Experiment-1

Buck converter Design document

CONTENTS

- # SYSTEM UNDER CONSIDERATION:

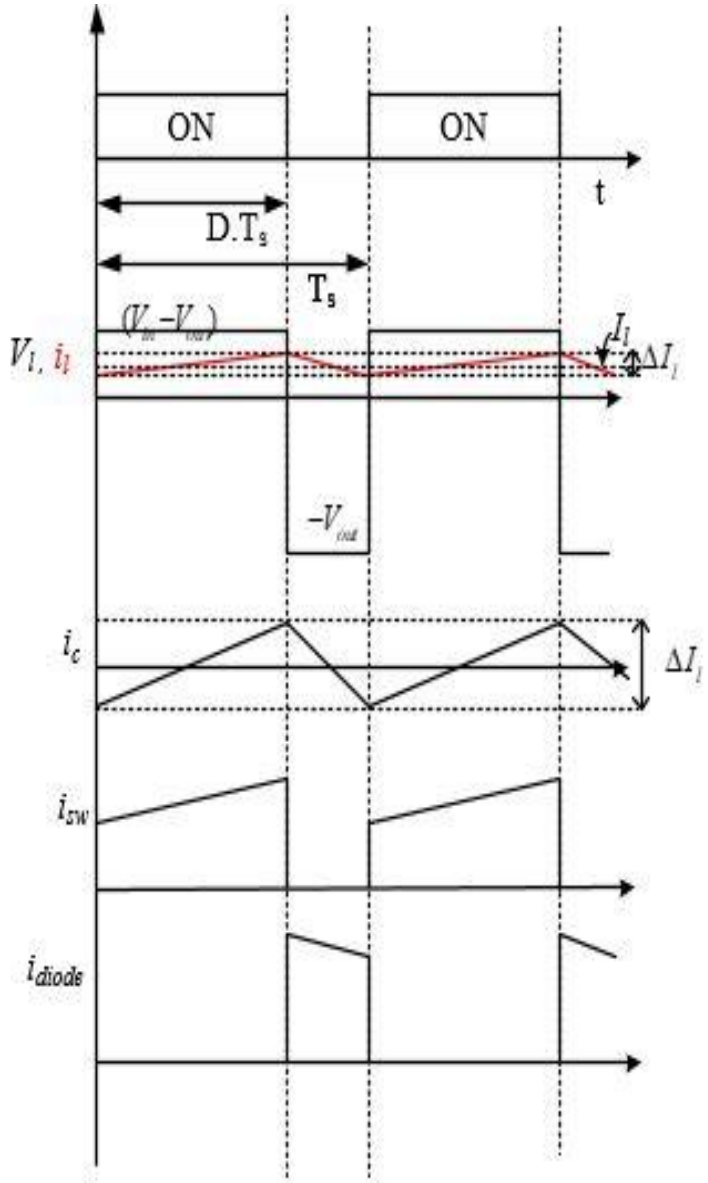
Let us consider a system:

100V < V_{in} <120V V, $P_{out,rated}$ = 200 W, f_{sw} = 50kHz, V_{out} =48V.

Under a load variation of 20% i.e. (160W < P_{out} <200W), the converter should always be operated under CCM.

Design the system for the worst-case condition considering the above-mentioned criteria such that the inductor current ripple (p-p) $i.e. \Delta I_{L(p-p)}$ and capacitor voltage ripple (p-p) $i.e. \Delta V_{Cp-p)}$ should not exceed 30% and 2% respectively for full load condition and find out upto what load the converter will operate in CCM. Consider the non-idealities like $R_{ds_{ON}}, R_L, V_D$ $and\ ESR\ of\ Capacitance$ etc.

- # KEY BUCK CONVERTER WAVEFORMS :



- **Validation of CCM condition:**

$$\frac{\Delta I_L}{2} \leq I_L$$

$$\frac{2L}{RT_s} \geq (1-D)$$

$$L \geq \frac{(1-D_{min}) \times R_{max}}{2 \times f_{sw}} = \frac{0.6 \times 14.4}{2 \times 50 \times 1000} = 86.4\ \mu H$$

- **Inductance (L) calculation:** In all operating condition the % current ripple should not exceed 30%.

$$\Delta I_L = \frac{V_{out}.(1-D)}{Lf_{sw}}$$

$$\frac{\Delta I_L}{I_L} = \frac{R.(1-D)}{Lf_{sw}}$$

$$L \geq \frac{R_{max}}{f_{sw}} \times (1-D_{min}) \times \frac{100}{30}$$
$$= \frac{14.4}{50 \times 1000} \times 0.6 \times \frac{100}{30} = 576\mu H$$

The chosen value of L $=576\mu H$. So, as per design the converter is always in CCM. The maximum average current through the converter can be given as-

$$< i_L >_{T_S} = I_L = \frac{V_{out}}{R}$$

$$I_{L,max} = \frac{V_{out}}{R_{min}} = \frac{48}{11.52} = 4.17A$$

The maximum peak current through the inductor is considered as, $i_{L,peak} = I_{L,max} \times 1.3 = 5.421A$.

- The DCM load condition for the chosen L can be found out as shown below-

$$\frac{2L}{RT_s} \leq (1-D)$$

$$R \geq \frac{2.L.\ f_{sw}}{(1-D_{max})} = 110.77\Omega$$

- **Capacitance(C) choice:** In all operating condition output voltage ripple should be less than 2%.

$$\frac{\Delta V_{out}}{V_{out}} = \frac{1}{8} \times \frac{(1-D)}{L f_{sw}{}^2} \times \frac{1}{C} \le \frac{2}{100}$$

$$C \ge \frac{1}{8} \times \frac{(1-D_{min})}{L f_{sw}{}^2} \times 50$$
$$= 2.61\ \mu F$$

Capacitor current will be maximum when ΔI_L is maximum. Rms capacitor current= 0.3A, Peak-Peak ripple current =1A, Average capacitor voltage= 48V.

- Conductive Polymer Hybrid Aluminum Electrolytic Capacitors (standard product: EEHZA1H100R) has been chosen.
- Rated Voltage =63V.
- Capacitance (C) = 10μF.
- ESR= 120 mΩ.
- Max. ripple current(rms) =1000mA.
- Data Sheet: http://www.farnell.com/datasheets/2842914.pdf?_ga=2.100048157.249828137.1600968886-1009838117.1593006503

SELECTION OF MOSFET:

Blocking Voltage= 120V. Average switch current can be expressed as-

$$< i_{sw} >_{T_s} = D.I_L = D.\frac{V_o}{R_{min}}$$
$$< i_{sw} >_{T_s,max} = \frac{0.48 \times 48}{11.52} = 2A$$

Maximum switch current= 5.421A (during transients).

- **BSC12DN20NS3G** is chosen as a MOSFET switch.
- Blocking voltage = 200 V.
- Max. drain current @100^0 C = 8A.
- $R_{ds,on}$ (at 100^0C and I_d = 6A, for V_{gs} =10V) = 188 mΩ.
- C_{gd1} = 5 pF, C_{gd2} = 55 pF.
- Gate driver voltage (V_{dr})=10V and gate resistance $(R_g) = 10\Omega$.
- Current rise time $(t_{ri}) = 4ns$.
- Current fall time $(t_{fi}) = 3ns$.
- @150^0C, V_{gs1} =4V and I_{d1} = 3.75A, V_{gs2} =5V and I_{d2} = 15A

$$V_{th} = \frac{V_{gs1}\sqrt{I_{d2}} - V_{gs2}\sqrt{I_{d1}}}{\sqrt{I_{d2}} - \sqrt{I_{d1}}} = 3V$$

$$k = \frac{I_{d1}}{(V_{gs1} - V_{th})^2} = 3.75$$

$$V_{gs,miller} = V_{th} + \sqrt{\frac{I_{load}}{k}} = 4.05V$$

$$V_{adj} = (100 - 150) \times (-0.007) = +0.35V$$

$$V_{plateau} = V_{gs,miller} + V_{adj} = 4.4V$$

- Average voltage fall time (t_{fv}) can be expresses as-

$$t_{fv} = \left(V_d - I_d R_{ds,on}\right) \times \frac{R_g}{\left(V_{dr} - V_{plateau}\right)} \times \frac{\left(C_{gd1} + C_{gd2}\right)}{2} = 6.4ns$$

- Average voltage rise time (t_{rv}) can be expresses as-

$$t_{rv} = \left(V_d - I_d R_{ds,on}\right) \times \frac{R_g}{V_{plateau}} \times \frac{\left(C_{gd1} + C_{gd2}\right)}{2} = 8.12ns$$

- Average Switching loss can be expressed as-

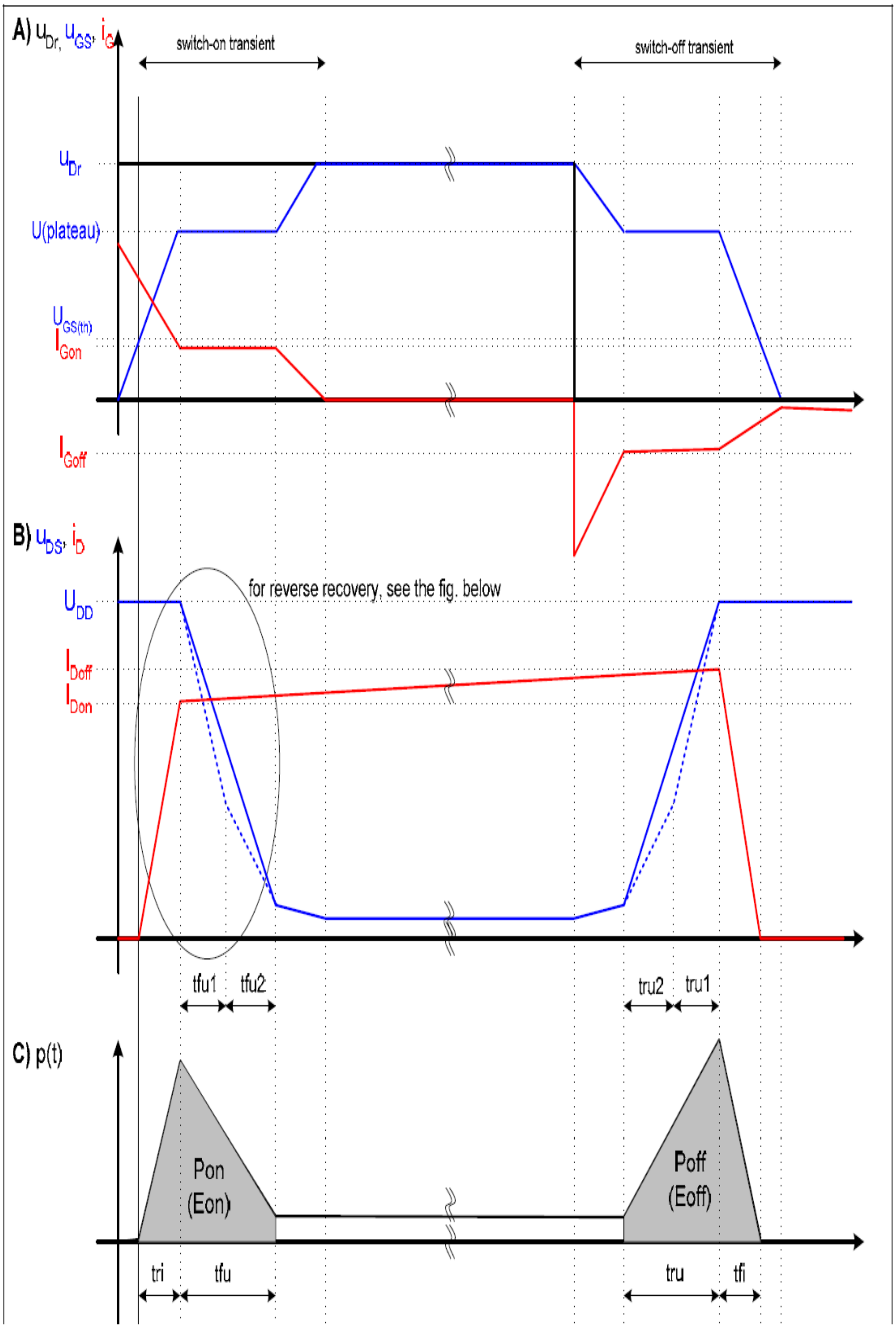
$$P_{sw} = \frac{f_{sw}}{2} \times V_{block} I_{load} \times \left[\left(t_{ri} + t_{fv}\right) + \left(t_{fi} + t_{rv}\right)\right] = 0.27W$$

- Conduction loss in switch, $P_{conduction} = {I_{load}}^2 R_{ds,on} = 3.269W$
- Total loss in switch, $P_{loss,sw} = 3.269 + 0.27 = 3.54W$

Data sheet: https://www.infineon.com/dgdl/Infineon-BSC12DN20NS3-DS-v02_02-en.pdf?fileId=db3a30432ad629a6012b146334d419ec

Heat Sink designing:

- Transient thermal impedance junction to case (@ 50 kHz and D=0.48) = 1.3K/W.
- Junction temp. rise w.r.t case = $P_{loss} \times Z_{thc} = 4.6K = 4.6C$
- Let ambient temp. be 40^0 C and allowable junction temp. 100^0 C.
- Max. heat sink thermal impedance (Z_a) = $\frac{T_c - T_a}{P_{loss,sw}} = \frac{95.4-40}{3.4} = 15.64^0 C/W$.
- Selected heat sink thermal impedance(case to impedance): $\mathbf{3.2^0 C/W}$ **(1.625'' wide × 12'' flatback heatsink)**
- Case temp. rise w.r.t ambient with selected heatsink= $P_{loss} \times Z_a = 11.328^0 C$
- Junction Temp.= $40 + 11.328 + 4.6 = 55.91^0 C$. Hence junction temp. is well within operating temp. of selected MOSFET.



SELECTION OF DIODE:

Blocking Voltage= 120V, Average maximum diode current can be expressed as-

$$< i_D >_{T_s} = (1-D).I_L = \frac{(1-D_{min}).V_{out}}{R_{min}}$$

$$< i_D >_{T_s,max} = \frac{0.6 \times 48}{11.52} = 2.5A$$

Maximum diode current= 5.421A (during transients).

- **Schottky diode DSTF10200C** has been chosen for the above mentioned buck converter.
- Peak inverse voltage 200V
- Average forward current per leg (@ 90^0C) = 5A
- Forward voltage drop (@125^0C and 3A) = 0.6V.
- Reverse leakage current (@125^0C and 120V blocking voltage) = 0.1 mA.
- Conduction loss in diode = 2.5× 0.6=1.5W.
- Reverse leakage loss in the diode = 200× $0.1 \times 10^{-3} \times 0.6$=0.012W
- Total loss in diode, $P_{loss,D} = 1.5 + 0.012 = 1.512W$
- Data Sheet: https://m.littelfuse.com/~/media/electronics/datasheets/power_semiconductors/littelfuse_power_semiconductor_schottky_diode_dstf10200c_datasheet.pdf.pdf

Heat Sink Design:

- Thermal impedance Junction to case per diode = $7^0 C/W$
- Junction temp. rise w.r.t case = $P_{loss,D} \times Z_{thc} = 10.58^0 C$
- Let ambient temp. be 40^0 C and allowable junction temp. 100^0 C.
- Max. heat sink thermal impedance (Z_a) = $\frac{T_c - T_a}{P_{loss,sw}} = \frac{95.58-40}{3.4} = 32.68^0 C/W$.
- Selected heat sink thermal impedance(case to impedance): $\mathbf{3.2^0 C/W}$ **(1.625'' wide × 12'' flatback heatsink)**
- Case temp. rise w.r.t ambient with selected heatsink= $P_{loss} \times Z_a = 4.838^0 C$
- Junction Temp.= $40 + 4.838 + 10.58 = 55.4^0 C$. Hence junction temp. is well within operating temp. of selected Diode.

• <u>DESIGN OF INDUCTOR MAGNETICS:</u>

Inductance(L)	576 μH
I_p	5.421A
I_{rms}	4.17A
B_m	0.2 wb/m^2
J(initial)	3A/mm^2
K_w(initial)	0.3

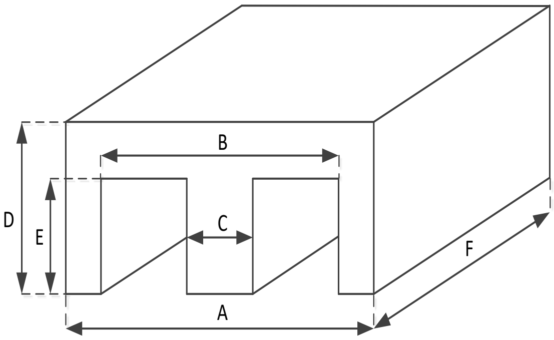


Fig.: E – core

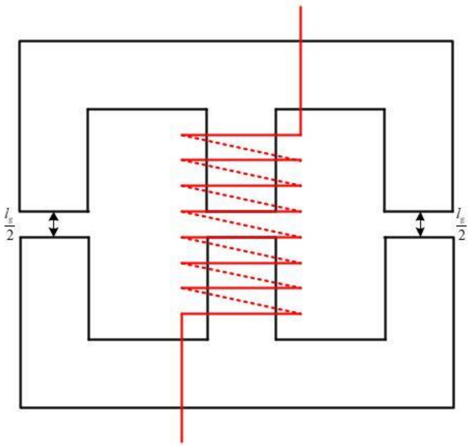


Fig.: Inductor Winding on EE core

Area Product,

$$A_cA_w = \frac{L.I_p.I_{rms}}{K_w.B_m.J}$$
$$= \frac{576\times10^{-6}\times5.421\times4.17}{0.3\times0.2\times3}\times10^6$$
$$= 72337.8\ mm^4$$

Selected Core:
E 56/24/19 , A_c = 364.81 mm^2 , A_w = 271.7 mm^2, C = 19.1 mm F = 19.1 mm

- Number of turns(N) can be found as-
$$N = \frac{L.I_p}{B_m.A_c} = \frac{576\times10^{-6}\times5.421}{0.2\times364.81\times10^{-6}} \approx 43$$
- Calculated wire size, $a_w = \frac{I_{rms}}{J} = 1.39\ mm^2$
- From wire table, the chosen wire is SWG 17.
- Updated wire size, $a_w{}^* = 1.589\ mm^2$.
- Updated current density, $J^* = \frac{I_{rms}}{a_w{}^*} = 2.624A/mm^2$.
- Updated winding factor, $K_w{}^* = \frac{N\times a_w{}^*}{A_w} \approx 0.251$
- Air gap length, $l_g = \frac{N^2.\ A_c.\ \mu_o}{L} = 1.47\ mm \ll \sqrt{A_c}$
- Average length of each turn of coil = $2\times(C+F) = 76.4\ mm$
- Average length of inductor coil = $N\times76.4 = 3285.2\ mm = 3.28m$
- Coil resistance of inductor =$\frac{10.85}{1000}\times3.28 = 35.64m\Omega$.
- Updated area product: $A_cA_w = 98858.57mm^4$

- **<u>TOTAL LOSS AND EFFICIECNY CALCULATION AT RATED LOAD:</u>**

Total Power Loss = 0.0108W +3.54W+1.512W+0.619W = 5.68W

Full load efficiency of Buck converter $= \frac{Output\ Power}{Output\ Power+Losses} * 100\% = \frac{200}{205.68} * 100 = 97.2\%$

REFERENCES

1. Dr. Dušan Graovac , Marco Pürschel, and Andreas Kiep ,"*MOSFET Power Losses Calculation Using the Data-Sheet Parameters*", Application Note, V 1.1, July 2006, by infenion
2. "*Calculation of reverse losses in a power diode, **AN4021***" Application Note by ST Microelectronics.
3. V. Ramanarayanan, "Course Material on Switched Mode Power Conversion", Department of Electrical Engineering Indian Institute of Science Bangalore 560012, second edition 2006.