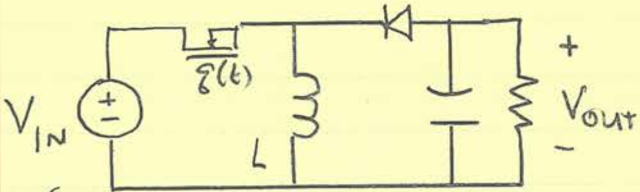
6.334 Lecture Notes — Isolated dc-dc #1

Isolated converter motivations:

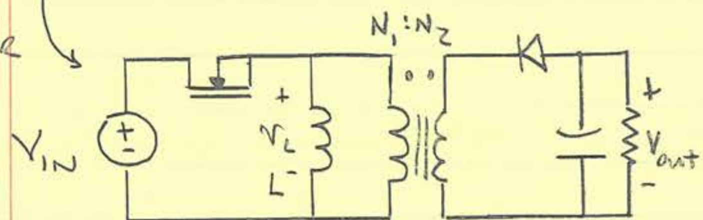
1. Galvanic isolation between input + output (+ different reference nodes)
2. High conversion ratios
3. Ease of generating multiple outputs

Example #1: "Flyback" converter (Isolated buck/boost)



$$\frac{V_{OUT}}{V_{IN}} = \frac{-D}{1-D}$$

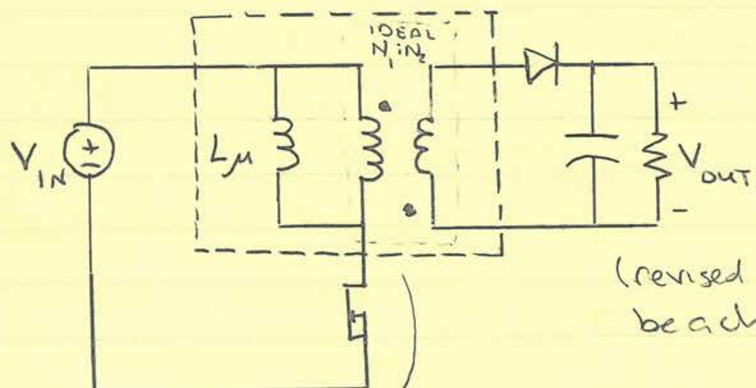
INSERT XFORMER



$$\langle v_L \rangle = D V_1 + (1-D)\frac{N_1}{N_2} V_2 = 0$$

$$\therefore \frac{V_2}{V_1} = -\frac{N_2}{N_1} \cdot \frac{D}{1-D}$$

no common ref: can Δ switch positions + definition of V_{OUT}



$$\boxed{\frac{V_2}{V_1} = +\frac{N_2}{N_1} \frac{D}{1-D}}$$

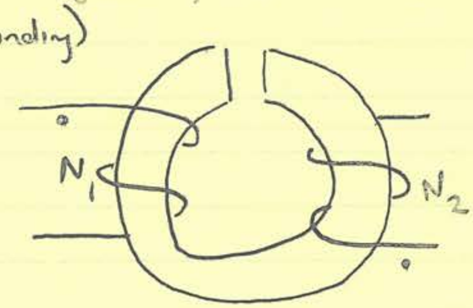
(revised output polarity can be achieved when desired)

Design magnetics as one element: A gapped (energy storage) xformer where the energy is stored in the magnetizing inductance (like a buck-boost inductor w/ a second winding)

⇒ most energy stored in the gap!

1st part of cycle: store energy in xformer through winding #1

2nd part of cycle: remove energy from xformer through winding #2



⇒ Magnetizing energy is continuous, but λ_μ switches between terminals

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Notes ① Energy stored in the magnetizing inductance of the xformer. Design like an inductor (with gap for the energy storage) but add a second winding

② Voltage inversion required in non-isolated version may be eliminated if desired by changing polarity of definition (no common terminals, so this is easy)

③ Can use ground-referenced active switch

④ Turns ratio helps reduce switch + component ratings (keep D near 0.5)

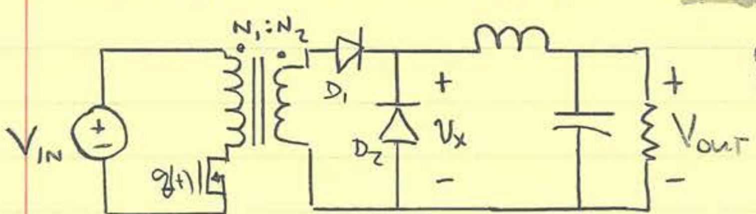
Consider 1 kW @ $V_{IN} = 100$, $V_{OUT} = 10\,V$

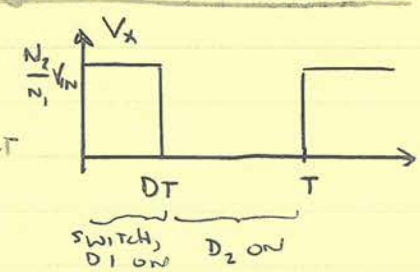
Buck/Boost	Flyback @ $N_2:N_1 = 1:10$
$V_{SW}, V_D = 110\,V_{pk}$	$V_{SW} = 200\,V$, $V_D = 20\,V$
$I_{SW}, I_D = 110\,A_{pk}$	$I_{SW} = 20\,A$, $I_D = 200\,A$

BETTER BALANCES DEVICES

⑤ EASY TO OBTAIN MULTIPLE OUTPUTS BY ADDING MORE WINDINGS

Isolation in a direct converter: <u>Single-Ended Forward Conv</u>





This is essentially a buck converter w/ a transformer!

$$\langle V_{OUT} \rangle = \langle V_x \rangle = D\underbrace{\left(\frac{N_2}{N_1} V_{IN}\right)}_{\text{Switch on } V_x} + (1-D)\cdot \underbrace{0}_{V_x \text{ switch off}} \Rightarrow \boxed{\frac{V_{OUT}}{V_{IN}} = \frac{N_2}{N_1} D}$$

But consider the effect of the (undesired) magnetizing inductance L_μ of the transformer!

→ we must keep $\langle v_{L\mu} \rangle = 0$ or xformer will saturate

→ must provide a path for i_μ until core "resets" to zero flux

★ ⇒ Unlike in the flyback converter, the magnetizing inductance is <u>not</u> a desired circuit element, + <u>hurts</u> performance

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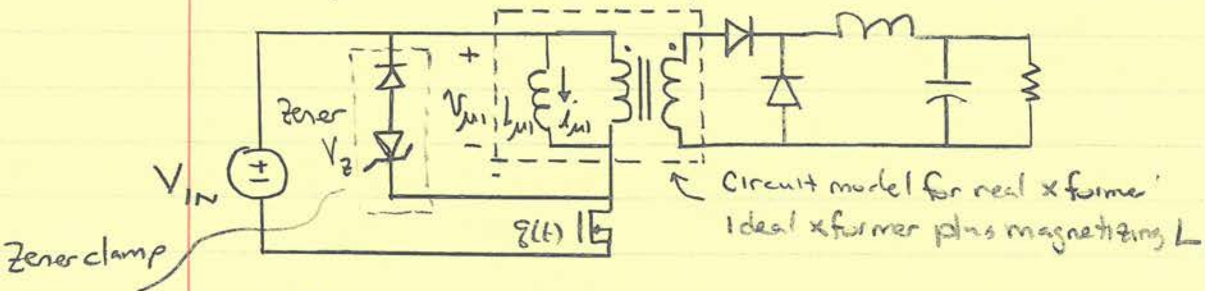
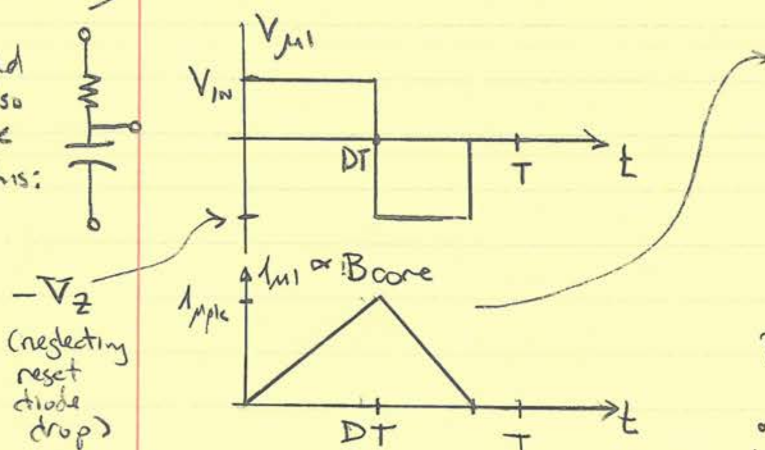
We must "reset" the core flux to zero each cycle!
One simple method: "clamp" reset circuit



Could also use this:



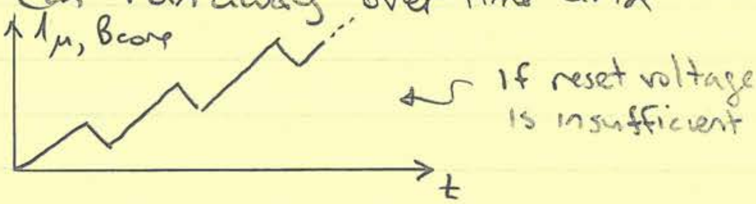
$$\lambda_{\mu 1} = L_{\mu 1} i_{\mu 1} = N_1 B_{core} A_c$$

$$\therefore B_{core} = \frac{L_{\mu 1}}{N_1 A_c} \cdot i_{\mu 1} = \frac{\lambda_1}{N_1 A_c}$$

Peak core flux $\Delta i_{\mu 1} = \frac{V_1}{L_{\mu 1}} DT$

$$\therefore B_{pk} = \frac{V_1 DT}{N_1 A_c}$$

We need to ensure that $\int V_\mu \, dt \to 0$ to "reset" the core.
Otherwise i_μ, B_{core} can "run away" over time and saturate the core:



To reset the core:

$$V_Z(1-D)T \geq V_{IN} DT \Rightarrow V_Z \geq V_{IN} \cdot \frac{D}{1-D}$$

The peak switch voltage is $V_{SW,pk} = V_Z + V_{IN}$

So, $V_{pk} \geq V_{IN}\left(\frac{1-D}{1-D}\right) + V_{IN}\left(\frac{D}{1-D}\right) = V_{IN} \cdot \frac{1}{1-D}$!

@ $D_{MAX} = 0.5 \rightarrow V_{SW,pk} = 2V_{IN}$
$D_{max} = 0.75 \rightarrow V_{SW,pk} = 4V_{IN}$
} with minimum clamp voltage

This is poor compared to the non-isolated buck where $V_{pk} = V_{IN}$!

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How much <u>power</u> do we lose in resetting the core this way? (we dissipate stored magnetizing energy in Zener)

$$W_{DISS} = \frac{1}{2} L_{\mu 1} i_{\mu 1, pk}^2 = \frac{1}{2} L_\mu \left(\frac{V_{IN} D T}{L_\mu} \right)^2 = \frac{V_{IN}^2 D^2 T^2}{2 L_\mu}$$

$L = \frac{N^2 \mu_c A_c}{l_c}$

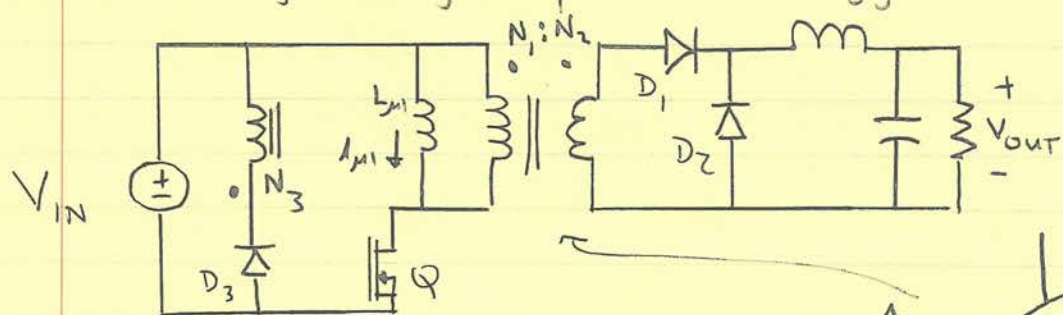
$$P_{DISS} = \left(\frac{1}{T}\right) \cdot W_{DISS} = \frac{V_{IN}^2 D^2 T}{2 L_\mu}$$

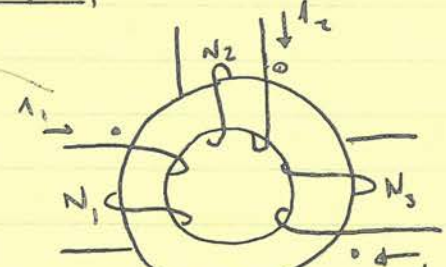
($\frac{1}{T}$ ← f_{sw})

∴ we want L_μ <u>as big as possible</u> to minimize energy stored in xformer + dissipated. ∴ we typically use an <u>ungapped</u> (or minimally gapped) core to maximize L_μ and minimize reset loss.

Other clamp methods allow us to <u>recover</u> magnetizing energy:

① Tertiary winding clamp: recover energy back to input





When Q is off D_3 turns on until magnetizing energy returned to input (or next cycle starts)

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} = \frac{V_3}{N_3}$$

To reset the core we require

$$\boxed{D V_{IN} T \le (1-D)\left(\frac{N_1}{N_3}\right) V_{IN} T}$$

The voltage stresses are the same (<u>neglecting</u> leakage inductance effects)

Advantages: Magnetizing energy is (mostly) recovered

Disadvantages:
- still need a snubber to handle leakage inductance
- more transformer windings.

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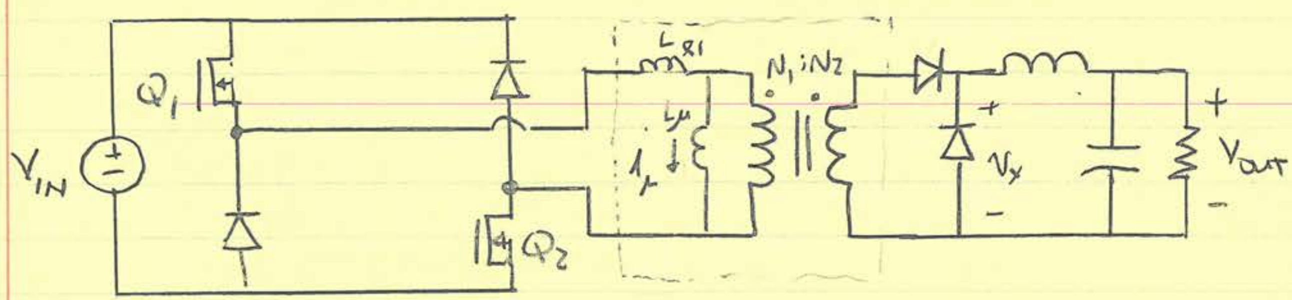
(2) Two-switch single-ended forward converter



- Turn switches Q_1, Q_2 on and off together with duty ratio D
  - ⇒ $0 < D < 0.5$ to guarantee core reset (energy recovered back to input)
  - ⇒ leakage energy of transformer is also recaptured

- Requires two active switches, each with $V_{sw,pk} > V_{IN}$ (only one is ground referenced). This compares to a single switch rated at $>2V_{IN}$ for a normal forward with a maximum 50% duty ratio.