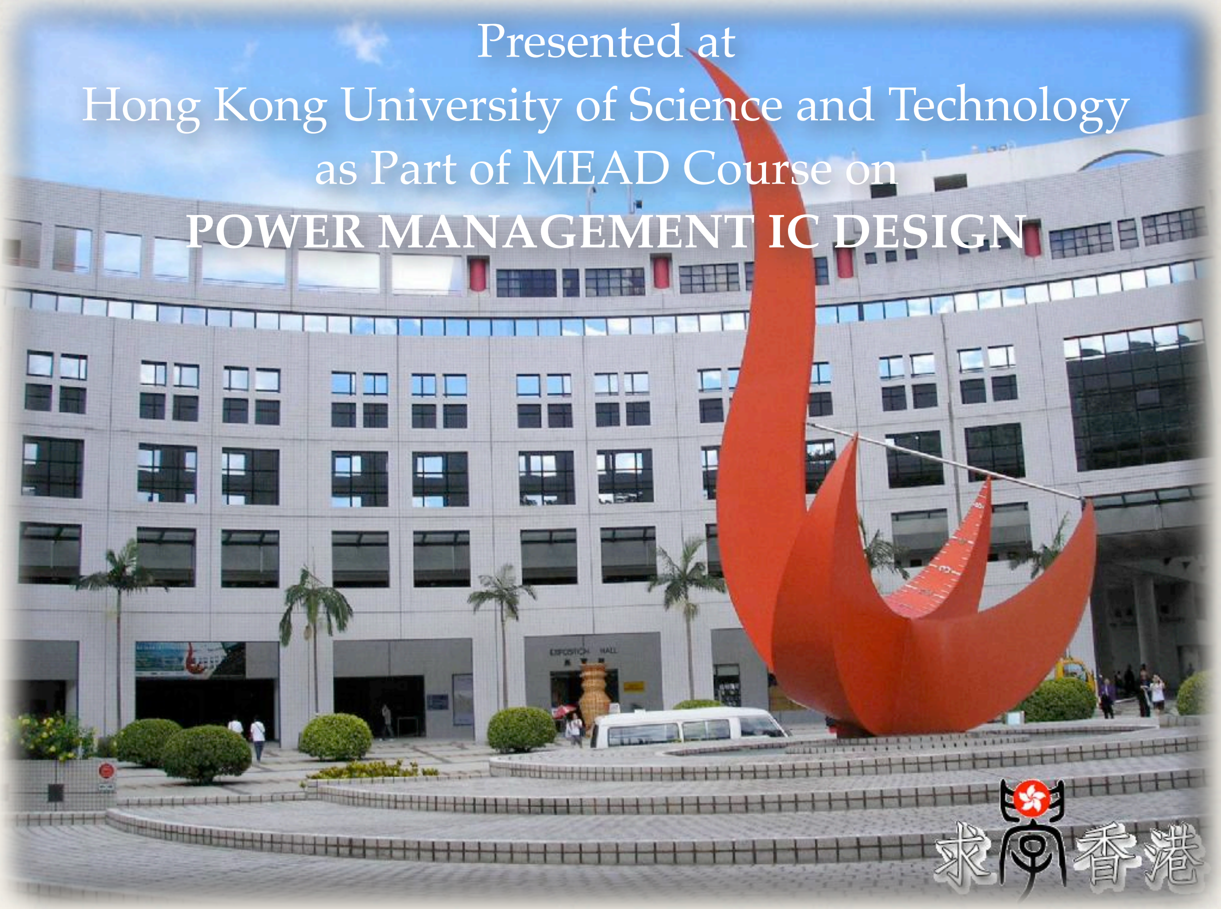

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POWER MANAGEMENT IC DESIGN

Overview of the Design of Switch-Mode Power Converters: From Theory to Practice

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How theory works for us?

- How basic theory helps design and analysis?
- What can we do if the theory doesn't match the outcome?
- Can we live without heuristics?
- Are complex models always better?
- What makes the engineers lose faith in the theory?
- Can theory really be applied in practice?

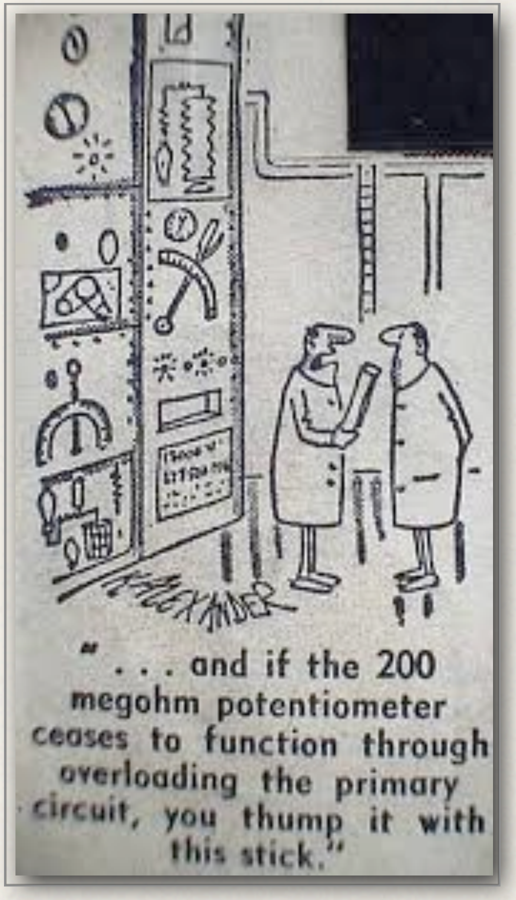
The theorist errs!

- The EMI filter isn’t quite doing what it is supposed to do. Let me use a different filter configuration, and try again.
- When the converter loses stability, the theory says that it diverges to infinity.

- Oh! I have found the answer from my theoretical prediction. I need a duty cycle of 1.2 for this theoretical power factor control!! How could I achieve this?

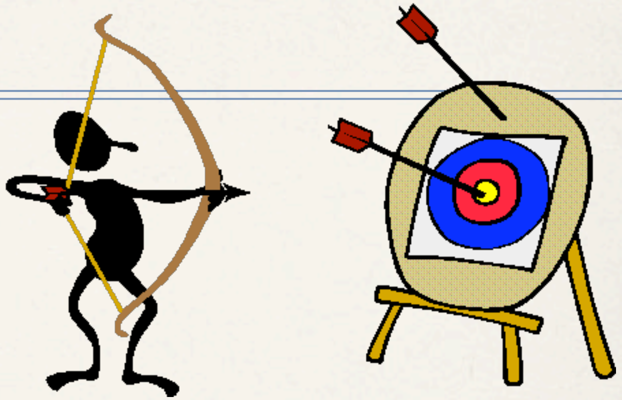
The engineer misinterprets!

- The snubber gets pretty hot. Perhaps a smaller resistance would reduce loss.
- The transformer behaves differently when used in a flyback converter and in a forward converter.
- Air gap stores more energy.
- The output voltage of my constant-power-controlled flyback circuit isn't high enough. A few more turns in the secondary side would raise the output voltage.



"... and if the 200 megohm potentiometer ceases to function through overloading the primary circuit, you thump it with this stick."

Objectives of this overview



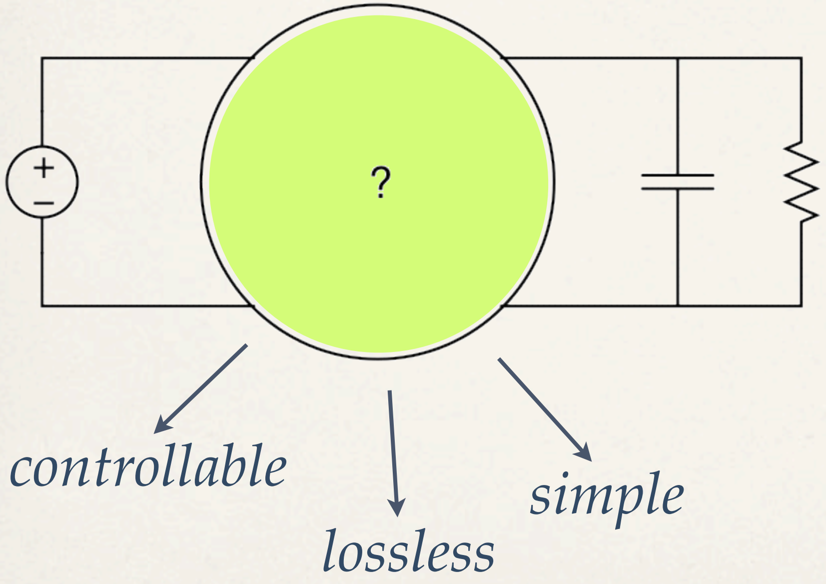
- Overview!
- To show how one can arrive at a practical circuit from *proper* consideration of basic theory.
- To show how circuit theory can be used to explain problems encountered in practical circuits.
- To show how a switch mode power supply can be systematically constructed, starting from the simplest converter topology.

Contents

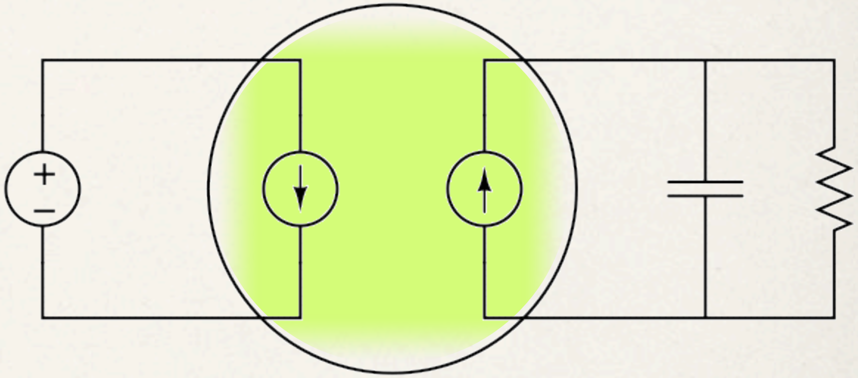
- Basic topologies and practical requirements
- How theory solves problems:
  - First problem: practical transformer
  - Second problem: real device switching
  - Third problem: closed-loop control
  - Fourth problem: isolation
  - Fifth problem: input filter
- Conclusion

Genesis of converters

- Aim: To convert controllable power from a voltage source to a load, with NO LOSS.



- Kirchhoff’s laws restrict terminal conditions



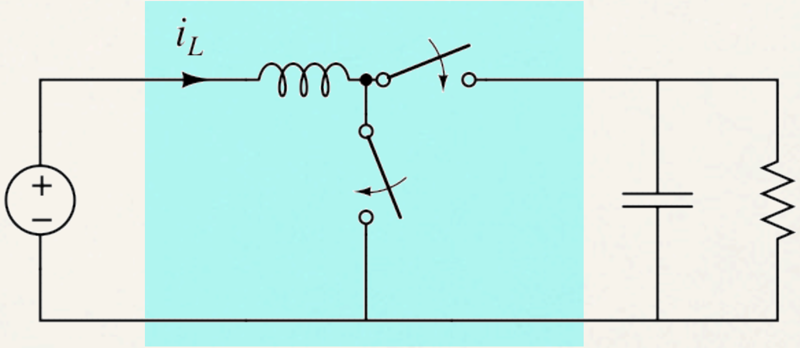
Elements wanted

- Lossless requirements
  - current sinking for input
  - current sourcing for output
- Ideas
  - An inductor switching between source and load
  - Relative sourcing and sinking durations would control the energy flow

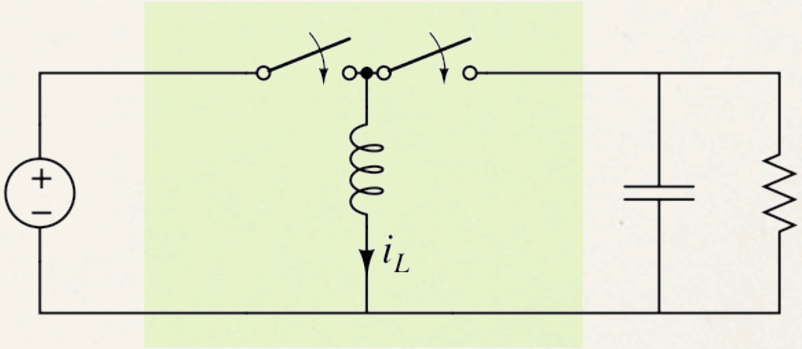
- From Kirchhoff's laws,
  - ***Inductors must not be left open.***
    - ➡ An inductor switching between source and load.
    - ➡ At least one current path must be available at all times.
    - ➡ At least two switches are needed to divert the inductor current
    - ➡ THREE POSSIBILITIES

Three possibilities

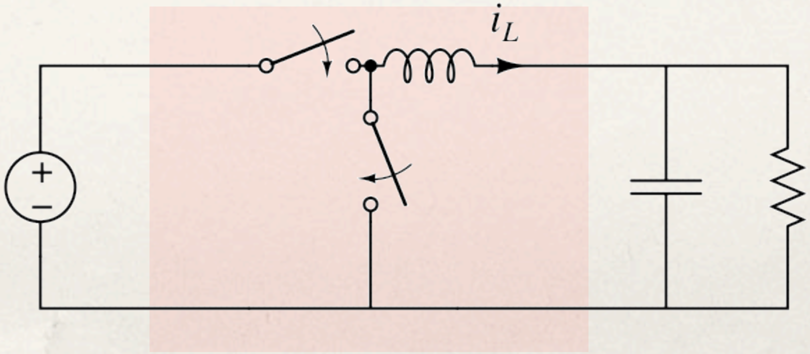
Boost converter



Buck-boost converter



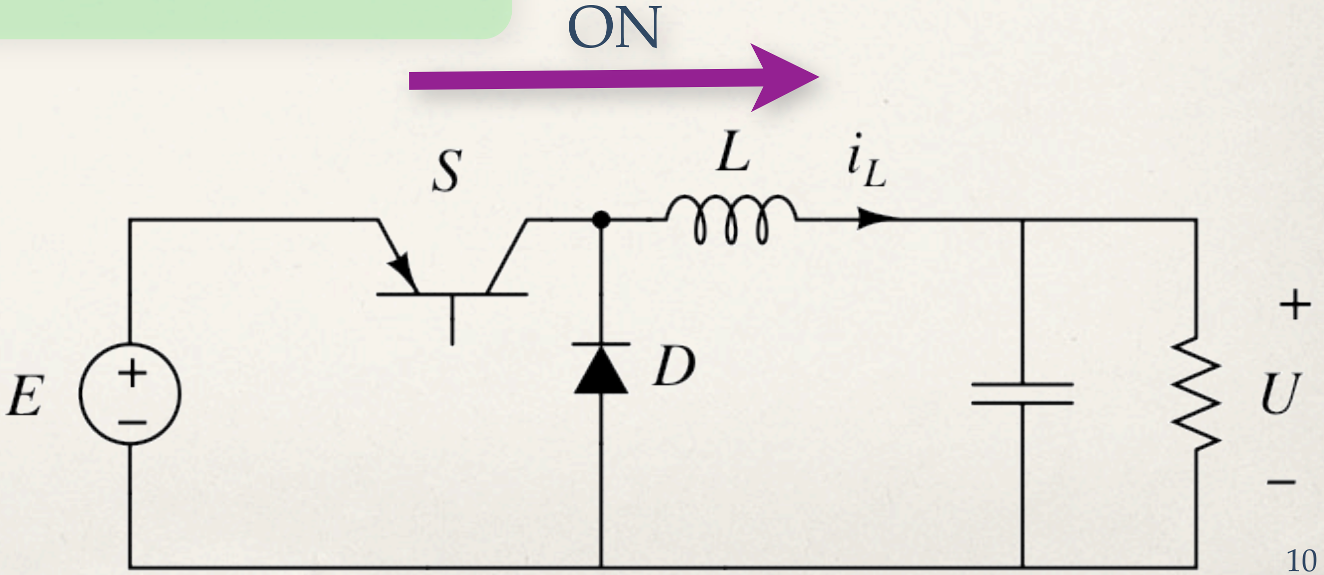
Buck converter



Quick glimpse: the buck converter

- Switch S is turned on and off very quickly, at a rate much greater than the output filter natural frequency
- Control parameter is ***duty cycle, d***

$$d = \frac{\text{duration when } S \text{ is on}}{\text{period}} = \frac{t_{\text{on}}}{T}$$



Steady-state operation

- Suppose we fix the duty cycle and wait until a steady state is reached.
- Inductor current goes up during the ON time, and goes down during the OFF time.
- Periodic operation forces:

$$\text{Increment during ON} = \text{Decrement during OFF}$$

$$\frac{(E-U)DT}{L} = \frac{U(1-D)T}{L}$$

$$U = D \times E$$

Putting it to practice

- We need
  - transformer isolation
  - closed-loop control
  - drivers for MOSFETs
  - self start-up
  - snubbers as switching aids
  - protection
  - input EMI filter
  - Proper component selection
  - and mechanical design:
    - heat sink, layout, packaging, etc.

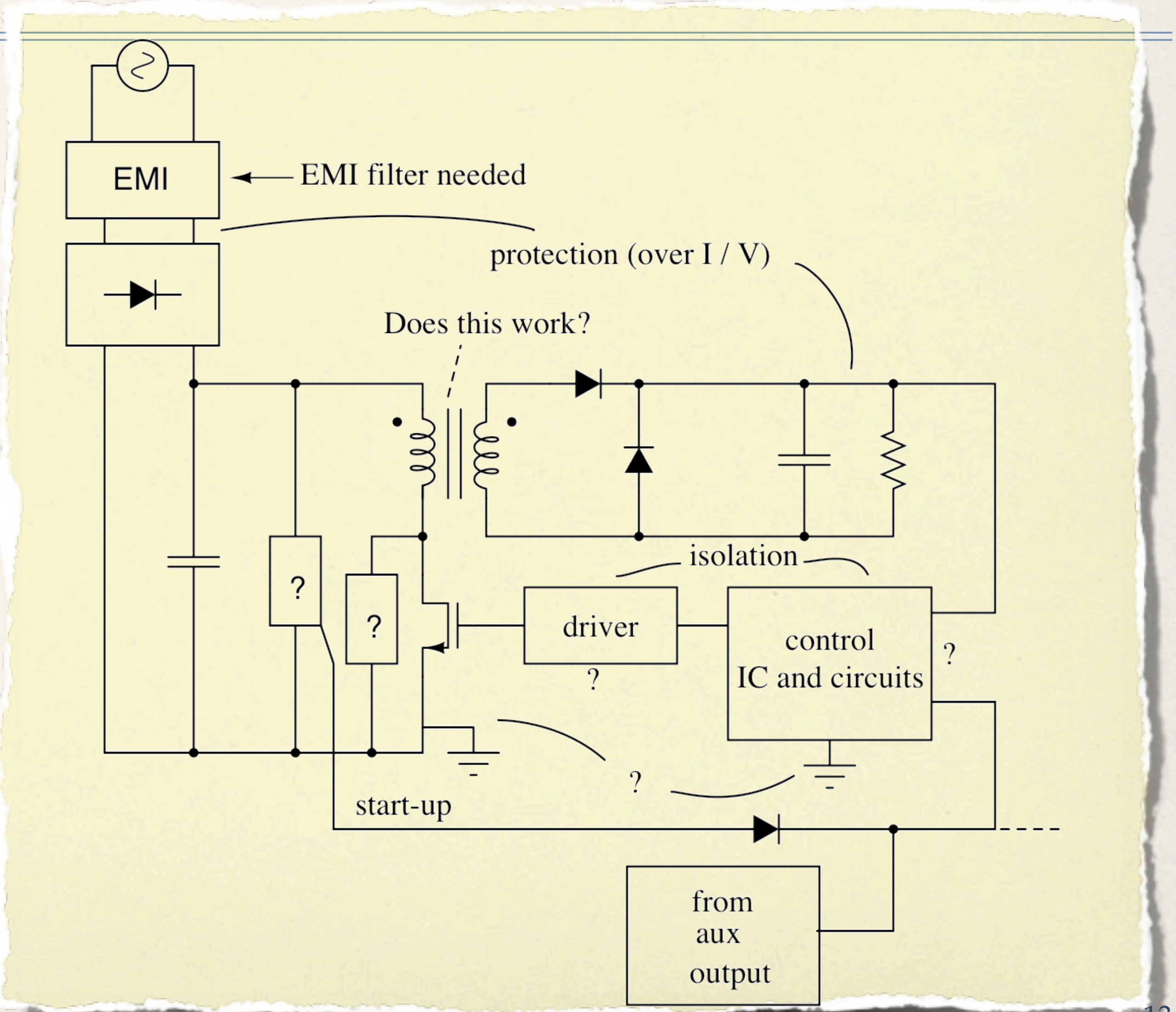
Direct mandatory requirements

Indirect mandatory requirements

Regulatory requirements

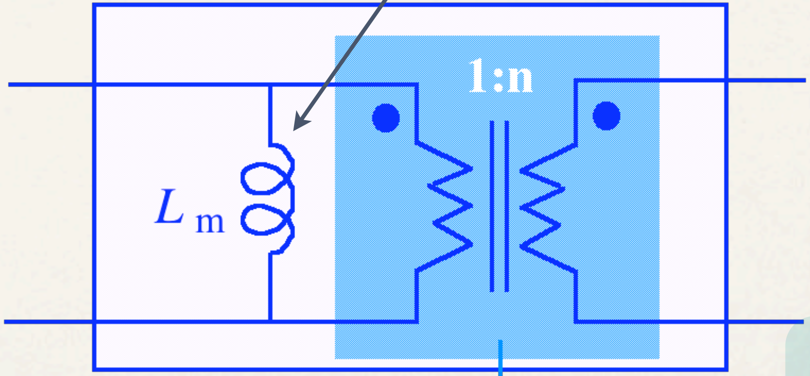
Practical circuit requirement

- Forward converter – transformer isolated buck converter



First problem: transformer

- The previous forward converter worked only if the transformer were ideal.
- However, practical transformers have ***magnetizing inductance***.



Ideal transformer

$$v_2 = n v_1$$

$$i_2 = \frac{1}{n} i_1$$

What the theory says?

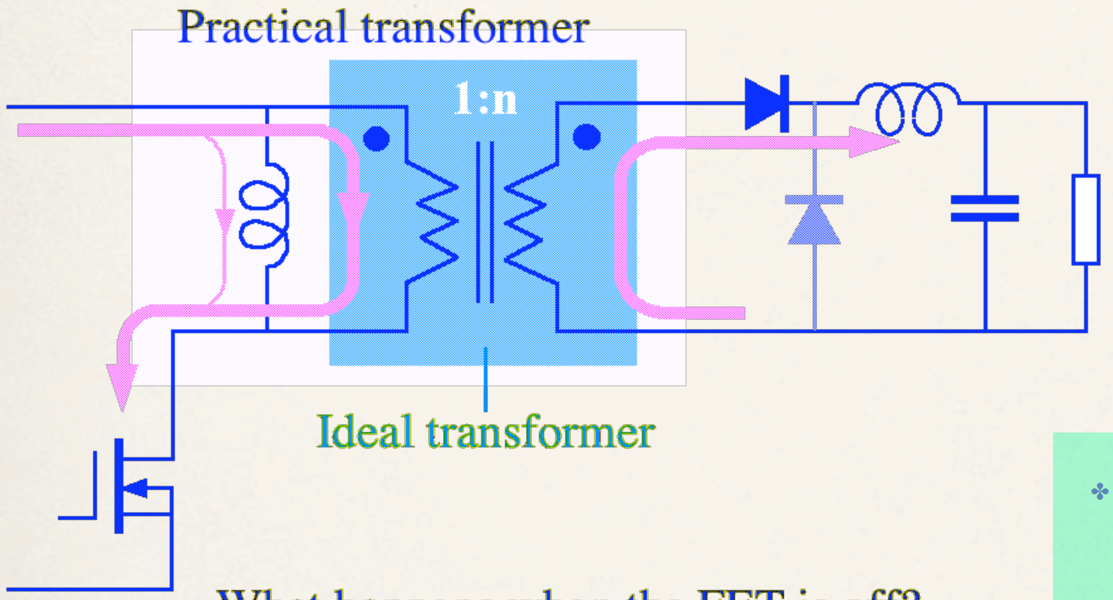
- If we have to use a transformer for the forward converter, the transformer should be ideal.
- That means INDEFINITELY LARGE magnetizing inductance.

- Either an infinitely permeable core
  - OR an infinite number of turns

- THAT'S IMPOSSIBLE!!

Probing further

- First, consider the ON time

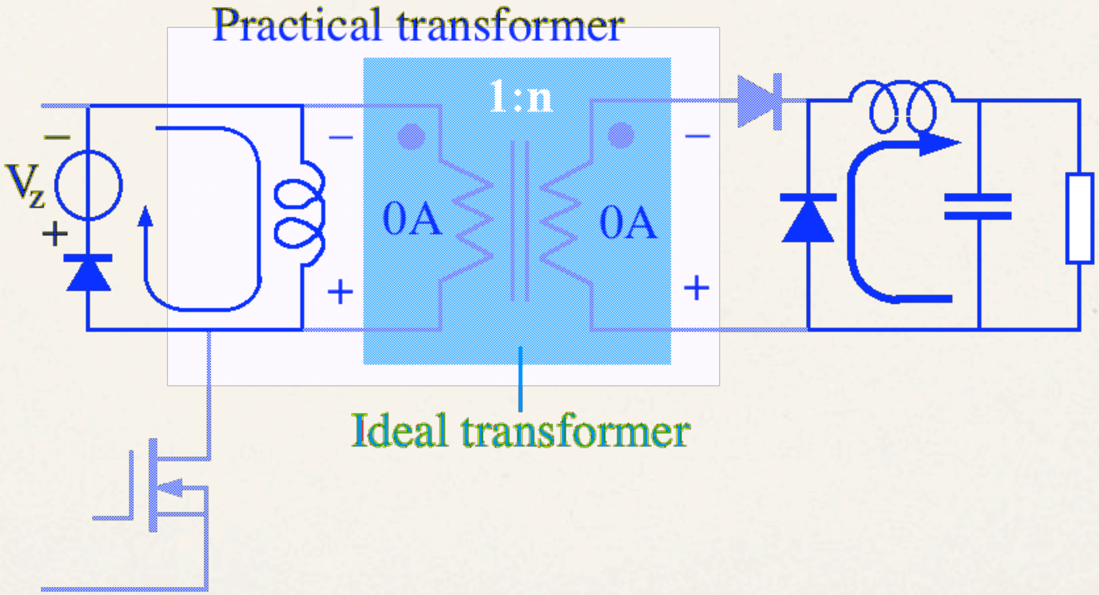


What happens when the FET is off?

- Secondary of T/F has no current.
- Primary has no current either.
- Current in magnetising inductance can go nowhere!!

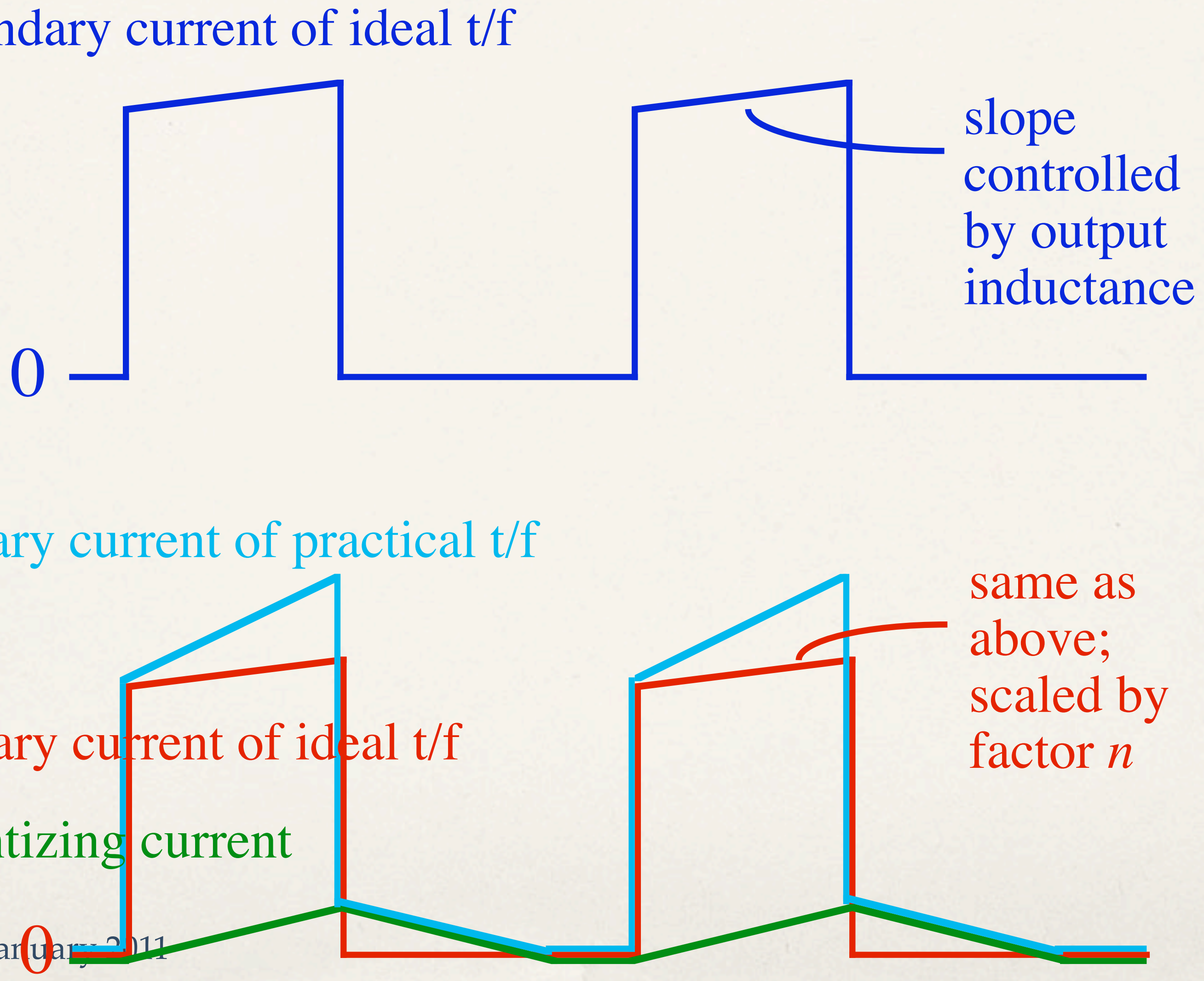
Deriving solution: core reset

- A path must exist during OFF time to bring the magnetizing current back to zero



- Circuit theory works and explains the problem.

Waveforms with core reset


Secondary current of ideal t/f

slope controlled by output inductance

Primary current of practical t/f

same as above; scaled by factor *n*

Primary current of ideal t/f

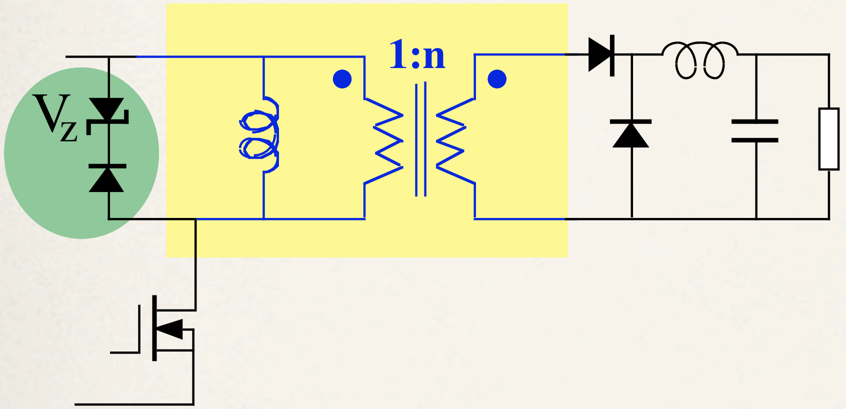
Magntizing current

Requirement for core reset

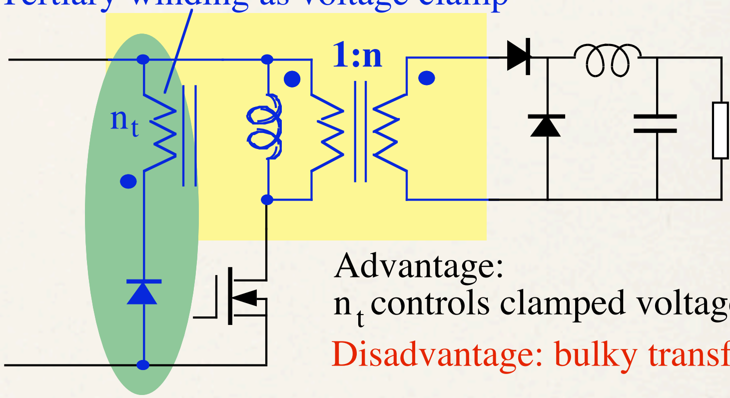
- Negative voltage polarity applied to the winding during OFF time.
- This voltage must be large enough to bring the magnetising current back to zero.
  - If $d = 0.5$, then $V_z > V_{in}$.
  - If $d = 0.8$, then $V_z > 4V_{in}$.

- Technique: ***clamping the voltage during OFF time.***

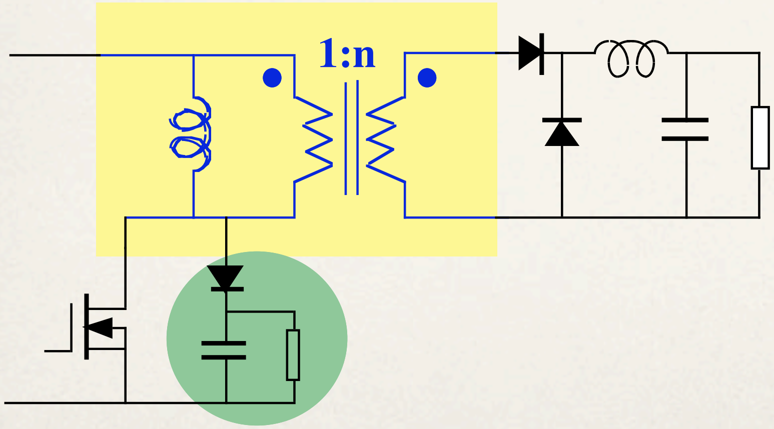
Some possibilities



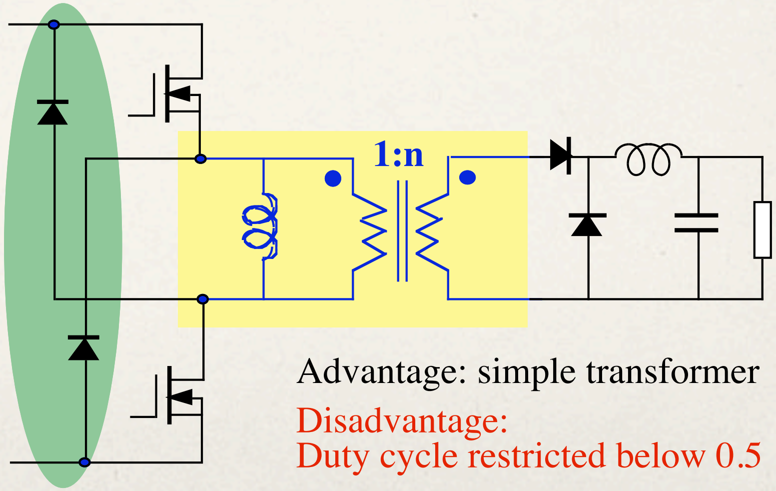
Tertiary winding as voltage clamp



Advantage:
n_t controls clamped voltage for re-set
Disadvantage: bulky transformer



Two-wheeler forward converter



Advantage: simple transformer
Disadvantage:
Duty cycle restricted below 0.5

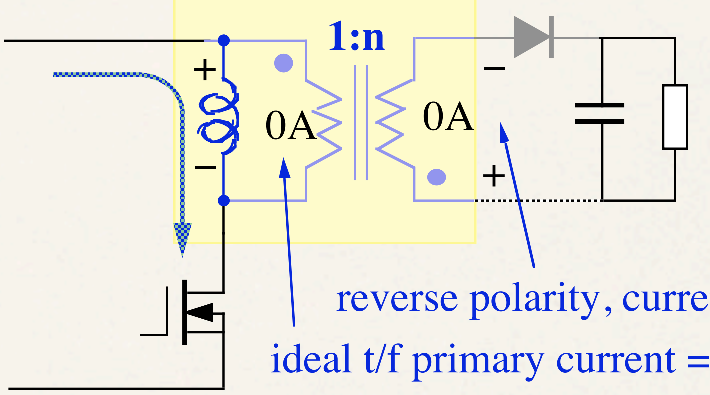
Recapitulation

- Although we cannot make an ideal transformer, we solve the problem with a reset circuit.
- We now care much less how large L_m is, since we have a way to get around it.
- QUESTION: Can the magnetizing inductance be used to advantage?
  - YES, in a flyback converter!

Flyback converter

- In this case, we don't need an ideal transformer. That's good. We don't have it anyway.
- The magnetizing inductance becomes crucial as part of the circuit element.
- Requirement:
  - Linear inductor!
  - Air-gap to augment BH curve (then more turns to obtain inductance)

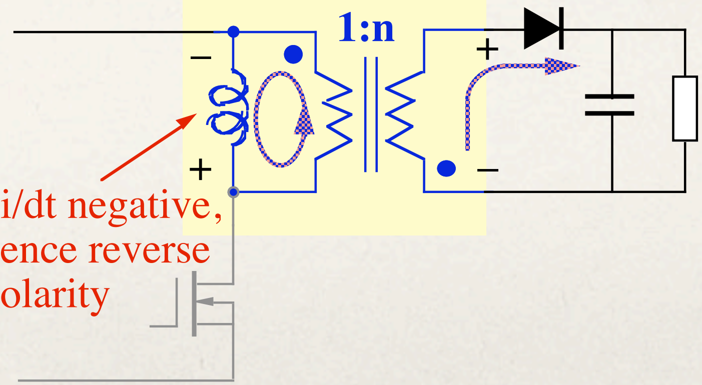
During ON-time, magnetizing inductance charges up.



reverse polarity, current can't go!

ideal t/f primary current = 0

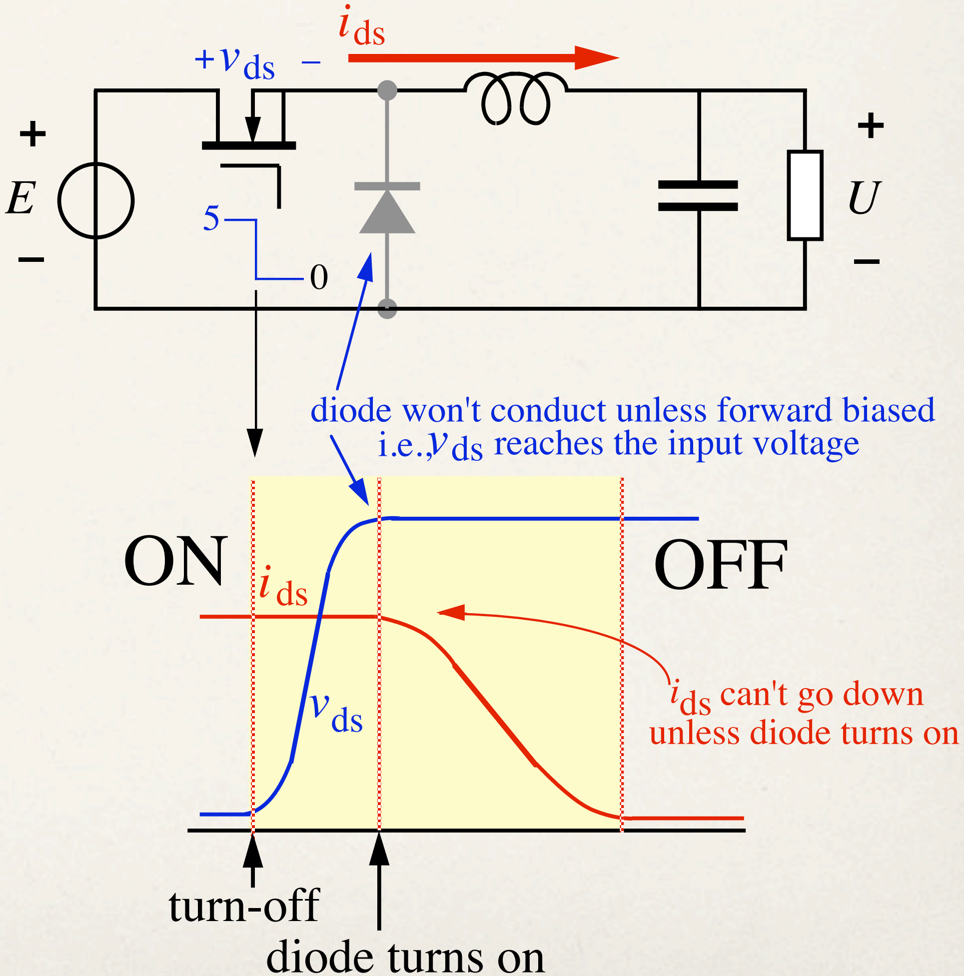
During OFF-time, magnetizing current forces its way out through the ideal t/f primary.



di/dt negative, hence reverse polarity

Second problem: real switching

- Consider turning the switch in a buck converter.
- The result of this real device switching is
    - **POWER LOSS (switching loss)**

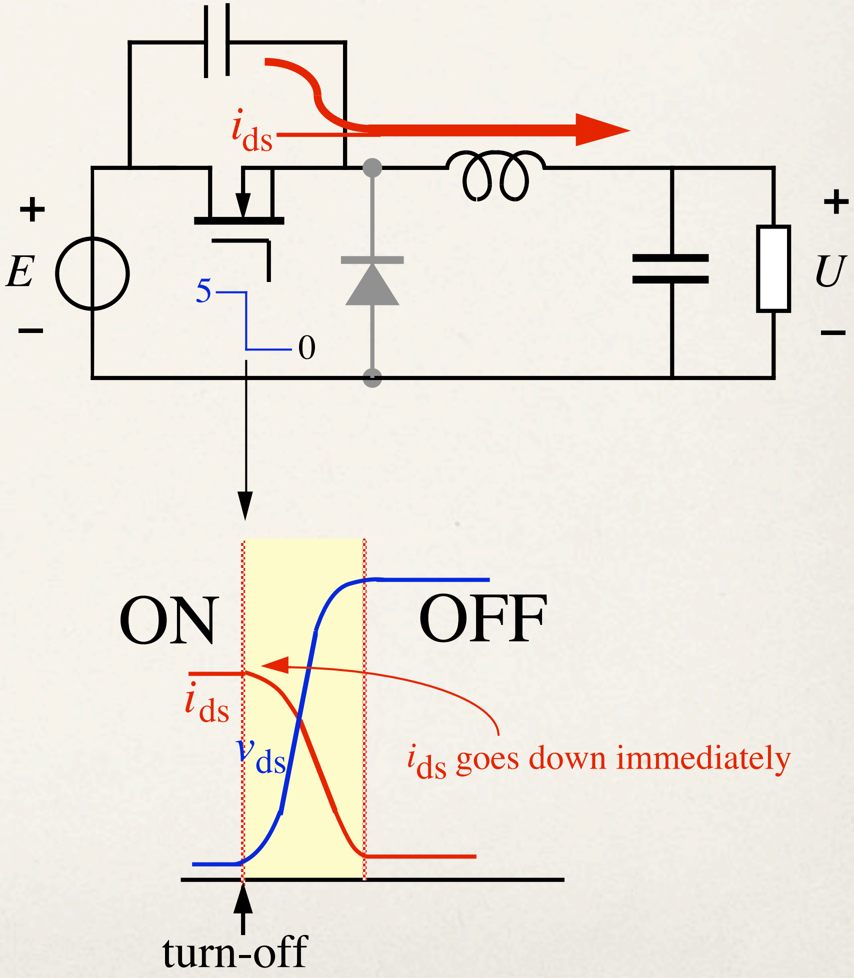


Deriving solution: snubber

- Give the switch current a chance to go down before the diode turns on.

- Set up a PARALLEL CURRENT PATH right after the turn-off instant.

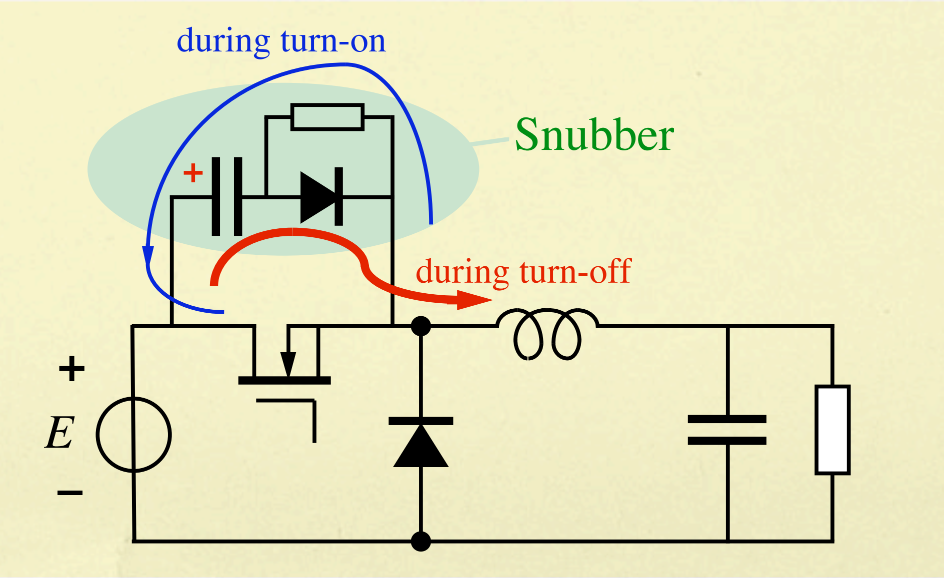
- Place a capacitor across the switch at turn-off to supply current for the output inductor.



Completing the solution

- What happens when the switch is turned on again in the next cycle?
- The current will rush through the switch!!

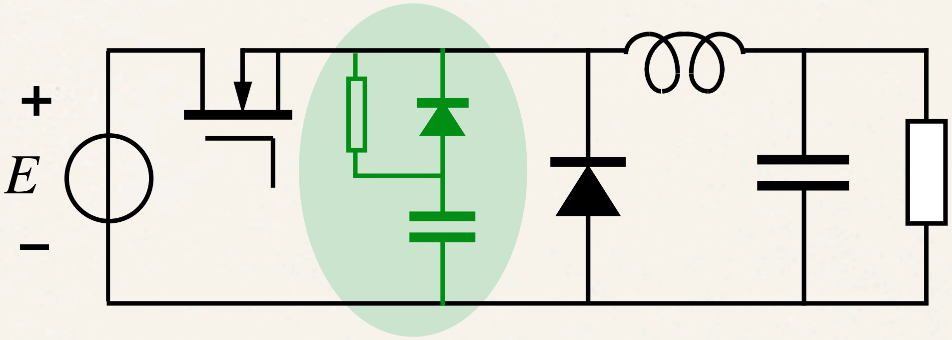
- We must protect the switch from such huge in-rush.
- The complete snubber is:

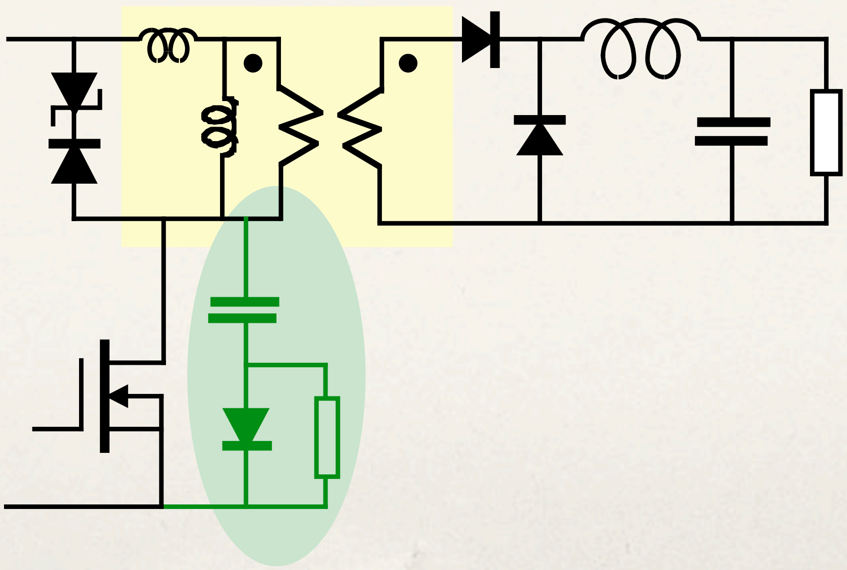


- Energy loss per cycle is

$$\frac{1}{2} C_{\text{snubber}} {v_s}^2$$

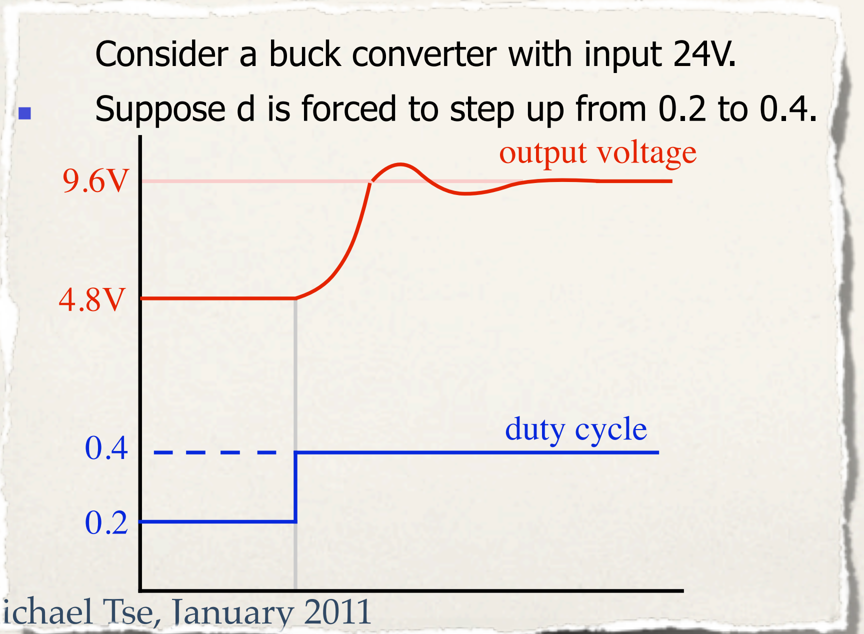
Other examples





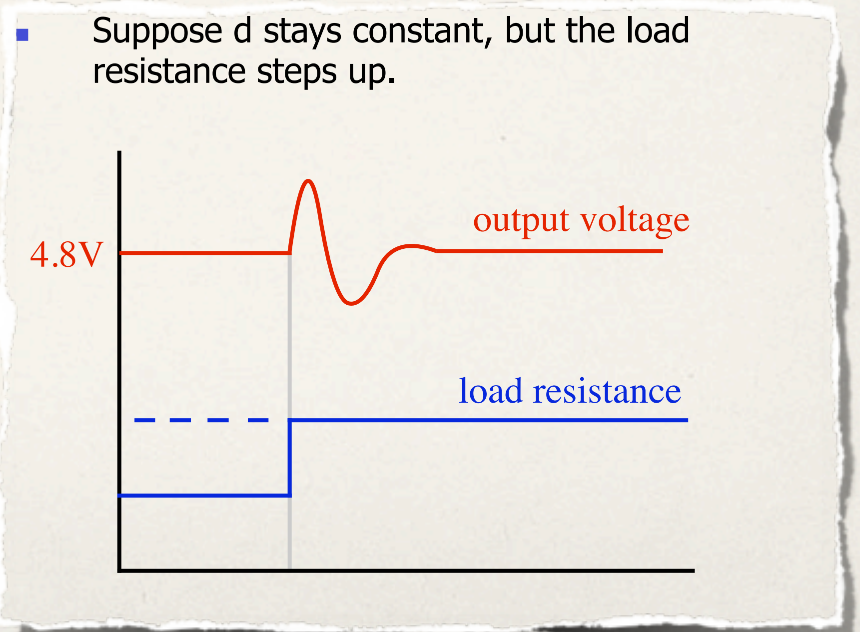
Third problem: closed loop control

- Why?
  - Because the system is dynamic.
- What is a dynamical system?
  - A simplified definition: a system that does not assume an operating point instantly when an input parameter is changed.



Consider a buck converter with input 24V.

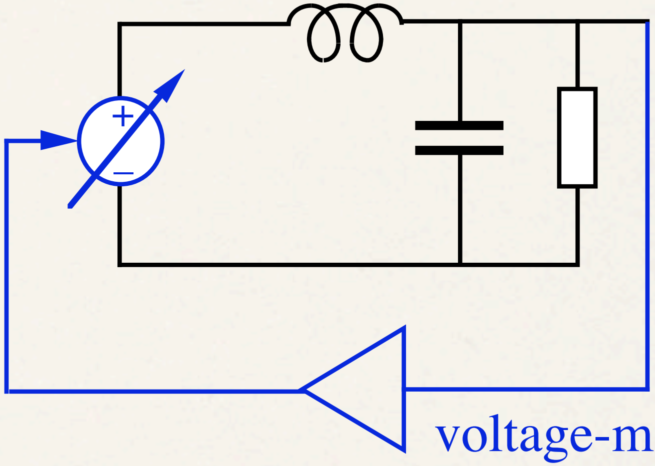
- Suppose d is forced to step up from 0.2 to 0.4.



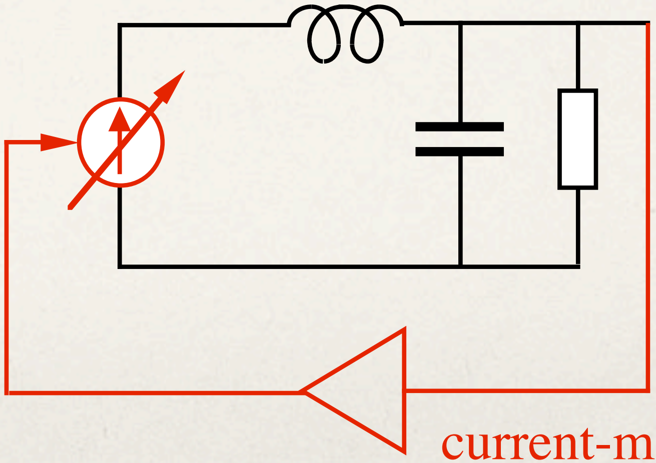
- Suppose d stays constant, but the load resistance steps up.

The need for control

- Obviously we need to control the duty cycle if we want the system to have a dynamic behavior different from the natural behavior.
- 2 common approaches
  - ***Voltage mode control***
  - ***Current mode control***



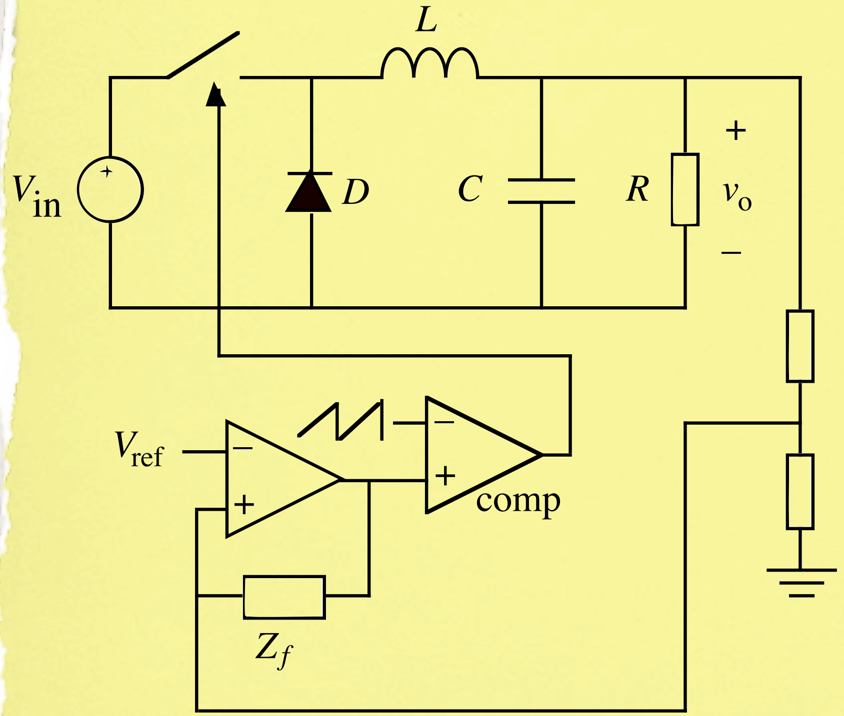
voltage-mode fb



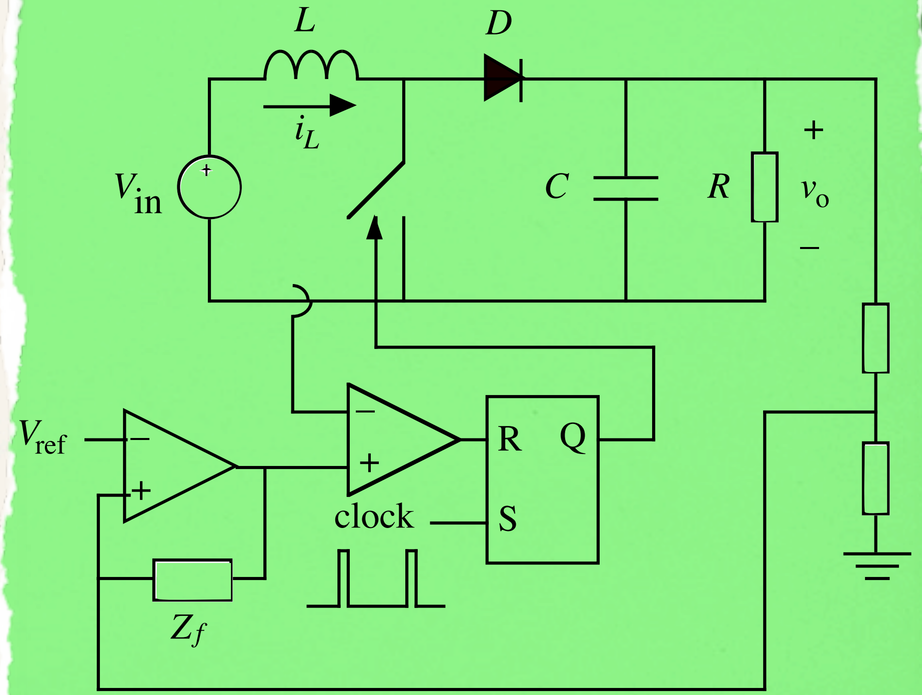
current-mode fb

General control configurations

Voltage-mode control

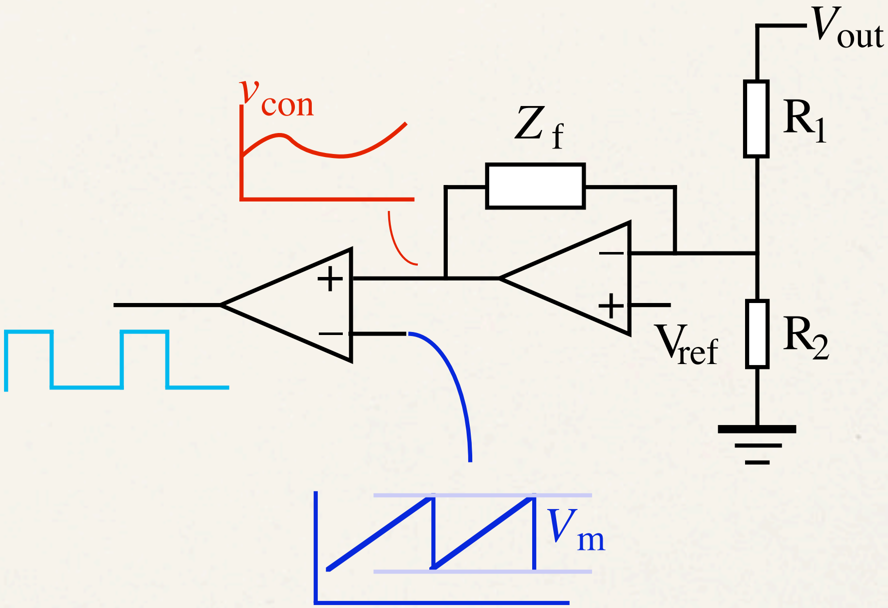


Current-mode control



Voltage-mode control

- A general feedback circuit representation is:



$$v_{\text{con}}\left(\frac{R_1\|R_2}{Z_f+(R_1\|R_2)}\right)=v_{\text{ref}}-\frac{R_2}{R_1+R_2}\left[\frac{Z_f}{Z_f+(R_1\|R_2)}\right]v_{\text{out}}$$

Small-signal analysis

$$v_{\mathrm{con}}\left(\frac{R_1\|R_2}{Z_f+(R_1\|R_2)}\right)=v_{\mathrm{ref}}-\frac{R_2}{R_1+R_2}\left[\frac{Z_f}{Z_f+(R_1\|R_2)}\right]v_{\mathrm{out}}$$

- We can separate the AC from the DC component.
- Let's not worry about the steady-state operating point.
- The small-signal AC equation is:

$$\Delta v_{\mathrm{con}}=-\frac{Z_f}{R_1}\Delta v_{\mathrm{out}}$$

- Taking into account the PWM, we have

$$\Delta d=-\frac{1}{V_m}\frac{Z_f}{R_1}\Delta v_{\mathrm{out}}$$

If we know the duty-cycle-to-output small-signal transfer function, then we can find the loop gain and hence be able to design the required compensator to give ***sufficient bandwidth and stability.***

HERE, we need small-signal models from circuit theory.

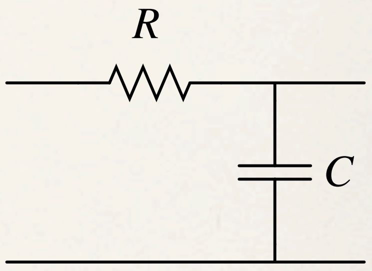
Design criteria

- Fast response — high gain and wide bandwidth of loop gain
- Stability — phase shift must be well below 180deg at 0dB crossover.

- The converter is a second-order system which can become unstable under closed-loop condition, especially when the gain is high causing the phase shift of the loop gain to get close to 180deg at 0dB crossover.

- We must limit the bandwidth somehow if we allow a high DC gain.

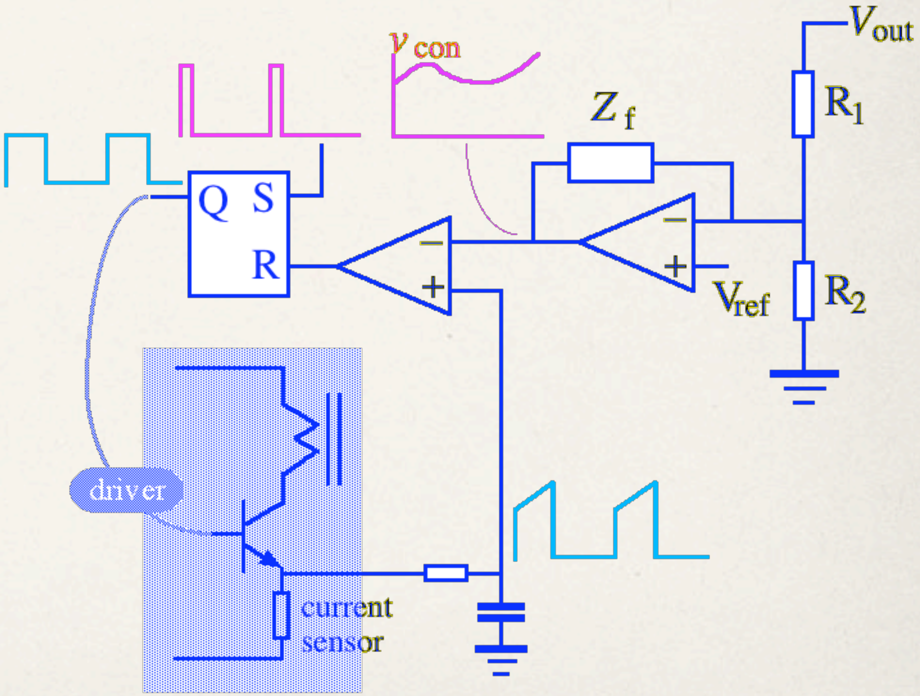
A simple practical approach



- ***POLE*** — frequency location where the gain begins to roll off.
  - Simplest circuit analogy: a resistance connected to a grounded capacitor forming an RC network. A low-frequency pole exists at $1/2\pi CR$ Hz.
- A simple ***educated*** trial-and-error to achieve lag compensation:
  - Select an RC combination (in the compensation circuit associated with the control IC) for a deep lag compensation — narrow band first.
  - Then, relax the time constant (widen the band) until the circuit begins to loss stability!
  - Finally, reduce the capacitor value down 10 times to restore stability.

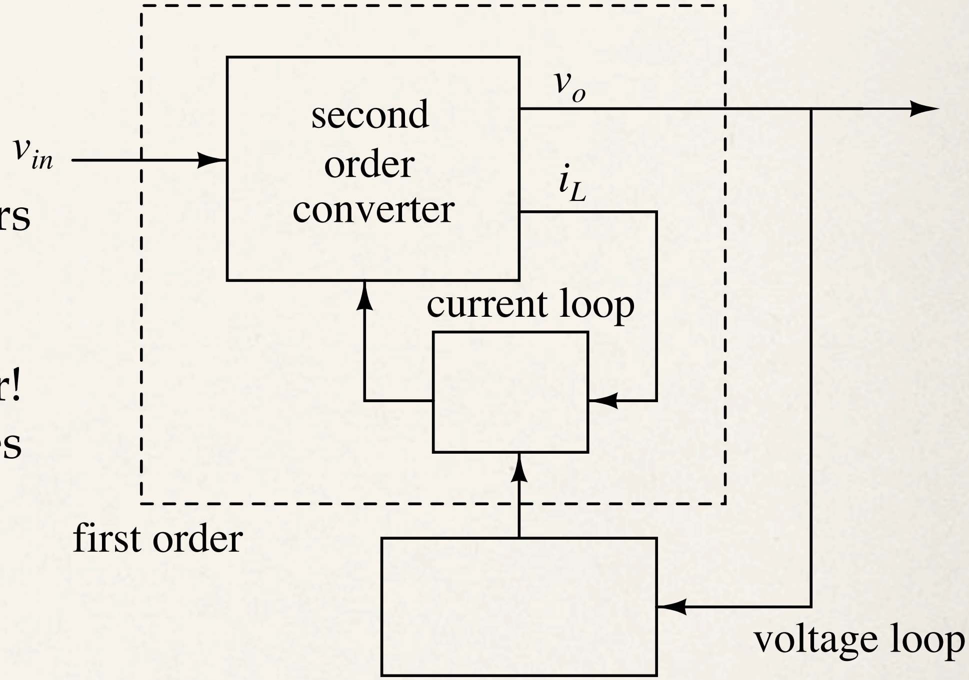
Current-mode control

- Essential concept — The system reduces to first order, more or less!
- The system is therefore faster, with less chance for instability.
- IDEA:
  - Make the inductor current dependent on the output voltage by forcing the current peak to follow the output voltage analog.
  - Disqualify the inductor current as a state variable.
  - The converter becomes first order.



Application

- Current-mode control is particularly useful for ***controlling boost and buck-boost types*** of converters.
    - Boost and buck-boost types of converters are **non-minimum phase systems***. Current-mode control essentially “destroys” the dynamics of the inductor! The resulting first-order system becomes much easier to control.
- The design of the outer voltage loop is relatively simple, mainly for achieving adequately fast output voltage regulation.

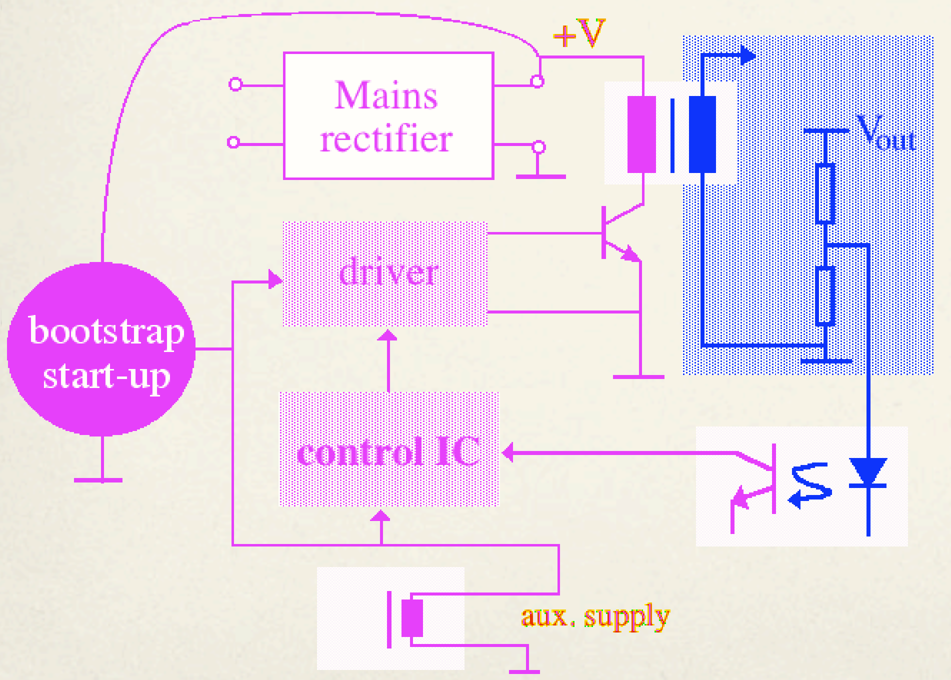


* The origin of non-minimum phase response will be examined in detail when we study the basic topologies and models of converters.

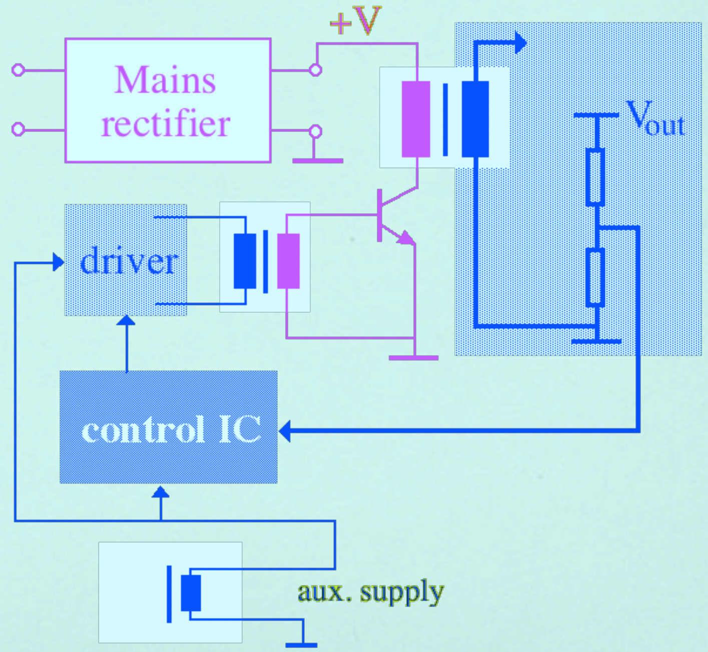
Fourth problem: isolation

- Need for isolating the load from the mains.
- But the control circuit connects the two!

Primary side control



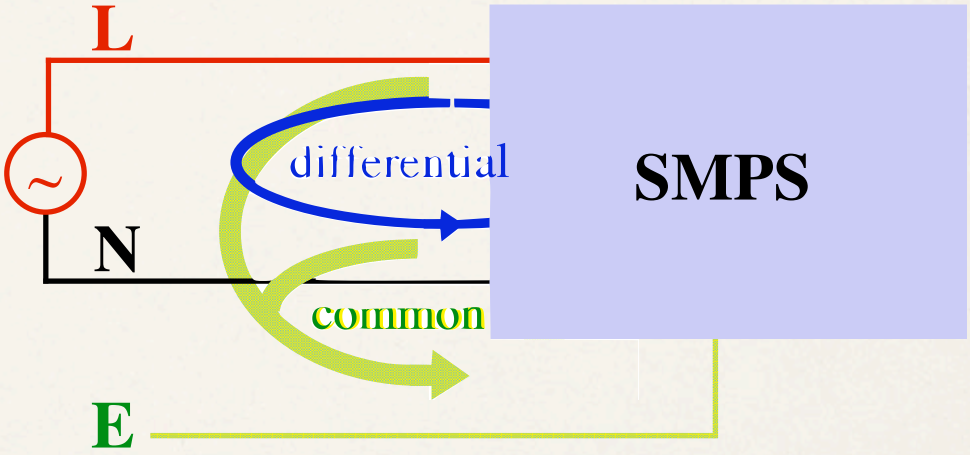
Secondary side control



Fifth problem: filter

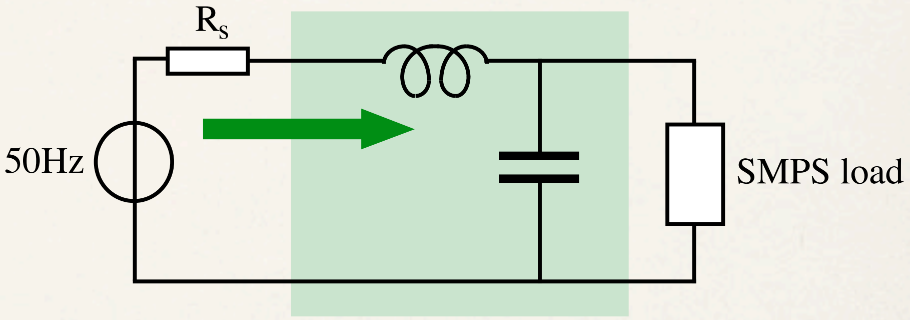
- An input filter is always needed to prevent differential-mode and common-mode noise from getting into the mains.

Basic requirement:
Let 50Hz gets in, but prevent high frequencies from getting out!

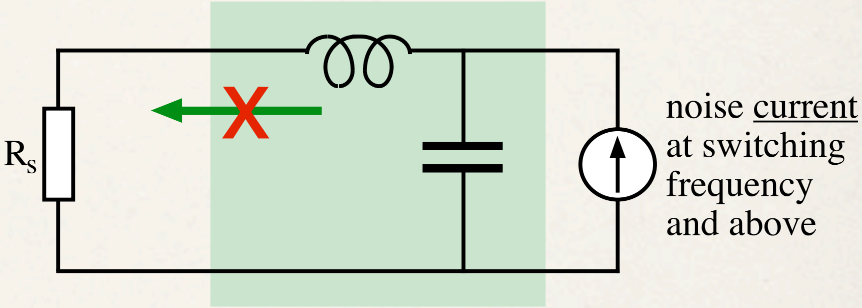


Basic theory

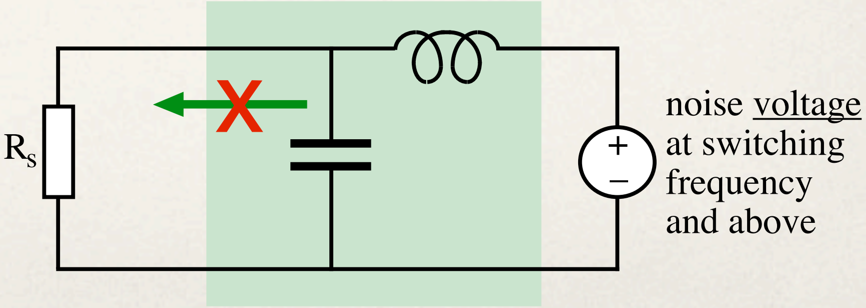
- Voltage filter (low-pass left-to-right)



- Current filter (low-pass right-to-left)

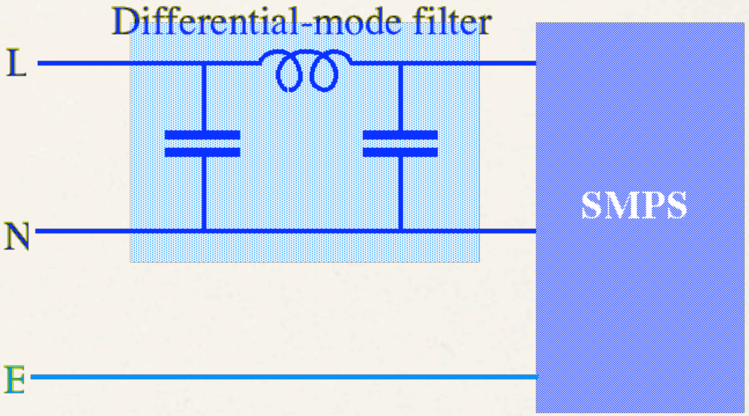


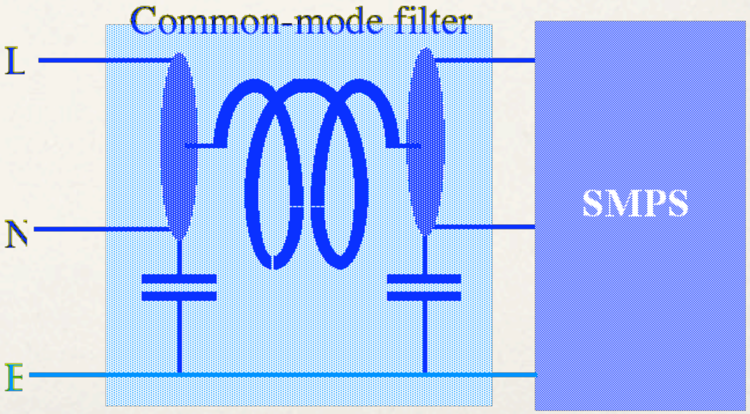
- Voltage filter (low-pass right-to-left)



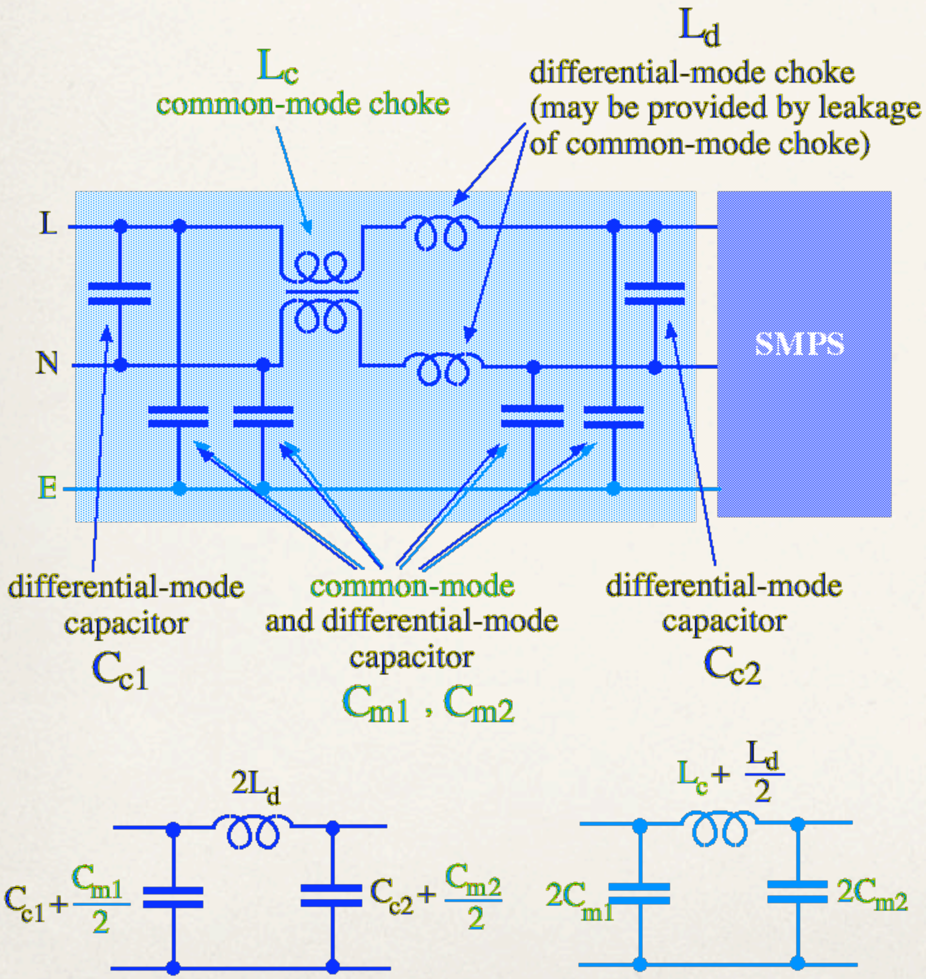
Conceptual placements

- Voltage filter (low-pass left-to-right)
- Current filter (low-pass right-to-left)
- Voltage filter (low-pass right-to-left)





Practical placements



- NOTE:
  - The EMI filter often fails to do what it is supposed to do.
  - Does the theory fall short of anything?
  - Or have we missed out some important things?!

Conclusion

- Theory is often made inadequate or even inconsistent!
  - In an EMI filter, a capacitor may not behave as a capacitor, and an inductor may not behave as an inductor.
  - Signals get around the filter, instead of being filtered.
  - Parasitics and nonlinearity come into play and have contributed sufficiently to invalidate the theory that has been constructed from ideal considerations.

- The theory does not fail. The problem is that we often fail to take into consideration all important relevant practical conditions when we construct our models for analysis.

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