Experiment-1

Boost converter Design document

CONTENTS

1. SYSTEM UNDER CONSIDERATION:

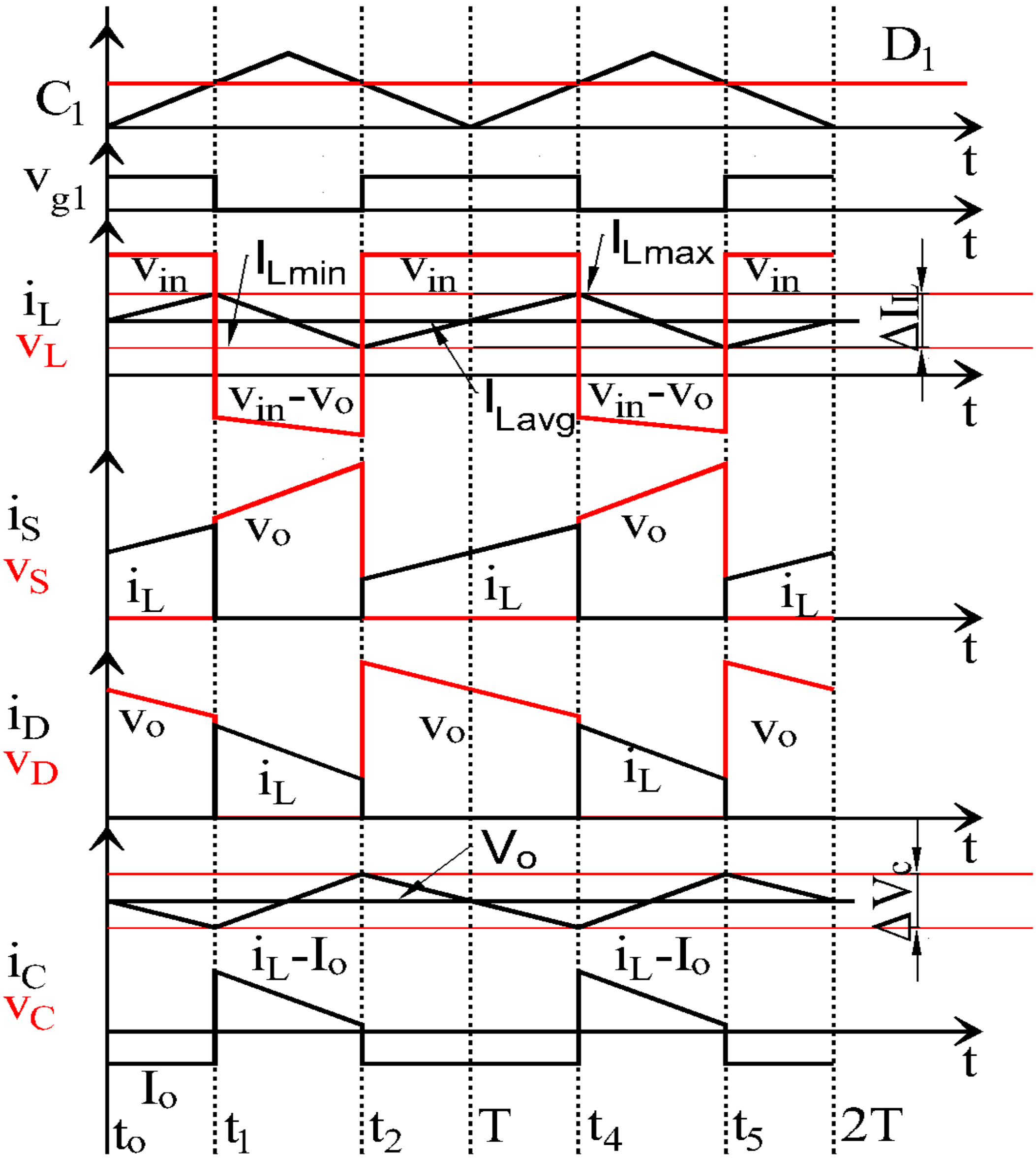
Let us consider a system:

V_{in} = 20 to 28.8V (2 Lead acid battery of 12V in series), Rated V_{in} = 24V

V_{out} = 48V (DC bus), Rated Power = 200 W, and switching frequency (fs) =50 kHz.

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.

2. KEY BOOST CONVERTER WAVEFORMS:



3. SELECTION OF MOSFET:

Blocking voltage of mosfet and diode ($\boldsymbol{V_{dd}}$) = load voltage (V_o) = 48V

Safety factor to be considered = 2 (due to voltage spikes due to parasitic inductance and reverse recovery of diode)

Voltage rating of MOSFET (V_{br}) = 100V

Also Maximum current through switch = inductor current = 200W/20V = 10A.

- ## CONDUCTION LOSS:

Without considering inductor ripple.

RMS switch current ($\boldsymbol{I_{srms}}$) = $I_{in}\sqrt{D}$ = 7.635A ($10\sqrt{0.583}$)

IRF540NLPbF is the mosfet chosen for the boost converter.

Blocking voltage of mosfet = 100V

Maximum Drain current at 125°C = 17.5A (From fig 9).

R_{ds} of MOSFET at 125°C = 2.25*44mΩ = 99mΩ

Maximum conduction Loss in the switch = $\boldsymbol{I_{srms}^2 R_{ds}}$ = 5.77W

- ## SWITCHING LOSS:

Since for low power and low voltage system, Power Schottky diode is selected which has negligible reverse recovery loss during its turn-off.

From fig. 5 of **IRF540NLPbF** datasheet

C_{gd} at V_{dd}(50V) C_{gd1} = 40pF

C_{gd} at I_{ds}*Rd_{ds} (0.99V) C_{gd2} = 500pF

Gate Threshold voltage V_{gth} = 4V

From fig. 3 of **IRF540NLPbF** datasheet

At 175°C V_{g1} = 4V i_{d1} = 12A; V_{g2} = 6V i_{d2} = 60

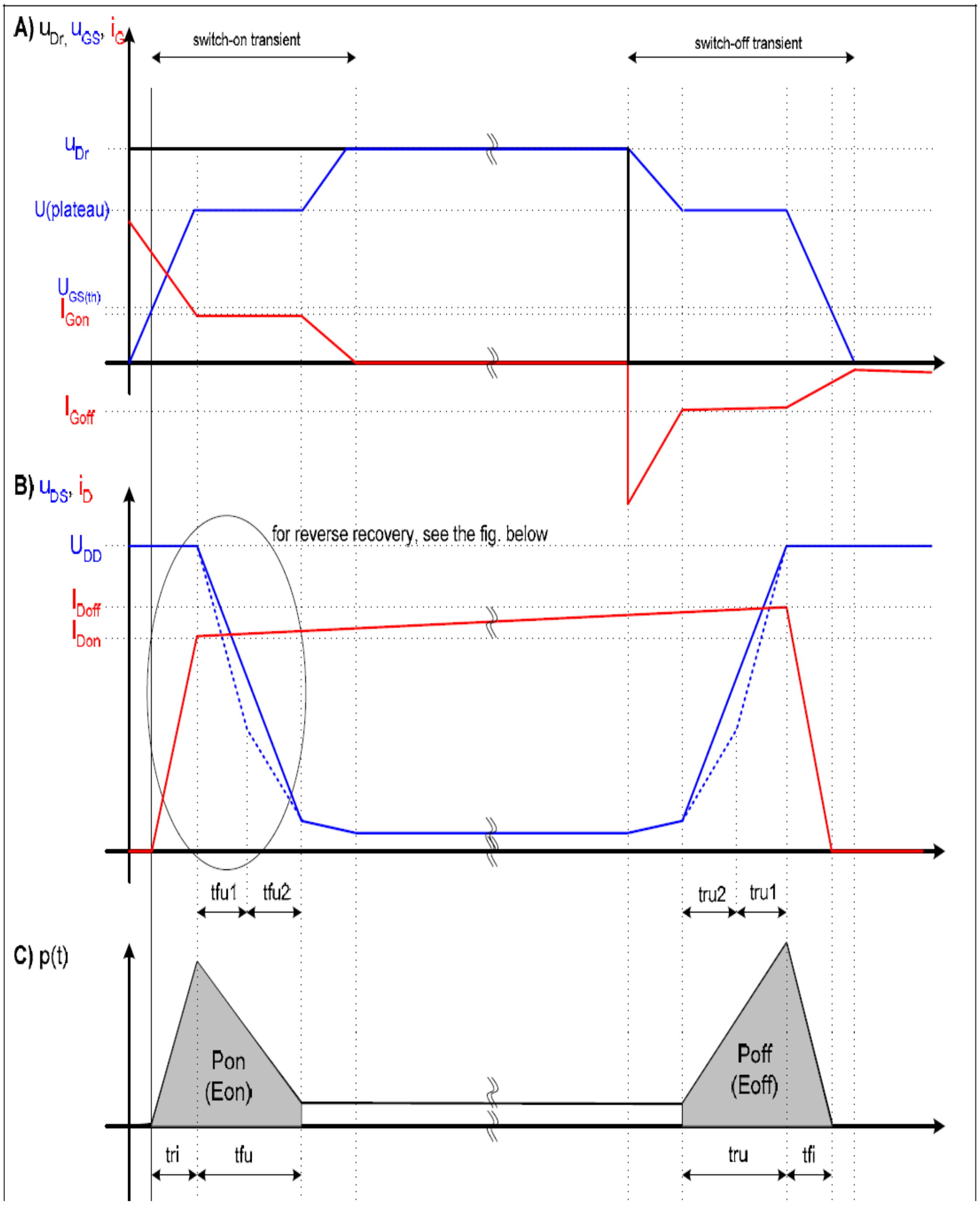
$$V_{th} = \frac{V_{g1}\sqrt{i_{d2}} - V_{g2}\sqrt{i_{d1}}}{\sqrt{i_{d2}} - \sqrt{i_{d1}}} = 2.382V;\ k = \frac{i_{d1}}{(V_{g1} - V_{th})^2} = 4.584$$

$$V_{GS,miller} = V_{th} + \sqrt{\frac{I_{load}}{k}} = 2.382 + \sqrt{\frac{10}{4.584}} = 3.859$$

$$V_{adj} = (125 - 175) * \left(-0.007\frac{°C}{V}\right) = +0.35V;\ (From\ class\ notes)$$

$$V_{plateau} = 3.859 + 0.35 = 4.21V$$

Gate drive voltage (V_{dr}) = 15V; Gate resistance R_g= 10Ω



Current rise time of the switch (t_r) = 35ns (from datasheet).

Voltage fall time 1 $t_{fu1} = (V_{dd} - I_{ds} * R_{ds}) * R_g * \frac{C_{gd1}}{V_{dr} - V_{plateau}} = 1.74ns$

Voltage fall time 1 $t_{fu2} = (V_{dd} - I_{ds} * R_{ds}) * R_g * \frac{C_{gd2}}{V_{dr} - V_{plateau}} = 21.78ns$

Average voltage fall time $t_{fu} = \frac{t_{fu1} + t_{fu2}}{2} = 11.76ns$

Current fall time of the switch (t_f)= 35ns (from datasheet)

Voltage rise time 1 $t_{ru1} = (V_{dd} - I_{ds} * R_{ds}) * R_g * \frac{C_{gd1}}{V_{plateau}} = 0.447ns$

Voltage rise time 1 $t_{ru2} = (V_{dd} - I_{ds} * R_{ds}) * R_g * \frac{C_{gd2}}{V_{plateau}} = 5.583ns$

Average voltage rise time $t_{ru} = \frac{t_{ru1}+t_{ru2}}{2} = 3.02ns$

Power Schottky diode is selected which has negligible reverse recovery loss during its turn-off.

Switching loss in the switch = $V_o f_s((i_{son} * \frac{t_r+t_{fu}}{2}) + (\frac{t_{ru}+t_f}{2} * i_{soff}))$

$$= \frac{1}{2}\ 48 * 50000 * 10\big((2 * 35) + 11.76 + 3.02\big) * 10^{-9} = 1.02W$$

Total Loss of the switch (P_g) = 5.77W +1.02W = 6.79W.

- ## MOSFET HEAT SINK DESIGN:

Transient Thermal Impedance Junction-to-Case at 50Khz 0.5 duty cycle (Z_{thc})= 0.7°C/W (From fig 11).

Junction Temperature rise with respect to case = $P_g * Z_{thc} = 6.79 * 0.7 = 4.75°\ rise.$

Let maximum junction temperature T_j be 125°C.

Then, maximum case temperature T_c = 125 - 4.75 = 120.25°C

Let the ambient temperature be 40°C;

Maximum heat sink thermal Impedance (Case to ambient) $(Z_a) = \frac{T_c - T_a}{P_g} = \frac{120.25-40}{P_g} = 11.81°\frac{C}{W}$

Selected heat sink thermal Impedance (Case to ambient)= 8°C/W (1.10" Wide x 12" BGA Heatsink Extrusion 16240 xx8052-65)

Case Temperature rise with respect to ambient with selected heatsink = $P_g * Z_a = 54.32°\ rise$

Junction Temperature (T_j) = 40° + 54.32° +4.75°C = 99.07°C.

Here junction temperature is well within the operating temperature range of the MOSFET.

4. SELECTION OF DIODE:

Schottky diode STPS20S100C is the diode chosen for this boost converter.

Voltage rating of diode (V_{br}) = 100V

RMS diode current (I_{drms}) = $I_{in}\sqrt{(1-D)}$ = 6.458A ($10\sqrt{0.417}$) < 30A (rating)

Average diode current (I_{dav}) = $I_{in}(1-D)$ = 4.17A <20A(rating)

- ## CONDUCTION LOSS:

Forward Voltge of the diode at 10A at 125°C (V_f)= 0.71V.

Conduction Loss of the diode = $V_f * i_d * (1-D)$ = 0.71*10*0.417 = 2.96W.

- **REVERSE LEAKAGE LOSS:**

Since **Schottky** diode is used, the reverse leakage losses are more significant than switching losses.

Reverse leakage current (I_r) at 50V blocking = 0.3mA @ T_j= 125°C. (From fig 6)

Reverse Leakage Loss of the diode = $V_o * I_r * D = 48 * 0.3 * 10^{-3} * 0.583$ = 0.0084W

Total Loss of the diode (P_g) = 2.97W.

- **DIODE HEAT SINK DESIGN:**

Transient Thermal Impedance Junction-to-Case per diode at 1Khz (Z_{thjc})=2.2° C/W.

Transient Thermal Impedance coupling at 1Khz (Z_{thc}) = 0.3C/W.

Junction Temperature rise with respect to case = $P_g/2 * (Z_{thjc} + Z_{thc})$ (from datasheet)

= 3.71°C rise

Let maximum junction temperature T_j be 125°C.

Then, maximum case temperature T_c = 125 – 3.71 = 121.29°C

Let the ambient temperature be 40°C.

Maximum heat sink thermal Impedance (Case to ambient) $(Z_a) = \frac{T_c - T_a}{P_g} = \frac{121.29-40}{P_g} = 27.37° \frac{C}{W}$

Heat sink thermal Impedance (Case to ambient) (Z_a)= 16°C/W (ATS-PCB1008)

Case Temperature rise with respect to ambient= $P_g * Z_a = 2.97 * 21.2 = 47.52° \, rise.$

Junction Temperature (T_j) = 40° + 62.96° +3.71°C = 91.23°C.

Here junction temperature is well within the operating temperature range of the diode.

Total semiconductor Loss = 6.79W + 2.97W = 9.76W

5. DESIGN OF INDUCTOR:

For Boost converter, Inductor current = Input current.

Inductor ripple current has to be 30% at rated load.

Case 1:	Case 1:
V_{in} = 28.8V	V_{in} = 20V
$I_{in} = \frac{1}{(1-D)} I_o = 6.94A$	$I_{in} = \frac{1}{(1-D)} I_o = 10A$
$\Delta I_l = 0.3 * 6.94 = 2.08A$	$\Delta I_l = 0.3 * 10 = 3A$
$L = \frac{1}{\Delta I_l f_s} V_{in} D = 110.66 \mu H$	$L = \frac{1}{\Delta I_l f_s} V_{in} D = 77.73 \mu H$

Worst case Inductor Value L = 110.66µH

For I_L = 10A. $\Delta I_l = \frac{20*0.583}{500000*110.66\mu} = 2.11A$

$$I_{Lrms} = \sqrt{\frac{1}{T}(\int_0^{DT}(\frac{\Delta I_L}{DT}t + I_{Lmin})^2\,dt + \int_{DT}^{T}(-\frac{\Delta I_L}{(1-D)T}t + I_{Lmax})^2)}$$

$$I_{Lrms} = \sqrt{I_{Lmax}^2(1-D) + I_{Lmin}^2(D) + \frac{\Delta I_L{}^2}{3} + \Delta I_L(DI_{Lmin} - (1-D)I_{Lmax})}$$

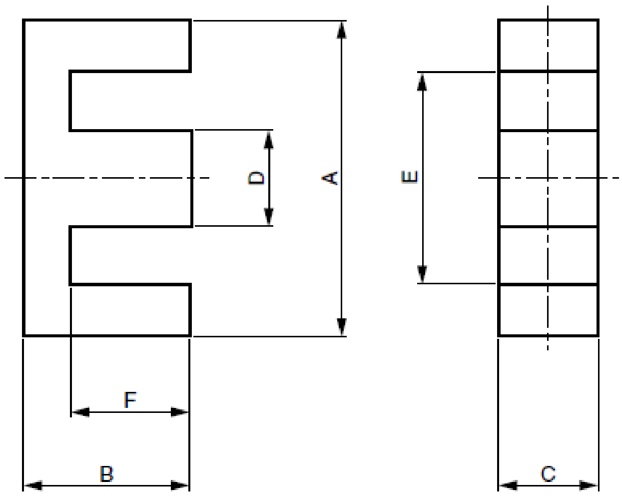
$$= \sqrt{10.725^2 * 0.417 + 9.275^2(0.583) + \frac{1.45^2}{3} + 1.45(0.583 * 9.275 - 0.417 * 10.725)}$$

=10.008A

Inductance(L)	110.66μH
$Peak\ Current(I_p)$	11.06A*1.1 = 12.17A(To account for losses)
Max. average current (I_{avg})	10A
B_m	0.2 wb/m^2
J(initial)	3A/mm^2
K_w(initial)	0.3

Area Product, $A_cA_w = \frac{L.I_p.I_{avg}}{K_w.B_m.J} = 74818.46mm^4$

Selected core: EE55/28/25 is selected.



Selected core: EE55/55B

A = 55mm +1.2mm, -0.9mm

B = 27.8mm, +0mm ,-0.6mm,

C= 25mm, +0mm ,-0.8mm,

D= 17.2mm, +0mm ,-0.5mm,

E = 37.5mm, +1.2mm, -0mm

F = 18.5mm +0.8mm,-0mm

. $Minimum\ A_c = C * D = (25 - 0.8) * (17.2 - 0.5) = 404.14mm^2$

$A_w = (E - D) * F = (37.5 - 17.2) * 18.5 = 375.55\ mm^2$,

Number of turns: N = $\frac{LI_p}{B_mA_c} = 18.25 \approx 19$

Wire Size: $a_w = \frac{I_{rms}}{J} = \frac{10.008}{3} = 3.34mm^2$

Chosen wire: SWG 21 *4* 2.

Updated wire size: $\boldsymbol{a_w^*} = 0.5189 * 8 = 4.15mm^2$ (Even no is chosen due to manufacturing reason)

Thickness of the wire $(t_c) = 0.874 * 4 * 1.05(5\%\ tolerance) = 3.67mm$

Minimum Window width = 8.35mm

Height of the winding = 0.874*2*19*1.1(10% Tolerance) = 36.53mm (10% for transposing conductors for all eight strands to have nearly equal length).

Minimum Window height = 18.5 * 2mm = 37mm

Updated current density: $\boldsymbol{J^*} = \frac{\boldsymbol{I_{rms}}}{\boldsymbol{a_w^*}} = \mathbf{2.411}\boldsymbol{A/mm^2}$

Updated area product: $A_cA_w = 151774mm^4$

Air gap length: $\boldsymbol{l_g} = \frac{N^2A_c\mu_o}{L} = 1.66mm \ll \sqrt{A_c}$ (To avoid fringing effect)

Average length of each turn of a conductor $= 2 * (C + D + t_c) = 91.74mm$

Average length of inductor coil: $\boldsymbol{N} * t_c = 1.743m$

Coil resistance of inductor: $\frac{\mathbf{33.23*1.743}}{\mathbf{1000*8}} = \mathbf{7.24}\boldsymbol{m\Omega}$

Updated inductance $(\boldsymbol{L}) = \frac{NB_mA_c}{I_p} = 115.18\mu H$

Conduction Loss in Inductor $= I_{Lrms}^2 * r_l = 0.725W$.

6. DESIGN OF OUTPUT CAPACITOR:

Capacitor voltage ripple has to be 2% at rated load.

Capacitor Ripple Voltage $\boldsymbol{\Delta V_{C(p-p)}} = \frac{V_{out}*D_{max}*Ts}{R_{Lmin}*C}$

Value of Capacitance C = $\frac{V_{out}*D*Ts}{R_{Lmin}*\Delta V_{C(p-p)}} = \frac{48*0.583}{50000*11.52*0.96} = 50.6\mu F \approx 47$

Rms current of the capacitor $\boldsymbol{I_{crms}} = \sqrt{\frac{1}{T}(\int_0^{DT} {I_o}^2\,dt + \int_{DT}^{T}(-\frac{\Delta I_L}{(1-D)T}t + I_{Lmax})^2)}$

$$= \sqrt{I_o^2D + I_{Lmax}^2(1-D) + \frac{{\Delta I_L}^2}{3}(1-D) - \Delta I_L(1-D)I_{Lmax}}$$

$$= \sqrt{4.167^2 * 0.583 + 10.725^2(0.417) + \frac{1.45^2}{3}(0.417) - 1.45 * 0.417 * 10.725}$$

=7.203A

Capacitor Chosen is 3xelectrolytic capacitor type : (3x 100V 18μF 100SXE18M) capacitors in parallel, with a ripple current rating of 3A and ESR of 30mΩ each.

Electrolytic capacitors is not chosen because of their low ripple current rating

Power loss in capacitor == $I_{crms}^{2} * ESR = 7.203^{2} * \frac{30}{3} m\Omega = 0.52\text{W}$

7. TOTAL LOSS AND EFFICIECNY CALCULATION AT RATED LOAD:

Total Power Loss = 9.76W +0.725W+0.52 = 10.635W

Full load efficiency of Boost converter $= \frac{Output\ Power}{Output\ Power+Losses} * 100\% = \frac{200}{211.005} * 100 =$ 94.78%

REFERENCES

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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.