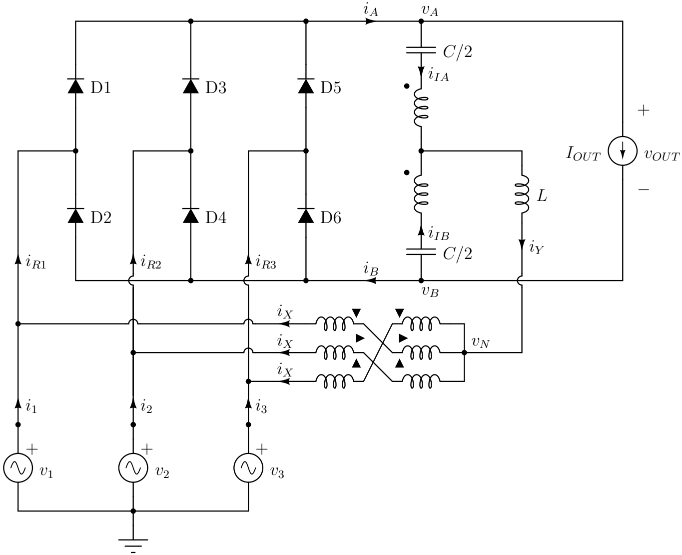
The Discontinuous Conduction Mode

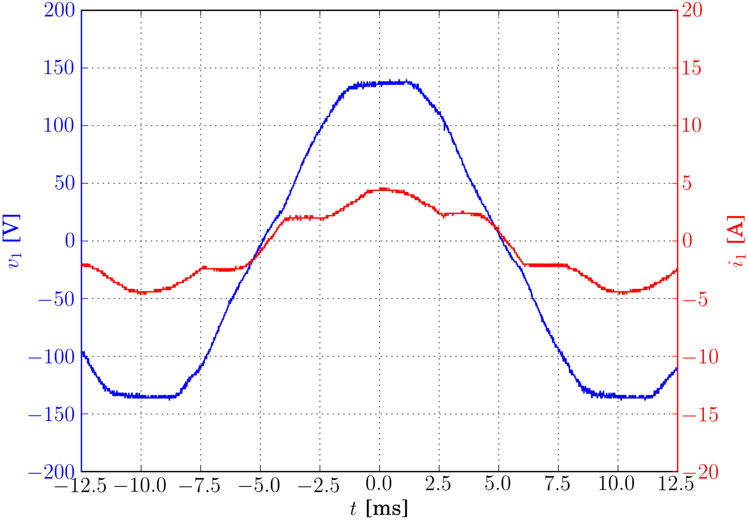
what happens if R is omitted?



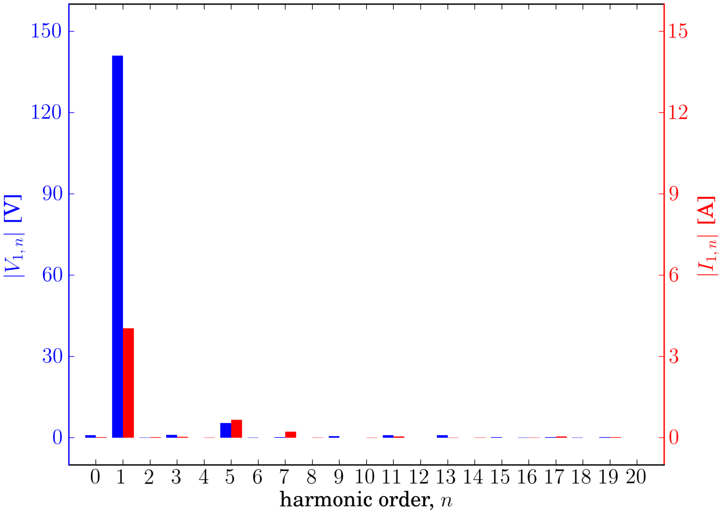
what really happens?

- in the case $V_{A,1}$ and $V_{B,1}$ remain the same as in the CCM, the amplitude of i_Y won't be limited
- something, though, limits the amplitude; try and see …
- let's look at the circuit and search for the answers:
  1. what limits the amplitude of i_Y?
  2. is it safe to operate in this mode?
  3. is there any use of this operating mode?

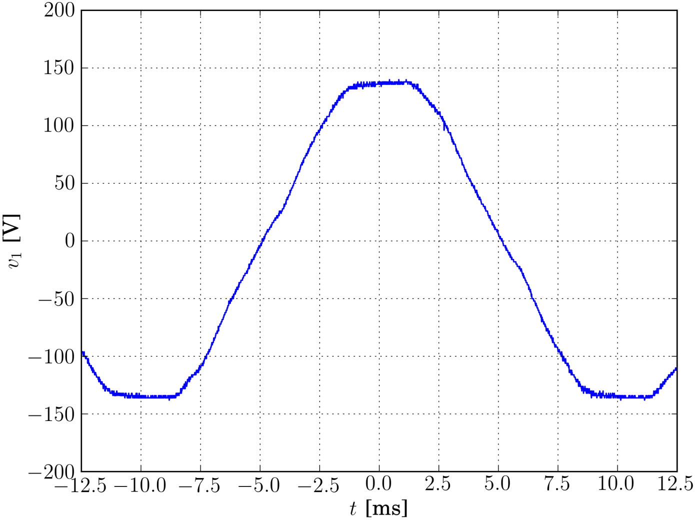
v_1, i_1, $I_{OUT} \approx 3\,\mathrm{A}$



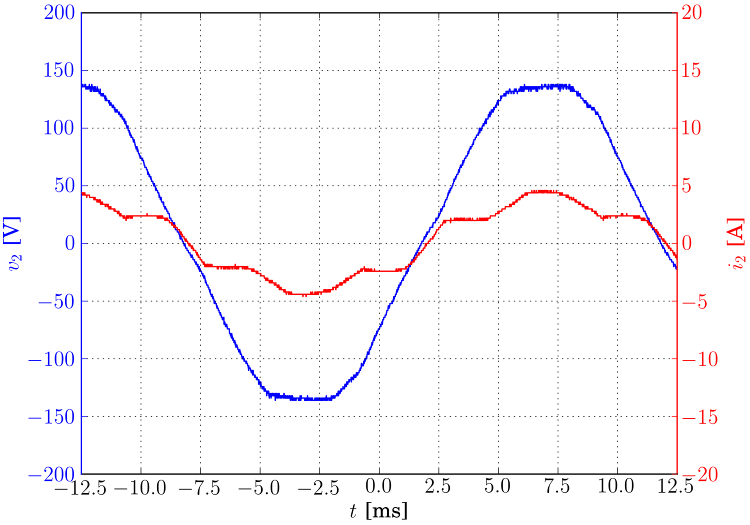
v_1, i_1, $I_{OUT} \approx 3\,\mathrm{A}$, spectra



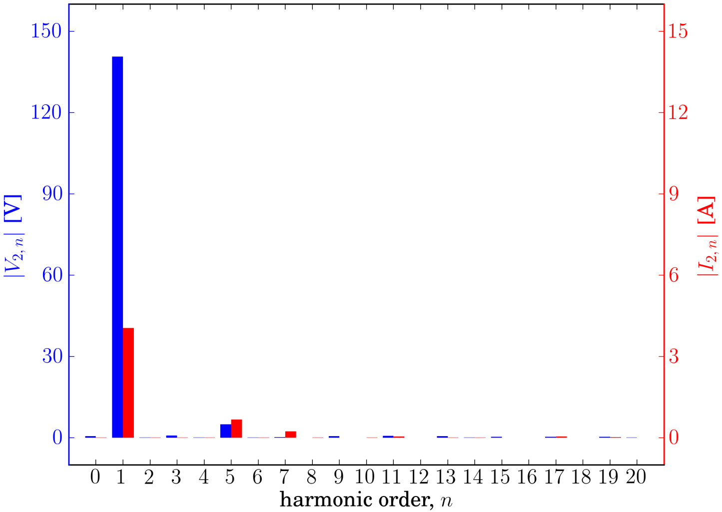
v_1, $I_{OUT} \approx 3\,\mathrm{A}$



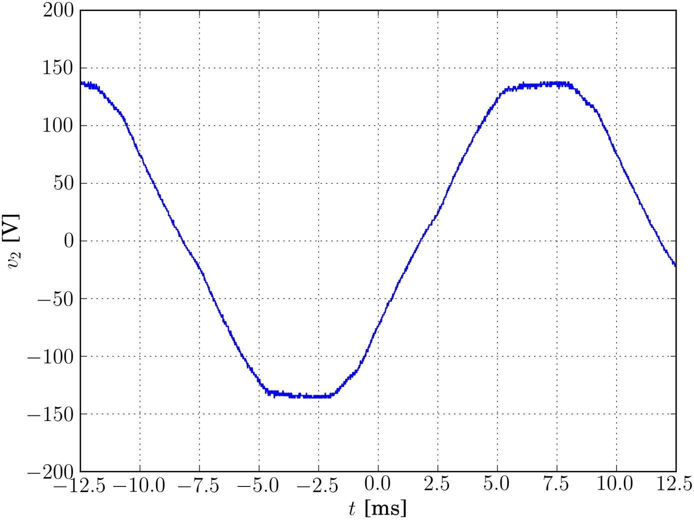
v_2, i_2, $I_{OUT} \approx 3\,\mathrm{A}$



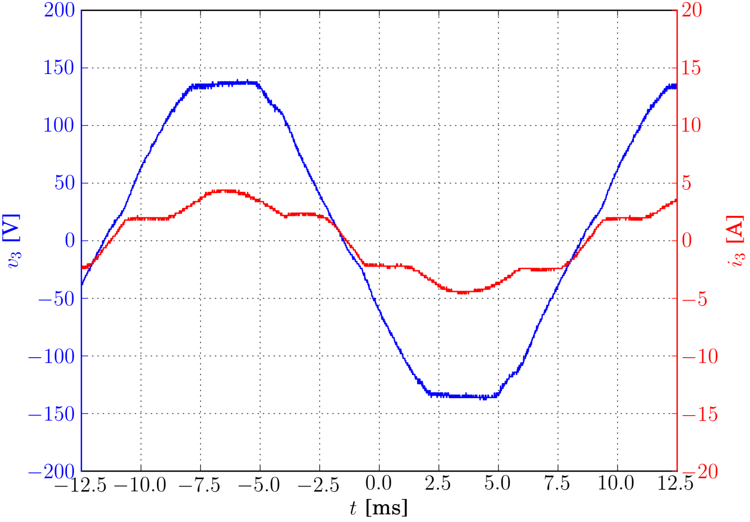
v_2, i_2, $I_{OUT} \approx 3\,\mathrm{A}$, spectra



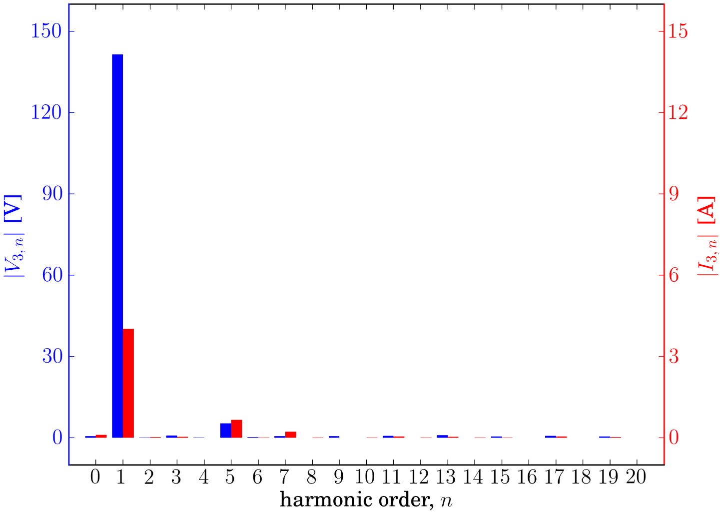
v_2, $I_{OUT} \approx 3\,\mathrm{A}$



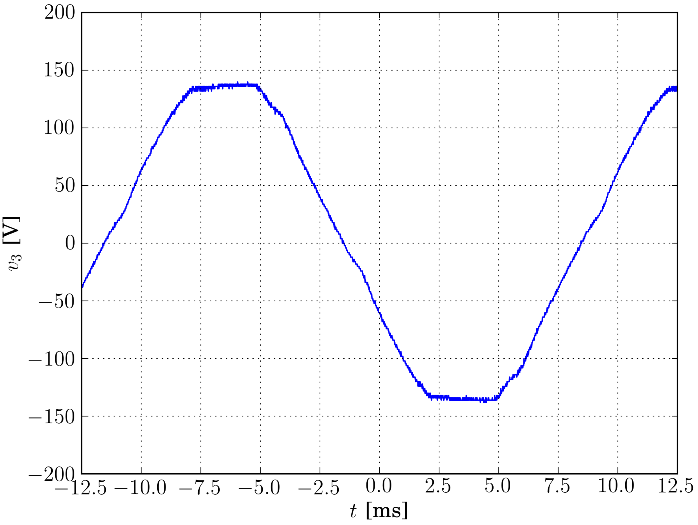
v_3, i_3, $I_{OUT} \approx 3\,\mathrm{A}$



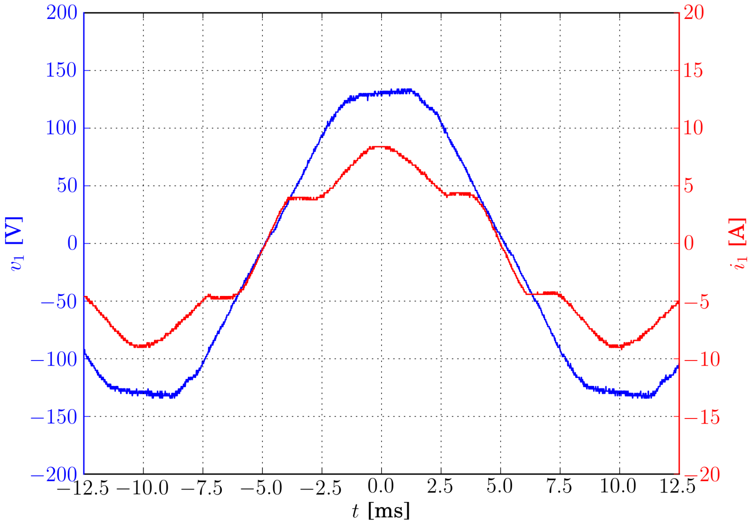
v_3, i_3, $I_{OUT} \approx 3\,\mathrm{A}$, spectra



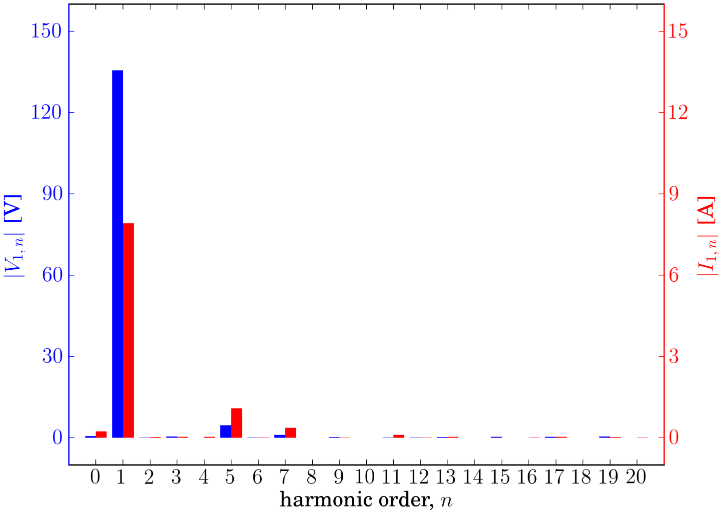
v_3, $I_{OUT} \approx 3\,\text{A}$



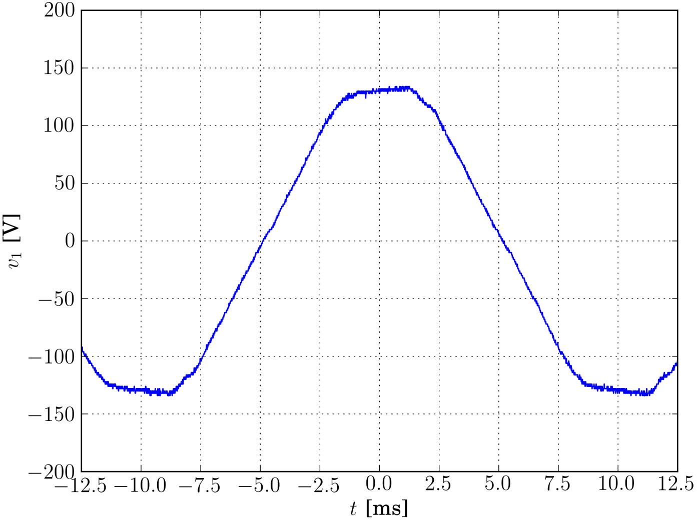
v_1, i_1, $I_{OUT} \approx 6\,\text{A}$



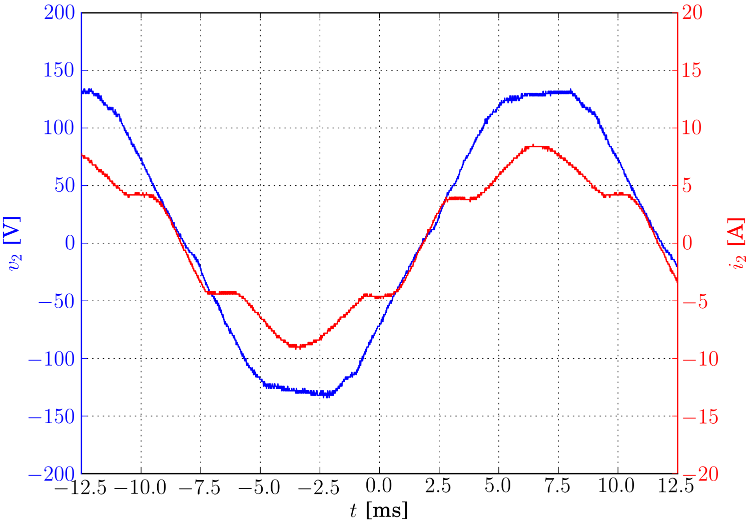
v_1, i_1, $I_{OUT} \approx 6$ A, spectra



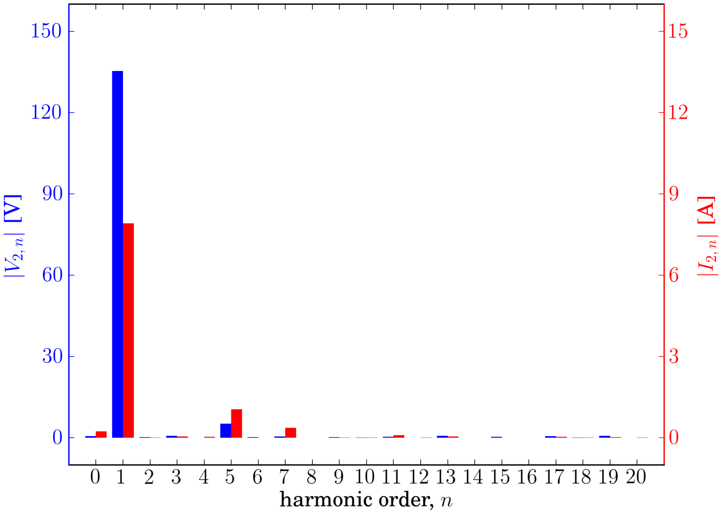
v_1, $I_{OUT} \approx 6\,\mathrm{A}$



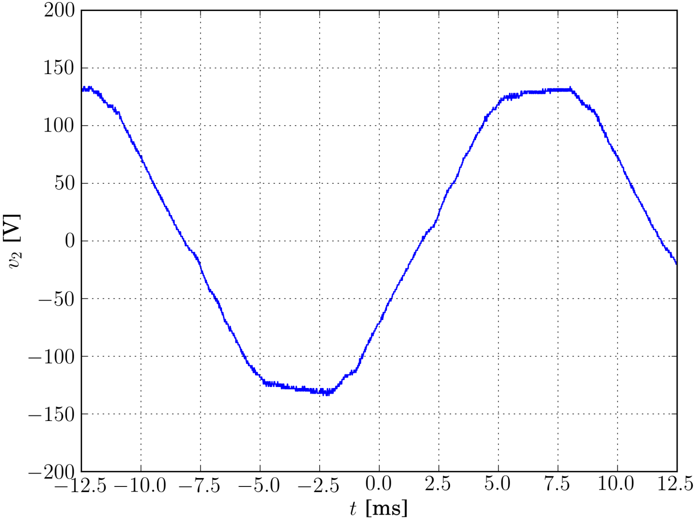
v_2, i_2, $I_{OUT} \approx 6\,\mathrm{A}$



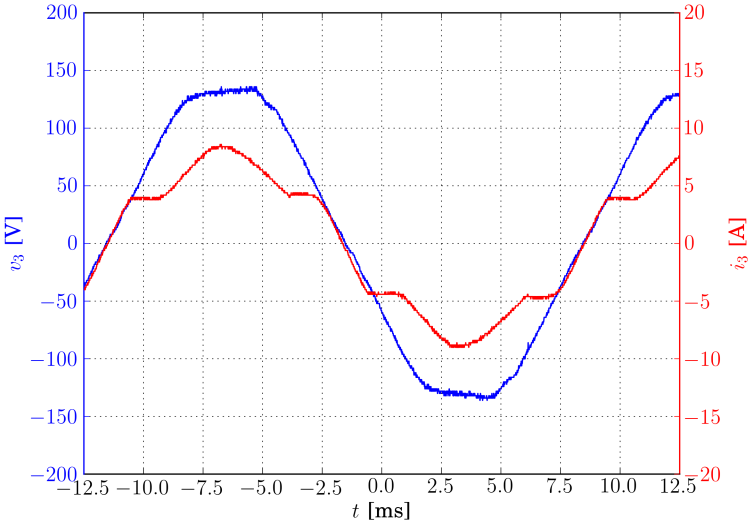
v_2, i_2, $I_{OUT} \approx 6\,\text{A}$, spectra



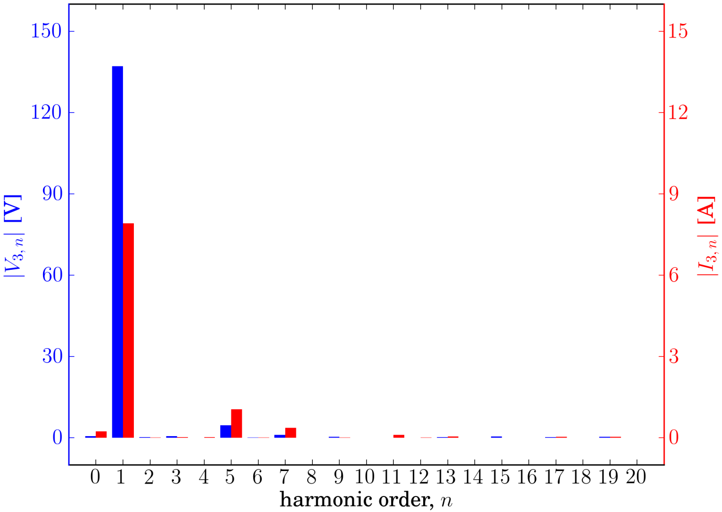
v_2, $I_{OUT} \approx 6\,\mathrm{A}$



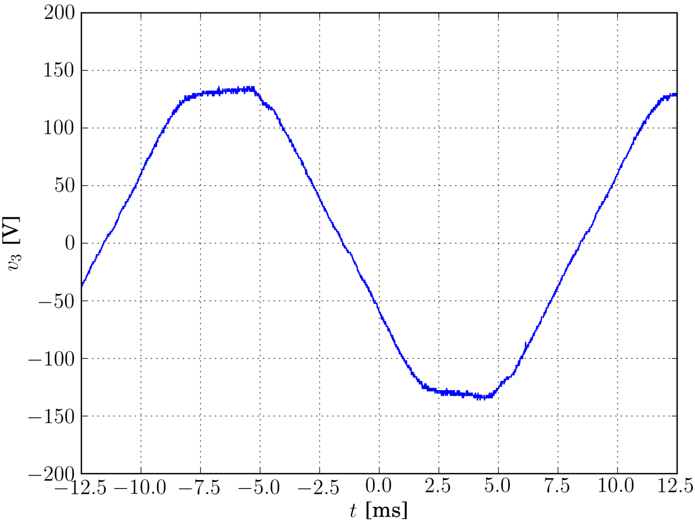
v_3, i_3, $I_{OUT} \approx 6\,\mathrm{A}$



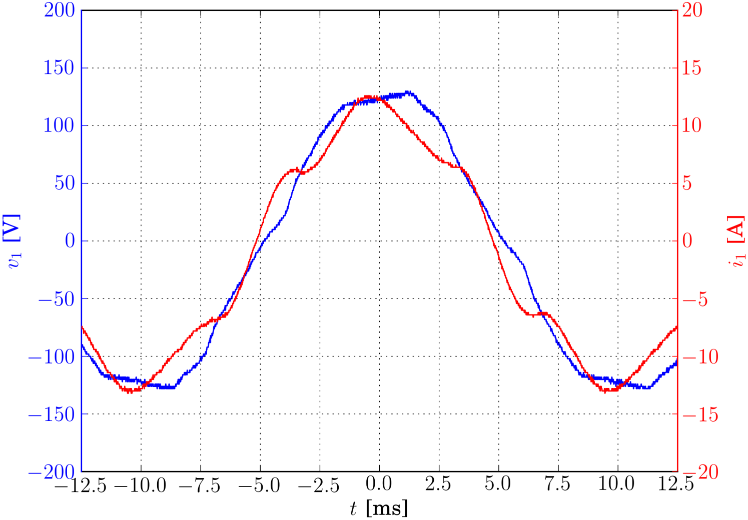
v_3, i_3, $I_{OUT} \approx 6\,\mathrm{A}$, spectra



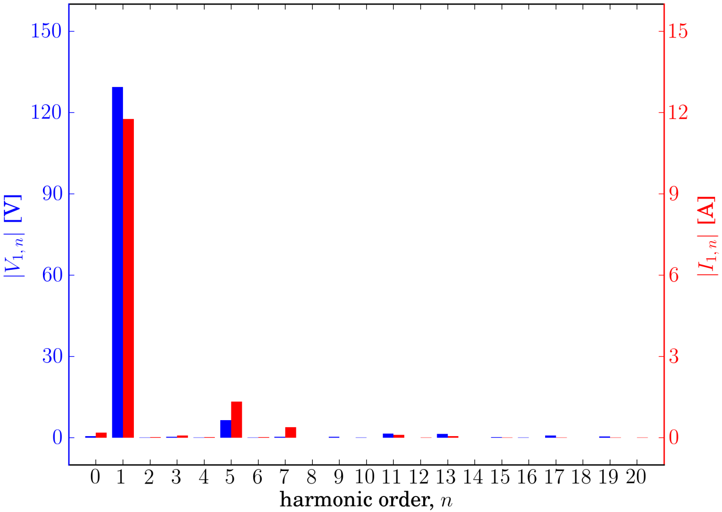
v_3, $I_{OUT} \approx 6\,\mathrm{A}$



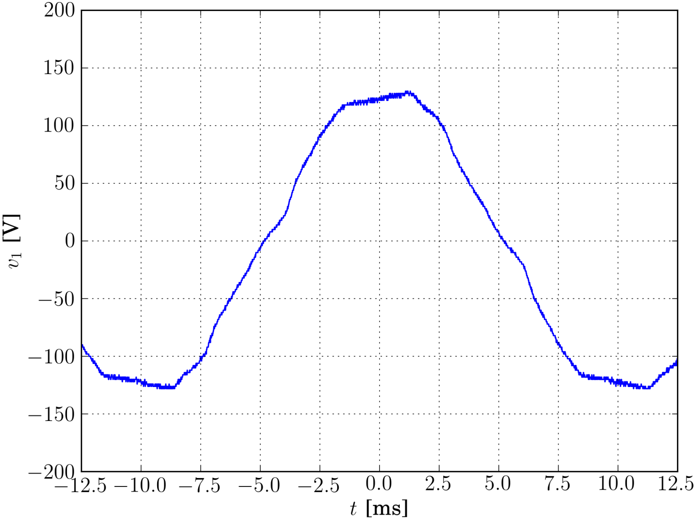
v_1, i_1, $I_{OUT} \approx 9\,\mathrm{A}$



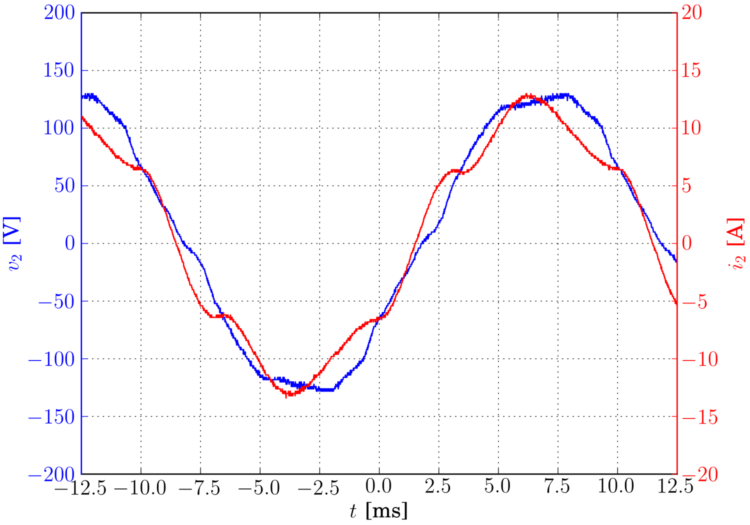
v_1, i_1, $I_{OUT} \approx 9$ A, spectra



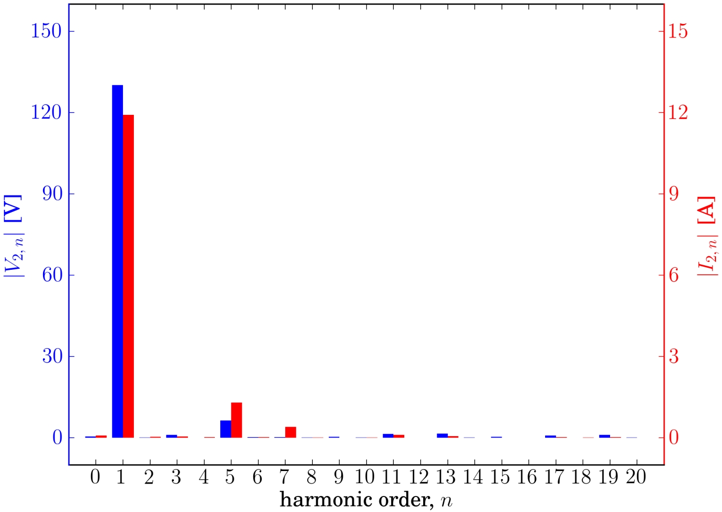
v_1, $I_{OUT} \approx 9\,\mathrm{A}$



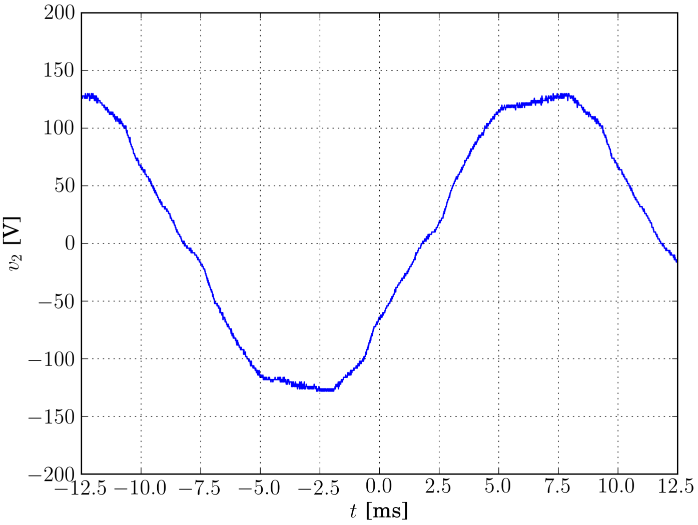
v_2, i_2, $I_{OUT} \approx 9\,\mathrm{A}$



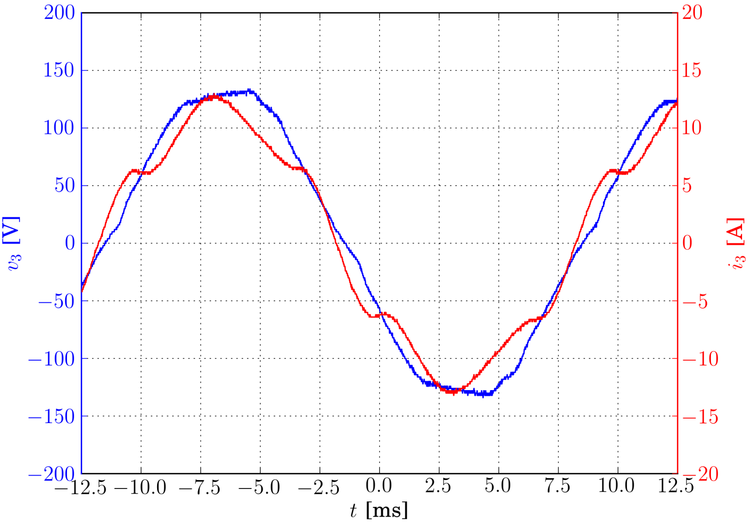
v_2, i_2, $I_{OUT} \approx 9\,\mathrm{A}$, spectra



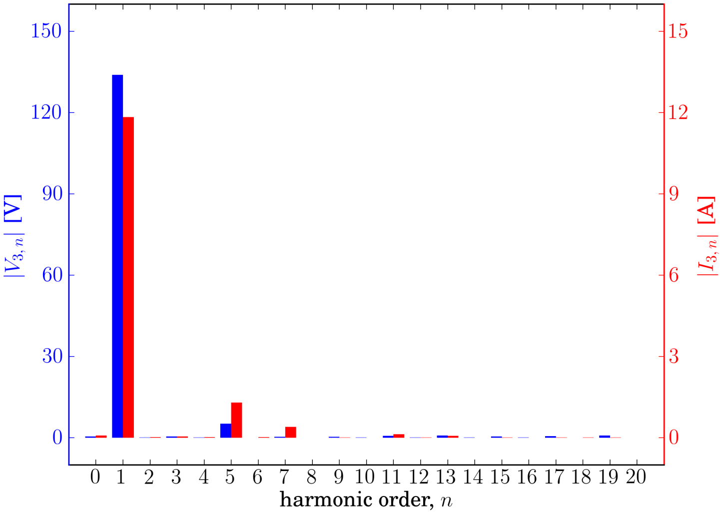
v_2, $I_{OUT} \approx 9\,\mathrm{A}$



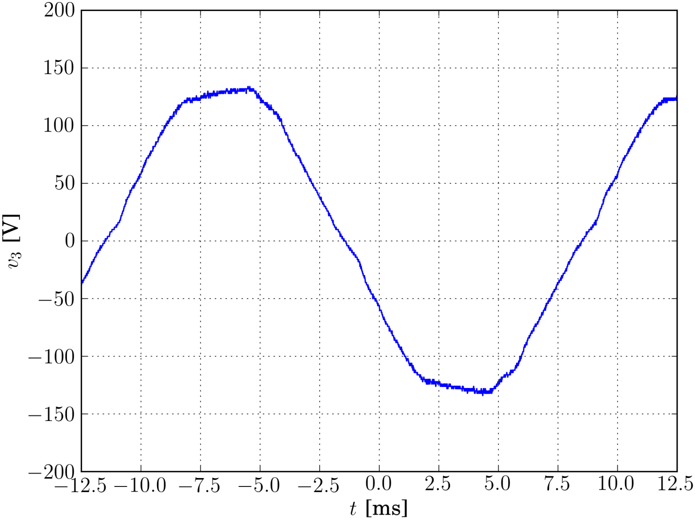
v_3, i_3, $I_{OUT} \approx 9\,\mathrm{A}$



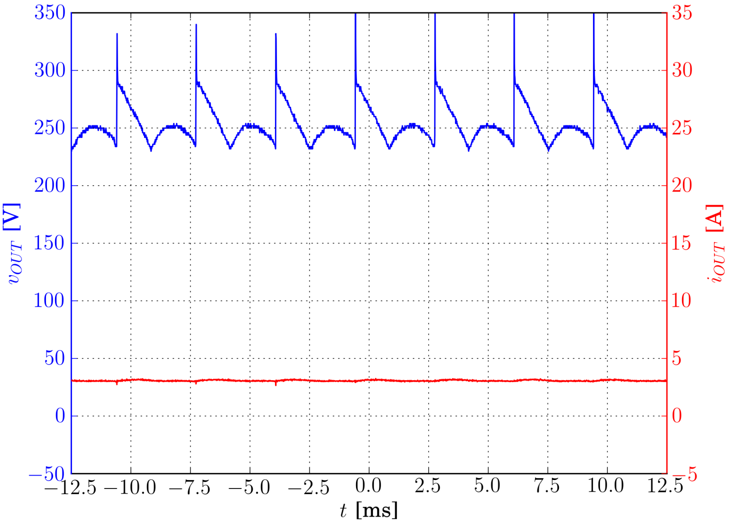
v_3, i_3, $I_{OUT} \approx 9\,\text{A}$, spectra



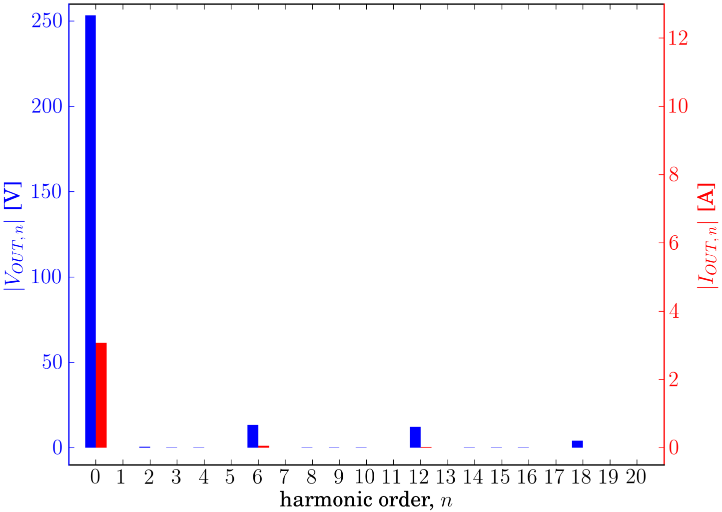
v_3, $I_{OUT} \approx 9\,\text{A}$



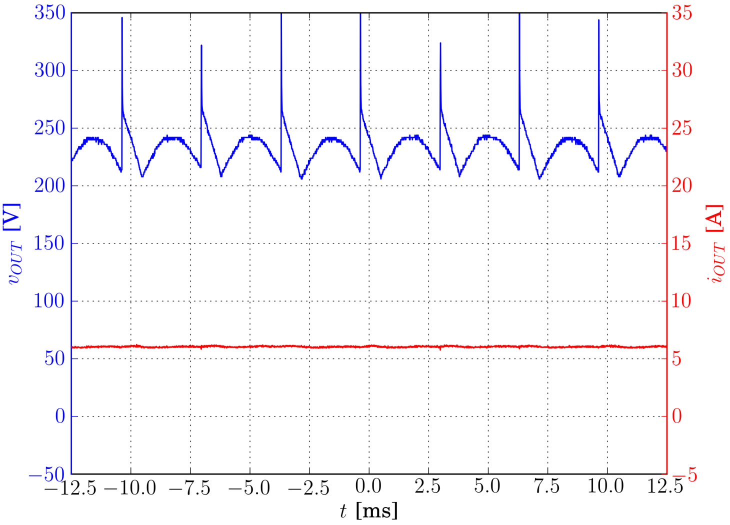
v_{OUT}, i_{OUT}, $I_{OUT} \approx 3\,\mathrm{A}$



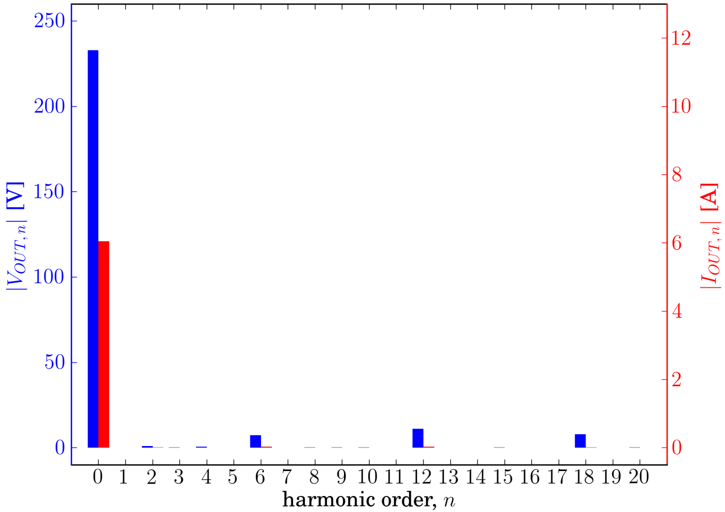
v_{OUT}, i_{OUT}, $I_{OUT} \approx 3\,\text{A}$, spectra



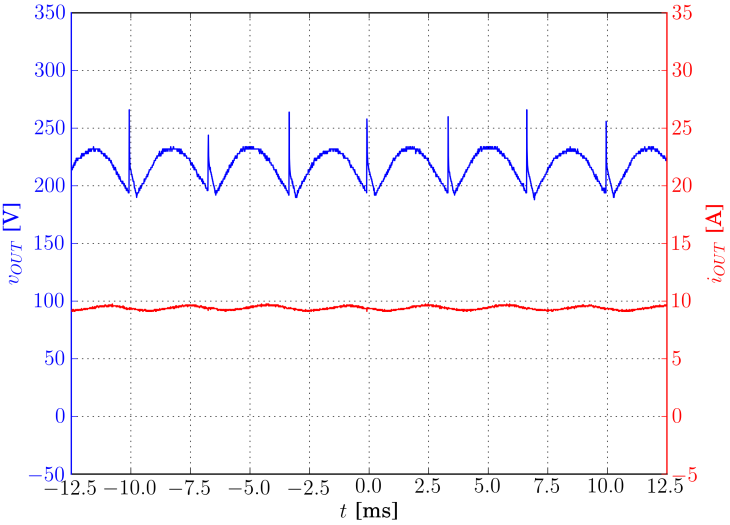
v_{OUT}, i_{OUT}, $I_{OUT} \approx 6\,\mathrm{A}$



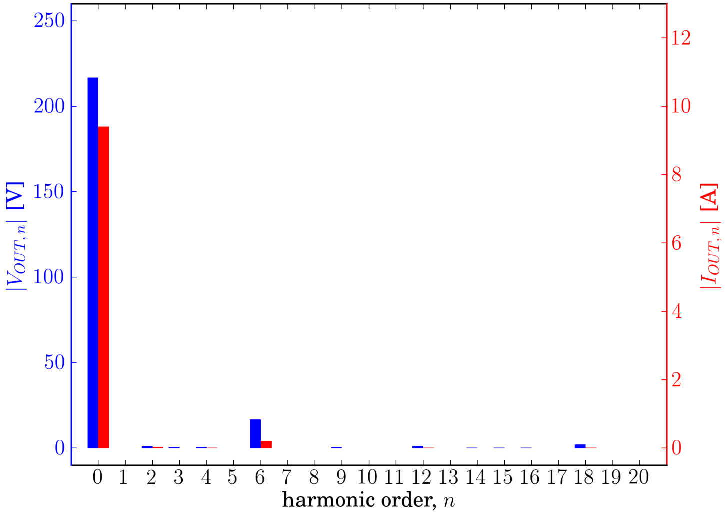
v_{OUT}, i_{OUT}, $I_{OUT} \approx 6\,\mathrm{A}$, spectra



v_{OUT}, i_{OUT}, $I_{OUT} \approx 9\,\mathrm{A}$



v_{OUT}, i_{OUT}, $I_{OUT} \approx 9\,\mathrm{A}$, spectra



does it worth?

I_{OUT} [A]	k	$I_{k\,RMS}$ [A]	$V_{k\,RMS}$ [V]	S [VA]	P [W]
≈ 3 A	1	2.90	99.78	289.66	282.36
	2	2.91	99.47	289.58	282.42
	3	2.88	100.12	288.67	281.42
≈ 6 A	1	5.66	95.89	542.29	533.10
	2	5.66	95.75	541.53	532.38
	3	5.65	97.01	548.57	539.83
≈ 9 A	1	8.38	91.67	767.90	752.36
	2	8.48	92.14	781.43	767.26
	3	8.42	94.72	797.43	785.45

does it worth?

I_{OUT} [A]	k	PF	$THD(i_k)$ [%]	$THD(v_k)$ [%]
≈ 3 A	1	0.9748	17.76	4.22
	2	0.9753	17.86	3.91
	3	0.9749	17.74	4.14
≈ 6 A	1	0.9830	14.69	3.76
	2	0.9831	14.19	4.21
	3	0.9841	14.19	3.80
≈ 9 A	1	0.9798	11.98	5.47
	2	0.9819	11.53	5.47
	3	0.9850	11.69	4.32

does it worth?

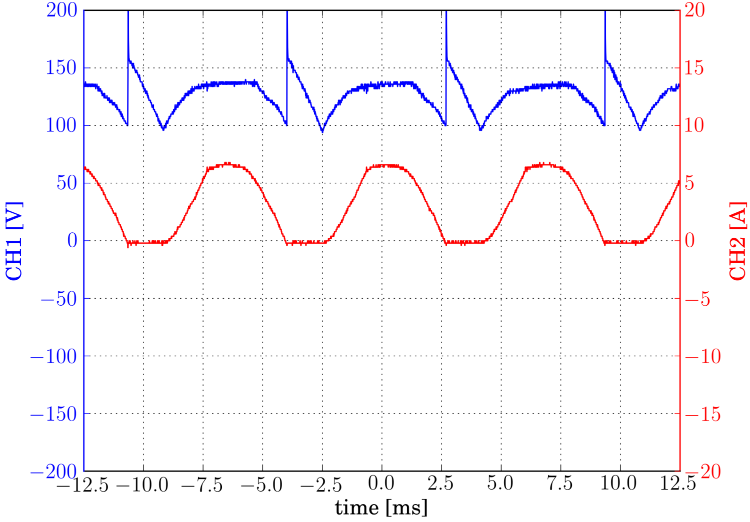
I_{OUT} [A]	V_{OUT} [V]	P_{OUT} [W]	P_{IN} [W]	η [%]
3.08	253.32	781.38	846.21	92.34
6.06	232.91	1410.35	1605.31	87.86
9.41	216.86	2041.09	2305.07	88.55

really low η; quite unexpected! is this a mistake?

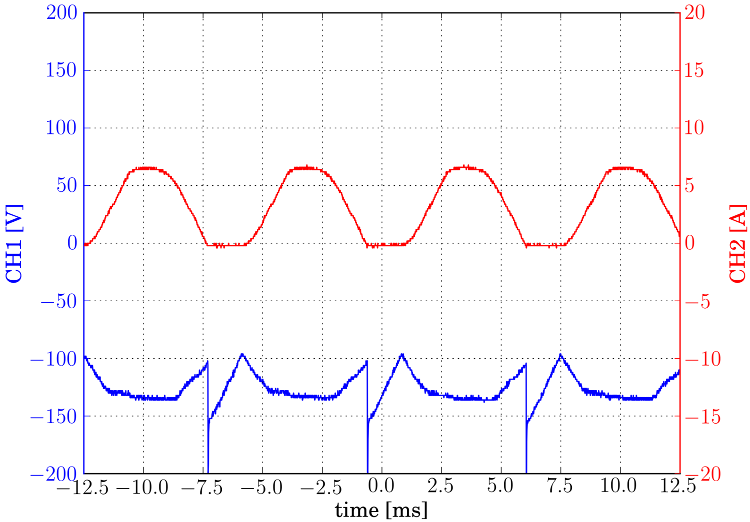
user's point of view ... and a conclusion

- the input currents are not so good, but better than without injection
- THD is in the range from 10 % to 20 %
- absolutely no notches in the input voltages
- spikes in the output voltage, rich with harmonics
- the spikes decrease with increases of the output current
- the spikes increase the output voltage average, V_{OUT}
- there are some losses in the system, unexpected?
- the efficiency is much lower than expected!
- at 9 A the rectifier operates close to the CCM
- spikes are the answer! what causes them?
- let's take a closer look ...

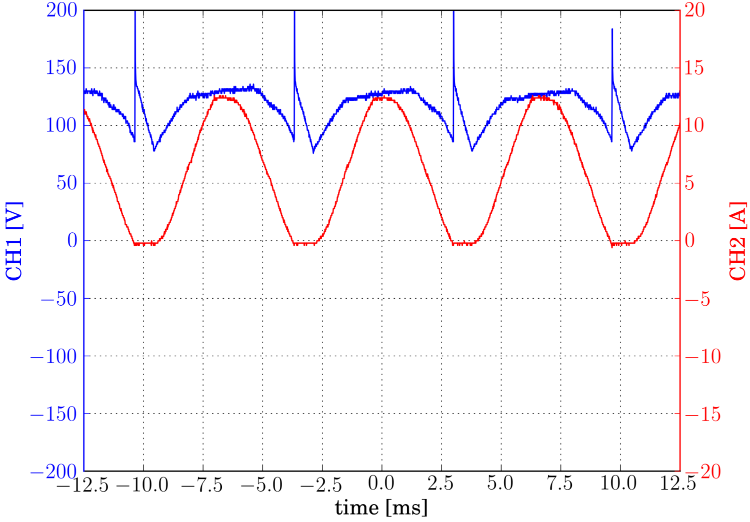
v_A, i_A, $I_{OUT} \approx 3\,\mathrm{A}$



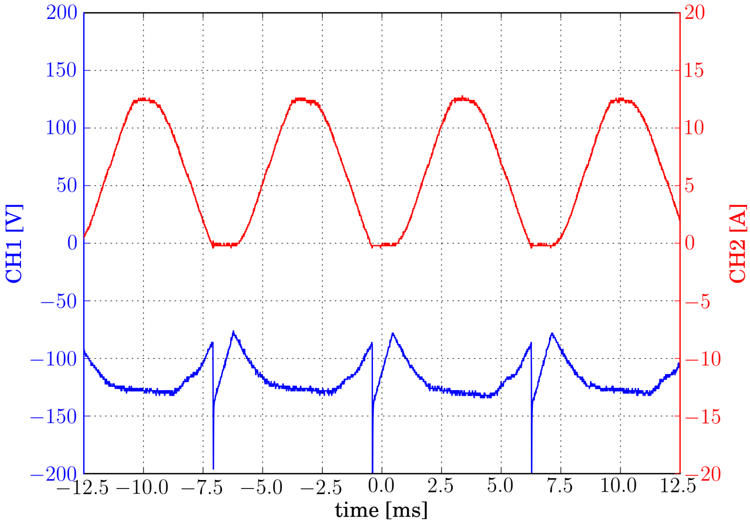
v_B, i_B, $I_{OUT} \approx 3\,\mathrm{A}$



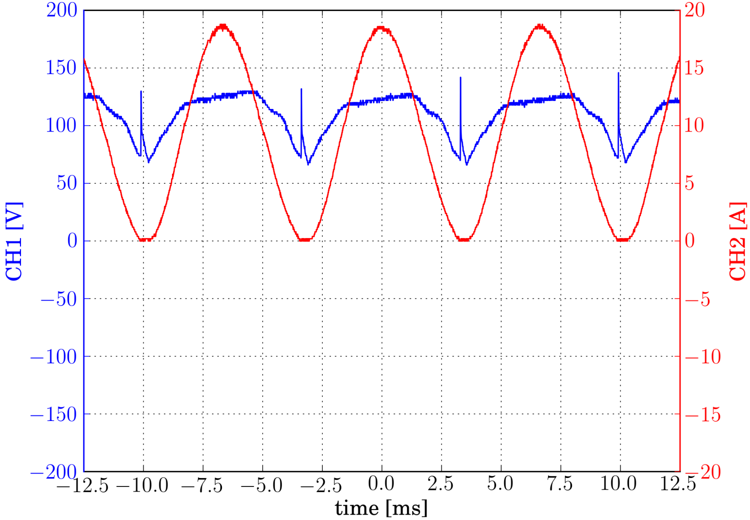
v_A, i_A, $I_{OUT} \approx 6\,\mathrm{A}$



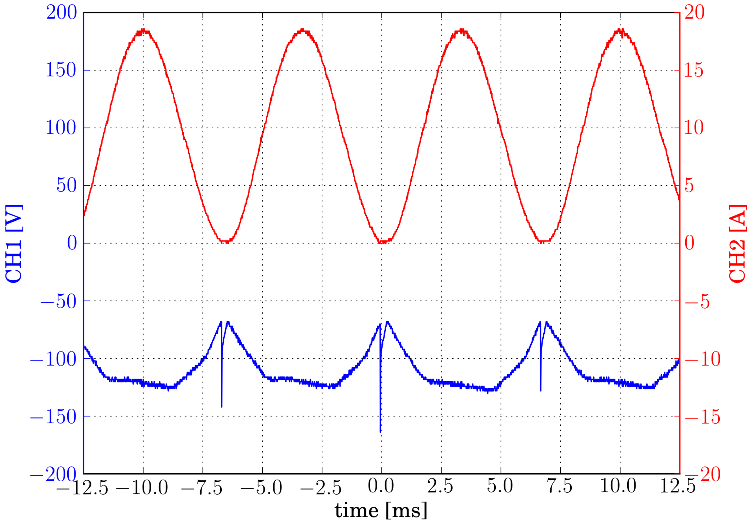
v_B, i_B, $I_{OUT} \approx 6\,\mathrm{A}$



v_A, i_A, $I_{OUT} \approx 9\,\mathrm{A}$



v_B, i_B, $I_{OUT} \approx 9\,\mathrm{A}$



let's start from the end ...

Q: what the end is?
A: CCM-DCM boundary, close to $I_{OUT} = 9\,\text{A}$ in our case

at that point:

$$i_Y = 2\, I_{OUT}\, \cos\left(3\omega_0 t\right)$$

normalize, ...

$$j_Y = J_{Ym}\, \cos\left(3\omega_0 t\right) = 2\, \cos\left(3\omega_0 t\right)$$

$J_{Ym} = 2$ instead of $\frac{3}{2}$, which would be optimal

efficiency at the boundary . . .

$$P_{INJ} = \frac{1}{2} J_{Ym} M_{A,1}$$

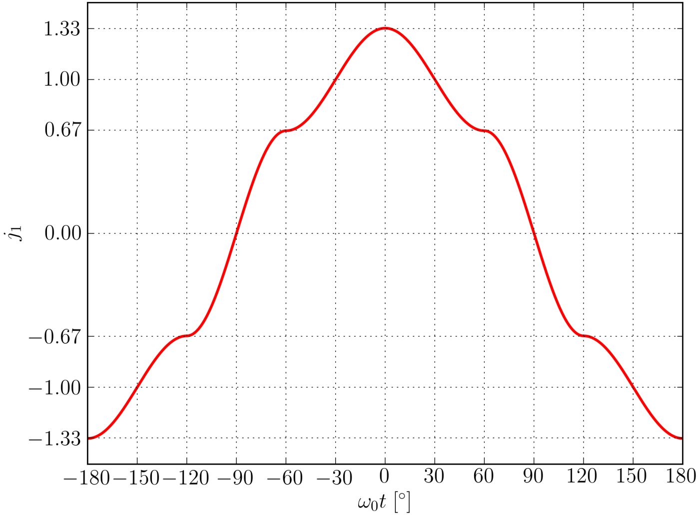
$$P_{INJ} = \frac{1}{2} \times 2 \times \frac{3\sqrt{3}}{8\pi} = \frac{3\sqrt{3}}{8\pi}$$

$$P_{OUT} = \frac{3\sqrt{3}}{\pi}$$

$$\eta = \frac{P_{OUT}}{P_{OUT} + P_{INJ}} = \frac{8}{9} \approx 88.89\,\%$$

experimental results make sense now?

j_1 at the boundary (and not just there) ...



at the boundary ...

to get to the boundary

$$\rho = \frac{M_{A,1}}{J_{Ym}} = \frac{3\sqrt{3}}{8\pi} \times \frac{1}{2} = \frac{3\sqrt{3}}{16\pi}$$

and at the boundary ...

wxMaxima will be heavily needed from here ...

$$J_{RMS} = \frac{\sqrt{7}}{3}$$

$$J_{1m} = \frac{9\sqrt{3}}{4\pi}$$

$$J_{1RMS} = \frac{9\sqrt{3}}{4\pi\sqrt{2}}$$

THD and the PF at the boundary

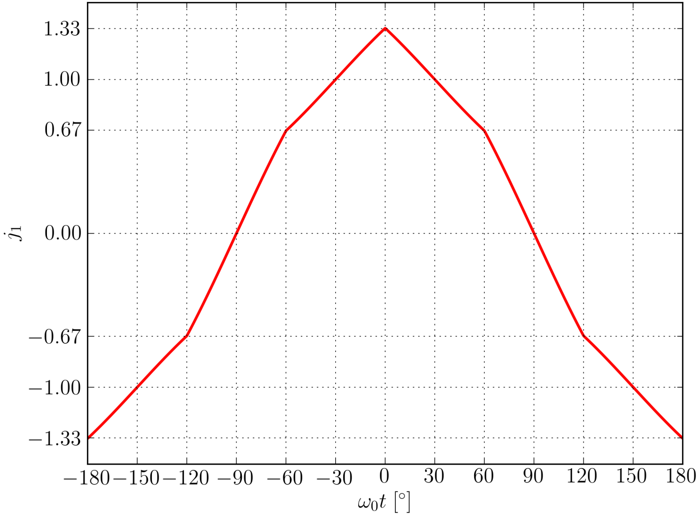
$$THD = \sqrt{\frac{224\pi^2}{2187} - 1} \approx 10.43\,\%$$

$$PF = \frac{27\sqrt{3}}{4\pi\sqrt{14}} \approx 0.9946$$

not that bad . . .

but, the efficiency **is** bad!

and what if $Q = 0$?



parameters for $Q = 0$?

this boundary requires a different value of ρ ...

$$\rho = \frac{\max\left(m_{AV}\right)}{\max\left(j_Y\right)} = \frac{1}{4} \times \frac{1}{2} = \frac{1}{8}$$

at the boundary ...

$$J_{RMS} = \sqrt{\frac{10}{9} - \frac{2}{\sqrt{3}\pi}}$$

$$J_{1m} = \frac{\sqrt{3}}{\pi} + \frac{2}{3}$$

$$J_{1RMS} = \frac{\sqrt{3}}{\pi\sqrt{2}} + \frac{\sqrt{2}}{3}$$

η, THD, and PF at the boundary, $Q = 0$

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{M_{OUT}}{\frac{3}{2}\, J_{1m}} = \frac{6\sqrt{3}}{2\pi + 3\sqrt{3}} \approx 90.53\,\%$$

$$THD = \sqrt{\frac{16\pi^2 - 24\pi\sqrt{3} - 27}{4\pi^2 + 12\pi\sqrt{3} + 27}} \approx 4.93\,\%$$

$$PF = \sqrt{\frac{4\pi^2 + 12\pi\sqrt{3} + 27}{20\pi^2 - 12\pi\sqrt{3}}} \approx 0.9988$$

THD and PF okay, but η is not …

better THD and PF are achieved in CCM **with** better η, this mode does not make any sense in practice …

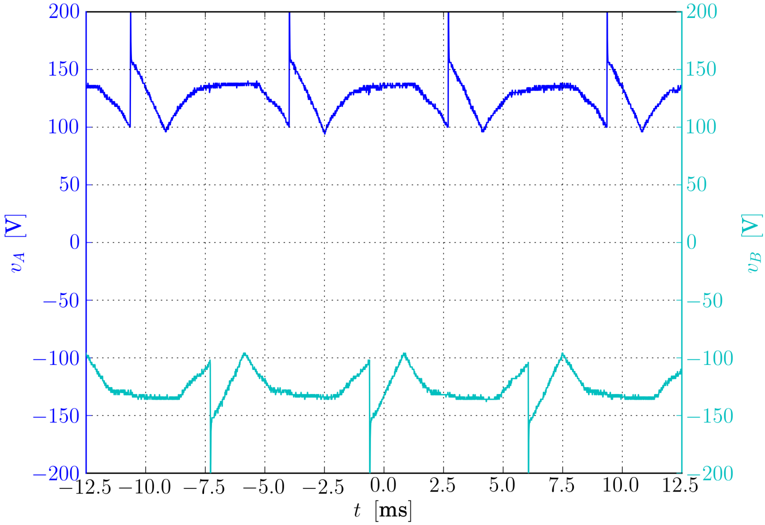
partial conclusions . . .

- there is some interest in the DCM, due to the relatively acceptable THD
- the boundary between the CCM and the DCM suffers from poor efficiency, not of practical interest
- we should analyze the DCM somewhere away from the boundary . . .

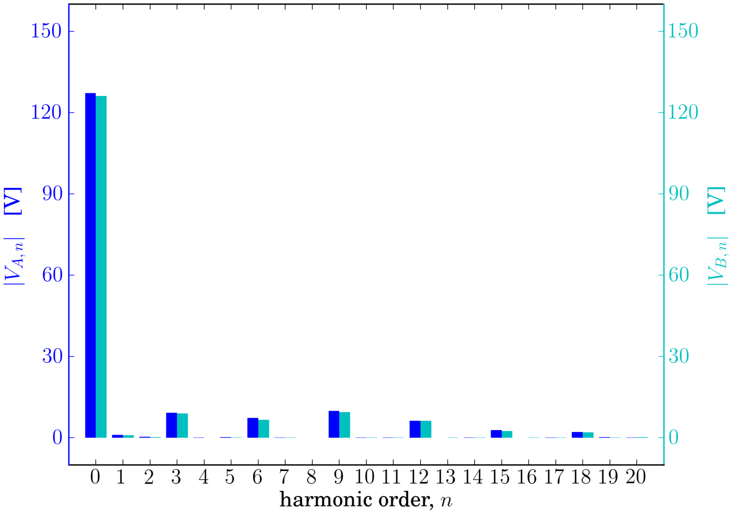
case $Q \to \infty$, $R \to 0$

- $Q = R_0/R$, $R_0 = \sqrt{L/C}$
- let's analyze large R_0 and low R case ... not just huge Q
- in that case $j_Y \approx 2\cos(3\omega_0 t)$
- and the spikes limit the amplitude of j_Y ...
- ... since there is no other cause
- let's model the spikes somehow ...
- maybe with Dirac impulses?
- that's why I stressed the "flat" spectrum
- let's take a look ...

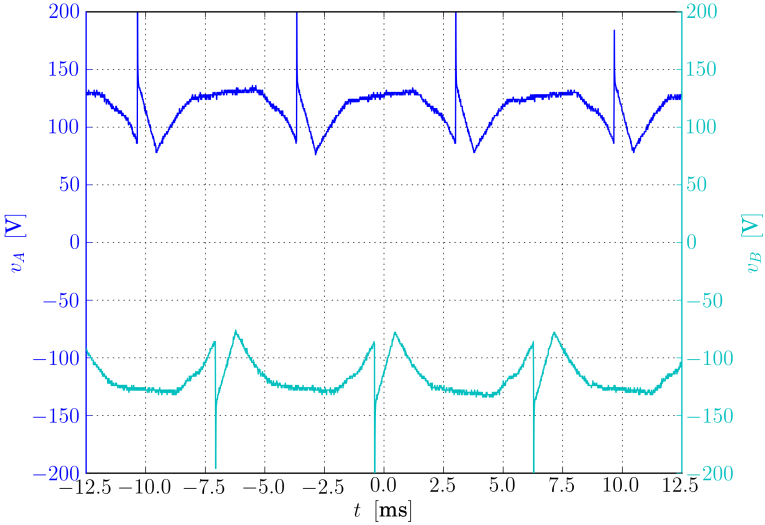
v_A and v_B, $I_{OUT} \approx 3\,\mathrm{A}$



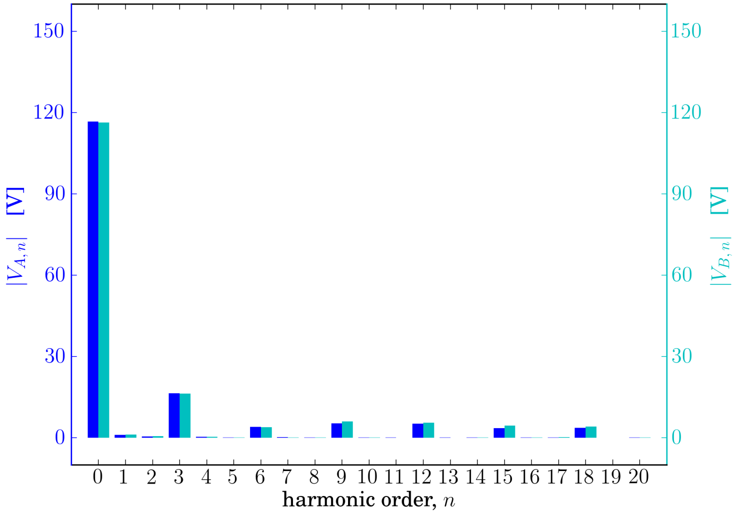
v_A and v_B, $I_{OUT} \approx 3\,\mathrm{A}$



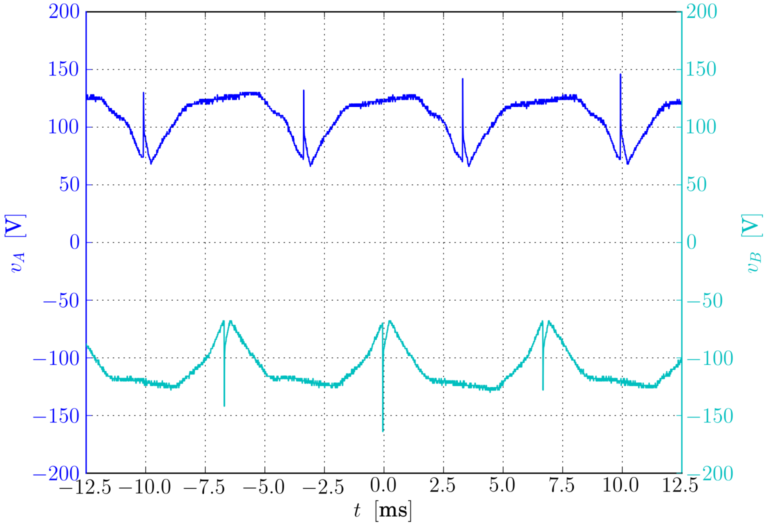
v_A and v_B, $I_{OUT} \approx 6\,\mathrm{A}$



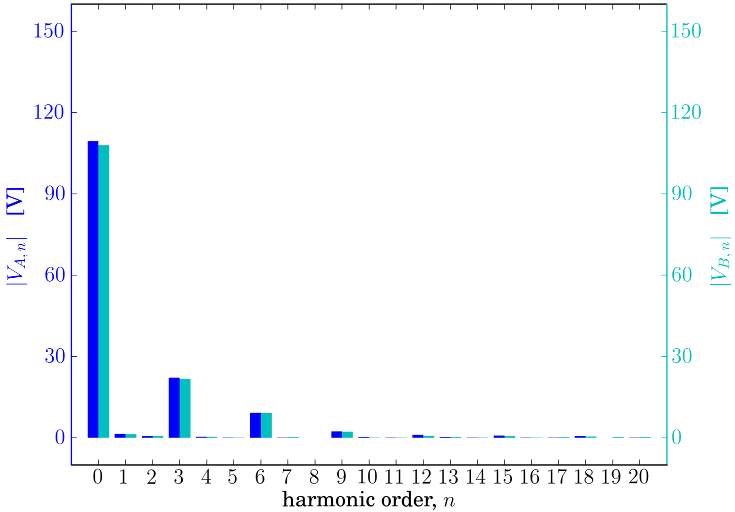
v_A and v_B, $I_{OUT} \approx 6\,\mathrm{A}$



v_A and v_B, $I_{OUT} \approx 9\,\text{A}$



v_A and v_B, $I_{OUT} \approx 9\,\text{A}$



definitely, the spikes ...

definitely, the spikes are the answer for the DCM:

- the spikes reduce the 3rd harmonic (at $3\omega_0$) in m_A and m_B
- the spikes depend on the output current
- the spikes are disappearing as we are getting close to the CCM
- the spikes introduce new harmonics, needed to distort i_Y
- the spikes have flat-looking spectrum ...
- ... which makes them suitable to model with Dirac δ impulses!
- and I personally like δ impulses and Dirac's approach ...
- P. A. M. Dirac: "The aim of science is to make difficult things understandable in a simpler way; the aim of poetry is to state simple things in an incomprehensible way."

definitions of m_{A0} and m_{B0}, no spikes

$$m_{A0} = \max\left(m_1,\, m_2,\, m_3\right)$$

$$m_{B0} = \min\left(m_1,\, m_2,\, m_3\right)$$

the same as m_A and m_B before ...

thus, they have the same spectra, ...

let's model the spikes . . .

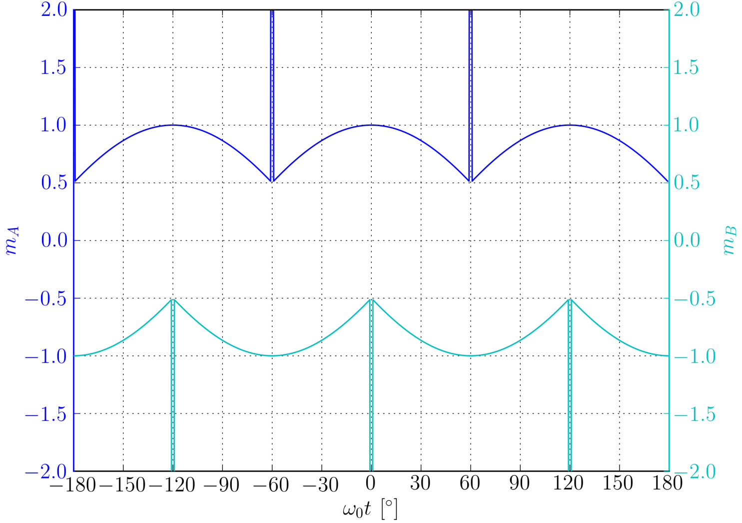
$$m_A = m_{A0} + M_X \sum_{n=-\infty}^{+\infty} \delta\left(\omega_0 t - \frac{\pi}{3} - n\,\frac{2\pi}{3}\right)$$

$$m_B = m_{B0} - M_X \sum_{n=-\infty}^{+\infty} \delta\left(\omega_0 t - n\,\frac{2\pi}{3}\right)$$

where V_X is yet to be determined . . .

a word about physical dimension of δ impulses . . .

the model of spikes, DSP version . . .



a DSP note . . .

- when it comes to δ impulses, the DSP approach becomes extremely error prone
- be VERY careful in forming the spectra, a tiny error could destroy the results
- this is not a story, this is an experience . . .
- much worse than Gibbs phenomenon . . .
- the higher the level of discontinuity — the worse
- with δ impulses spectral leakage is a problem, since the is a lot to leak

the spectra, m_A ...

$$m_A = \max\left(m_1,\, m_2,\, m_3\right) + M_X \sum_{n=-\infty}^{+\infty} \delta\left(\omega_0 t - \frac{\pi}{3} - n\,\frac{2\pi}{3}\right)$$

$$m_A = M_{A,\,0} + \sum_{k=1}^{\infty} M_{A,\,k}\,\cos\left(3k\omega_0 t\right)$$

$$M_{A,\,0} = \frac{3\sqrt{3}}{2\pi} + \frac{3}{2\pi}\,M_X$$

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

the spectra, m_B ...

$$m_B = \min\left(m_1,\, m_2,\, m_3\right) - M_X \sum_{n=-\infty}^{+\infty} \delta\left(\omega_0 t - n\,\frac{2\pi}{3}\right)$$

$$m_B = M_{B,\,0} + \sum_{k=1}^{\infty} M_{B,\,k}\,\cos\left(3k\omega_0 t\right)$$

$$M_{B,\,0} = -\frac{3\sqrt{3}}{2\pi} - \frac{3}{2\pi}\,M_X$$

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

since we are already here, m_{OUT}, the spectrum ...

$$m_{OUT} = m_A - m_B$$

$$m_{OUT} = M_{OUT,0} + \sum_{k=1}^{\infty} M_{OUT,k} \cos\left(3k\omega_0 t\right)$$

$$M_{OUT,0} = \frac{3\sqrt{3}}{\pi} + \frac{3}{\pi} M_X$$

$$M_{OUT,k} = \begin{cases} 0 & \text{for } k \text{ odd} \\ -\frac{6\sqrt{3}}{\pi}\frac{1}{9k^2-1} + \frac{6}{\pi} M_X & \text{for } k \text{ even} \end{cases}$$

let's use the spectra ...

to push j_Y ...

$$\rho\, J_{Ym} = M_{A,\,1} = M_{B,\,1} = \frac{3\sqrt{3}}{8\pi} - \frac{3}{\pi}\, M_X$$

and we get M_X ...

$$M_X = \frac{\sqrt{3}}{8} - \frac{\pi}{3}\,\rho\, J_{Ym} = \frac{\sqrt{3}}{8} - \frac{2\pi}{3}\,\rho$$

to get M_{OUT} ...

$$M_{OUT} = \frac{27\sqrt{3}}{8\pi} - 2\,\rho$$

a double check . . .

at $\rho = 0$:

$$M_{OUT} = \frac{27\sqrt{3}}{8\pi} \approx 1.8607$$

at $\rho = \frac{3\sqrt{3}}{16\pi}$:

$$M_{OUT} = \frac{27\sqrt{3}}{8\pi} - \frac{3\sqrt{3}}{16\pi} \times 2 = \frac{3\sqrt{3}}{\pi} \approx 1.6540$$

M_{OUT} variation within $+12.5\,\%$ . . .

dependence of V_{OUT} on I_{OUT}

$$M_{OUT} = \frac{27\sqrt{3}}{8\pi} - 2\,\rho$$

denormalize ...

$$\frac{V_{OUT}}{V_m} = \frac{27\sqrt{3}}{8\pi} - 2\,\frac{R\,I_{OUT}}{V_m}$$

$$V_{OUT} = \frac{27\sqrt{3}}{8\pi}\,V_m - 2\,R\,I_{OUT}$$

the output impedance is $2\,R$, ...

a word about efficiency . . .

$$P_{OUT} = M_{OUT} = \frac{27\sqrt{3}}{8\pi} - 2\rho$$

$$P_{IN} = P_{OUT} + \frac{1}{2} \times \rho \times 2^2 = \frac{27\sqrt{3}}{8\pi}$$

$$\eta = 1 - \frac{16\pi}{27\sqrt{3}}\,\rho$$

η passes the double check at the CCM-DCM boundary . . .

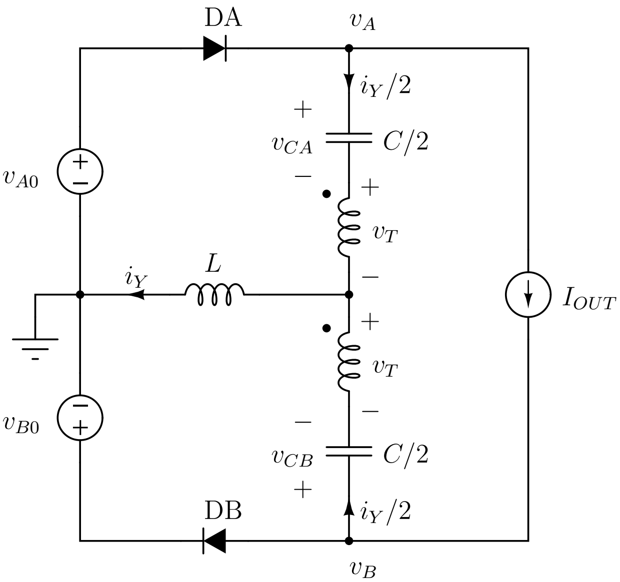
δ conclusions ...

- the spikes are modelled by δ impulses
- prediction of the output voltage obtained, V_{OUT} ...
- prediction of the output impedance, $2\,R$ ...
- prediction of the efficiency obtained ...
- however, this is just an approximation ...
- ... although experimentally verifiable
- how good the approximation is?
- is there a better model?
- avoid exact solution, it is not available in a closed form ...
- ... like it was in the CCM
- how about "simulation"?
- but not just in a form of a cheap experiment ...

simplify the circuit ...

- originally, there are 6 diodes
- deep theory says there are $2^6 = 64$ states
- fortunately, we do not care about all of them ...
- in the CCM only 6 states occur
- in the DCM there are more than 6 ...
- first, let's reduce the problem as much as we can ...
- but not more than that ...

an equivalent circuit to study the DCM



some voltages defined . . .

as defined earlier . . . just rename . . .

$$v_{A0} = \max\left(v_1,\, v_2,\, v_3\right)$$

$$v_{B0} = \min\left(v_1,\, v_2,\, v_3\right)$$

and another voltage waveform which would be needed . . .

$$v_{AV0} = \frac{v_{A0} + v_{B0}}{2}$$

about DA and DB

- DA and v_{A0} represent v_1, v_2, v_3, and D1, D3, D5
- DB and v_{B0} represent v_1, v_2, v_3, and D2, D4, D6
- DA and DB model the DCM
- from 6 diodes to 2
- from $2^6 = 64$ states to $2^2 = 4$
- and out of these four, one is irrelevant …
- an improvement … helps us understand …
- only 3 states to take care of!
- but that's not that only …

how to get the currents?

in the same way as before:

$$i_1 = d_1\, i_A - d_2\, i_B - \frac{1}{3}\, i_Y$$

$$i_2 = d_3\, i_A - d_4\, i_B - \frac{1}{3}\, i_Y$$

$$i_3 = d_5\, i_A - d_6\, i_B - \frac{1}{3}\, i_Y$$

where d_n functions are as defined earlier, $n \in \{1, \ldots 6\}$

i_Y is really important ...

$$i_A = I_{OUT} + \frac{1}{2}\, i_Y$$

$$i_B = I_{OUT} - \frac{1}{2}\, i_Y$$

$$\dots$$

$$i_1 = (d_1 - d_2)\; I_{OUT} + \frac{3\,(d_1 + d_2) - 2}{6}\; i_Y$$

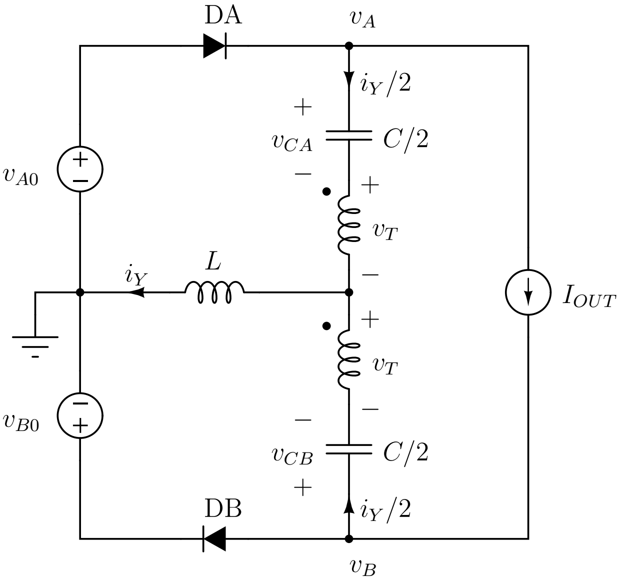
$$i_2 = (d_3 - d_4)\; I_{OUT} + \frac{3\,(d_3 + d_4) - 2}{6}\; i_Y$$

$$i_3 = (d_5 - d_6)\; I_{OUT} + \frac{3\,(d_5 + d_6) - 2}{6}\; i_Y$$

reduced number of states …

- instead of $2^6 = 64$ we deal with 4 states now
- states, I mean diode state combinations
- and it is not 4, but 3 for $I_{OUT} > 0$
- which is why the equivalent circuit has been introduced …
- we need i_Y …
- v_A and v_B would also be useful …
- let's find i_Y, v_A, and v_B in each of the states …

back to the circuit . . .



and some circuit theory ...

- at most, for DA and DB on, the circuit is of the third order
- when a diode goes off, algebraic degeneration over $i_L = i_Y$ occurs, since $i_Y = \pm 2\, I_{OUT}$ in such a case ...
- ... but that's not a big problem; the capacitors are ...

and some circuit theory, capacitors ...

- the capacitors share the same current, $i_Y/2$
- thus, their voltages differ for a constant ...
- the circuit (with DA and DB on) has three poles, one of them in $s = 0$
- the capacitors have the same AC components in their voltages
- but the DC components are different!
- it is not a big deal to find the DC components ... well ...
- especially since $V_{CA} = -V_{CB}$ due to the symmetry ...
- but to find the AC component is a problem ...
- which we are going to solve!

after some dirty job . . .

let's introduce

$$v_C = \frac{v_{CA} + v_{CB}}{2}$$

which turns out to be the AC component of the voltages across C_A and C_B, since the DC components are the opposite . . .

it can be shown that the resistance distribution parameter does not have any influence . . .

the circuit exposes algebraic degeneration if a diode is off, as already stated . . .

a lot of effort to solve in a sort of elegant way . . .

state 0, DA is on, DB is on

equations:

$$L\,\frac{di_Y}{dt} = -R\,i_Y - v_C + v_{AV0}$$

$$C\,\frac{dv_C}{dt} = i_Y$$

conditions:

$$-2\,I_{OUT} \leq i_Y \quad \text{if violated switch to state } -1$$

$$i_Y \leq 2\,I_{OUT} \quad \text{if violated switch to state } +1$$

state −1, DA is off, DB is on

$$i_Y = -2\, I_{OUT}$$

$$C\,\frac{dv_C}{dt} = -2\, I_{OUT}$$

condition:

$$v_C > v_{AV0} + 2\,R\,I_{OUT} \quad \text{if violated switch to state 0}$$

state +1, DA is on, DB is off

$$i_Y = 2\, I_{OUT}$$

$$C\, \frac{dv_C}{dt} = 2\, I_{OUT}$$

condition:

$$v_C < v_{AV0} - 2\, R\, I_{OUT} \quad \text{if violated switch to state 0}$$

v_A and v_B

state	DA	DB	v_A	v_B
0	on	on	v_{A0}	v_{B0}
-1	off	on	$v_A = v_{A\,DCM}$	v_{B0}
$+1$	on	off	v_{A0}	$v_B = v_{B\,DCM}$

$$v_{A\,DCM} = -v_{B0} - 4\,R\,I_{OUT} + 2\,v_C$$

$$v_{B\,DCM} = -v_{A0} + 4\,R\,I_{OUT} + 2\,v_C$$

new normalization, motivation

- existing normalization of currents, with $I_{base} = I_{OUT}$ is inadequate ...
- the problem is in the dependence of ρ on I_{OUT}, $\rho = R\, I_{OUT}/V_m$
- R remains constant, while I_{OUT} varies
- it is inconvenient to consider variations of I_{OUT} as variations of ρ, but not that big of a deal ...
- we need a solid foundation for I_{base}
- besides, $R_0 \triangleq \sqrt{L/C}$ plays a significant role now ...
- it's time to renew normalization ...

new normalization

$$V_{base} = V_m$$

$$R_{base} \triangleq R_0 = \sqrt{\frac{L}{C}}$$

$$I_{base} = \frac{V_m}{R_0}$$

$$J_{OUT} = \frac{I_{OUT}}{I_{base}} = \frac{R_0 \, I_{OUT}}{V_m}$$

$$\rho = \frac{R}{R_0} = \frac{1}{Q}$$

the resonance parameter, r

$$\omega_R \triangleq \frac{1}{\sqrt{L\,C}}$$

$$r \triangleq \frac{\omega_R}{3\,\omega_0}$$

in resonance $r = 1$, the CIN should be designed to meet this, this is the resonance constraint

state 0, DA is on, DB is on, normalized

equations:

$$\frac{dj_Y}{d\varphi} = 3\,r\,\left(-\rho\,j_Y - m_C + m_{AV0}\right)$$

$$\frac{dm_C}{d\varphi} = 3\,r\,j_Y$$

conditions:

$$-2\,J_{OUT} \leq j_Y \quad \text{if violated switch to state } -1$$

$$j_Y \leq 2\,J_{OUT} \quad \text{if violated switch to state } +1$$

state −1, DA is on, DB is off, normalized

$$j_Y = -2\,J_{OUT}$$

$$\frac{dm_C}{d\varphi} = -6\,r\,J_{OUT}$$

condition:

$$m_C > m_{AV0} + 2\,\rho\,J_{OUT} \quad \text{if violated switch to state 0}$$

state +1, DA is off, DB is on, normalized

$$j_Y = 2\,J_{OUT}$$

$$\frac{dm_C}{d\varphi} = 6\,r\,J_{OUT}$$

condition:

$$m_C < m_{AV0} - 2\,\rho\,J_{OUT} \quad \text{if violated switch to state 0}$$

m_A and m_B

state	DA	DB	m_A	m_B
0	on	on	m_{A0}	m_{B0}
-1	off	on	$m_A = m_{A\,DCM}$	m_{B0}
$+1$	on	off	m_{A0}	$m_B = m_{B\,DCM}$

$$m_{A\,DCM} = -m_{B0} - 4\,\rho\,J_{OUT} + 2\,m_C$$

$$m_{B\,DCM} = -m_{A0} + 4\,\rho\,J_{OUT} + 2\,m_C$$

simulation is an easy task?

- all the equations derived ...
- just to solve them ...
- equations piecewise-linear, nonhomogeneous ...
- trapezoidal rule to integrate ...
- simple discretization ...
- but the steady state is required!
- which is a problem of itself!
- and remains to be a problem ...
- a new steady state acceleration method had to be derived to solve the model in a reasonable time ...
- the original intention was to include the method in this presentation ...

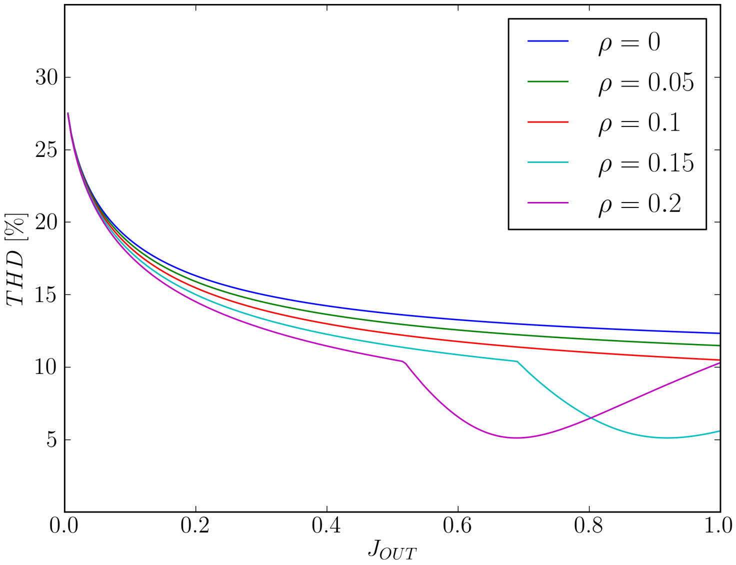
the steady state acceleration method published in ...

Marija Stojsavljević, Predrag Pejović

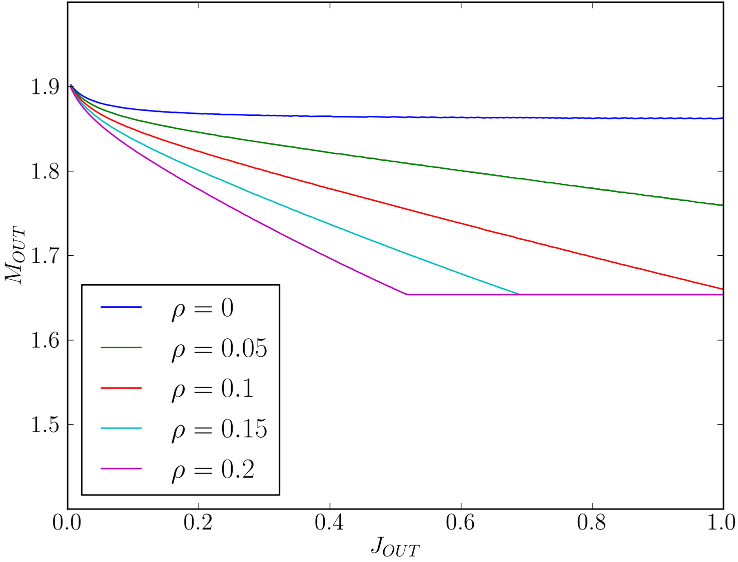
"An Extrapolation Method for Accelerated Convergence to Steady State Solution of Power Electronics Circuits"

Power Conversion and Intelligent Motion, PCIM Europe 2005, pp. 574–578, Nuremberg, Germany, June 2005

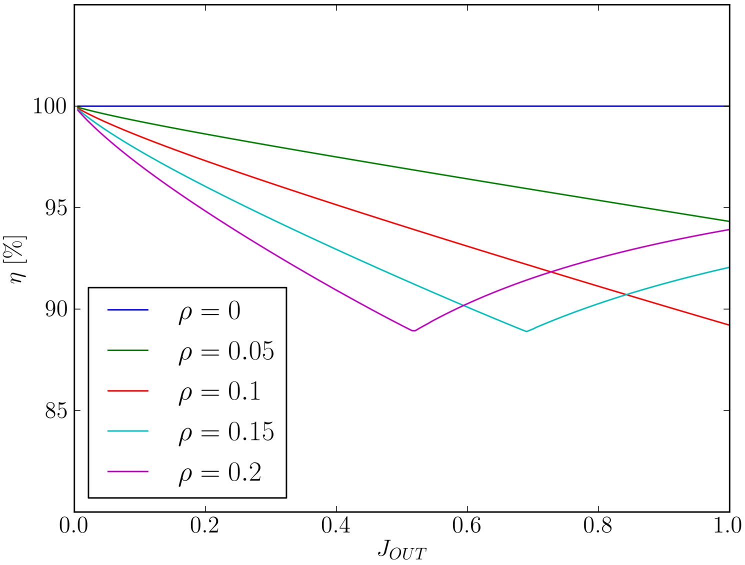
THD versus J_{OUT}, the simulation result



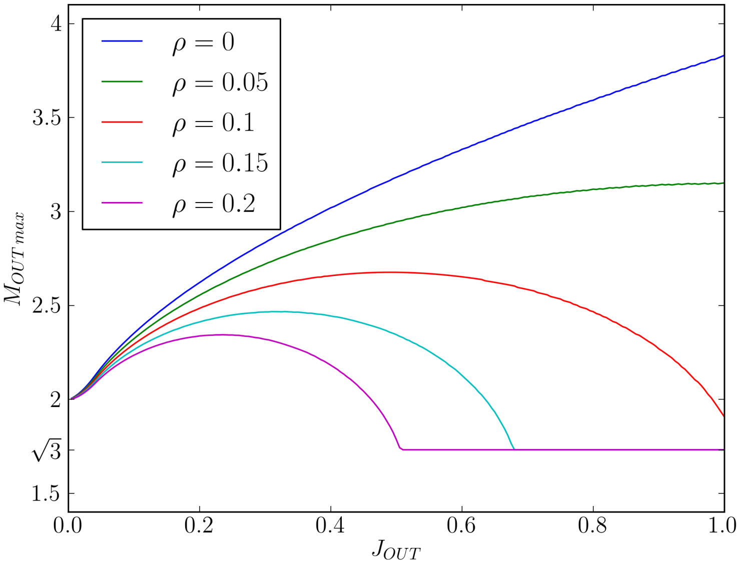
M_{OUT} versus J_{OUT}, the simulation result



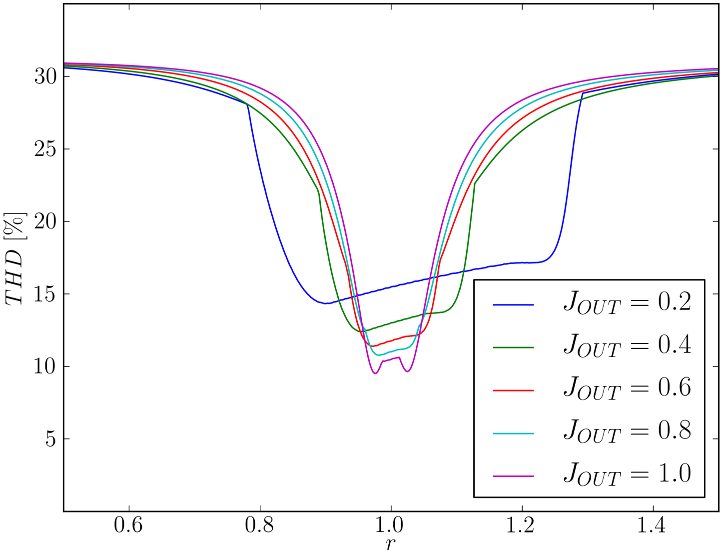
η versus J_{OUT}, the simulation result



$M_{OUT\,max}$ versus J_{OUT}, the simulation result



THD versus r, the simulation result



after the simulation . . .

- simulation may be used even to draw fairly general conclusions
- but this requires analytical preparation and normalization
- obtained diagrams should be denormalized to apply for a specific circuit
- agreement with δ impulse approach?
- disagreement only at low I_{OUT}
- which was expected . . . after we got the results

published in . . .

Predrag Božović, Predrag Pejović

"Current Injection Based Low Harmonic Three Phase Diode Bridge Rectifier Operating in Discontinuous Conduction Mode"

IEE Proceedings Electric Power Applications,
vol. 152, no. 2, pp. 199–208, March 2005

without any problem!

after the DCM . . .

- finally, there is some understanding of the DCM . . .
- but is there any use of it?
- at first, it seems pretty useless . . .
- but do we study only the things to be applied at the very moment?
- actually, we do!
- but there is resistance emulation . . .
- where these concepts turned out to be useful
- although this was not an original idea
- and this is our next topic . . .