Modern Design

Keynote Presentation at Vicor Power Seminar

October 2019

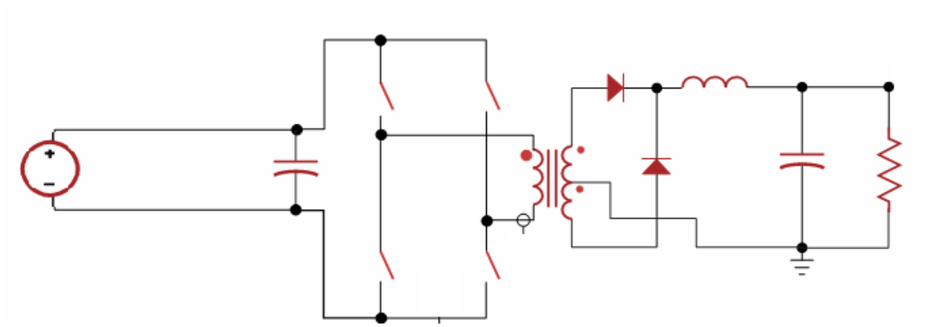
Dr. Ray Ridley

www.ridleyengineering.com

Ridley Engineering

My First Encounter with Vicor (1983)….

0.7 W/cu in



Aphrodite 240v Configuration, Nominal Output, Nominal Input

Input Line Vrms	Input Curr Arms	Input Power W	Out 5.1v +12V -12V	DCBus Max Min V	Ripple (120) 5.1v+12v-12v mV mV mV	Ripple(SW) Rip. + Noise 5.1v+12v-12v mV mV mV	P.f.	Freq kHz	Eff %	Load 5.1v +12v -12v
240.0	01.19	0120	5.133 11.95 12.19	330.0 325.0	000 000 000	040 000 000 040 070 030	0.42	070.9	64	015 0.0 0.0
240.0	06.64	0910	5.123 11.94 12.16	330.0 315.0	000 000 000	020 010 020 055 040 050	0.57	090.9	76	120 3.0 3.0
240.0	07.28	1010	5.123 11.88 12.09	330.0 310.0	000 000 000	020 020 020 055 045 050	0.58	087.7	75	120 6.0 6.0
240.0	07.99	1110	5.120 11.85 12.05	330.0 310.0	000 000 000	020 025 030 055 045 050	0.58	089.3	75	130 7.0 7.0
264.0	07.36	1110	5.121 11.83 12.01	375.0 350.0	000 000 000	020 040 020 055 055 050	0.57	079.4	75	130 7.0 7.0

Full bridge 150 kHZ ripple
First FETs instead of BJTs
Current-mode (before there were ICs)
State of the Art!

50 W/cu in
1 MHz
ZCS forward
87% efficiency

Two questions arise……
Can we learn how to do this?
Should we just buy Vicors?

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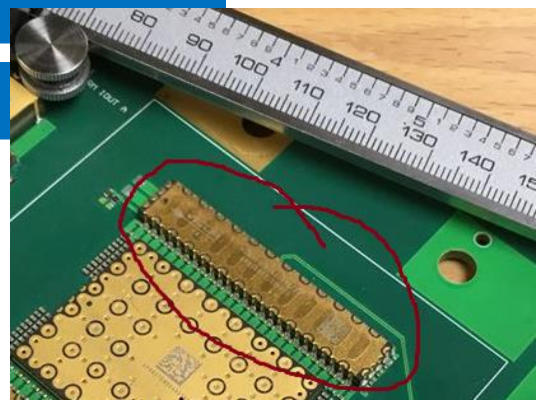
How to Make High Density Power

- Advanced Magnetics Design
- Soft Switching on All Devices (ZVS)
- Minimum Magnetic Energy Storage
- High-Frequency Switching > 1MHz
- Synchronous Rectifiers
- Advanced Controllers
- Full Control of Manufacturing
- Aggressive R&D Funding



**Magnetics Design is First on the List..
Do you know how to make a
500 A transformer this small?**

Don’t be afraid of magnetics…...
…..many engineers need some

Magnetics Therapy

Magnetics Undergraduate Education at University

What is this?

Most engineering students cannot identify the object on the left.

Maxwell's Equations

$$\nabla \bullet D = \rho$$

Gauss' Law (Electric Field Only)

$$\nabla \bullet B = 0$$

Gauss' Law on Magnetism
(No monopoles)

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

Faraday's Law Magnetic Induction

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

Ampere's Circuital Law – Magnetic Field and Current Relationship

Magnetics Education (Maxwell's first equation)

It all starts out well before schooling even starts….

Rub a balloon on your shirt, and it will stick to the ceiling.

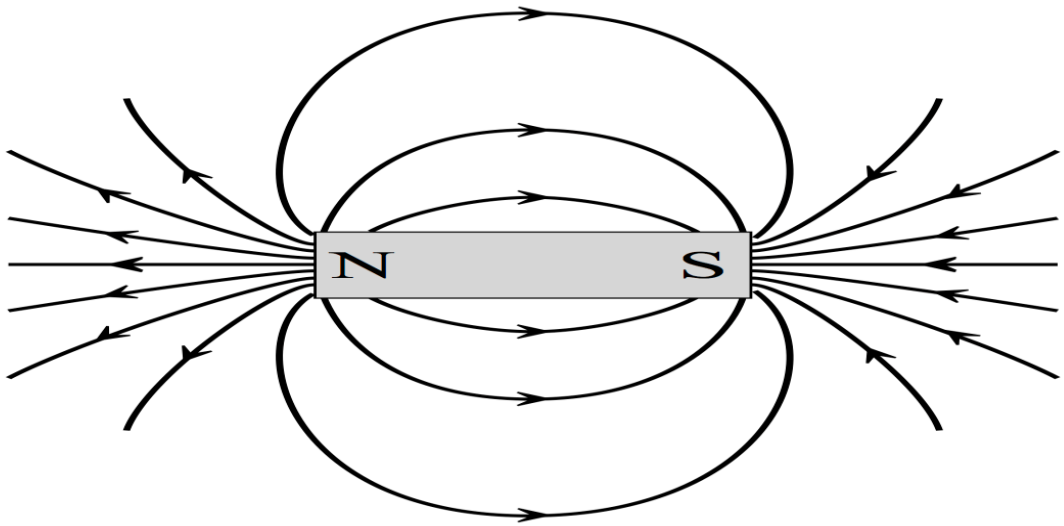
$$\nabla \bullet D = \rho$$

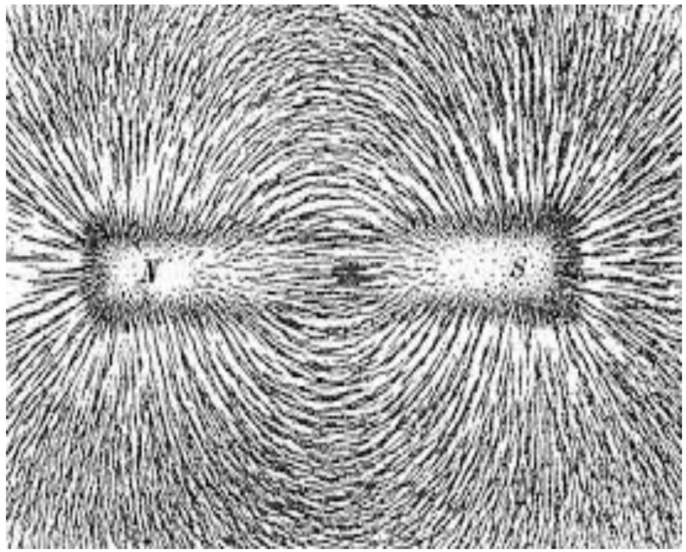
Gauss' Law You can create a monopole charge

Magnetics Education (Maxwell's Second Equation)

It continues well in early schooling……..

Sprinkle iron filings on a sheet, see the closed flux lines





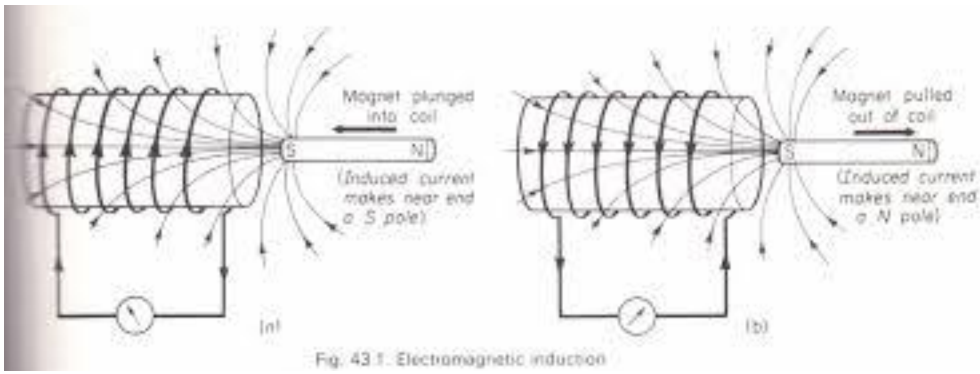
$$\nabla \bullet B = 0$$

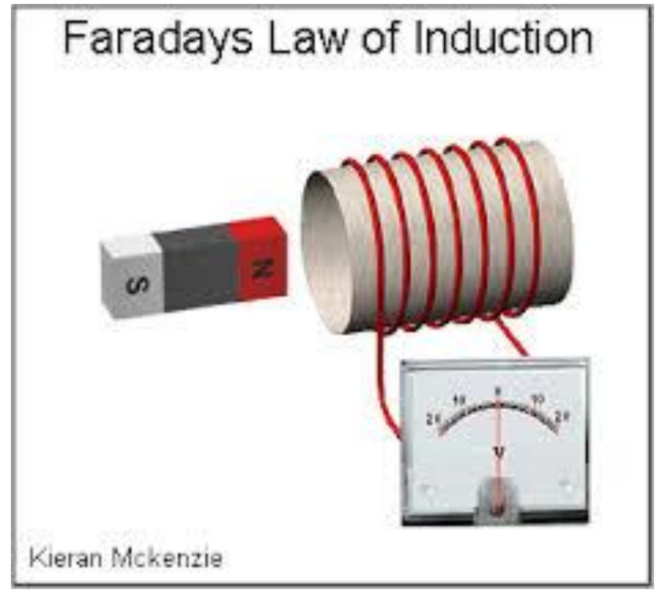
Gauss' Law on Magnetism

No monopoles – magnetic lines must complete the loop

Magnetics Education (Maxwell's Third Equation)

It continues further around age 16……..





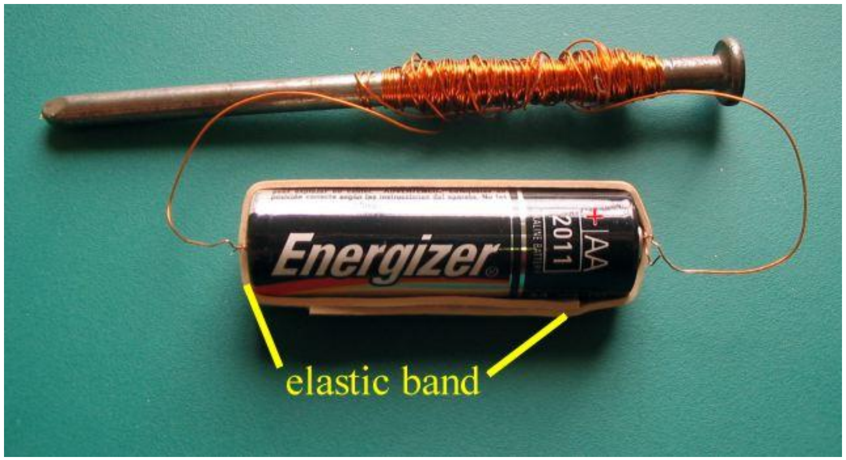
$$\nabla \times E = -\frac{\partial B}{\partial t}$$

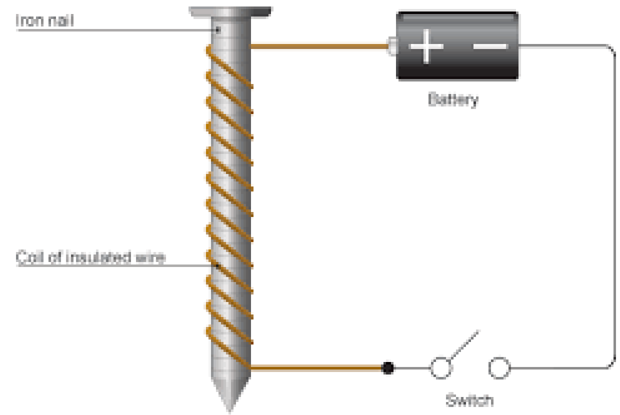
Faraday's Law of Magnetic Induction

1830's experiment

Magnetics Education (Maxwell's Fourth Equation)

Also at a young age ....





$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

Ampere's Law

Fields induced by a flowing current
or a changing E field (displacement current)

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Magnetics Education

We have everything we need to build a transformer now.

First and second law experiments - static

Third law is slow-moving: magnet is plunged by hand into a coil.
Fourth experiment is also slow-moving, iron nail is used to pick up a magnet

An important point is obscured here during the experiments

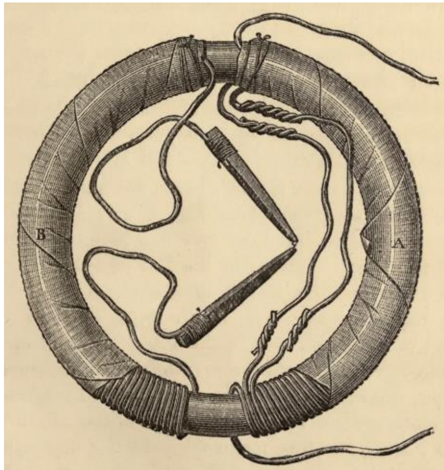
– the magnetic field moves at the **Speed of Light**!

Hence there are **no theoretical bounds** on the frequency of operation of magnetics.

There are also **no theoretical limits** as to the efficiency of transformers 99.9% can be achieved.

Downside of this is that the field goes everywhere - EMI

The Birth of the Transformer



Michael Faraday’s Transformer 1831

William Hammer’s Rectifier 1881

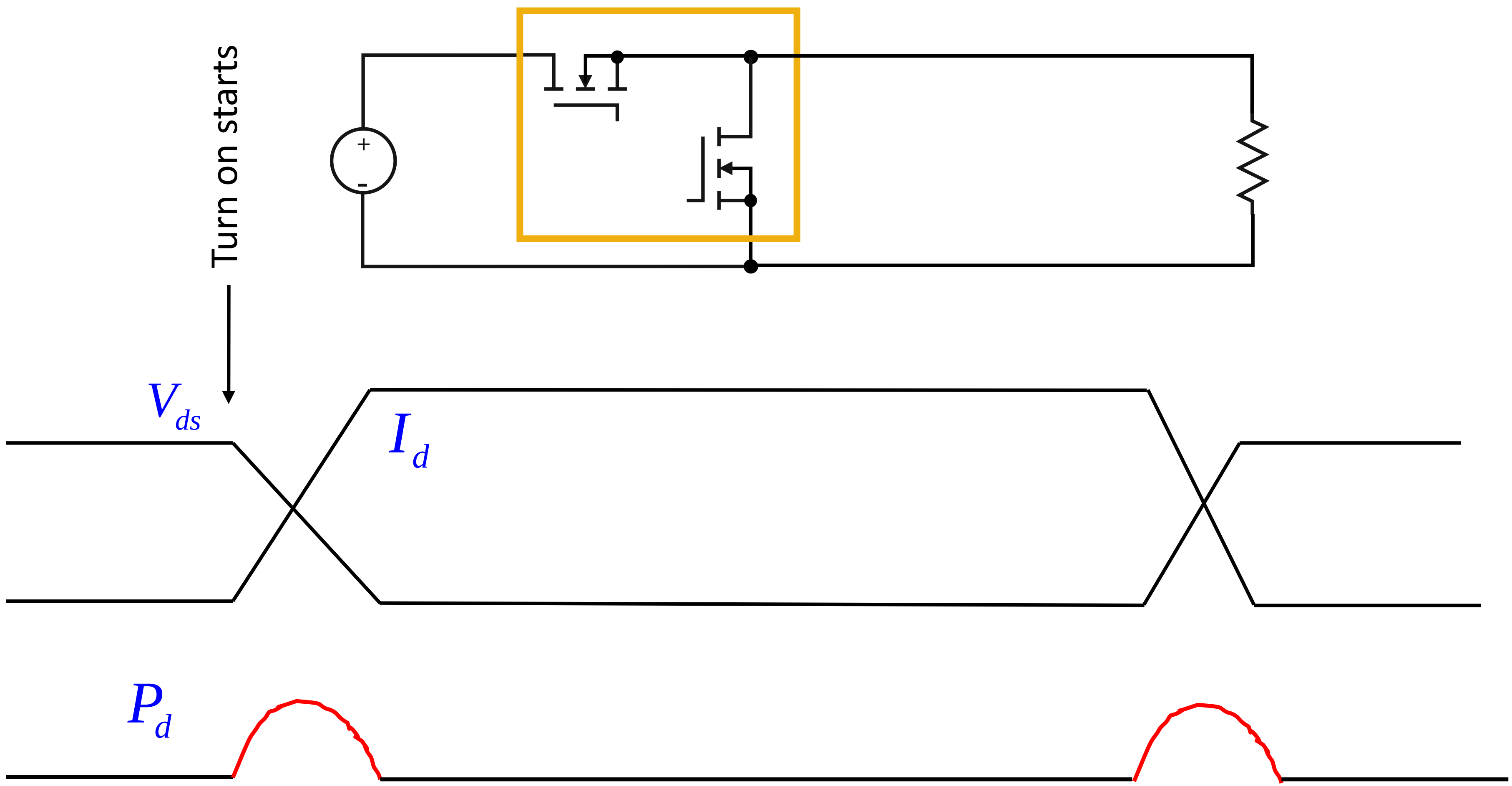
Be like Faraday – don’t obsess over math, just make a transformer.
(We do that in Day 1 of our Workshop)

Soft Switching on All Devices (ZVS)

Semiconductor Switching Losses

and Soft Switching

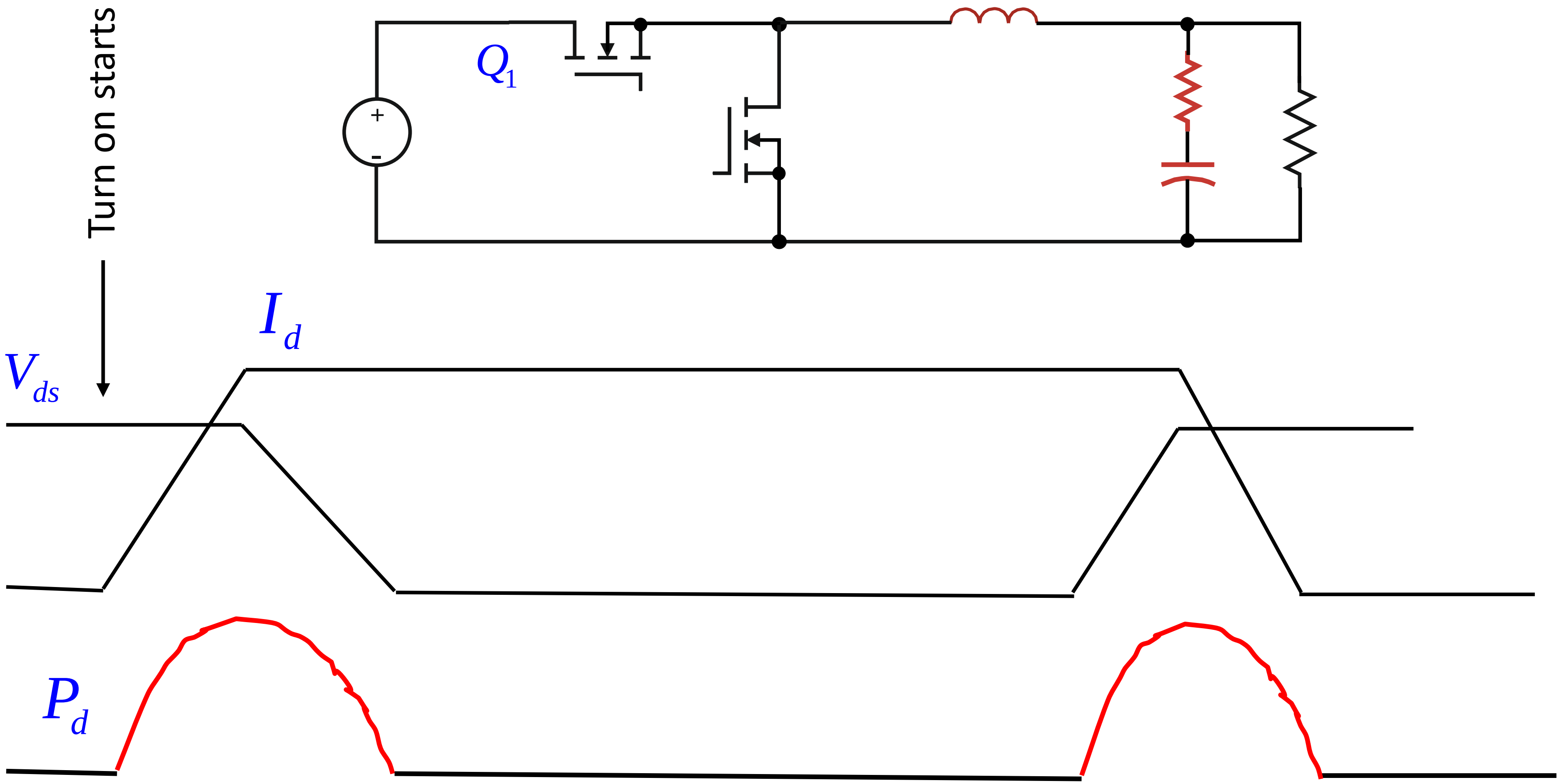
Basic Buck Converter Resistive Switching Loss



Voltage falls as current rises
Switching time determines loss

This never happens!

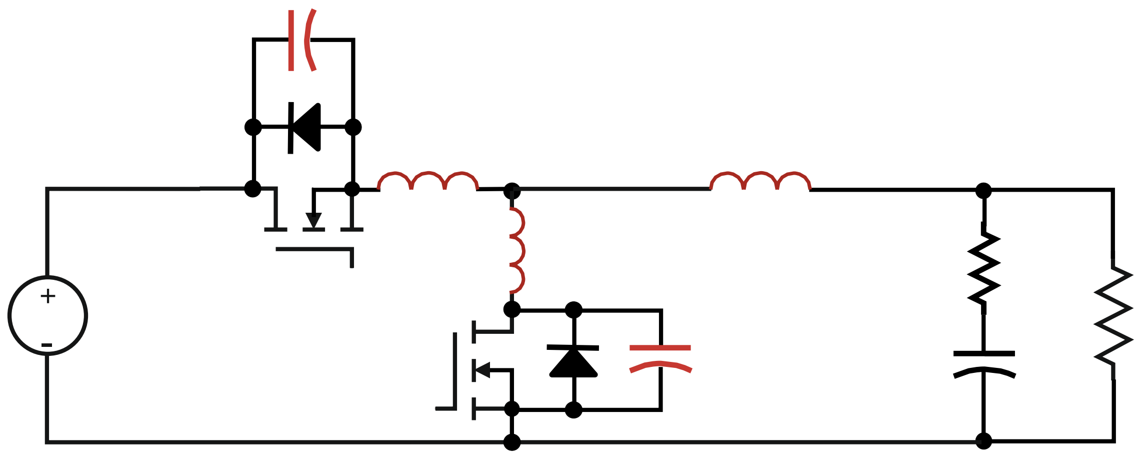
Basic Buck Converter Inductive Switching Loss



Voltage falls after current rises
Switching time determines loss

This never happens either!

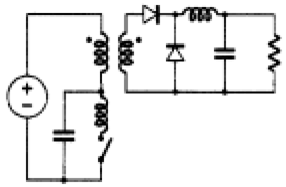
Basic Buck Converter Real Switching Loss

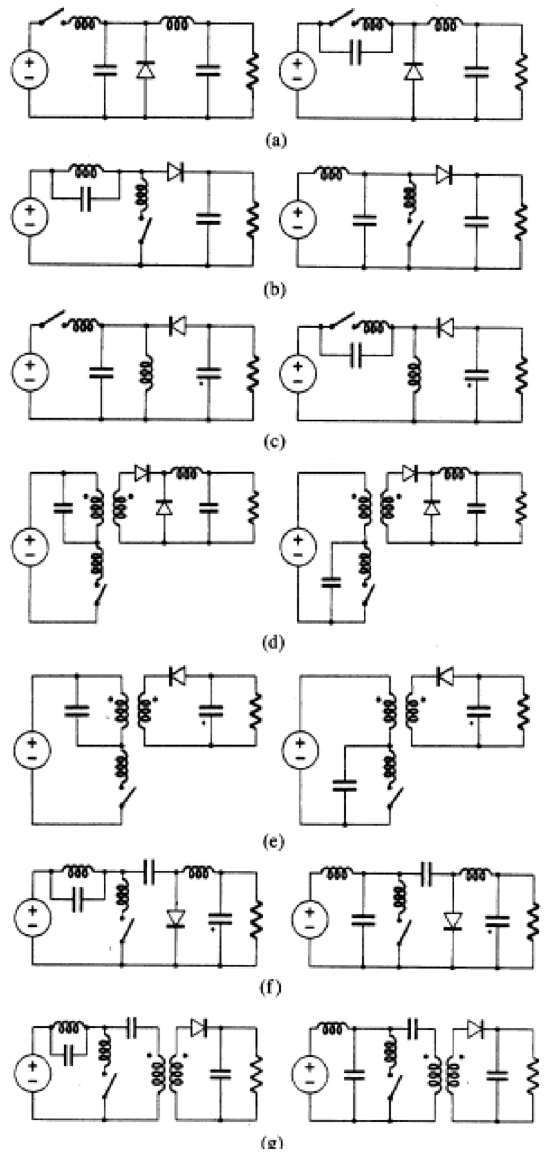


Parasitic components greatly complicate the switching mechanisms

This can be used to your advantage if you know how to use this

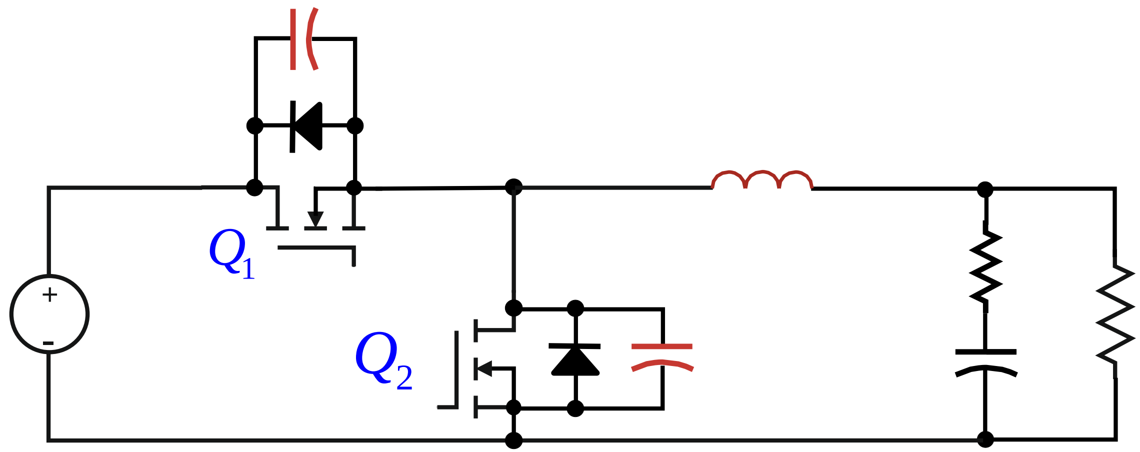
Vicor ZCS Converter Topology and Research at Virginia Tech



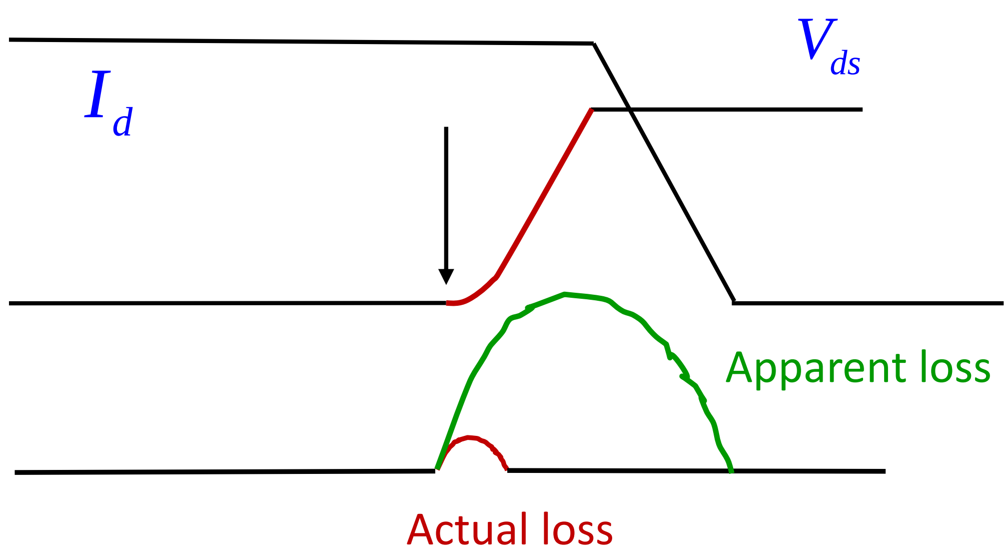


The next Vicor surprise – they Developed ZCS AND ZVS for a Converter, leading the entire industry again.

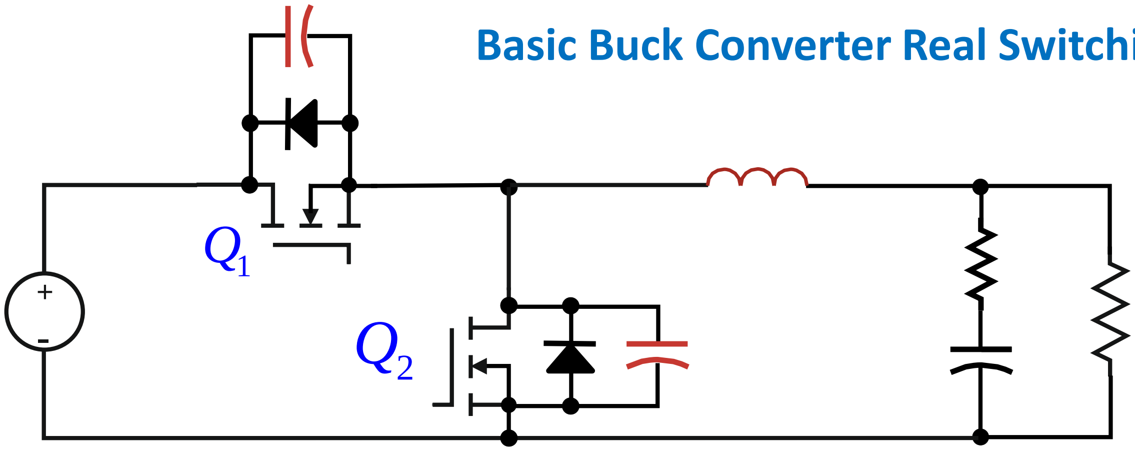
Basic Buck Converter Real Switching Loss: Q1 Turn-Off



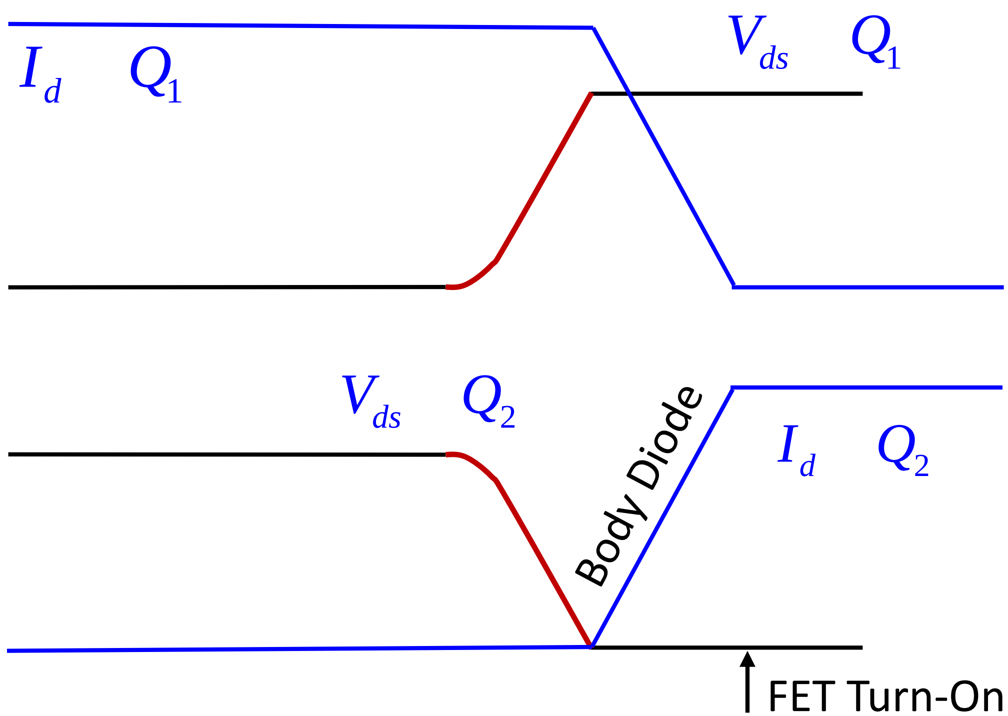
Assuming fast switching, turn-off loss of Q1 is low. (Scope waveforms cannot see this.)



Basic Buck Converter Real Switching Loss: Q2 Turn-On



Turn-on loss of Q2 is low.



Transition is close to lossless

Zero-Voltage Switching Origins

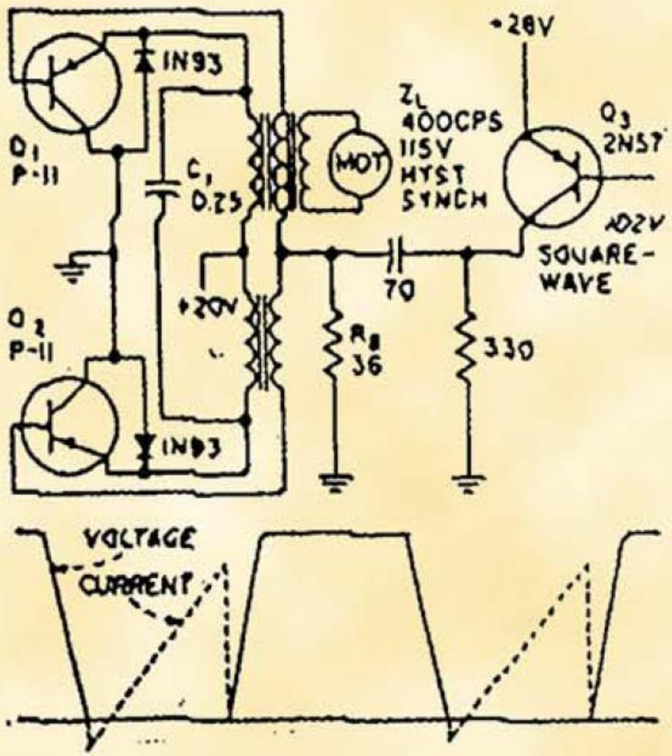


Fig. 3 Published in 1958

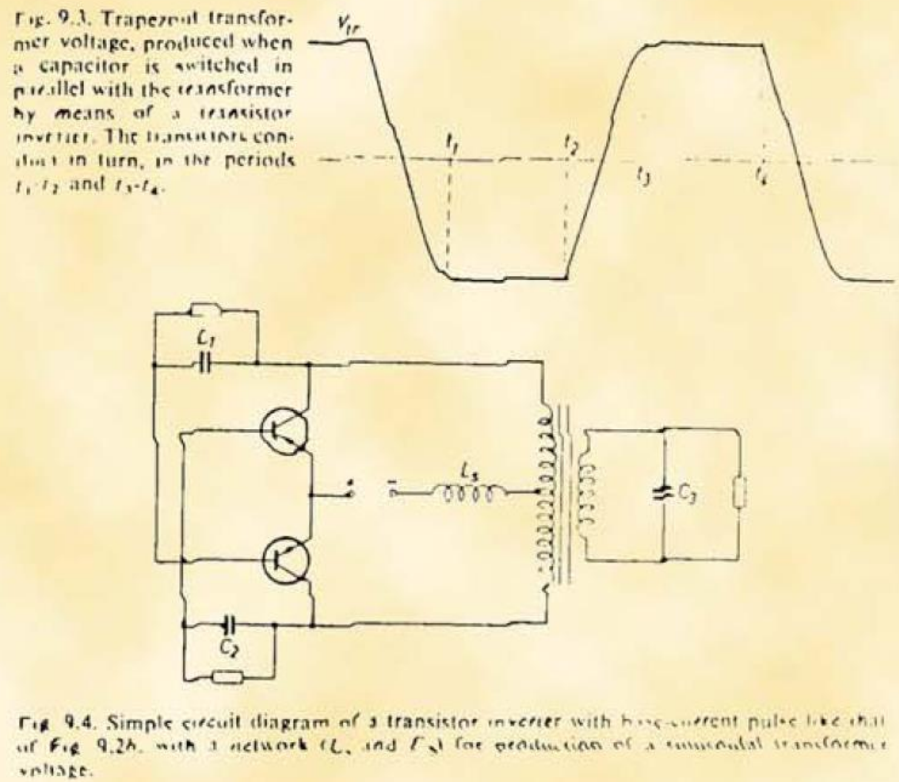


Fig. 4 Published in 1959

Switching losses were of concern a long time ago

Zero-Voltage Switching Origins

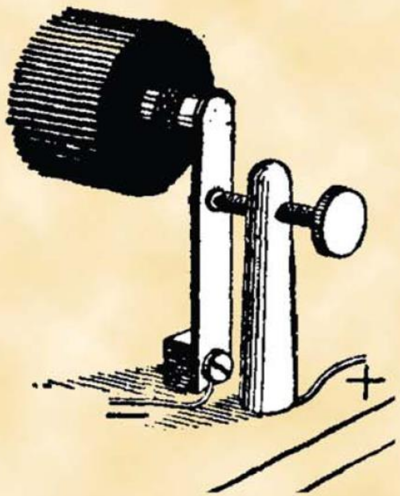


Figure 3. Neef's hammer interrupter

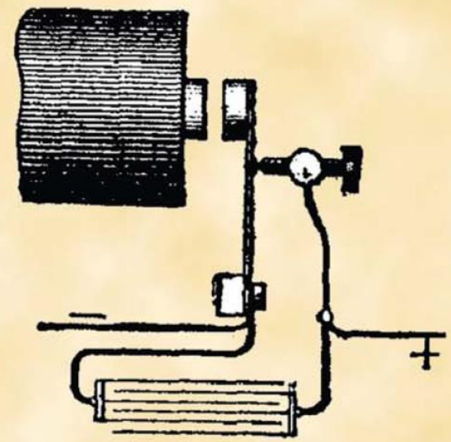
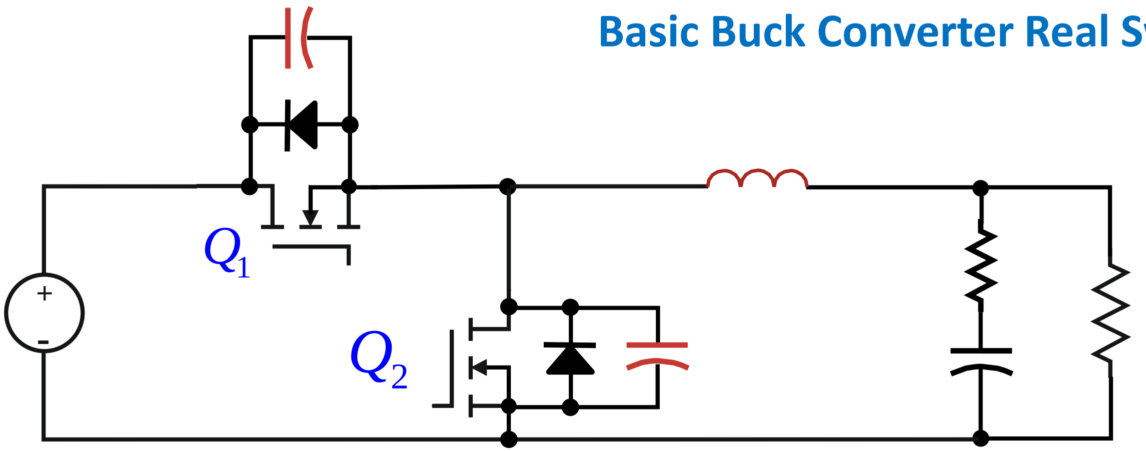


Figure 4. Fizeau's condenser around break

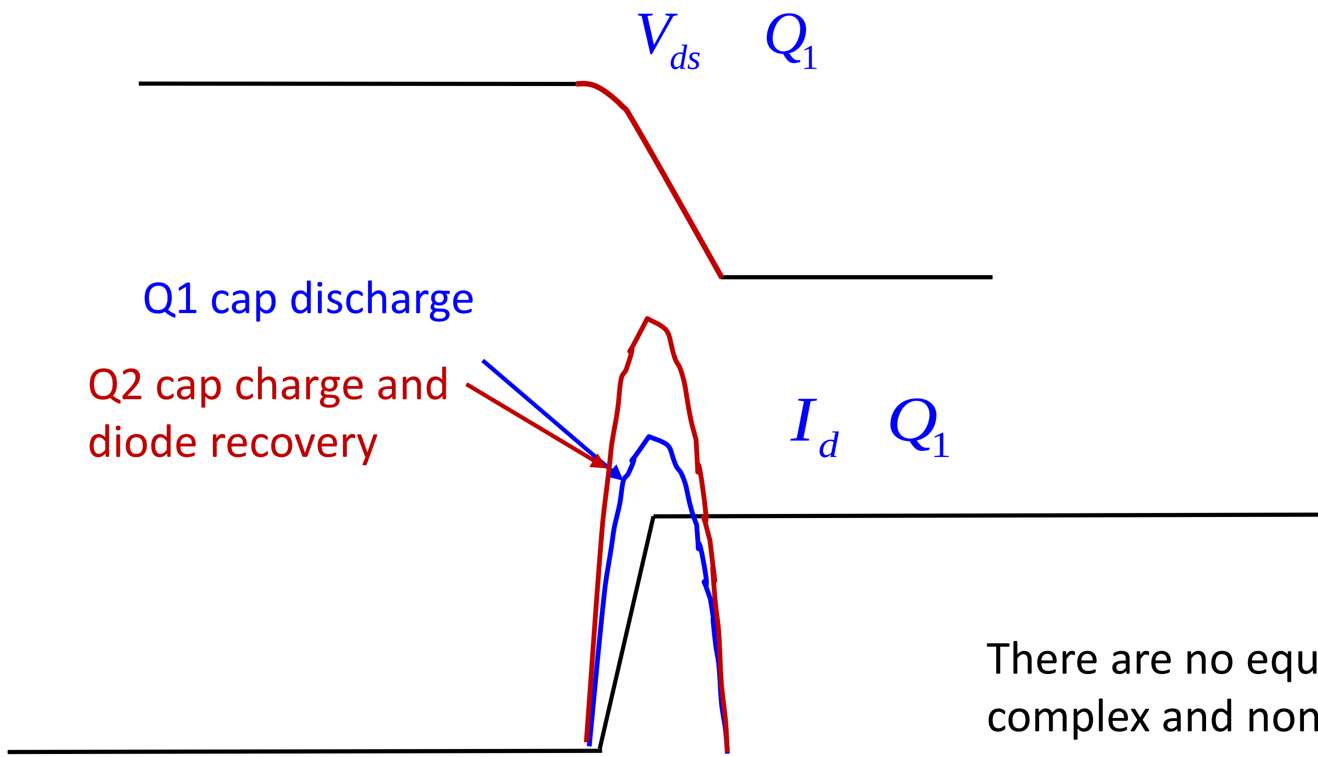
ZVS turn-off in 1853

(Thanks to Rudy Severns for finding this reference.)

Basic Buck Converter Real Switching Loss: Q1 Turn-On

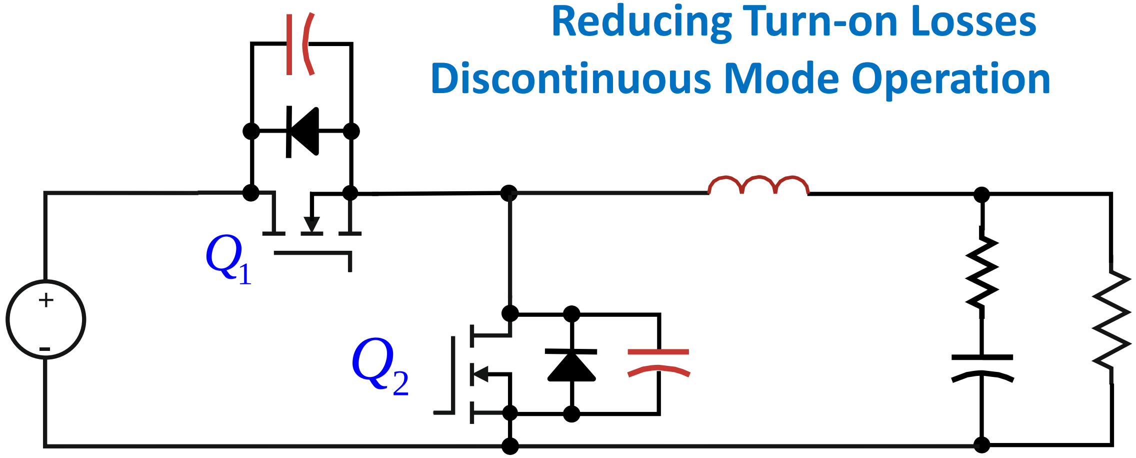


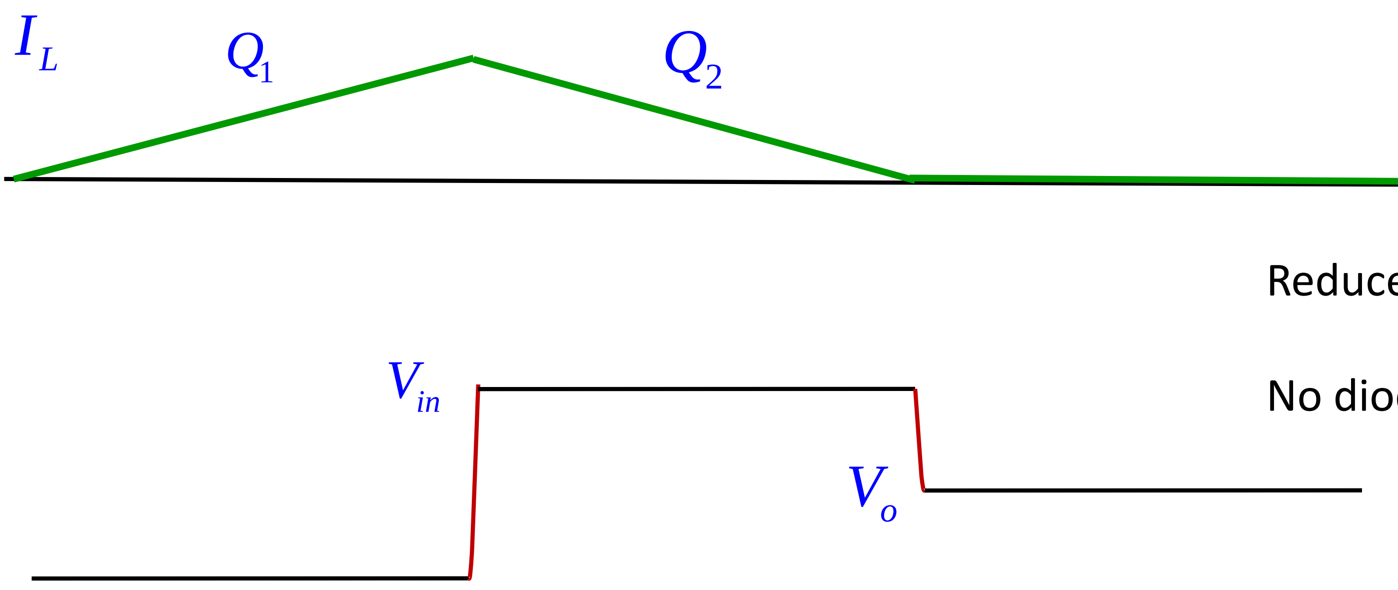
Turn-on loss of Q1 is high.
(Scope waveforms don't show all loss.)



There are no equations. It is too complex and nonlinear

Reducing Turn-on Losses
Discontinuous Mode Operation

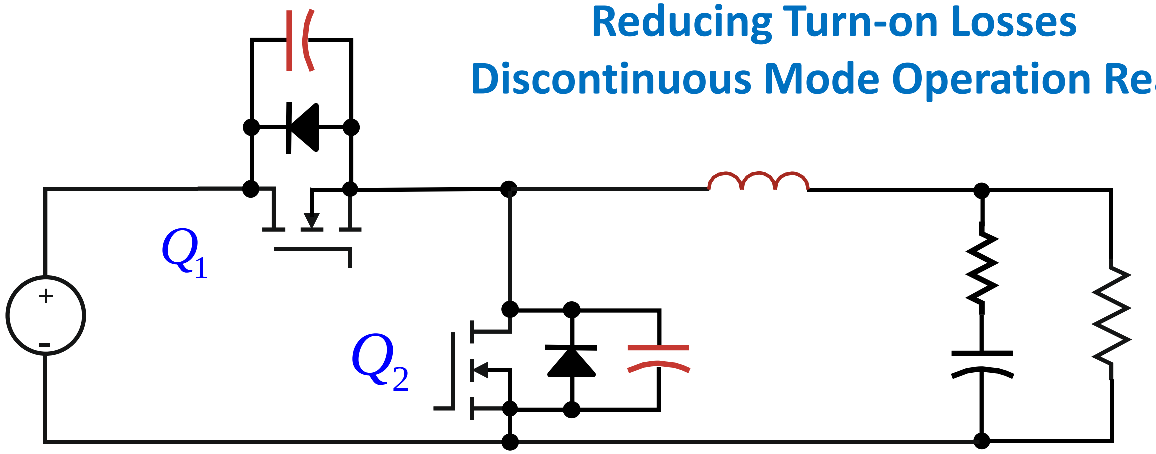


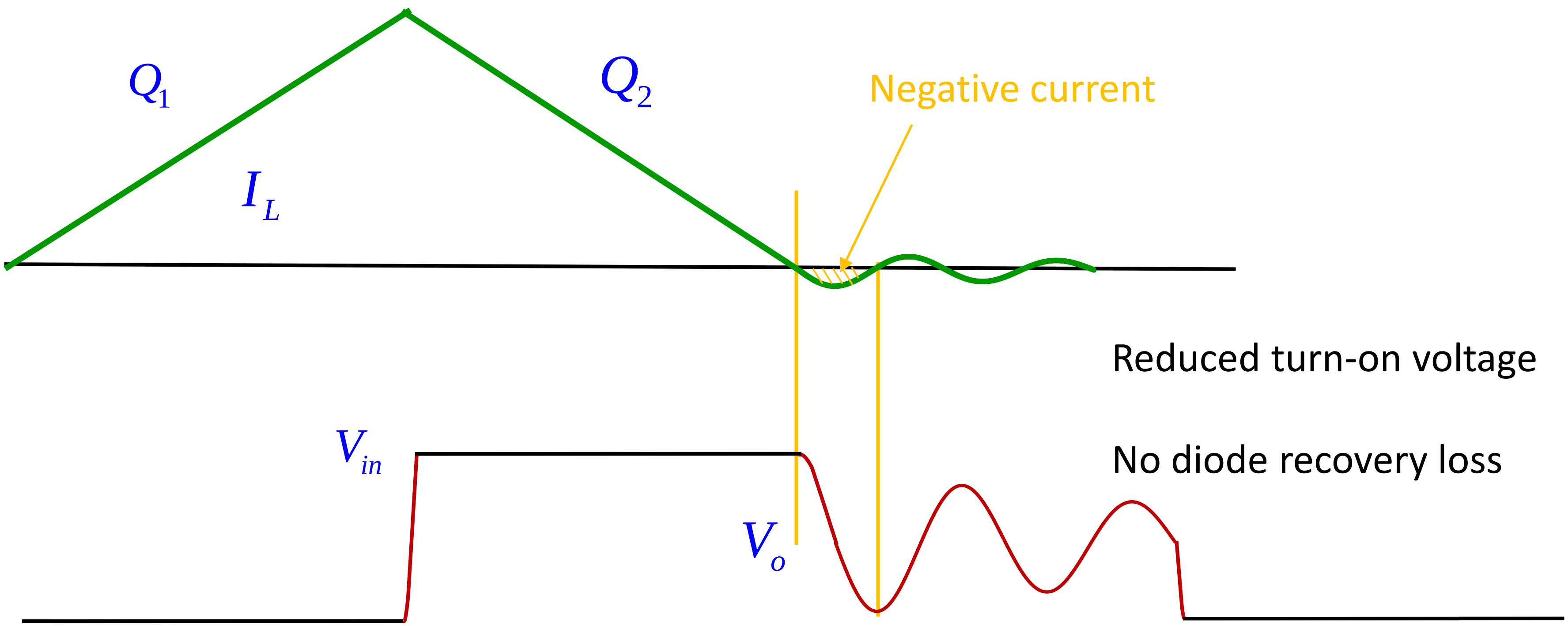


Reduced turn-on voltage

No diode recovery

Reducing Turn-on Losses
Discontinuous Mode Operation Real Waveforms





Reduced turn-on voltage

No diode recovery loss

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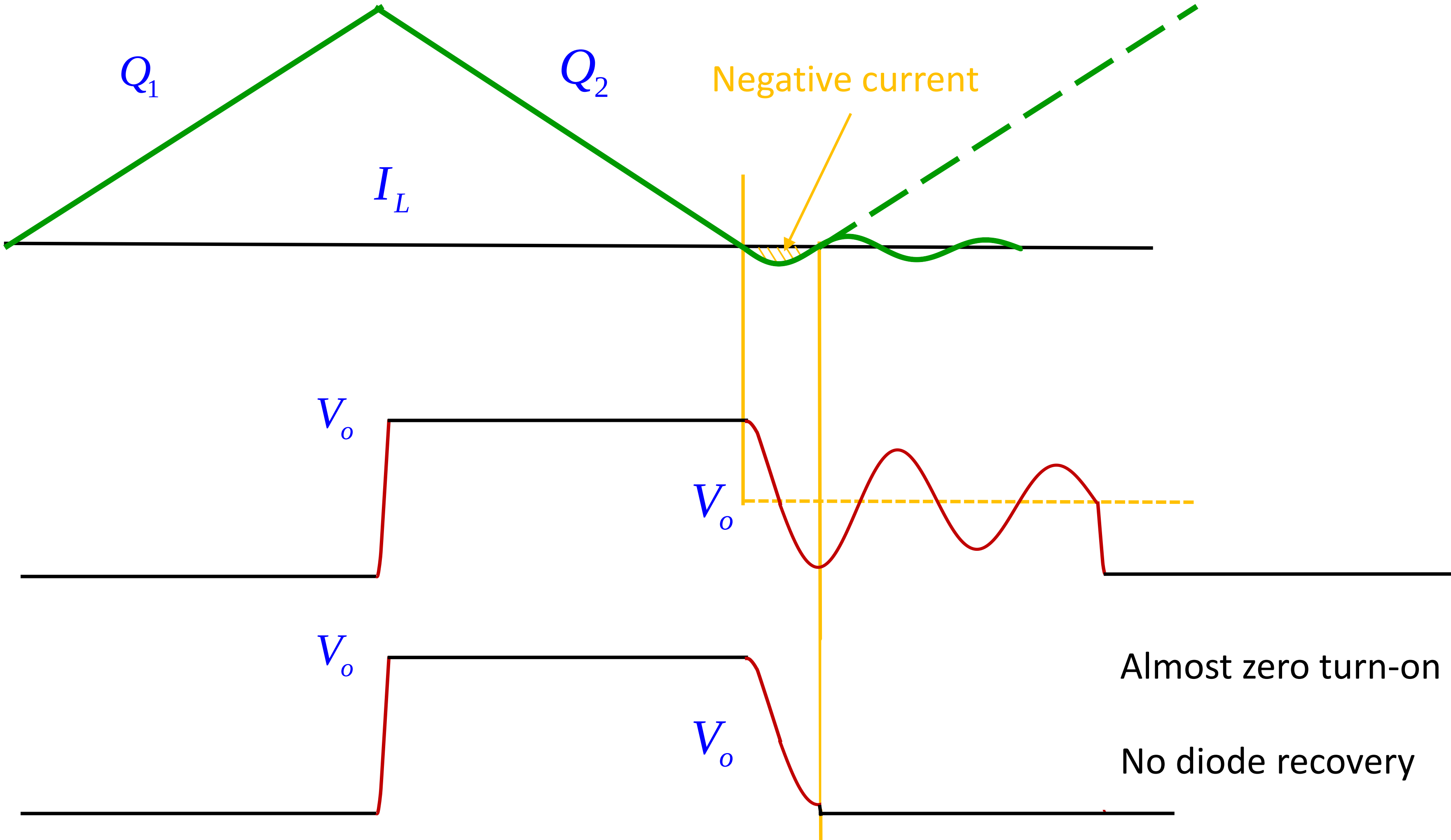
Quasi-Resonant Operation



Almost zero turn-on voltage

No diode recovery

Works for Vo < Vi/2

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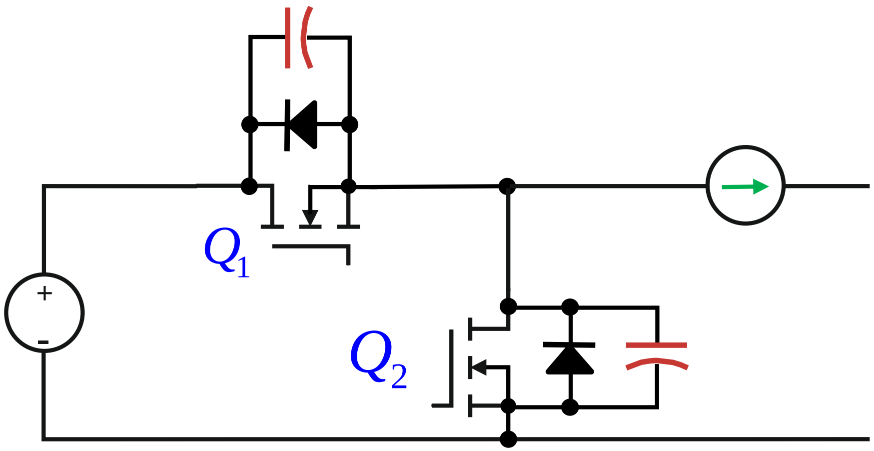
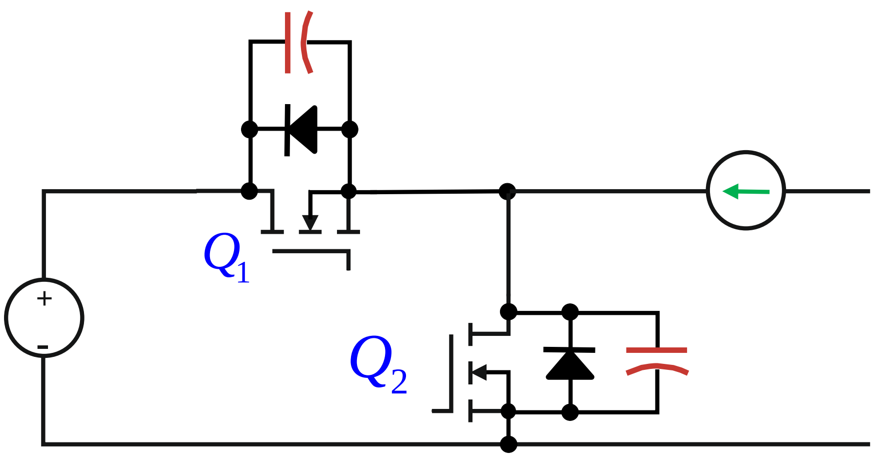
Reducing Turn-on Losses
Discontinuous Mode Operation

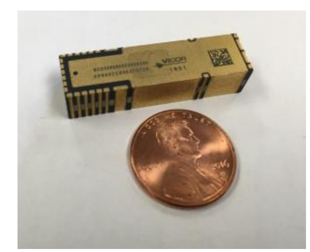


Positive current source commutates Q2



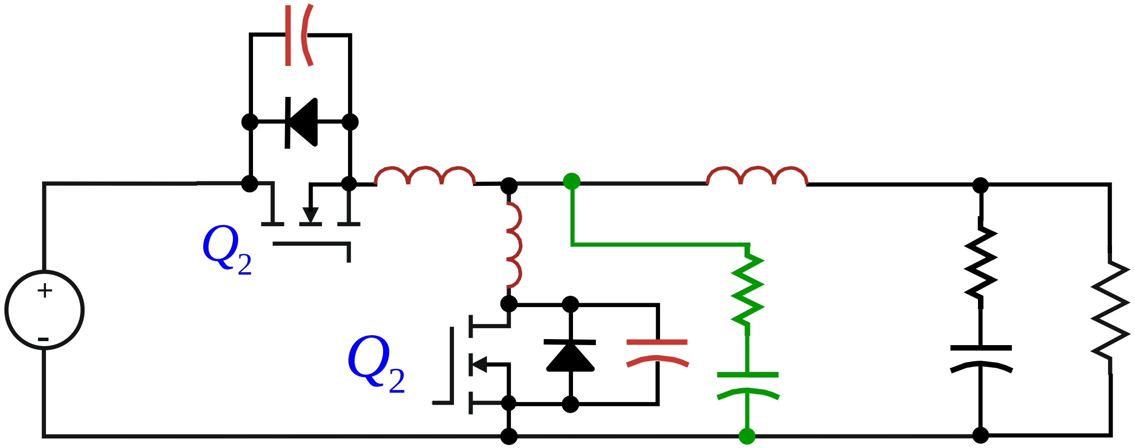
Negative current source commutates Q1

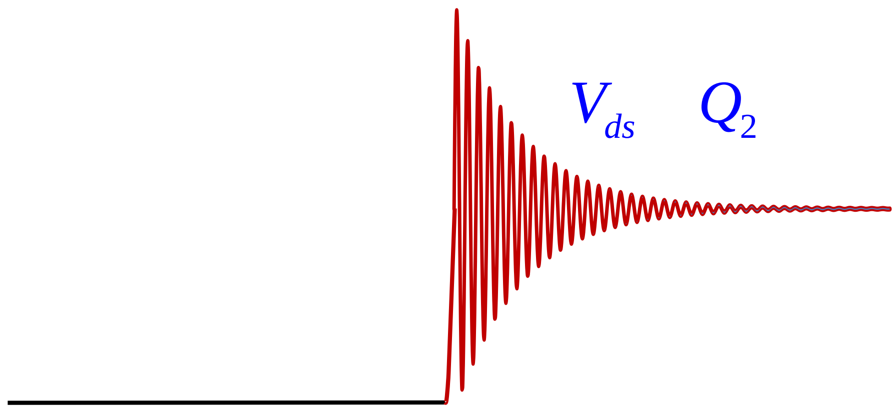
400 W Buck-Boost DCM



LLC Converters

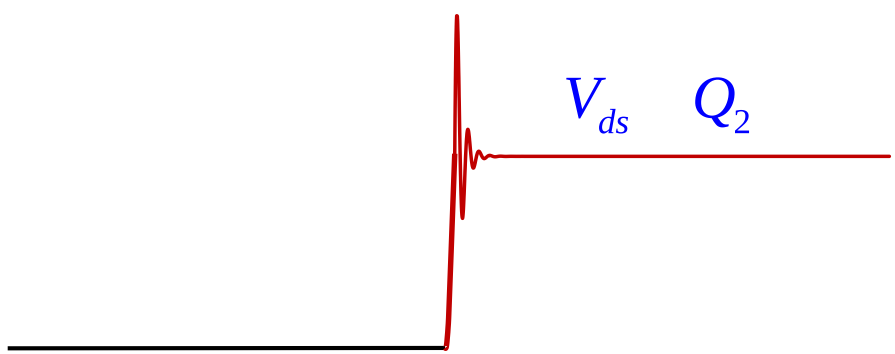
Brute Force Solution to Parasitics





Undamped ringing

20-100 MHz natural frequency



Damped ringing

Some Observations About GaN

This is NOT like FETs versus Bipolar revolution in the 1980s

Gate drive is tough – but this is a GOOD thing.

It is NOT going to boost switching frequencies by 100x

It IS going to take over long term -

- Very low gate driver power
- Ruggedness of "no package"
- Built in drivers for simple design

Very low Rds on

High switching speeds

It will still need ZVS to provide full advantages

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