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TECHNICAL UNIVERSITY

ELECTRICAL-ELECTRONICS ENGINEERING
DEPARTMENT

EE463 HW3- Duty Controlled Full Bridge Isolating Converter Design

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Homework 3

Duty Controlled Full Bridge Isolating Converter Design

Introduction

The homework problem involves the overall design and simulation of a 250-W duty-controlled full bridge isolating converter. The homework problem includes the entire engineering process, from the analytical design of the circuit parameters such as the turns ratios and filters to satisfy particular ripple specifications. A major part of the homework problem involves magnetic designs, including the choice of cores and wires for maximizing efficiency and reducing losses in both the transformer and the inductor. The final step involves validating the designs through simulation and thermal analysis of the commercial semiconductor devices to verify the satisfaction of rated operating conditions.

Experimental Results

Q1)

a)

$$V_{out} = 2 \cdot \frac{N_s}{N_p} \cdot D \cdot V_{in}$$

$$n = \frac{N_s}{N_p} = \frac{V_{out}}{2 \cdot D \cdot V_{in}}$$

$$n = \frac{24}{2 \cdot 0.45 \cdot 100}$$

n= 4/15

b)

$$I_{L,avg} = I_{out} = \frac{P_{out}}{V_{out}}$$

$$I_{L,avg} = \frac{250\text{ W}}{24\text{ V}} \approx 10.42\text{ A}$$

$$\Delta i_L = 0.10 \times I_{L,avg} = 0.10 \times 10.42\text{ A} = 1.042\text{ A}$$

$$L_x = \frac{(V_x - V_{out}) \cdot D \cdot T_s}{\Delta i_L}$$

V_x=V_{sec}=n.V_{in}=0.2667*100= 26.67 V

$$\frac{D}{f_{sw}} = \frac{0.45}{200{,}000\text{ Hz}} = 2.25\text{ µs}$$

$$V_{sec} - V_{out} = 26.67\text{ V} - 24\text{ V} = 2.67\text{ V}$$

$$L_x = \frac{2.67\text{ V} \times 2.25\text{ µs}}{1.042\text{ A}}$$

$$L_x \approx \frac{6.0075 \times 10^{-6}}{1.042}$$

$$L_x \approx 5.76\text{ µH}$$

The required inductance value to have an inductor ripple 10% of the average inductor current value is calculated as 5.76 mu H.

c)

When the switch is on, V_L= V_{in}*(N_s/N_p)-V_{out}, so inductor current rises:

$$\Delta i_L = \frac{(V_{in} \cdot \frac{N_s}{N_p}) - V_{out}}{L} \cdot DT_s$$

The capacitor current is the AC part of the inductor current ($i_c(t)=i_L(t)-I_{out}$).

$$\Delta Q = \frac{1}{2} \cdot \text{Taban} \cdot \text{Yükseklik} = \frac{1}{2} \cdot \left(\frac{T_{ripple}}{2}\right) \cdot \left(\frac{\Delta i_L}{2}\right) = \frac{\Delta i_L \cdot T_{ripple}}{8}$$

Where f_{ripple}= 2*f_{sw}, Tripple= 1/(2*f_{sw}).

$$C = \frac{\Delta i_L}{16 \cdot f_{sw} \cdot \Delta V_o}$$

Δi_L=1.042 A
fsw=200 kHz
V_{out}=24 V
ΔV_o= %1 of V_{out}= 0.24 V

$$C = \frac{1.042 \text{ A}}{16 \cdot 200,000 \text{ Hz} \cdot 0.24 \text{ V}}$$

$$C = \frac{1.042}{768,000}$$

$$C \approx 1.357 \times 10^{-6} \text{ F}$$

$$C \approx 1.36 \, \mu\text{F}$$

Q2)
a)
I chose the material as R material since its losses are lower.
I chose Magnetics E 2515 (Part Number: 0R42515EC)

Ae (Effective Cross Section): 40.1 mm^2=0.401 cm^2.

le (Magnetic Path Length): 73.5 mm.

Ve (Volume): 2950 mm^3.

To prevent core saturation and optimize fill factor for the 40.1 mm^2 cross-section, a maximum flux density (Bmax) of 1500 Gauss (0.15 T) is selected. At 200 kHz, for ferrite R material saturation occurs approximately at 0.3 T.

$$N_p = \frac{V_{in} \cdot 10^8}{4 \cdot f \cdot B_{max} \cdot A_e}$$

Put in the values:

$$N_p = \frac{100 \cdot 10^8}{4 \cdot 200000 \cdot 1500 \cdot 0.401} = 20.78$$

N_p=21 Turns

I chose the turn ratio as 3:1 since 4:1 would make the duty cycle larger than 0.45.

Ns=7 Turns

$$V_{out} = V_{in} \cdot \frac{N_s}{N_p} \cdot 2 \cdot D$$

Vout=24 V, then our new D=0.36.

$$L_m = N_p^2 \cdot A_L$$

$$L_m = 21^2 \cdot 2400\, nH = 441 \cdot 2400 \cdot 10^{-9}\ H$$

L_m= 1.06 mH

b)
Skin effect is calculated as follows:

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu_0 \cdot \mu_r}}$$

$$\delta = \sqrt{\frac{2.3 \times 10^{-8}}{\pi \cdot 200,000 \cdot (4\pi \times 10^{-7}) \cdot 1}}$$

$$\delta = \sqrt{\frac{2.3 \times 10^{-8}}{0.7896}} \approx \sqrt{2.91 \times 10^{-8}} \approx 1.70 \times 10^{-4}\ m$$

$$\delta \approx \mathbf{0.17\ mm}$$

If we want to utilize 100% of the conductor area, the wire radius must be less than δ. I chose AWG29 since its radius is less than 0.17 mm (0.28702/2=0.14351 mm) and it is rated for frequencies up to 210 kHz.

A_{strand} = 0.0647 mm^2, Resistance= 268.4 ohms/km.

I_{in}=250/100=2.5 A

$$S_{req} = \frac{2.5\ \text{A}}{4\ \text{A/mm}^2} = 0.625\ \text{mm}^2$$

$$\text{Strands} = \frac{0.625}{0.0647} = 9.66 \Rightarrow \mathbf{10}\ \text{Strands (Parallel)}$$

Actual Primary Area: 10* 0.0647= 0.647 mm^2

$$S_{req} = \frac{10.42 \text{ A}}{4 \text{ A/mm}^2} = 2.605 \text{ mm}^2$$

$$\text{Strands} = \frac{2.605}{0.0647} = 40.26 \Rightarrow \mathbf{41} \text{ Strands (Parallel)}$$

I_{out}=250/24= 10.42 A

Actual Seconder Area: 41* 0.0647= 2.6527 mm^2

Fill Factor Calculation:

$$A_{Cu\_Pri} = 21 \text{ Turns} \times 0.647 \text{ mm}^2 = 13.59 \text{ mm}^2$$

$$A_{Cu\_Sec} = 7 \text{ Turns} \times 2.6527 \text{ mm}^2 = 18.57 \text{ mm}^2$$

$$A_{Cu\_Total} = 13.59 + 18.57 = \mathbf{32.16} \text{ mm}^{\mathbf{2}}$$

$$K_u = \frac{32.16}{80.6} \times 100 = \mathbf{39.9\%}$$

DC Resistance:

ρ_{100} (Copper Resistivity @ 100°C): $2.3 \times 10^{-8}\ \Omega \cdot m$.

MLT (Mean Length Turn): $0.055\ m$ (55 mm).

A_{strand}: $0.0647 \times 10^{-6}\ m^2$.

$$L_{pri} = N_p \times MLT = 21 \times 0.055\ m = \mathbf{1.155\ m}$$

$$A_{pri} = 10 \times 0.0647 \times 10^{-6}\ m^2 = \mathbf{0.647 \times 10^{-6}\ m^2}$$

$$R_{pri} = \frac{2.3 \times 10^{-8}\ \Omega m \times 1.155\ m}{0.647 \times 10^{-6}\ m^2}$$

$$R_{pri} = \frac{2.6565 \times 10^{-8}}{0.647 \times 10^{-6}} = \mathbf{0.0411\ \Omega}\ (41.1\ m\Omega)$$

$$L_{sec} = N_s \times MLT = 7 \times 0.055\ m = \mathbf{0.385\ m}$$

$$A_{sec} = 41 \times 0.0647 \times 10^{-6}\ m^2 = \mathbf{2.6527 \times 10^{-6}\ m^2}$$

$$R_{sec} = \frac{2.3 \times 10^{-8}\ \Omega m \times 0.385\ m}{2.6527 \times 10^{-6}\ m^2}$$

$$R_{sec} = \frac{0.8855 \times 10^{-8}}{2.6527 \times 10^{-6}} = \mathbf{0.00334\ \Omega}\ (3.34\ m\Omega)$$

Since r_{wire} < Skin Depth, we assume $R_{ac} \approx R_{DC}$

$$P_{Cu} = I_{pri}^2 \cdot R_{pri} + I_{sec}^2 \cdot R_{sec}$$

$R_{ac}=R_{DC}$

$P_{Cu}=(2.5^2*0.0411)+(10.24^2*0.00334)= 0.607$ W

c)

From the core loss vs. flux density table in the magnetics website, at 0.15 T and 200 kHz, the core loss is approximately 600-700 mW/cm^3. Taking the worst case, 700 mW/cm^3 * 2.95 cm^3=2.065 W.

The core loss is dominant, as expected for the high frequency ferrite designs that operates at optimal flux densities.

d)

Kool Mu material 0077848A7 (Kool Mu, 60 mu) is ideal for output inductors because of its distributed air gap (soft saturation characteristics) and low core losses at high frequencies (200 kHz).

Core Parameters (from Datasheet):

Permeability (mu): 60 mu

A_L Value (Inductance Factor): 32 nH/T^2

Magnetic Path Length (l_e): 50.9 mm

Cross Section Area (A_e): 22.1 mm^2

Window Area (W_a): 114 mm^2

$$N = \sqrt{\frac{L_{target}}{A_L}}$$

$$N = \sqrt{\frac{5760}{32}} = \sqrt{180} \approx 13.41$$

Choose N=14

$$L_{actual} = N^2 \cdot A_L = 14^2 \cdot 32\, nH = 6,272\, nH = \mathbf{6.27\ \mu H}$$ (no load)

$$NI = N \cdot I_{out}$$

$$NI = 14 \text{ Turns} \cdot 10.42 \text{ A} = \mathbf{145.88\ A \cdot T}$$

When we examine the graph given in the datasheet, At 146 A*T, the curve shows the inductance factor drops slightly but stays above 28 nH/T^2

Percentage=(28/32)*100=87.5%

$$L_{load} \approx 6.27\ \mu H \times 0.87 \approx \mathbf{5.45\ \mu H}.$$

Iteration is required

N=15

$$L_0 = N^2 \cdot A_L = 15^2 \cdot 32\ nH = 7,200\ nH = \mathbf{7.20\ \mu H}$$ (no load)

$$NI = 15 \text{ Turns} \cdot 10.42 \text{ A} = \mathbf{156.3\ A \cdot T}$$

At 156 A*T, the curve intersects at approximately 26.5 nH/T^2.

This corresponds to a permeability retention of 82.8.

$$L_{load} = N^2 \cdot A_{L(biased)}$$

$$L_{load} = 15^2 \cdot 26.5\ nH = 225 \cdot 26.5 = 5,962.5\ nH$$

$$L_{load} \approx \mathbf{5.96\ \mu H}$$

In this iteration, the inductance value is satisfied.

e)

Since the output ripple frequency is twice the switching frequency, we have to choose the cable accordingly. I chose AWG34 since its radius is less than 0.085 mm (0.16/2=0.08 mm) and it is rated for frequencies up to 690 kHz.

$$S_{req} = \frac{I_{out}}{J} = \frac{10.42\ A}{4\ A/mm^2} = 2.605\ mm^2$$

$$n = \frac{2.605\ mm^2}{0.0201\ mm^2} = 129.6 \Rightarrow \mathbf{130\ Strands}$$

$$A_{total} = 130 \times 0.0201\ mm^2 = \mathbf{2.613\ mm^2}$$

$$A_{Cu} = N \times A_{total} = 15 \text{ Turns} \times 2.613\ mm^2 = \mathbf{39.2\ mm^2}$$

$$K_u = \frac{A_{Cu}}{W_a} \times 100 = \frac{39.2}{114} \times 100 \approx \mathbf{34.4\%}$$

MLT= 0.03 m

L_{ind}(length of wire) = 15 Turns*0.03 m = 0.45 m

$$R_{DC} = \frac{L_{ind} \times 0.8558\ \Omega/m}{130 \text{ Strands}} = \frac{0.3851}{130} = \mathbf{0.00296\ \Omega}\ (2.96\ m\Omega)$$

R_{ac}=R_{DC}

$P_{Cu} = I_{out}^2 * R_{DC}$

$$P_{Cu} = I_{out}^2 \times R_{DC}$$

$$P_{Cu} = 10.42^2 \times 0.00296 \approx \mathbf{0.32\ W}$$

f)

f_{ripple} = 2*200 kHz = 400 kHz

T = 1/400 kHz = 2.5 mu s

$D_{eff} = 2*D_{sw}$ = 2*0.45 = 0.90

$t_{off} = (1 - D_{eff})*T$ = (1 - 0.90)*2.5 mu s = 0.25 mu s

Flux Swing (Delta B): Using the volt-second balance equation with datasheet area values:

A_e (Cross Section): 22.1 mm^2.

N (Turns): 15 (Calculated in part d).

V_L (during off-time): V_{out} = 24 V.

$$\Delta B = \frac{V_L \cdot t_{off}}{N \cdot A_e} = \frac{24\ V \cdot 0.25 \times 10^{-6}\ s}{15 \cdot 22.1 \times 10^{-6}\ m^2}$$

$$\Delta B = \frac{6}{331.5} \approx \mathbf{0.0181\ T}\ (181\ Gauss)$$

$$B_{pk} = \frac{\Delta B}{2} = \mathbf{90.5\ Gauss}$$

Core Loss Density Calculation: We scale the reference loss density provided in the datasheet to our operating frequency (400 kHz) and flux density (90.5 G).

Datasheet Reference Value:

Condition: 100 kHz, 100 mT (1000 Gauss).

Max Watt Loss: 750 mW/cm^3.

Scaling (Steinmetz Equation for Kool Mu): Using the standard exponents for Kool Mu ($f^{1.5}$ and B^2):

$$P_v \approx P_{ref} \times \left(\frac{f_{op}}{f_{ref}}\right)^{1.5} \times \left(\frac{B_{op}}{B_{ref}}\right)^2$$

$$P_v \approx 750 \times \left(\frac{400}{100}\right)^{1.5} \times \left(\frac{90.5}{1000}\right)^2$$

$$P_v \approx 750 \times (4)^{1.5} \times (0.0905)^2$$

$$P_v \approx 750 \times 8 \times 0.00819 \approx \mathbf{49.1\ mW/cm^3}$$

Core Volume (V_e): 1,120 mm^3 (1.12 cm^3)

$$P_{core} = P_v \times V_e = 49.1\ mW/cm^3 \times 1.12\ cm^3 \approx \mathbf{0.055\ W}$$

The core loss is much lower than the copper loss due to the fact that the large value of the effective duty cycle (D_{eff}=0.9) brings about a small value for the current ripple and also the magnetic flux swing of Delta B is approximately equal to 180 G, and core loss depends on B^2.

Q3)

a)

b)

c)

d)

Conclusion