OUTLINE LECTURE 9

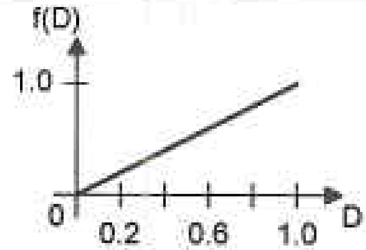
A. Buck-Boost Converter Design

1. Volt-Sec Balance: f(D), steady-state transfer function
2. DC Operating Point via Charge Balance: I(D) in steady-state
3. Ripple Voltage / "C" Spec
4. Ripple Current / "L" Spec
5. Peak Switch Currents and Blocking Voltages / Worst Case Transistor Specs

B. Practical Issues for L and C Components

1. Inductor: $L = f(I)$? $L = f(f_{sw})$? Lower Q "10"
   a. Cost of Cores
   b. Inductor Core Materials Unique to Each f_{sw} Choice
   c. Core Saturation above i(crit)
      $B > B_{sat}$, $L = f(i)$
      $B < B_{sat}$, $L \neq f(i)$
2. Capacitor: $C(f_{sw}, i_c, v_c)$ Higher Q "100"
   a. Costs
   b. Dielectric Materials
      (1) $\varepsilon(f_{sw})$
      (2) E(breakdown)

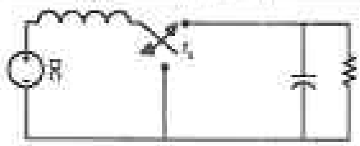
SIMPLE SWITCH MODE CONVERTERS

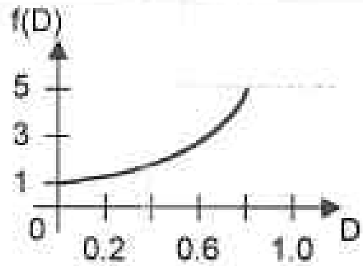


$V_L=V_o$ or $V_{DC}-V_o$
- f(D)=D
- Never get negative output
- $V_o(min) = 0$

BUCK

The buck is limited in that $V_{out} < V_{in}$ only



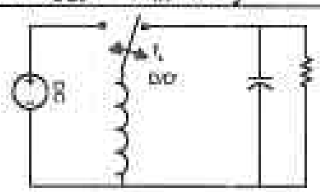


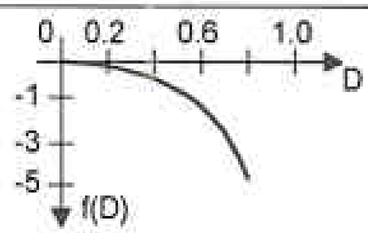
- f(D)=1/(1-D)
- Never get zero output: $V_o(min) \neq 0$

$V_L=V_{DC}-V_o$ or V_o

BOOST

The boost is limited in that $V_{out} > V_{in}$ only





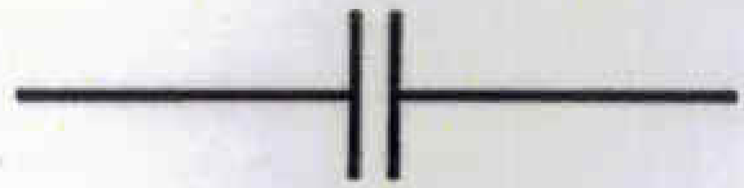
- f(D)=-D/(1-D)
- Inverting output w.r.t. V_g

$V_L = V_o = -V_{DC}$ for D = ½

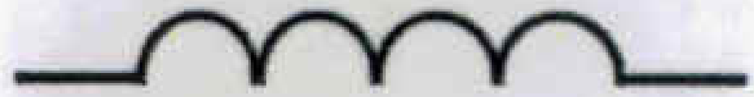
BUCK-BOOST

The buck-boost is limited to negative voltages

4. UNSYMMETRIC i_L AND v_C WAVEFORMS OF EQUAL INTEGRATED AREA IN THE ABOVE THREE CONVERTERS



$$X_C = \frac{1}{2\pi f C}$$



$$X_L = 2\pi f L$$

(X in ohms, f in hertz, C in farads, L in henries)

Figure 1 · The simplest frequency-dependent behaviors are capacitive and inductive reactance.

Definitions

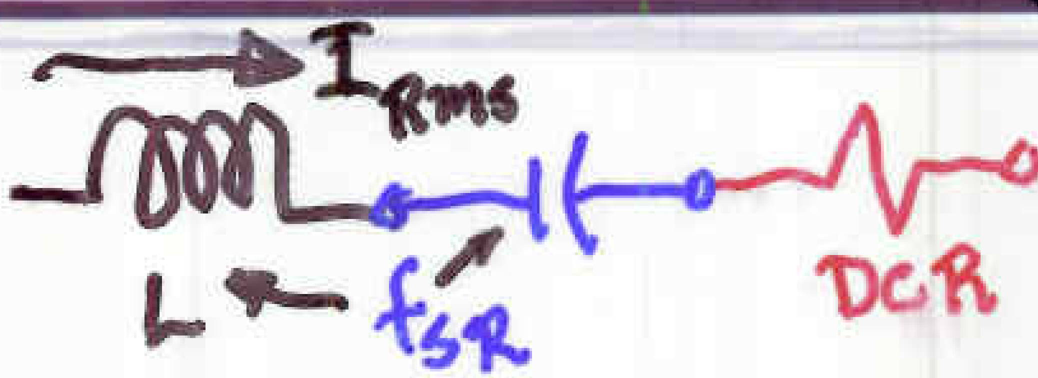
L – Inductance The primary functional parameter of an inductor. This is the value that is calculated by converter design equations to determine the inductors ability to handle the desired output power and control ripple current.

DCR – DC Resistance The resistance in a component due to the length and diameter of the winding wire used.

SRF – Self Resonant Frequency The frequency at which the inductance of an inductor winding resonates naturally with the distributed capacitance characteristic of that winding. $W = 1/\sqrt{LC}$

Isat – Saturation Current The amount of current flowing through an inductor that causes the inductance to drop due to core saturation.

Irms – RMS Current The amount of continuous current flowing through an inductor that causes the maximum allowable temperature rise.



① Depends on How made ... effects

f_{SR} is self resonant frequency

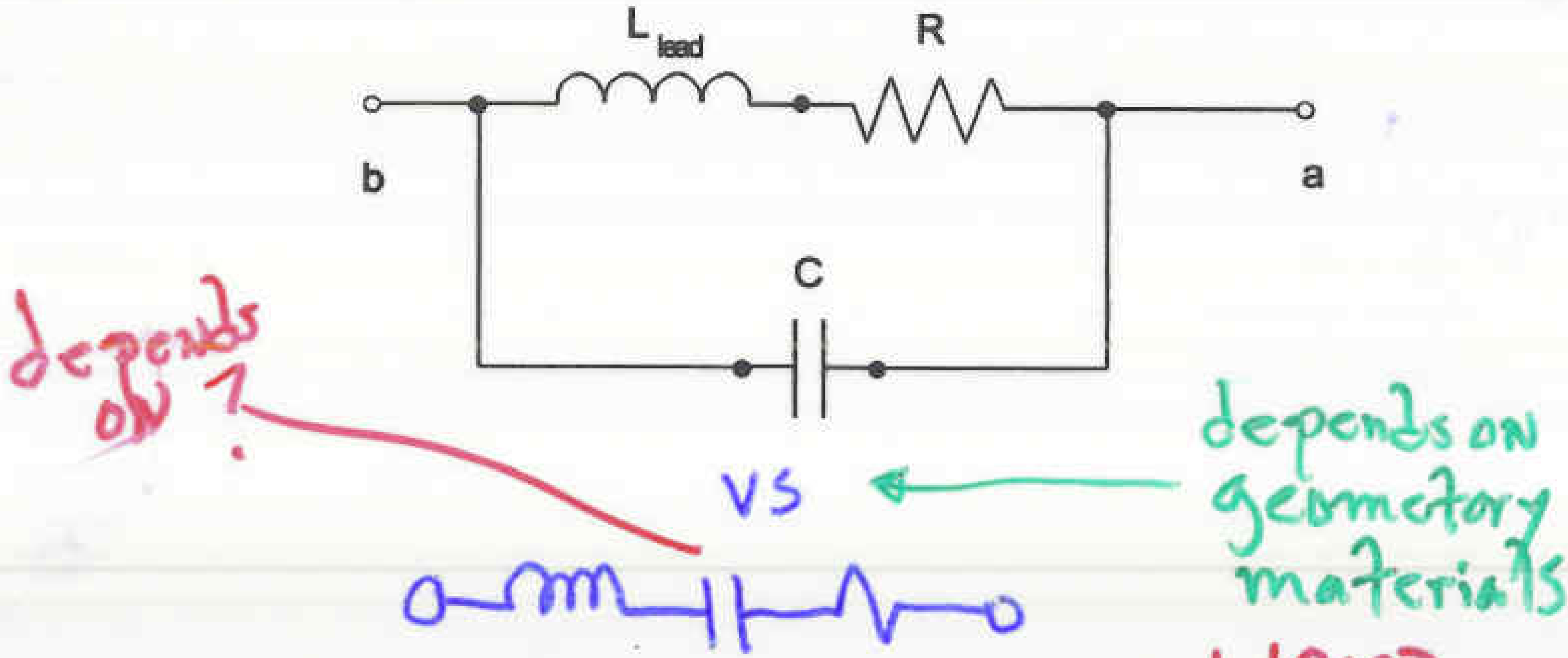


Figure 18. Simplified equivalent circuit for inductor.

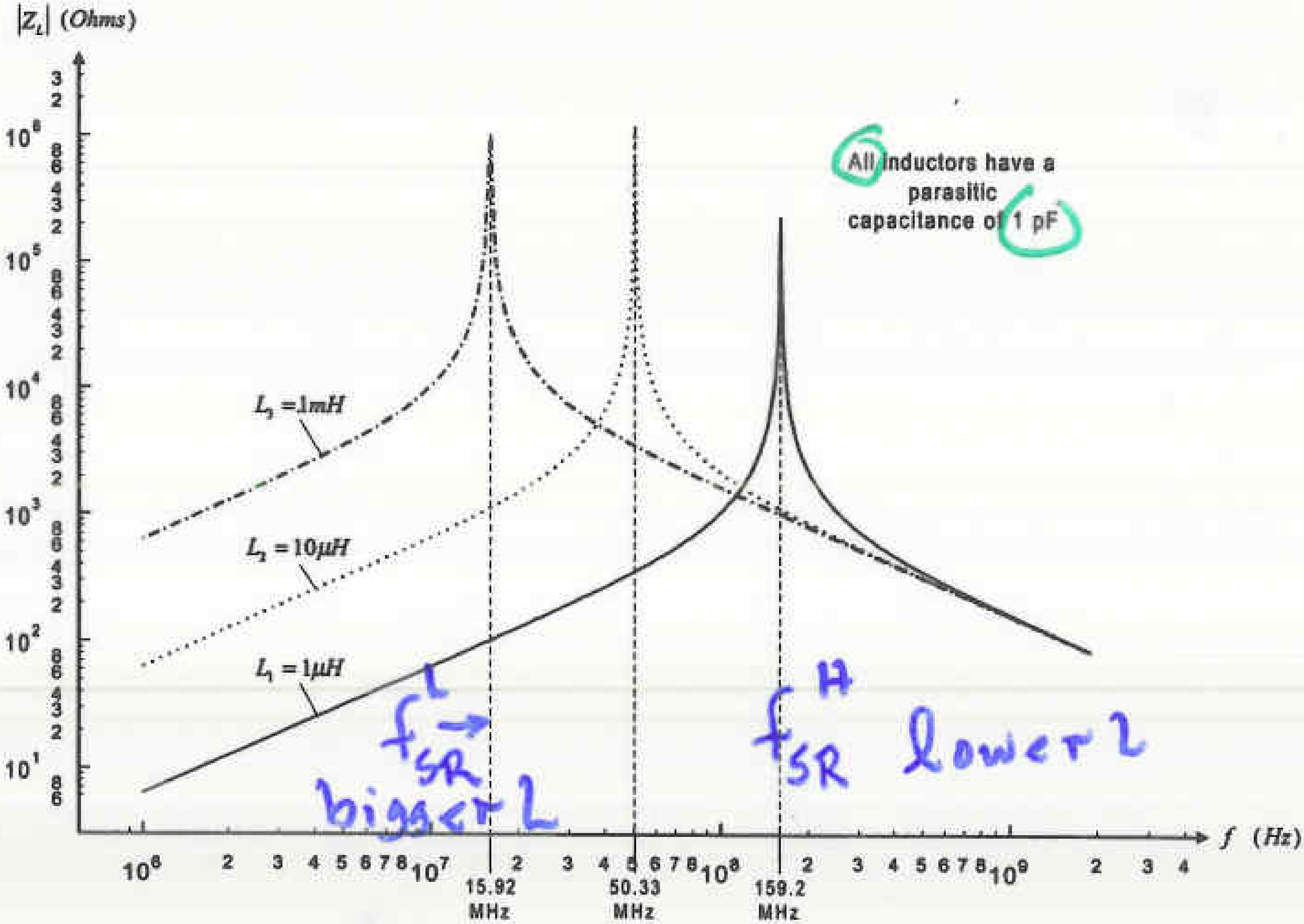


Figure 19. Plot of frequency dependent behavior of equivalent circuits for various inductors.

The MAX of the Current Limit

The MAX of the current limit is not completely irrelevant. As we move to *higher and higher input voltages*, this may become worth watching out for. The reason is that whenever we start-up, or submit the converter to sudden transients, the current no longer stays at the steady value it has under normal operation (when delivering the required maximum load current). For example, if we suddenly short the output, the control, in an effort to regulate the output, expands the duty cycle to the highest permissible value. The current then ramps up to the current limit.

Ouch

But that means the inductor could be saturating!

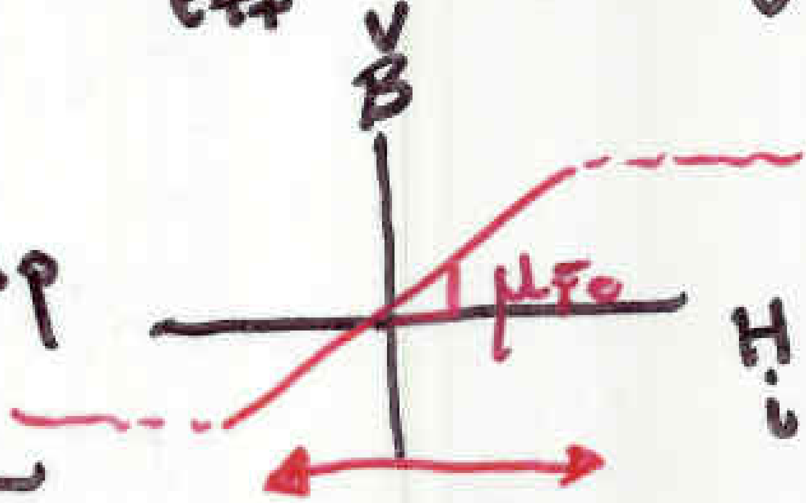
For example, if we are using a 5A fixed current limit buck switcher IC for a 3A application, we have probably picked an inductor rated for around 3A. But when we short the output, the current momentarily hits the current limit (which may be around 5.5A nominal). And that clearly exceeds the rating of the inductor.

$$L = \frac{N^2}{\mathcal{R}_{eff}} \qquad \mathcal{R}_{eff} = \mathcal{R}_{Fe} + \mathcal{R}_{gap}$$

$\mathcal{R}_{Fe} >> \mathcal{R}_{gap}$

$$\mathcal{R}_{Fe} = \frac{l_{Fe}}{\mu_{Fe} A_{Fe}}$$

μ_{Fe} = $f(I)$



$\mu_{Fe} \neq f(I)$

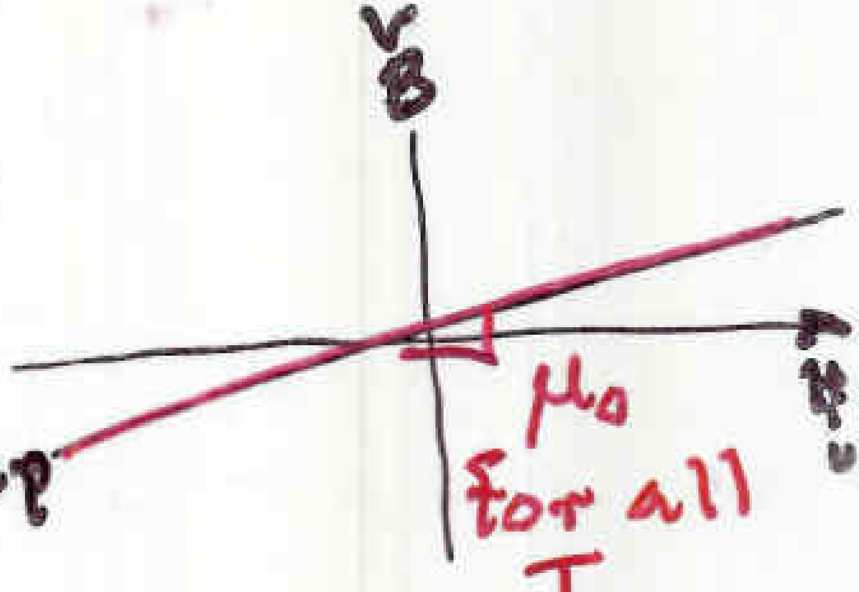
$L \neq f(I)$

$I_L < I_{critical}$

$\mathcal{R}_{gap} >> \mathcal{R}_{Fe}$

$$\mathcal{R}_g = \frac{l_g}{\mu_0 A_{gap}}$$

$\mu_0 \neq f(I_L)$



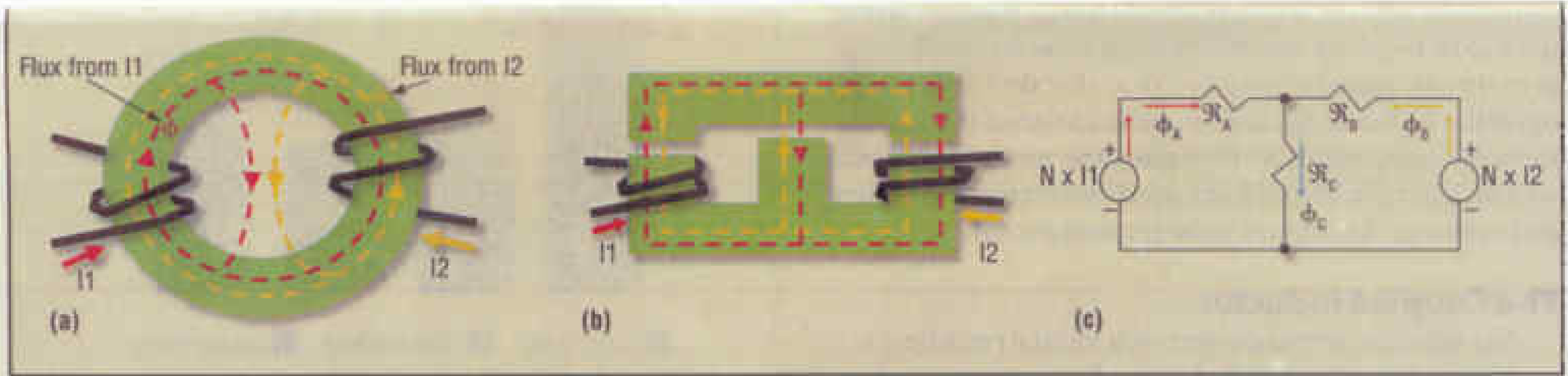
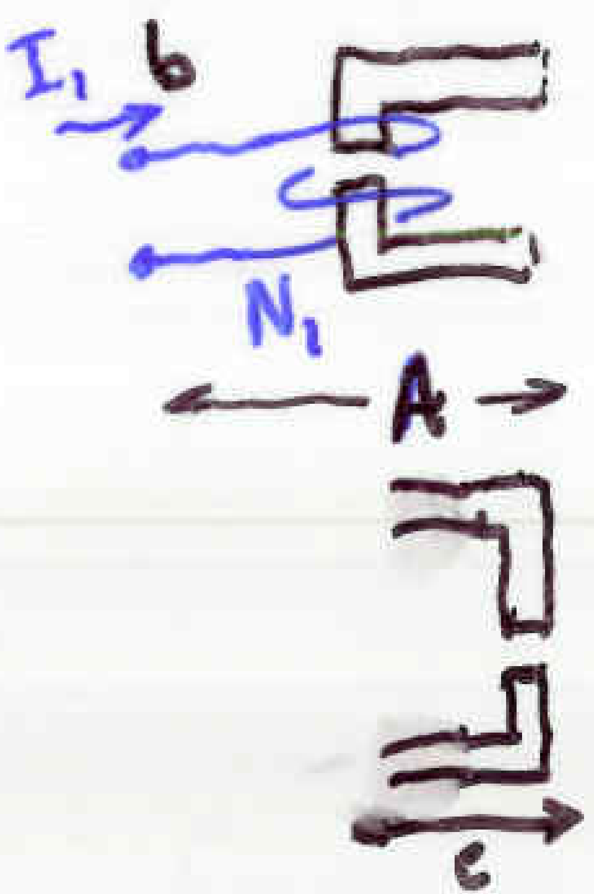
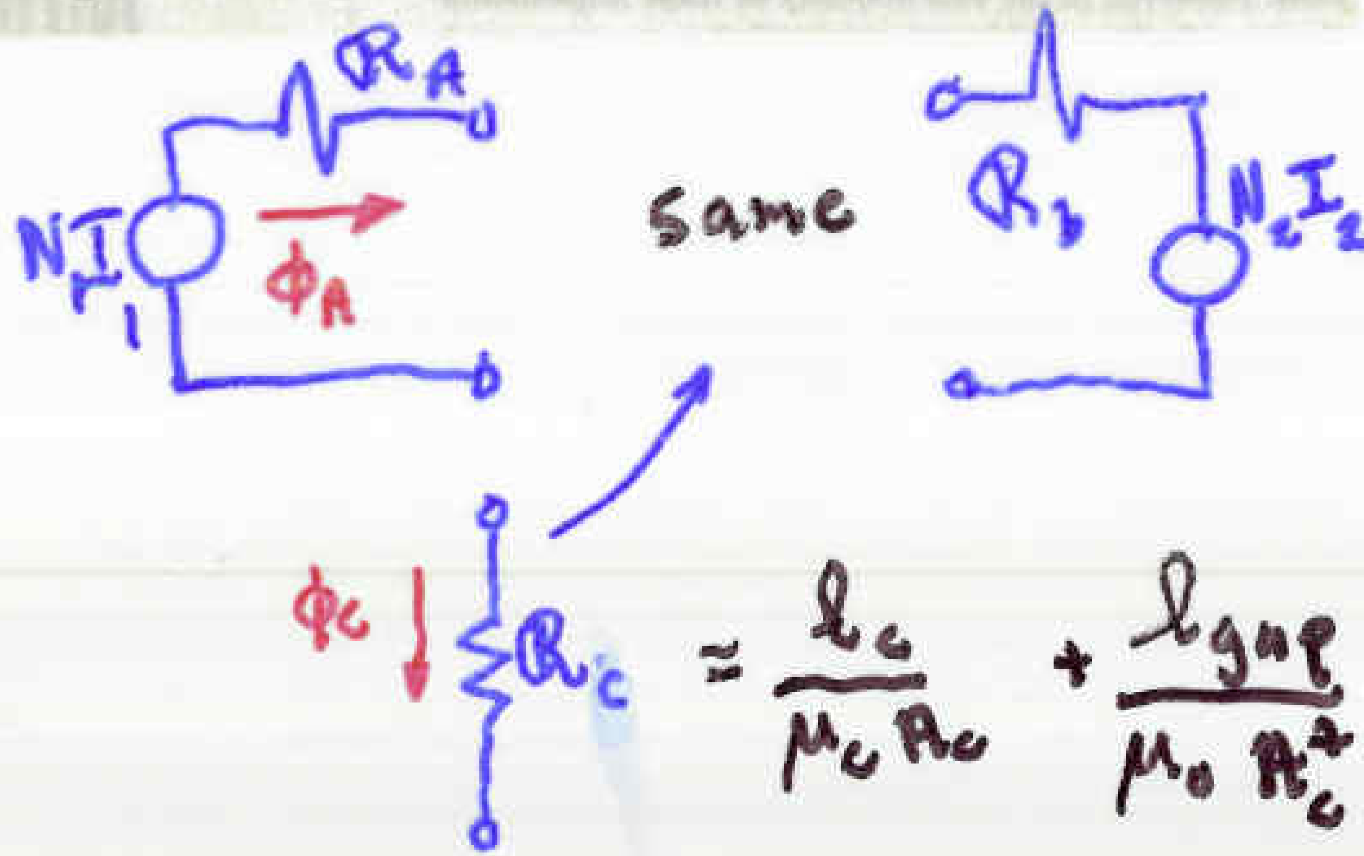


Fig. 2. Both the toroid design (a) and the E-core design (b) can be reduced to the same reluctance model (c).





$$\approx \frac{l_c}{\mu_c A_c} + \frac{l_{gap}}{\mu_0 A_c^2}$$

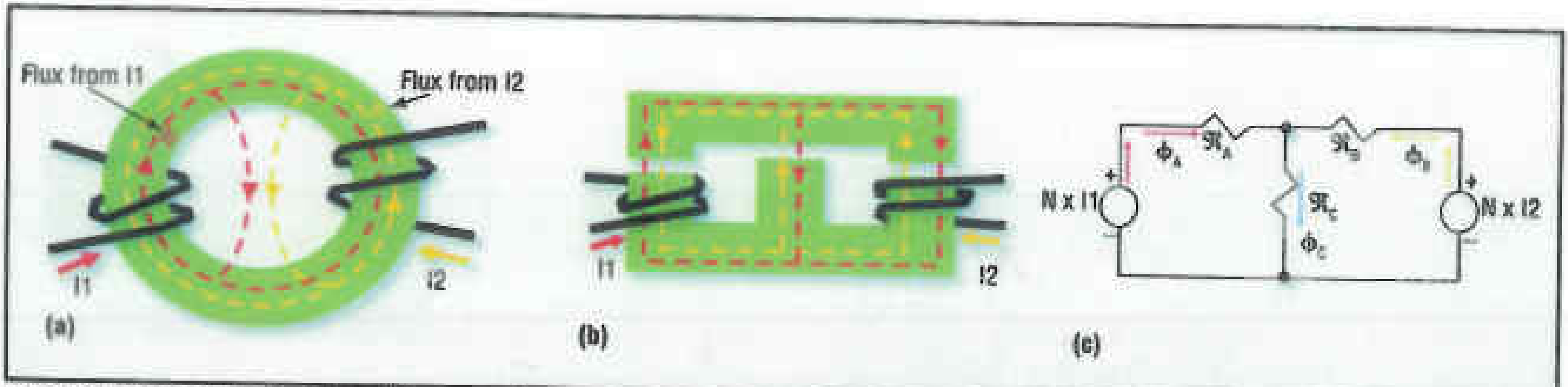


Fig. 2. Both the toroid design (a) and the E-core design (b) can be reduced to the same reluctance model (c).

$$MMF = NI = \sum_x \phi_x \mathcal{R}_x \, , \quad \mathcal{R}_x = \frac{l_x}{\mu_x A_x}$$

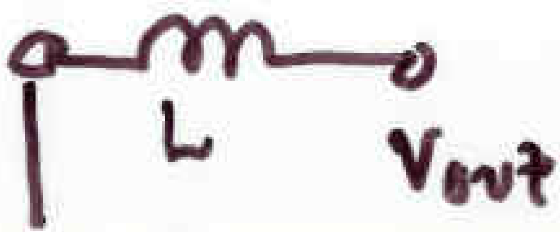
Similiar to "K's" loop equations

(a) $N_1 I_1 + N_2 I_2 = \phi_c \mathcal{R}_c$ ($\mathcal{R}_c \to 0$ for $\mu \to \infty$)

$\mu = \infty$ $\quad I_2 = \left(\frac{N_1}{N_2}\right) I_1$ ideal trf

$\mu \neq \infty$

Step	Instruction
1	Time Period (switching frequency fsw is 150kHz) $T = \frac{1}{fsw} \Rightarrow 6.67\mu s$
2	Duty Cycle (ignoring forward drops) $D = \frac{Vo}{Vin} = \frac{5}{48} \Rightarrow 10.4\%$ D = 0.1 nominal
3	Off-time $toff = (1 - D) \times T = \frac{100 - 10.4}{100} \times 6.67\mu s = 5.98\mu s$
4	Voltuseconds $Et = Voff \times toff = Vo \times toff = 5 \times 5.98 = 29.9V\mu s$



be aware Lmin for this condition

5	Check limit of current ripple ratio 'r' at maximum load current. I_{CLIM}(MIN) is 2.3A. $r\,\text{limit} = 2 \times \frac{I_{CLIM}(MIN) - Io}{Io} = 2 \times \frac{2.3 - 2}{2} = \frac{0.6}{2} = 0.3$
6	Select 'r' for application: if rlimit (calculated above) is less than ideal of 0.4, select r=rlimit, otherwise pick r=0.4. Therefore in this case we select r=0.3 (to guarantee output power)
7	Calculate MIN value of inductance using general equation LxI=Et/r (where I is the average inductor current --- equal to Io for a buck, and Io/(1-D) for the remaining) $L(MIN) = \frac{Et}{I \times r} = \frac{29.9}{2 \times 0.3} = 49.83\mu H$
8	Pick Calculated Nominal Value of Inductance (assume final inductor will have +,- 10% tolerance --- so pick nominal value 10% higher than calculated value above). $L(NOM) = 1.1 \times L(MIN) = 1.1 \times 49.83 = 54.8\mu H$

available from vendors

9	Choose next highest standard inductance value. So in this case we choose L=56uH
10	Current Rating of Inductor ---- if the input voltage was less than 40V, we would pick a current rating of (1+r/2)xIo=1.15x2=2.3A. However, in this case, since input is greater than 40V, we pick the inductor rating as per the MAX of the current limit i.e. 4A (from datasheet)
11	Final selected inductor is 56uH, 4A.

Snubbers

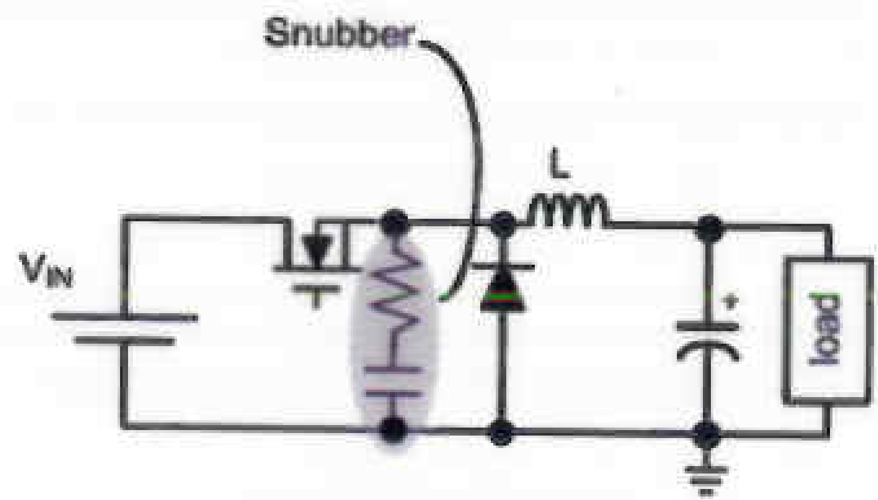
A small RC snubber from Switch Node to Ground helps as shown below

<u>Typical Values:</u>
C=470pF to 4.7nF
R=10 ohms to 100 ohms

Dissipation in resistor is:

$C \times V^2 \times fsw$

where fsw is the switching frequency and V is the voltage that appears across the capacitor when charged up (equal to V_{INMAX})



Buck regulator