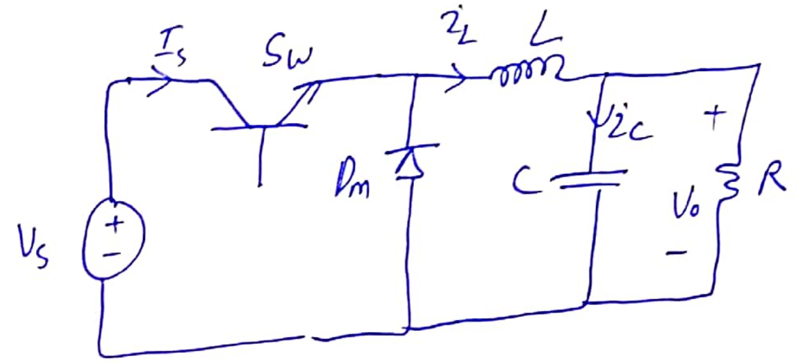
Isolated DC-DC Converters

Why we need isolation?



$V_s = 200V$ Required $V_o = 2V$

$f_s = 200KHz.$

$$D = \frac{V_o}{V_s} = \frac{2}{200} = 0.01$$

$$D = \frac{T_{on}}{T_s} \Rightarrow T_{on} = DT_s$$

$$T_{on} = (0.01)(5\times10^{-6}) = 50ns.$$

→ The ON time of the switch is very small, the switch needs to be closed before its turns-on completely

→ For such high conversition ratio, isolated dc-dc converters are preferred

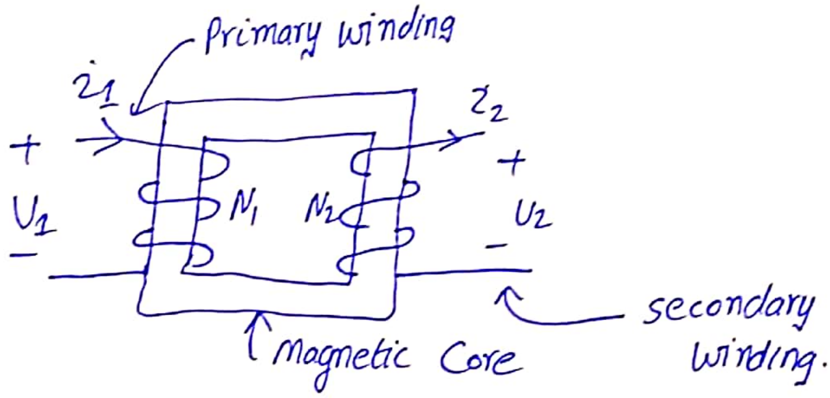
→ Many applications such as medical devices require isolation for saftey reasons.

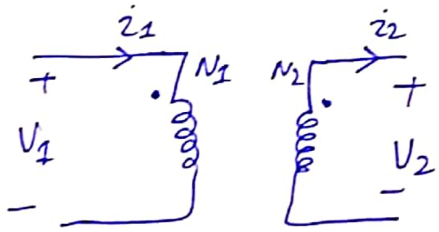
→ Isolation is some required by regulatory agencies.

Transformer Model :-

→ Transformer are used to provide electrical isolation between the input and output.

→ To step-up or stepdown time Variying voltages and Currents.





Dot Convention :-

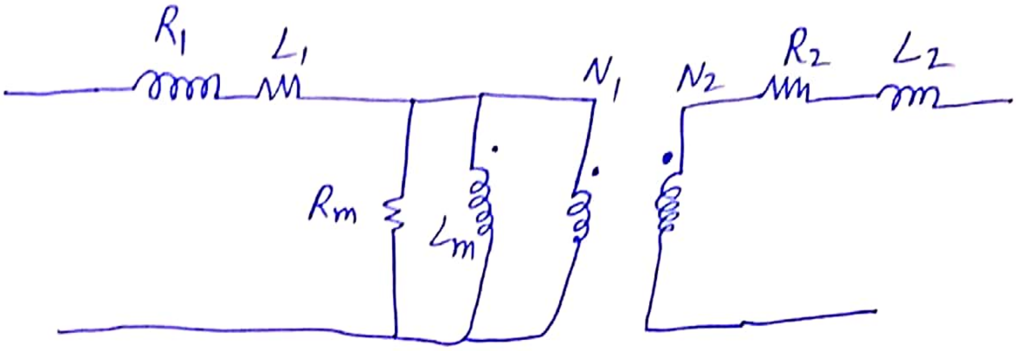
→ Dot convention is used to indicate relative Polority between the two windings.

→ When the Voltage at the dotted terminal of one winding is Positive, then the Voltage at the dotted terminal of the other winding is also positive

→ when current enters the dotted terminals on one winding then current leaves the dotted terminal on the other winding.

For an ideal transformer

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$



Actual transformer model.

$R_1 \Rightarrow$ Primary winding Resistance

$R_2 \Rightarrow$ Secondary winding Resistance

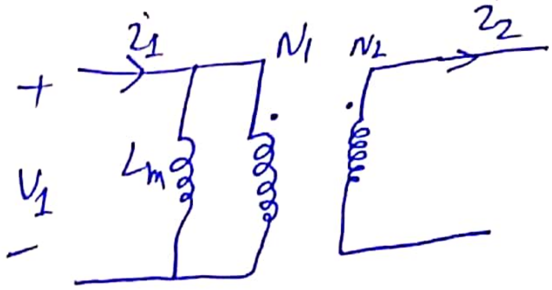
$R_m \Rightarrow$ Core Loss

$L_1 \Rightarrow$ Primary winding Leakage Inductance

$L_g \Rightarrow$ Secondary winding Leakage Inductance

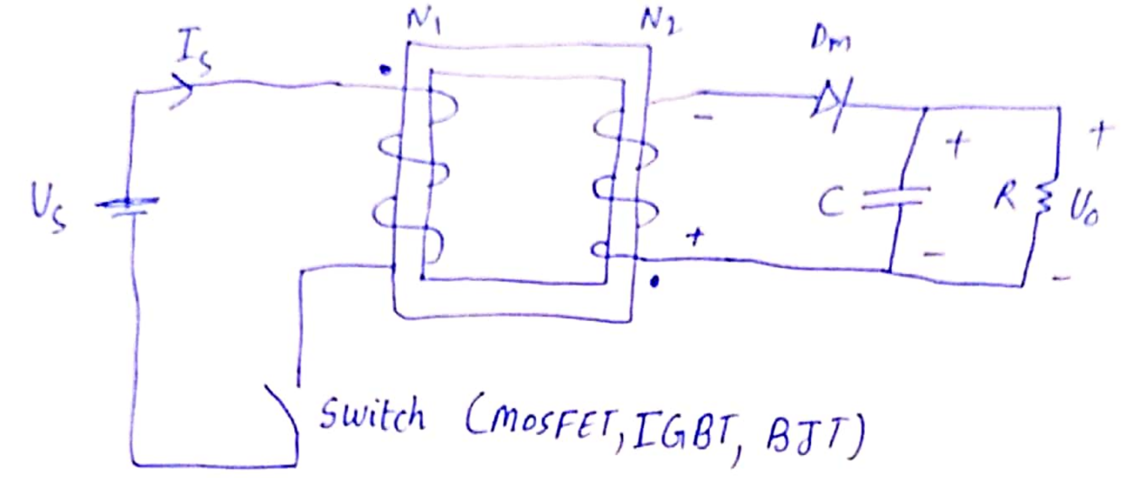
$L_m \Rightarrow$ Magnetizing inductance

→ Generally R_1, R_2, R_m, L_1 and L_g has no effect on the operating principle of the converter.

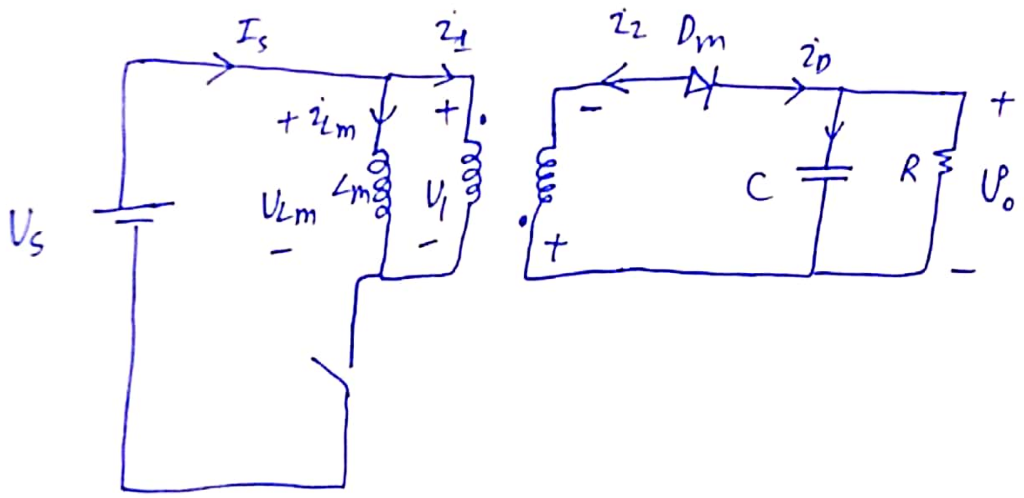


Simplified Model.

Flyback Converter :-



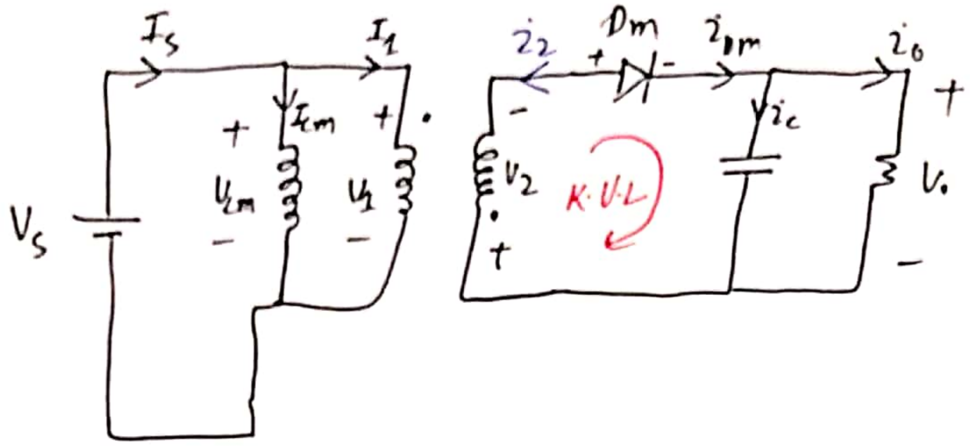
→ Replace the transformer with its simplified equivalent circuit model.



Assumption for analysis

- → The Converter is operating in steady-state.
- → The leakage inductance current is continous.
- → The output voltage ripple is small (small ripple approximation)
- → The switch is closed for some time and open for some time during each switching cycle.

Analysis for switch Closed:-



→ The current I_1 in the primary winding is entering the dotted terminal, therefore the current i_2 should be leaving the dotted terminal. But current can not flow from cathode to anode, therefore diode D_m should be reversed bias.

Alternatively

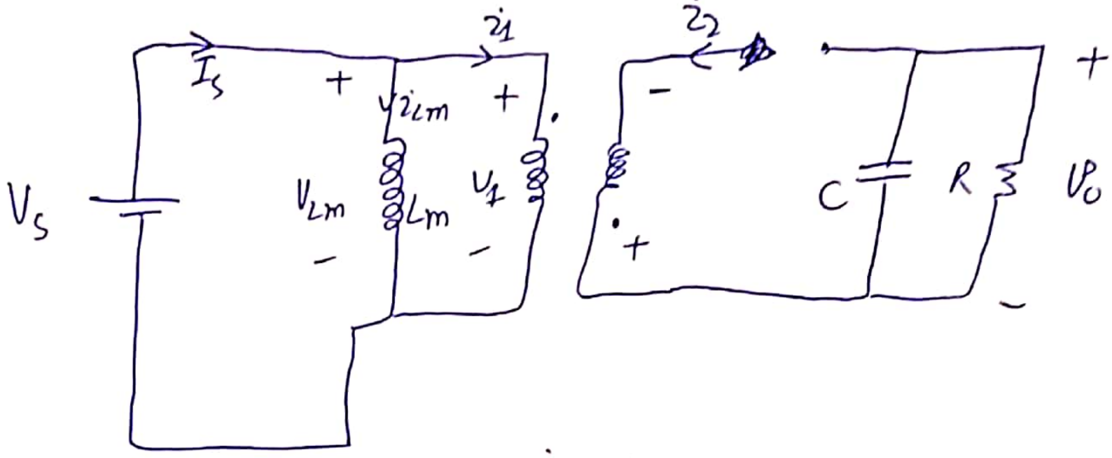
Apply K·V·L

$$V_2 + V_{Dm} + V_0 = 0$$

$$V_{Dm} = \underbrace{-V_2 - V_0}$$

The voltage across the diode is negative therefore diode will be reversed bias.

Thus the equivalent circuit will become:



$$i_2 = 0$$

$$\frac{i_1}{i_2} = \frac{N_2}{N_1}$$

$$i_1 = \frac{N_2}{N_1} i_{o2}$$

$$i_1 = 0$$

$$I_s = i_{Lm}$$

$$V_{Lm} = L_m \frac{di_{Lm}}{dt} = V_s \rightarrow Eq\ (1)$$

$$\int_{i_{Lmin}}^{i_{Lm}(t)} di_{Lm} = \int_0^t \frac{V_s}{L_m} dt$$

$$i_{Lm}(t) - i_{Lmmin} = \frac{V_s}{L_m} t$$

$$i_{Lm}(t) = \frac{V_s}{L_m} t + i_{Lmin} \rightarrow Eq\ (2)$$

$$y = mx + c$$

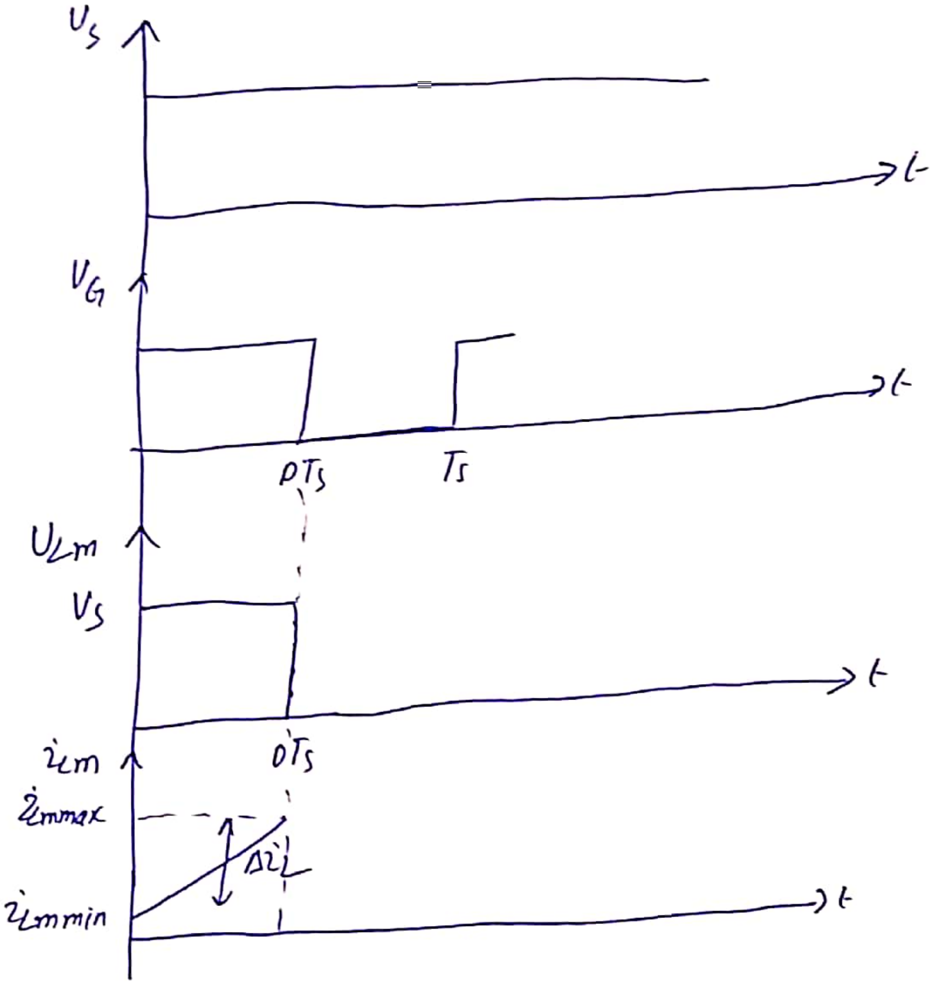
At $t = DT_s$ $\quad i_{Lm}(t) = i_{Lmmax}$

From Eq (2)

$$i_{Lmmax} = \frac{V_s}{L_m} DT_s + i_{Lmmin} \rightarrow (3)$$

$$\Delta i_{Lm} = i_{Lmmax} - i_{Lmmin}$$

$$= \frac{V_s}{L_m} DT_s \rightarrow Eq\ (4)$$



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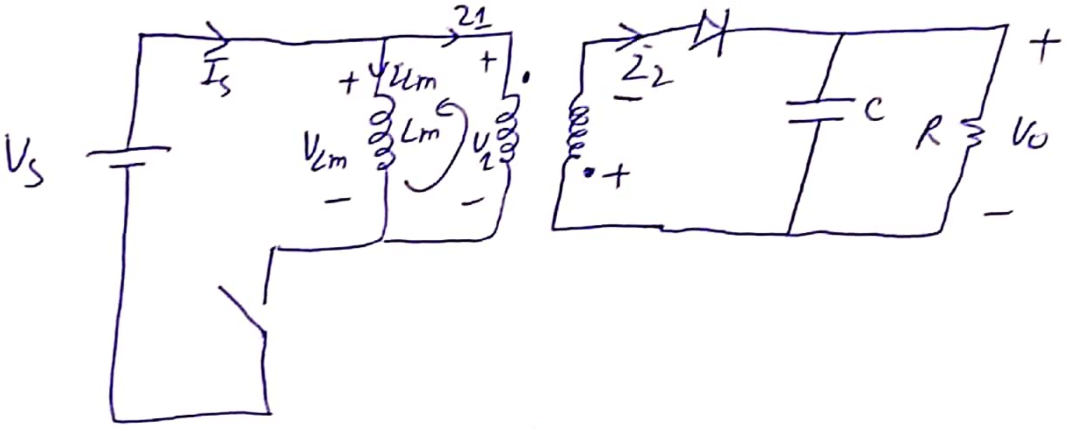
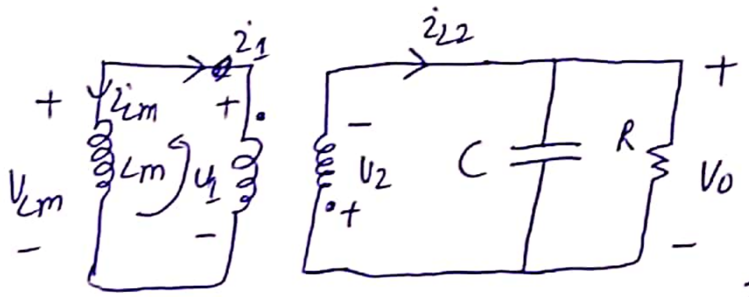
Analysis for Switch open $DT_s < t < T_s$



$$i_{Lm} = i_1$$

→ The current i_1 is leaving the dotted terminal. Therefore according to dot convention the current i_2 should be entering the dotted terminal. Thus the diode will be forward bias. The equivalent circuit will become.



$$i_1 = -i_{Lm}.$$

$$V_2 = -V_o$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$V_1 = \frac{N_1}{N_2} V_2$$

$$V_1 = -\frac{N_1}{N_2} V_2$$

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$$V_{Lm} = V_1 = L_m \frac{di_{Lm}}{dt} = -\frac{N_1}{N_2} V_o \rightarrow Eq\ (5)$$

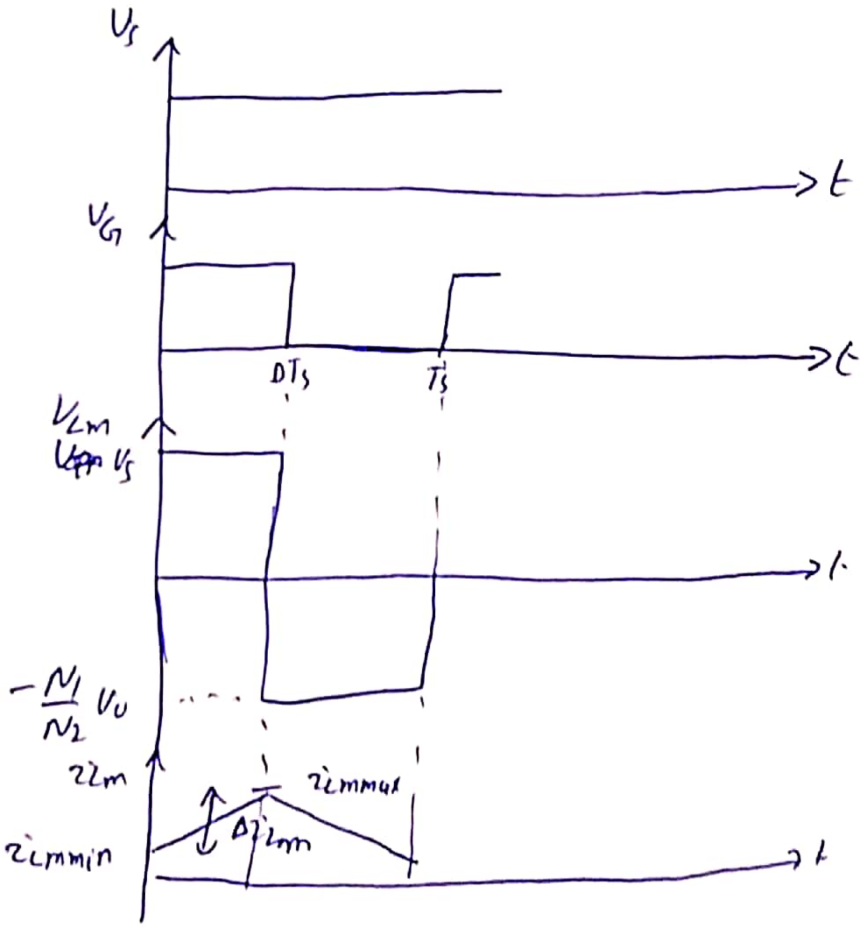
$$\int_{i_{Lmax}}^{i_{Lm}(t)} di_{Lm} = \int_{DT_s}^{t} -\frac{N_1}{N_2}\frac{V_o}{L_m}\, dt$$

$$i_{Lm}(t) - i_{Lmmax} = -\frac{N_1}{N_2}\frac{V_o}{L_m}(t - DT_s)$$

$$i_{Lm}(t) = -\frac{N_1}{N_2}\frac{V_o}{L_m}(t - DT_s) + i_{Lmmax} \rightarrow Eq\ (6)$$

at $t = T_s$ $\quad i_{Lm}(t) = i_{Lmin}$.

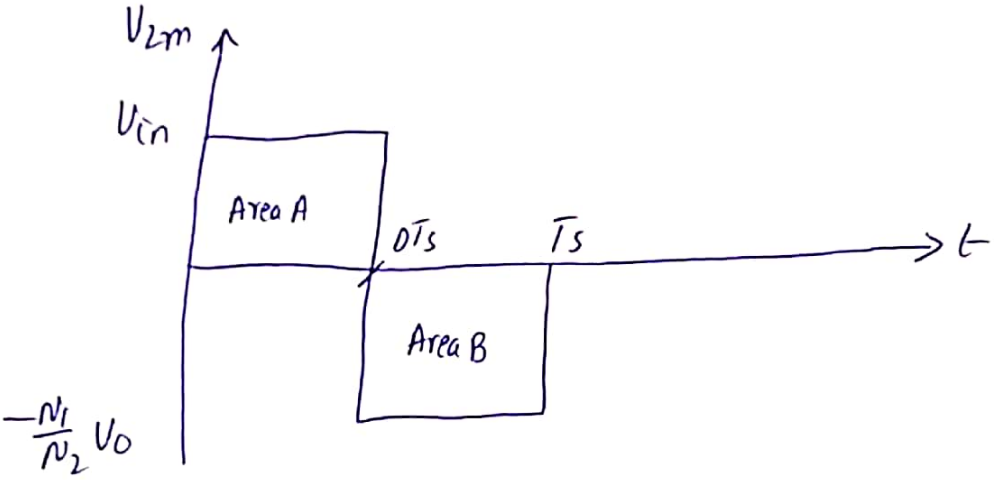
$$i_{Lmmin} = -\frac{N_1}{N_2}\frac{V_o}{L_m}(1-D)T_s + i_{Lmmax} \rightarrow Eq\ \cancel{(8)}\ 7$$



$$\Delta i_{Lm} = i_{Lm\,max} - i_{Lm\,min}$$

$$= \frac{N_1 V_0}{N_2 L_m}(1-D)T_s \longrightarrow Eq\ 8$$

Voltage Conversition Ratio :-



From Volt-Second balance

$$DT_s V_s + \left(-\frac{N_1}{N_2} V_0\right)(1-D)T_s = 0$$

solving for V_0

$$V_0 = \left(\frac{D}{1-D}\right)\left(\frac{N_2}{N_1}\right)V_s$$

Alternatively

$$(\Delta i_{m})_{open} = (\Delta i_{m})_{closed}.$$

$$V_0 = \underbrace{\left(\frac{D}{1-D}\right)}\left(\frac{N_2}{N_1}\right)V_s$$

similar to buck-boost Converter but with additional term the turns ratio of the transformer $\left(\frac{N_2}{N_1}\right)$

→ Flyback Converter is actually the isolated version of the buck-boost converter.

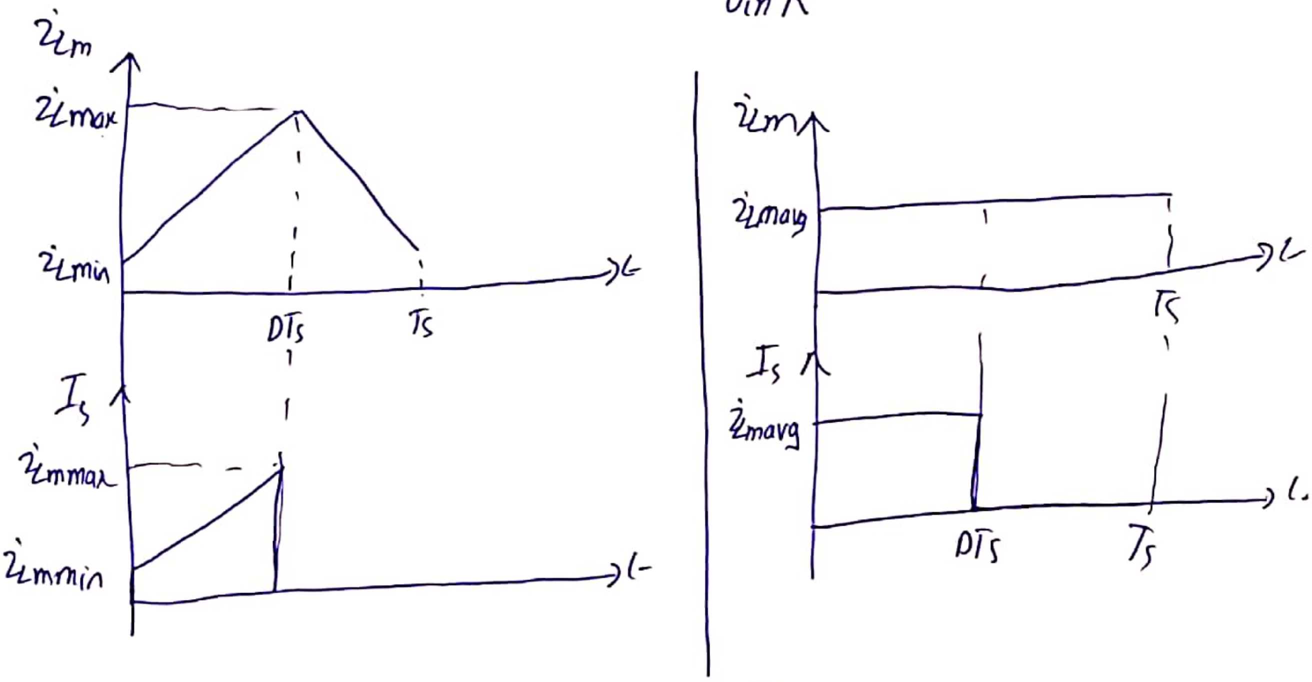
Average, Minimum and Maximum Value of the Magnitizing Inductance Current:-

$$P_o = V_o I_o = \frac{V_o^2}{R}$$

$$P_{in} = V_s \langle I_s \rangle$$

$$V_s \langle I_s \rangle = \frac{V_o^2}{R}$$

$$\langle I_s \rangle = \frac{V_o^2}{V_{in} R}$$



$$\langle i_s \rangle = \frac{1}{T_s}\int_0^{DT_s} i_{Lmavg} = D\, i_{Lmavg}$$

$$D\, i_{Lmavg} = \frac{V_o^2}{V_s R}$$

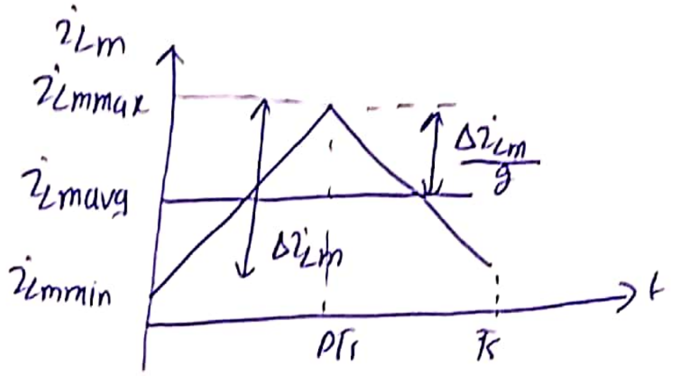
$$i_{Lmavg} = \frac{V_o^2}{D V_s R}$$

$$i_{Lmavg} = \frac{V_o^2}{D V_s R}$$

$$V_o = \frac{D}{(1-D)}\left(\frac{N_2}{N_1}\right) V_s$$

$$i_{Lmavg} = \frac{\frac{D^{\cancel{2}}}{(1-D)^2}\left(\frac{N_2}{N_1}\right)^2 V_s^{\cancel{2}}}{\cancel{D}\,\cancel{V_s} R}$$

$$= \frac{D V_s}{(1-D)^2 R}\left(\frac{N_2}{N_1}\right)^2$$



$$i_{Lmmax} = i_{Lmavg} + \frac{\Delta i_{Lm}}{2}$$

$$= \frac{D V_s}{(1-D)^2 R}\left(\frac{N_2}{N_1}\right)^2 + \frac{D V_s T_s}{2 L_m}$$

$$i_{Lmin} = i_{Lmavg} - \frac{\Delta i_{Lm}}{2}$$

$$= \frac{D V_s}{(1-D)^2 R}\left(\frac{N_2}{N_1}\right)^2 - \frac{D V_s T_s}{2 L_m}$$

Boundary Condition for Continous Conduction Mode :-

$$i_{Lm\,min} = \frac{DV_s}{(1-D)^2R}\left(\frac{N_2}{N_1}\right)^2 - \frac{DV_sT_s}{2L_m}$$

At boundary condition $i_{Lm\,min} = 0$

$$0 = \frac{DV_s}{(1-D)^2R}\left(\frac{N_2}{N_1}\right)^2 - \frac{DV_sT_s}{2L_m}$$

Solving for L_m

$$L_{min} = \frac{(1-D)^2R}{2f_s}\left(\frac{N_1}{N_2}\right)^2$$

$$L > L_{min}$$

Output Voltage Ripple :-

Similar to Buck-Boost Converter output voltage ripple can be derived in the same way as derived for the buck-boost converter

$$C = \frac{DV_o}{\Delta V_o R f_s}$$