Experiment-1

Buck-Boost converter Design document

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Experiment-1

(BUCK-BOOST converter)

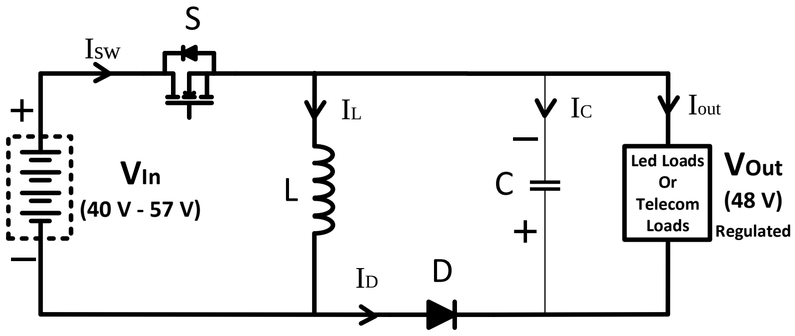

Fig. 1. Buck Boost Converter

1. System under consideration:

Pout= 200 W (rated).

Vout=48 V (Telecom DC BUS or LED Loads).

fs=50 kHz.

Vin= 40 V to 57 V (Considering four Lead Acid batteries of 12 V each are connected in series in the input port, nominal voltage is 48 V)

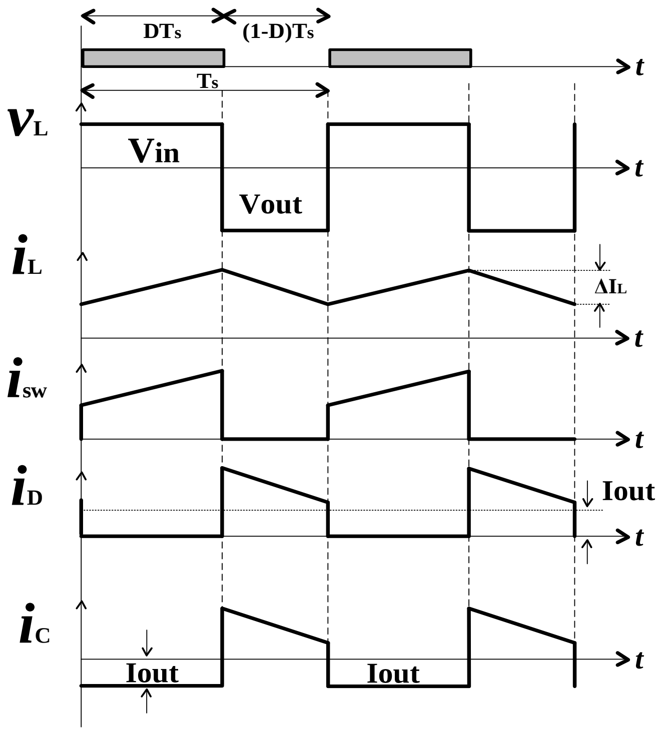

Fig. 2. Voltage and current waveforms

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 also 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.

Solution:

- The duty (D) can be calculated as $\frac{D}{(1-D)} = \frac{V_{out}}{V_{in}} => D = 0.457\ to\ 0.545$.
- The rated load current can be calculated as 200/48=4.16A.
- The corresponding rated inductor current can be calculated as $I_{L\_D_{max}} = \frac{I_{out\_rated}}{1-D_{max}} = \frac{4.16}{1-0.545} = 9.14 Amps$. Similarly corresponds to D_{min}, $I_{L\_D_{min}} = 7.66\ Amps$.
- Now the L can be designed considering the ON time of the switch,

$$\Delta I_{L(p-p)} = \frac{V_{in}}{L} * (D) * Ts$$

$$\text{So, } L = \frac{V_{in}}{\Delta I_{L(p-p)}} * (D) * Ts$$

$$\Rightarrow L_{worst} = \frac{V_{in\_max}}{0.3 * I_{L\_D_{min}}} * (D_{min}) * Ts$$

$$\Rightarrow L_{worst} = \frac{57}{0.3 * 7.66} * (0.457) * 20 * 10^{-6}$$

$$\Rightarrow L_{worst} = 0.226\, mH \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (i)$$

- Now let's find out the verge of CCM and DCM condition:

  - ⇨ $I_{L_{DCM}} \leq \frac{\Delta I_{L(p-p)}}{2} \leq 1.15\ Amps\ @\left(V_{in_{max}}\ \&\ D_{min}\right)$
  - ⇨ $\& I_{L\_DCM} \leq \frac{\Delta I_{L(p-p)}}{2} \leq\ 0.964\ Amps@\ (V_{in_{min}}\ \&\ D_{max})$, That means the system will always be in CCM above [Max(1.15A,0.964A)=1.15 A] of inductor current. So the corresponding load current can be calculated as:
  - ⇨ $I_{o_{avg}(DCM)} \leq\ I_{L_{DCM}} * (1 - D_{max}) = 0.523\ Amps$. i.e. for the load demand above 12.5% of the rated load, the system will always operate in CCM mode.
  - ⇨ For the calculated $L_{worst} = 0.226\ mH$, the corresponding maximum peak inductor current during rated load condition will be

    $$\frac{\Delta I_{L(p-p)}}{2} + I_{L\_rated} =\ 0.964\text{ A} + 9.14\text{ A} = 10.10\text{A @ } (V_{in_{min}}\ \&\ D_{max})$$

    and $\frac{\Delta I_{L(p-p)}}{2} + I_{L\_rated} = 1.15A + 7.66A = 8.81A$ @ $(V_{in_{max}}\ \&\ D_{min})$respectively.
  - ⇨ The rms current of inductor can be calculated as:

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

    $$\therefore I_{Lrms} = \sqrt{I_{Lmax}^2(1-D) + I_{Lmin}^2(D) + \frac{\Delta I_L{}^2}{3} + \Delta I_L(DI_{Lmin} - (1-D)I_{Lmax})}$$
  - ⇨ $\therefore \sqrt{10.10^2 * 0.455 + 8.17^2(0.545) + \frac{1.928^2}{3} + 1.928(0.545 * 8.17 - 0.455 * 10.10)} = 9.15A \simeq (I_{L\_Avg\_max} = 9.14A)$

2. <u>Selection of MOSFET:</u>

Blocking voltage of mosfet and diode = load voltage $(V_{in} + V_o)$ = 105V

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

So, the required Voltage rating of MOSFET (V_{br}) = 200V

Also peak current through switch = On time peak inductor current = $I_{Lmax} = I_{L\_rated} + \frac{\Delta I_{L(p-p)}}{2} = 9.14 + 0.964 = 10.10$ A.

The corresponding $I_{Lmin} = I_{L\_rated} - \frac{\Delta I_{L(p-p)}}{2} = 9.14 - 0.964 = 8.17$ A

The RMS switch current (I_{sw_rms})

⇨ $I_{sw\_rms} = \sqrt{\frac{1}{T}(\int_0^{DT}(\frac{\Delta I_L}{DT}t + I_{Lmin})^2\, dt}$

⇨ $I_{sw\_rms} = \sqrt{I_{Lmin}^2(D_{max}) + \frac{\Delta I_L{}^2 * D}{3} + \Delta I_L * D_{max} * I_{Lmin}}$

⇨ $I_{sw\_rms} = \sqrt{8.17^2 * (0.545) + \frac{1.928^2 * 0.545}{3} + 1.928 * 0.545 * 8.17} = 6.75A$

⇨ We can also calculate the approximate I_{sw_rms} in a very easy way.

i.e. $I_{L\_Avg\_max} * \sqrt{D_{max}}$ = 9.14*$\sqrt{0.545} = 6.747A$ (Nearly same answer)

"IPP320N20N3 G" is the mosfet chosen for the Buck-Boost converter.

Blocking voltage of mosfet = 200V and the Drain current= 34 Amps

Maximum Drain current at Case temp of 100°C ≃ 26A (From fig 2) and it also coming under the safe operating area corresponding to "10 usec" pulse duration curve (From fig 3).

R_{ds} of MOSFET at junction temperature of 125°C ≃ 50mΩ

Maximum conduction Loss in the switch =$P_{Cond\_Loss} = I_{srms}^2 R_{ds} = 6.75^2 * 0.05 = 2.278W$

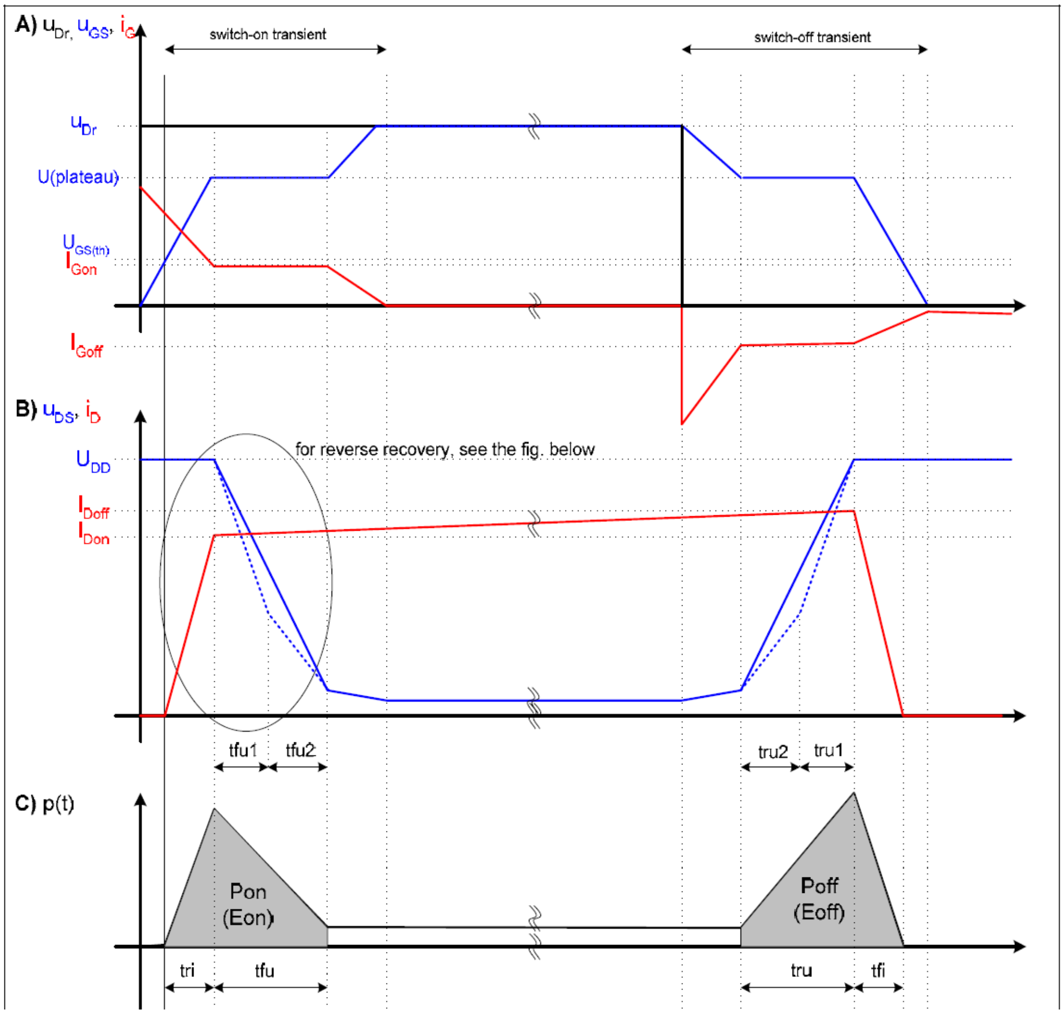

Fig. 3. Voltage and current profile of the switch during switching transient

Switching Loss calculation:

- Now from the datasheet (Fig. 11. Typ. Capacitance curve, check C_{rss} value)
  $C_{gd1}\ at\ V_{dd\ @100V} = 4pF$ (When the switch is OFF)

  $C_{gd1}\ at\ I_{ds} * R_{ds}(10.1 * 0.05 \simeq 0.5\ V) = 200pF$ (When the switch is ON)

  $So, C_{gd\_Avg} = \frac{C_{gd1}+C_{gd2}}{2} = 102\ pF.$
- Gate Threshold Voltage $V_{gth} = 4\ V.$
- Now from the datasheet (Fig. 7. Typ. Transfer characteristic curve)

  At 175°C, $I_{d1} = 14A, @\ V_{g1} = 4V$ and $I_{d2} = 50A, @\ V_{g2} = 5V.$
- Now the threshold voltage can be calculated as V_{th}:
  $V_{th} = \frac{V_{g1}\sqrt{I_{d2}} - V_{g2}\sqrt{I_{d1}}}{\sqrt{I_{d2}} - \sqrt{I_{d1}}} = 2.87V; K = \frac{I_{d1}}{(V_{g1} - V_{th})^2} = 3.085$
- $V_{gs\_miller} = V_{th} + \sqrt{\frac{I_{Load}}{K}} = 2.87V + \sqrt{\frac{10}{3.085}} = 4.67$
  $V_{adj} = (125 - 175) * \left(-0.007 \frac{°C}{V}\right) = +0.35\ V.$
  So, $V_{Plateau} = 4.67 + 0.35 = 5.02\ V$
- Gate drive voltage $(V_{dr}) = 15\ V\ and\ \left(R_{g\_on}\right) = 10\Omega$ and $\left(R_{g\_off}\right) = 1.6\Omega$
  From the datasheet, the current rise time (t_r) =9 nsec
  Voltage fall time $t_{fu} = (V_{dd} - I_{ds} * R_{ds})* R_{g\_on} * \frac{C_{gd_{Avg}}}{V_{dr}-V_{Plateau}} = 10.16\ nsec$
  Similarly From the datasheet, the current fall time =4 nsec.
  Voltage rise time $t_{ru} = (V_{dd} - I_{ds} * R_{ds})* R_{g\_off} * \frac{C_{gd_{Avg}}}{V_{Plateau}} = 3.23\ nsec$
- **Since for low power and low voltage system, Power Schottky diode is selected which has negligible reverse recovery loss during its turn-off.**
  So the switching loss in the switch can be calculated as:
  $P_{Sw\_Loss} = (V_{in} + V_o)f_s(i_{son} * \frac{t_r + t_{fu}}{2} + \frac{t_f + t_{ru}}{2} * i_{soff})$
  $= \frac{1}{2} * 105 * 50000 * 10 * [(9 + 10.16) + (4 + 3.23)] = 0.69W$
- So the total loss in the switch can be calculated as $P_{g\_SW} = 2.278 + 0.69 = 2.97W$
- Transient Thermal Impedance Junction-to-Case at 50Khz 0.5 duty cycle (Z_{thc})= 0.6°C/W (From fig 4. Max transient thermal impedence).

  Juction Temperature rise with respect to case $= P_{g\_SW} * Z_{thc} = 2.97 * 0.6 = 1.782°\ rise$

  Now, let ambient temperature be 40°C & the junction temperature should not exceed 100° C. So the the maximum thermal impedance of heat sink (Case to ambient) can be calculated as $Z_{a\_max} = \frac{T_{Case}-T_{Amb}}{P_g} = \frac{98.218-40}{2.97} = 19.6°C/W.$

The selected Heat sink is a Stamped standard Board level Aluminium Heat sink as shown in Fig below (Part Number: **ATS-PCB1037**). Heat sink thermal Impedance (Case to ambient) (Z_a)= 18°C/W. The dimensions are specified in the Fig. 4..

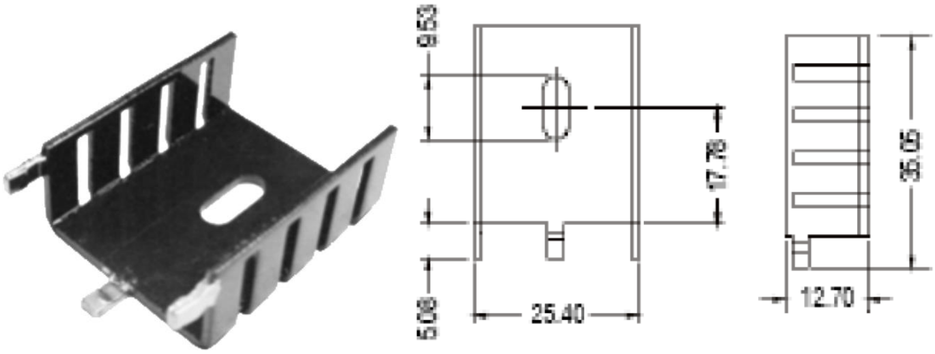

Fig. 4. Stamped standard Board level Aluminium Heat sink

Case Temperature rise with respect to ambient $= P_{g\_SW} * Z_a = 2.97 * 18 = 53.46° \, rise$

Junction Temperature (T_j) = 40° + 53.46°C+1.782° $C \simeq$ 95.242°C.

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

3. Selection of Diode:

- **Schottky diode "STPS20200C"** is the diode chosen for this boost converter with safety factor of nearly two for voltage and three current.
  Voltage rating of diode $(V_{br}) = 2 * (V_{in} + V_o) = 200\ V$
  RMS diode current $(I_{drms}) = I_{ind}\sqrt{(1-D)} = 10.1\sqrt{1-0.545}$ =6.81A
  Average diode current $(I_{dav}) = I_{ind}(1-D)$ = 4.6 A
  Forward Voltge of the diode at 10A at 125°C junction temp (V_f)= 0.6V.
- Conduction Loss of the diode = $[V_f * i_d * (1-D)] + [R_D * {I_{drms}}^2]$ = [0.7*10.01*(1-0.545)]+[0.01* 6.81^2]= 3.216+0.463=3.679 W.
- **Since Schottky diode is used, the reverse leakage losses are more significant than switching losses**.
  Reverse leakage current (I_r) at 100V blocking = 0.3mA @ T_j= 125°C. (From fig 3)
  Reverse Leakage Loss of the diode = $(V_{in} + V_o) * I_r * D = 105 * 0.3 * 10^{-3} * 0.545$ = 0.017W
- Total Loss of the diode (P_{g_Diode}) = 3.679+0.017 = 3.6965W.
- Transient Thermal Impedance Junction-to-Case per diode at 1Khz (Z_{thjc})=0.1*$R_{th_{j-c}} \simeq 0.1 * 5 = 0.5$°C/W. (Fig.6 of Data sheet)
  Transient Thermal Impedance coupling at 1Khz (Z_{thc}) = 0.1*$R_{thc} = 0.1 * 3 = 0.3$°C/W.
  So, the Juction Temperature rise with respect to case = $P_{g\_Dode}/2 * (Z_{thjc} + Z_{thc})$ (from datasheet)=(3.6965/2)*(0.5+0.3)=1.478°C rise .
- The selected Heat sink is a Stamped standard Board level Aluminium Heat sink as shown in Fig below (Part Number: **ATS-PCB1037**). Heat sink thermal Impedance (Case to ambient) (Z_a)= 18°C/W. The dimensions are specified in the Fig. 4.

Case Temperature rise with respect to ambient $= P_{g\_Diode} * Z_a = 3.6965 * 18 = 66.357° \, rise.$
Let ambient temperature be 40°C
Junction Temperature (T_j) = 40° + 66.357° +1.478°C = 108.015°C.
Here junction temperature is well within the operating temperature range of the diode.

- Total semiconductor Loss = 2.97W + 3.6965W **= 6.66W**

4. Inductor Design:

Inductance(L)	226μH
$Peak\ Current(I_p)$	1.1*10.10=11.11A (Safety factor of 1.1 chosen due to non-idealities of the converter)
Max. rms current (I_{rms})	9.15 A
B_m	0.2 wb/m^2
J(initial)	3A/mm^2
K_w(initial)	0.3

Area Product, $A_c A_w = \frac{L.I_p.I_{rms}}{K_w.B_m.J} = \frac{226*10^{-6}*9.15*11.11}{0.3*0.2*10^{-6}*3}$ =127635 mm^4

Selected core: Part no: **E 55/28/21** cores connected in Up and down fashion.

A_c=361.2mm^2, $A_w = 375.55\ mm^2$, $A_c * A_w$ = 135648.7, C=17.2 mm, F= 21 mm.

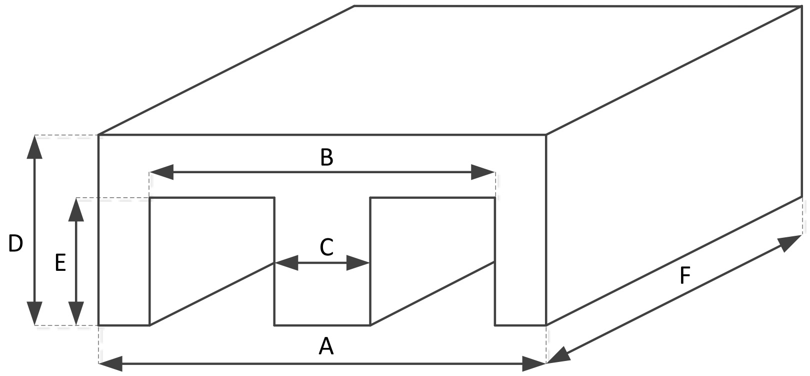

Fig. 5. E type ferrite core for inductor

Number of turns: N=$\frac{LI_p}{B_m A_c} = \frac{226*10^{-6}*11.11}{0.2*10^{-6}*361.2} = 34.75 \simeq 35$

Wire Size: $a_w = \frac{I_{avg}}{J} = \frac{9.14}{3} = 3.04\ mm^2$

Chosen wire: SWG 14.

Updated wire size: $\boldsymbol{a_w^*}$ =3.243mm^2

Updated current density: $\boldsymbol{J^*} = \frac{\boldsymbol{I_{avg}}}{\boldsymbol{a_w^*}} = \mathbf{2.81}\boldsymbol{A/mm^2}$

Updated winding factor: $\boldsymbol{K_w^*} = \frac{\boldsymbol{Na_w^*}}{A_w} = \frac{\mathbf{35*3.243}}{\mathbf{375.55}} = \mathbf{0.302} \simeq K_w(Initial)$

Updated area product: $A_cA_w = \frac{L.I_p.I_{rms}}{K_w^*.B_m.J^*} = \frac{226*10^{-6}*9.15*11.11}{0.302*0.2*10^{-6}*2.81} = 135363\ mm^4$,

$(Calculated\ Area\ product\ is\ matching\ with\ the\ selected\ Core\ Area\ Product)$

Air gap length: $\boldsymbol{l_g} = \frac{\boldsymbol{N^2A_c\mu_o}}{\boldsymbol{L}} = \frac{\mathbf{35*35*361.2*10^{-6}*4*3.14*10^{-7}}}{\mathbf{210*10^{-6}}} = 2.45\boldsymbol{mm} \ll \sqrt{\boldsymbol{A_c}}$ or Air gap length in each limb=1.225 mm**.**

Average length of each turn of coil: $\mathbf{2} \times (\boldsymbol{C} + \boldsymbol{F}) = 76.4\boldsymbol{mm}$

Average length of inductor coil: $\boldsymbol{N} \times 76.4mm = \mathbf{2674}\boldsymbol{mm} = 2.674m$

Coil resistance of inductor (R_L): $\frac{1.76*10^{-6}*30*76.4*10^{-1}}{3.243*10^{-2}} = 14.5\boldsymbol{m\Omega}$

So, the losses in the inductor can be calculated as: $P_{Inductor}$

$P_{Inductor} = I_{L\_rms}^2 * R_L = 9.15^2 * 14.5\ \boldsymbol{m\Omega} = \mathbf{1.21}\ \boldsymbol{W}$

5. <u>Capacitor Design:</u>

- Now the C can be designed considering the Maximum charge delivered by the capacitor during ON time,

$$Q = C * \Delta V_{C(p-p)} = \frac{V_{out}}{R_L} * (D) * Ts$$

$$\Rightarrow\ C_{worst} = \frac{V_{out}*D_{max}*Ts}{R_{L\_rated}*\Delta V_{C(p-p)}}$$

$$\Rightarrow\ C_{worst} = \frac{48*0.545*20*10^{-6}}{9.14*0.02*48}$$

$$C_{worst} = 59.62\ uF \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(ii)$$

- The rms current of capacitor can be calculated as:

$$I_{crms} = \sqrt{\frac{1}{T}(\int_0^{DT} I_{0ut}{}^2\,dt + \int_{DT}^{T}(-\frac{\Delta I_L}{(1-D)T}t + I_{Lmax})^2)}$$

$$\therefore I_{crms} = \sqrt{I_{Lmax}^2(1-D) + I_{0ut}{}^2(D) + \frac{\Delta I_L{}^2}{3} * (1-D) - \Delta I_L\big((1-D)I_{Lmax}\big)}$$

$$\Rightarrow\ \therefore \sqrt{\begin{matrix}10.10^2 * \\ (1-0.545) + 4.16^2(0.545) + \frac{1.928^2}{3} * (1-0.545) - 1.928\big((1-0.545) * 10.10\big)\end{matrix}}$$

$$\Rightarrow\ I_{crms} = 6.895A$$

- Note: Coming to the capacitor selection, either we can choose a Metallized Polypropylene Film Capacitor Type: 630V 50µF with a ripple current rating of 23.5A and where the ESR of the capacitor is very small i.e. 2.9mΩ but it's too costly. Or, as an alternative, we can even go with electrolytic capacitors (three to four electrolytic capacitors can be connected in parallel to meet the required ripple current rating and to decrease the ESR value) to make the system robust and chipper.

- Here in our case three electrolytic capacitor are connected in parallel: **(Part no: 100SXE18M)**

  Each are of 100V, 18µF, with a ripple current rating of 3A and the ESR of the capacitor is 30mΩ each.

  Now, the Power loss in capacitor $P_{capacitor} = I_{c_{rms}}^2 * ESR = 6.895^2 * 10\ m\boldsymbol{\Omega}$

  $= \mathbf{0.475\ W}$

6. <u>Efficiency calculation:</u>

- Now the total power loss in the system can be calculate as (P_{Loss_total})

$$P_{Loss_{total}} = P_{g_{SW}} + P_{g_{Diode}} + P_{inductor} + P_{capacitor}$$

$$= 2.97 + 3.6965 + 1.21 + 0.475 \simeq 8.35\ W$$

- The full load efficiency of the selected Buck-Boost converter

$$\frac{Rated\ Output\ power}{Rated\ Output\ power + Losses} * 100\% = \frac{200}{208.35} * 100 = \mathbf{95.99}\ \%$$

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