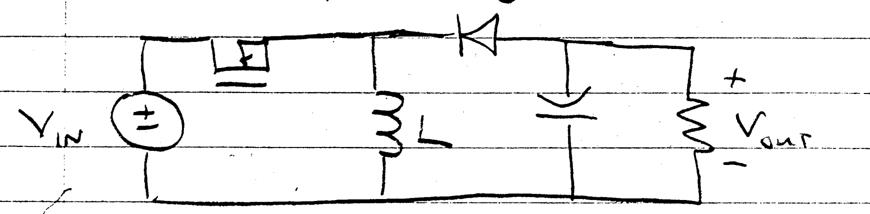
6.334 Power Electronics
Spring 2007

Power Electronics Notes - D. Perreault

★★ Isolated DC/DC Converters

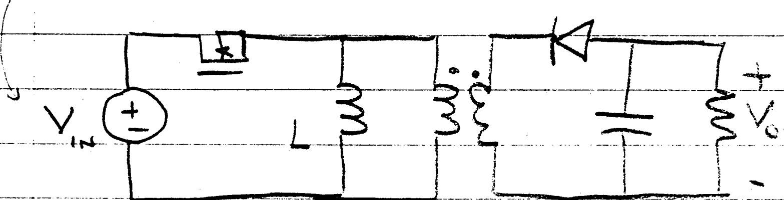
motivations: 1. Galvanic Isolation between input + output
2. High Conversion ratios
3. Ease of generating multiple outputs

★ First example: Flyback Converter (indirect converter)



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

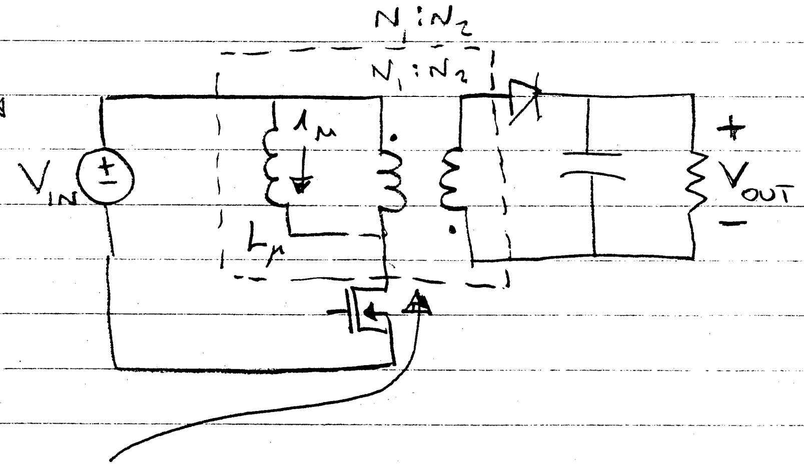
INSERT XFORMER



$$D V_{IN} + (1-D)\frac{N_1}{N_2} V_{OUT} = 0$$

$$\frac{V_{OUT}}{V_{IN}} = -\frac{D}{1-D}\left(\frac{N_2}{N_1}\right)$$

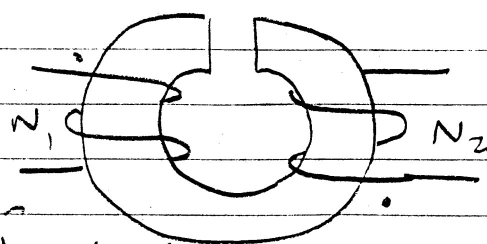
Δ switch positions, V_{OUT} definition



$$\boxed{\frac{V_{OUT}}{V_{IN}} = \frac{D}{1-D}\left(\frac{N_2}{N_1}\right)}$$

Design magnetics as one element: A gapped transformer where the energy is stored in the magnetizing inductance of the transformer [Like a flyback inductor w/ a second winding]

e.g. Flyback Xformer



1st part of cycle: Energy is stored in xformer through winding 1
2nd part of cycle: Energy is removed from xformer through winding 2.

→ λ_μ is ≃ constant, but switches between terminals

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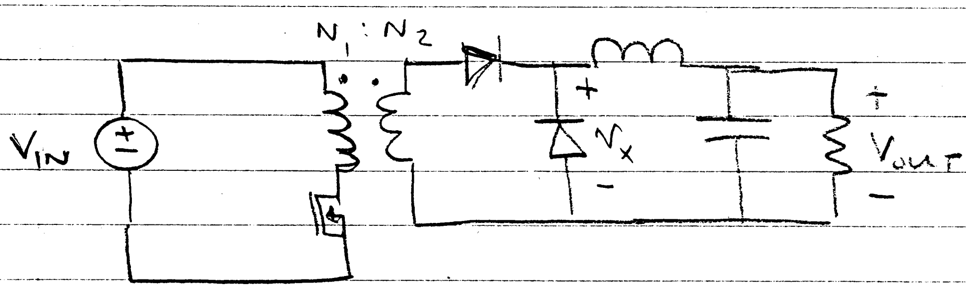
1. Energy stored in magnetizing inductance of transformer (Design like inductor, but w/ 2nd winding)
2. Voltage inversion of nonisolated indirect may be eliminated (if desired) by winding direction
3. Can use ground-referenced primary switch
4. Turns ratio helps reduce switch + component ratings (keep D near 0.5)
5. Could add more outputs by adding more windings.

Isolation can also be added in direct converters, e.g.:

★ Single – ended forward converter (isolated buck converter)



This is Essentially a buck w/a transformer inserted.

switch on $V_x = \left(\frac{N_2}{N_1}\right) V_{IN}$

switch off $V_x = 0$

$$\frac{V_{OUT}}{V_{IN}} = \left(\frac{N_2}{N_1}\right) D$$

But consider the effect of (undesired) magnetizing inductance L_μ
→ we need $\langle V_{L\mu} \rangle = 0$ or core will saturate
→ must provide a path for i_μ until core "resets" to zero flux

(Unlike in the flyback converter, the magnetizing inductance is not a desired circuit element!)

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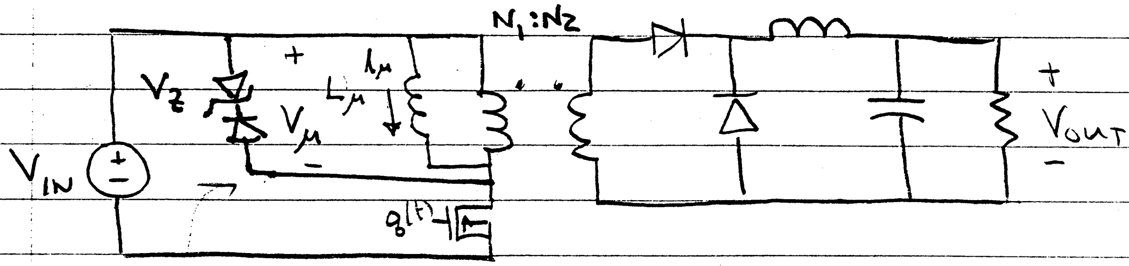
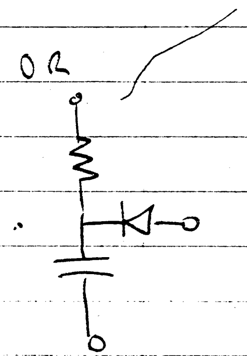
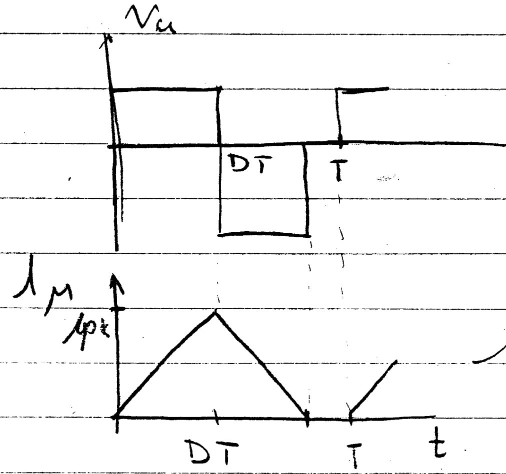
We must reset the core flux to zero each cycle!

One simple method: Clamp reset circuit



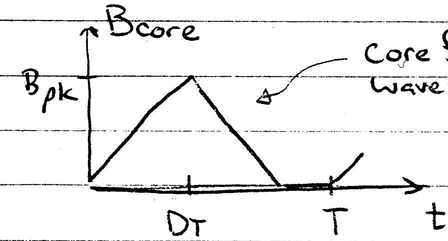
OR





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

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



$$\text{peak core flux: } B_{pk} = \frac{V_{IN} DT}{N_1 A_c}$$

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

The required zener voltage for the clamp is:

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

* The peak switch voltage is: $V_{pk} = V_{IN} + V_Z$

$$\therefore V_{pk} \geq V_{IN}\left(\frac{1-D}{1-D}\right) + V_{IN}\left(\frac{D}{1-D}\right) = \boxed{\frac{V_{IN}}{1-D}}$$

@ $D_{MAX} = 0.5 \rightarrow V_{pk} = 2 V_{IN}$

$D_{max} = 0.75 \rightarrow V_{pk} = 4 V_{IN}$

This is poor compared to the nonisolated case, where $V_{pk} = V_{IN}$!

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How much power do we lose resetting the core this way?

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

$$\Rightarrow P_{diss} = (W_{diss}) \left(\underbrace{\frac{1}{T}}_{f} \right) = \frac{V_{IN}^2 D^2 T}{2 L_\mu}$$

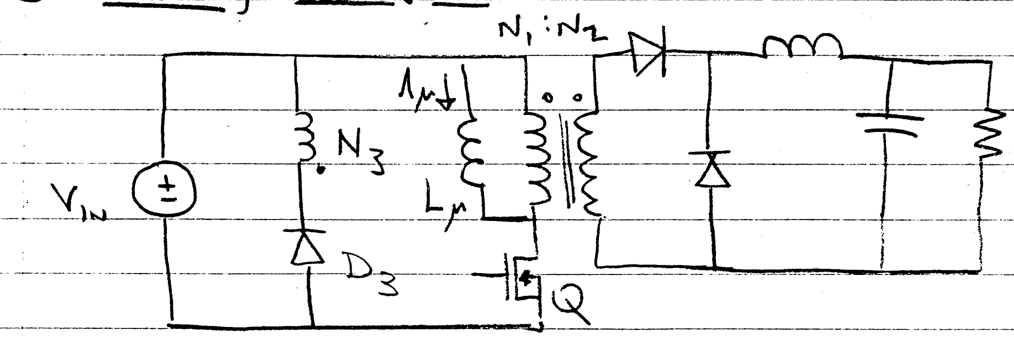
∴ we want L_μ as big as possible to minimize energy stored in xformer + dissipated ∴ We typically use an ungapped (or minimally-gapped) core to maximize L_μ, and minimize reset loss.

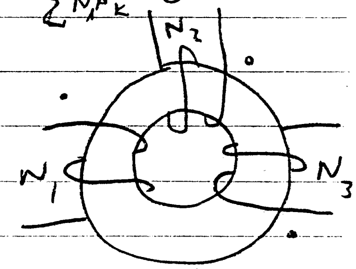
Other clamp methods allow us to recover magnetizing energy:

① Tertiary winding clamp

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

$$\sum N_k i_k = 0$$





magnetizing energy returned to V_{IN} (when Q off, D_3 on to discharge L_μ)

To reset core, we require $\boxed{\frac{N_1}{N_3} V_{IN} (1-D) T \geq V_{IN} D T}$

∴ The voltage stresses are the same (neglecting leakage L)

Advantages: Magnetizing energy is mostly recovered

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

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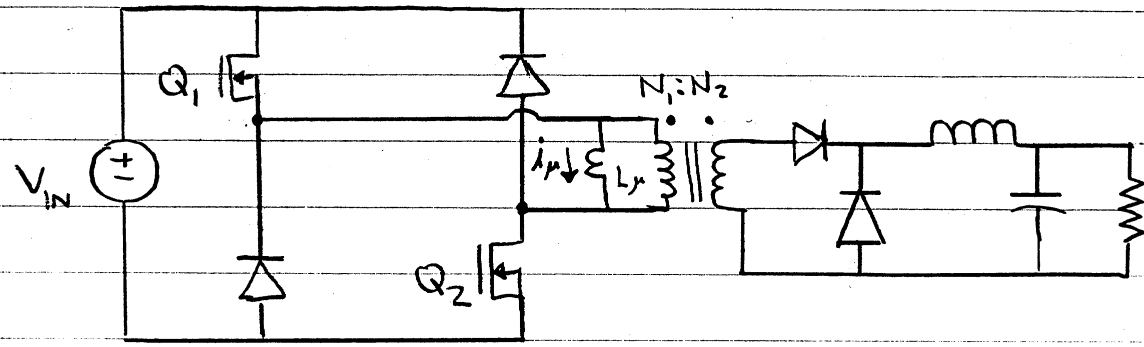
(2) Two-switch single-ended forward converter

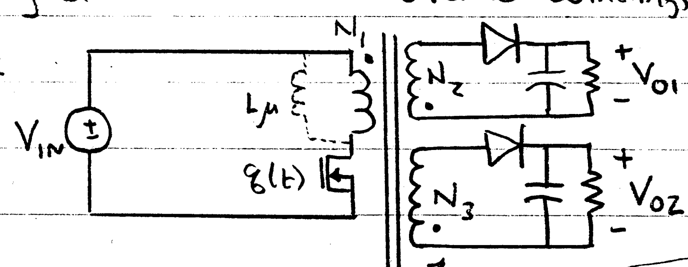


- Turn switches Q_1 and Q_2 on and off together with duty ratio D
- Diodes conduct to reset core (recovering energy to input)
  - $\Rightarrow 0 \leq D < 0.5$ to guarantee core reset
  - $\Rightarrow$ leakage energy of transformer is also recaptured
- Requires two switches rated at V_{IN} (only one gnd referenced)

★ MULTIPLE OUTPUTS FROM ISOLATED CONVERTERS

- To get additional outputs having proportionally-related outputs, we need only add additional transformer windings and output stages

e.g., flyback



SERIES-WOUND TRANSFORMER CORE

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

IDEALLY: $\frac{V_{01}}{V_{IN}} = \frac{D}{1-D}\left(\frac{N_2}{N_1}\right)$, $\frac{V_{02}}{V_{IN}} = \frac{D}{1-D}\left(\frac{N_3}{N_1}\right) \Rightarrow \frac{V_{02}}{V_{01}} = \frac{N_3}{N_2}$

- We can get multiple outputs with only modest increases in complexity
- Additional outputs often used to power converter control logic (with bootstrap!)
- Transformer nonidealities can become a significant issue (nonideal voltage relationships)

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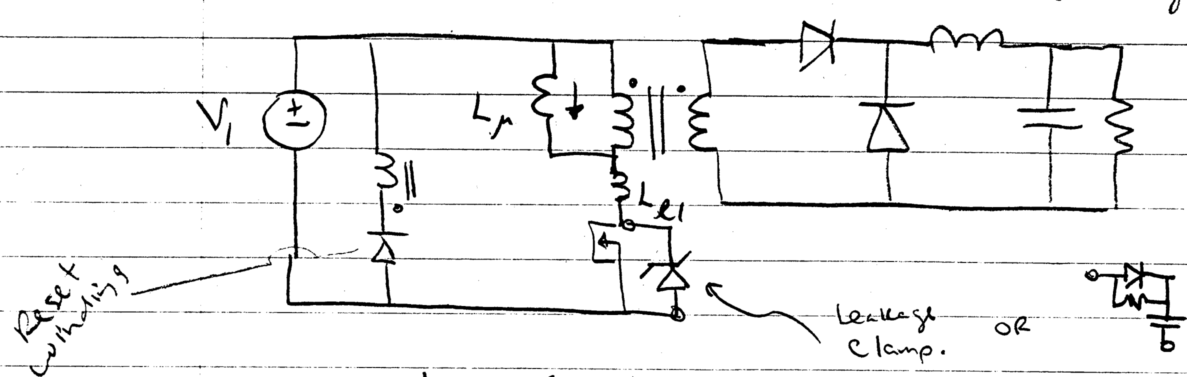
* TRANSFORMER LEAKAGE INDUCTANCES

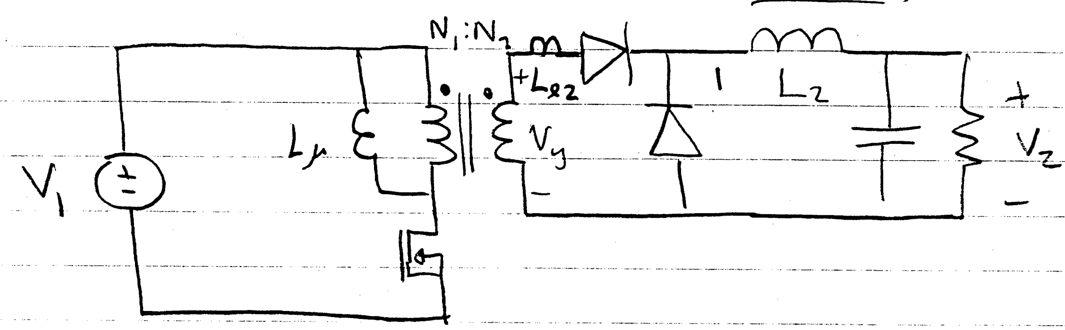
Leakage inductance parasitics also influence operation:

Consider a forward converter with primary leakage (only)



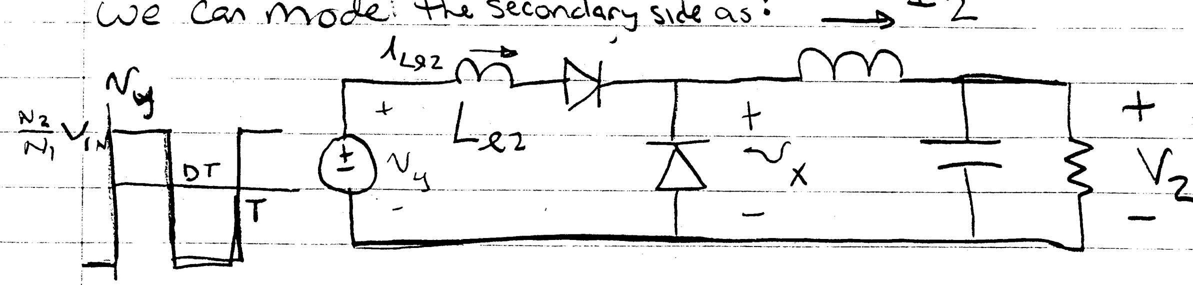
when we turn off the main switch, the reset winding can handle magnetizing current/energy, but not primary-side leakage inductance. We may need to add additional circuitry to absorb or recycle this energy! (e.g. Zener).

Consider a forward converter with secondary-side leakage only



$L_2 >> L_{\ell 2}$

we can model the secondary side as:



From this, we can calculate the voltage conversion ratio

⇒ Load regulation effects due to secondary leakage result in a load current dependence of the conversion ratio!

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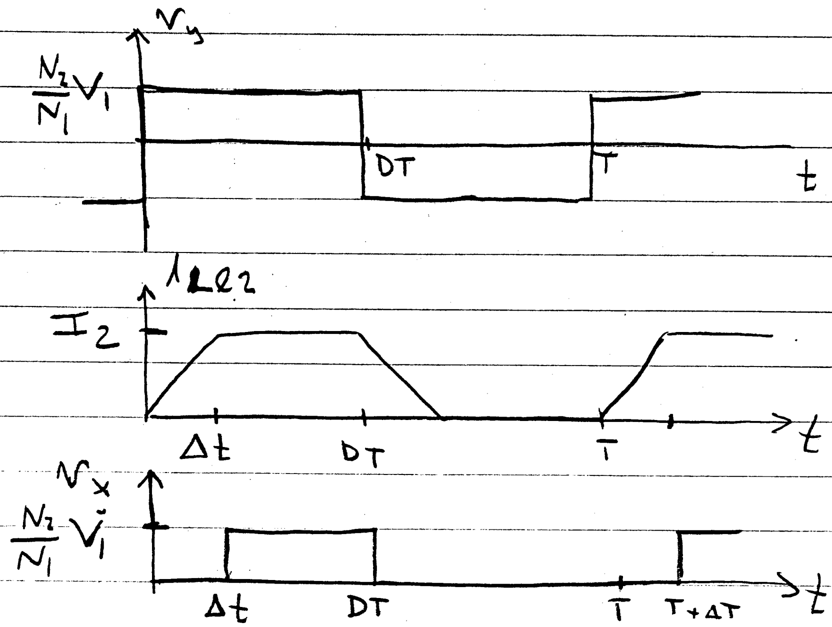

$$V = L\frac{di}{dt}$$

$$\therefore \Delta t = \frac{L_{\ell 2} I_2}{\left(\frac{N_2}{N_1}\right)V_1}$$

$$V_2 = \langle v_x \rangle = \frac{N_2}{N_1}\left(D - \frac{\Delta t}{T}\right)V_1$$

So we may calculate the conversion ratio as:

$$\boxed{V_2 = \frac{N_2}{N_1} D V_1 - \frac{L_{\ell 2}}{T} \cdot I_2}$$

SO THE CONVERSION RATIO NOW NOT ONLY DEPENDS ON DUTY RATIO, BUT LOAD CURRENT

- WE WILL HAVE TO INCREASE DUTY RATIO AS LOAD ↑
- THIS IS CALLED <u>LOAD REGULATION</u>! (as with rectifiers)

This becomes <u>VERY IMPORTANT</u> with multiple outputs.

- we can only adjust D to regulate one output
- since conversion ratios now depends on load currents, the output voltages are not related by turns ratio (adjusting for load variations on one output can change the voltage at the other output!)

⟹ This is called "cross regulation" + is undesirable!

∴ The transformer parasitics are important for isolated converter operation

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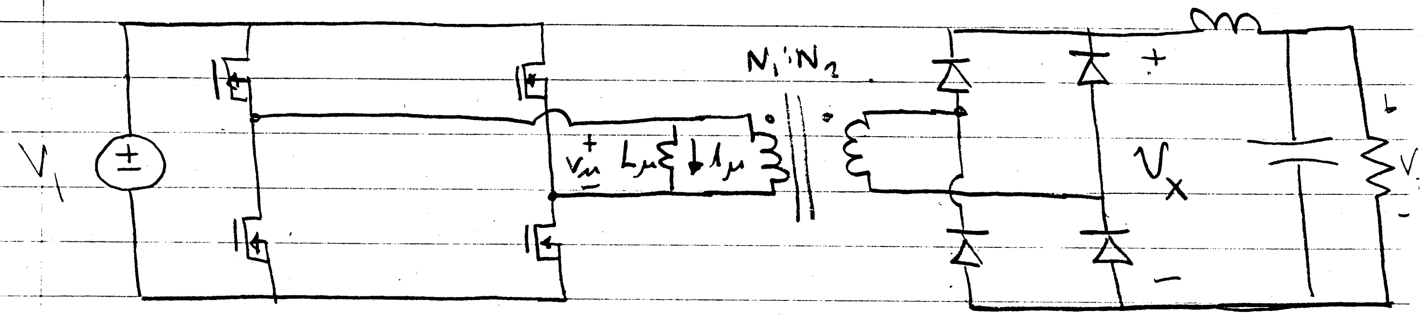
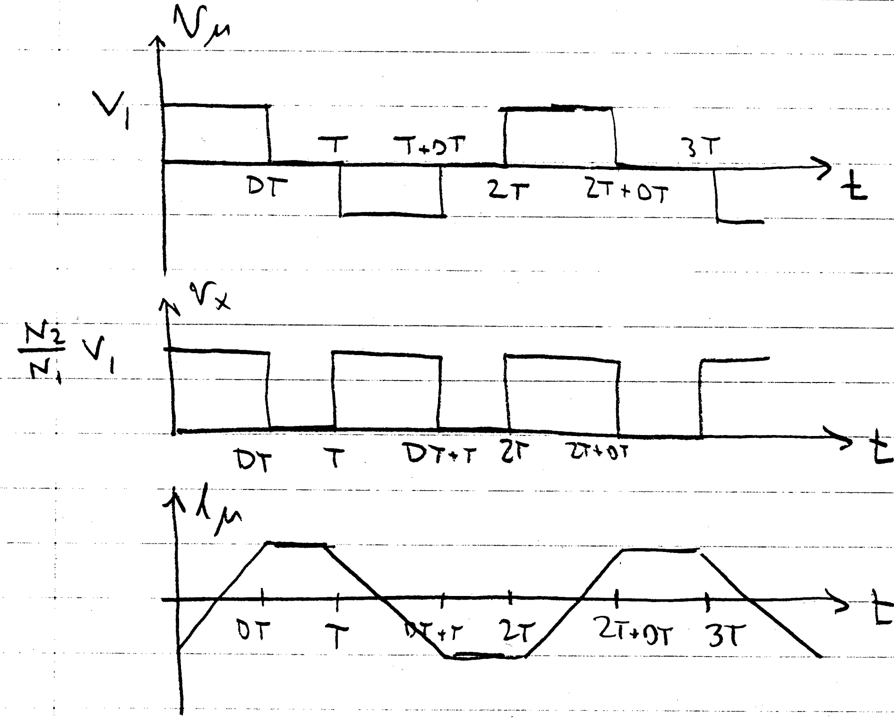
⋆ Double-Ended Converters:

So far we have considered converters that only use unidirectional primary-side xformer magnetizing current. We can better utilize the transformer with bidirectional current/flux.





fundamental ripple frequency doubles! (smaller filters, xformer)

Core flux swing is bidirectional! – Bmax to + Bmax instead of 0 to Bmax

- Bidirectional flux swing allows smaller xformer
- frequency doubling allows smaller filters

- However we must use control or a blocking capacitor to ensure that $\langle i_\mu \rangle \sim 0$, or we will saturate the transformer! (TRICKY)

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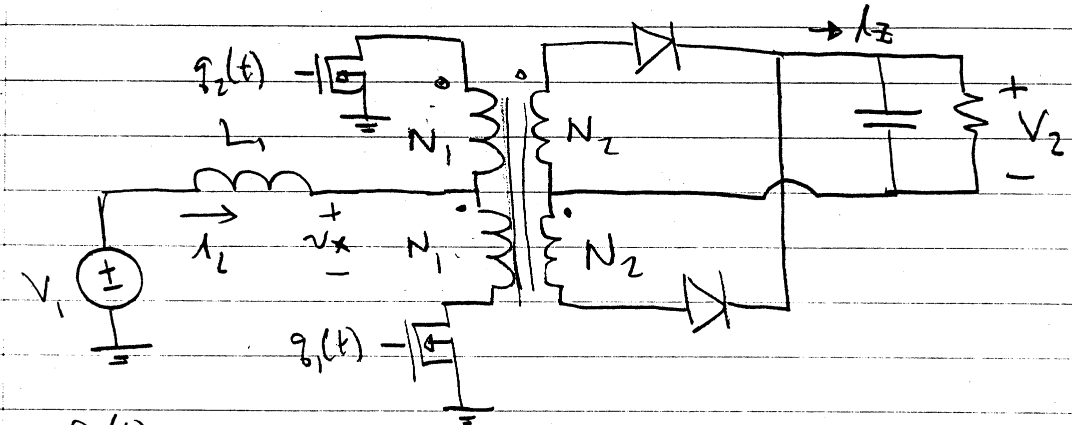
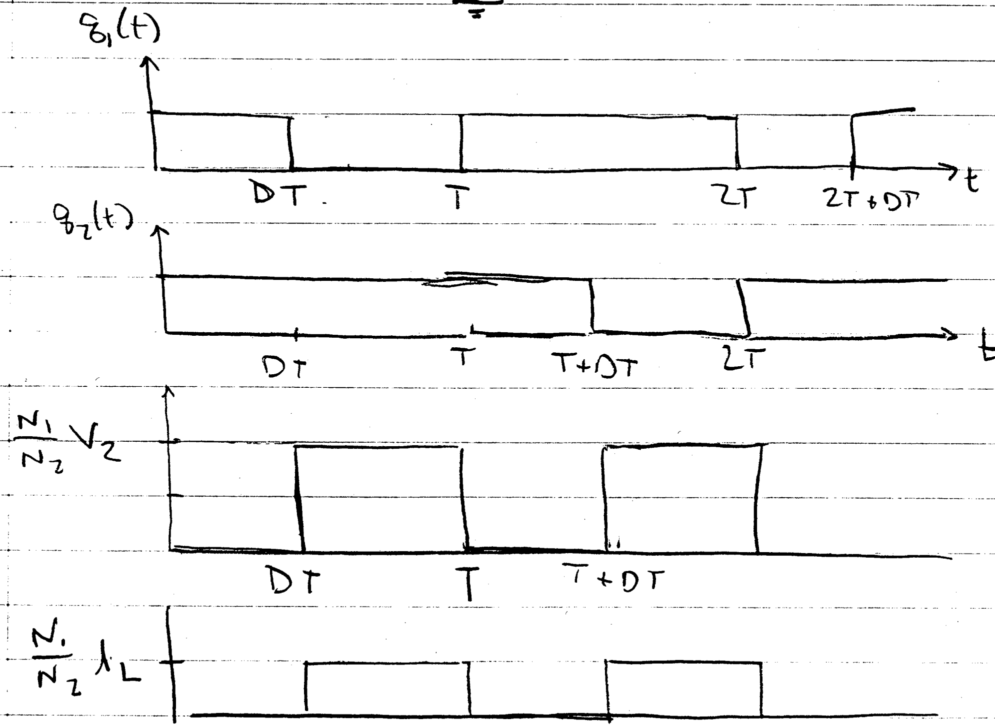
MANY OTHER KINDS OF ISOLATED CONVERTER VARIANTS EXIST!

e.g. current-fed push-pull (like isolated boost)





like a boost

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

we can also create structures that don't exist in nonisolated; e.g. flyforward
and use different rectifiers (e.g. current doubler)