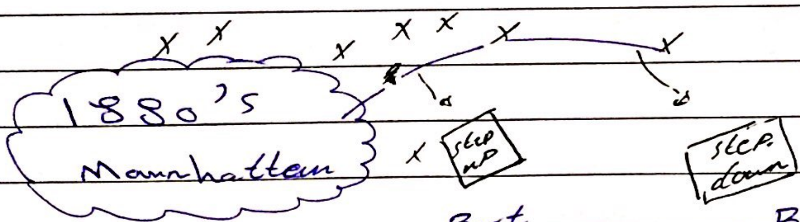
Power Electronics

Power Electronics: is about how to Convert & monitor electric Power from one form to another

⇒ War of currents.

Edison

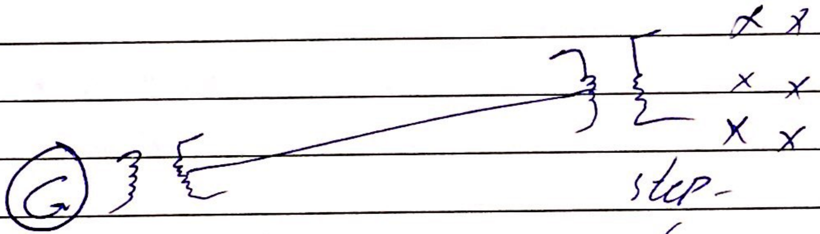


Boost converter

Buck converter

DC Power Distribution

Tesla

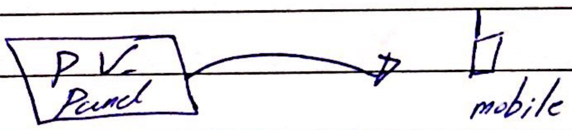


step-up

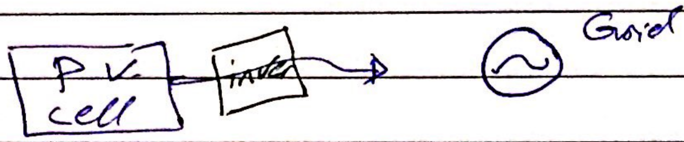
step-down

Power conversion types:

① DC/DC   Conversion: [converter]



② DC/AC   Inversion   [Inverters]



Green Cooridor

③ AC / DC Rectification [Rectifiers]

~ → Rec. → DC

④ AC/AC controllers [for low Power Applications]

Applications:

→ Renewables
- → Solar
  - → PV [light] DC → AC, → DC
  - → CPS [Heat]
- → Wind → AC → A

Tafileh ⇒ 100 MVA

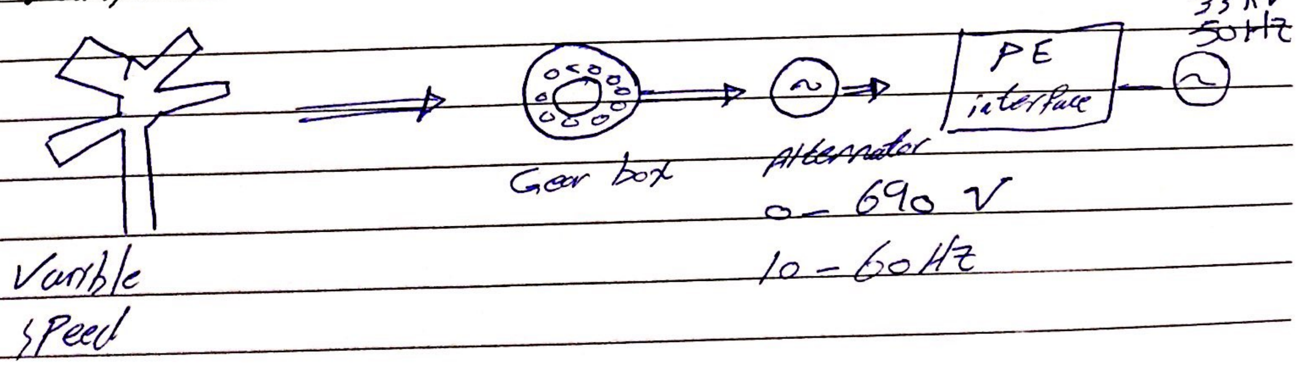
maan ⇒ 50 MVA

→ Transportation
- → Train
- → EV

→ Electronic Devices

Source → Interface → Load

Examplek : wind Generator



Example: PV - Panels

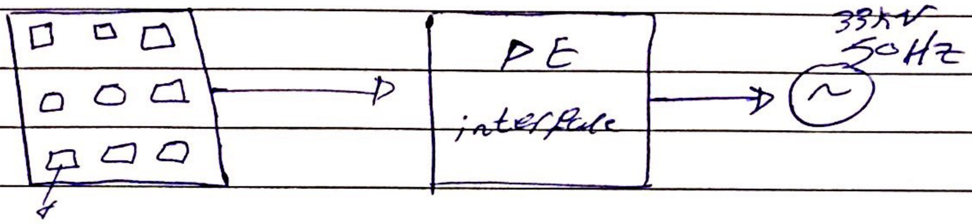
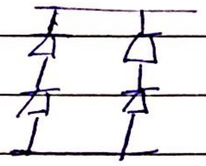


photo-diode

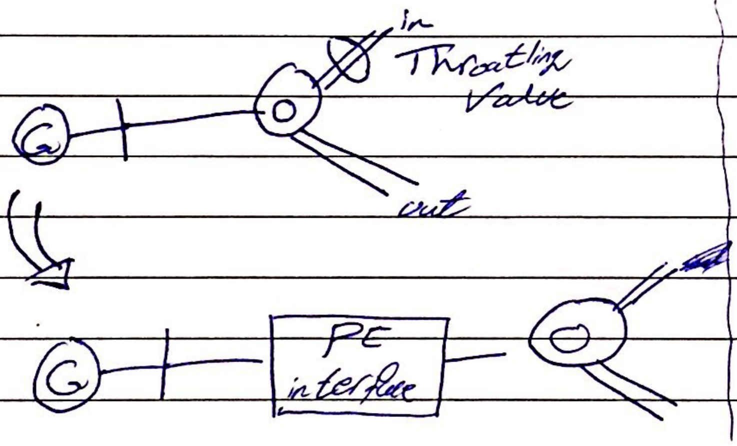
DC - voltage

DC - current

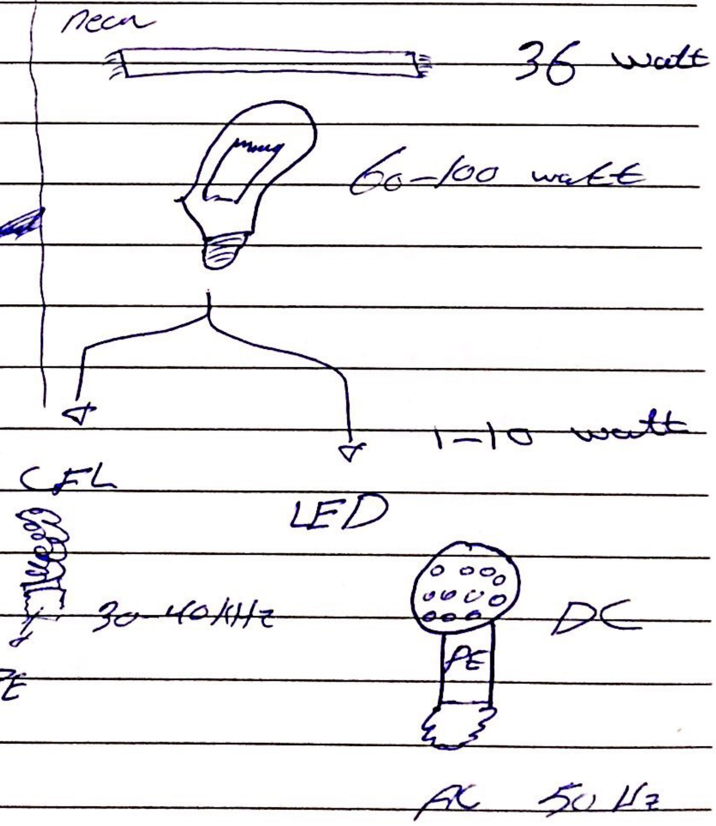


Example: Effeciency improvment

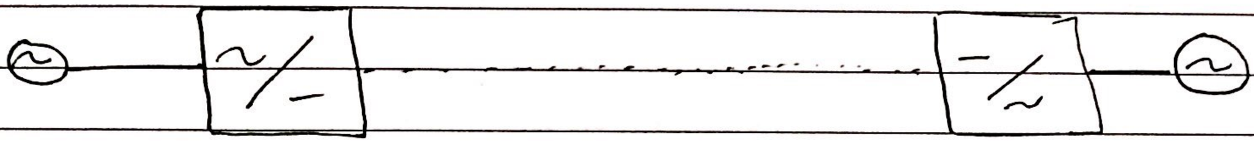
Motors [Drive] :-



Lighting :-



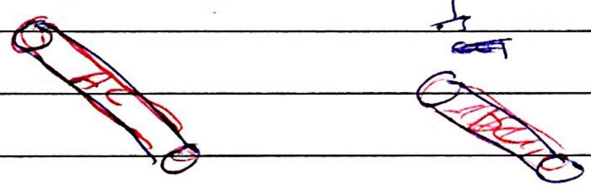
Example: Utility applications



HVDC

- losses
- copper

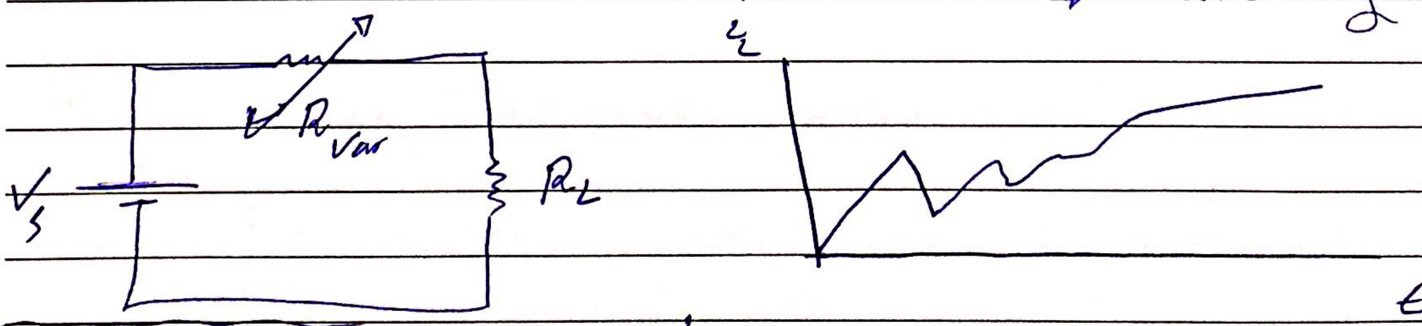
AC ⇒ 4-conductors
DC ⇒ 2- "

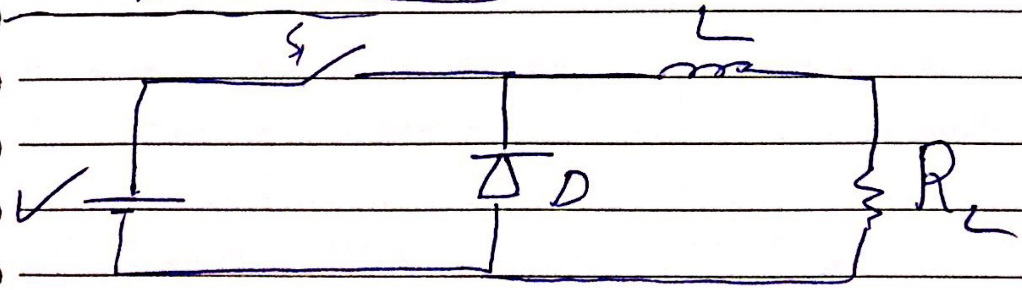


$$R_{AC} = \frac{\rho L}{A} \Rightarrow R_{AC} > R_{DC}$$

What is the essence of Power Electronics!

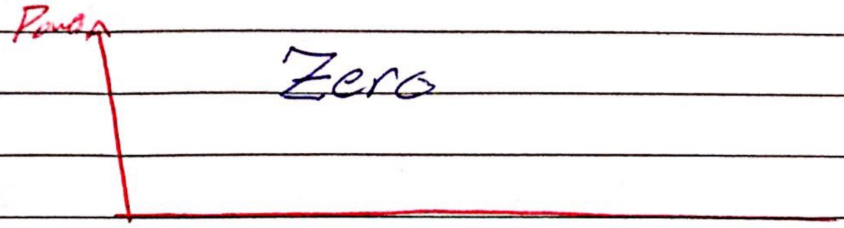
⇒ Switching



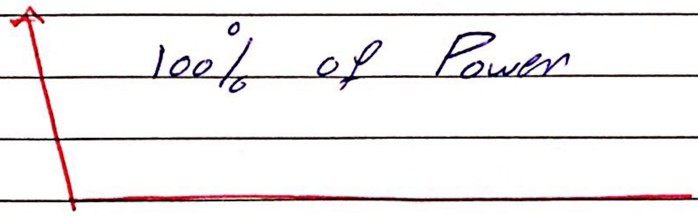


S_1 : off

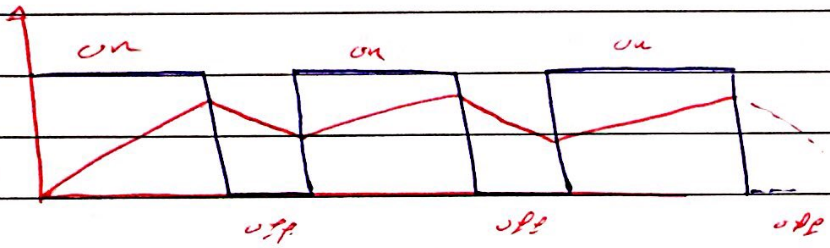
% ohmic & cutoff

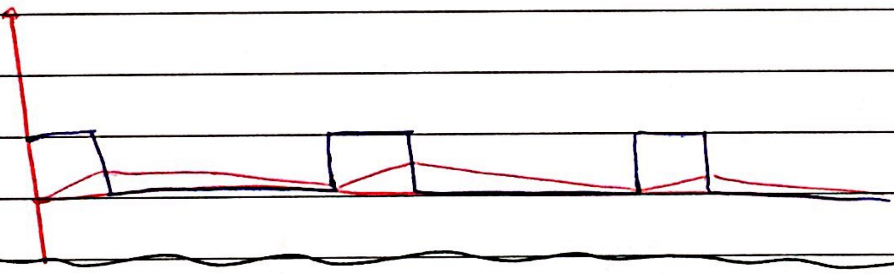


S_1 : ON

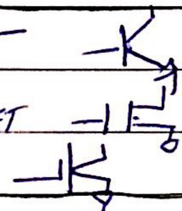
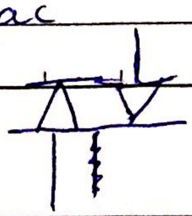
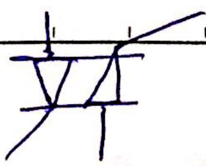
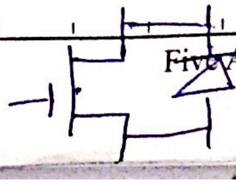


S_1 : on & off

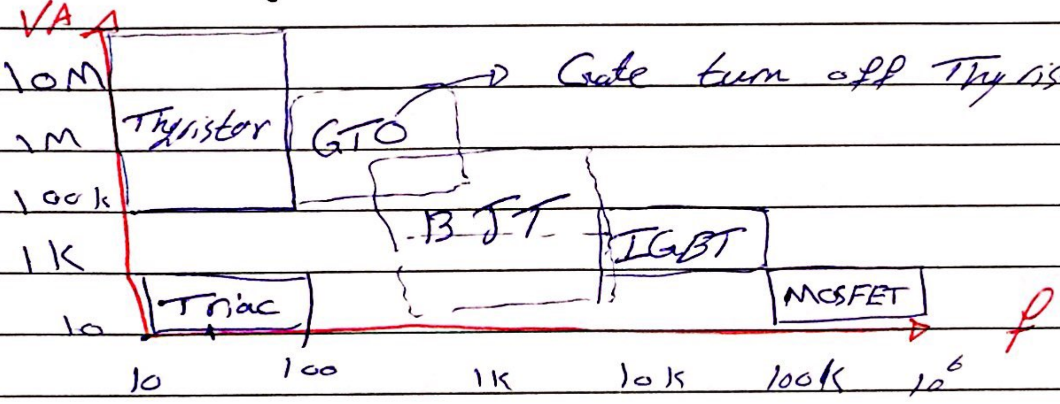




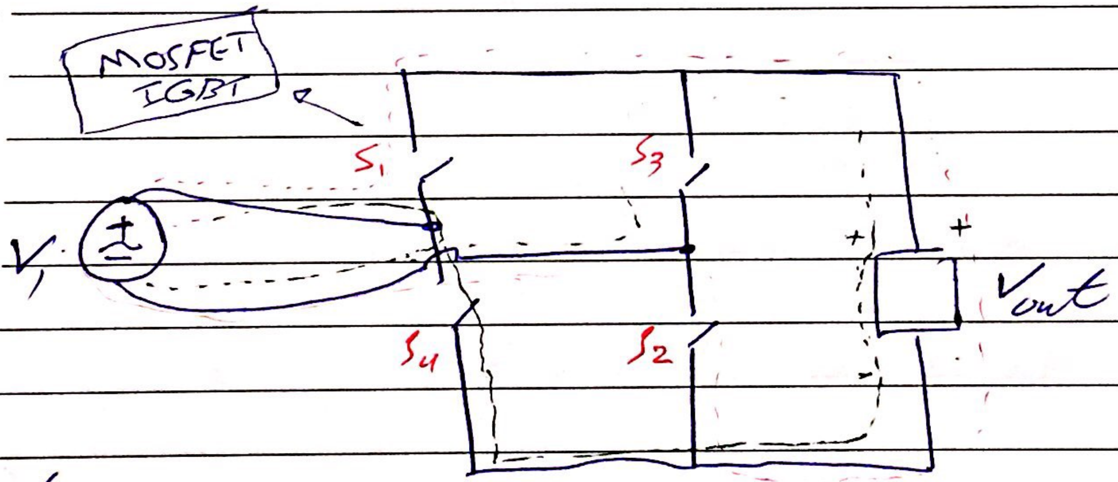
Switching Devices : Controllability & Direction

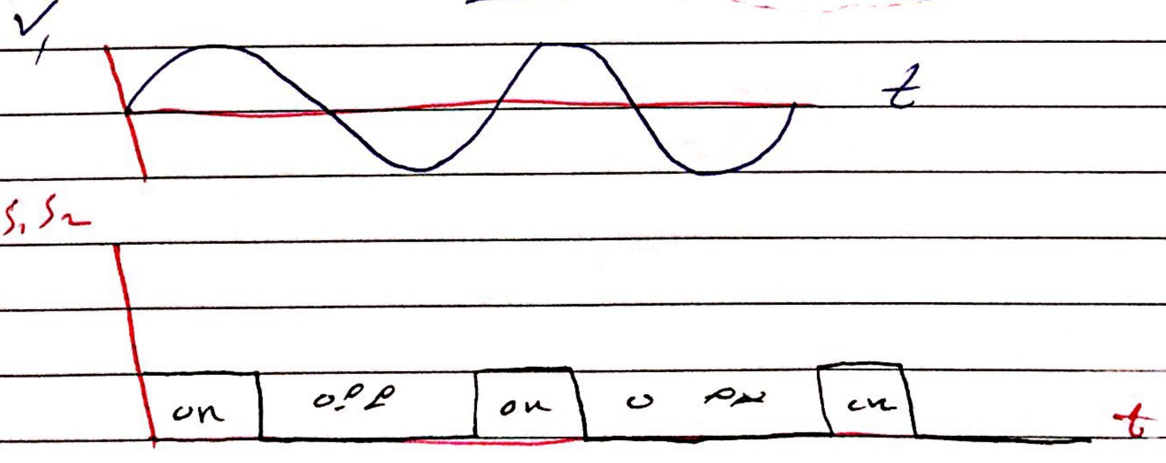
	Uncontrollable	~~Un~~controllable ~~off~~ on	controllable
Uni-Directional	Diode 	Thyristor (SCR) 	BJT, MOSFET, IGBT  GTO
Bi-Direction	Diac 	Triac 	Modules 

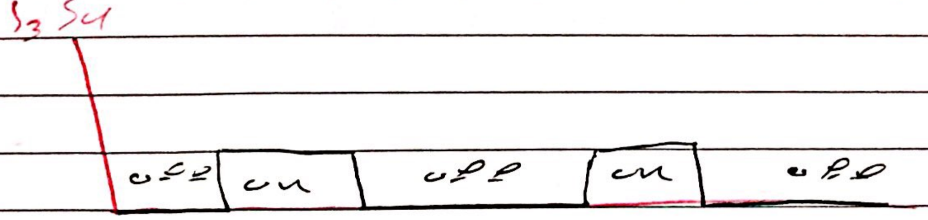
Switching Devices: Frequency & VA Rating



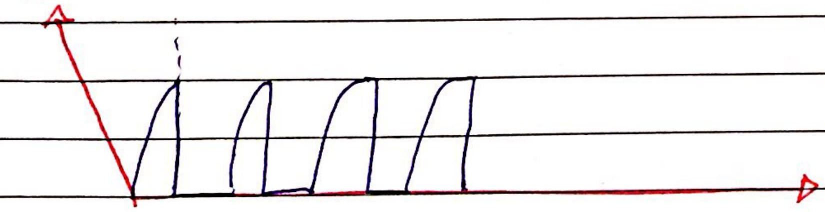
① Principle of AC-DC (Rectifier)



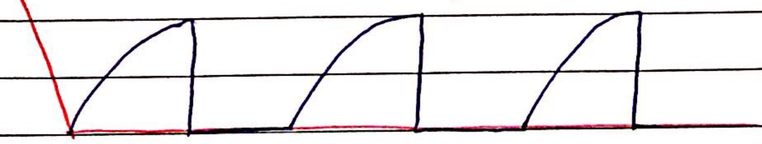




V_{out}

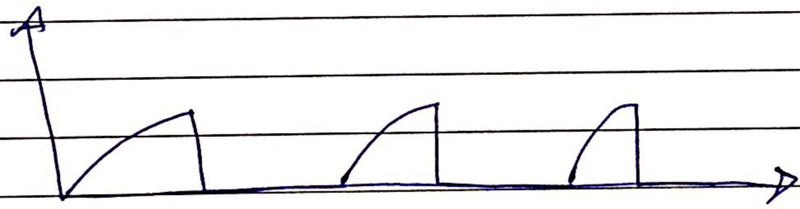


DC + ripple



+ve ✓ ⇒ DC signal
AVG ✓

$$v(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \sin(n\omega t) + \sum_{n=1}^{\infty} b_n \cos(n\omega t)$$

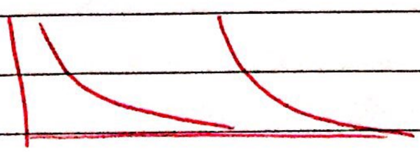


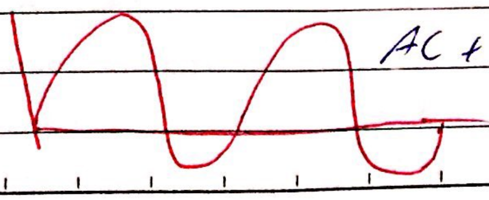
$$V_{avg} = \frac{1}{T}\int_0^T v(t)\,dt \neq 0 \Rightarrow DC$$

Fourier Series:

$a_0 \equiv DC$

$c_1 = \sqrt{b_1^2 + a_1^2} \equiv AC$

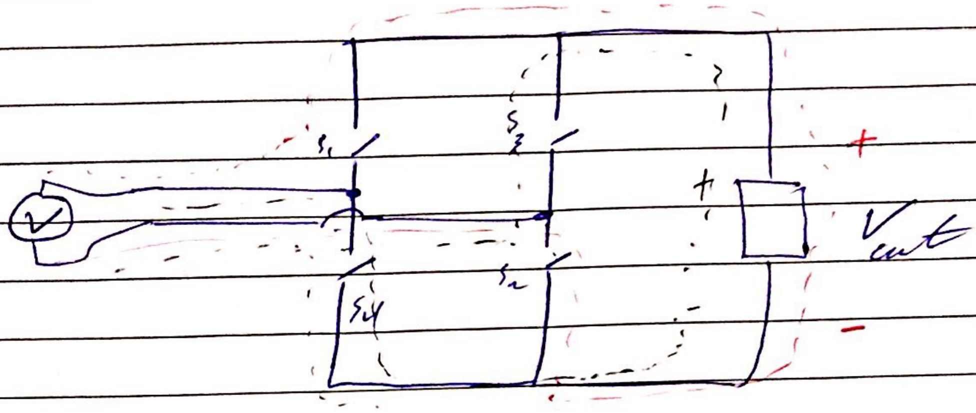


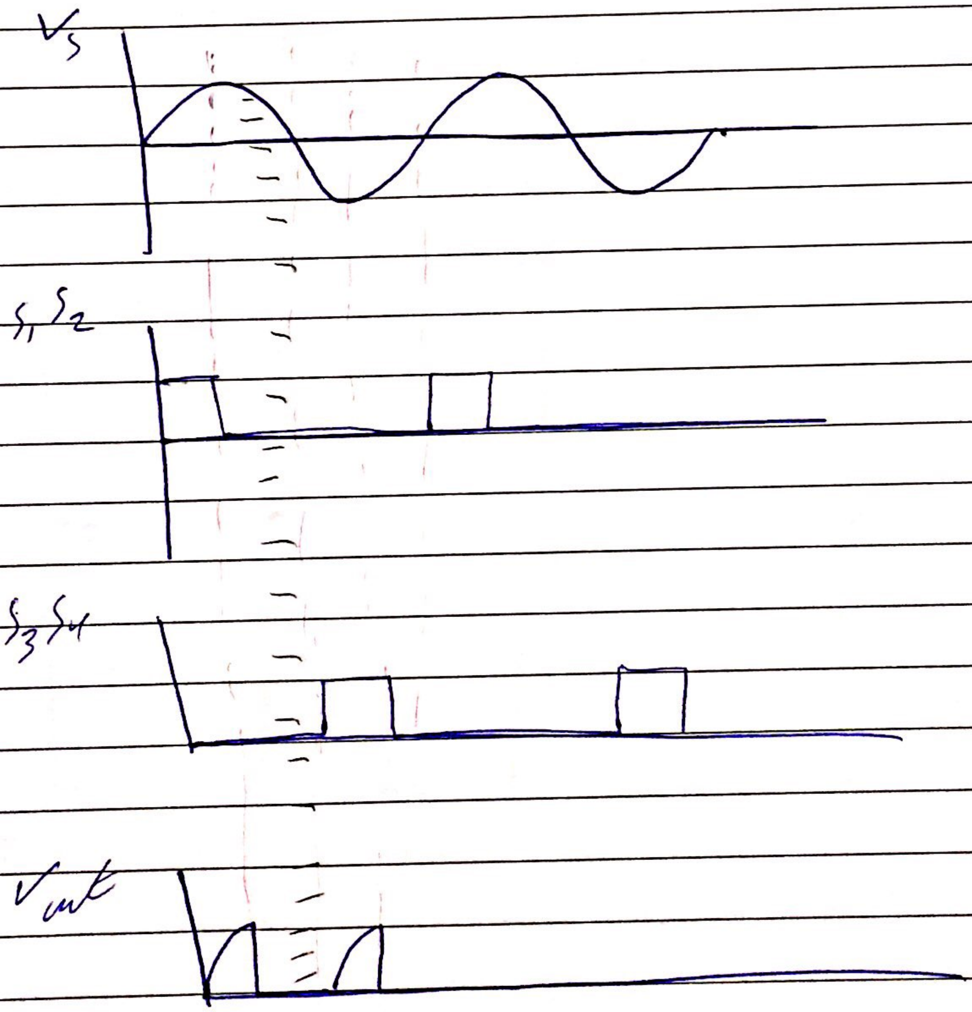


AC + DC offset

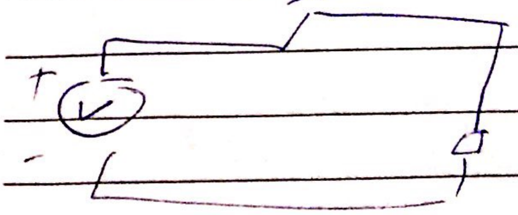
DC with ripple

AC - DC Rectification



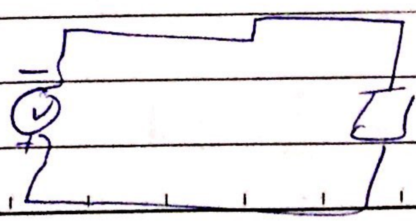


when S_1 & S_4 are on



$V_{Load} = V_s$

when S_3 & S_4 are on



$V_{Load} = V_s$

$V_o = (S_1 - S_3) V_s$

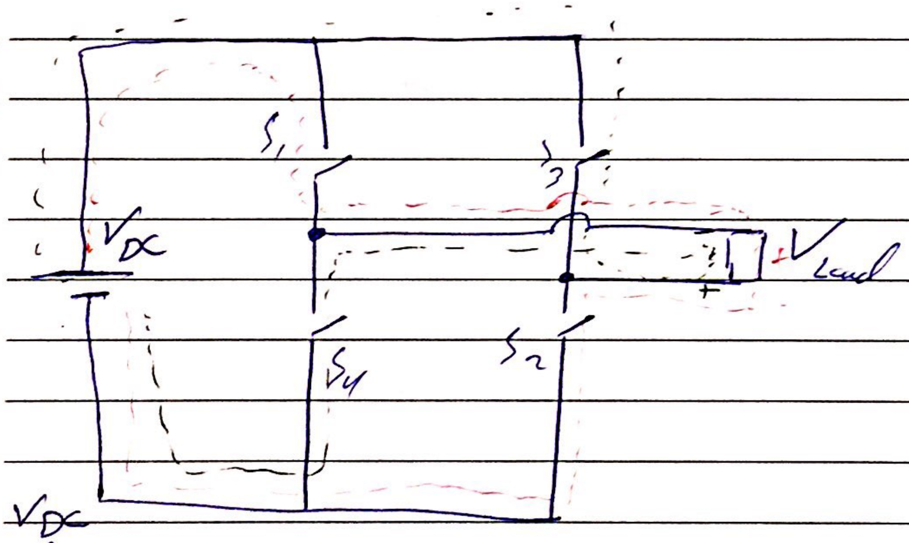
S_1: 1 on $\quad$ S_3: 1 on

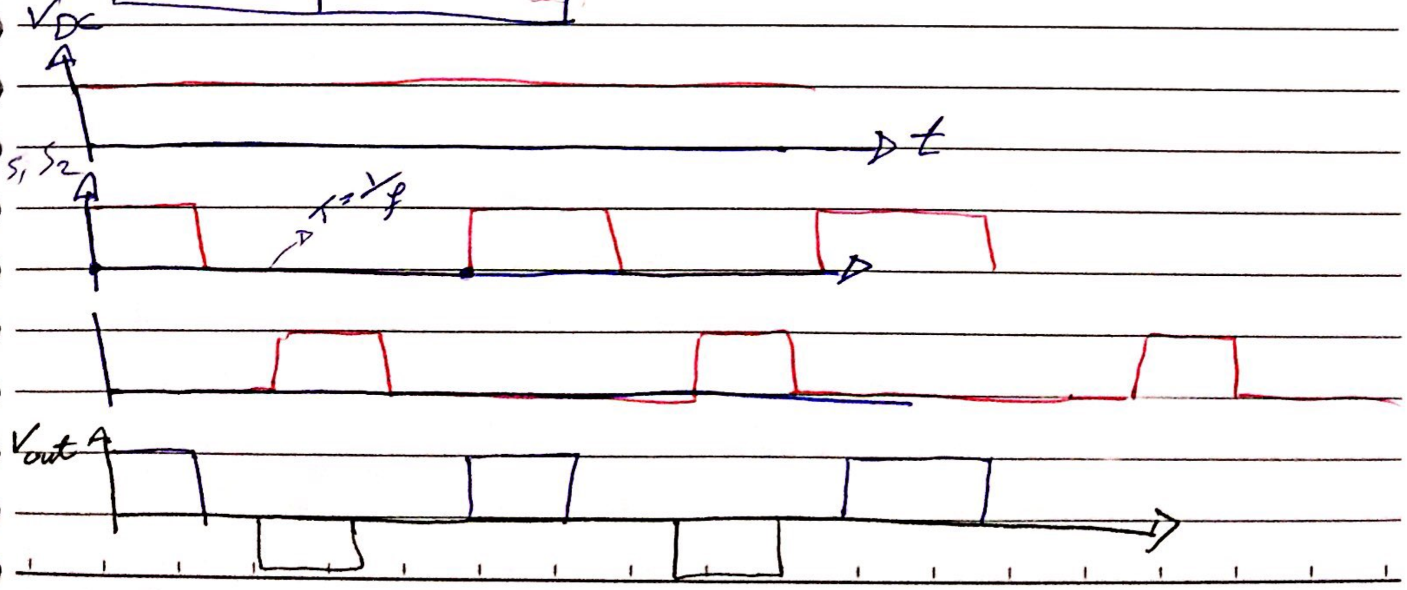
0 off $\quad$ 0 off

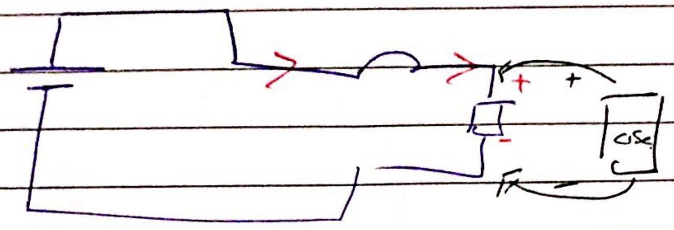
or S_2 $\quad$ or S_4

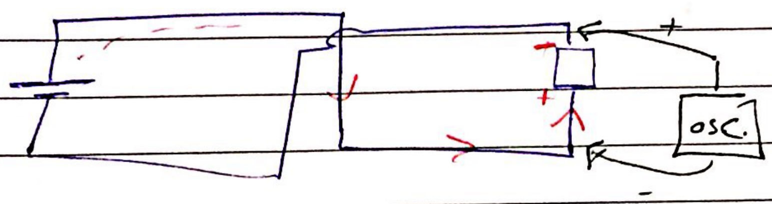
S_1	S_3	V_{out}
1	1	
0	0	0
1	0	V_s
0	1	$-V_s \Rightarrow -(-) = +ve$

DC – AC Inversion



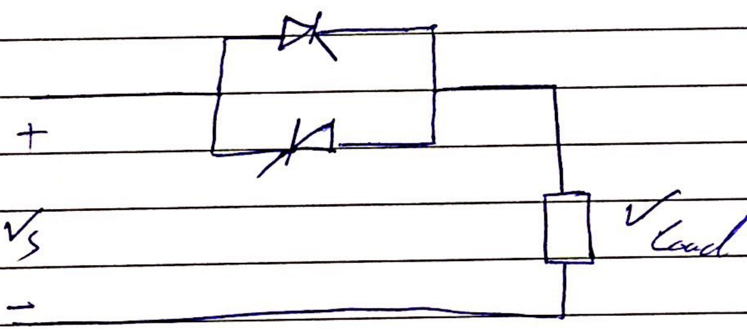


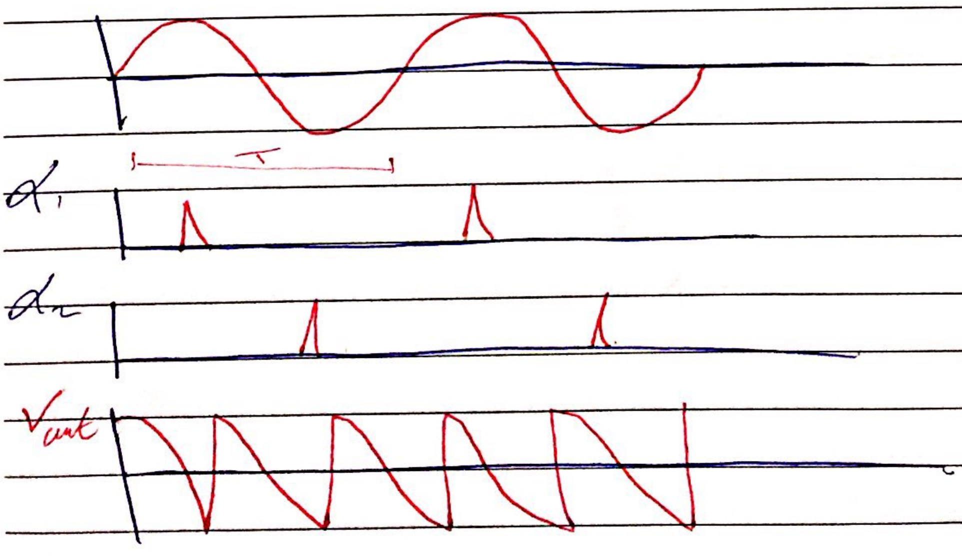


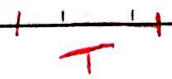


$$V_{AC} = (S_1 - S_3) V_{DC}$$

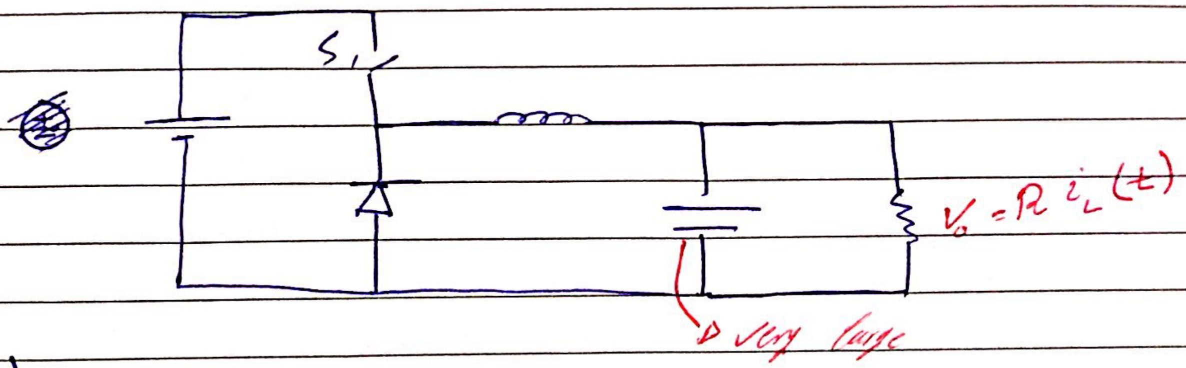
AC – AC Controllers :-

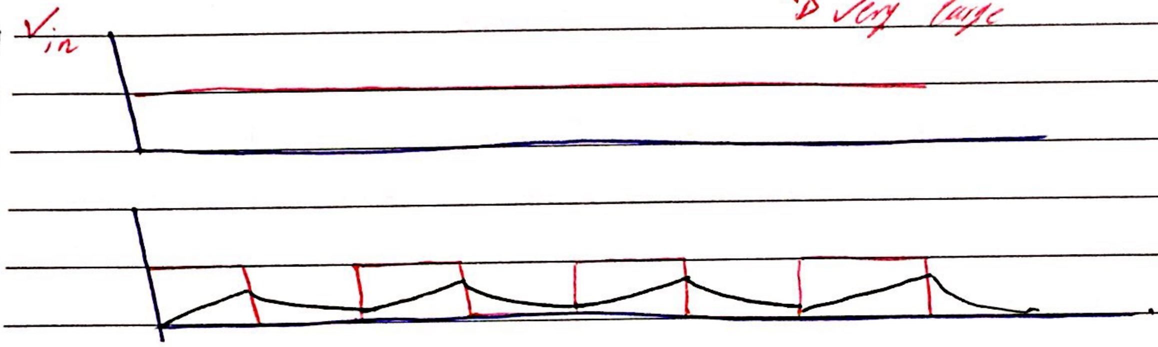


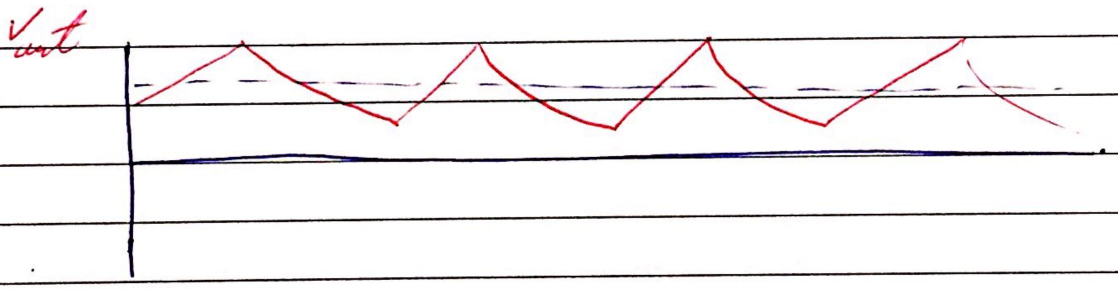


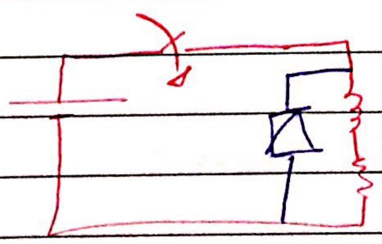


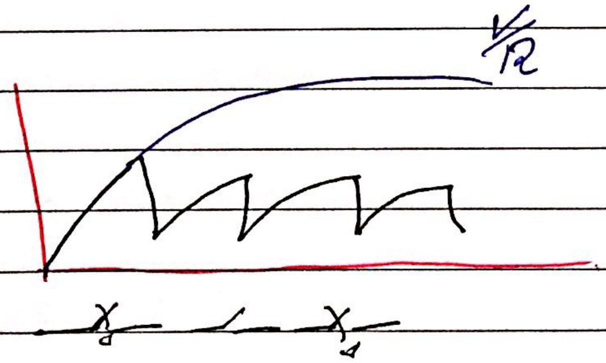
Principle of DC-DC converter :-

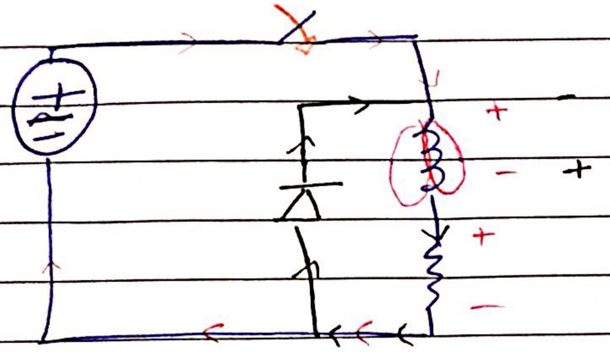








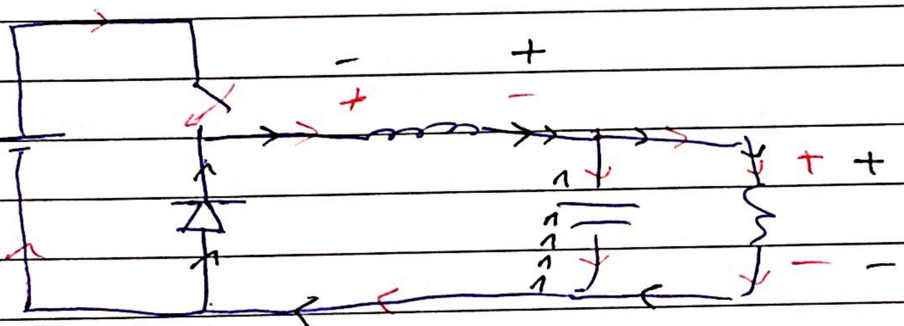


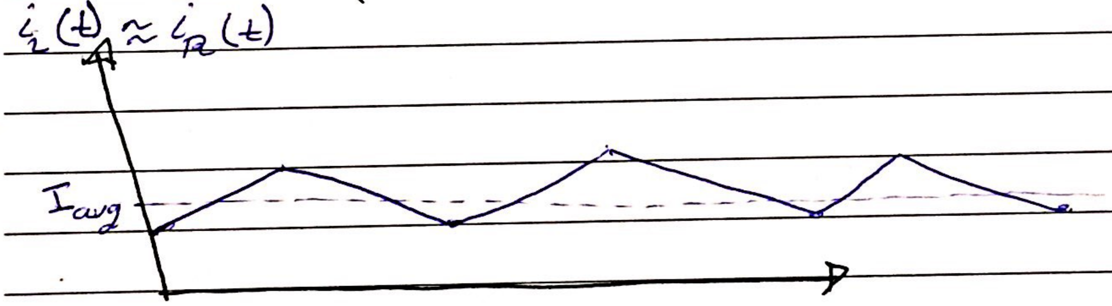


$$V_L = L\frac{di}{dt}$$

$$i_c = C\frac{dv_c}{dt}$$

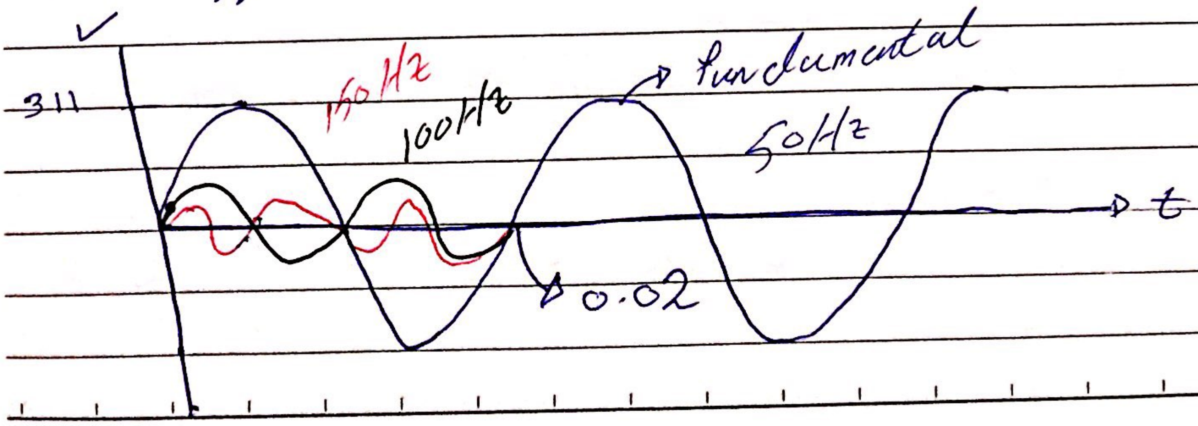
Buck DC/DC converter

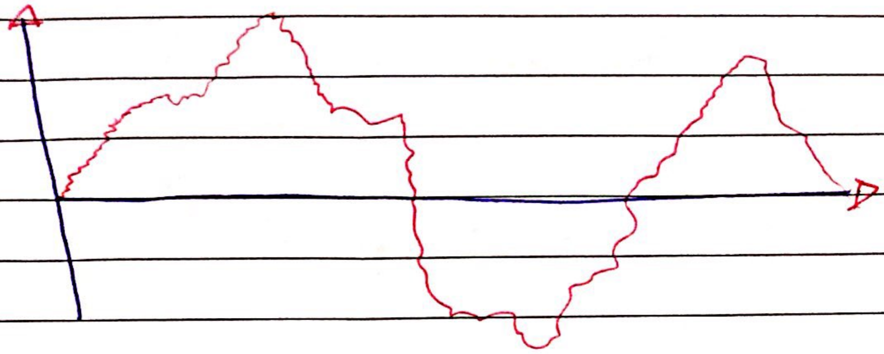




$V_{out} = R\, I_{avg}$ = DC Value

PE biggest Problem is harmonics

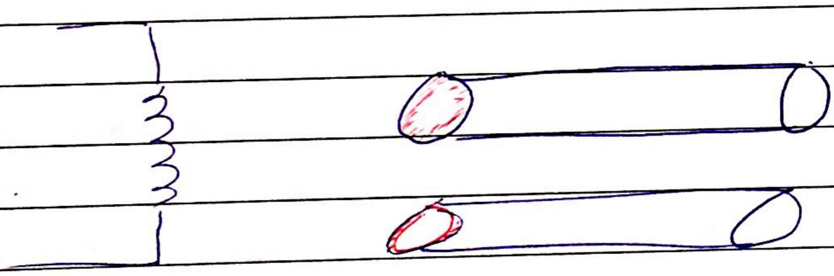




⇒ We need to charactrized the harmonics using the Fourier Series

$$V = -N \frac{d\phi}{dt} = -N\omega \phi_m$$

$$V = \sqrt{V_1^2 + V_2^2 + V_3^2 + \cdots}$$



Skin effect

$$\delta = \frac{1}{\sqrt{\mu_0 f \pi}}$$

$$V(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)$$

$$= \frac{a_0}{2} + \sum_{n=1}^{\infty} C_n \cos(n\omega t + \phi_n)$$

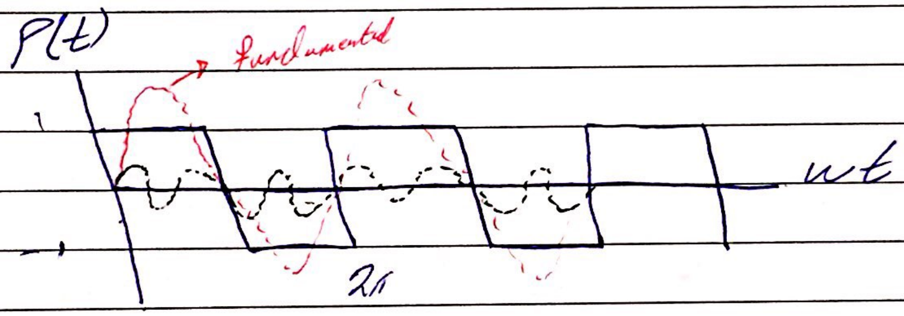
$$a_0 = \frac{2}{T} \int_0^T V_0(t)\, dt = \frac{1}{\pi} \int_0^{2\pi} V_0(\omega t)\, d\omega t$$

$$a_n = \frac{2}{T}\int_0^T V_o(t)\cos n\omega t \, dt = \frac{1}{\pi}\int_0^{2\pi} V_o(\omega t)\cos n\omega t \, d\omega t$$

$$b_n = \frac{2}{T}\int_0^T V_o(t)\sin n\omega t \, dt = \frac{1}{\pi}\int_0^{2\pi} V_o(\omega t)\sin n\omega t \, d\omega t$$

$$C_n = \sqrt{a_n^2 + b_n^2} \quad , \quad \emptyset_n = \tan^{-1}\left(\frac{b_n}{a_n}\right)$$

Example: Find the first & 3rd harmonics for:-



So we find C_1 & C_3

$$a_o = \frac{2}{2\pi}\int_0^{2\pi} f(t)\, d\omega t$$

$$= \frac{2}{2\pi}\left[\int_0^{\pi} 1 \, d\omega t + \int_{\pi}^{2\pi} -1 \, d\omega t\right] = 0$$

$$a_n = \frac{2}{2\pi}\int_0^{2\pi} f(t)\cos n\omega t \, d\omega t$$

$$= \frac{1}{\pi}\left[\int_0^{\pi}\cos n\omega t \, d\omega t + \int_{\pi}^{2\pi} -\cos n\omega t \, d\omega t\right]$$

$$= 0$$

$$b_n = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin n\omega t \, d\omega t$$

$$= \frac{1}{\pi} \left[\int_0^{\pi} \sin n\omega t \, d\omega t + \int_{\pi}^{2\pi} -\sin n\omega t \, d\omega t \right]$$

$$= -\frac{1}{n\pi} \cos n\omega t \Big|_0^{\pi} + \frac{1}{n\pi} \cos n\omega t \Big|_{\pi}^{2\pi}$$

$$= \frac{2}{n\pi} - \frac{2}{n\pi} \cos n\pi$$

$$C_n = b_n$$

$$C_1 = C_n \Big|_{n=1} = b_1 = \frac{4}{\pi}$$

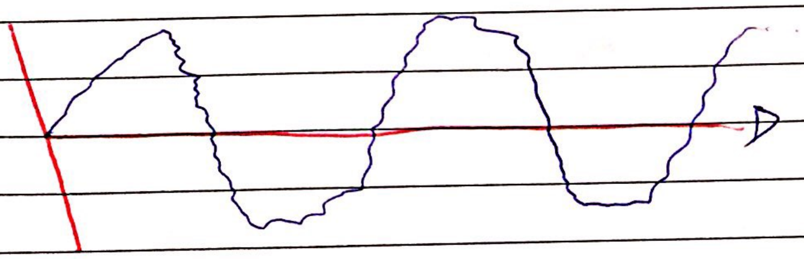
$$C_3 = C_n \Big|_{n=3} = b_3 = \frac{4}{3\pi}$$

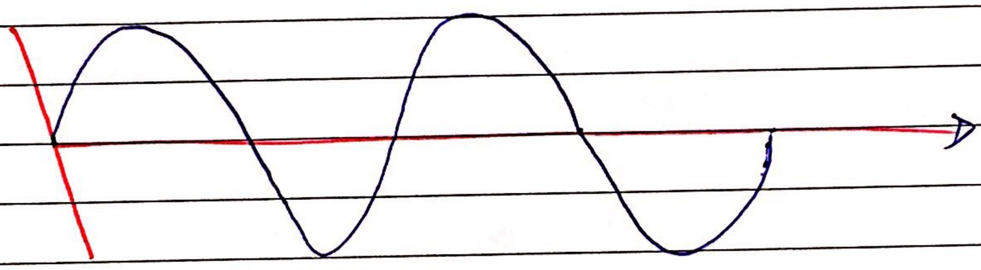
$$b_n = \begin{cases} 0 & , n \text{ even} \\ \frac{4}{n\pi} & , n \text{ odd} \end{cases}$$

$v(t) = \frac{a_0}{2} + \Sigma \ldots$

$= \underline{A} + A_1\cos(\omega t) + A_2\cos(2\omega t) + A_3\cos(3\omega t) + \ldots$

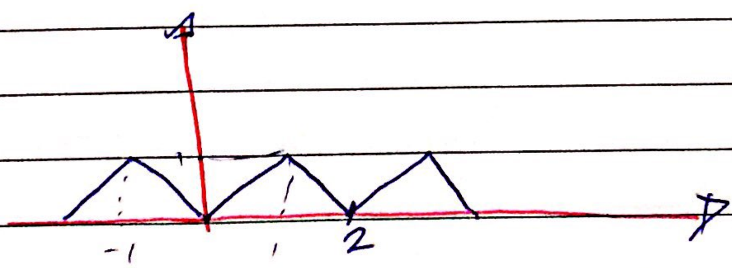
Total harmonic Distortion (THD): it is a measure of the closeness in shape between a wave form & its fundamental frequency





$$\%THD = \frac{\sqrt{\sum_{n=2}^{\infty}(I_n)^2}}{I_1}$$

Ex: Find the THD for the Signal:-



$T = 2$

$$\int_0^{2\pi} d\omega t$$

$$\int_0^{T} dt$$

$$\frac{a_0}{2} \overset{?!}{=} \frac{1}{2}$$

$$a_n = \frac{2}{T}\int_0^T v(t)\cos(n\omega t)\,dt$$

$$v(t) = \begin{cases} t & 0 < t \le 1 \\ 2-t & 1 < t \le 2 \end{cases}$$

$$= \frac{2}{2}\int_{-1}^{1} v(t)\cos(n\omega t)\,dt$$

$$= 2\int_0^1 v(t)\cos(n\omega t)\,dt$$

$$= 2\int_0^1 t\cos(n\omega t)\,dt$$

$u = t \qquad dv = \cos(n\omega t)\,dt$

$du = dt \qquad v = \frac{1}{n\omega}\sin(n\omega t)$

$$= 2\left[\frac{t}{n\omega}\sin(n\omega t)\right]_0^1 - \int_0^1 \frac{1}{n\omega}\sin(n\omega t)\,dt$$

$$\omega = 2\pi f = \frac{2\pi}{2} = \pi$$

$$= \frac{2}{n^2\omega^2}\cos(n\omega t)\Big|_0^1 = \frac{2}{n^2\omega^2}\left(\cos(n\pi) - 1\right)$$

$$= \begin{cases} 0 & , n \text{ even} \\ \frac{-4}{n^2\omega^2} & , n \text{ odd} \end{cases}$$

$$a_n = \frac{1}{n\pi}, \quad b_n = \frac{1}{n^2}$$

Find 3rd harmonic ; $C_n = \sqrt{a_n^2 + b_n^2}$

$$C_3 = \sqrt{\left(\frac{1}{3\pi}\right)^2 + \left(\frac{1}{9}\right)^2}$$

⇒ For even functions

$$\boxed{b_n = 0}$$

⇒ For odd functions

$$\boxed{a_n = 0}$$

⇒ $C_n = |a_n|$

$$a_1 = \frac{-4}{\pi^2}$$

$$a_2 = 0$$

$$a_3 = \frac{-4}{9\pi^2}$$

$$a_4 = 0$$

$$a_5 = \frac{-4}{25\pi^2}$$

$$a_7 = \frac{-4}{49\pi^2}$$

$$a_9 = \frac{-4}{81\pi^2}$$

⇒ Find THD (consider the first 4 non zero harmonics)

$$THD = \frac{\operatorname{sqrt}\left(\sum_{n=2}^{9} (I_n)^2\right)}{I_1}$$

$$= \frac{\operatorname{sqrt}\left(\left(\frac{-4}{9\pi^2}\right)^2 + \left(\frac{-4}{25\pi^2}\right)^2 + \left(\frac{-4}{49\pi^2}\right)^2 + \left(\frac{-4}{81\pi^2}\right)^2\right)}{4/\pi^2}$$

$$\cong \cancel{20}\% \qquad = 12\%$$

Part 1 : DC/DC converters :-

Applications :

① PV Systems [DC load]

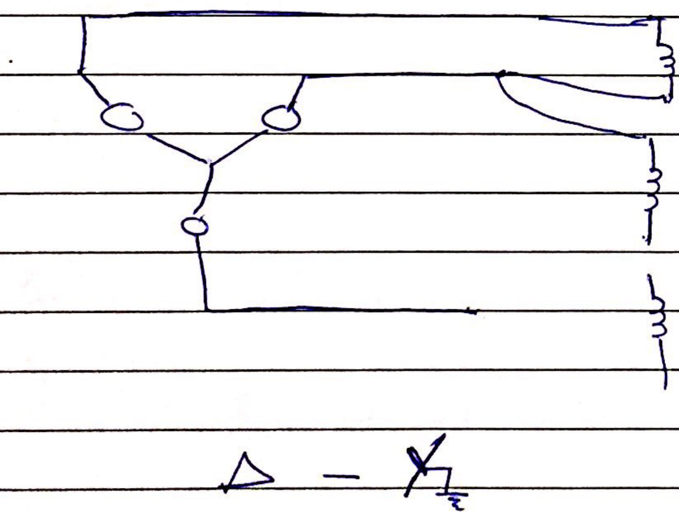
② DC Power Supplies

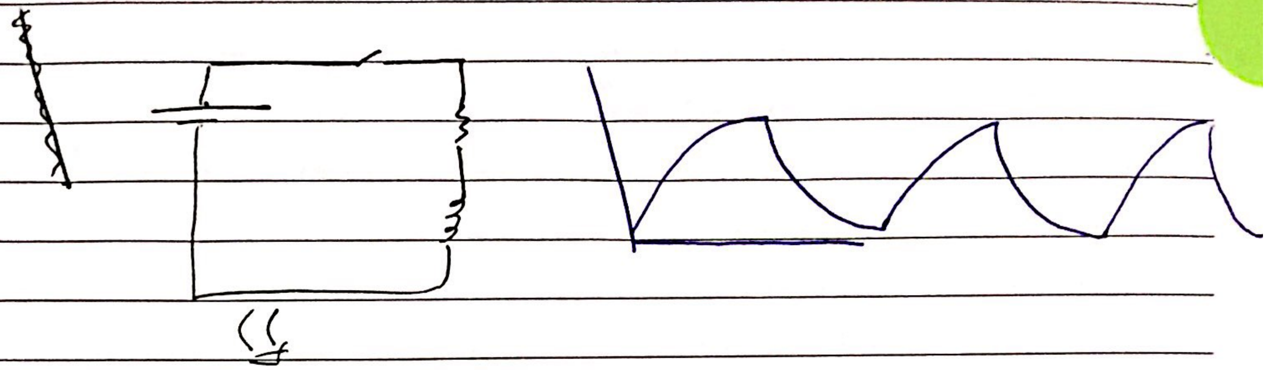
③ E.V.

Classification of DC/DC converters

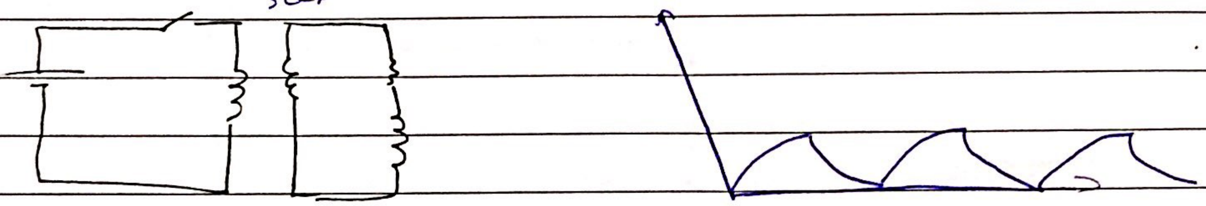
Non-Isolated
- → Buck
- → Boost
- → Buck/Boost

Isolated
- → Forward
- → Fly back
- → Full bridge

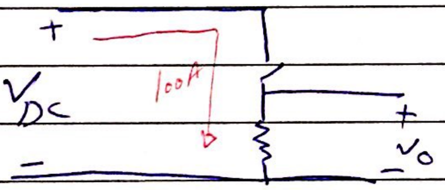




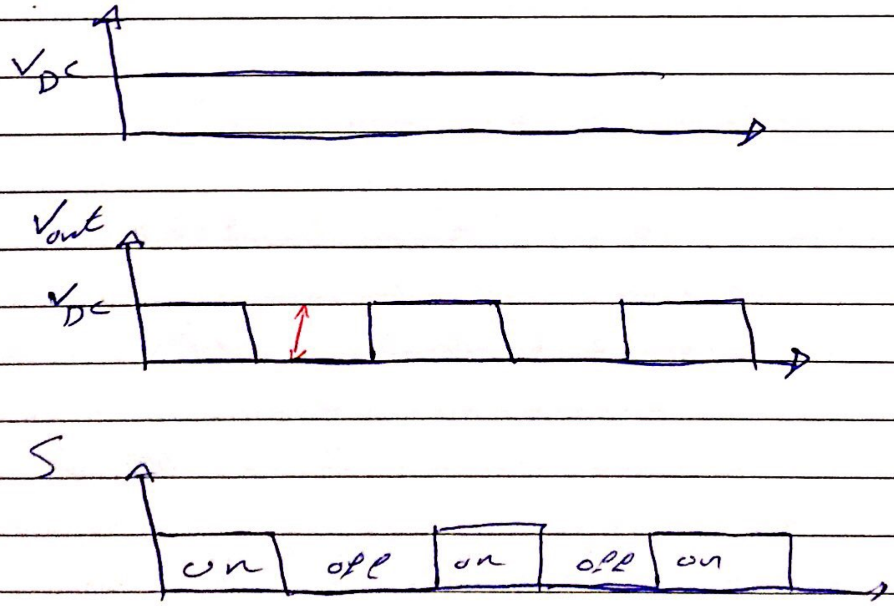
step up



① Buck converter origin.
"step down converter"



Trial [T]

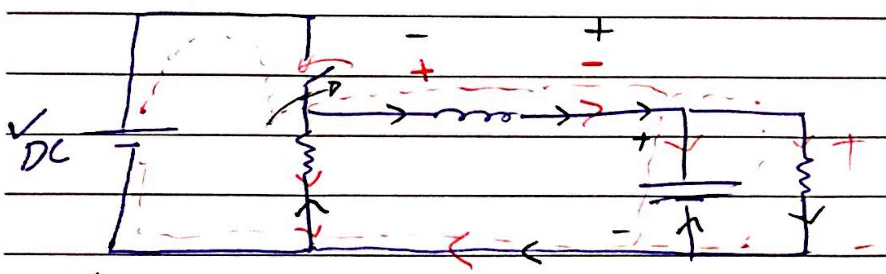


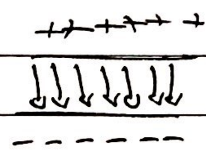
Duty ratio (D) $= \dfrac{T_{on}}{T_{on} + T_{off}} = \dfrac{T_{on}}{T}$

$T = T_{on} + T_{off}$

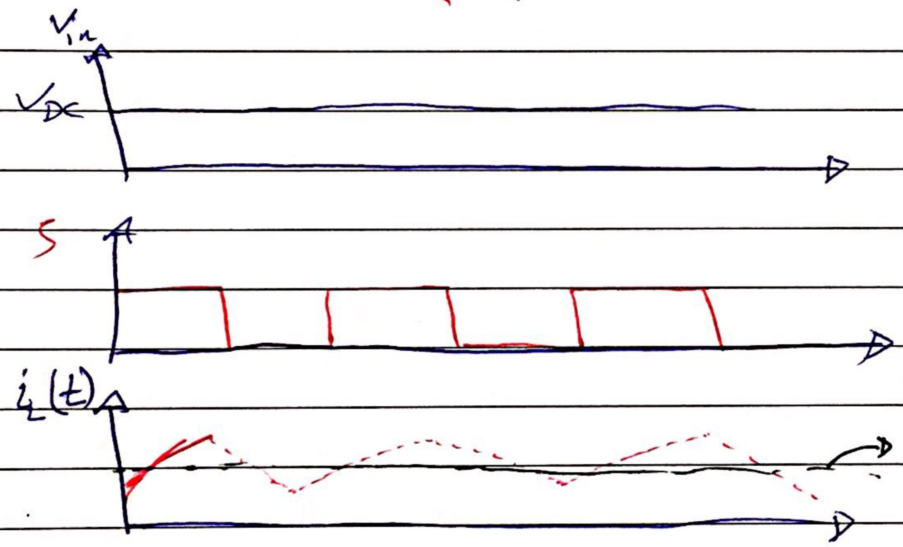
Trial [2]

$V_L = L \dfrac{di}{dt}$





$D = \varepsilon E$



I_R ~~average~~ average current of the resistor

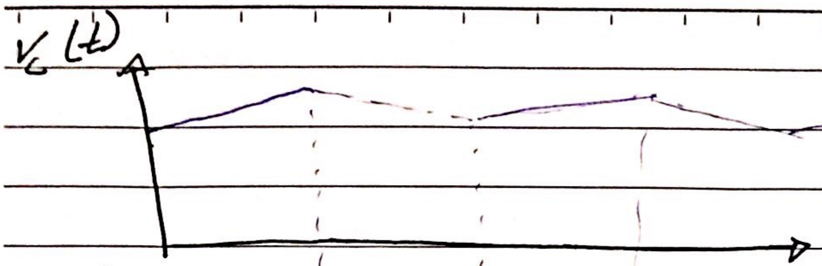
→ In steady state and & if C is very large

on state : $i_L(t) = i_c(t) + i_R(t)$

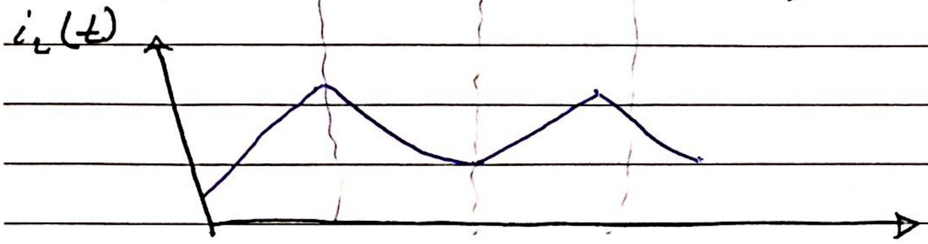
off state ; $i_L(t) + i_c(t) = i_R(t)$

$i_c(t) \cong 0$

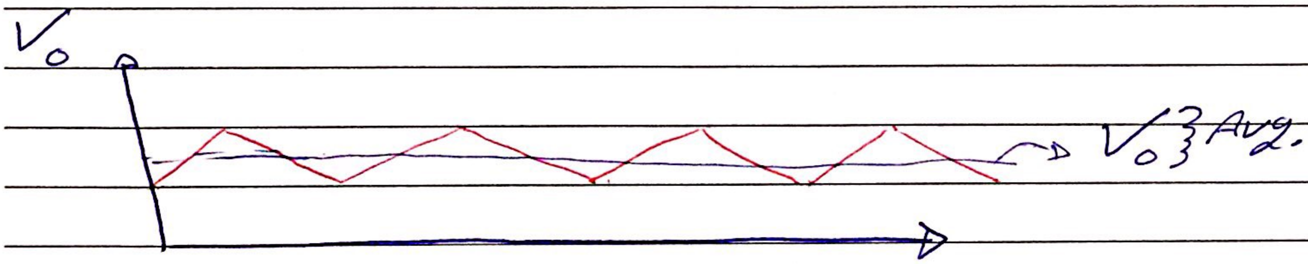
$i_L(t) \cong i_R(t) \Rightarrow I_R = \frac{1}{T}\int_0^T i_R(t)$



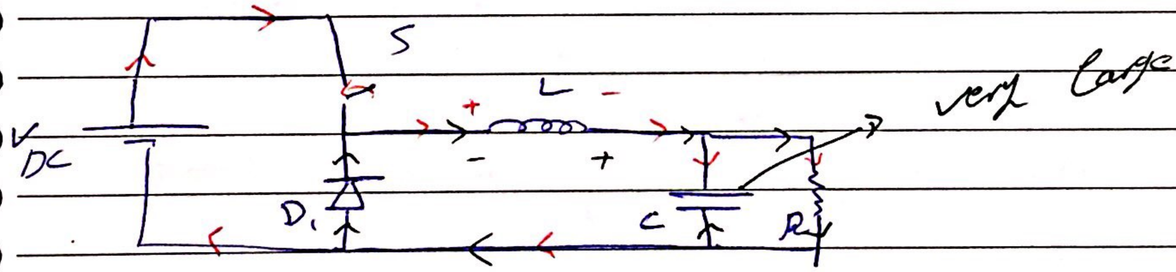
$i_c = C \frac{dv_c}{dt}$



$V_L = L \frac{di}{dt}$

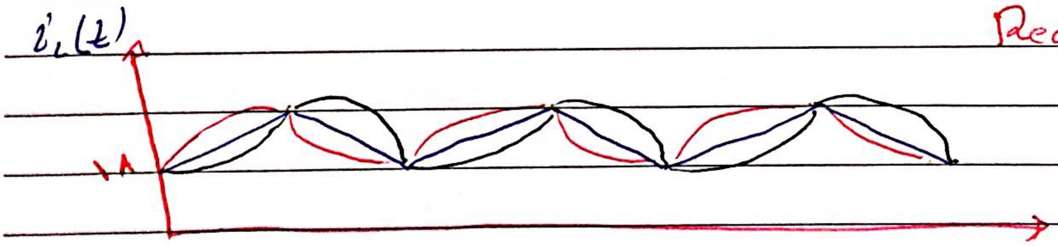


Final Version:

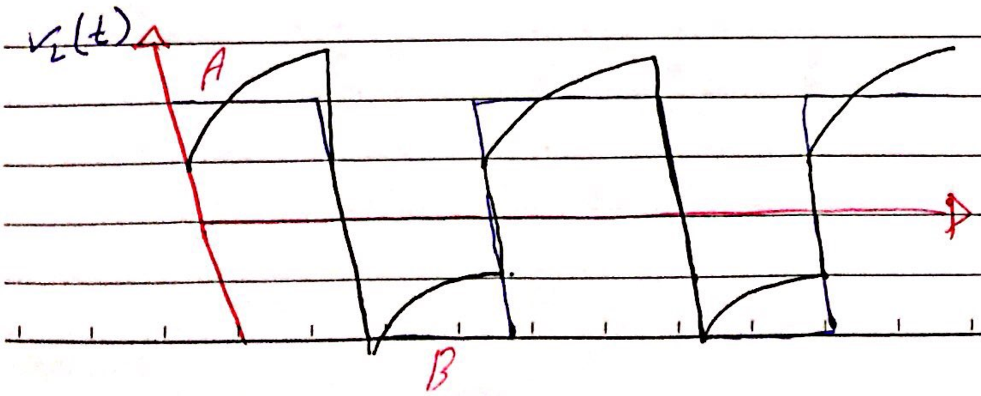


$\Rightarrow$ more efficient

Red is correct!



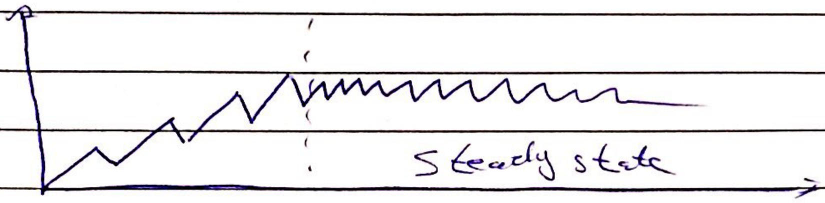
$V_L = L \frac{di(t)}{dt}$



A=B

In steady state & considering the charge reservation Principle

$i(t=0) = i(t=T_s)$



$V_L = L \frac{di}{dt}$

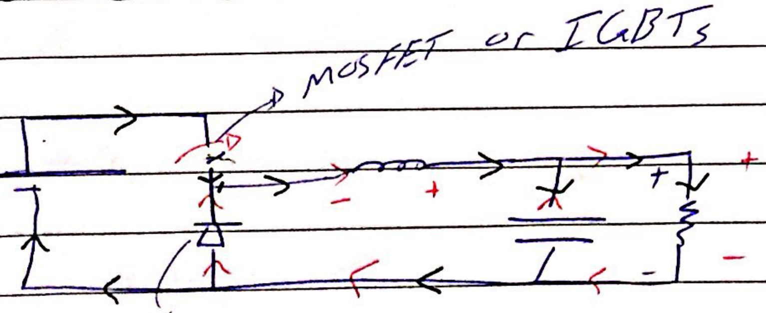
$d\,i(t) = \frac{1}{L} V_L \, dt$

$\int_{i(0)}^{i(T_s)} d\,i(t) = \frac{1}{L} \int_0^{T_s} v_L \, dt$

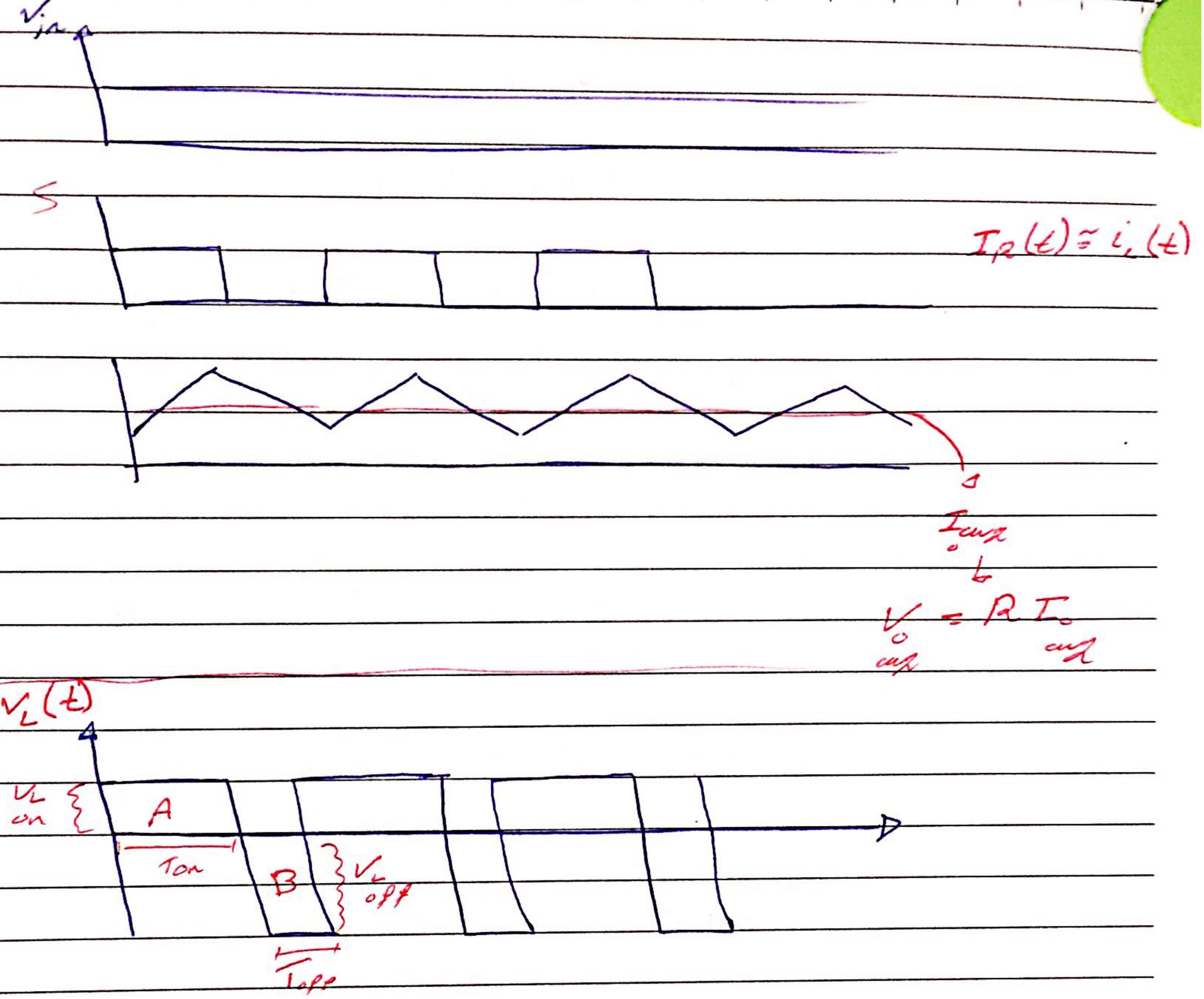
$\therefore i(T_s) - i(0) = \frac{1}{L} \int_0^{T} V_L(t) \, dt$

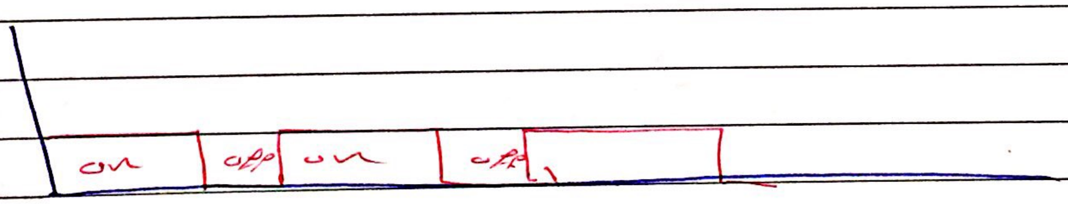
$\therefore A = B$ (Area A = Area B)

Buck converter



step down





Area A = Area B

$V_{L\,on} * T_{on} = V_{L\,off} * T_{off}$

$V_{L\,on} = V_{in} - V_o$

$V_{L\,off} = V_o$ [talking about areas]

$\boxed{{}_{L} = -V_o}$

$\because (V_{in} - V_o) * T_{on} = V_o * T_{off}$

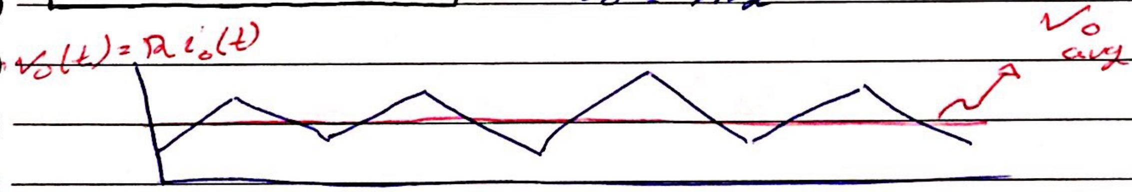
$D = \frac{t_{on}}{T} \Rightarrow t_{on} = DT$

$t_{off} = T - DT = (1-D)T$

$\Rightarrow (V_{in} - V_o) D\cancel{T} = V_o (1-D) \cancel{T}$

$D V_{in} - D\cancel{V_o} = V_o - D \cancel{V_o}$

$\boxed{V_o = D V_{in}}$; $V_{in} = DC$
$V_o = Avg.$

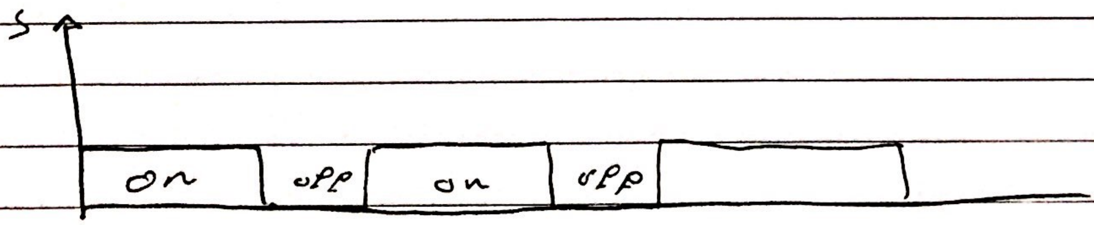


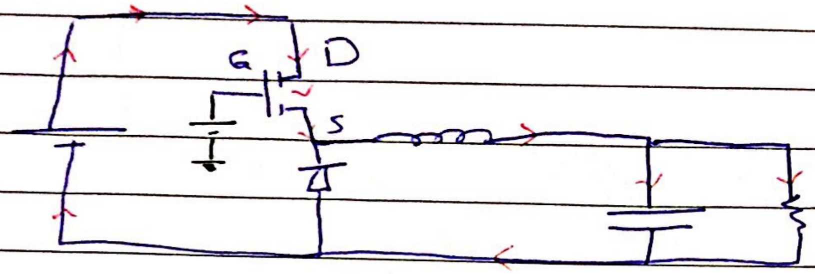
$V_{in} I_{in} = V_o I_o$ [considering lossles converter]

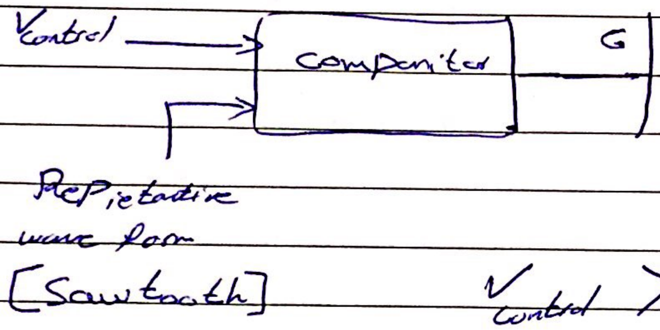
$\cancel{V_{in}} I_{in} = (D \cancel{V_{in}}) I_o$

$\boxed{I_{in} = D I_o} \Rightarrow I_o = \frac{I_{in}}{D}$

* How to control Switch [~~PM~~ [PWM]

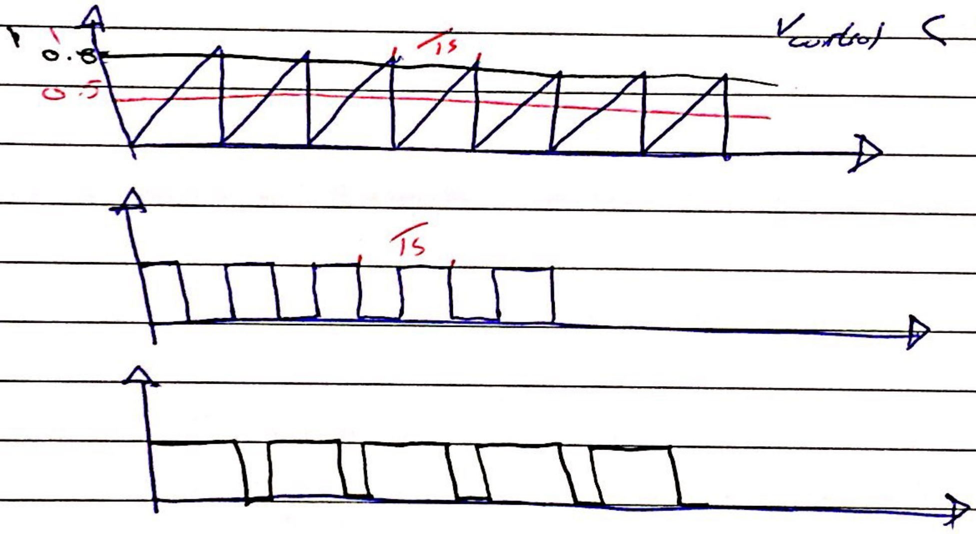






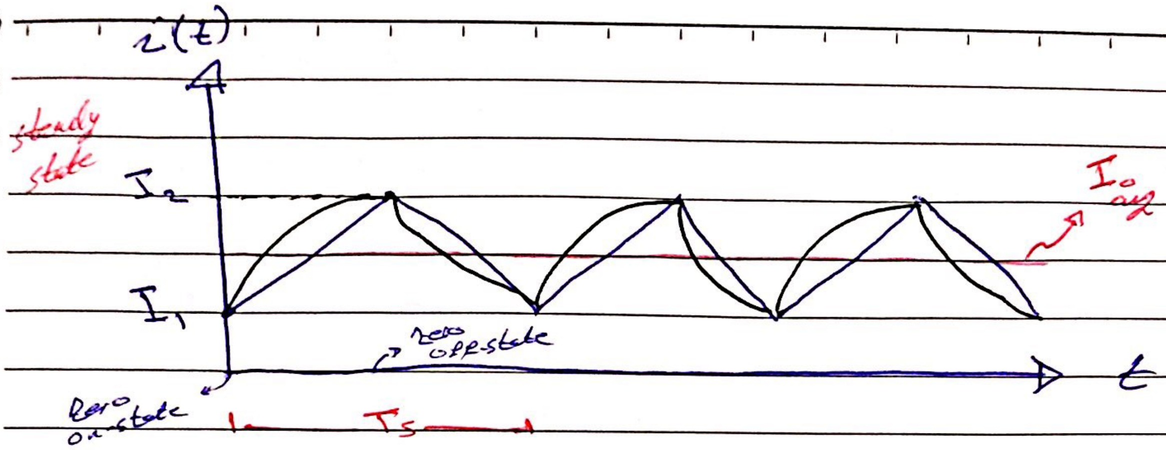
$V_{control} > V_{ST} \Rightarrow 1$

$V_{control} < V_{ST} \Rightarrow 0$

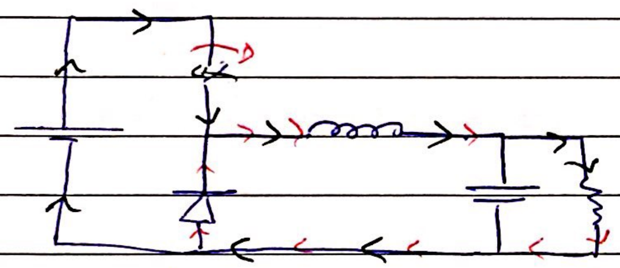


PWM= Pulse width modulation

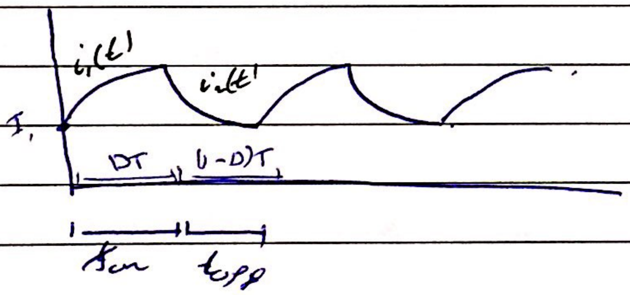
Back to Buck converter



$$I_o = \frac{I_1 + I_2}{2}$$



Considering exact solution



In the on-state

$$-V_s + L\frac{di(t)}{dt} + R\,i(t) = 0 \qquad \left[i_1(0) = I_1 \right]$$

$$\rightarrow V_s = R\, i_1(t) + L\frac{d\, i_1(t)}{dt}$$

$$i_1(t) = \underbrace{I_1 e^{-t\frac{R}{L}}}_{\text{natural}} + \underbrace{\frac{V_s}{R}\left[1 - e^{-t\frac{R}{L}}\right]}_{\text{Forced}}$$

off- State

Apply KVL $\qquad i_2(0) = I_2$

$$R_L i_2(t) + L\frac{di_2(t)}{dt} = 0$$

$$i_2(t) = I_2 e^{-\frac{tR}{L}}$$

$$i_1(t = DT) = I_2 \quad \cdots\cdots (1)$$

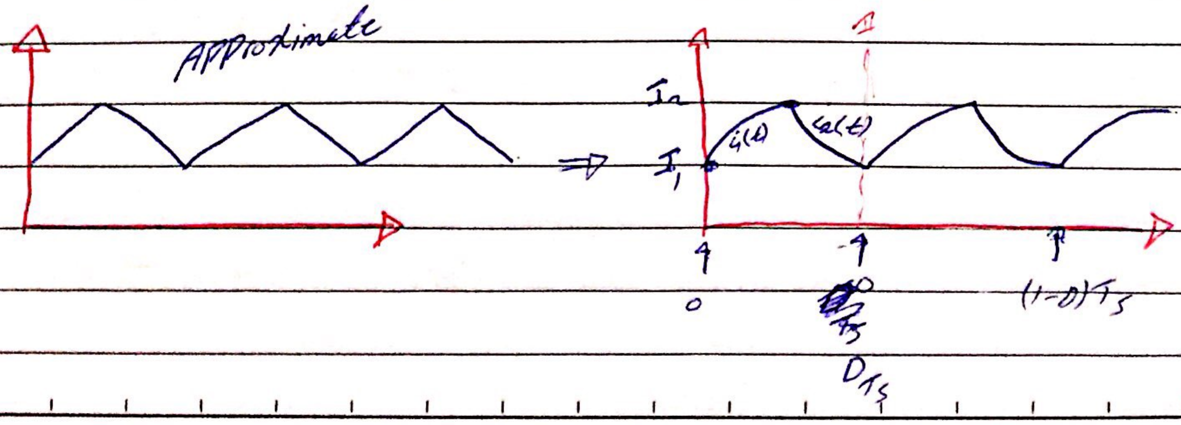
$$i_2(t = (1-D)T) = I_1 \quad \cdots\cdots (2)$$

@ $t = DT$ sub. in (1)

$$I_1 e^{-\frac{DTR}{L}} + \frac{V_s}{R}\left[1 - e^{-\frac{DTR}{L}}\right] = I_2$$

@ $t = (1-D)T$ sub. in (2)

$$I_2 e^{-\frac{(1-D)TR}{L}} = I_1$$

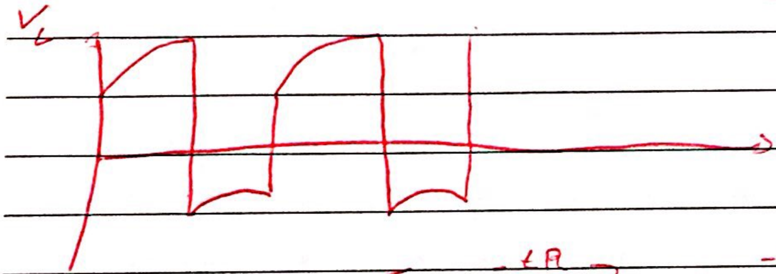


$$i_1(t = DT_s) = I_2$$

$$i_2(t = (1-D)T_s) = I_1$$

$$I_2 = I_1 e^{\frac{-DT_sR}{L}} + V_s/R\left[1 - e^{\frac{-DT_sR}{L}}\right] \quad \dots \text{①}$$

$$\to I_1 = I_2 e^{\frac{-(1-D)T_sR}{L}} \quad \text{②}$$



1 ?

مش B

$$i_L(t) = \frac{v_s}{R}\left[1 - e^{\frac{-tR}{L}}\right] + I_1 e^{\frac{-tR}{L}}$$

sub. ② in ①

$$I_2 = \left[I_2 e^{\frac{-(1-D)T_sR}{L}}\right] e^{\frac{-DT_sR}{L}} + \frac{v_s}{R}\left[1 - e^{\frac{-DT_sR}{L}}\right]$$

$$I_2 = \frac{V_s\left(1 - e^{\frac{-DTR}{L}}\right)}{R\left(1 - e^{\frac{-TR}{L}}\right)}$$

$$I_1 = \frac{V_s\left(e^{\frac{DTR}{L}} - 1\right)}{R\left(e^{\frac{TR}{L}} - 1\right)}$$

⇒ The Peak to Peak ripple

$$\Delta I = I_2 - I_1$$

$$= \frac{V_s}{R}\left[\frac{\left(1-e^{-\frac{DTR}{L}}\right)\left(+e^{+\frac{TR}{L}}\right)}{\left(1-e^{-\frac{TR}{L}}\right)\left(+e^{+\frac{TR}{L}}\right)} - \frac{\left(e^{\frac{DTR}{L}}-1\right)}{\left(e^{\frac{TR}{L}}-1\right)}\right]$$

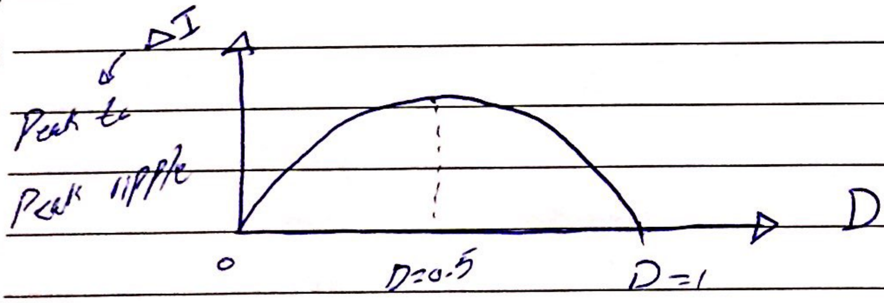
$$= \frac{V_s}{R}\left[\frac{-e^{+(1-D)\frac{TR}{L}} + e^{\frac{TR}{L}} - e^{\frac{DTR}{L}} + 1}{e^{\frac{TR}{L}} - 1}\right]$$

When it is going to be maximum w.r.t D

⇒ Derive ΔI w.r.t. D & = 0

$$\frac{d\Delta I}{dD} = \frac{V_s}{R\left(e^{\frac{TR}{L}}-1\right)}\left[\frac{TR}{L}e^{+(1-D)\frac{TR}{L}} - \frac{TR}{L}e^{\frac{DTR}{L}}\right]$$

$$1-D = D \Rightarrow \boxed{D = \frac{1}{2} = 0.5}$$



ΔI_{max} occurs when $D = 0.5$

$$\Delta I_{max} = \frac{V_s}{R}\left[\frac{-e^{\frac{0.5TR}{L}} + e^{\frac{TR}{L}} - e^{\frac{0.5TR}{L}} + 1}{e^{\frac{TR}{L}} - 1}\right]$$

$$= \frac{V_s}{R}\left[\frac{\left(1-e^{0.5\frac{TR}{L}}\right)^2}{\left(1-e^{0.5\frac{TR}{L}}\right)\left(1+e^{0.5\frac{TR}{L}}\right)}\right]$$

$$= \frac{V_s}{R}\left[\frac{e^{0.5\frac{TR}{L}}-1}{e^{0.5\frac{TR}{L}}+1}\right]$$

$$= \frac{V_s}{R}\tanh\left(\frac{TR}{4L}\right)$$

$\to (x-y)^2 = x^2 - 2xy + y^2$

$\to \tanh(x) = \dfrac{e^{2x}-1}{e^{2x}+1}$, $2x = \dfrac{TR}{2L}$

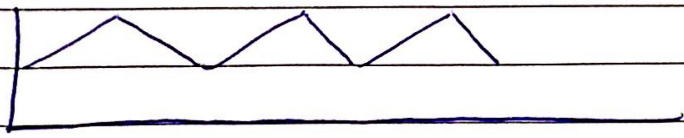
$x = \dfrac{TR}{4L}$

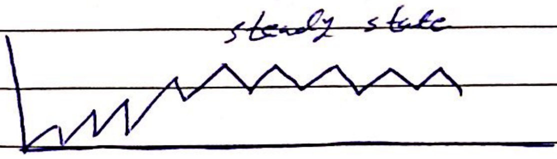
For very small θ

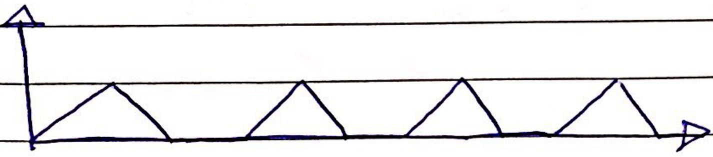
$\tan\theta = \theta$

i.e. $\Delta I_{max} = \dfrac{V_s}{R} * \dfrac{TR}{4L}$

$$\boxed{\Delta I_{max} = \frac{V_s}{4fL}}$$ for a Buck converter



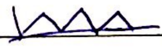




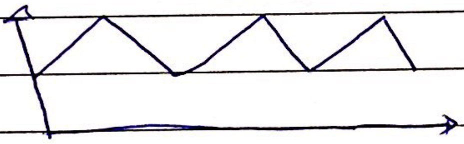
min. ripple
& wanted voltage

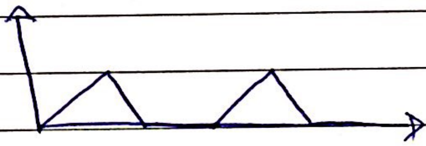
2 Modes of operation

Continous mode



Discont. mode





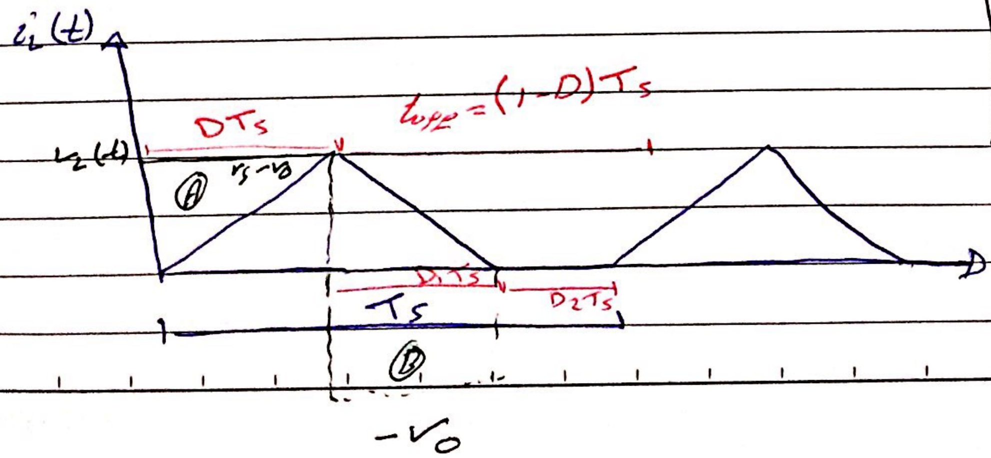
$\frac{L}{R} = \tau \gg T$

$\frac{L}{R} = \tau \sim T$

(Q) Find which mode will be having higher output voltage [with the same duty ratio]

Continous mode $V_o = D V_{in}$

$T_s = DT_s + D_1 T_s + D_2 T_s$



$(V_s - V_o) D T_s = V_o (\Delta_1 T_s)$

$V_s D T_s - V_o D T_s = V_o \Delta_1 T_s$

$V_{out} = V_s \left[\dfrac{D}{D + \Delta_1} \right]$ Discont.

$V_{out} = V_s \left[\dfrac{D}{D + (1-D)} \right]$ Cont.

V_{out} is greater in Discont. mode !!