① Non-Isolated Buck Converter & Non-Isolated Boost Converter

ⓐ Roles of L and C

ⓑ Size of L and C when f_s Increasing with ΔI_L, ΔV_C is Constant

ⓐ In Non-Isolated Buck Converter,

L and C both are acts as a Voltage Averaging Circuit.

i.e; Inductor and Capacitor (L/C) both are formed Low pass Second order filter.

$$\Delta I_L = \frac{V_{in} - V_o}{L} d T_s = \frac{(1-d) V_o}{f_s L}$$ [Ripple in Inductor Current]

$$\Delta V_C = \frac{d(1-d) V_{in}}{8 f_s^2 LC} = \frac{(1-d) V_o}{8 f_s^2 LC}$$ [Ripple in Capacitor voltage]

to reduce the ripple in the Current & Voltage L & C values we have to Increase.

In Non-Isolated Boost Converter,

L and C are have different roles. Here L (Inductor) is used to Convert Voltage into Constant Current. and C is used to remove the AC Component across the output.

i.e; C is act like a filter (1st order)

$$\Delta I_L = \frac{d V_{in}}{L f_s}$$

$$\Delta V_C = \frac{d I_o}{f_s C}$$

To reduce the ripple in the Current, we have to Increase the L value & to decrease the ripple voltage we have to Increase C value.

Here ΔV_C in terms of 1st order of frequency But in Buck Converter it is 2nd order of frequency.

ⓑ From ΔI_L & ΔV_c equations,

For Buck Converter,

If ΔI_L is Constant & ΔV_c is Constant. and f_s Increases L and C values are decreases.

i.e; If you Increase switching frequency the size of Inductor and Capacitor will be decreases for given Peak to Peak ripple in Current and voltage.

For Boost Converter,

If ΔI_L is Constant & ΔV_c is Constant and f_s Increases then L and C values are decreases

i.e; If you Increase switching frequency the size of Inductor & Capacitor will be decreases for given Peak to Peak ripple in Current and Voltage.

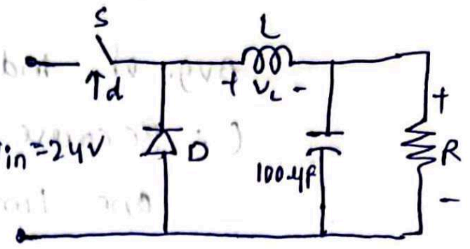
② Buck Converter Specifications

$V_{in} = 24V$ $C \times ESR = 30\mu s$

$d = 0.5$ $R_L = R$

$f_s = 100\ KHz$

$C = 100\mu F$



Inductor Current varying between 2.5A and 3.5A (under steady state)

i) L ii) R iii) V_o and % P-P ripple in output Voltage.

Assumptions:

① All Components are Ideal (S, D)

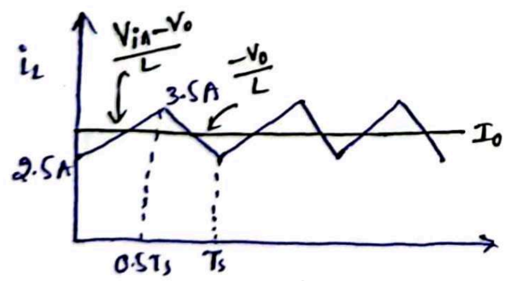
② Switching is Instantanuoes

③ L is Ideal i.e; zero Core loss, resistance of winding is zero. and zero winding Capacitance.

④ C is Ided i.e; zero ESR and ESL and Infinite Parallel resistance

⑤ The Converter is in steady state Conduction in CCM with Vin that is Pure DC Input voltage.

Inductor Current is Given with $d = 0.5$; $V_o = d V_{in} = 12V$



ΔI_L, Peak to Peak Ripple Current $= 1A = i_{Lmax} - i_{Lmin}$

$$\Delta I_L = \frac{(V_{in}-V_o)}{L} dT_s \quad (\text{In CCM mode})$$

$$1A = \frac{(24-12)}{L}(0.5)\frac{1}{100 \times 10^3}$$

$$L = \frac{12 \times 0.5}{100 \times 10^3} = 0.06\ mH$$

$V_o = d\,V_{in}$

$= 0.5 \times 24 = 12V$

Avg. of Inductor Current = Load current

($\because$ Because Avg Current through Capacitor during one time period (in steady state) is zero

Avg. value of Inductor Current = 3A = I_o

$\therefore \quad R = V_o / I_o = \frac{12}{3} = 4\Omega$

$\Rightarrow$ P-P ripple in output voltage = $\Delta I_L * r_c$

$C \times ESR = 30\mu s$

$C = 100\mu F$

$r_c = ESR = \frac{30\mu s}{100\mu F}$

$r_c = 0.3\Omega$

$\therefore$ P-P ripple in output voltage = $0.3 \times 1A$

$\Delta V_o = 0.3V$

$V_o = 12V$

% P-P ripple in output voltage = $\frac{30}{12}$

= 2.5% of V_o

③ Non Isolated Buck Converter

$V_{in} = 120V$

$V_o = 24V$

operating with a fixed duty ratio, $d = 0.2$

$f_s = 40 KHz$

$L = 0.48 mH$

output Current in the range ⇒ 0 to 5A

Variation of output DC voltage levels Derivation & Plot ??

P-P ripple current through Inductor, $\Delta I_L = \frac{V_{in} - V_o}{L} d T_s$

$$= \frac{120 - 24}{0.48 \times 10^{-3}} (0.2) \frac{1}{40 \times 10^{3}}$$

$$\Delta I_L = 1A$$

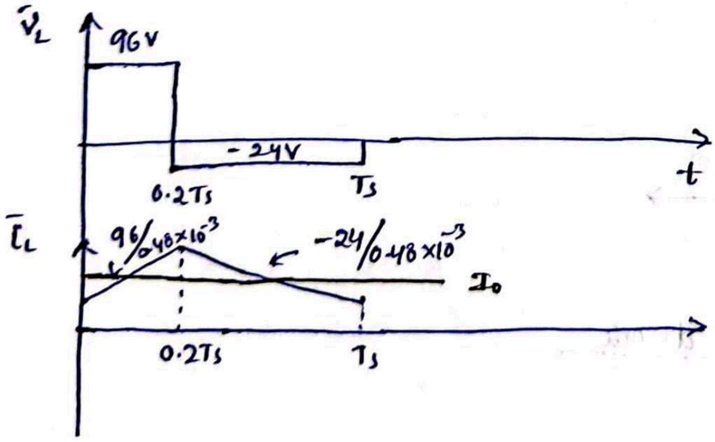
i.e; output Current from 0.5A to 5A, Non Isolated Buck Converter in ccm for given L value. &

at 0.5A, Buck Converter operates in BCM &

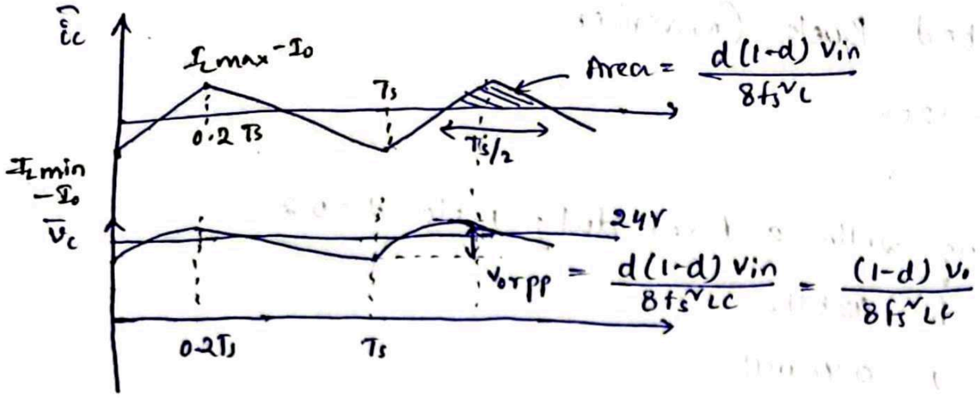
0 to 0.5A, Buck Converter operates in DCM

[∵ due to $I_{o min} \geq \frac{\Delta I_L}{2}$ then Converter operates in ccm]

$V_o = d V_{in} = 24V$ for c.c.m [under steady state]



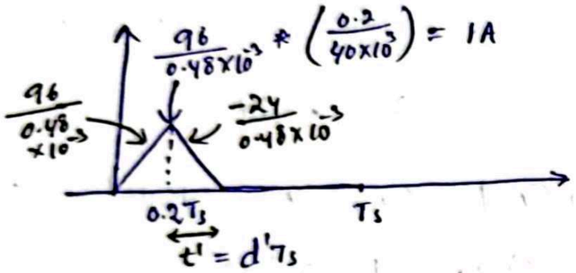
above Graph v_L, i_L for $I_o > 0.5A$ under steady state ccm mode.



Avg output voltage is always 24V in ccm mode (under Ideal Condition) for $I_o > 0.5A$.

Here peak - peak output ripple is Inverely proportional to c

$I_o < 0.5A$, Converter operates in DCM:



$$(i_L)_{Avg} = \left[\frac{1}{2}\left(\frac{V_{in}-V_o}{L}dT_s\right)(d+d')T_s\right] \div T_s$$

$$i_{L\,Avg} = \frac{d^2}{2f_sL}\frac{(V_{in}-V_o)}{V_o}V_{in} = I_o$$

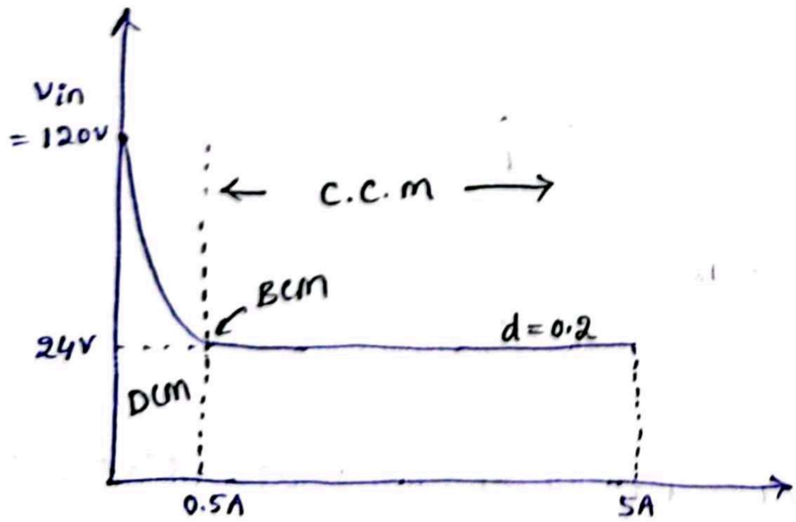
$$\frac{24}{0.48\times10^{-3}}t' = 1A$$

$$t' < 2\times10^{-5}$$

$$\frac{V_o}{V_{in}} = \frac{1}{V_{in} + \frac{2f_sLI_o}{d^2}}$$

$$\boxed{V_o = \frac{V_{in}}{1+\frac{2f_sLI_o}{d^2V_{in}}}}$$

If you Substute $I_o < 0.5$ then, Relation b/w output & input is non - linear. It shows below characteristics at $I_o = 0A$, $V_o = V_{in}$ Because at $I_o = 0$ denominator is 1.



(4) Boost Converter has specifications as follow

$V_{in} = 24V$; $d = 0.5$

$f_s = 100KHz$; $C = 100\mu F$

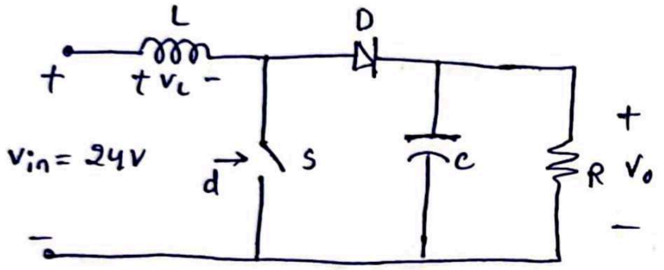
$C \times ESR = 30\mu s$

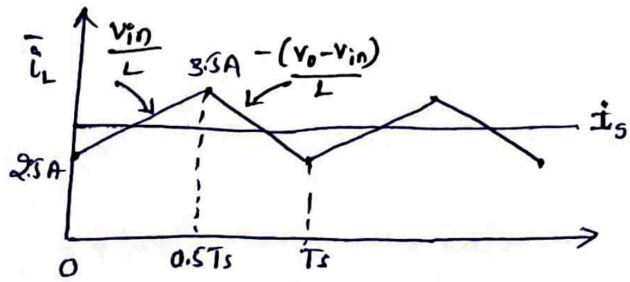
steady state current is periodic & Raised triangular waveform between 2.5A to 3.5A

Load Resistance, $R_L = R$

find i) L ii) R iii) V_o and % P-P ripple in o/p voltage.

All Components are Ideal.





Peak to Peak Inductor Current, $\Delta I_L = 1A = I_{Lmax} - I_{Lmin}$

$$\Delta I_L = \frac{V_{in}}{L} dT_s \quad [\text{CCM under steady state}]$$

$$1A = \frac{24}{L}(0.5)\left[\frac{1}{10^5}\right]$$

$$L = \frac{12}{10^5} = 120\mu H$$

(∵ Converter operating Continuous conduction mode (CCM) Because i_L Current always above zero)

$$V_o = \frac{1}{1-d} V_{in} = \frac{1}{1-0.5} 24$$

$$= 48V$$

Avg. Current of ($\bar{i}_L$) Inductor = 3A

Load Current, $I_o = (1-d)\, i_{L\,Avg}$

$$= 1/2 \times 3 = 1.5A$$

Load Resistance, $R_L = V_o/I_o = 48/1.5$

$$R = 32\Omega$$

Peak to Peak ripple Voltage = $i_{Lmax} * r_c$

$C = 100\mu F$ & $ESR * C = 30\mu s$

$$ESR = r_c = \frac{30\mu s}{100\mu F} = 0.3\,\Omega$$

Peak to Peak ripple Voltage $= 0.3 \times 3.5$

$\Delta V_c = 1.05\,V$

$V_o = 48\,V$

% Peak to peak ripple in output voltage $= \frac{1.05}{48}$

$= 2.18\,\%$

(5) Ideal Buck Converter:

$V_{in} = 120V$

$d = 0.4$

$f_s = 50kHz$

$L = 576\mu H$

$C = 10\mu F$

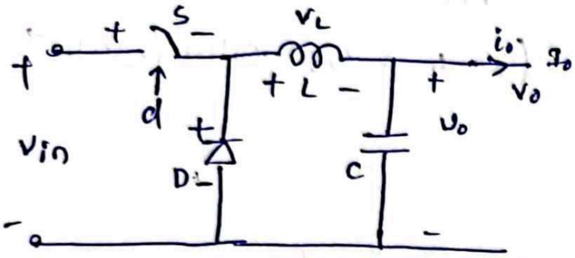
i) $V_o = ?$

b) $\Delta I_L = ?$

c) $\Delta V_c = ?$ } @ $I_o = 5A$

ii) $i_s, v_s, i_d, v_d, i_L, v_L, i_c$ and v_c with $d=0.4$ & $I_o = 5A$

iii) output voltage if Load Current is reduced to 0.2A @ $d=0.4$ (Derivation)



$V_o = dV_{in} = 0.4 \times 120$

$= 48V$

P-P Ripple Current in Inductor, $\Delta I_L = \dfrac{V_{in} - V_o}{L} dT_s$

$= \dfrac{120-48}{576\times10^{-6}} (0.4) \left[\dfrac{1}{50\times10^3}\right]$

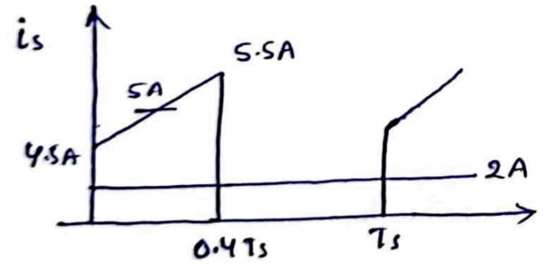
$= \dfrac{28.8}{28.8} = 1A$

Peak-Peak Ripple Voltage in Capacitor, $\Delta V_c = \frac{1}{2}\left(\frac{T_s}{2}\right)\left[\frac{V_{in}-V_o}{2L}\right]\frac{dT_s}{C}$

$= \dfrac{0.5\times0.5\times0.5}{50\times10^3\times10\times10^{-6}}$

$= 0.25V$

ii)



$\bar{i}_s = 5\times0.4$

$i_{s_{Avg}} = 2A$

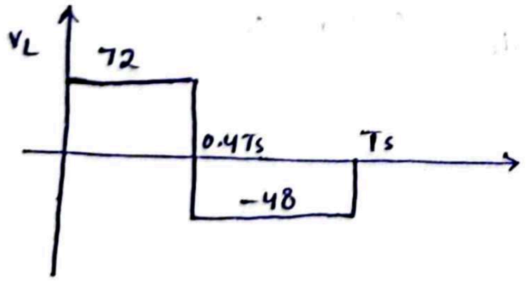
$i_{s_{RMS}} = \sqrt{\int_0^{0.4} (4.5+2.5t)^2}$

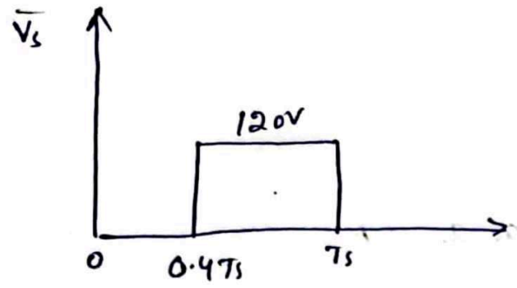
$= \sqrt{\int_0^{0.4} (4.5)^2 + 6.25t^2 + 22.5t}$

$= \sqrt{20.25(0.4) + 6.25\left(\frac{0.4^3}{3}\right) + 22.5\,\frac{0.4^2}{2}}$

$= 8.1 + 0.133 + 1.8$

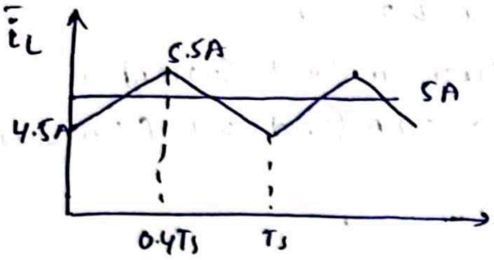
$= 3.16A$





$$\bar{v}_{s\,AVG} = \frac{120}{T_s}(0.6T_s) = 72V$$

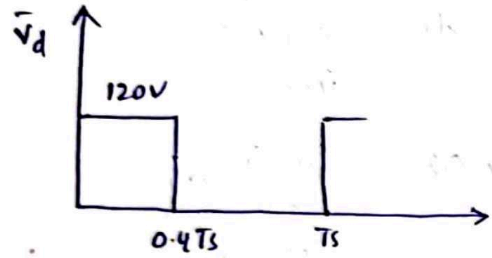
$$\bar{v}_{s\,RMS} = 120\sqrt{0.6}$$
$$= 92.95V$$



$$\bar{i}_{L\,AVG} = 5A$$

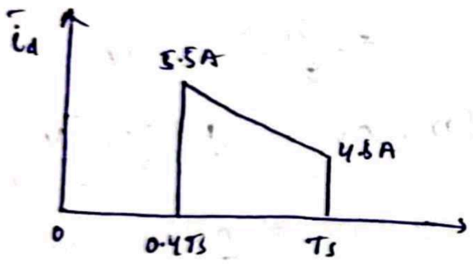
$$i_{L\,RMS} \cong 5A$$

(∵ $\bar{i}_L$ & $\tilde{i}_{Lr}$ orthogonal to each other,



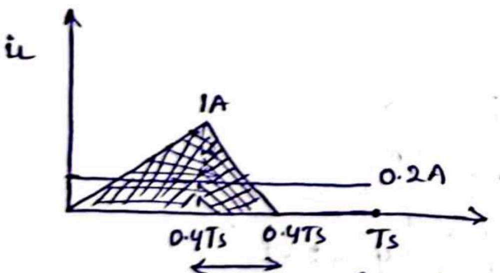
$$v_{d\,AVG} = 120(0.4)$$
$$= 48V$$

$$v_{d\,RMS} = 120\sqrt{0.4}$$
$$= 75.89V$$



$$i_{d\,AVG} = 5\times 0.6$$
$$= 3A$$

$$i_{d\,RMS} = 5\sqrt{0.6}$$
$$= 3.87A$$



$d'T_s = 0$ (In this Case)

$$T_s I_o = \frac{(d+d')T_s * \Delta I_L}{2} \Rightarrow I_o = \frac{(d+d')\Delta I_L}{2}$$

$$\cancel{T_s}\,0.2 = \frac{(0.4+d')\cancel{T_s} * 1}{2}$$

$$0.4 = (0.4+d') * 1$$

$$d' = 0$$

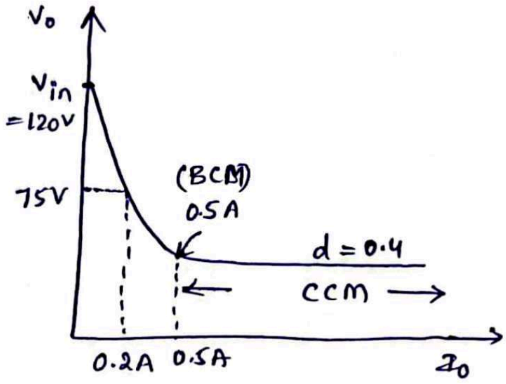
$$d'T_s = \frac{V_{in}-V_o}{L} dT_s \div V_o/L = \frac{V_{in}-V_o}{V_o} dT_s$$

$$i_{L\,Avg} = \left[\frac{1}{2}\left(\frac{V_{in}-V_o}{L}\right) dT_s \, (d+d')T_s\right] \div T_s$$

$$= \frac{d^2}{2f_sL} \, \frac{V_{in}-V_o}{V_o} \, V_{in}$$

$$i_{L\,Avg} = I_o$$

$$\frac{d^2}{2f_sL}\left(\frac{V_{in}^2}{V_o} - V_{in}\right) = I_o$$



$$\frac{V_o}{V_{in}^2} = \frac{1}{V_{in} + \frac{2f_sLI_o}{d^2}}$$

$$V_o = \frac{V_{in}}{1 + \frac{2f_sLI_o}{d^2V_{in}}}$$

$$V_o = \frac{120}{1 + \frac{2(50\times10^3)(576\times10^{-6})(0.2)}{(0.4)^2\times120}}$$

$$V_o = 75V$$

(6) Buck Converter - CCM design

$V_{in} = 40V$ to $56V$

$V_o = 24V$

$I_o = 0.4A$ to $4A$

Max. P-P ripple in $V_o < 50mV$.

Max. P-P ripple in $i_L < 1A$

$f_s = 40KHz$; $r_C C = 50\mu s$

$$d_{max} = \frac{V_o}{V_{in\,min}} = \frac{24}{40} = 0.6$$

$$d_{min} = \frac{V_o}{V_{in\,max}} = \frac{24}{56} = 0.428$$

$$\Delta I_L = \frac{V_{in} - V_o}{L} d T_s = \frac{V_o(1-d_{min})}{Lf}$$

$$L_{min1} = \frac{24(1-0.428)}{40 \times 10^3} = 0.343mH$$

$$L_{min1} = 343\mu H$$

CCM Condition check, L_{min2}

$$0.4 = \frac{V_o(1-d_{min})}{2L_{min2} f_s}$$

$$L_{min2} = \frac{24(1-0.428)}{2 \times 0.4 * 40 \times 10^3}$$

$$= 0.429 mH$$

$$= 429\mu H$$

$$L = \max(L_{min1} \text{ \& } L_{min2})$$

$L = 429\mu H$ for CCM.

$$\Delta V_C = \frac{V_o(1-d)}{8Lf^2C}$$

$$50 \times 10^{-3} = \frac{24(1-d_{min})}{8 * 429 \times 10^{-6} \times 40 \times 40 \times 10^6 \times C}$$

$$C = \frac{24(1-0.428)}{8 \times 40 \times 40 \times 10^6 \times 10^{-6} \times 429 * 50 \times 10^{-3}} = 50\mu F$$

$\therefore$ Electrolytic Capacitor is used.

$$50mV = \Delta I_L * r_c$$

$$50mV = 0.8 * r_c$$

$$r_c = \frac{50}{0.8} * 10^{-3} = 62.5\, m\Omega$$

from this $r_c * C = 50\mu s$

$$C = \frac{50 \times 10^{-6}}{62.5 \times 10^{-3}} = 800\mu F$$

$\therefore$ $C \cong 1000\mu F$

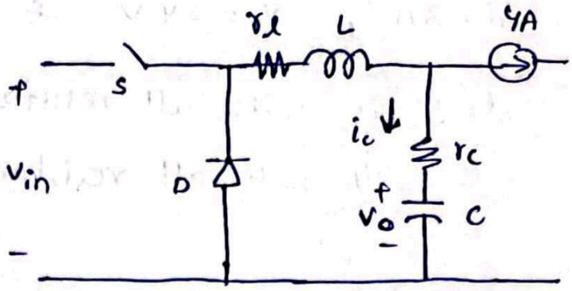
(7) Given data:

IRF 540 : $r_s = 44\,m\Omega$

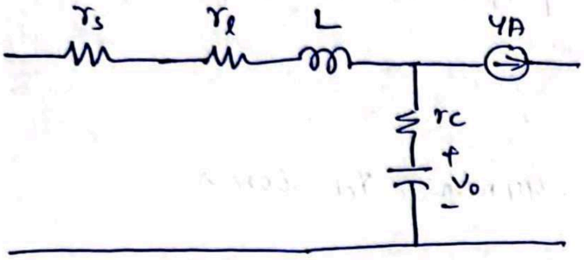
MBR10100 : $r_d = 60\,m\Omega$; $V_\gamma = 0.2V$

$d = 0.5$; $r_l = 30\,m\Omega$

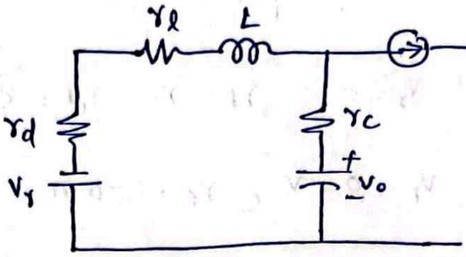
$V_{in} = 48V$; $I_o = 4A$



$L = 429\,\mu H$; $C = 800\,\mu F$; $r_c = 62.5\,m\Omega$



switch −ON



Switch−OFF

$$v_L(t) \cong v_{in} - v_o(t) - (r_s + r_l)\, i_L(t)$$

$$A_+ = dT_s V_{in} - \int_0^{dT_s} v_o(t)dt - (r_s + r_l)\int_0^{dT_s} i_L(t)dt$$

$$V_\gamma + (r_d + r_l)\, i_L(t) + v_L(t) + v_o(t) = 0$$

$$A_- = \int_{dT_s}^{T_s} v_o(t)\,dt + V_\gamma(1-d)T_s + (r_d + r_l)\int_{dT_s}^{T_s} i_L(t)dt$$

$$A_+ = A_-$$

$$dT_s V_{in} - \int_0^{dT_s} v_o\,dt - (r_s + r_l)\int_0^{dT_s} i_L\,dt = \int_{dT_s}^{T_s} v_o\,dt + (1-d)T_s V_\gamma + (r_d + r_l)\int_{dT_s}^{T_s} i_L\,dt$$

$$\therefore \quad V_o = \left[d V_{in} - (1-d)V_\gamma\right] - r_l I_o - r_s\left(\frac{1}{T_s}\int_0^{dT_s} i_L\,dt\right) - r_d \frac{1}{T_s}\int_{dT_s}^{T_s} i_L\,dt.$$

$$V_o = \left[d V_{in} - (1-d)V_\gamma\right] - \left[r_l + d r_s + (1-d) r_d\right] I_o$$

$$\therefore \quad V_o = \left[0.5(48) - (1-0.5)0.2\right] - \left[30\times10^{-3} + 0.5(44\times10^{-3}) + (1-0.5)\,60\times10^{-3}\right]4$$

$$= 24 - 0.1 - 0.328$$

$$= 23.572V$$

(8) Problem (7) $\Rightarrow$ $I_o = 4A$, $d = 0.5$; $V_{in} = 48V$

find Switching power loss in MOSFET = ??

Conduction power loss in MOSFET = ??

$R_g = 22\Omega$

IRF540: $r_{ds\,on} = 44\,m\Omega$, $C_{gd1} = 450\,pf$, $C_{gd2} = 125\,p.f$, $C_{gs1} = 2400\,pf$

$C_{gs2} = 1800\,pf$, $C_{ds1} = 1100\,p.f$, $C_{ds2} = 500\,p.f$

Conduction losses =

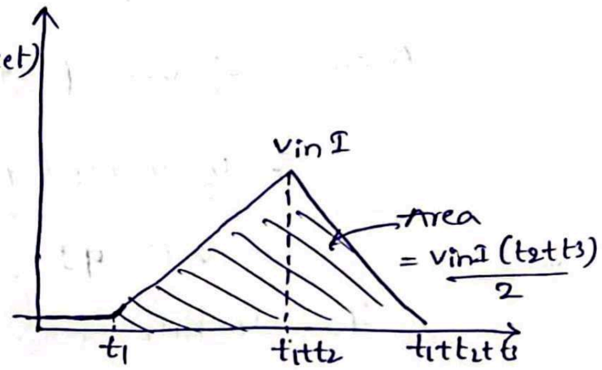
=

=

Switching losses = Switch off Losses + Switch ON losses.

Switch off Losses:

we know that, $V_{gscr} \cong 3.76V$ (from datasheet)



$$t_2 = \frac{V_{in} - V_{dscr}}{\frac{V_{gscr}}{R_g C_{gd}}} \cong \frac{V_{in}}{V_{gscr}} R_g C_{gd2}$$

$$t_2 = \frac{48}{3.76}\; 22 * 125 \times 10^{-12}$$

$$= 35.10\,ns$$

$$t_3 = \tau \ln \frac{V_{gscr}}{V_T} = R_g\,(C_{gd2} + C_{gs2}) \ln \frac{V_{gscr}}{V_T}$$

$$= 22\,(125 + 1800) \times 10^{-12} \ln\left[\frac{3.76}{2.5}\right]$$

$$= 17.28\,ns$$

$$\text{Area} = \frac{1}{2} V_{in} I\,(t_2 + t_3)$$

$$= \frac{1}{2}\, 48 * 4 * (17.28 + 35.10) \times 10^{-9}$$

$$= 5.028 \times 10^{-6}$$

$f_s = 40\,KHz$

$\therefore$ Power loss due to Switch-off operations

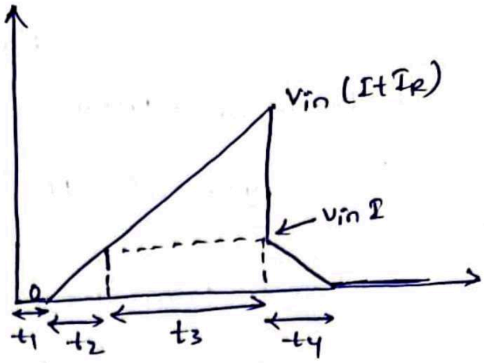
$$= 40\,KHz * 5.02\,\mu J$$

$$= 0.201\,W$$

Switch ON losses:

Here schottcky diode is used & there is no reverse recovery

i.e; $t_3 = 0$ (in below graph)



so, we know that,

$$t_2 = R_g C_{iss2} \ln \frac{V - V_T}{V - V_{gscr}}$$

$$= 22\,(125 + 1800) \times 10^{-12} \ln \left[\frac{10 - 2.5}{10 - 3.76}\right]$$

$$= 7.789 \text{ ns}$$

$$t_4 = \left(\frac{V_{in} - V_{dscr}}{V - V_{gscr}}\right) R_g C_{gd2}$$

$$= \left(\frac{48 - 1.26}{10 - 3.76}\right) 22 \times 125 \times 10^{-12}$$

$$= 20.59 \text{ ns}$$

$$\text{Area} = \frac{1}{2} V_{in} I \left(\frac{t_2 + t_4}{1}\right)$$

$$= \frac{1}{2}\, 48 * 4\,(7.789 + 20.598) \times 10^{-9}$$

$$= 2.725\ \mu J$$

$$f_s = 40 \text{ KHZ}$$

Power loss due to switch-ON operations

$$= 40 \text{ KHZ} * 2.725 \times 10^{-6}$$

$$= 0.109 \text{ W}$$

Total switching power loss in MOSFET

$$= 0.201 + 0.109$$

$$= 0.31 \text{ watt}$$

8. Converter spec's:

$I_o = 3A$; $V_o = 24V$ & $V_{in} = 40V$

$d = ?$ i) with all resistances & V_r ignored

ii) with all resistances & V_r Included.

Sol) We know that, from Ans 7

$$V_o = \left[d V_{in} - (1-d) V_r\right] - \left[r_l + d r_s + (1-d) r_d\right] I_o$$

Case: i) $V_r = 0$; $r_l = r_s = r_d = 0$

ii) $V_r = 0.2V$, $r_l = 30m\Omega$, $r_s = 44m\Omega$, $r_d = 60m\Omega$

i)

$$V_o = d V_{in}$$

$$24 = d(40)$$

$$d = \frac{24}{40} = 0.600$$

ii)

$$V_o = \left[d \times 40 - (1-d)0.2\right] - \left[30\times10^{-3} + d(44\times10^{-3}) + (1-d)60\times10^{-3}\right]3$$

$$24 = 40d - 0.2 + 0.2d - (90\times10^{-3}) - d(132\times10^{-3}) - (180\times10^{-3}) + (180\times10^{-3})d$$

$$24 = 40d - 0.2 + 0.2d - 0.27 + 0.048d$$

$$24.47 = 40.248d$$

$$d = \frac{24.47}{40.248}$$

$$d = 0.6079$$

(10) Boost Converter – ccm design

$V_{in} = 10.5$ to $12.5V$

$V_o = 24V$

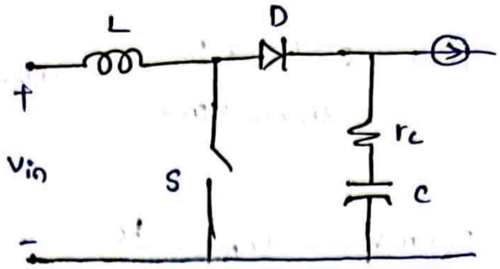
$I_o = 1A$ to $3A$

$\Delta V_o < 200mV$.

$\Delta i_L < 1A$

$f_s = 40KHz$

$r_C C = 30\mu s$



$$d_{min} = 1 - \frac{12.5}{24} = 0.479$$

$$d_{max} = 1 - \frac{10.5}{24} = 0.5625$$

$d_{min} < 0.5$ and $d_{max} > 0.5$

Taker $d = 0.5$ in Calculating L_{min1}

$$1A \geq \frac{d(1-d)V_o}{f_s L} = \frac{0.25 * 24}{40 \times 1000 \times L}$$

$$L = 150\mu H$$

Another value of L is L_{min2} obtained by ccm.

$$I_o \geq \frac{d(1-d)^2 V_o}{2 f_s L}$$

$$1 \geq \frac{0.479(1-0.479)^2 24}{2 * 40 \times 10^3 * L}$$

d_{min} & $d_{max} > 1/3$

So, d_{min} we taken for I_o Calculation.

$$L = 39\mu H$$

Choose $L = \max(L_{min1}$ & $L_{min2})$

$\simeq 150\mu H$

Calculate C value,

$$\Delta V_c = 200mV = \frac{dI_o}{f_s C} \quad [\because \text{ here } d_{max} \text{ \& } I_{omax} \text{ for max} C]$$

$$C \geq \frac{0.5625 * 3}{40\times10^3 \times 0.2} = 210 \mu F$$ (more than 20μF so electrolyte Cap)

So,

$$200mV = i_{Lmax} r_c$$

$$i_{Lmax} = \frac{I_o}{1-d} + \frac{1}{2}\frac{d(1-d)V_o}{f_s L}$$

$$= \frac{3}{1-0.5625} + \frac{1}{2}\frac{0.5625(1-0.5625)24}{40\times10^3 \times 150\times10^{-6}}$$

$$= 6.857 + 0.4921$$

$$i_{Lmax} = 7.349A$$

$$200\times10^{-3} = 7.349 \times r_c$$

$$r_c = 27.21 m\Omega$$

$$C \geq \frac{30\times10^{-6}}{27.21\times10^{-3}}$$

$$C = 1.1 mF.$$

(11) Given data: (Boost Converter)

IRF 540 ; $r_s = 44\,m\Omega$ (100V/23A)

MUR 820 ; $V_\gamma = 0.5V$, $r_d = 40\,m\Omega$

$r_l = 50\,m\Omega$

i) $V_{in} = 10.5V$, $I_o = 1A$

ii) $V_{in} = 10.5V$, $I_o = 3A$

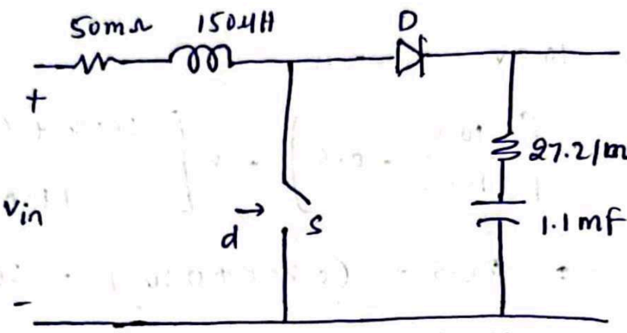
iii) $V_{in} = 12.5V$, $I_o = 1A$

iv) $V_{in} = 12.5V$, $I_o = 3A$

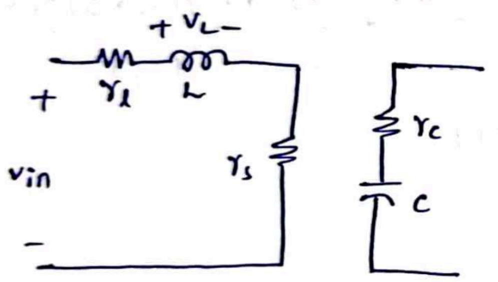
V_o Versus duty ratio in the range $d = 0.5$ to $d = 0.8$

Duty ratio variation range that is needed to maintain output voltage at 24V

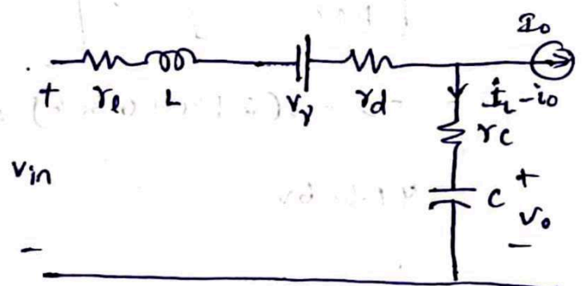
from Q10. $C = 1.1\,mF$ & $L = 150\,\mu H$; $r_c = 27.21\,m\Omega$



i) S-ON



ii) S-off



$$V_L(t) = V_{in} - i_L(t)\left[r_l + r_s\right]$$

$$A_+ = V_{in}\,dT_s - (r_l + r_s)\int_0^{dT_s} i_L(t)\,dt$$

$$V_L(t) = V_{in} - i_L(t)\left[r_l + r_d + r_c\right] - V_\gamma - V_o + I_o r_c$$

$$A_- = (V_{in} - V_o - V_\gamma + I_o r_c)(1-d)T_s - (r_l + r_d + r_c)\int_{dT_s}^{T_s} i_L(t)\,dt$$

$$A_+ = A_-$$

$$V_{in}\,dT_s - (r_l + r_s)\int_0^{dT_s} i_L(t)\,dt = (V_o + V_\gamma - V_{in} - r_c I_o)(1-d)T_s + (r_l + r_d + r_c)\frac{I_o}{T_s}$$

$$\therefore\ V_o = \left[\frac{V_{in}}{1-d} - V_\gamma\right] - I_o\left[\frac{r_l + d\,r_s}{(1-d)^2} + \frac{r_d + d\,r_c}{1-d}\right]$$

i) $V_{in} = 10.5V$, $I_o = 1A$

$\underline{d=0.5}$ $V_o = \left[\frac{10.5}{1-0.5} - 0.5\right] - 1\left[\frac{50\times10^{-3} + (0.5\times44\times10^{-3})}{(1-0.5)^2} + \frac{40\times10^{-3} + (0.5\times27.21\times10^{-3})}{1-0.5}\right]$

$= 20.5 - (0.288 + 0.107) = 20.5 - 0.395$

$= 20.104V$

$\underline{d=0.8}$ $V_o = \left[\frac{10.5}{1-0.8} - 0.5\right] - 1\left[\frac{50\times10^{-3} + (0.8\times44\times10^{-3})}{(1-0.8)^2} + \frac{40\times10^{-3} + (0.8\times27.21\times10^{-3})}{1-0.8}\right]$

$= 52 - (2.130 + 0.308) = 52 - 2.438$

$= 49.562V$

ii) $V_{in} = 10.5V$, $I_o = 3A$.

$\underline{d=0.5}$ $V_o = \left[\frac{10.5}{1-0.5} - 0.5\right] - 3\left[\frac{50\times10^{-3} + (0.5\times44\times10^{-3})}{(1-0.5)^2} + \frac{40\times10^{-3} + (0.5\times27.21\times10^{-3})}{1-0.5}\right]$

$= 20.5 - 3(0.288 + 0.107) = 20.5 - 1.185$

$= 19.315V$

$\underline{d=0.8}$ $V_o = \left[\frac{10.5}{1-0.8} - 0.5\right] - 3\left[\frac{50\times10^{-3} + (0.8\times44\times10^{-3})}{(1-0.8)^2} + \frac{40\times10^{-3} + (0.8\times27.21\times10^{-3})}{1-0.8}\right]$

$= 52 - 3(2.130 + 0.308) = 52 - 7.314$

$= 44.686V$

iii) $V_{in} = 12.5V$, $I_o = 1A$

$\underline{d=0.5}$ $V_o = \left[\frac{12.5}{1-0.5} - 0.5\right] - 1\left[\frac{50\times10^{-3} + (0.5\times44\times10^{-3})}{(1-0.5)^2} + \frac{40\times10^{-3} + (0.5\times27.21\times10^{-3})}{1-0.5}\right]$

$= 24.5 - 0.395$

$= 24.105V$

$\underline{d=0.8}$ $V_o = \left[\frac{12.5}{1-0.8} - 0.5\right] - 1\left[\frac{50\times10^{-3} + (0.8\times44\times10^{-3})}{(1-0.8)^2} + \frac{40\times10^{-3} + (0.8\times27.21\times10^{-3})}{1-0.8}\right]$

$= 62.5 - 2.348$

$= 60.062V$

iv) $v_{in} = 12.5V \;,\; I_o = 3A$

$\underline{d=0.5}$ $$V_o = \left[\frac{12.5V}{1-0.5} - 0.5\right] - 3\left[\frac{50\times10^{-3} + (0.5\times44\times10^{-3})}{(1-0.5)^2} + \frac{40\times10^{-3} + (0.5\times27.21\times10^{-3})}{1-0.5}\right]$$

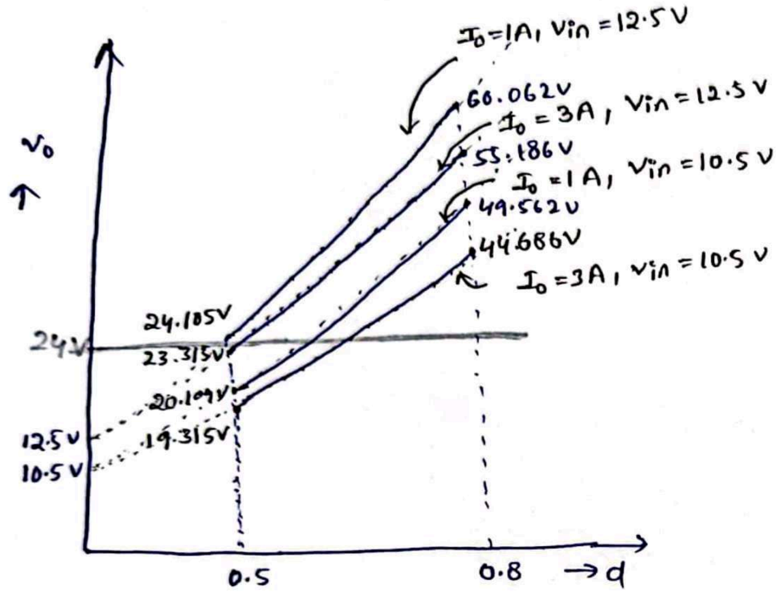
$= 24.5 - 1.185$

$= 23.315V$

$\underline{d=0.8}$ $$V_o = \left[\frac{12.5}{1-0.8} - 0.5\right] - 3\left[\frac{50\times10^{-3} + (0.8\times44\times10^{-3})}{(1-0.8)^2} + \frac{40\times10^{-3} + (0.8\times27.21\times10^{-3})}{1-0.8}\right]$$

$= 62.5 - 7.314$

$= 55.186V$



(12) Given data:

Problem no. 11

$I_o = 3A$, $V_o = 24V$

$V_{in} = 12V$

i) Conduction losses in the Switch & Diode.

ii) Switching losses in the Inductor &

iii) Conduction losses in Inductor & Capacitor.

$d = 0.52$ from Prob (11) from graph.

i) Rms value of MOSFET Current $I_{DS(rms)} = \frac{I_o}{(1-d)} \sqrt{d}$

$$= \frac{3}{(1-0.52)} \sqrt{0.52}$$

$$= 4.51A$$

ON state resistance of MOSFET $r_{ds(on)} = 44m\Omega$

Conduction losses on MOSFET $= I_{rms}^2 \, r_{ds(on)}$

$$= (4.51)^2 * 44 \times 10^{-3}$$

$$= 0.8937 W$$

Rms value of diode Current $I_{d(rms)} = \frac{I_o}{(1-d)} \sqrt{1-d}$

$$= \frac{3}{1-0.52} \sqrt{01-0.52}$$

$$= 4.33A.$$

ON state resistance or diode, $r_d = 40m\Omega$

Conduction loss on diode $= 4.33^2 \times 40 \times 10^{-3}$

$$= 0.75W$$

ii) For switch off losses

$V_{DS} = V_o = 24V$

$I = \frac{I_o}{1-d} = \frac{3}{1-0.52} = 6.25A$

$R_g = 22\Omega$ & $C_{gd2} = 125 \, p.f$

$V_{gscr} = 4.2\text{ V}$

$V_T = 2.5\text{ V}$

$V_{dscr} = 1.5\text{ V}$

$$t_2 = \frac{V_{DS}}{V_{gscr}} R_g C_{gd} = \frac{24}{4.2} * 22 \times 125 \times 10^{-12}$$

$= 15.71\text{ ns}$

$$t_3 = R_g (C_{gs2} + C_{gd2}) \ln \frac{V_{gscr}}{V_T}$$

$= 22 * (1800 + 125) \times 10^{-12} \ln \left[\frac{4.2}{2.5}\right]$

$= 21.97\text{ ns}$

Turn off loss $= \frac{1}{2} V_{DS} I (t_2 + t_3) f_s$

$= \frac{1}{2} (24 \times 6.25) * (5.71 + 21.97) \times 10^{-9} * 40 \times 10^{3}$

$= 0.11304\text{ W}$

for switch on losses

$\tau_F = 20\text{ ns}$ & $I = 1\text{ A}$

$Q = 20\text{ns} * \text{A}$

$$E_{on} = V_{DS} I \left[\tau_F + \frac{V_{DS} - V_{dscr}}{V - V_{gscr}} \frac{R_g C_{rss2}}{2} \right]$$

$$= 24 * 6.25 \left[20 \times 10^{-9} + \frac{24 - 1.5}{10 - 4.2} \frac{22 \times 125 \times 10^{-12}}{2} \right]$$

$= 3.8 \times 10^{-6}$

Turn on loss. $= E_{on} f_s$

$= 3.8 \times 10^{-6} \times 40 \times 10^{3}$

$= 0.152\text{ W}$

Total switching loss $= 0.1130 + 0.152$

$= 0.26504\text{ W}$

iii) RMS value of inductor current $= \frac{I_o}{1-d} = \frac{3}{1-0.52}$

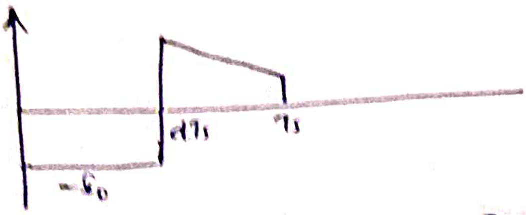
$= 6.25\text{ A}$

$r_e = 50\text{ m}\Omega$

Conduction loss in inductor $= 6.25^2 * 50 \times 10^{-3}$

$= 1.95\text{ W}$

iv) Capacitor Current



RMS value of Capacitor Current

$= I_o\sqrt{d} + \left[\frac{I_o}{1-d} - I_o\right]\sqrt{1-d}$

$= 3\sqrt{0.52} + \left[\frac{3}{1-0.52} - 3\right]\sqrt{1-0.52}$

$= 4.415A$

$r_c = 0.02721$

Capacitor Conduction losses $= 4.415^2 * 0.02721$

$= 0.53040W.$

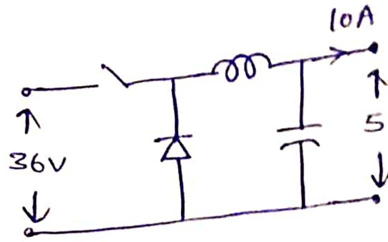
(13) 1. Converter

Buck Converter spec's

36V/5V , 10A

MOSFET : 60V, 25A, 40mΩ [designed]

: 300V, 75A, 20mΩ [available]



frequent MOSFET Burnout of the MOSFET due to Gate driver voltage, Parasitic Components (Inductance, Capacitance). i.e; New MOSFET have more Capacitances (C_{iss}, C_{oss}, C_{rds}) Compared to older MOSFET it Causes more time taken for Switching ON & Switching OFF. This time Causes Increases the switching losses in the Circuit (i.e; MOSFET losses) It Causes over heating.

One more reason is Parasitic Components. i.e; This Parasitic Inductance & Capacitance produce the dampings i.e; this damping Causes Extra losses in the circuit. so it produce the heating.

Problem Solutions:

1) Use Proper heat sinks Based on rating & Thermal effects.

2) Use Snubber Circuit to Protect from over heating.

3) Give/design Proper Gate driver voltage/circuit.

(14) 12V/120V Converter

$I_o = 0.5A$

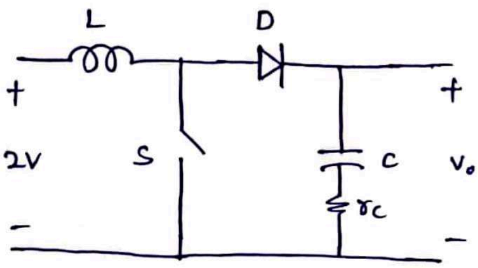
Designed Converter: Boost

$d = 0$ to 1 Max $V_o = 50V$ @ $I_o = 0.5A$.

For 12V/120V, $I_o = 0.5A$ Conversion, Boost topology is not suitable. Because you want 120V as output with 12V input. i.e; 10 times of input voltage. But you will get maximum output at Practical Boost topology is 4-8 times of input voltage.

In Boost Converter,

we know that,



$$V_o = \left[\frac{V_{in}}{1-d} - V_\gamma\right] - I_o\left[\frac{r_l + d r_s}{(1-d)^2} + \frac{r_d + d r_c}{1-d}\right] \quad -(1)$$

In practical,

$V_\gamma \cong 0.2V$

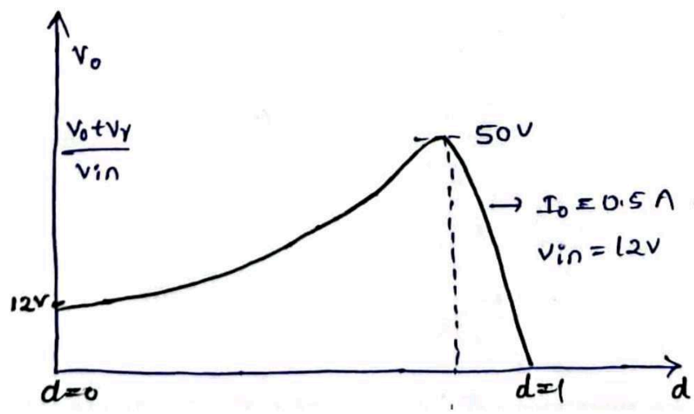
$r_l, r_s, r_d \cong$ 10's to 100's of milli ohms.

And your $V_{in} = 12V$, $I_o = 0.5$

If you placed above values in eq(1) and you will ~~get~~ very the duty ratio then you will Get V_{omax} as 5-8 times. Thats why you are getting 50V. as V_{omax}.

i.e; If you draw the graph between V_o vs d for fixed $V_{in} = 12V$ & $I_o = 0.5A$

You are getting 50V output at duty ratio near to 1.



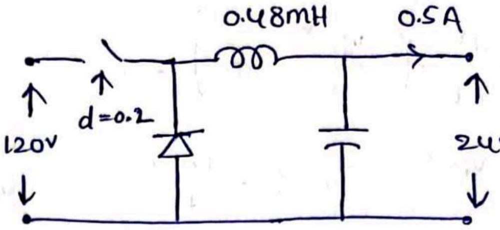
(15)

$120V = V_{in}$ }
$24V = V_o$ } Buck Converter

$d = 0.2$; $f_s = 20 kHz$

$L = 0.48 mH$

$I_o = 0.5 A$



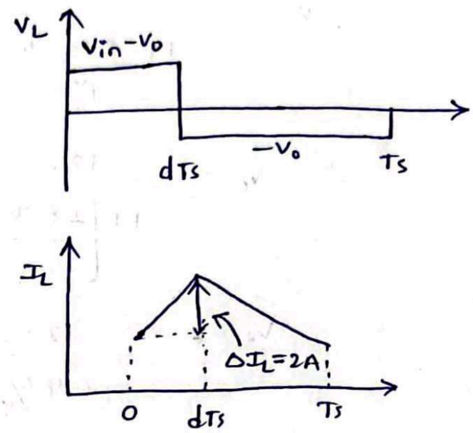
Ideal Components

from Buck Converter, Inductor Basic Principle (at steady state)

$$\Delta I_L = \frac{V_{in} - V_o}{L} dT_s$$

$$\Delta I_L = \frac{120 - 24}{0.48 \times 10^{-3}} * \frac{0.2}{20 \times 10^{3}}$$

$$= 2A$$



But in Quary I_o is given 0.5 A

i.e; Minimum Current of I_o, to maintain Converter in CCM is

$I_{omin} > \frac{\Delta I_L}{2}$ i.e; $I_{omin} > 1A$ then Converter operates in CCM.

Here, $I_o = 0.5 A$ i.e; Converter operates in DCM

so, DCM (Dis Continous Conduction)

From the graph,

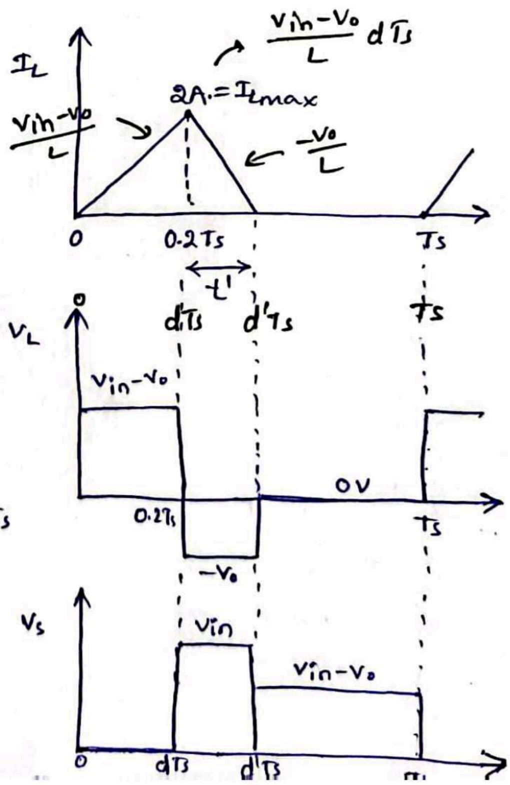
$$d'T_s = \frac{V_{in} - V_o}{L} dT_s \div \frac{V_o}{L}$$

$$= \frac{V_{in} - V_o}{V_o} dT_s$$

$$(i_L)_{Avg} = \frac{\text{Area of Triangle}}{\text{Total time}}$$

$$= \left[\frac{1}{2} \left[\frac{V_{in} - V_o}{L} dT_s\right] \left[d + d'\right] T_s\right] \div T_s$$

$$(i_L)_{Avg} = \frac{d^2}{2 f_s L} \left(\frac{V_{in} - V_o}{V_o}\right) V_{in}$$



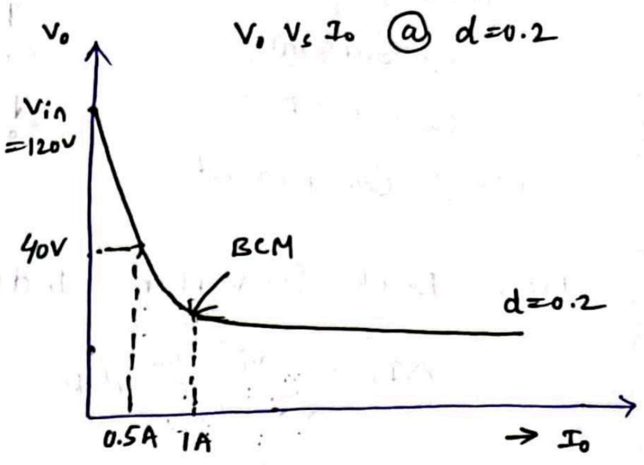
This must be I_o = Avg. load Current.

$$\frac{d^2}{2f_sL}\left(\frac{V_{in}^2}{V_o} - V_{in}\right) = I_o$$

$$\frac{V_{in}^2}{V_o} = V_{in} + \frac{2f_sLI_o}{d^2}$$

$$\frac{V_o}{V_{in}^2} = \frac{1}{V_{in} + \frac{2f_sLI_o}{d^2}}$$

$$V_o = \frac{V_{in}}{1 + \frac{2f_sLI_o}{d^2 V_{in}}}$$



$$\therefore \quad V_o = \frac{120}{1 + \left[\frac{2 * 20\times10^{3} * 0.48\times10^{-3} * 0.5}{(0.2)^2 * 120}\right]}$$

$$V_o = \frac{120}{1 + 9.6/4.8} = \frac{120}{3} = 40V$$

(16) Buck Converter

$V_{in} = 48V$; $V_o = 12V$; $I_o = 10A$

$L = 100\mu H$; $f_s = 20kHz$

$V_{GS} = 7.5V$; $48A = I_D$; $V_T = 3.5V$

$V_G = 12V$; $R_g = 47\Omega$; $C_{iss1} = 2000pF$; $C_{iss2} = 1300pF$

$C_{rss1} = 600pF$; $C_{rss2} = 200pF$; $C_{oss1} = 1200pF$; $C_{oss2} = 400pF$

$1.24C/1A = T$

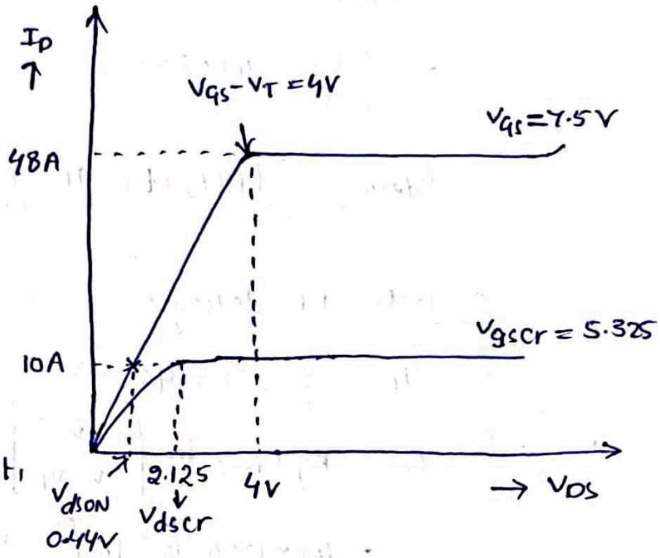
(a) Switching delays in the voltage across the diode.

(b) find switching power loss ?? (Relevant waveforms & calculations)

saturation Drain Current, I_D

$I_D = \frac{\beta}{2}(V_{GS} - V_T)^2$

∵ from Quary & Semiconductor Physics.



$48 = \frac{\beta}{2}(7.5 - 3.5)^2$

$\beta = 48/8 = 6$

~~Active~~ ohmic region Drain Current,

$I_D \cong \frac{\beta}{1}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right) V_{DS}$

$10 = 6\left(7.5 - 3.5 - \frac{V_{DSON}}{2}\right) V_{DSON}$

$V_{ds\,on} = 0.44V$

for $I_D = 10A$; $V_{gs} = V_{gscr}$; $V_T = 3.5$

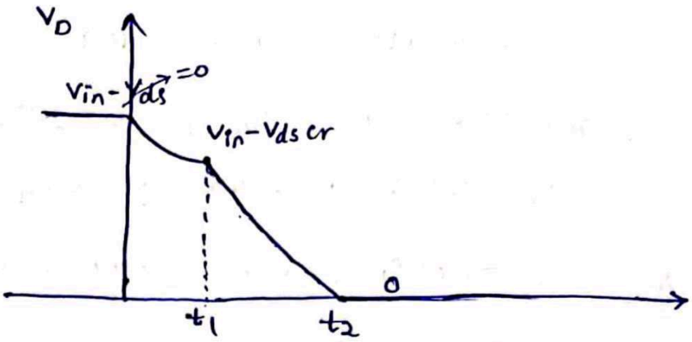
$10 = \frac{6}{2}(V_{gscr} - 3.5)^2$

$V_{gscr} = 5.325V$ [∵ for $V_{GS} = 12V$ & $I_D = 10A$]

$V_{dscr} = 2.125V$

Switching delays in the voltage across diode:

Switch ON delay:



$$t_1 = \tau \ln \frac{V}{V_{gscr}}$$

$$= R_g (C_{gs1} + C_{ds1}) \ln \frac{V}{V_{gscr}}$$

$$= 47 (2000 \times 10^{-12}) \ln \left[\frac{12}{5.325}\right]$$

$$= 76.37 \text{ ns}$$

$$t_2 \simeq \frac{V_{in}}{V_{gscr}} R_g C_{gd}$$

$$= \frac{48}{5.325} (47 \times 200 \times 10^{-12}) = 84.73 \text{ ns}$$

$$t_3 = \tau \ln \frac{V_{gscr}}{V_T}$$

$$t_3 = 47 * 1300 \times 10^{-12} \ln \left[\frac{5.325}{3.5}\right]$$

$$= 25.64 \text{ ns}$$

$$t_{delay} = t_1 + t_2 + t_3 = 76.37 + 84.73 + 25.64 = 161.1 \text{ ns} + 25.64 \text{ ns}$$

$$\Rightarrow 186.74 \text{ ns}$$

Switch off delay:

$$\tau_F = \frac{Q}{I} = 1.2\,\mu s$$

$$t_1 = R_g C_{iss2} \ln \left[\frac{V}{V - V_T}\right]$$

$$= 47 * 1300 \times 10^{-12} \ln \left[\frac{12}{12 - 3.5}\right] = 21.06 \text{ ns}$$

$$t_2 = R_g C_{iss2} \ln \left[\frac{V - V_T}{V - V_{gscr}}\right]$$

$$= 47 * 1300 \times 10^{-12} \ln \left[\frac{12 - 3.5}{12 - 5.325}\right] = 14.76 \text{ ns}$$

$$t_3 = \sqrt{2 \tau_F t_2} - t_2$$

$$= \sqrt{2 (1.2 \times 10^{-6})(14.76 \times 10^{-9})} - (14.76 \times 10^{-9}) = 173.45 \text{ ns}$$

$$t_4 = \frac{V_{in} - V_{dscr}}{V - V_{gscr}} * R_g C_{iss2}$$

$$= \frac{48 - 2.125}{12 - 5.325} * 47 * 200 \times 10^{-12} = 64.6 \text{ ns}$$

$$t_{delay} = t_1 + t_2 + t_3 + t_4$$

$$= (21.06 + 14.76 + 173.45 + 64.6) \text{ ns} = 273.87 \text{ ns}$$

(b) <u>Switch ON</u>

Calculation already done before part.

$$I + I_R = I\sqrt{\frac{2T_F}{t_2}}$$

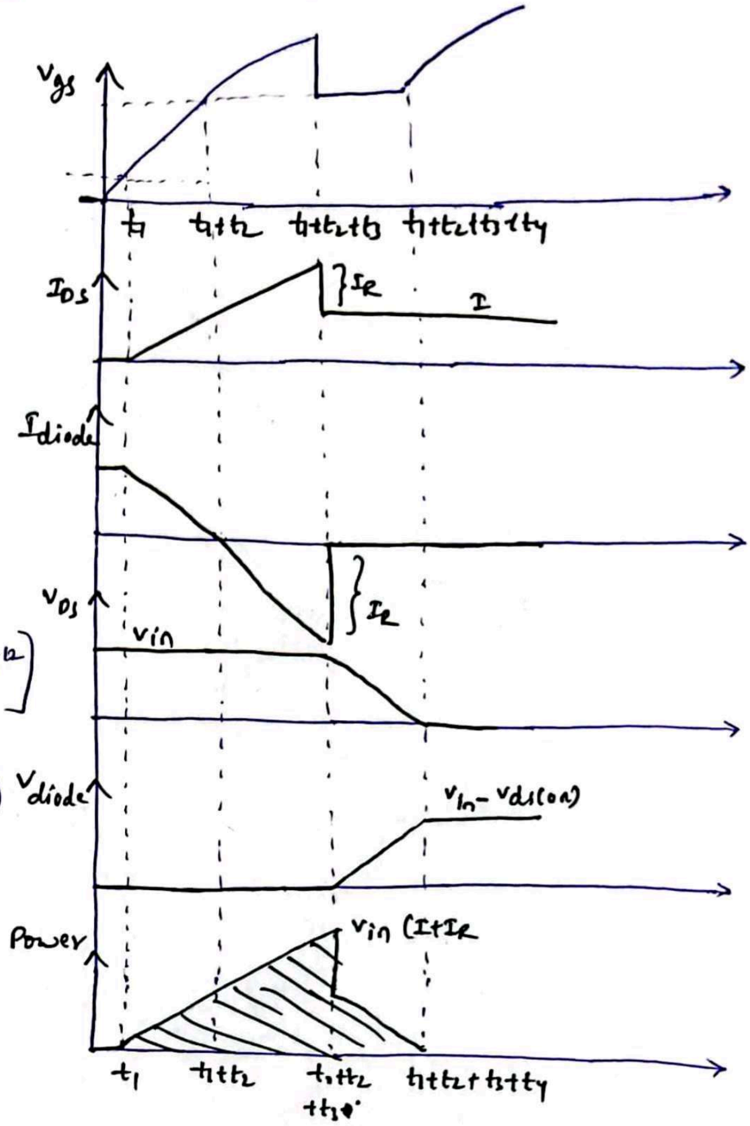
$$= 10\sqrt{\frac{2\,(1.2\times10^{-6})}{(14.76\times10^{-9})}}$$

$$= 127.51\,A$$

$$E_{on} = 48*10\left[1.2\times10^{-6} + \frac{48-2.125}{12-5.325} * \frac{47*200\times10^{-12}}{2}\right]$$

$$\left[\because E_{on} = V_{in} I\left[T_F + \frac{V_{in}-V_{dscr}}{V-V_{gscr}}\;\frac{R_g\,C_{rss2}}{2}\right]\right)$$

$$= 0.591\,mJ$$



Power loss at 20 KHz is,

$$= 0.591\,mJ \times 20\times KHz$$

$$= 11.82\,W$$

<u>Switch off</u>

$$\text{Area} = \text{Energy} = \frac{1}{2} * V_{in} * I_o * (t_2+t_3)/2$$

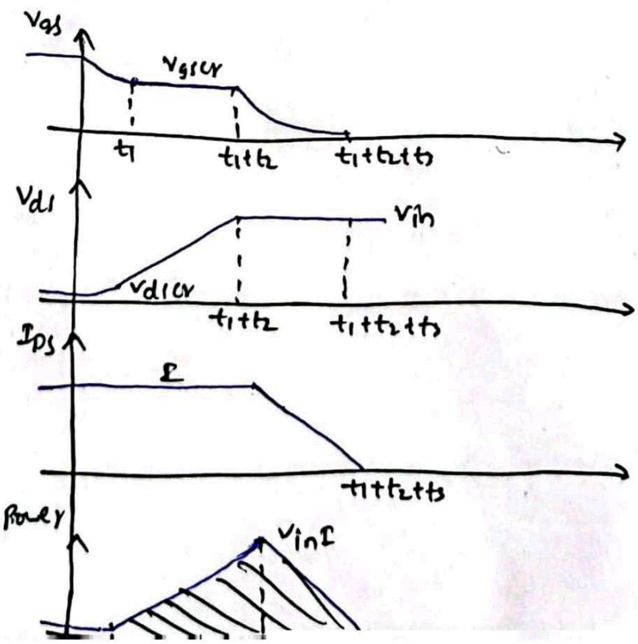
$$= \frac{1}{2}\,48*10*\left(\frac{84.72+25.64}{2}\right)\times10^{-9}$$

$$= 0.0132\,mJ$$

Power loss at 20 KHz is

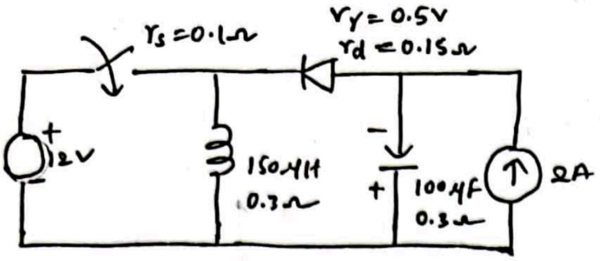
$$= 0.0132 * 20$$

$$= 0.264\,W$$



(18) $d = 0.5$; $f_s = 100\ \text{KHz}$

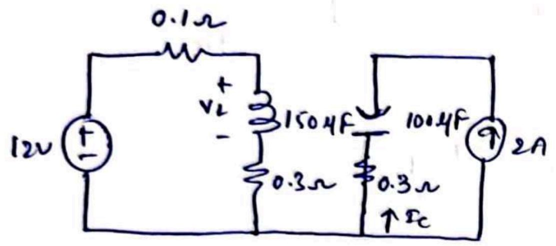
Circuit diagram



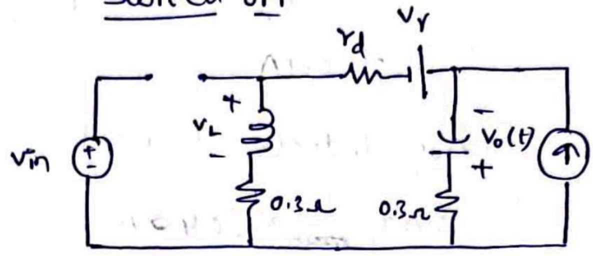
$V_o = ?$

$\Delta V_c = ?$

Switch ON :



Switch off



$$V_L(t) = 12 - I_L(t)\,[0.4]$$

Area of +ve half-cycle of $V_L(t)$

$$\int_0^{dT_s} V_L(t) = 12\int_0^{dT_s} dt - 0.4\int_0^{dT_s} I_L(t)$$

$$A_+ \Rightarrow \int_0^{dT_s} V_L(t) = V_{in}\int_0^{dT_s} dt - (r_s + r_l)\int_0^{dT_s} I_L(t)$$

$$-V_L(t) = I_L(t)\, r_l + (I_L(t) - I_o)\, r_c + V_o(t) + V_\gamma + r_d\, I_L(t)$$

Area of −ve half cycle of V_L

$$A_- = -\int_{dT_s}^{T_s} V_L(t) = V_o(t)\int_{dT_s}^{T_s} dt + V_\gamma\int_{dT_s}^{T_s} dt - I_o r_c (1-d)T_s + (r_l + r_c + r_d)\int_{dT_s}^{T_s} I_L(t)dt$$

$A_+ = A_-$ (Avg. voltage across Inductor zero)

$$\therefore\ V_{in}\, dT_s - (r_l + r_s)\frac{I_o d}{(1-d)} T_s = (V_o + V_\gamma - I_o r_c)(1-d)T_s + (r_l + r_c + r_d) I_o T_s$$

$$dV_{in} - (r_l + r_s)\frac{I_o d}{1-d} = (V_o + V_\gamma - I_o r_c)(1-d) + (r_l + r_c + r_d) I_o$$

$$V_o(1-d) = dV_{in} - V_\gamma(1-d) + I_o r_c(1-d) - (r_l + r_c + r_d) I_o - (r_l + r_s)\frac{I_o d}{1-d}$$

$$V_o(1-d) = dV_{in} - V_\gamma(1-d) + I_o\left[r_c(1-d) - (r_l + r_c + r_d) - \frac{(r_l + r_s)d}{1-d}\right]$$

$$\therefore\ V_o = \left[\frac{d}{1-d}V_{in} - V_\gamma\right] + I_o\left[r_c - \frac{r_l + r_c + r_d}{1-d} - \frac{d(r_l + r_s)}{(1-d)^2}\right]$$

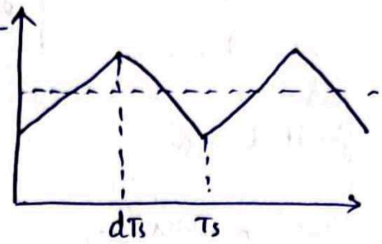
from above formulas ⇒

$$V_o = \left(\frac{12(0.5)}{1-0.5} - 0.5\right) - 2\left(0.3 - \frac{0.3+0.3+0.15}{0.5} - \frac{0.5(0.3+0.1)}{(0.5)^2}\right)$$

$$= 11.5 - 2\left[0.3 - 1.5 - 0.8\right]$$

$$= 11.5 - 4$$

$$V_o = 7.5V$$



$$\Delta I_L \cong \frac{V_{in}}{L} dT_s = \frac{12}{150\times10^{-6}}\left(\frac{0.5}{100\times10^3}\right)$$

$$\cong 0.4A$$

Avg. Inductor Current ⇒ 4A (from graph)

$\therefore \Delta I_L = 0.4A$

$\therefore \quad \Delta V_c = 0.4 * 0.3$

$= 0.12V$

(b) If you Increase the no. of MOSFETS (Parallel Connected MOSFET's then you will less Conduction power loss due to less $r_{ds\,on}$ ($\because$ Parallel Connected r_{ds}'s results less $r_{ds\,on}$) But switching losses will Increases due to more no. of switches Because, Switching losses are dissipated each switch i.e; If you Connected MOSFET's in Parallel then due to more MOSFET more switching's are needed to operate the Converter i.e; more switching losses thatsway you are getting Instead of 94% you got 75%. (Conduction loss ⇓ But switching Losses ⇑)

Improve the Converter Efficiency by

* wound the Inductor very tightly i.e; near to ideal one.
* sholder the Components very closly i.e; Then you won't get parasitic Inductances.
* use proper R_g value & select MOSFET Based on rating.

(19)

Boost Converter

$V_{in} = 12V$, $d = 0.75$, $f_s = 50kHz$, $L = 60\mu H$

$C = 1000\mu F$, $C \times ESR = 30\mu s$

a) Converter operates no load means, circuit operates like a LC series circuit i.e; large current flows through Diode (D) and Capacitor charges upto $2V_{in}$. So there is no problem But Current in the ckt is very large Because

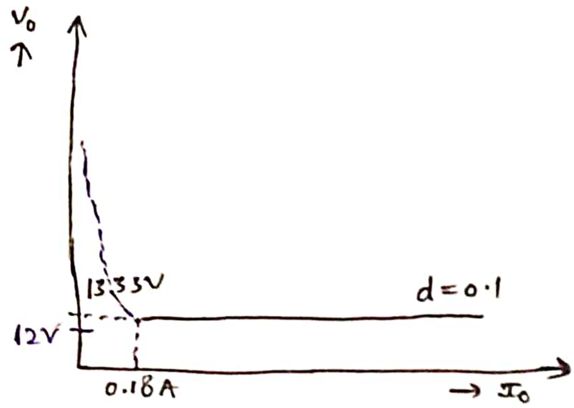
$i_p = V_{in}\sqrt{C/L} \cong 12\sqrt{\frac{1000}{60}} \cong 49A$. It causes diode will get damage and switch also get blown. when it is tested on no load.

b) $d = 0.1$

$$\frac{\Delta I_L}{2} = \frac{d(1-d)V_{in}}{2f_s L}$$

$$= \frac{(0.1)(1-0.1)\,12}{2 * 50*10^3 * 60\times10^{-6}}$$

$$= \frac{0.1\,(12)\,(0.9)}{6} = 0.18A$$



Min. Current, $I_{o_{min}} > \frac{\Delta I_L}{2}$ then Converter operates CCM.

$\therefore I_{o_{min}} = 0.18A$

$V_o = \frac{V_{in}}{1-d} = 13.333V$

$R_{min} = \frac{V_o}{I_{o_{max}}}$; $R_{max} = \frac{V_o}{I_{o_{min}}}$

$\therefore R_{max} = \frac{13.333}{0.18}$

$= 74.07\Omega$