Buck inductor design

---Prepared by Bean

1. Calculate inductance:

   1). Determine Duty cycle

$$D := \frac{Vo}{Vin}$$

   2). Calculate inductance

   Analysing the circuit, we can get the followed equations easily.

   a). Continued mode

$$L := (Vin - Vo)\cdot\frac{D}{2Kf\cdot f\cdot Io} \quad \text{or} \quad L := Vo\cdot\frac{(1-D)}{2Kf\cdot f\cdot Io}$$

   Where: Vin is input voltage (V)   Vo is output voltage (V)
   f is operation frequency (Hz)   Io is output current (A)
   Kf is the ripple factor (0.1~0.2 for typical application)

   b). Discontinued mode

$$L := (Vin - Vo)\cdot\frac{D}{f\cdot Ipk} \quad \text{or} \quad L := Vo\cdot\frac{(1-D)}{f\cdot Ipk}$$

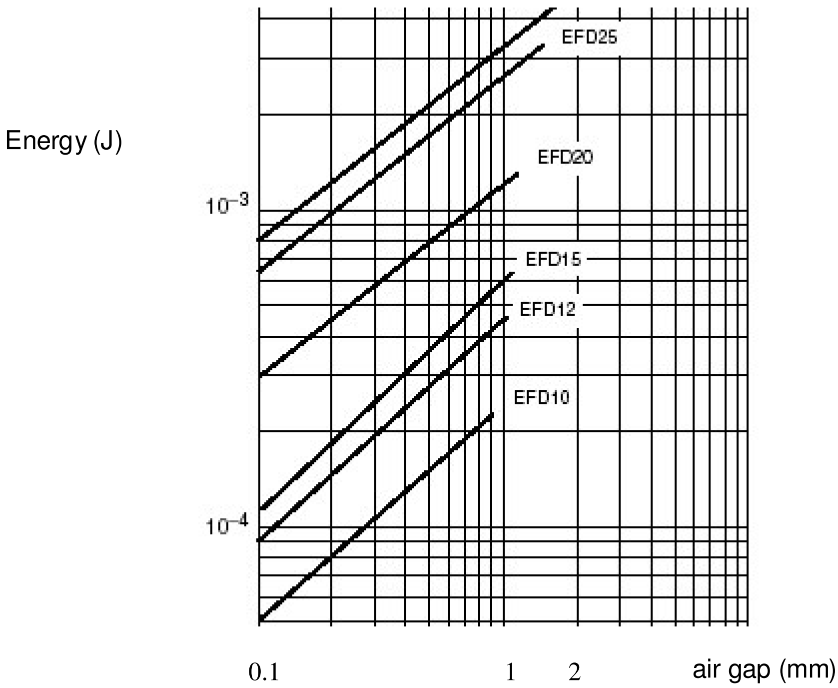
   Note: The diode need to be considered on some cases especially for low output voltage application.

2. Choose core (Ferrite core design)

   1). Calculate the energy storage

$$W := L\cdot I^2$$

   2). Choose the core and determine the gap based on energy vs air-gap curve



3. Calculate the number of turns:

From step 2, the core and gap length were determined. Now we can use related factors of core to calculate turns number.

$$N := [L\cdot(Rc + Rg)]^{0.5}$$

Where: L ---inductance in Henry
Rc---Magnetic resistance of core
Rg---Magnetic resistance of air gap

$$Rc := \frac{le}{\mu\cdot Ae} \qquad Rg := \frac{lg}{\mu o\cdot Ae}$$

Where: le---effective length of core in meter
Ae---cross area of core in square meter
lg---gap length in meter
μ---permeability of core
μo----permeability of air

4. Determine wire size

a). Chinese method

$$\phi := 1.13\cdot\sqrt{\frac{I}{J}}$$

Where: ϕ---diameter of wire in mm
J---current density (7~16 for typical application)

b). American method

$$CM := J\cdot I$$

Where: CM---Area in circular mils
J---current density (100~250 for typical application)

Then go to wire table to find right wire.

5. Verify the design

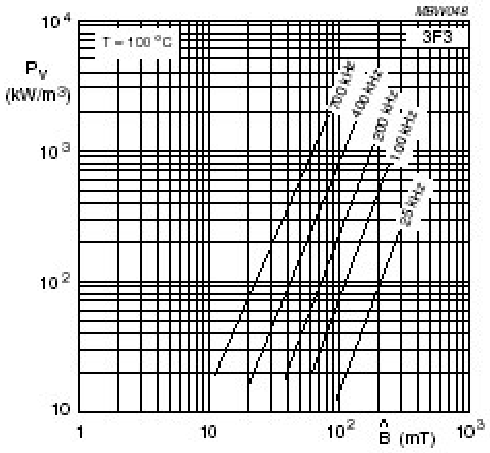
Normally, the inductor has two limitations: one is the temperature rise, the other one is saturation of core. So need to verify if these two factors can meet requirement.

1). Verify if the core saturation

$$\Delta B := \Delta I\cdot\frac{L\cdot 10^{-2}}{N\cdot Ae}$$

Where: ΔB is the flux swing in Tesla
ΔI is the peak to peak current
L is inductance in μH
N is number of turns
Ae is core cross area in cm^2

The flux swing divided by 2, then go to the core loss curve and find the core loss.
If the core loss higher than 100mW/cm^3, the core is saturation.
*This rule come from Lloyd's technical paper. Actually, if you choose the core and gap based on this method, the core don't want to saturate.

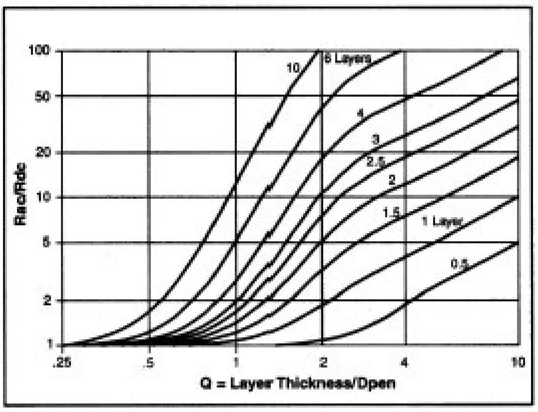


2). Temperature rise

a). copper loss

$$Pcopper := Idc^2 \cdot Rdc + Iac^2 \cdot Rac$$

Where: Idc is DC current
Rdc is direct current risistance
Iac is effective value of AC current
Rac is AC risistance can got from Dewll's curve



b). core loss Pcore

The core loss can be gotten based on section 5.1. Normally, the core loss isn't a significant effect for ferrite design in continued mode.

c) Temperature

$$\Delta\tau := \sqrt[0.833]{\frac{Pt}{As}}$$

Where: Pt is the total loss in mW
As is the surface area in cm^2

Note: This method just for reference, the best way is to build a sample to test.

Up to now, a method to design a ferrite inductor was given. Actually, most buck inductors are designed with a powder material and toroid core. Now show a step by step design with powder core.

Ferrite: 1. large fringing
2. high ac loss
3. EMI problem

Powder:1. high core loss
2. high saturation flux density
3. soft bias performance

Buck: Input voltage: 5V
Output voltage: 1.25V
Output current: 6.5A
Frequency: 1MHz

$Vin := 5 \quad Vo := 1.25 \quad Io := 6.5 \quad f := 1000000$

1. Calculate duty cycle and inductance (Normally, the buck inductor is designed to continued mode

$D := \frac{Vo}{Vin} \qquad D = 0.25 \qquad Kf := 0.1$

$Lmin := (Vin - Vo)\cdot\frac{D\cdot 10^6}{2\cdot Kf\cdot f\cdot Io} \qquad Lmin = 0.721$ or

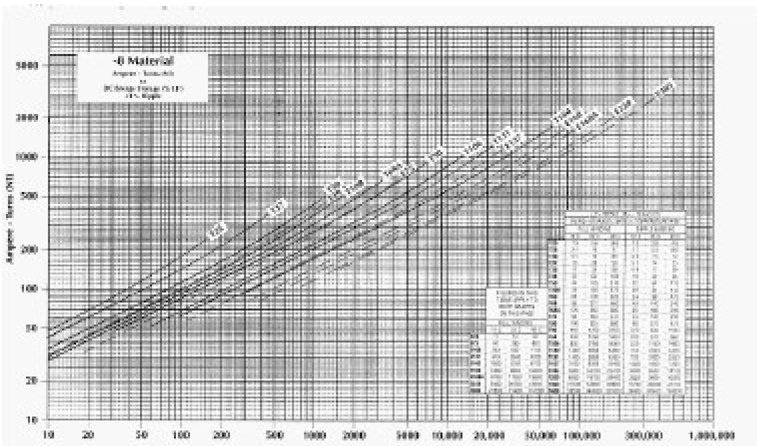
$Lmin := (Vo + 0.085\cdot Io)\cdot\frac{(1 - D)\cdot 10^6}{2\cdot Kf\cdot f\cdot Io} \qquad Lmin = 1.04$

*This use a IC with a switcher instead of Diode. The resistance of swither is 85mOHM

2. Choose the core and material: chosse -8 material for frequency requirement.

$W := 0.5Lmin\cdot Io^2 \qquad W = 21.968$

Go to core selection cure and chart:



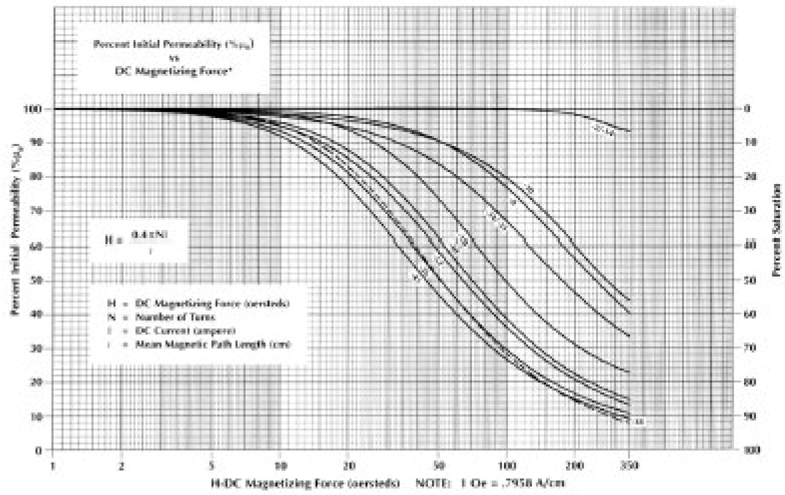
Found that T30 will yield such energy with single winding. The ampere turns will be about 67. So the pri-turns will be 10.

$Ae := 0.06 \quad le := 1.84 \quad Np := 10 \quad AL := 14 \quad Ve := .11$

3. Adjust turns

Magnetizing force: $H := 0.4 \cdot \pi \cdot Np \cdot \frac{Io}{le}$ $H = 44.392$

Then go to μ% vs H cure and find the μ% is 93.5%.



$$N := \left(Lmin \cdot \frac{10^3}{AL \cdot 0.935} \right)^{0.5} \quad N = 8.913 \quad N := 9$$

Actually, the inductance will be about 1.06uH at 9 turns.

4. determine wire size

Assume: $J := 13$

$$\phi := 1.13 \cdot \sqrt{\frac{Io}{J}} \qquad \phi = 0.799$$

This will be AWG20, but the winding space is not enough. So change to AWG21.

The design goes to:

$N := 9$ AWG21

5. Verify the temperature rise

T30: $MLT := 1.44$ $As := 2.79$

AWG21 $\Omega := 12.77 \quad \frac{\Omega}{1000ft}$

$$DCR := MLT \cdot \frac{N}{2.54 \cdot 12} \cdot \Omega \qquad DCR = 5.43 \qquad m\Omega$$

$$Pcu := Io^2 \cdot DCR \qquad Pcu = 229.408$$

Because the inductor was designed in continued mode, the AC resisitance can be ignored.

Use maximum voltage cross coil to calculate core loss. Here:

$$Vpk := Vin - Vo$$

$$\Delta B := Vpk \cdot \frac{D \cdot 10^8}{2 \cdot Ae \cdot N \cdot f} \qquad \Delta B = 86.806 \quad G$$

For -8 matrerial: the relationship between loss and AC flux & frequency can be gotten from core catalog.

$$P := \frac{f}{\left(\frac{1.9 \cdot 10^9}{\Delta B^3}\right) + \frac{2 \cdot 10^8}{\Delta B^{2.3}} + \frac{9 \cdot 10^5}{\Delta B^{1.65}}} + 2.5 \cdot 10^{-14} \cdot \Delta B^2 \cdot f^2 \qquad P = 284.252$$

$$Pcore := P \cdot Ve \qquad Pcore = 31.268$$

$$Pt := Pcu + Pcore \qquad Pt = 260.675$$

$$\Delta\tau := \left(\frac{Pt}{As}\right)^{0.833}$$

$$\Delta\tau = 43.795$$

References:
[1] Lloyd H.Dixon: Unitrode Magnetics Design Handbook
[2] Micrometals Catalog, 2000
[3] Ferroxcube Catalog, 2002

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