NUMERO: 2199A

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A P P U N T I

STUDENTE: Navaretti Silvio

MATERIA: Power Electronics - Temi D'Esame - Prof. Maddaleno

Power electronics: every time we are concerned about efficiency → Electrical energy

DC → DC
DC → AC
AC → DC
AC → AC

Main conversions

In this course we only study these two

DC → DC : converter
DC → AC : ~~the~~ inverter
AC → DC : rectifier
AC → AC : (cyclo converters, nowadays not so much used, better performances with AC → DC → AC)

All electronic circuits need~~s~~ ~~a~~ DC supplier

Power levels from fractions of W to MW and it's still power electronics.

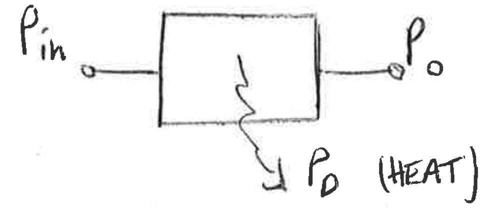
To be precise, POWER EFFICIENCY

efficiency, $\eta = \frac{P_o}{P_{in}}$

Important for many reasons, most important one money.

Measurements are not so easy. Your instruments can lie to you.

$P_{in} - P_o = P_D$ D = dissipated



"Keep it cool"

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1-2 (2)

2) POWER SAVING

3) How much does the electric energy from the main cost? 0,2 €/(KW/h)

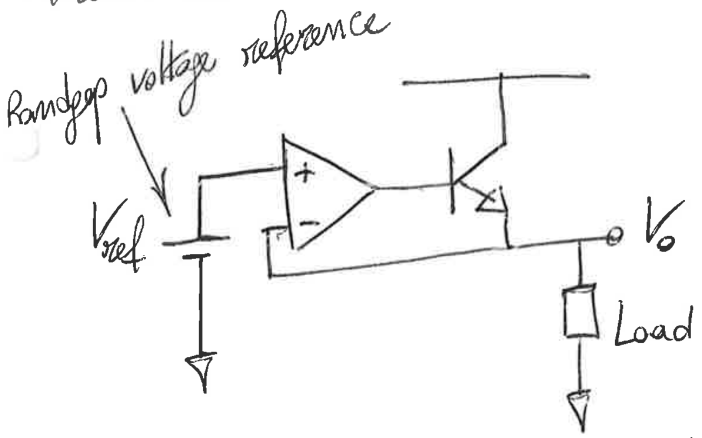
But in some applications the energy cost A LOT for example with batteries, ~20 €/(KW/h)
Portable objects, like self phones.

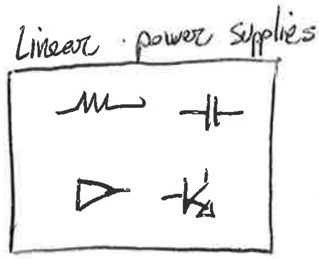
PORTABLE DEVICES: LONGER ENDURANCE

SWITCH MODE CONVERSION to obtain an high efficiency. It's the only way.

LINEAR POWER SUPPLIES: transistor used as a linear device.

closed loop negative feedback circuit.





power dissipation: voltage across the transistor and current through it

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1_2

With linear conversion we can only step down the voltage. The collector/drain has to be highter than the load.

With switch conversion we can even obtain an opposite voltage, an isolated voltage, ecc. Even an highter voltage.

With switch mode we can have multiple outputs.

Switch converters are complicated

Over the crossover frequency the system do what it can.

The linear ones can be fast, the switching ones are slower.

Linear power supplies have very little E.M. noise, while a switching power supplier is a good noise source.

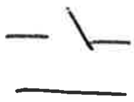
1_3

Can we use synthetized inductors? No for several reasons, first one: in our inductors flow several amps. We should use POWER OPAMPS ... which have very bad efficiency!

We can use synthetized inductors in filters.

HYPOTHESES

- Switches ideal



no voltage across a closed switch.

- RC or $\frac{L}{R}$ time constants, τ

$$\tau \gg T_{SW} \quad \text{period of switching}$$

there are capacitors and inductors and capacitors
we will deal with LINEAR (and not exponential)
waveforms.
R could be the parasitic resistance of an inductor,
for example
for a short period of time a sinusoidal waveform is
linear
<u>this hypothesis means that efficiency is one!</u>

- Output voltage is constant, that means no ripple!
we are cheating

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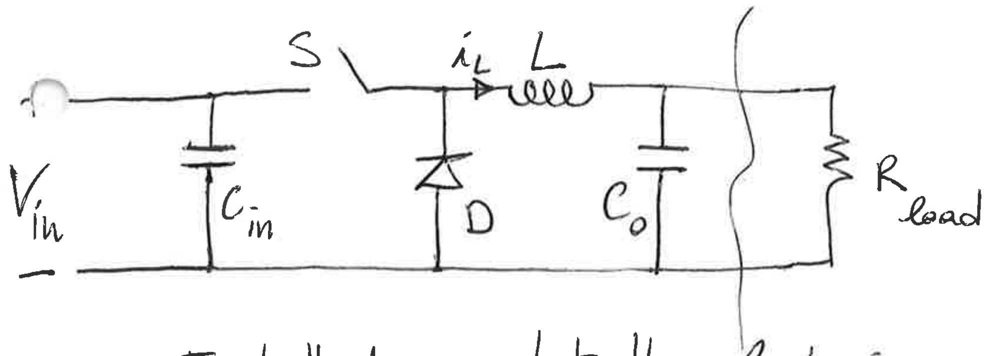
BUCK

Modellamo 5
1_3



I don't know what the load is

The switch can be a BJT, a THYRISTOR, an IGBT...

THYRISTOR: switched on by a command, but it turns off only when the current through it goes to ϕ.

Is a diode a switch as well? Well, if you patent it so...

HERE IT IS A NON-CONTROLLED BY YOU SWITCH

MODES OF OPERATION 1_4

CCM, Continuous Conduction Mode

DCM, Discontinuous Conduction Mode

The difference is the behaviour of the inductor current i_L

<u>CCM</u> $i_L \neq 0$, in some cases $i > 0$ A

<u>DCM</u>: $i_L = 0$ in part of the cycle

(The real fact is about the derivative of i_L)

CCM/DCM change completely the behaviour of the circuit.

We can't recognize the behaviour looking at the schematic.

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1_4 6

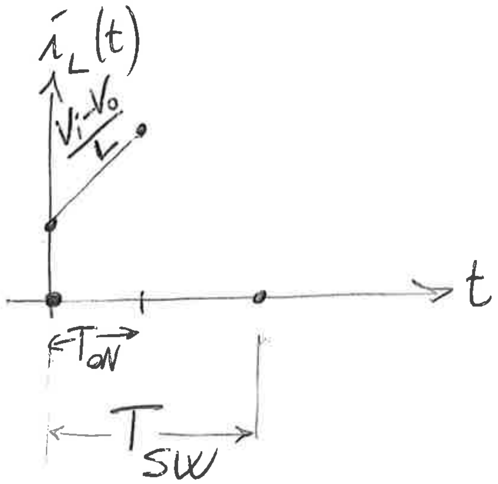
$\bar{i}_C = C \frac{d\bar{v}_C}{dt} = 0$ too in cyclostationary conditions.

A capacitor for a DC is an open circuit.

Capacitor with a constant current and a constant current: the capacitor fails!

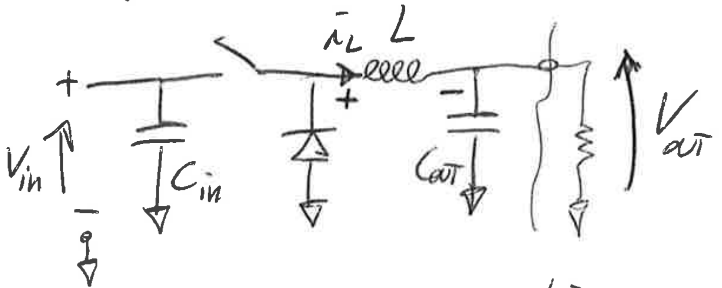
CYCLOSTATIONARY CONDITIONS
$$\begin{cases} \bar{v}_L = 0 \\ \bar{i}_C = 0 \end{cases}$$

FIND OUT $i_L(t)$



CCM: at the beginning the current has an initial value which is the final value from the previous cycle

BUCK



If the switch is ON:

$$v_L = L \frac{di_L}{dt} = V_{in} - V_{out} \qquad v_L = L \frac{di_L}{dt}$$

The derivative is constant. The slope of the current is constant. The current will go up with a slope of $\frac{V_{in} - V_{out}}{L}$ while the switch is ON (closed)

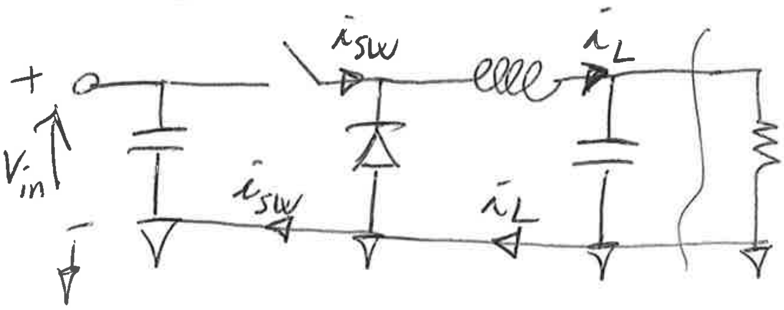
But we made a lot of assumptions! Maddalena 1_4 7

with a real switch

$$\frac{\left(V_{in} - V_{switch\ \cancel{open}\ closed}\right) - V_o}{L} T_{ON} - \left(\frac{V_o + V_{switch\ open}}{L}\right) = 0$$

The waveforms are "partial parts" of a sinusoid.

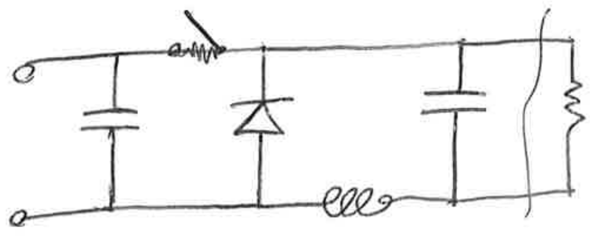
BUCK 2_1



CCM: the inductor current is never constant

$$V_o = V_{in} D \quad , \quad D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{T_{ON}}{T_{SW}}$$

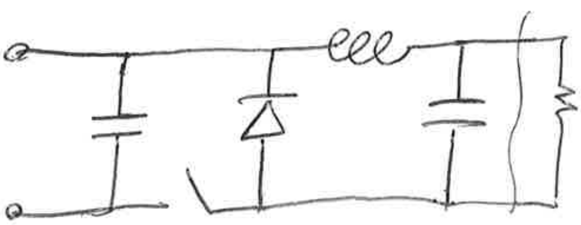
Topologies: there are other topologies.

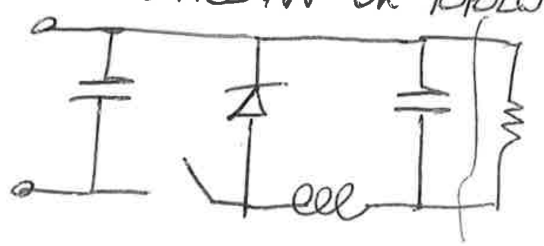


Still a buck

BAD TOPOLOGIES

STILL AN OK TOPOLOGY

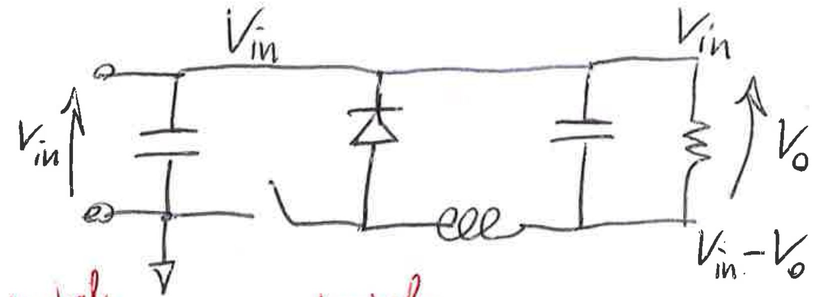


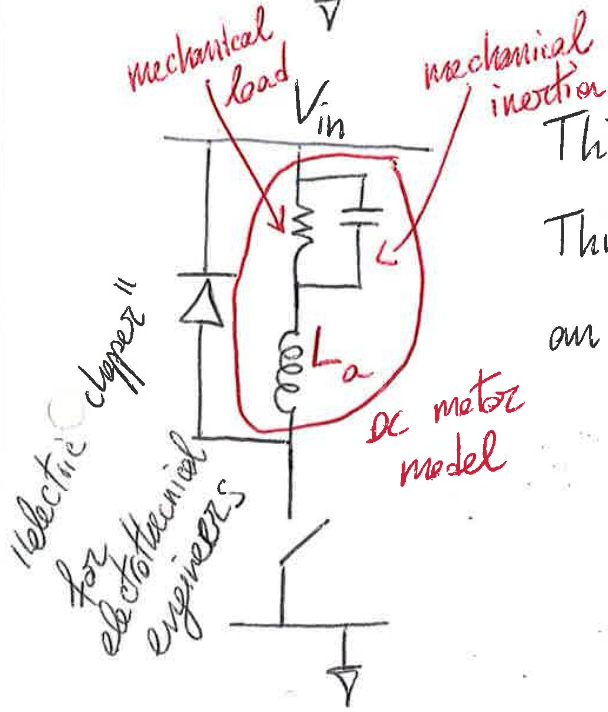


Maddaleno
2-1 (8)

The ground plane / chassie acts like a big capacitor in conjunction with the rest of the universe. We are moving fast a lot of voltage across it: radio transmitter.

So we have to pay attention.

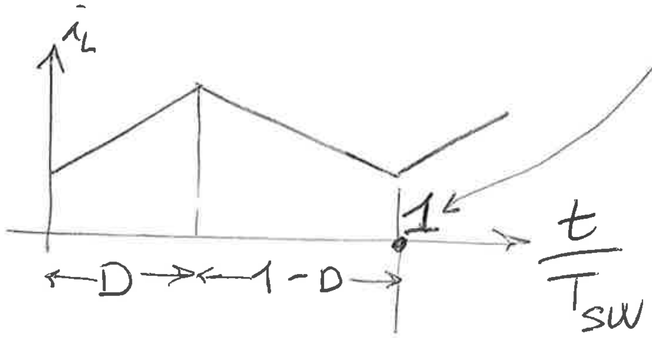




This is still a buck

This is the typical circuit to drive an electric DC motor

$$\frac{T_{ON}}{T_{SW}} = D \qquad \frac{T_{OFF}}{T_{SW}} = 1 - D$$



one cycle

strictly speaking D is dimensionless, in fact we change the time dimension

$$\frac{V_{IN} - V_{SW} - V_O}{L} D - \frac{V_O + V_D}{L}(1 - D) = 0$$

↳ We cannot avoid the inductor!
L can not be zero (mathematical answer)

$$V_{O_{real}} = (V_{in} - V_{SW}) D - V_D (1 - D)$$

V_O is always smaller than V_{in}

How much duty cycle I want to get the voltage I want?

$$D_{real} = \frac{V_O - V_D}{V_{in} - V_{SW} + V_D}$$

Nowadays 1,2 V for a processor, the numbers become important

Maddalena

2_1 10

$$\frac{\Delta V_o}{\Delta I_o} = \text{LOAD REGULATION}$$

$$V_o = V_{IN} \cdot D$$

$$\frac{\partial V_o}{\partial V_{in}} = D$$ audio susceptibility

$$\frac{\partial V_o}{\partial D} = V_{in}$$ gain, if the input voltage changes, the gain changes.

$$\frac{\partial V_o}{\partial I_o} = 0$$ if I don't consider any loss

$$\frac{V_o}{V_{in}} = M$$ for any converter

only for buck, $M = D$

for any converter $V_o = V_{in} \cdot M$

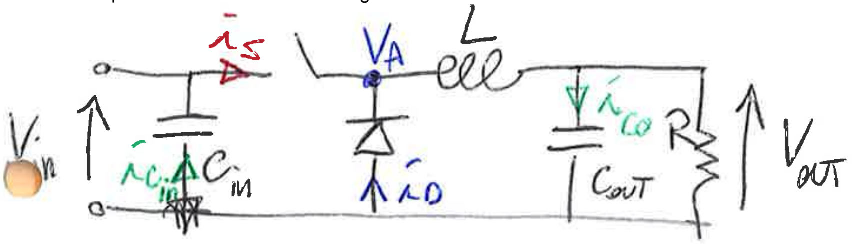
$$\frac{\partial V_o}{\partial V_{in}} = M$$ audio susceptibility

$$\frac{\partial V_o}{\partial I_o} = 0$$ wonderful, it looks like a voltage source

in CCM $\frac{\partial V_o}{\partial I_o} \simeq 0$, no matter what converter is

in DCM it becomes quite larger than 0.

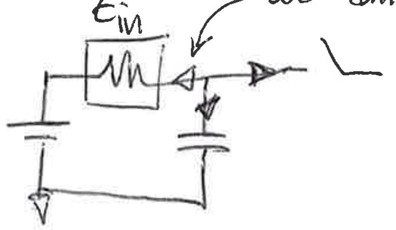
Maddaleno 2_2 (11)



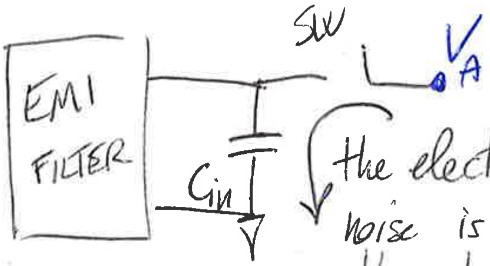
With a constant and ideal V_{in}, if C_{in} is charged (already), no current flows through C_{in}

No ideal V_{in} exists! So something always flows in the capacitor

we cannot inject things in V_{in}!



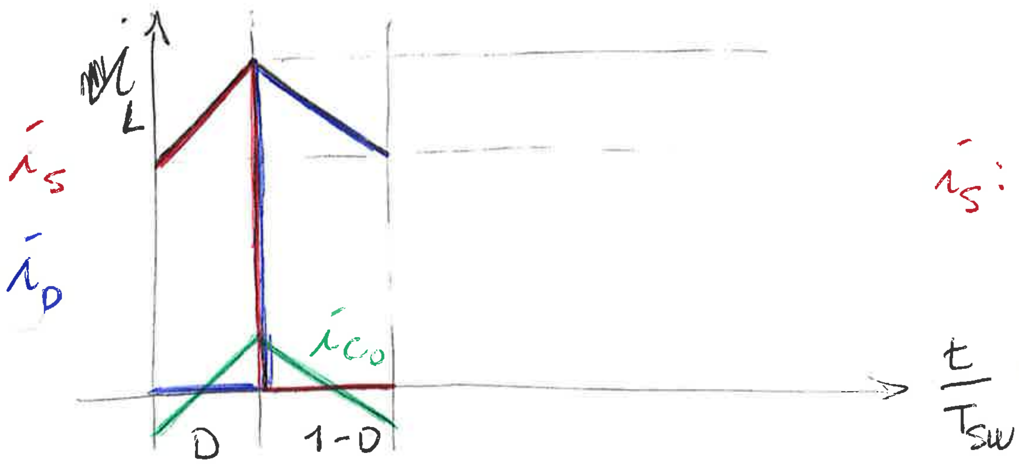
C_o is there to mantein small L (second order filter)



the electromagnetic noise is shorted through the capacitor

We even put an emi filter

We already draw two waveforms: $V_A(t)$, $i_L(t)$



during T_{ON},

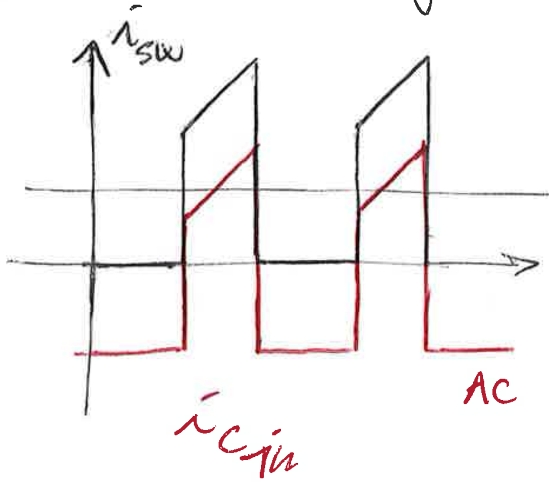
i_S: $i_S \simeq i_L$

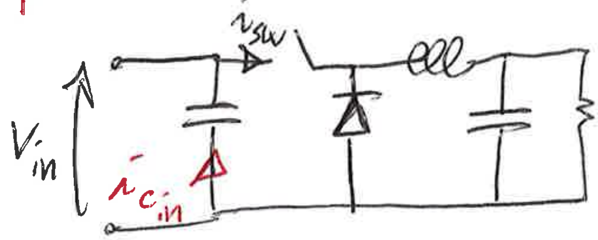
during T_{ON}, $i_D = 0$

i_D: during T_{OFF}, $i_D \simeq i_L$

The capacitor "steals" all the ripple. Maddalena 12

We apply the same reasoning for C_{in} 2-2

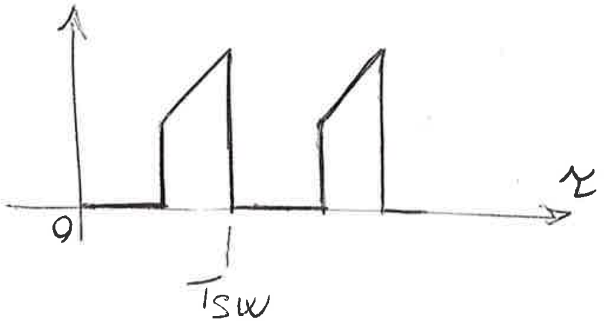




The output capacitor has a good life.

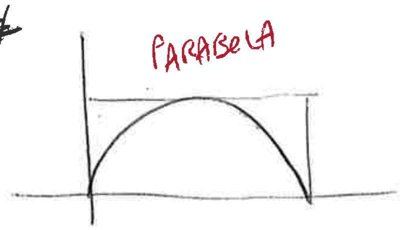
The input capacitor has a STRESSFULL LIFE: it has to substain high currents!

FIND THE AVERAGE VALUE OF A PERIODIC WAVEFORM



$$\tau = \frac{1}{T_{sw}} \int_0^{T_{sw}} i(\tau)\,d\tau$$

Let's find the area, spread it along one period



Area of the parabola: $\frac{2}{3}$ of the rectangle.

Maddaleno (13)

3_1

$$\Delta I_L = \frac{V_{in} - V_o}{L f_{sw}} D = -\frac{-V_o \, (1-D)}{L \; f_{sw}}$$

We will use $\Delta I_L = \frac{V_o}{L} \frac{(1-D)}{f_{sw}}$

- Attention: hypothesis!

No switch voltage (perfect one), no ripple, straight lines

$$I_{max} - I_{min} = \frac{V_o}{L f_{sw}} (1-D)$$

$$\frac{I_{max} + I_{min}}{2} = \frac{V_o}{R}$$

$$2 I_{max} = 2 \frac{V_o}{R} + \frac{V_o}{L f_{sw}} (1-D)$$

$$\boxed{\begin{aligned} I_{max} &= V_o \left(\frac{1}{R} + \frac{1}{2 L f_{sw}} (1-D) \right) \\ I_{min} &= V_o \left(\frac{1}{R} - \frac{1}{2 f_{sw} L} (1-D) \right) \end{aligned}}$$

peak current for the inductor!

$\frac{V_o}{R}$ is the output current!

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Maddalena 14

3_1

10 W 1 MHz → 300 kHz
it goes down a bit using
BJT or IGBT ~~[illegible]~~

100 W 500 kHz → 100 kHz

1 kW 100 kHz → 20 kHz

IT IS CONVENIENT TO USE A LARGER FREQUENCY TO USE A SMALLER INDUCTOR

$$L = \frac{(1-D)R}{2 f_{sw}}$$ for a buck converter

↓ CRITICAL INDUCTANCE

"Crinale" part of the mountain that divides water

CRITICA → DISTINGUO

R changes! Variable loads

$$D = \frac{V_o}{V_{in}}$$ ← the main can change, universal power supplies...

$$\frac{V_o}{V_{in\,max}} < D < \frac{V_o}{V_{in\,min}}$$

To STAY IN CCM!

$I_{min} > 0$

Worst case: $$\frac{V_o}{R} - \frac{V_o(1-D)}{2 f_{sw} L} > 0$$

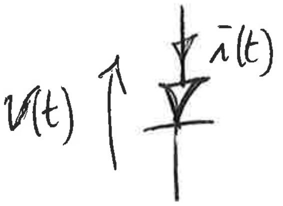
↓ R is maximum and D is minimum

Maddalena (15)

3-2

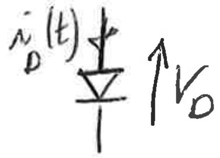
$\overline{p(t)} = \overline{v(t)\,i(t)}$ WHICH IS <u>NOT</u> $\overline{v(t)}\;\overline{i(t)}$

$$P_{AVE} = \frac{1}{T_{SW}} \int_0^{T_{SW}} v(t)\,i(t)\,dt$$



$v(t)$ is almost constant
(order of magnitude $\sim 1\,V$)
for power diodes.
schottky in signal domain, $\sim 0{,}1\,V$
in power electronics $\sim 0{,}5\,V$
Si-Carbide, $\sim$ very fast but $\sim 2\,V$

BJT, IGBT, $V_{CE_{sat}}$ is almost constant



$$P_{AVE} = \frac{1}{T_{SW}} V_D \int_0^{T_{SW}} i_D(t)\,dt = V_D\, I_{AVERAGE}$$

$$P_{AVE} = \frac{1}{T_{SW}} \int_0^{T_{SW}} v(t)\,i(t)\,dt = \frac{1}{T_{SW}} \int_0^{T_{SW}} R\,i^2(t)\,dt$$

$$P_{AVE} = R\, I_{RMS}^2 \qquad RMS(x) = \sqrt{\int x^2}$$

$\boxed{\text{There is no RMS power}}$

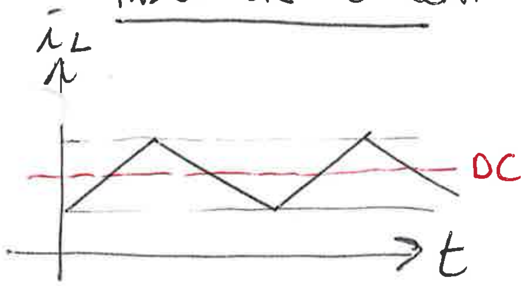
RMS power is meaningless, W_{RMS} does not exist

What is important is the average power

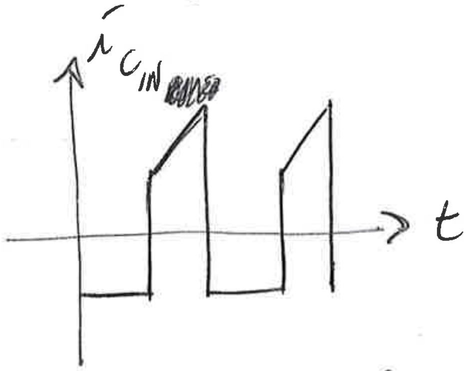
Maddalene (16)

3_2

INDUCTOR CURRENT



INPUT CAPACITOR CURRENT



$i_{L_{RMS}}$: this tell me the stress on the wire and how much power I loose.

$i_{C_{IN\,RMS}}$ is what stresses the capacitor, very important

A SORT OF KCL FOR RMS

$$i(t) = I_{DC} + i_{AC}(t)$$

$$\overline{i_{AC}(t)} = 0$$ the AC component has average 0

$$RMS\left(i(t)\right)^2 = \frac{1}{T_{SW}}\int_0^{T_{SW}} \left(I_{DC} + i_{AC}(t)\right)^2 dt =$$

$$= \frac{1}{T_{SW}}\int_0^{T_{SW}} I_{DC}^2\, dt + \underbrace{\frac{1}{T_{SW}}\int_0^{T_{SW}} 2 I_{DC}\, i_{AC}(t)\, dt}_{\text{zero because we have the average of } i_{AC}} + \frac{1}{T_{SW}}\int_0^{T_{SW}} i_{AC}^2(t)\, dt$$

$$RMS\left(i(t)\right)^2 = I_{DC}^2 + I_{AC_{RMS}}^2$$ that's a sort of KCL

$$I_{\substack{TOTAL\\AC+DC\\RMS}}^2 = I_{DC}^2 + I_{AC_{RMS}}^2$$

for a capacitor, we have no DC component

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$$I^2_{AC_{RMS}} = \frac{\Delta I_L^2}{12}$$

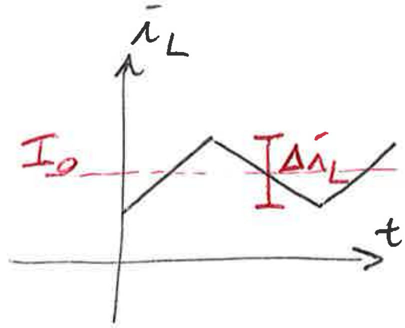
Maddalena (17)

3_3

$$I^2_{\substack{TOTAL\\AC+DC\\RMS}} = I^2_{DC} + I^2_{AC_{RMS}}$$

We are "adding two powers" but there is not a resistance...

in the Hilbert space they are orthogonal



So we have

$$I^2_{L_{RMS}} = I_0^2 + \frac{\Delta i_L^2}{12}$$

$$I_{L_{RMS}} = \sqrt{I_0^2 + \frac{\Delta i_L^2}{12}}$$

this is what makes the wire hot

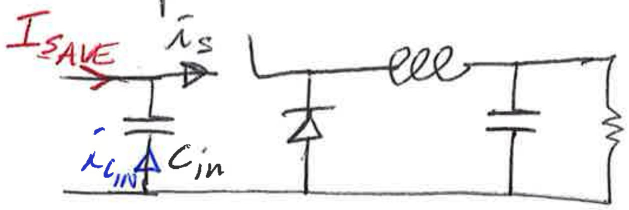
Only one assumption made: all the AC component in the capacitor.

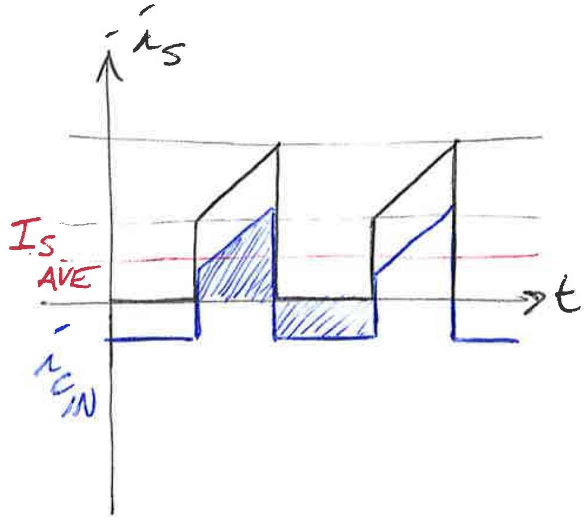
IN CASE OF CCM, $\frac{\Delta i_L}{12}$ IS NEGLIGIBLE

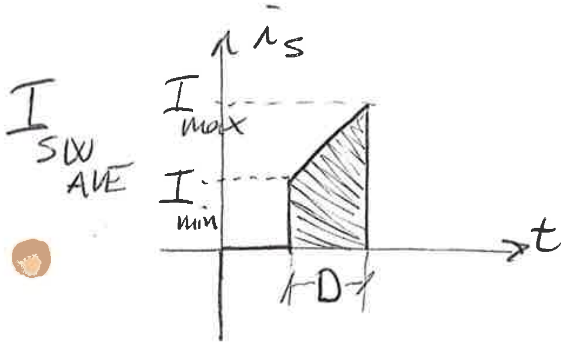
Maddalena 3-3 (18)

Buck, CCM: $I_{L_{RMS}} \simeq I_{L_{AVERAGE}}$

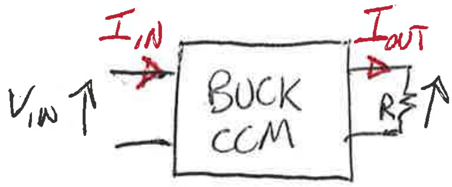
Input:







$$I_{SW_{AVE}} = \frac{I_{min} + I_{max}}{2} D = I_o D = I_{IN}$$



$V_{OUT} = V_{IN} D$ (no lossess)

$I_{IN} = I_o D$ $\qquad$ $I_o = I_{IN} \frac{1}{D}$ this is a transformer equation

$$V_o I_o = V_{IN} I_{IN}$$

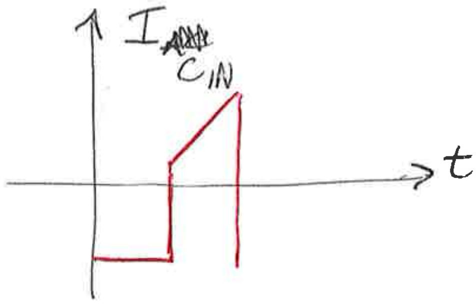
$P_o = P_{IN}$ $\qquad$ but this is not true because we have losses.

Any converter looks like a DC transformer

Maddalena

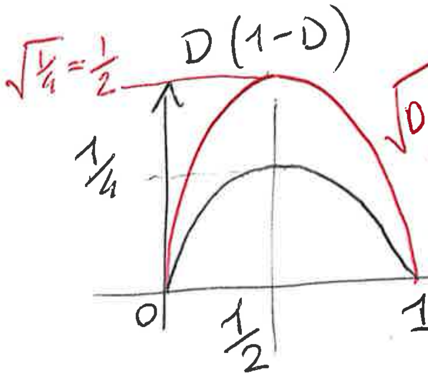
3_3 (19)

$I_{AC_{RMS}\,C_{IN}}$



$$I_{AC_{RMS}\,C_{IN}} = \sqrt{I_{TOT_{RMS}}^2 - I_{DC}^2} = \sqrt{I_o^2 D - I_o^2 D^2} =$$

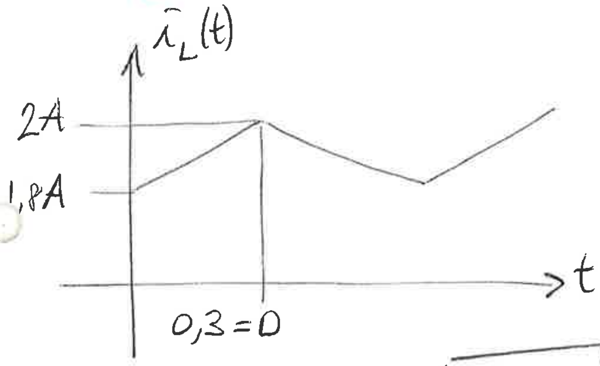
$$I_{TOT_{RMS}} = I_{SW_{RMS}} = I_o\sqrt{D}$$



$\sqrt{D(1-D)}$ is not a parabola anymore, it's like a panettone

$$I_{AC_{RMS}\,C_{IN}} = I_o\sqrt{D - D^2}$$

VERY STRONG RMS STRESS



$$\Delta i_L = 0{,}2A$$

$$I_{C_{OUT}\,RMS} = \frac{\Delta i_L}{\sqrt{12}} = 57{,}735\ mA$$

$$I_{C_{in}\,RMS} \cong I_o\sqrt{D - D^2} \simeq \frac{1}{2} I_o \cong 0{,}95A$$

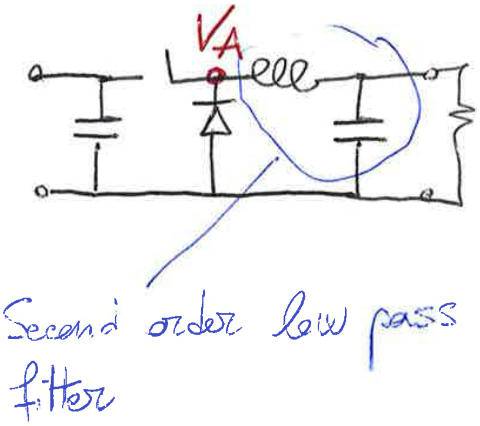
TOTALLY IN DIFFERENT CONDITIONS

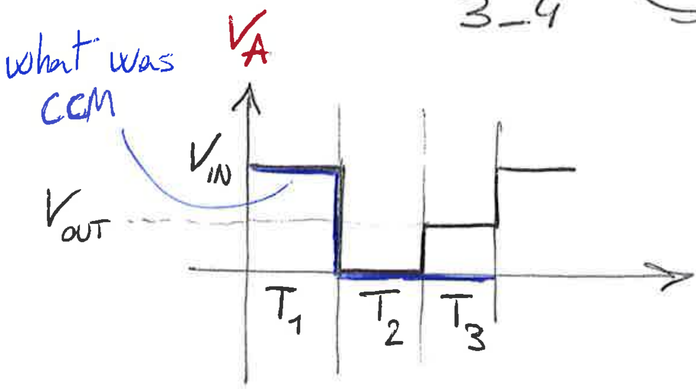
$$I_{C_{IN}\,RMS} = 1{,}9A\sqrt{0{,}3 \cdot 0{,}7} = 870{,}689\ mA$$

C_{IN} has to work at high frequencies and high currents

Maddaleno 3_4

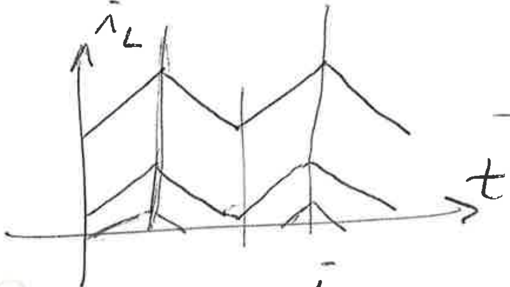
20

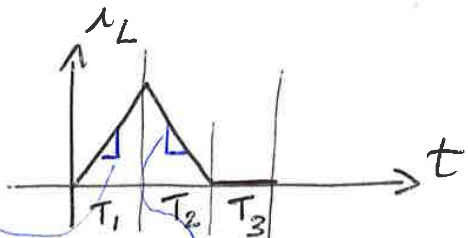




The DCM waveform has an "extra" and so a larger average value, so the output voltage will be larger.

If the load is very light the CCM i_L waveforms translates down until it reaches the boundary between CCM and DCM





$$\frac{V_{IN}-V_0}{L}T_1 + \left(\frac{-V_0}{L}T_2\right) = 0$$

$$\frac{V_0}{V_{IN}} = \frac{T_1}{T_1+T_2} \longrightarrow \text{IS NOT } T_{SW}\,!$$

We need a second equation because we don't know T_2

DCM BUCK

Maddaleno (21)

4_1

$$\frac{1}{R} = \frac{D^2}{2 f_{sw} L} \cdot \alpha (\alpha - 1)$$

$$\alpha = \frac{1}{M} = \frac{V_{IN}}{V_{OUT}}$$

$$\frac{D^2 R}{2 f_{sw} L} \cdot \alpha (\alpha - 1) - 1 = 0$$

$$\alpha^2 - \alpha - \frac{2 f_{sw} L}{D^2 R} = 0$$

We are looking for $\alpha = \frac{V_{IN}}{V_{OUT}}$

Good I can choose f_{sw} and L

Good I can impose D

But... R? BAD NEWS THIS IS NOT AN "IDEAL" VOLTAGE SOURCE

$$\alpha = \frac{1 \pm \sqrt{1 + \frac{8 f_{sw} L}{D^2 R}}}{2} = \frac{V_{IN}}{V_{OUT}}$$

$$M_{\substack{BUCK \\ DCM}} = \frac{2}{1 + \sqrt{1 + \frac{8 f_{sw} L}{D^2 R}}} = \frac{V_{OUT}}{V_{IN}} = \frac{1}{\alpha}$$

If D goes to 0, $V_{OUT} = 0$

V_{OUT} IS ALWAYS LESS THAN V_{IN} (the square ~~[illegible]~~ root has $1 +$ something inside)

Maddaleno 4_1 (22)

"Possible" advantage of DCM

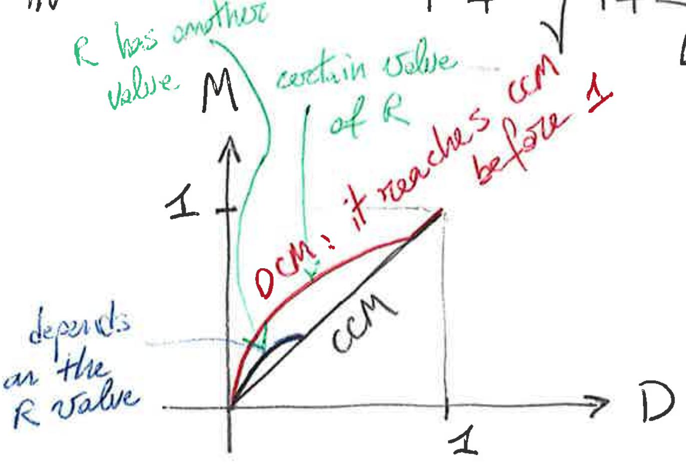
in CCM, $L_{CCM} > \dfrac{R_{MAX}(1-D_{MIN})}{2 f_{SW}}$

in DCM, $L_{DCM} < \dfrac{R_{MIN}(1-D_{MAX})}{2 f_{SW}}$

$L_{DCM} < L_{CCM}$ but a larger peak and rms current! It's not a real advantage.

There are cases when we are forced to work in DCM, for control reasons.

$$\frac{V_{OUT}}{V_{IN}} = M_{DCM} = \frac{1}{1+\sqrt{1+\frac{8 f_{SW} L}{D^2 R}}}$$



in CCM, $M = D$

Usually, $M_{CCM} \leq M_{DCM}$ but there is a value of D where they join

mancano il min alla fine della 4_1

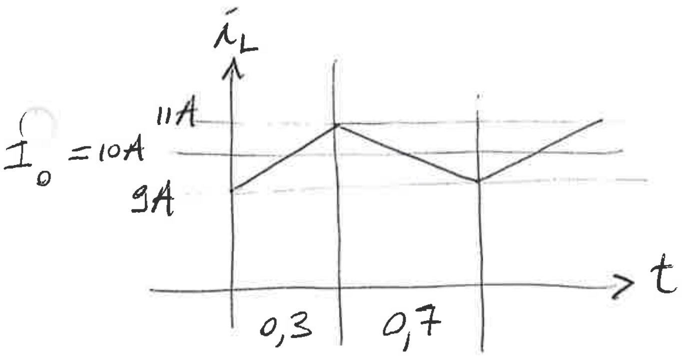
$L_{CRIT} = \dfrac{R(1-D)}{2 f_{SW}}$ value which separates CCM and DCM

Schematic changes, BUCK

Maddalena (23)

4_2

$$D = \frac{1V}{3{,}3V} = 0{,}3$$ ... maybe not. the voltage across the diode starts to be important.



What's the voltage drop across the diode? 0,5 V with a Schottky. The diode dissipates $0{,}5V \cdot 10A = 5W$

It's just an approximation!

Across the transistor switch we will have something like 0,1 V, $\simeq 1W$

The efficiency is low! Main loss on the diode.

And it's a good diode!

We need a different component. There are no diodes with a voltage drop of 0,1 V...

Maddalena 4_2 24

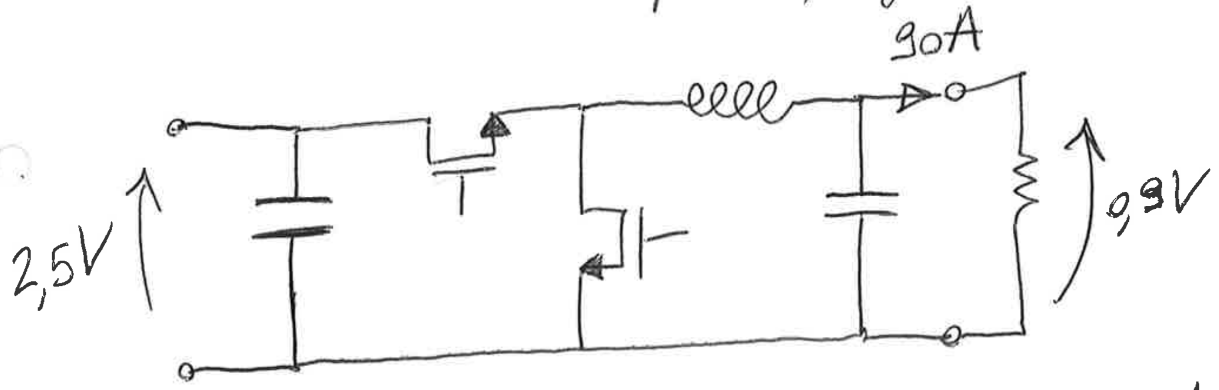
But 10A are not a lot

from 2,5V to 0,9V

$D = \frac{0,9V}{2,5V} = 0,36$

BUT $90A = I_{OUT}$

not a good idea to put 2-3 MOS transistor in parallel, they can oscillate and explode. It is possible, doing it.



Ok we can find MOS which can reach 90A

but C_{IN}? It has to resist 45 A

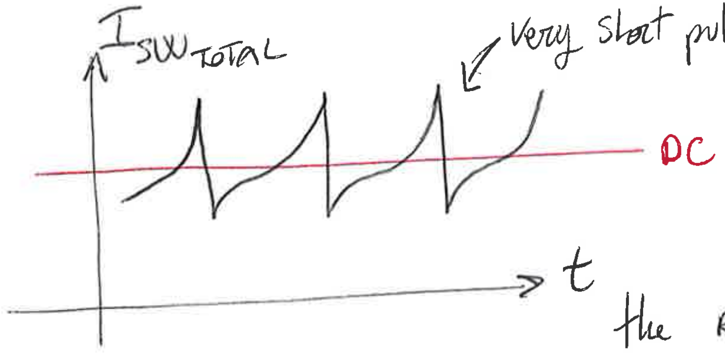
the inductor substains 90A!

DIVIDE ET IMPERA

We make 3 converters, 30A each, in parallel

But there is another idea... it works well with fixed voltages

Maddalena 4_2 (25)



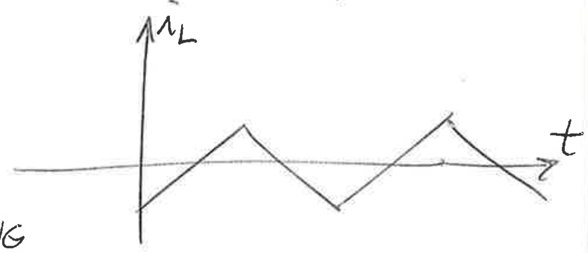
Very small pulses, the RMS current in the capacitor C_{IN} is very reduced

The output capacitors sees three triangular waveforms shifted by $\frac{1}{3}$ in phase ($\frac{1}{3}$ of a cycle) and the total ripple goes down a lot
Different channels on the motherboards

MULTI PHASE : low voltage, very high current

SYNCHRONOUS BUCK with a 5_1

load that increases : it remains in CCM, but i_L becomes negative



if I_o is very low, in some cases they switch off EVERYTHING to don't waste power

BURST MODE

Maddalena 5_1 (26)

To stay in CCM,

$$f_{SW} = 200 \text{ KHz}$$

$$L > \frac{(1 - D_{MIN}) R_{MAX}}{2 f_{SW}}$$

$$D \simeq \frac{V_0}{V_{IN}}$$ it is just an approximation because we are not considering losses.

$$D_{MIN} = \frac{V_0}{V_{IN_{MAX}}} = \frac{12V}{28V} \cong 0{,}43$$ including losses

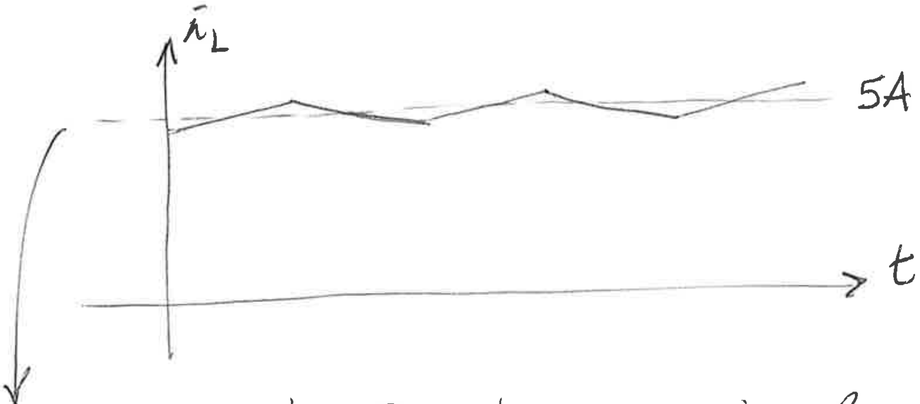
the duty cycle goes up.

$$R_{MAX} = \frac{V_0}{I_{o_{Min}}} = \frac{12V}{0{,}5A} = 24\,\Omega$$

if the minimum current was 50 mA : the inductor goes up by a factor of 10.

With $I_{min} = 0A$, we jump to DCM

Reasonable interval?



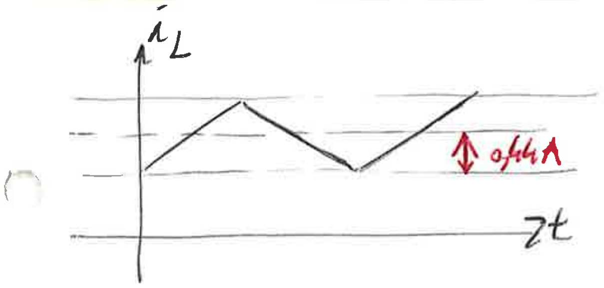
with a small ripple I need an expensive, large inductor because $I_{O_{min}}$ can be VERY LOW

Good choice : 10-15 % of the output current as ripple.

too large and the stress will be too high

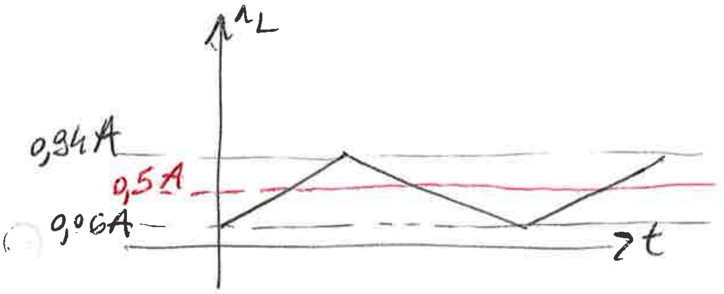
Maddalena
5_1

(27)



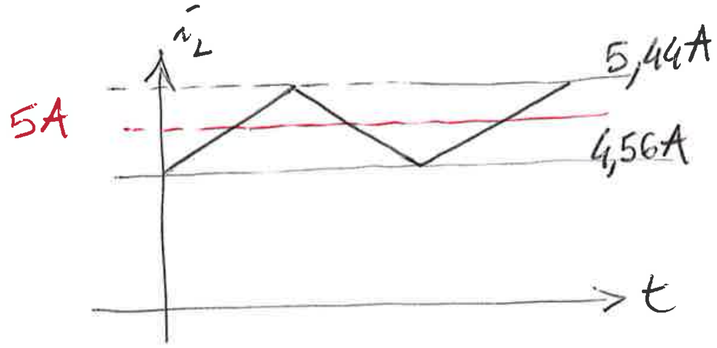
What happens when I_o decreases to 0,5 A?

The ripple stays the same: $\Delta i_L = \frac{V_o}{L} \frac{(1-D)}{f_{sw}}$



good, we stay in CCM
just a check

What's the maximum peak value?



max I_{OUT}
max ripple

The only component value that we guess from this part is the INDUCTOR.
From this point we think about stresses.

$L = 39\,\mu H$ We think about $I_{peak} = I_{pk_L}$
because we don't want the inductor to saturate

$I_{pk_L} \triangleq 5,5 A$

We need $I_{L_{RMS}}$, important for resistive losses and power dissipation. $I_{L_{RMS}} = 5 A$

Maddalena 5_2

28

We don't need it, but let's calculate the rms using the flattop approximation

$$I_{D_{RMS}} = I_o \sqrt{1-D} = 5A \sqrt{1-0{,}43} = 3{,}77A$$

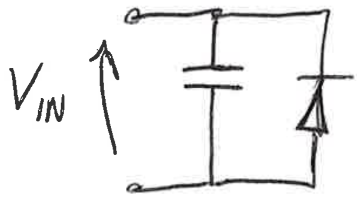
only for HIGH current diodes (1 MW converters) the internal resistance becomes important

$$\overline{I_D} = 2{,}85A, \quad I_{PK_D} = 5{,}44A$$

What's the maximum voltage in reverse bias?

The input voltage

$V_{max} = 28V$



but we take a 40V diode...

... in a car, truck, BIG overvoltages, 50-60V

So: $\overline{I_D} = 2{,}85A$, $I_{PK} = 5{,}44A$

$$V_{D_R} = 40V$$

Now we can estimate the dissipated power

The voltage in conduction is almost constant

Across a Schottky, $\simeq 0{,}5V$

$$P_D = 0{,}5V \cdot \overline{I_D} = 0{,}5V \cdot 2{,}85A \cong 1{,}5W$$

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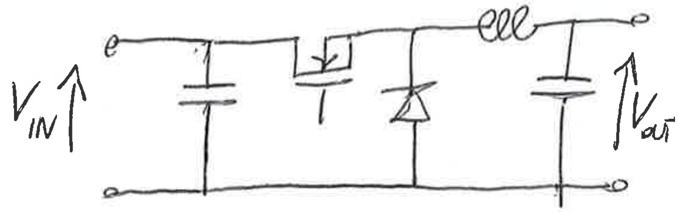
Maddalena 5_2 (29)

The average current through the switch is coming from the input, so I can find the input power



If the V_{input} changes, $I_{AVE_{SW}}$ changes too because the D changes.

Power dissipated on the MOS:

attention: we find the dissipated power on the diode with $I_{D_{AVE}} = I_0 (1 - D_{MIN})$

so using D_{MIN}

but for the MOS we think about I_{RMS} and D_{MAX}

$$I_{RMS_{MOS}} = 3{,}82\,A = I_0 \sqrt{D_{MAX}} \simeq 3{,}9\,A$$

maximum voltage across the MOS: when it is open

$$V_{DS_{max}} = V_{IN} - (-V_0) \simeq 29\,V$$

we need to ~~pike~~ pick a highter value.

the capacitor C_{IN} acts a bit as a protection against spikes. A bit.

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We could choose a VERY LOW small $r_{DS_{ON}}$ transistor. But we have disadvantages

1) Big package, which is more expensive (we need more Si area)

2) The bigger Si area means a bigger capacitance to charge and discharge.
We need a strong driver.

$$r_{DS_{ON}} = \frac{V_{DS_{ON}}}{I_{D_{MAX}}} = \frac{0{,}2\,V}{5{,}4\,A} = \boxed{37\ m\Omega}$$

HOT, NOT COLD AS DECLARED

if not limited by package, it surely can substain large currents.

A car with 60 hp = 44,74 kW

$r_{DS_{ON}}\Big|_{@ 25\,°C}$

PAY ATTENTION, IT WILL BE AT 80 °C NOT 25 °C

We will need 37 mΩ as an HOT resistance!

~~The~~ The hot resistance can be 1,7 X larger, it's a function of temperature

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INPUT CAPACITOR

Maddalena 5_3 (31)

- Working voltage : $> V_{IN}$

The minimum that we find is

Charles 1870 Renard

R5 : 10, 16, 25, 40, 63 — five values in a decade

R from a french capitain of the army

We choose 40 V

If the temperature goes up, the working voltage goes down

ALWAYS ~~REMEMB~~ REMEMBER THE RMS CURRENT

$$I_{C_{IN}\,RMS} = I_o \sqrt{D(1-D)}$$ approximation

if it reaches $0{,}5 = D$, use the maximum

when $D = 0{,}5$,

$$\boxed{I_{C_{IN}\,RMS} \simeq \frac{I_o}{2} = 2{,}5\ A \quad \text{real high stress}}$$

BAD news: in power electronics capacitance is not importance.

The larger is C, usually the smaller is the impedance.

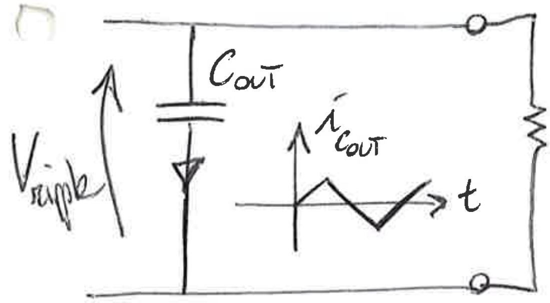
The input capacitor keeps the peaks inside

WE NEED the EMI FILTER

Ripple voltage

Maddaleno
5_3

32



What's the voltage across the capacitor?

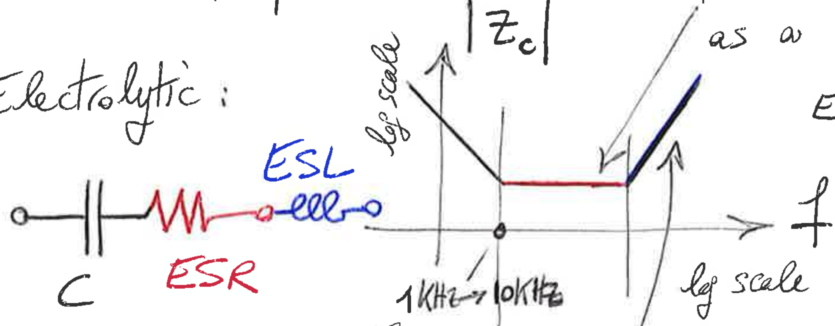
We could use $\Delta i_L \frac{1}{sC} = V$

but here we can avoid Laplace transforms.

$\frac{1}{sC}$: this is an ideal capacitor. It does not exists.

Two kind of parasitics:

Electrolytic:



from a certain frequency it acts as a resistance,

ESR = Equivalente Series Resistance

from another frequency it acts as an inductor

We can get 500 Hz! Bad!

10 KHz is optimistic

Tantalium capacitors: they have small working voltages but they act as capacitors up to 10 KHz → 50 KHz

OSCON: Brand name, up to 20 KHz

The armonics at 200 KHz see the ESR!

Maddalena 5_4 33

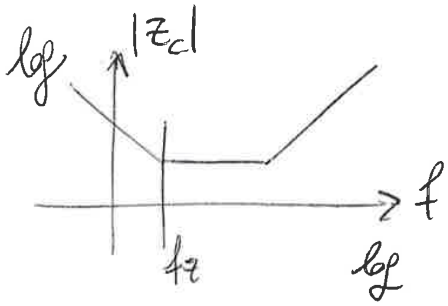
$$f_{z_{ESR}} = \frac{1}{2\pi C \cdot ESR}$$

We need something like

$$C = \frac{1}{2\pi f_z ESR}$$

ESR = 110 mΩ

We can estimate that



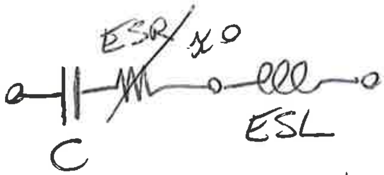
We guess f_z, from 1 KHz to 10 KHz

$$C = \frac{1}{2\pi \cdot 110 m\Omega \cdot 3 KHz} = 482 \mu F$$

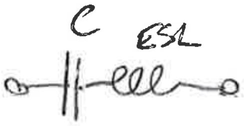
We need this value to design the control

CERAMIC AND FILM CAPACITOR

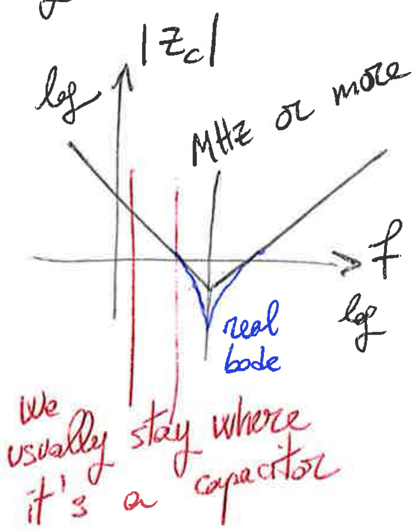
They have an ESR, but it's so small that it goes to 0.



but they have an ESL



resonant circuit



Maddalena 34
6_1

BOOST (STEP UP) $\frac{V_o}{V_{IN}} \geq 1$

Controlling a boost converter is not trivial.

IN MANY CASES, EXPECIALLY FOR HIGH POWER, we use other topologies.

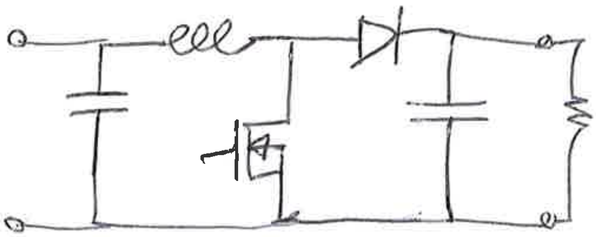
They have very specific field of application.

Mp3 players with 1,5 V ~~...~~ battery

not part of the boost. It is there to do not inject noise into V_{IN}

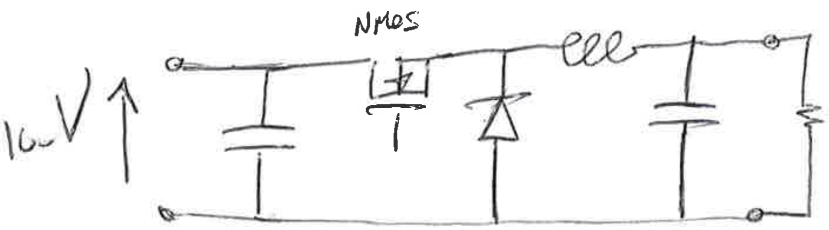
this is part of the boost. Not like the buck, where it was there to behave like a filter

The current through L is very smooth.
In a buck, a pulsed overvoltage of V_{IN} could kill the switch or the diode. Here L protects the switches of the circuit.



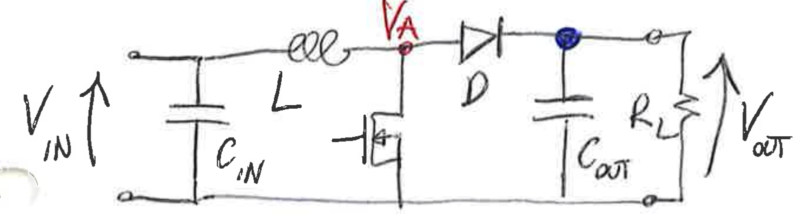
Low side switch, while in the buck it was an high side switch, more complicated and expensive to drive.

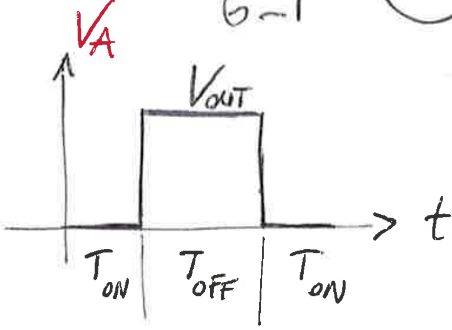
BUCK:



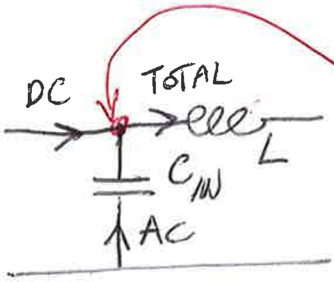
here we need to drive the mos ~~...~~ ~~...~~ putting the gate ~~...~~ at $\simeq$ 110 V from 0V, and 110V is more positive than the input voltage

Maddalena 6-1 (35)



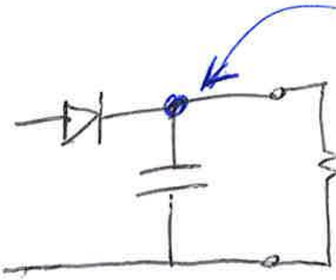


The RMS current through the inductor is more or less equal to the average current through the inductor itself, if we are in CCM. $I_{L_{RMS}} \simeq I_{L_{AVE}} \doteq I_{L_{DC}}$

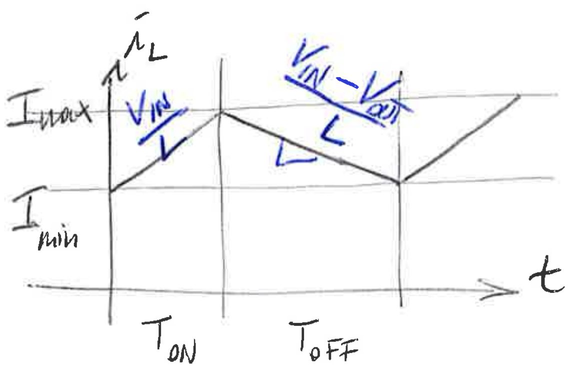


here there is just a ripple, it is not pulsating. We cannot use quadratic KCL because we have ~~[illegible]~~ a very large cancellation error.

That's because the currents are very similar



here instead there is a pulsing current, so we can use quadratic KCL



We can find $\frac{V_{OUT}}{V_{IN}} = M$ in CCM

CCM, ideal components:

$$\frac{V_{IN}}{\cancel{L}} T_{ON} + \frac{V_{IN}-V_0}{\cancel{L}} T_{off} = 0$$

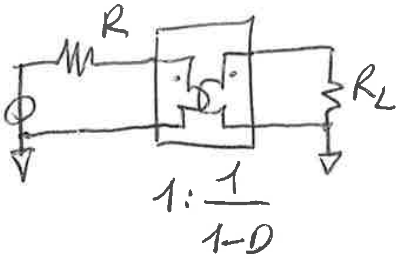
we can't eliminate L! without an inductance closing the MOS we short the input!

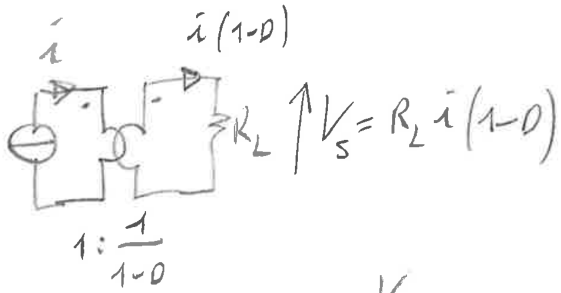
Limite all'M del boost

INSERTO

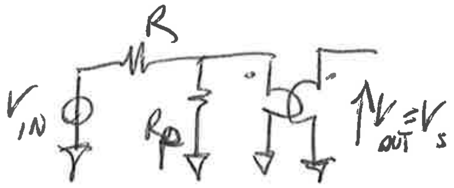
$$\left.\frac{V_0}{V_{IN}}\right|_{boost} = M = \frac{1}{1-D}$$

Ma anche solo considerando la R parassita dell'induttore...





$$V_p = V_s (1-D) = R_L\, i (1-D)^2 \qquad R_p = \frac{V_p}{i} = R_L (1-D)^2$$



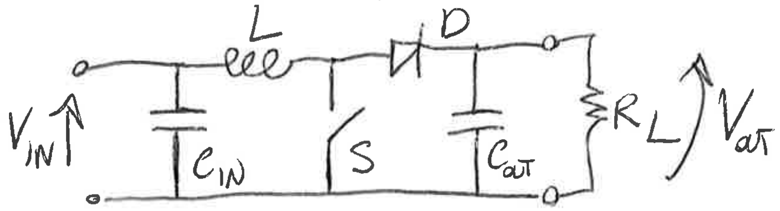
$$V_p = V_{IN} \frac{R_p}{R + R_p} = V_{IN} \frac{R_L (1-D)^2}{R + R_L (1-D)^2}$$

$$V_s = V_p \frac{1}{1-D} = V_{IN} R_L \frac{(1-D)}{R + R_L (1-D)^2} = V_{OUT}$$

Quindi ottengo

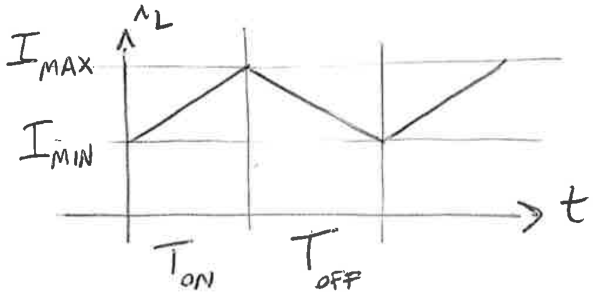
$$\frac{V_0}{V_{IN}} = M = \frac{R_L (1-D)}{R + R_L (1-D)^2} \quad \text{anziché} \quad \frac{V_0}{V_I} = \frac{1}{1-D}$$

che per $R_L \to \infty$ tende a $\frac{1}{1-D}$ quindi se la corrente di uscita è molto bassa...



Flash in cameras: we can't go up from 3V to 300V with a boost.

Defibrillator: ~6 KV, the current is 20 A

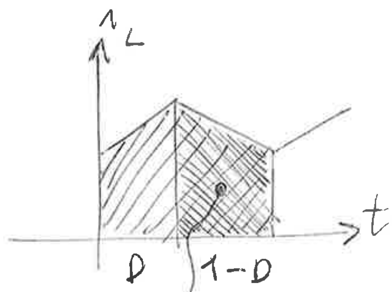


To guarantee CCM, $I_{MIN} > 0$

Unfortunately, we have to design them in DCM to control them.

$$\frac{I_{MAX} + I_{MIN}}{2} = I_{AVE_L} = I_{IN} \overset{\text{with 100\% efficiency}}{=} \frac{I_o}{1-D} = \frac{V_o}{R(1-D)}$$

bound between average current and output current



the total area is proportional to $\frac{I_o}{1-D}$

(I) $I_{IN} = \overline{I_{SW}} + \overline{I_D} = \overline{I_{SW}} + \frac{V_o}{R}$

(II) $I_{MAX} - I_{MIN} = \Delta i_L = \frac{V_{IN}}{L}\frac{D}{f_{SW}} =$

$$= \Delta i_L = \frac{D}{L f_{SW}}(1-D)V_{OUT}$$

Now we have two equations, we can add them

$$I_{MAX} = \frac{V_o}{R(1-D)} + \frac{D(1-D)V_o}{2 f_{SW} L}$$

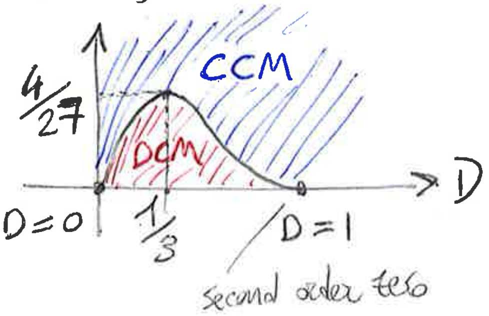
To stay in CCM:

$$L > \frac{D(1-D)^2 R_{MAX}}{2 f_{sw}}$$

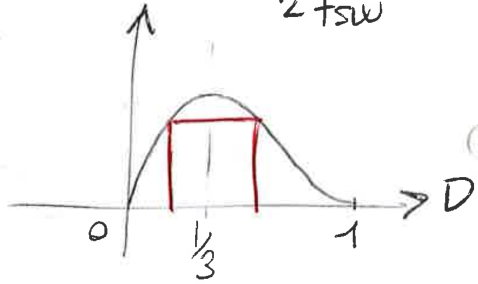
$$\frac{\partial}{\partial D}\left[D(1-D)^2\right] = (1-D)^2 + 2D(1-D)(-1)$$

$$3D^2 - 4D + 1 = 0 \qquad D_{1,2} = 1,\ \frac{1}{3}$$

$D(1-D)^2$

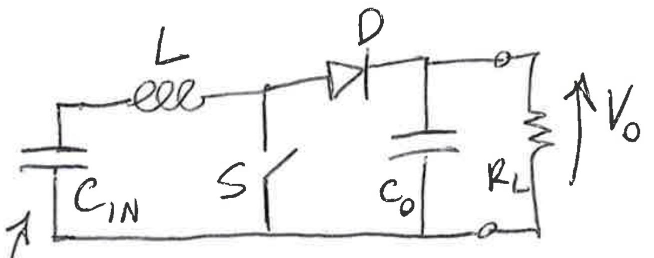


$$L = \frac{R D (1-D)^2}{2 f_{sw}}$$

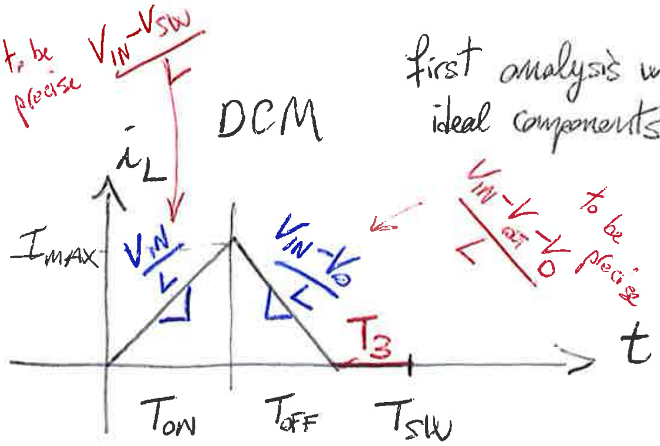


If the duty cycle moves:

DCM boost



it keeps the EMI noise inside the circuit



first analysis with ideal components

T_3, T_{IDLE}, during T_3 both sw and DIODE are open

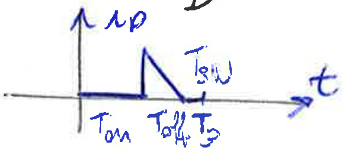
$$\frac{V_{IN}}{\cancel{L}} T_1 + \frac{V_{IN}-V_0}{\cancel{L}} T_2 = 0$$

$$V_{IN}(T_1+T_2) = V_0 T_2 \qquad M = \frac{V_0}{V_{IN}} = \frac{T_1+T_2}{T_2} = \frac{T_1}{T_2}+1$$

we need another equation because we don't know T_2.

Same of the buck converter, bound with $I_0 = \frac{V_0}{R_L}$

the DC component of I_D is equal to $\overline{I_0}$.

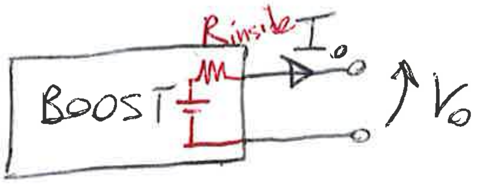


$$\frac{V_0}{R_L} = \text{average current through the diode} = \frac{1}{2}\, \underbrace{T_{OFF}}\, \underbrace{\frac{V_{IN}}{L} T_1} \cdot \frac{1}{T_{SW}}$$

D

area triangle $= \frac{1}{2} \cdot$ base $\cdot$ hight

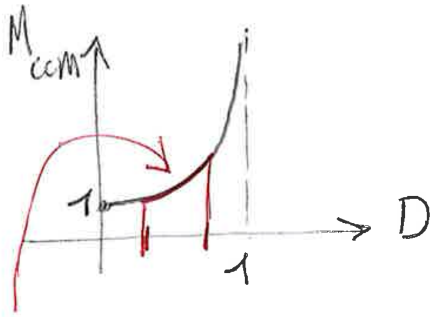
$$\frac{M}{R} = \frac{1}{2}\frac{D}{L} T_2 \qquad \text{from } M = 1+\frac{T_1}{T_2}, \quad T_2 = \frac{T_1}{M-1}$$



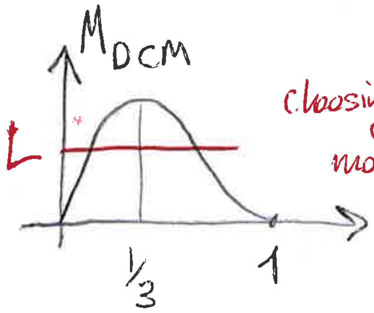
R_{inside} is a load but I'm using the source rule, so R_{inside} is negative

$$\frac{\partial V_o}{\partial D} = GAIN(V_{IN}, R, D, \dots)$$

life is bad



$$M_{CCM} = \frac{1}{1-D}$$



choosing this L I can move around CCM and DCM

IN DCM,

$$M = \frac{1 + \sqrt{1 + \frac{2RD^2}{f_{sw}L}}}{2}$$

this is much larger than 1

So it remains, neglecting the one,

constant slope

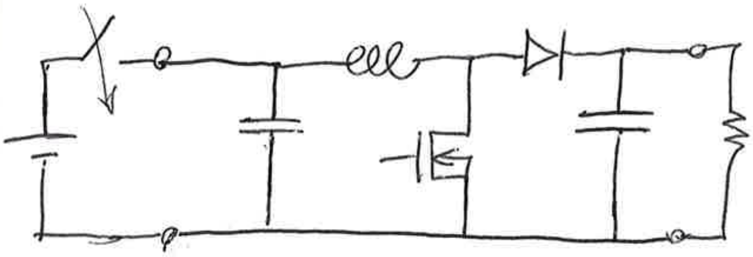
$$M \approx \frac{1}{2} + \frac{1}{2} D \sqrt{\frac{2R}{f_{sw}L}}$$

So

$$M = \frac{1 + \sqrt{1 + \frac{2RD^2}{f_{sw}L}}}{2}$$

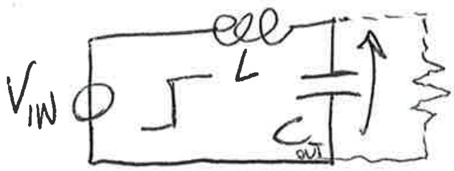
if $R \to \infty$, $M \to \infty$ if we disconnect the load the output voltage start to increase forever, KABOM

Some boards have a protection



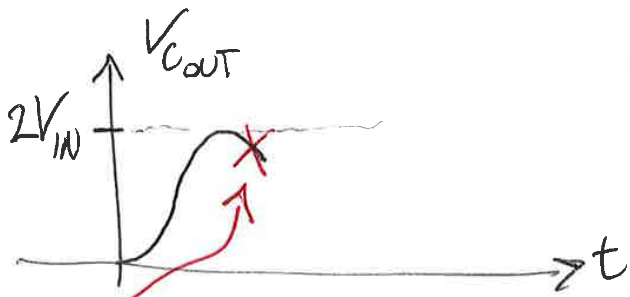
POWER ON

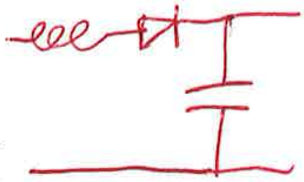
Inrush current in C_{IN}, but ok...



resonant circuit
what happens?

how big are the oscillation of the resonant circuit?



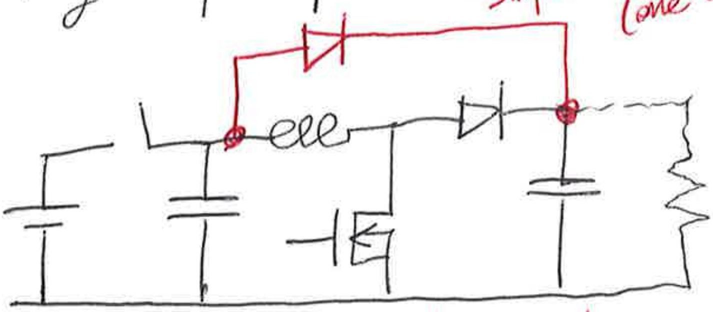


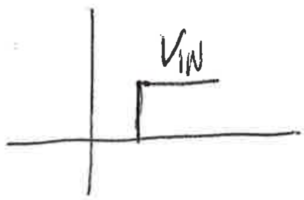
but in the real circuit we have a diode, the capacitor can't discharge back

If $V_{IN} = 330V$, and we want $V_{OUT} = 380V$,
THIS IS REALLY BAD, C_{OUT} WILL NOT STAND 660V DUE TO THE RESONANCE

How can we damp resonances? With resistors, but they dissipate power

Simple solution (one of them)



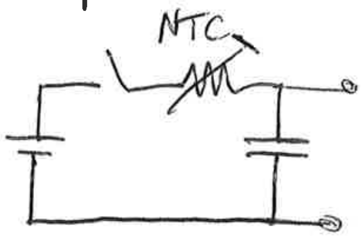


the current goes through the diode, no current in the resonant circuit.

we charge the output capacitor up to V_{IN}, that's fine.

OK for low power circuits.

We can put an NTC Negative Temperature Resistor 7_2

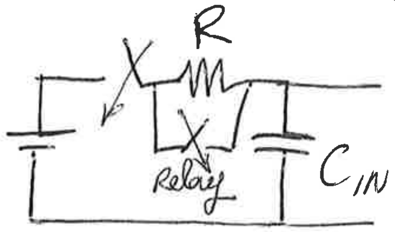


When it's hot the resistance greatly goes down (maybe from 20Ω to 0,1 Ω)

Hot is something like 150°C

Used ~~many~~ years ago in ~~laptops~~ desktops ... but if we switch it off and ~~off~~ on the NTC could still be hot. So Kaboom.

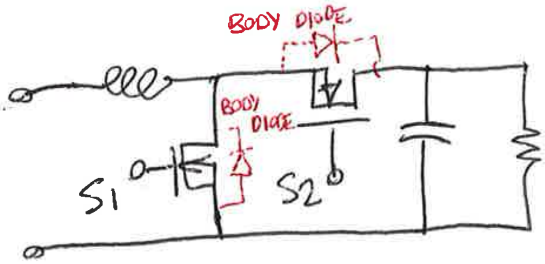
Another solution for large powers:



a timer circuit closes the relay some times after the ignition.

But the mechanical relay costs.

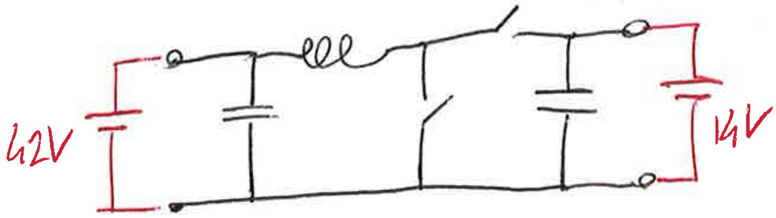
At home: 60 A limit, generally, but for a short time we can reach 100 A



SYNCHRONOUS BOOST

$S1 = \overline{S2}$

Not a great advantage as with low-voltage bucks, because we have generally an high output.

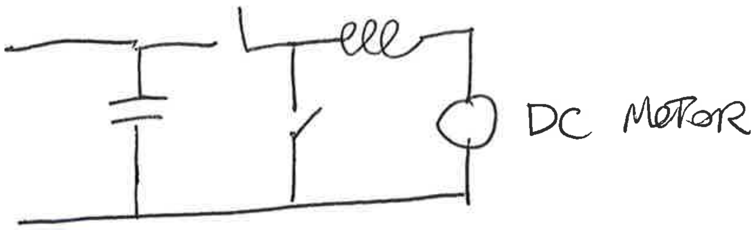


read from left to right: SYNCHRONOUS BOOST

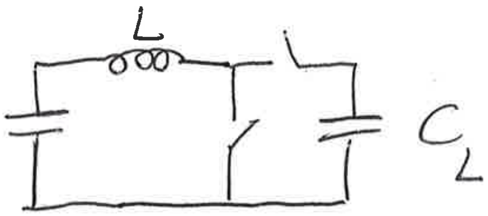
(read from right to left: SYNCHRONOUS BUCK

We can moove energy between batteries

When we need to recover energy

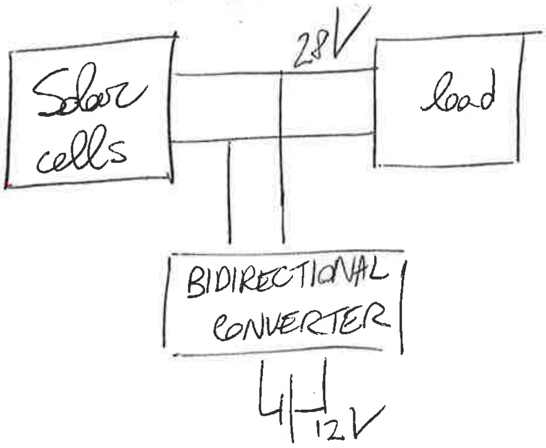


A DC motor could be used as a generator

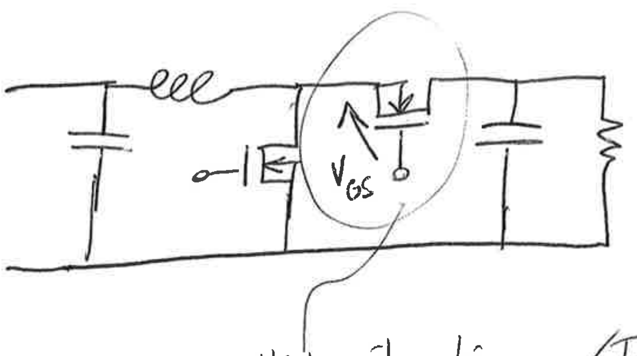


to much to boost from 12V to 200V, we use other methods

Satellites

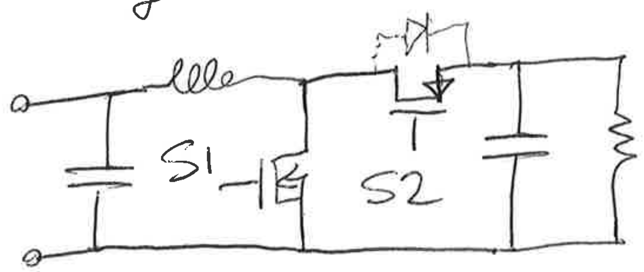


less mass using a bidirectional converter.



High side driver / Transformer

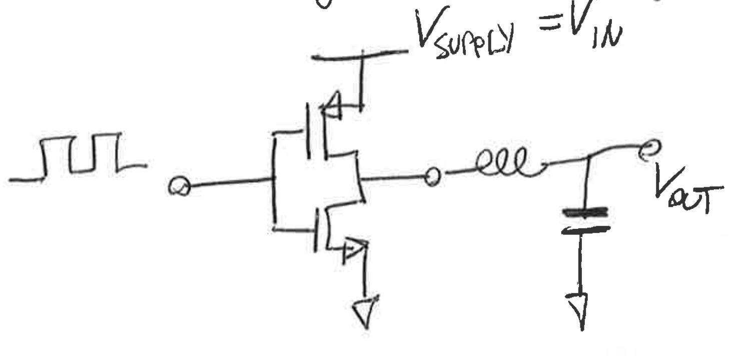
Using a PMOS instead:



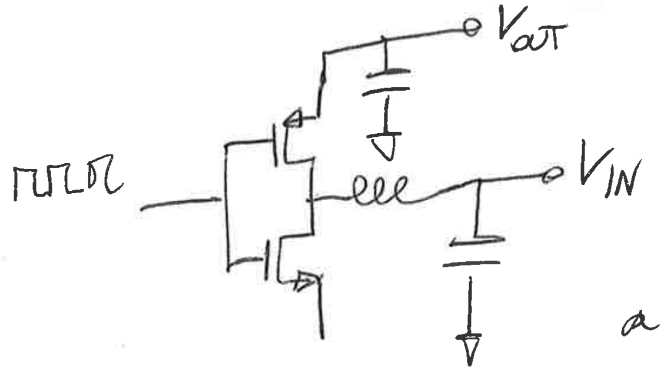
Same body diagram orientation high side, but to switch it on I need to put the gate down respect to the source

Sometimes, If lucky, we could drive the gates topheter.

BUT connecting the gates topheter is not a good idea:



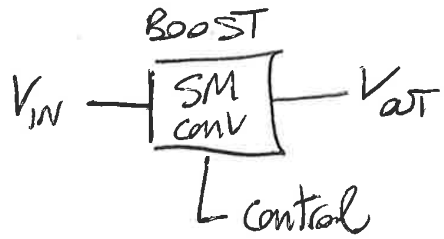
BUCK

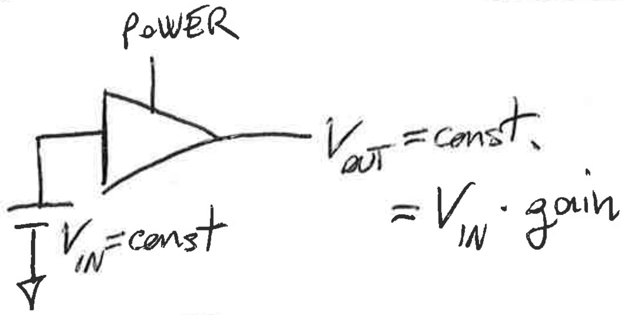


BOOST

During the switch phase for a period of time they both conduce (CROSS CONDUCTION / SHOOT THROUGH) which is loss of power

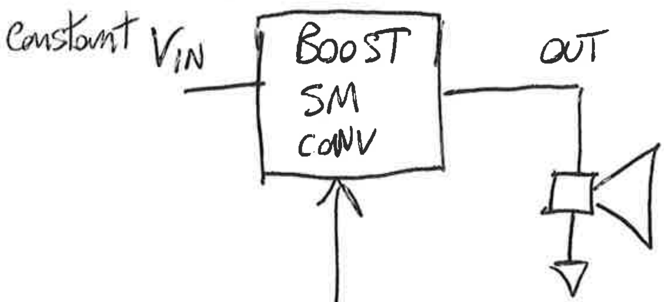
So we still need some delay





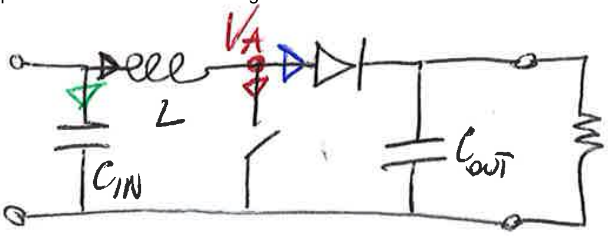
This is a power supply!

78XX ...



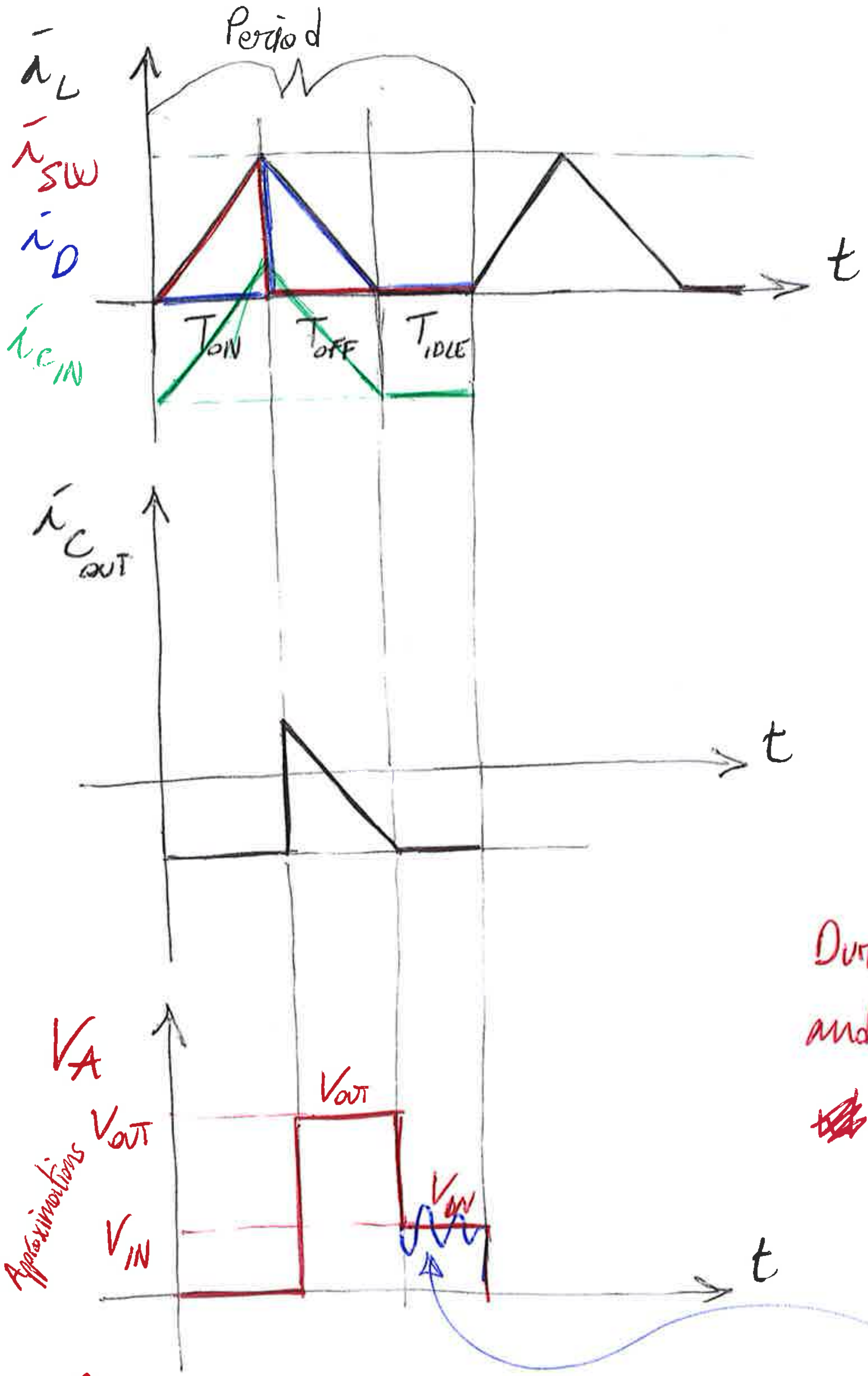
Class D amplifier

Control: duty changed, which is the "input signal"



DCM

What could change: f_{SW}, L, load, waveforms



During T_{IDLE} both SW and diode closed, so ~~we~~ we have $V_A = V_{IN}$

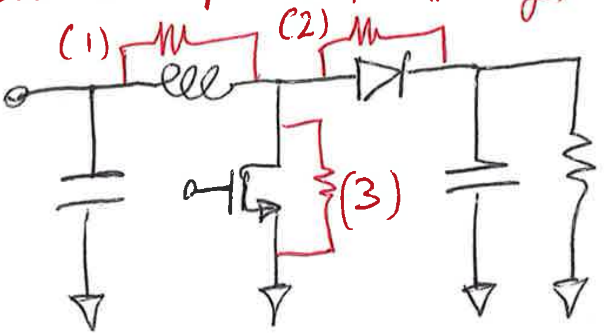
Supposed to be like this, BOOST DCM

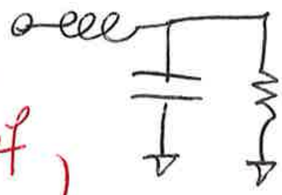
but we have RINGING

bad part: it generates electromagnetic noise, problems!
we want to DAMP IT

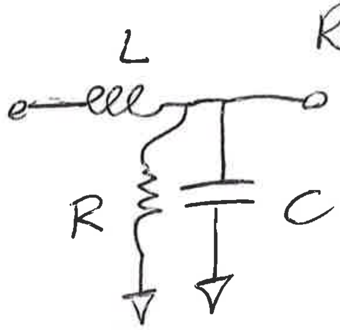
Then we will proceed.

We will put it, indifferently, in these positions: (only one of them)



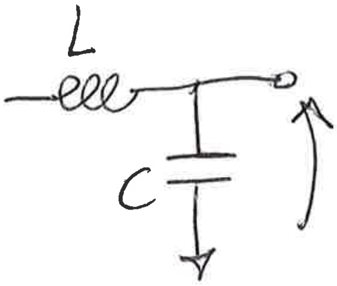


Resonant circuits



$$f_{RES} = \frac{1}{2\pi\sqrt{LC}}$$

Characteristic impedance $Z_0 = \sqrt{\frac{L}{C}}$



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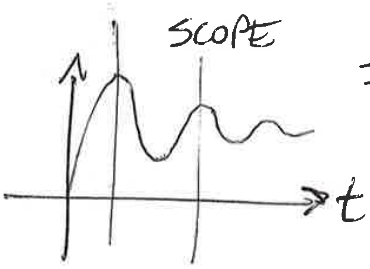
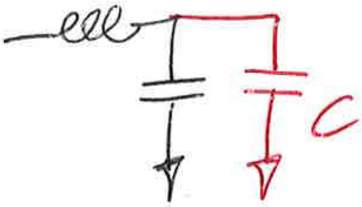


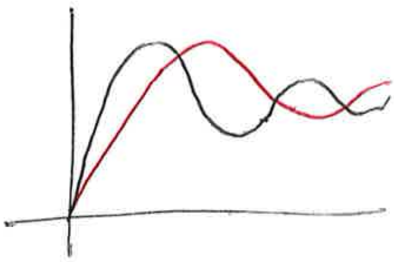
$$f_{MEASURED} = \frac{1}{2\pi\sqrt{LC}}$$

OK from the scope we obtain $f_{MEASURED}$, but we miss L AND C. We need a second equation, obtained like this:

We phisically put a known hardware capacitor

A small one! when the SW/DIODE closes it has to discharge it!





f_{RES} changes!

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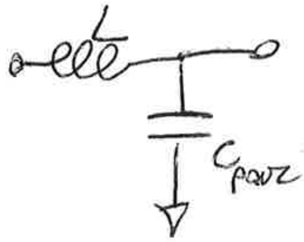


Now we know $f_{MEAS.}$ and C_{par}

$$f_{MEAS.} = \frac{1}{2\pi\sqrt{L\, C_{par}}}$$ and so

we can derive L.

$$L = \left[\frac{1}{(2\pi f_{MEAS})^2\, C_{par}}\right]$$

DO IT! to check any mistake

$$Z_0 = \sqrt{\frac{L}{C_{par}}}$$

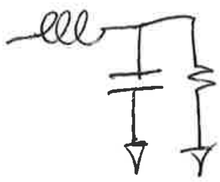
$\sqrt{\frac{L}{C}}$

$$Q = \frac{Z_0}{R} \quad \text{or} \quad Q = \frac{R}{Z_0}$$

what is the series one and what the parallel one?

What happens if $R \to \infty$? Circuit not damped and $Q \to \infty$

So the parallel term is $Q = \frac{R}{Z_0}$

for 

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