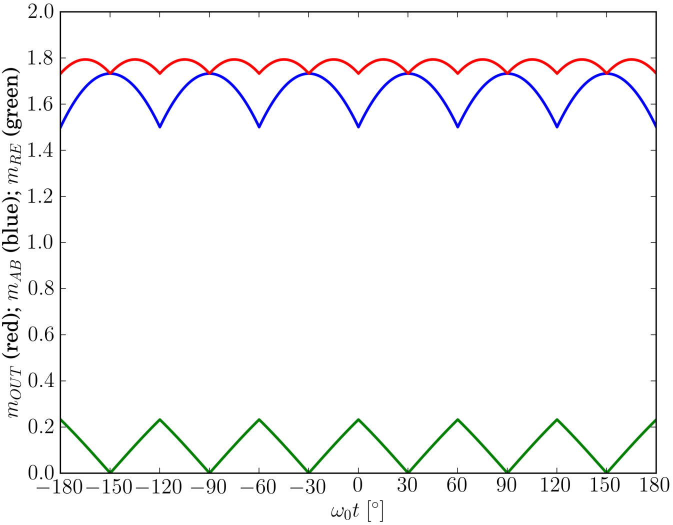
how does it work: j_A and j_B



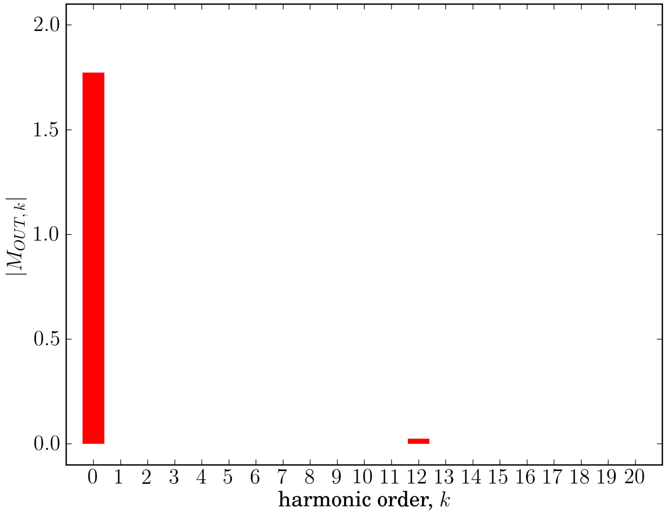
and the result is . . .



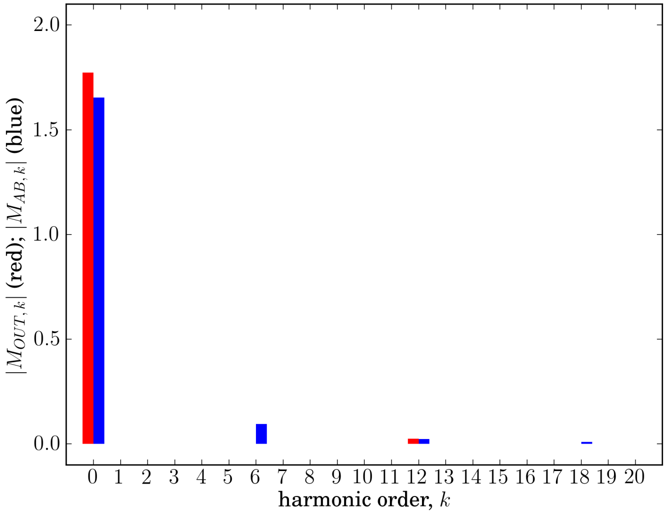
voltages at the output ...



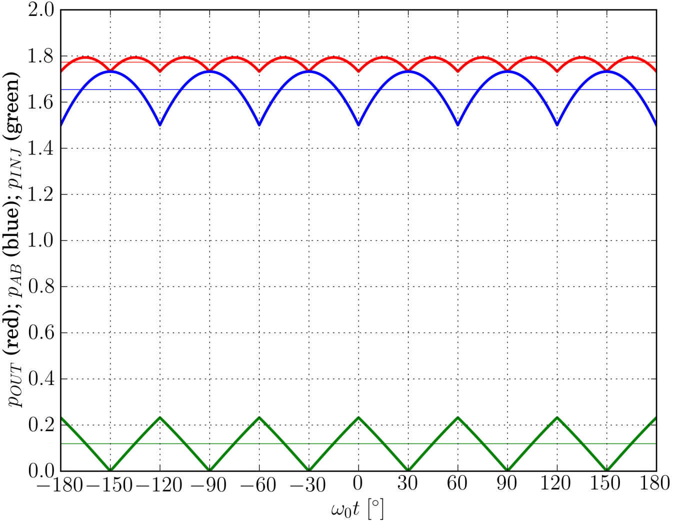
the output voltage spectrum ...



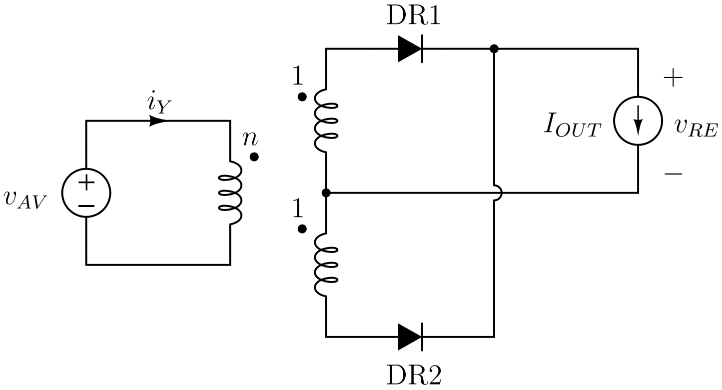
comparison of $|M_{OUT,k}|$ to $|M_{AB,k}|$ ...



and finally some power . . .



current loaded resistance emulator?



some equations . . .

$$v_{RE} = \frac{1}{n} \left| v_{AV} \right|$$

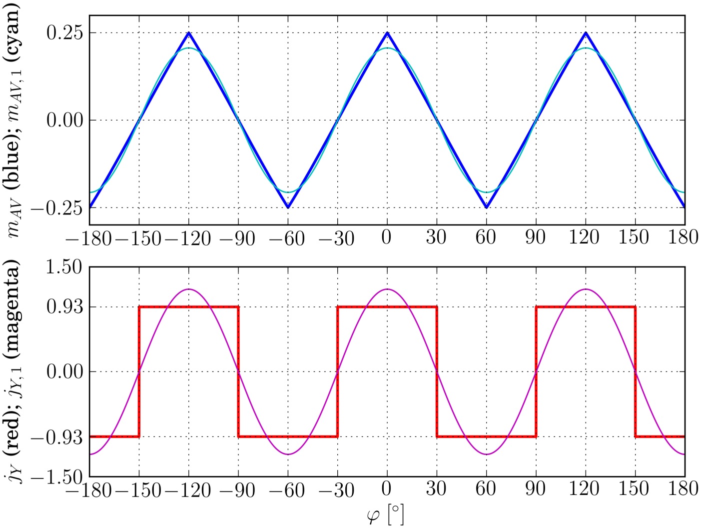
$$i_Y = \frac{1}{n} I_{OUT} \operatorname{sgn}\left(v_{AV} \right)$$

resulting in . . .

$$i_{Y,1} = \frac{4}{\pi n} I_{OUT} \cos\left(3\omega_0 t \right)$$

thanks to Professor Robert Warren Erickson and his class
Power Electronics 2
topic “Series Resonant Converter”

emulated resistance? sinusoidal approximation?

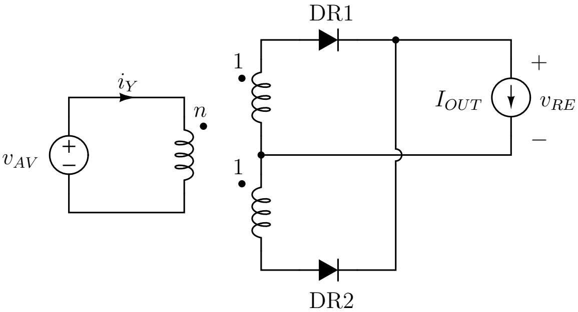


emulated resistance

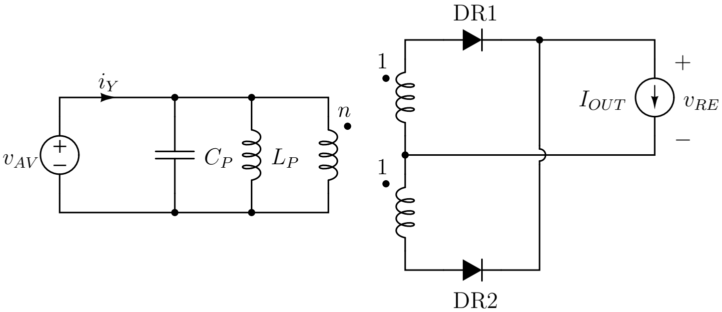
$$R_E = \frac{V_{AV,\,1}}{I_{Y,\,1}} = \frac{3}{64\left(2-\sqrt{3}\right)} \approx 0.17494$$

...in this case

is there a way to filter out the higher order harmonics?



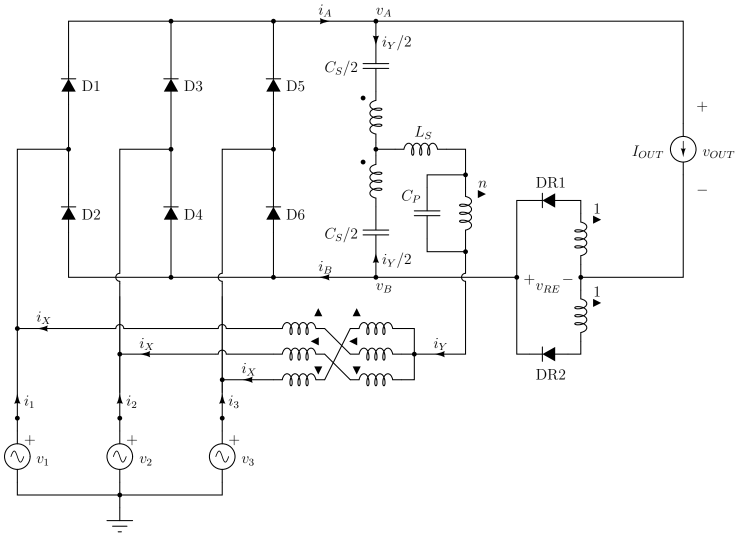
there is!



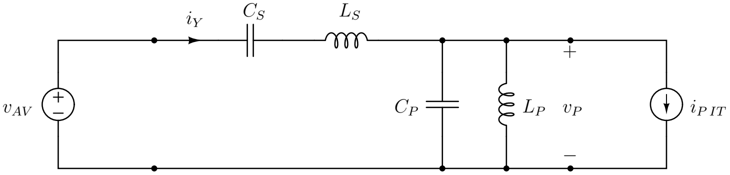
a few hints ...

- $3\,\omega_0 = 1/\sqrt{L_P\,C_P}$
- L_P should be realized as a magnetizing inductance of the transformer ...
- ... which I realized an inductor too late ...
- CIN will do the rest ...
- and there are **two** resonance constraints to satisfy ...
- thanks, Bob!
- ... and this is not the only time I used the series resonant converter and sinusoidal approximation...

the whole converter

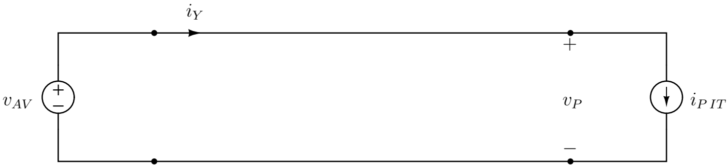


resistance emulator, AC side, equivalent circuit



$$i_{P\,IT} = \frac{1}{n}\, I_{OUT}\, \mathrm{sgn}\,(v_P)$$

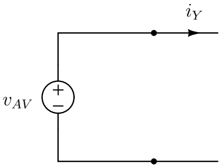
at $3\omega_0$, somewhat idealized

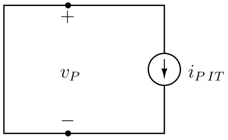


$$i_{P\,IT} = \frac{1}{n}\, I_{OUT}\, \mathrm{sgn}\,(v_P)$$

$\mathrm{sgn}\,(v_P)$, not $\mathrm{sgn}\,(v_{AV})$, please remember!

above $3\omega_0$, really idealized





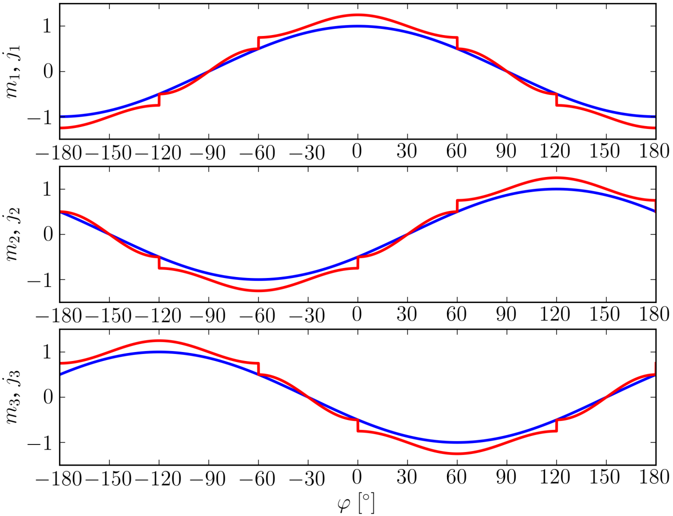
a word (an equation) about n

$$I_{Ym} = \frac{4}{n\pi} I_{OUT}$$

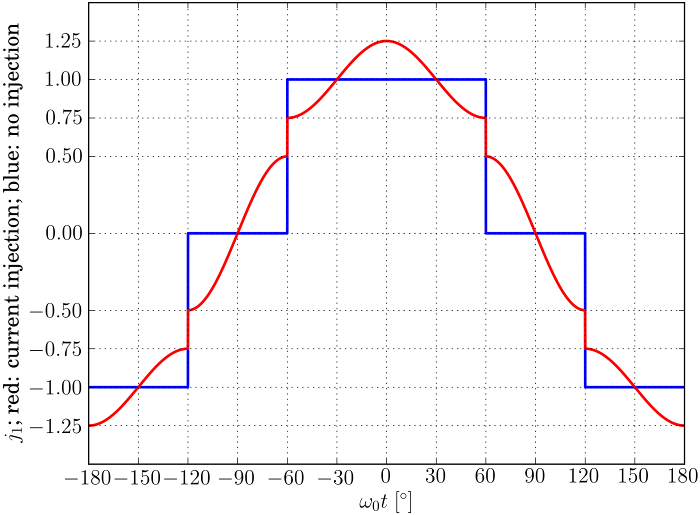
$$\frac{3}{2} = \frac{4}{n\pi}$$

$$\boxed{n = \frac{8}{3\pi} \approx 0.84883}$$

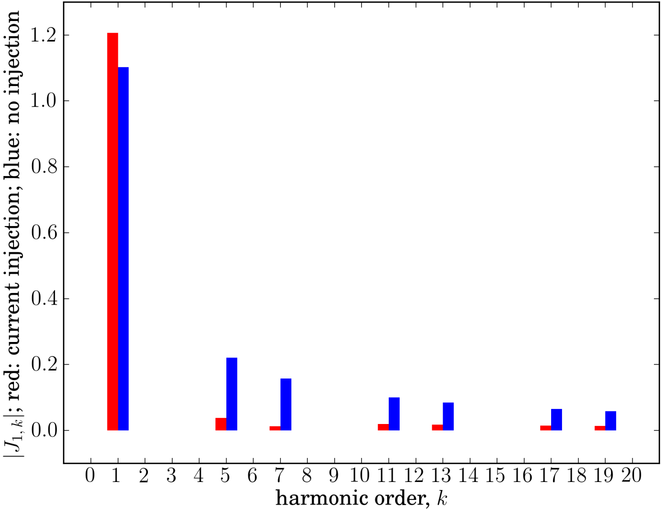
m_k and j_k, $k \in \{1, 2, 3\}$



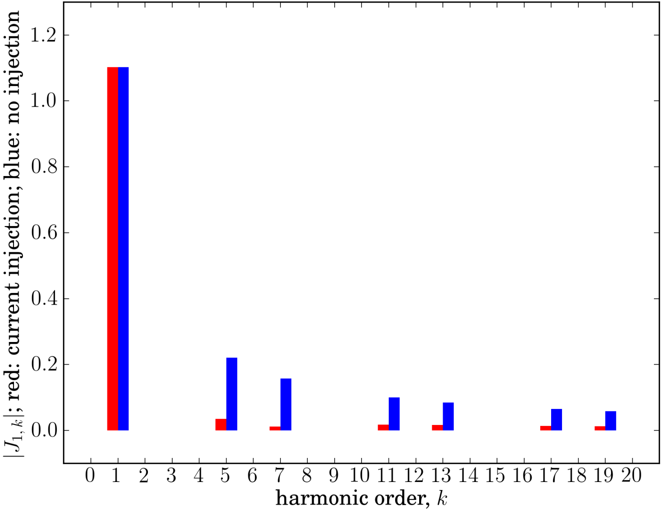
a closer look at j_1



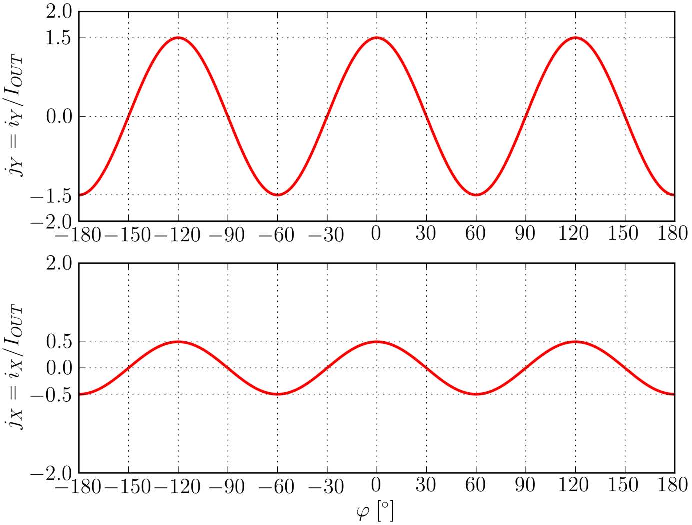
a closer look at j_1, spectrum



j_1, spectrum renormalized

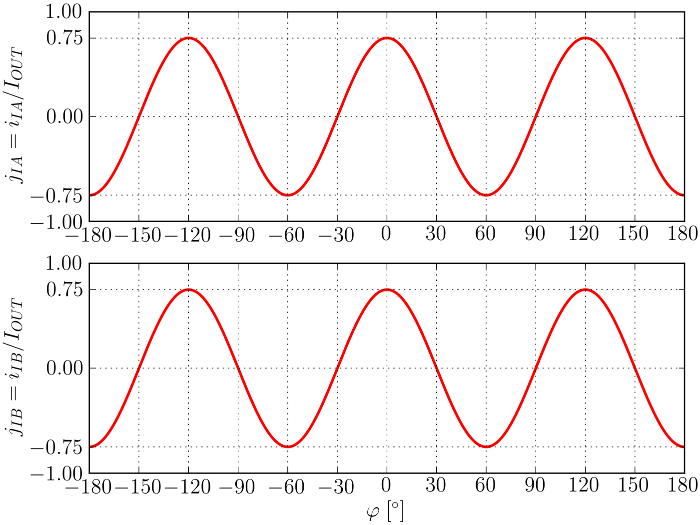


j_Y and j_X



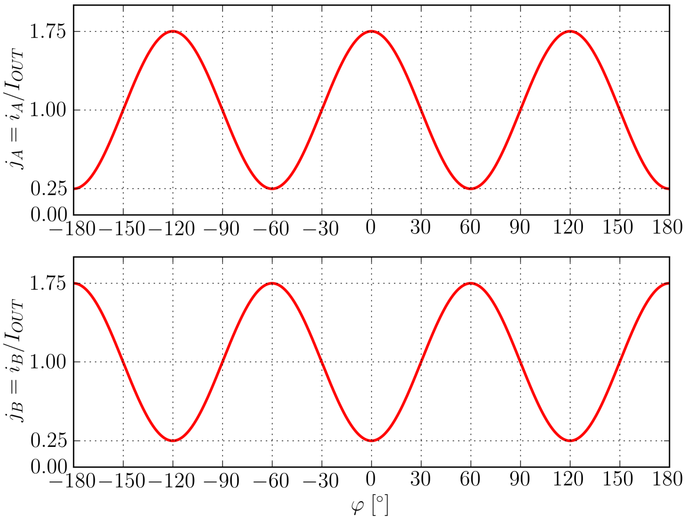
2.0
1.5
0.0
−1.5
−2.0
$j_Y = i_Y/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
2.0
0.5
0.0
−0.5
−2.0
$j_X = i_X/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

j_{IA} and j_{IB}



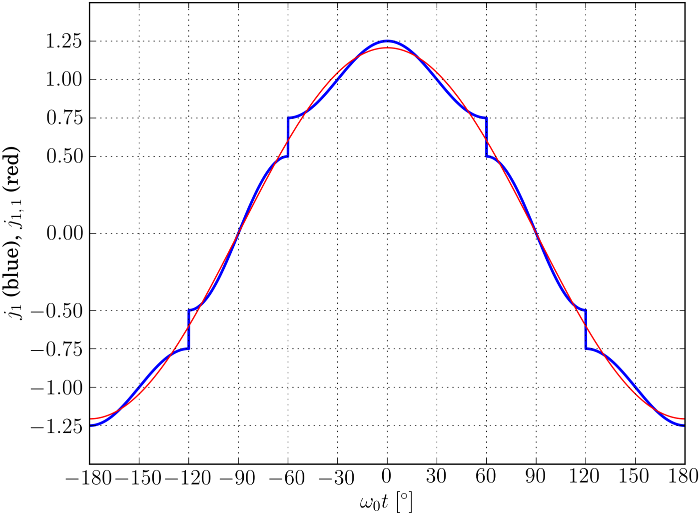
1.00
0.75
0.00
−0.75
−1.00
$j_{IA} = i_{IA}/I_{OUT}$
$j_{IB} = i_{IB}/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

j_A and j_B



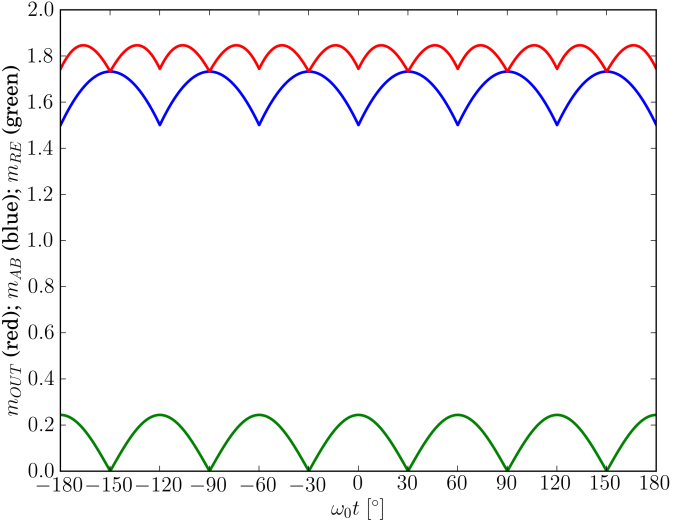
$j_A = i_A/I_{OUT}$
1.75
1.00
0.25
0.00
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$j_B = i_B/I_{OUT}$
1.75
1.00
0.25
0.00
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

the result ...

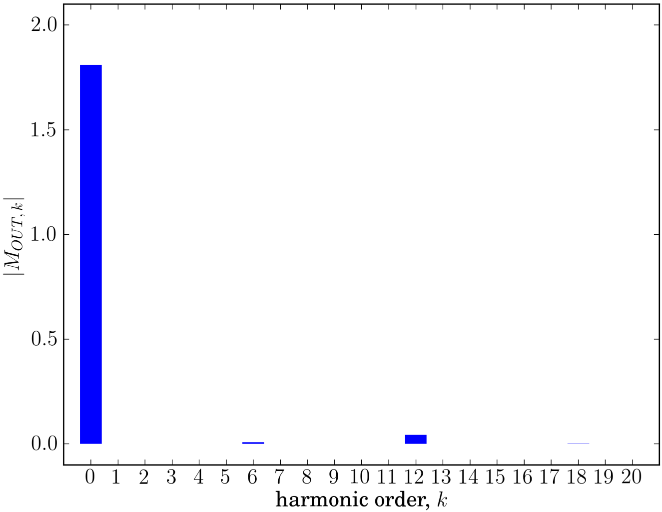


1.25
1.00
0.75
0.50
0.00
−0.50
−0.75
−1.00
−1.25
j_1 (blue), $j_{1,1}$ (red)
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

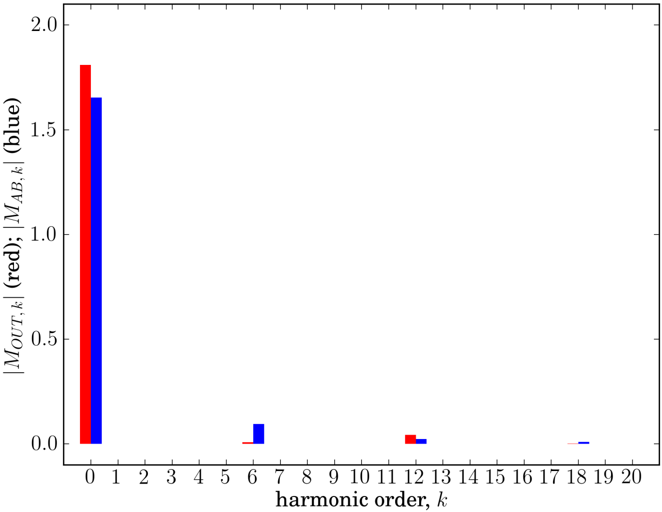
voltages at the output . . .



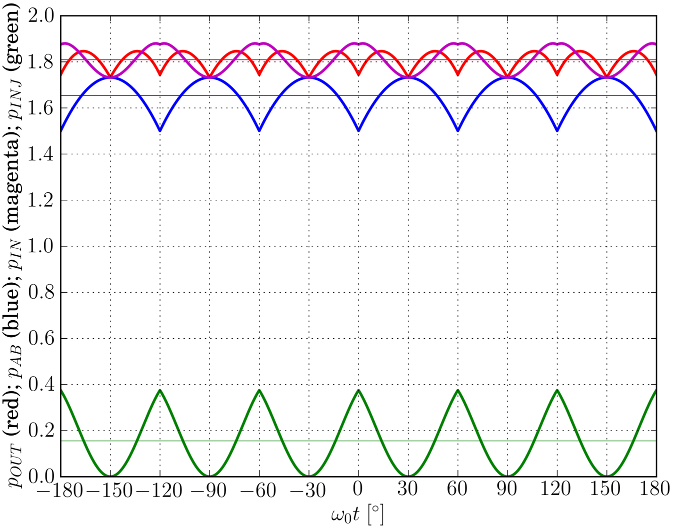
the output voltage spectrum . . .



comparison of $|M_{OUT,k}|$ to $|M_{AB,k}|$ ...



and finally some power . . .



published in . . .

Predrag Pejović

“Two Three-Phase High Power Factor Rectifiers that Apply the Third Harmonic Current Injection and Passive Resistance Emulation”

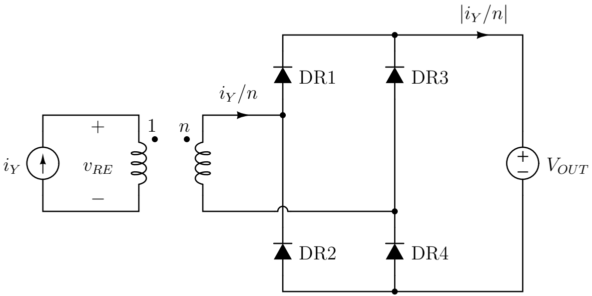
IEEE Transactions on Power Electronics,
vol. 15, no. 6, pp. 1228–1240, November 2000

with an overpage fee of more than US$ 1500.–

nice?

- some details not mentioned ...
- VA-ratings of the transformers are low ...
- effects caused by higher order harmonics analyzed ...
- generalized for switching CID ...
- nice result ...
- in theory ...
- well, it works in practice ...
- but there are two resonance constraints ...
- and the circuit is sensitive on leakage of the parallel resonant circuit at $3\omega_0$ ...
- anything better?

voltage loaded resistance emulator ...



some equations

$$v_{RE} = V_{OUT} \operatorname{sgn}(i_Y)$$

$$V_{RE,1} = \frac{4}{n\pi} V_{OUT}$$

and it is not dependent on $I_{Y,1}$ ...

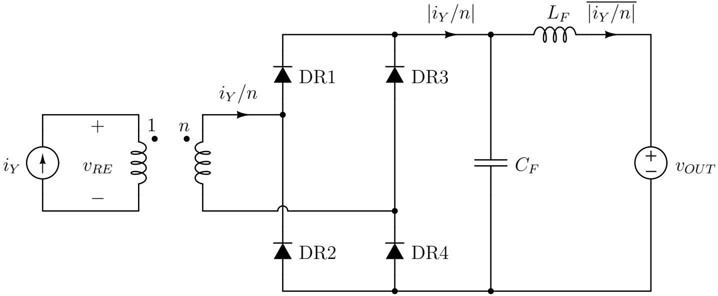
which is a problem, we cannot control $I_{Y,1}$ any more

besides, we do not have V_{OUT} available, but v_{OUT}

but, this could (should?) be solved ...

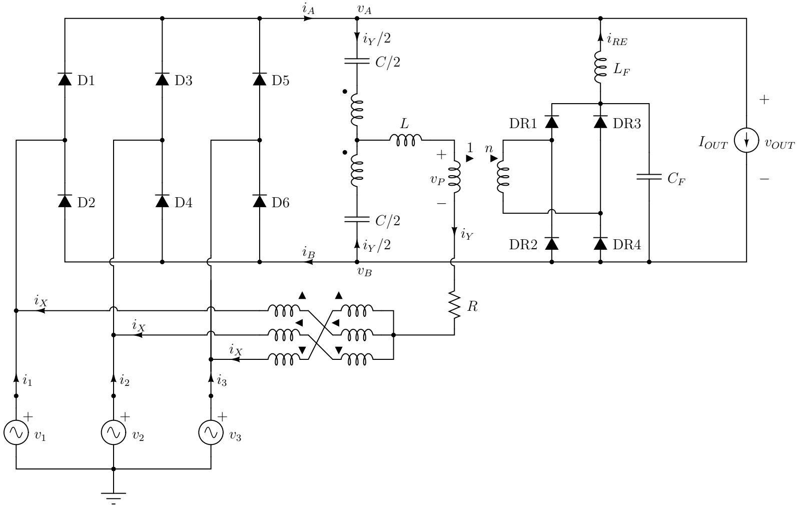
and the solution is ...

voltage loaded resistance emulator . . .



ingenious like the cosmological constant . . .

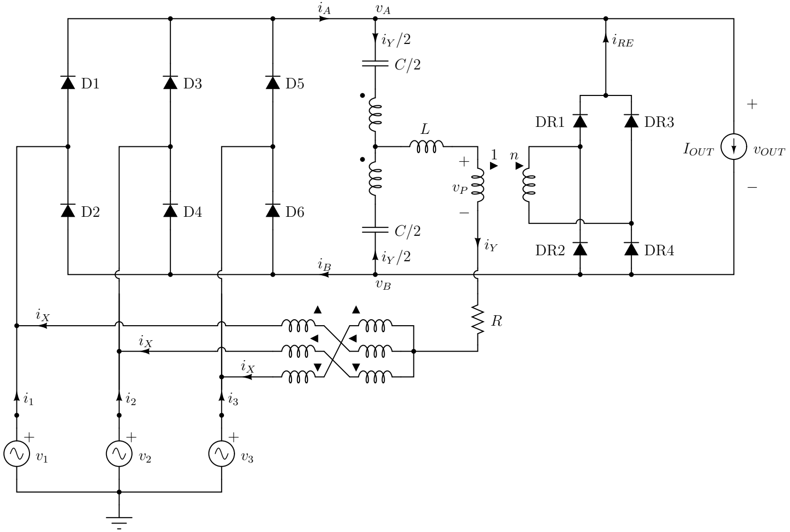
the whole circuit . . .



what really happened?

- we did not expect too much ...
- just a sort of shallow-DCM converter ...
- with poor control of I_{Ym} ...
- I did the experiments ...
- tired ...
- and not particularly motivated ...
- actually, not motivated at all ...
- since we did not expect much ...
- and I connected ...

the experimental circuit . . .



published in ...

Predrag Pejović, Predrag Božović, Doron Shmilovitz

"Low Harmonic, Three Phase Rectifier that Applies Current Injection and a Passive Resistance Emulator"

IEEE Power Electronics Letters,
vol. 3, no. 3, pp. 96–100, September 2005

which almost cost my student his Ph.D ...
since the journal didn't have the IF
neither ever got it!

though the paper was quite cited

but this was not the administrative requirement

now, we can play smart ...

- I was surprised that the results are so good ...
- much better than expected ...
- even at the first glimpse ...
- after that, I double checked the circuit ...
- but it was too late ...
- the better circuit than intended had already been built
- and it is not that hard to dig when you know where the gold is ...
- ripple of i_{RE} improved the THD ...
- instead of making it worse ...
- wrong assumption ...
- and a serendipity!
- although, it was presented in the paper in a different style

some figures . . .

obtained assuming the **CCM** with

$$j_Y = k\,\cos\left(3\omega_0 t\right)$$

where

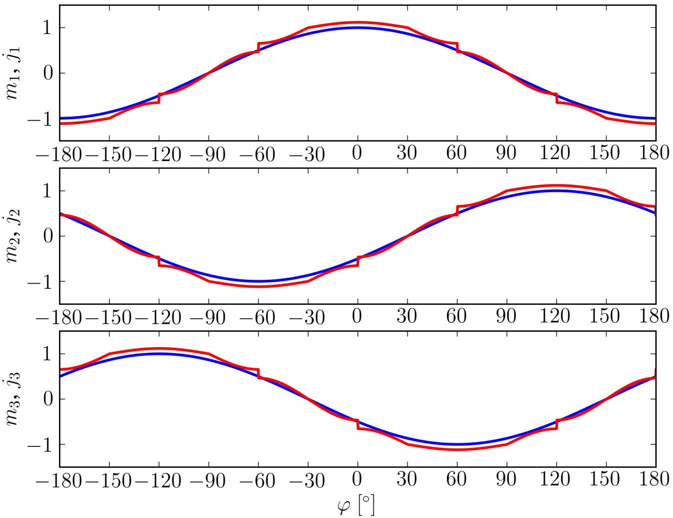
$$k = 1.39$$

and a value of n

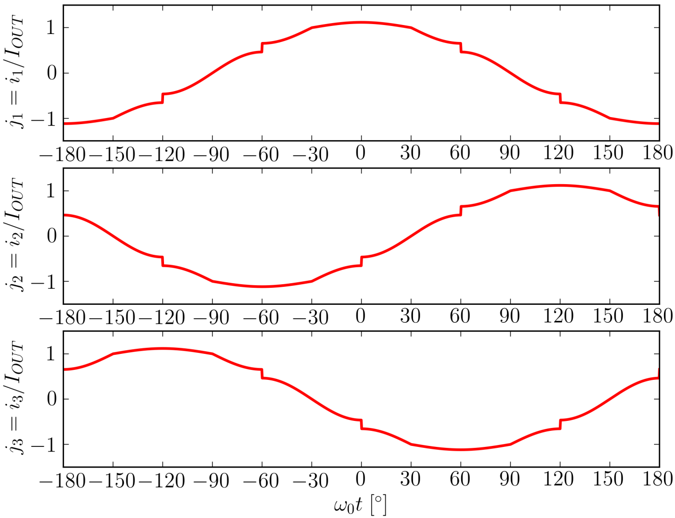
$$n = 12.23$$

don't ask why for a while . . .

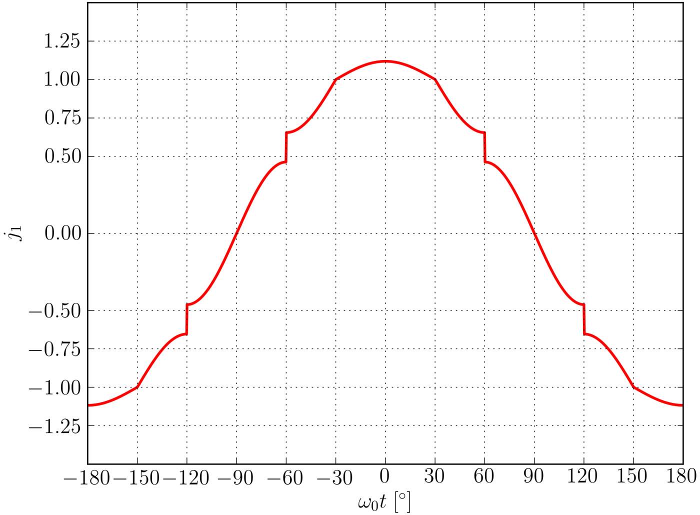
m_k and j_k, $k \in \{1, 2, 3\}$



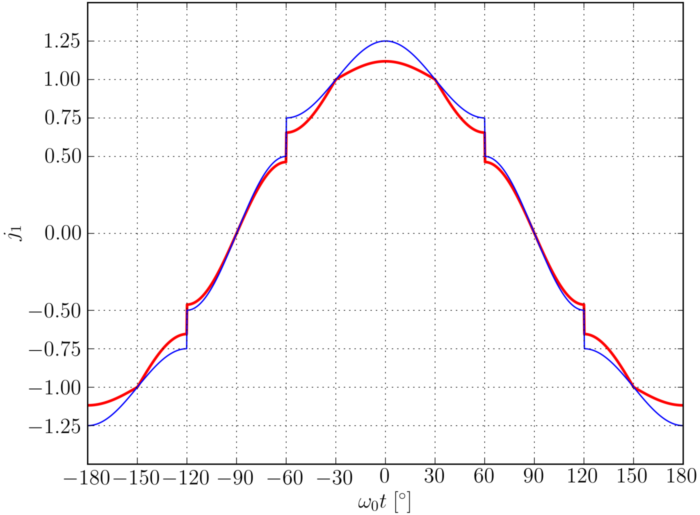
just j_k, $k \in \{1, 2, 3\}$



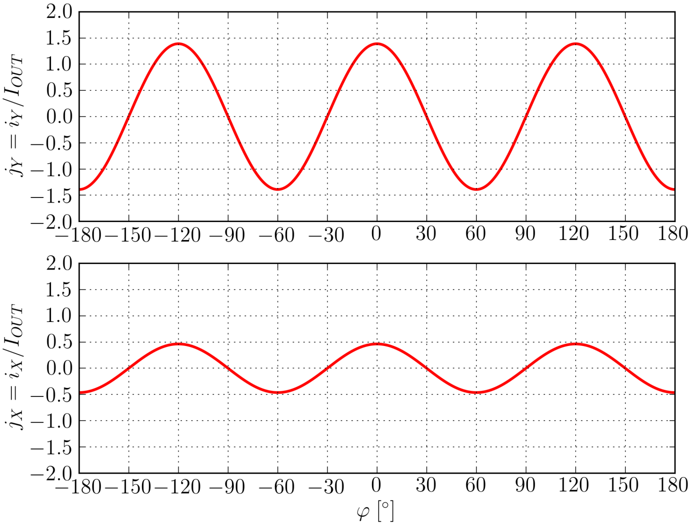
a closer look at j_1



a closer look at j_1 and a comparison . . .

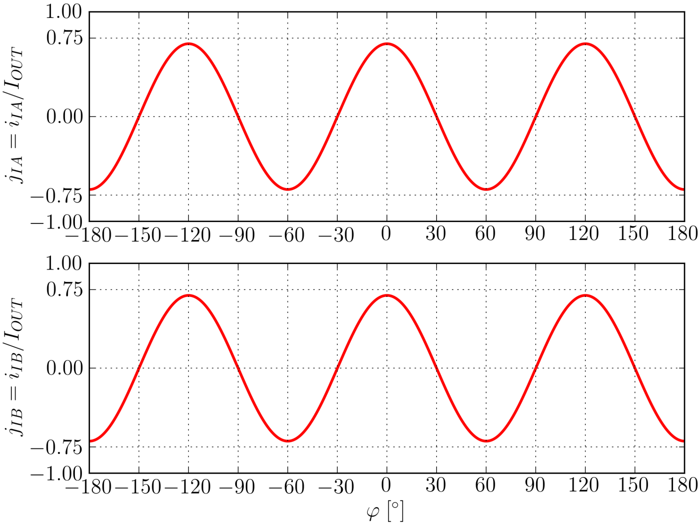


j_Y and j_X



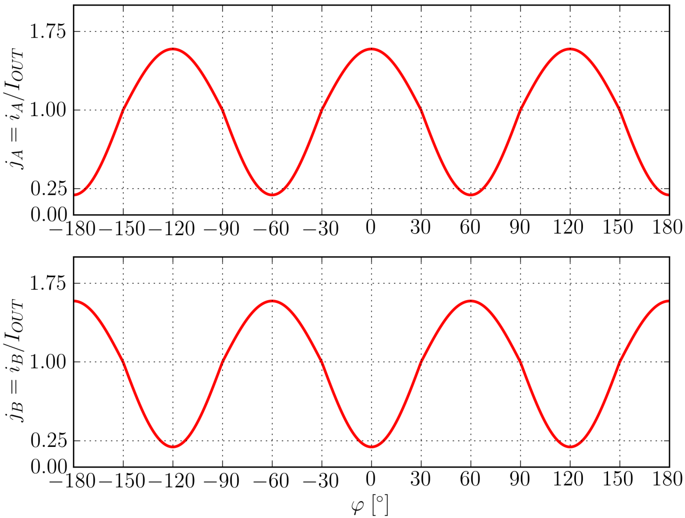
$j_Y = i_Y / I_{OUT}$
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$j_X = i_X / I_{OUT}$
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

j_{IA} and j_{IB}



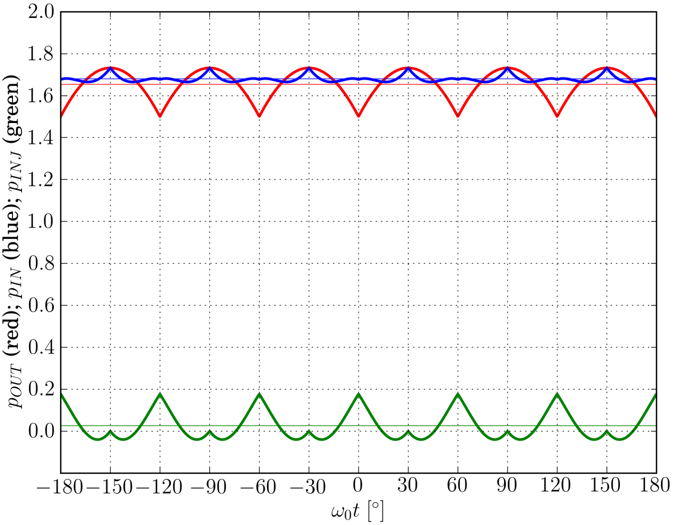
1.00
0.75
0.00
−0.75
−1.00
$j_{IA} = i_{IA}/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
1.00
0.75
0.00
−0.75
−1.00
$j_{IB} = i_{IB}/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

j_A and j_B



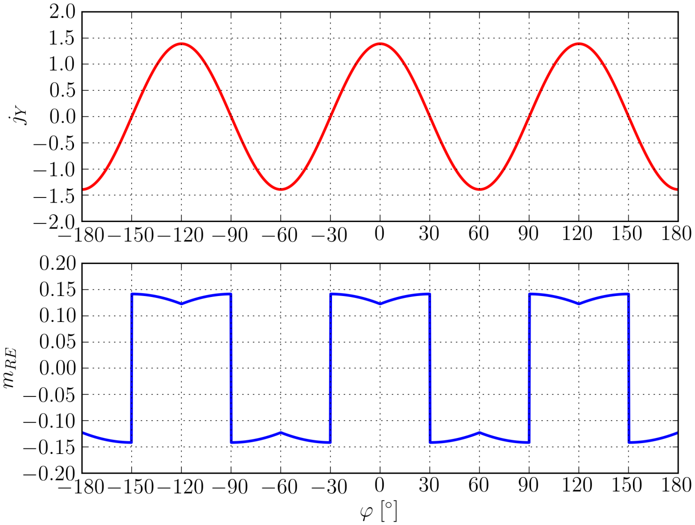
$j_A = i_A/I_{OUT}$
1.75
1.00
0.25
0.00
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$j_B = i_B/I_{OUT}$
1.75
1.00
0.25
0.00
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

power . . .



2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]
p_{OUT} (red); p_{IN} (blue); p_{INJ} (green)

resistance emulator, AC side . . .



achieved for ...

$$k_{opt} = \frac{3\left(\pi^2 - 8\right)}{\pi\left(2\pi - 5\right)} \approx 1.39$$

$$n_{opt} = \frac{6\left(\pi^2 - 8\right)}{\pi\left(16 - 5\pi\right)} \approx 12.23$$

where

$$THD_{min} = \frac{1}{3}\sqrt{\frac{8\pi^4 - 199\pi^2 + 360\pi + 54}{15\pi^2 - 40\pi - 6}} \approx 3.64\,\%$$

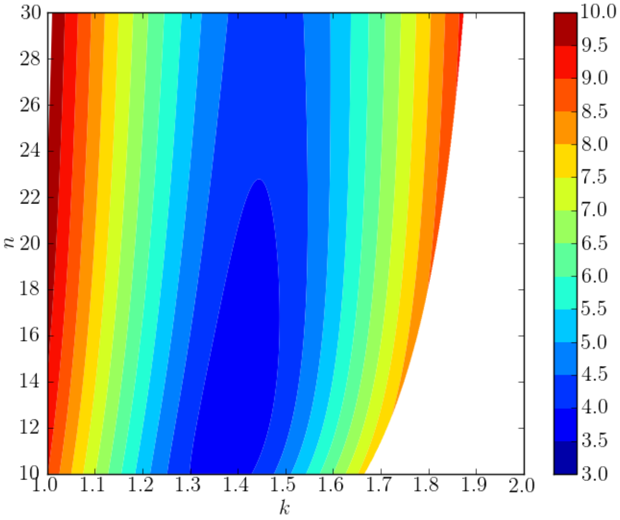
at the expense of ...

$$\rho_{opt} = \frac{\sqrt{3}\,(2\pi - 5)\left(7\pi^2 - 20\pi - 6\right)}{6\left(\pi^2 - 8\right)^2} \approx 0.027063$$

and

$$P_R = \frac{7\pi^2 - 20\pi - 6}{4\pi\,(2\pi - 5)} \approx 1.5837\,\%$$

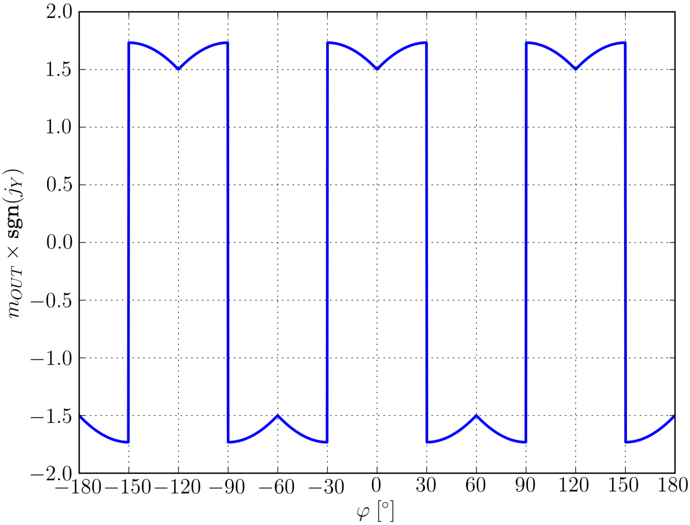
which we know from ...



how did it happen?

- since it started as a serendipity, it continued that way ...
- a close-to-the-best operating point is chosen, somewhere in the CCM
- the waveforms are recorded and analyzed
- the analytical optimum is found
- which is not something I'm gonna bother you with (now)
- but the numerical optimization is easy and fun ...
- and the result had been presented
- but why from $n = 10$?
- and what is the white area? lack of paint?

just one waveform



and just one spectrum

$$m_{XY} \triangleq m_{OUT}\,\mathrm{sgn}\,(j_Y)$$

$$m_{XY} = \sum_{k=1}^{\infty} M_{XY,\,k}\,\cos\,(3k\omega_0 t)$$

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

thus

$$M_{XY,\,1} = \frac{15\sqrt{3}}{4\pi}$$

to support one reasoning . . .

assuming

$$j_Y = J_Y \cos(3\omega_0 t)$$

to provide that the resistance emulator **takes** the power

$$\frac{1}{n} M_{XY,1} < M_{AV,1}$$

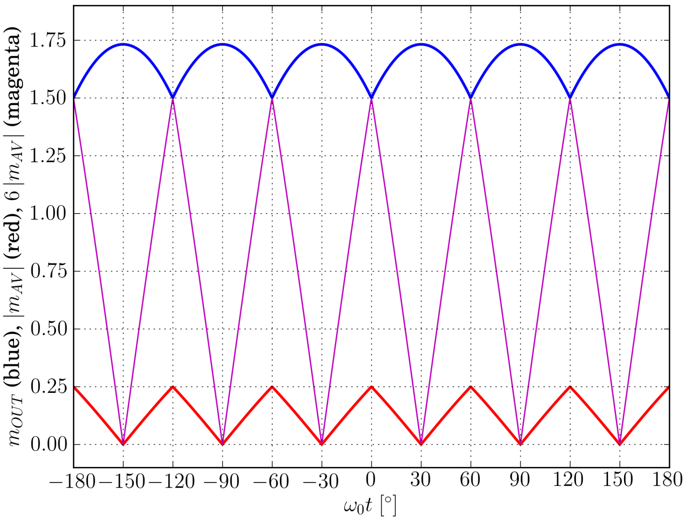
$$\frac{1}{n}\,\frac{15\sqrt{3}}{4\pi} < \frac{3\sqrt{3}}{8\pi}$$

$$\boxed{n > 10}$$

and that's why all the diagrams start at $n = 10$

and just a short note about $n > 6$

- to provide sinusoidal injected current that transfers the power to the resistance emulator we need $n > 10$
- but what is the minimum of n to get any j_Y?
- assume that $j_Y = 0$
- to push j_Y we need $n \times m_{AV} > m_{OUT}$
- according to the diagram from the next slide ...
- we need $n > 6$
- but that's too much for this presentation
- since it is too irrelevant in practice ...



m_{OUT} (blue), $|m_{AV}|$ (red), $6\,|m_{AV}|$ (magenta)
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

the white area ...

- the white area is beyond the DCM limitation
- which comes from two conditions ...
- $j_A > 0$ and $j_B > 0$
- any violation in the numerical simulation and the data point gets rejected
- some analytical preparation?

the DCM

$$j_A = 1 - \frac{|j_Y|}{n} + \frac{1}{2} j_Y > 0$$

$$j_B = 1 - \frac{|j_Y|}{n} - \frac{1}{2} j_Y > 0$$

which reduces to

$$\frac{1}{2} j_Y > -\left(1 - \frac{|j_Y|}{n}\right)$$

$$\frac{1}{2} j_Y < 1 - \frac{|j_Y|}{n}$$

$$\frac{|j_Y|}{2} < 1 - \frac{|j_Y|}{n}$$

the DCM

$$|j_Y| < \frac{2n}{n+2}$$

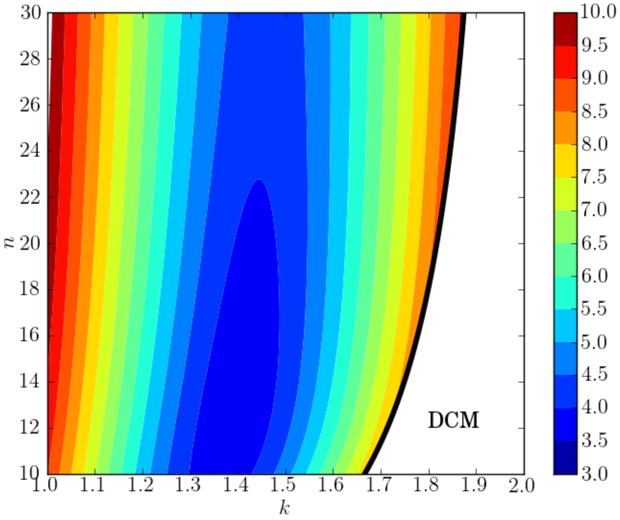
$$J_{Ym} < \frac{2n}{n+2}$$

$$\boxed{k < \frac{2n}{n+2}}$$

for the CCM

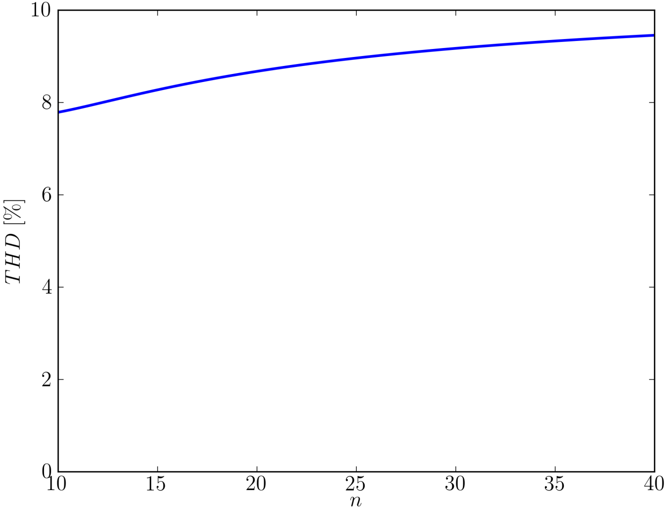
and the thick black line in the next diagram is $k = \frac{2n}{n+2}$

the (k, n) plane . . .



30
28
26
24
22
20
18
16
14
12
10
n
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
k
DCM
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0

the DCM, $THD\,(n)$



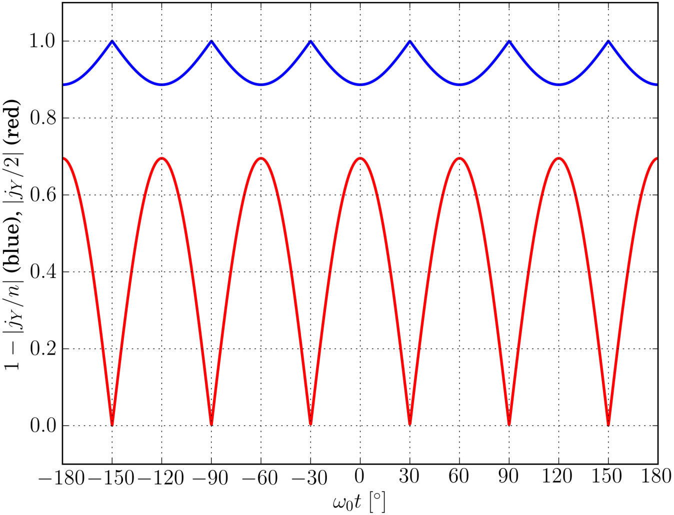
and the optimum is ...

$$THD_{min} = \frac{1}{9}\sqrt{\frac{61\pi^2 - 36\pi - 486}{6}} \approx 7.79\,\%$$

and there is more theory, there are more simulations, ...

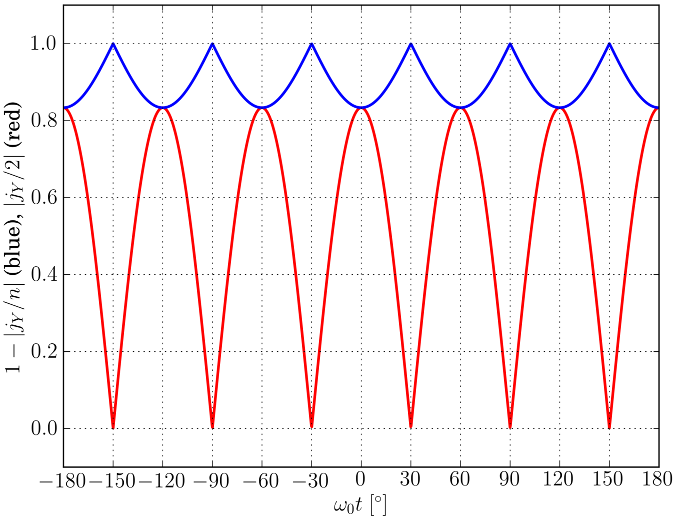
but we'll stop here.

in the CCM . . .

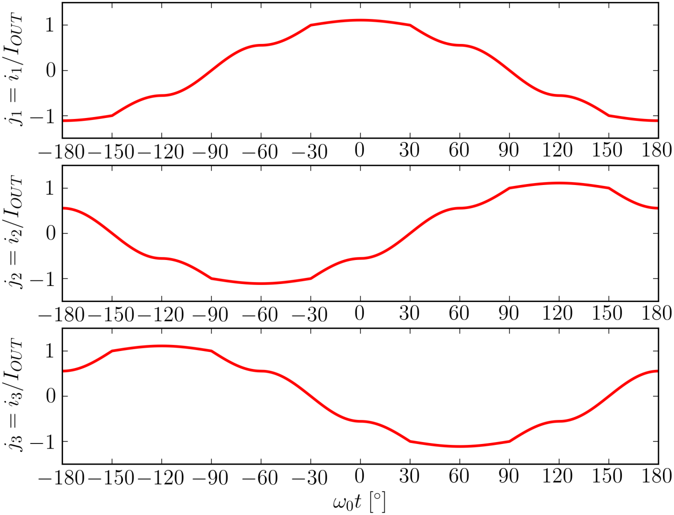


1.0
0.8
0.6
0.4
0.2
0.0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]
$1 - |j_Y/n|$ (blue), $|j_Y/2|$ (red)

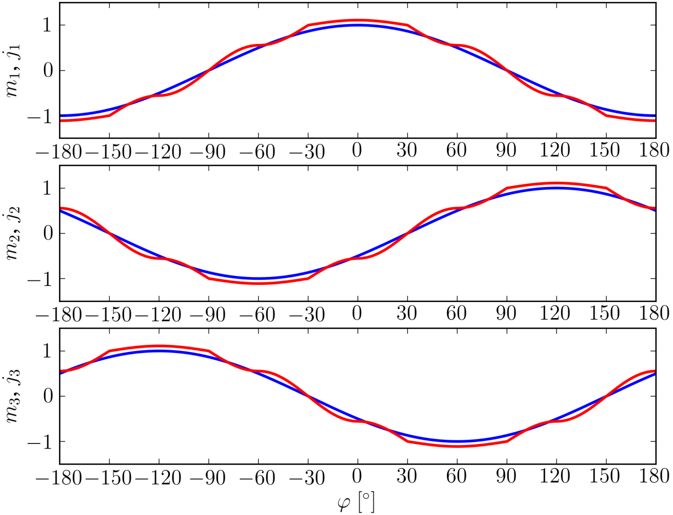
and in the DCM . . .



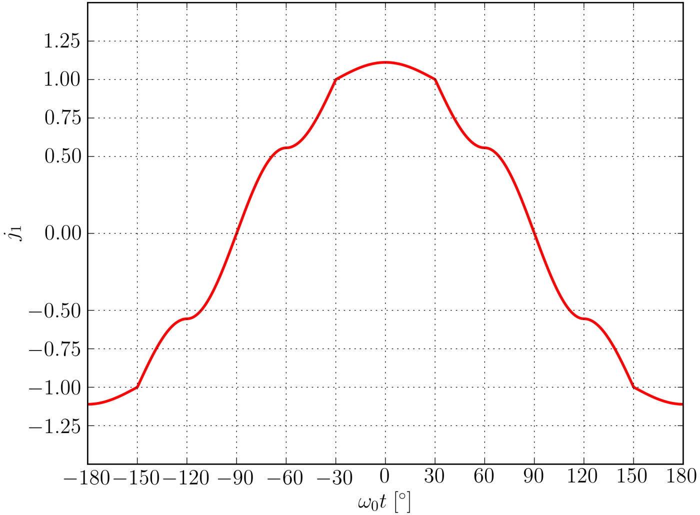
the input currents . . .



. . . accompanied with the voltages . . .

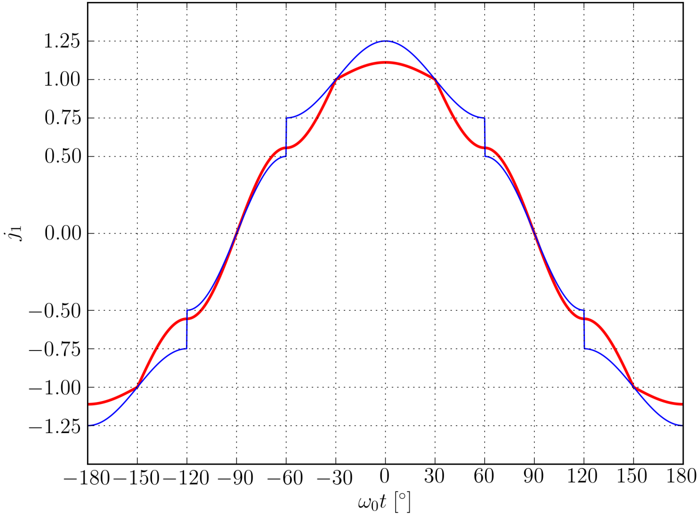


j_1

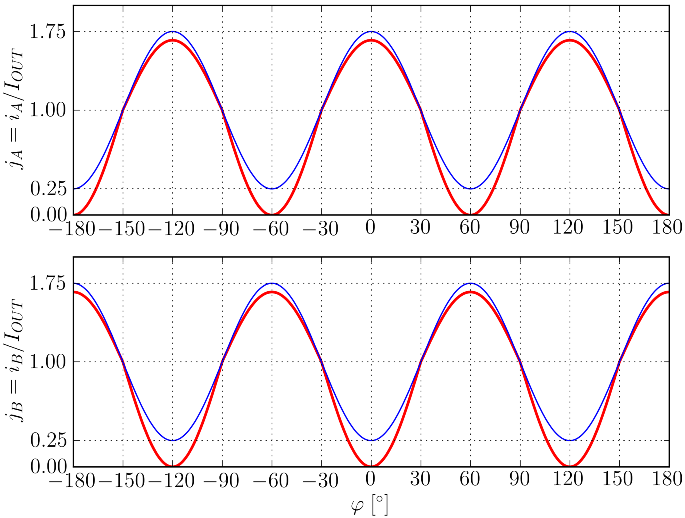


1.25
1.00
0.75
0.50
0.00
−0.50
−0.75
−1.00
−1.25
j_1
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

j_1 compared to the 3rd harmonic injection case

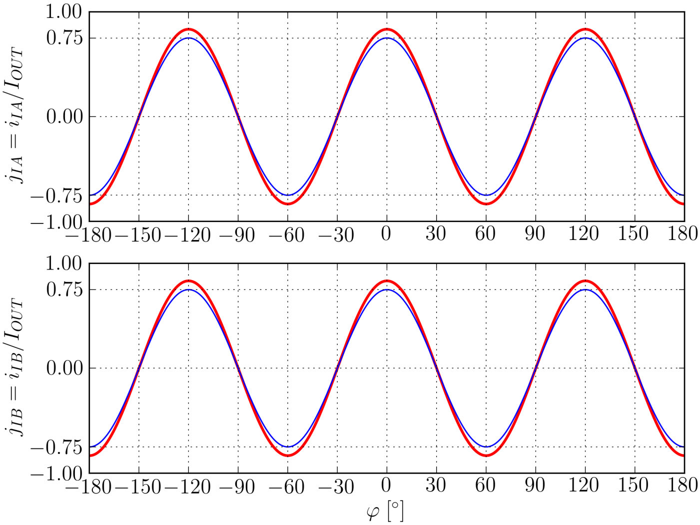


j_A and j_B



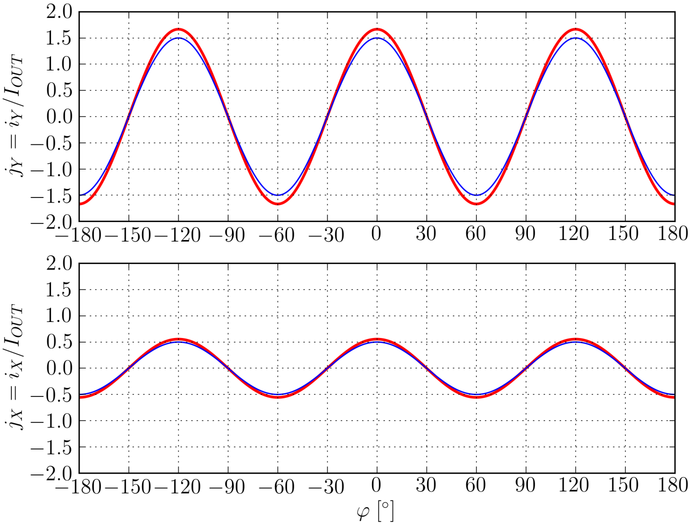
1.75
1.00
0.25
0.00
$j_A = i_A/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
1.75
1.00
0.25
0.00
$j_B = i_B/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

j_{IA} and j_{IB}



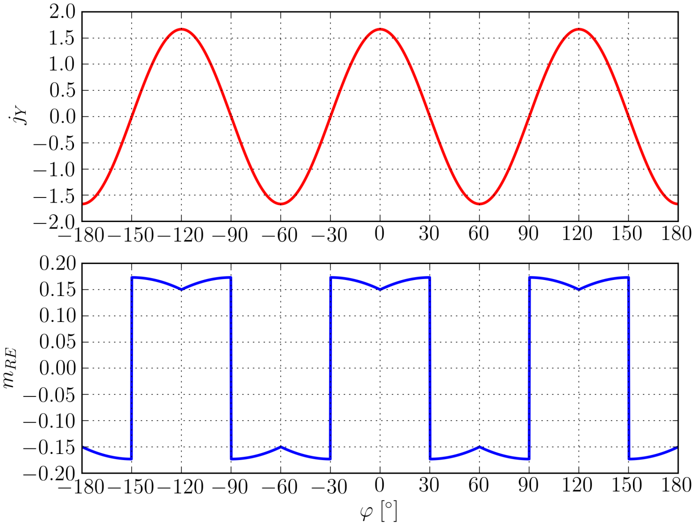
1.00
0.75
0.00
−0.75
−1.00
$j_{IA} = i_{IA}/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
1.00
0.75
0.00
−0.75
−1.00
$j_{IB} = i_{IB}/I_{OUT}$
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

i_Y and i_X



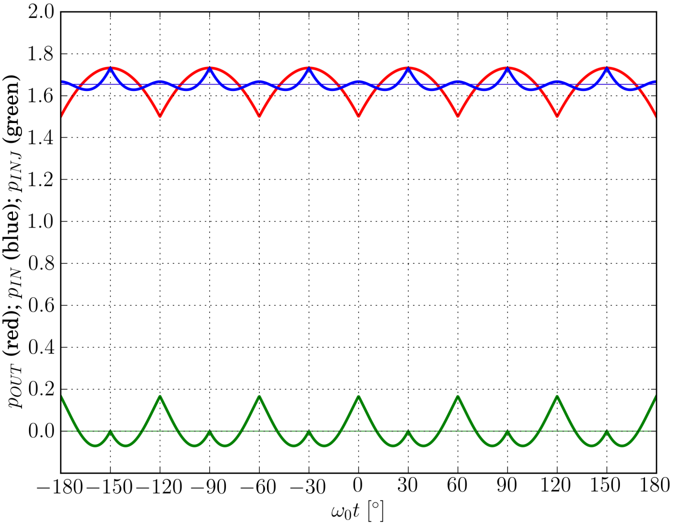
$j_Y = i_Y / I_{OUT}$
$j_X = i_X / I_{OUT}$
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
φ [°]

j_Y and m_{RE}



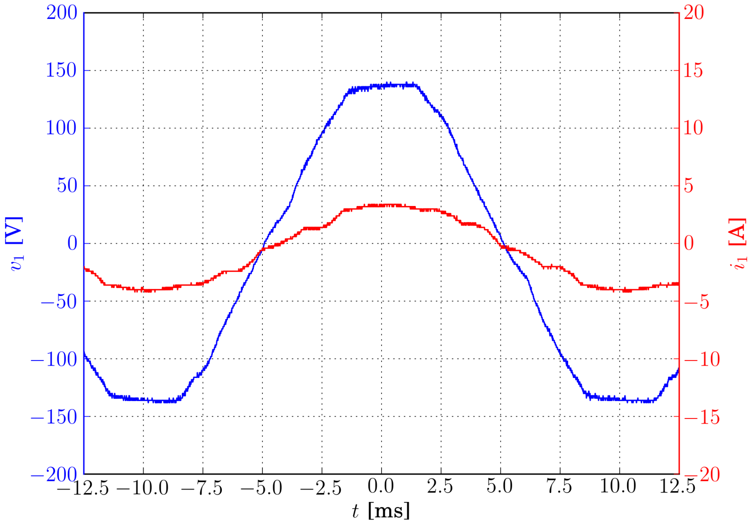
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
j_Y
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
m_{RE}
φ [°]

power ...

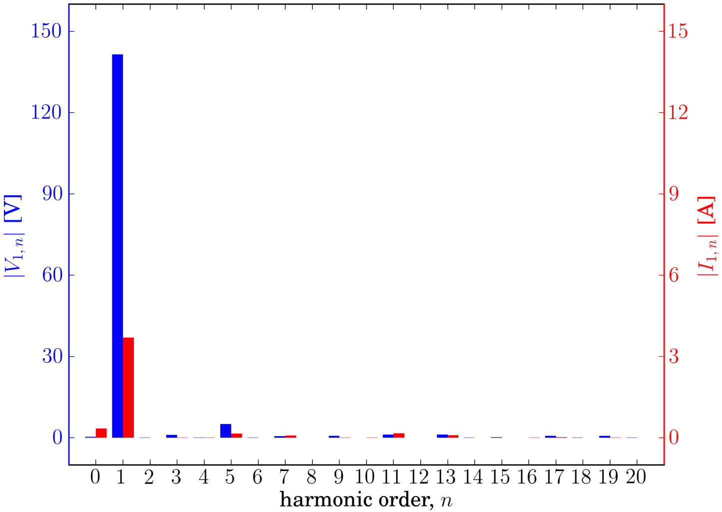


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
p_{OUT} (red); p_{IN} (blue); p_{INJ} (green)
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
$\omega_0 t$ [°]

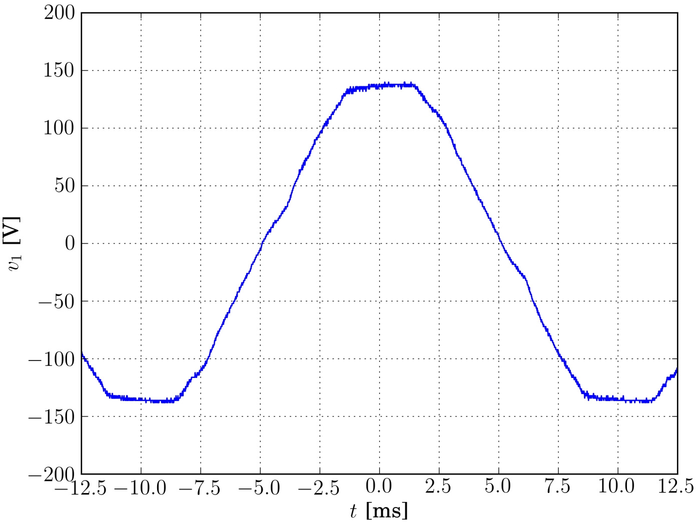
$v_1,\, i_1,\, I_{OUT} \approx 3\,\mathrm{A}$



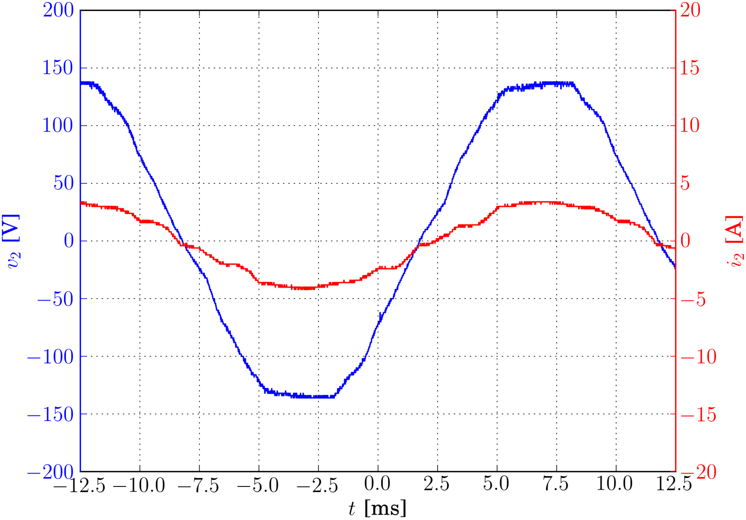
v_1, i_1, $I_{OUT} \approx 3\,\text{A}$, spectra



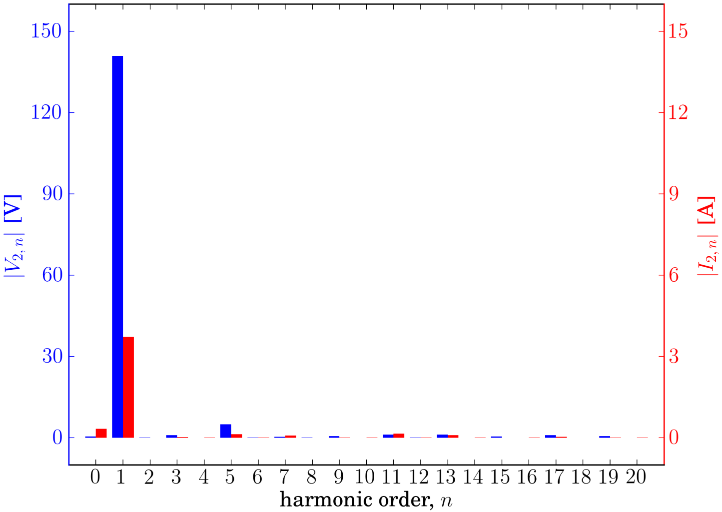
v_1, $I_{OUT} \approx 3\,\mathrm{A}$



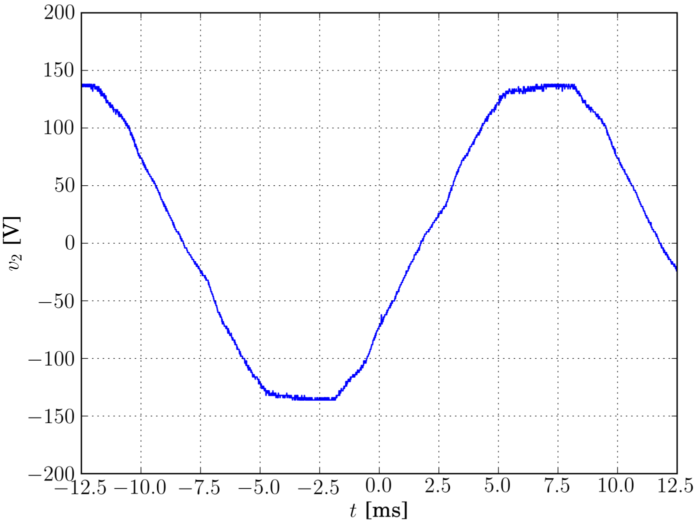
v_2, i_2, $I_{OUT} \approx 3\,\mathrm{A}$



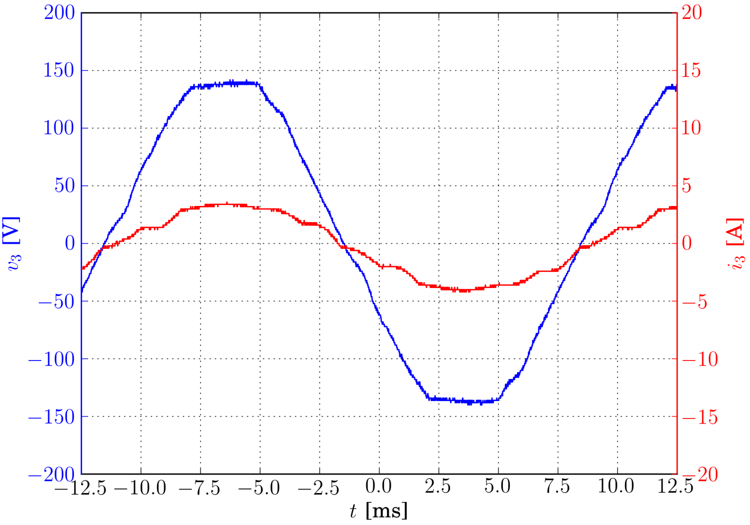
v_2, i_2, $I_{OUT} \approx 3\,\mathrm{A}$, spectra



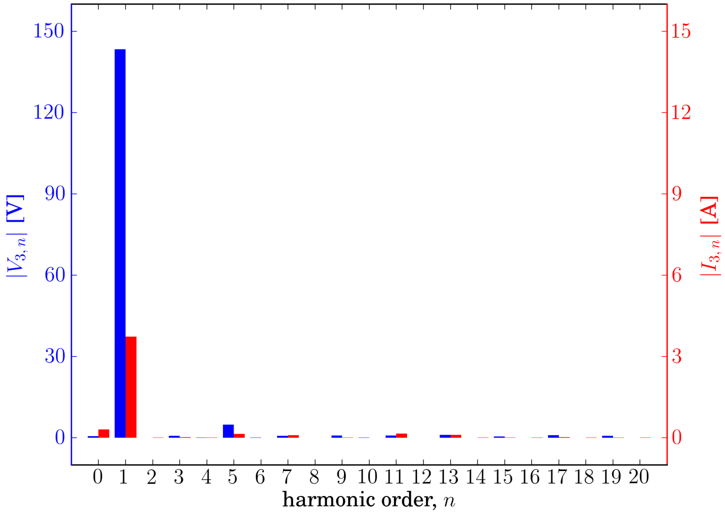
v_2, $I_{OUT} \approx 3\,\mathrm{A}$



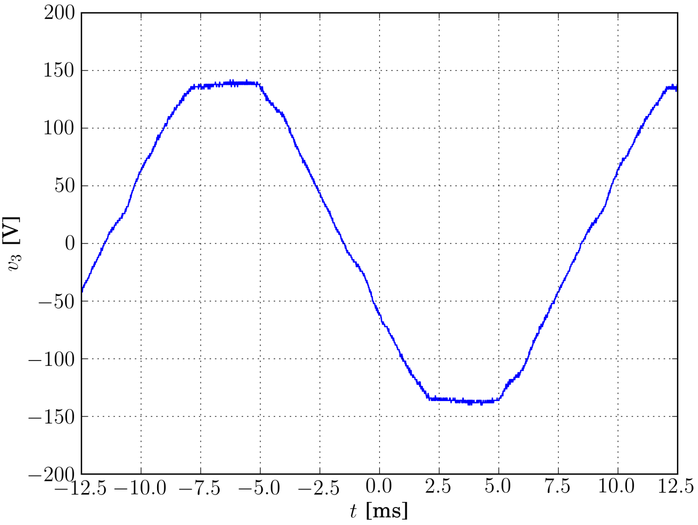
v_3, i_3, $I_{OUT} \approx 3\,\mathrm{A}$



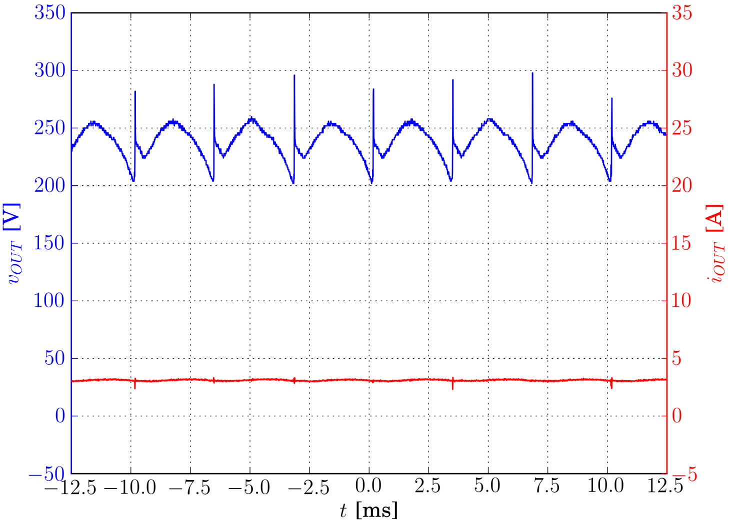
v_3, i_3, $I_{OUT} \approx 3\,\text{A}$, spectra



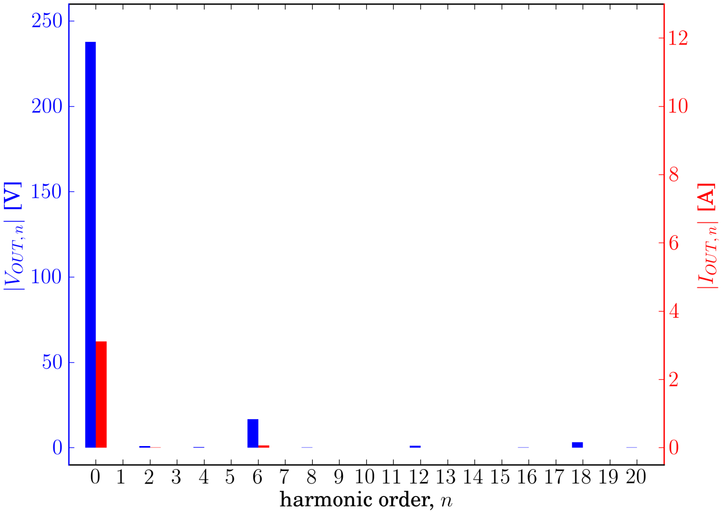
v_3, $I_{OUT} \approx 3\,\mathrm{A}$



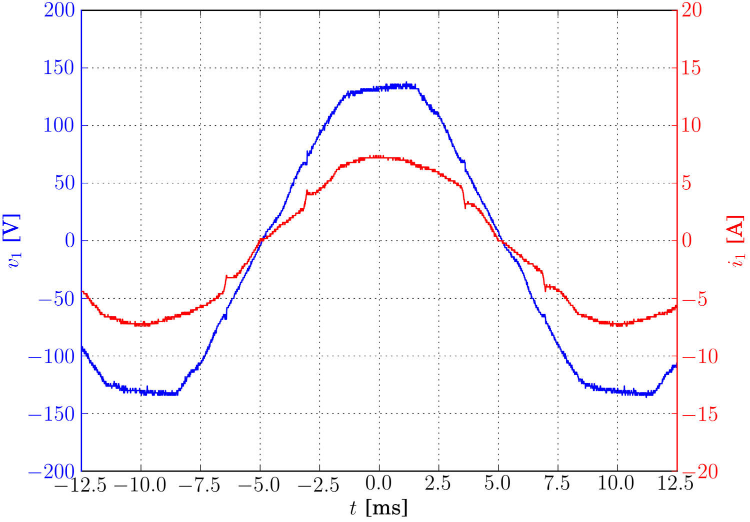
v_{OUT}, i_{OUT}, $I_{OUT} \approx 3\,\mathrm{A}$



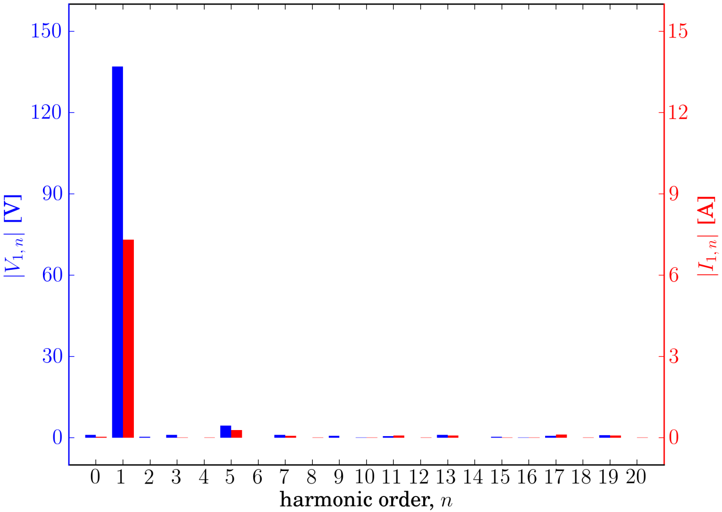
v_{OUT}, i_{OUT}, $I_{OUT} \approx 3\,\mathrm{A}$, spectra



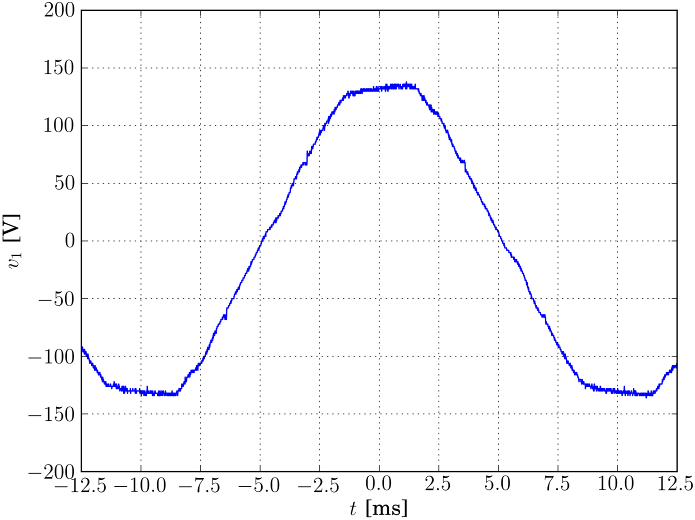
v_1, i_1, $I_{OUT} \approx 6\,\mathrm{A}$



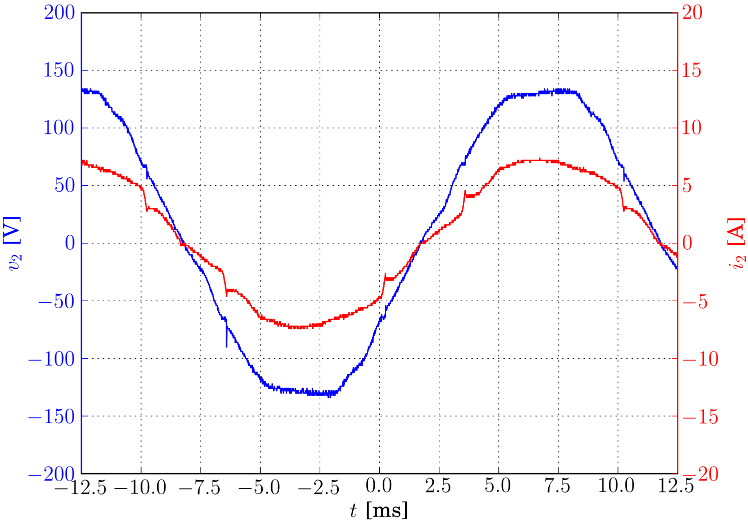
v_1, i_1, $I_{OUT} \approx 6\,\text{A}$, spectra



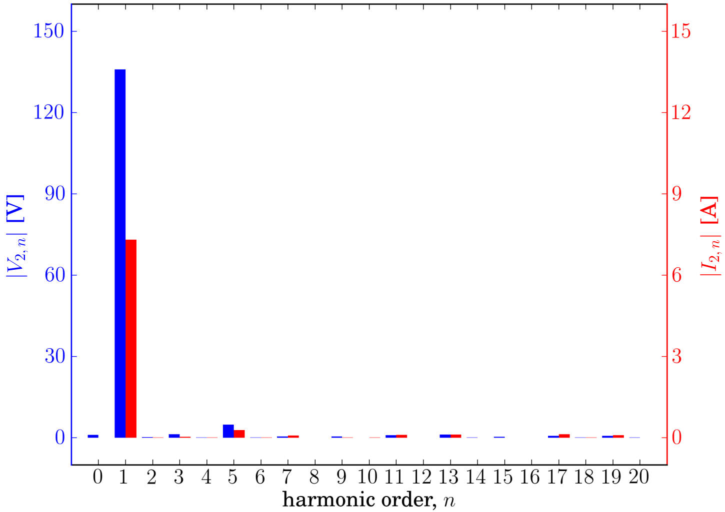
v_1, $I_{OUT} \approx 6\,\mathrm{A}$



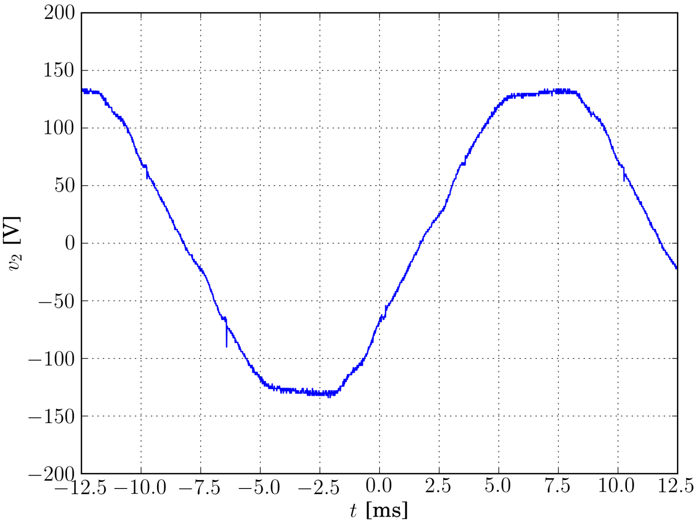
v_2, i_2, $I_{OUT} \approx 6\,\text{A}$



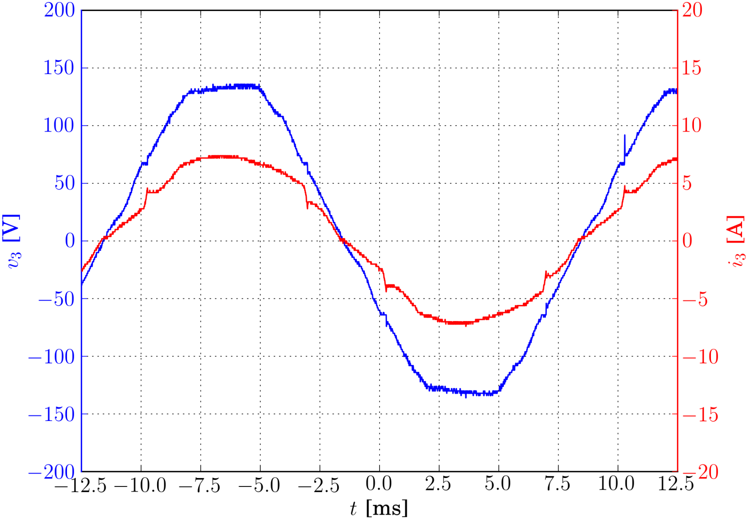
v_2, i_2, $I_{OUT} \approx 6\,\mathrm{A}$, spectra



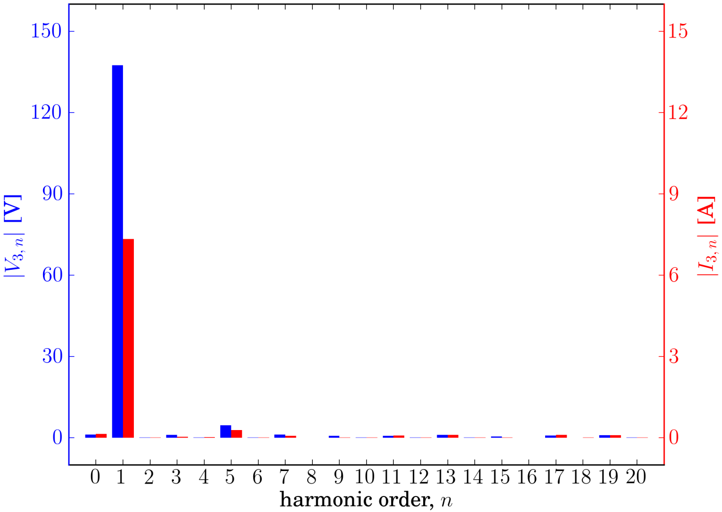
v_2, $I_{OUT} \approx 6\,\mathrm{A}$



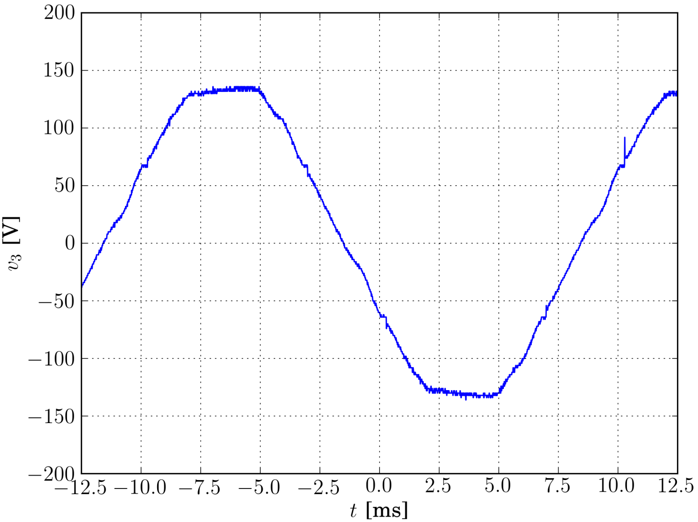
v_3, i_3, $I_{OUT} \approx 6\,\mathrm{A}$



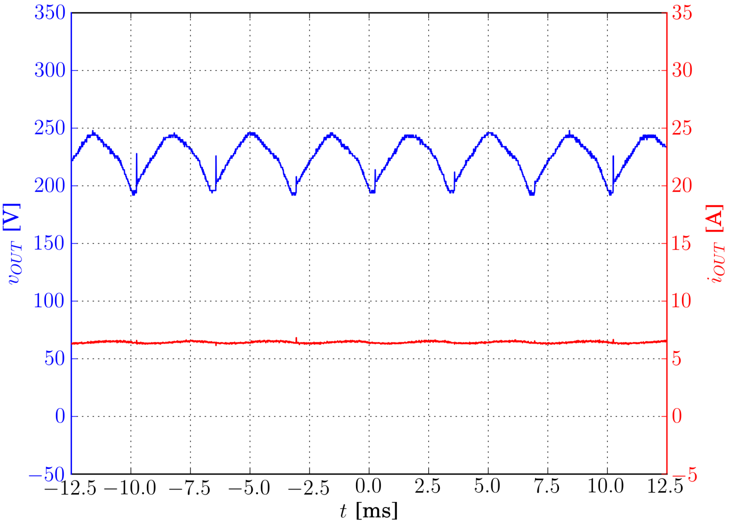
v_3, i_3, $I_{OUT} \approx 6\,\mathrm{A}$, spectra



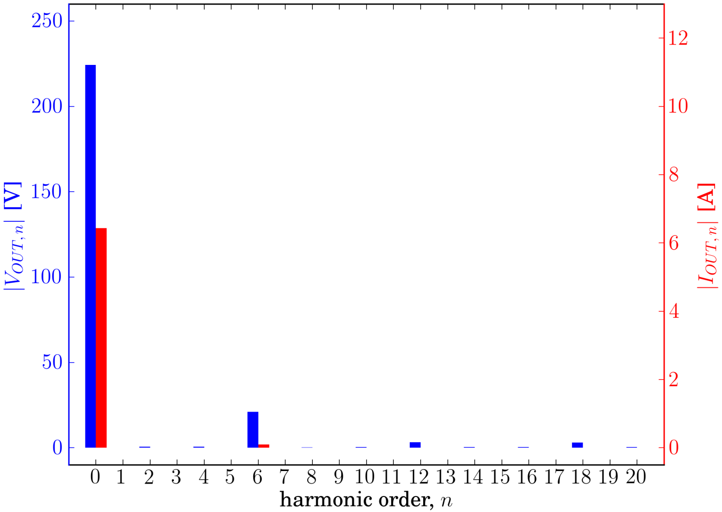
v_3, $I_{OUT} \approx 6\,\mathrm{A}$



v_{OUT}, i_{OUT}, $I_{OUT} \approx 6\,\mathrm{A}$



v_{OUT}, i_{OUT}, $I_{OUT} \approx 6\,\mathrm{A}$, spectra



experimental results, input, part 1

I_{OUT} [A]	k	$I_{k\,RMS}$ [A]	$V_{k\,RMS}$ [V]	S [VA]	P [W]
1	1	2.64	100.09	264.21	259.49
	2	2.65	99.66	264.54	260.11
	3	2.66	101.47	270.05	265.92
2	1	5.17	96.88	501.33	499.98
	2	5.18	96.19	497.95	496.36
	3	5.19	97.28	505.32	503.87

experimental results, input, part 2

I_{OUT} [A]	k	PF	$THD(i_k)$ [%]	$THD(v_k)$ [%]
1	1	0.9821	7.70	4.10
	2	0.9833	7.51	4.12
	3	0.9847	7.64	3.88
2	1	0.9973	5.40	3.92
	2	0.9968	5.91	4.22
	3	0.9971	5.47	4.05

experimental results, output

I_{OUT} [A]	V_{OUT} [V]	P_{OUT} [W]	P_{IN} [W]	η [%]
3.12	237.84	741.26	785.52	94.37
6.44	224.39	1444.48	1500.22	96.28

well, ...

- it seems that's it
- pretty good agreement with the theory
- promising to be applied
- there are more analyses and experimental results presented in the book and in some papers
- but ...

conclusions

- resistance emulators analyzed
- current loaded and voltage loaded
- the current loaded one seemed like a better fit ...
- since the adjustment to I_{OUT} is better
- however, the voltage loaded one turned out to be better
- although it was not expected
- simpler, with better THD, ...
- and its filter should be omitted
- and we are getting close to the end of our story ...
- but there is some more ...
- multipulse operation ...
- and switching resistance emulation ...