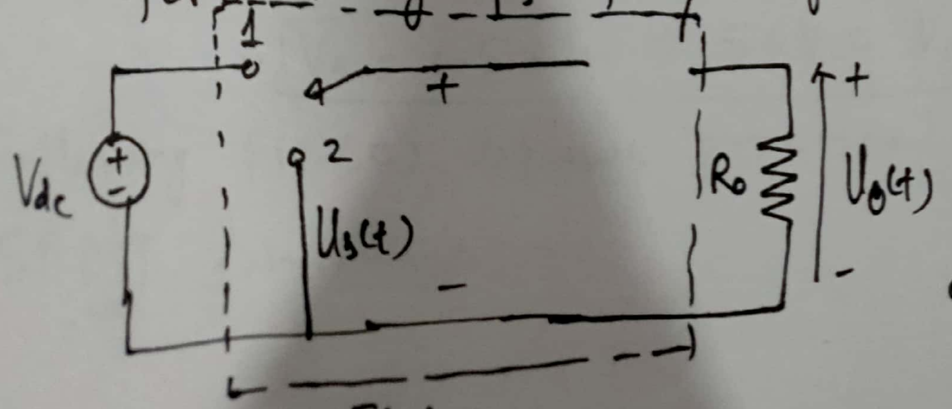
Unit-3

DC-DC converters or choppers:

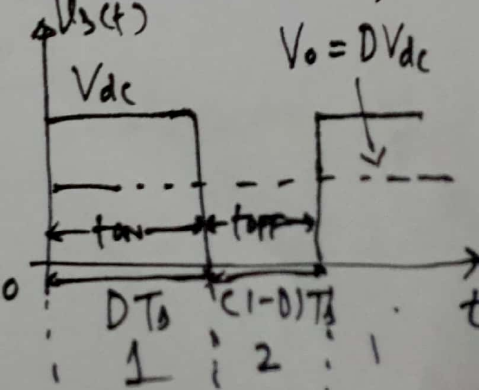
DC-DC converters are used in SMPS and in DC motor drives where they are known as choppers, thus, giving chopper-fed DC Motor drives.

In all electronic equipment components like transistors and ICs, regulated and reduced-rippled DC biasing voltage is required which is supplied by SMPS. DC-DC converters in SMPS cause regulated and reduced-rippled DC voltage.

Fig(a). Shows the basic working of a DC-DC converter where a Single-Pole-Double-Throw (SPDT) switch is used. The switch o/p voltage is equal to converter i/p voltage when switch is in position, 1 and zero when in position, 2. The switch position is varied periodically as shown in Fig (b) such that $v_s(t)$ is a rectangular waveform having 'f_s' frequency and period, $T_s = \frac{1}{f_s}$.



Fig(a).



Fig(b).

The duty ratio, D is defined as the fraction of time in which the switch occupies position 1.
Hence $0 \le D \le 1$.

Now, By Fourier series, the DC component of a periodic waveform is it's average value.

$\therefore$ Average switch o/p voltage,

$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt$$

or, $$V_s = \frac{1}{T_s}\left\{\int_0^{t_{ON}} v_s(t)\,dt + \int_{t_{ON}}^{T_s} v_s(t)\,dt\right\}$$

$$V_s = \frac{1}{T_s}\left\{\int_0^{t_{ON}} V_{dc} + 0\right\} = \frac{V_{dc}}{T_s}\int_0^{t_{ON}} dt$$

$$V_s = V_{dc}\cdot\frac{t_{ON}}{T_s} = \frac{t_{ON}}{t_{ON}+t_{OFF}}\cdot V_{dc}$$

$$\Rightarrow \boxed{V_s = D\,V_{dc}}$$

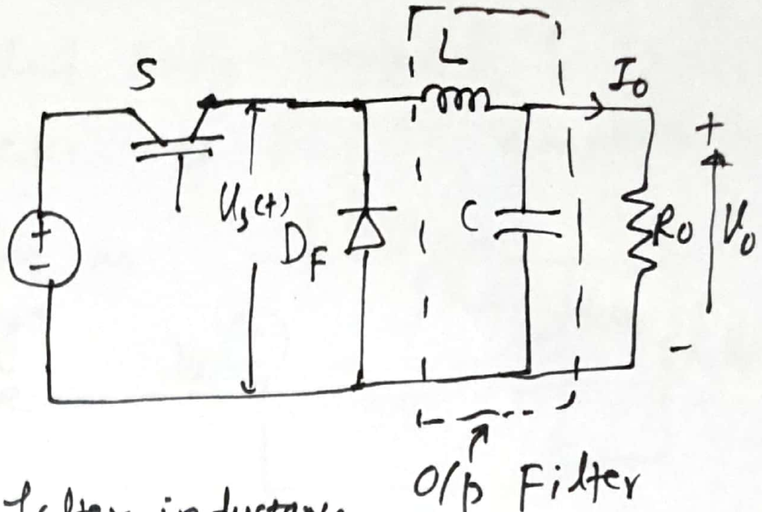
$$\therefore\ 0 \le D \le 1 \Rightarrow 0 \le V_s \le V_{dc}$$

Let $V_{dc} = 100V$ & $D = 0.5$

$$\therefore \boxed{V_s = 0.5 \times 100 = 50V = V_o}$$

Following Fig.(c) shows practical realization of SPDT switch.

DC-DC Buck Converter or Step-down chopper:



During t_{ON}, switch, S is closed and $v_s(t) = V_{dc}$

During t_{OFF}, S is opened (OFF), the energy released by filter inductance freewheels through free-wheeling diode, D_F and load gets shorted through D_F, making load voltage, V_o zero.

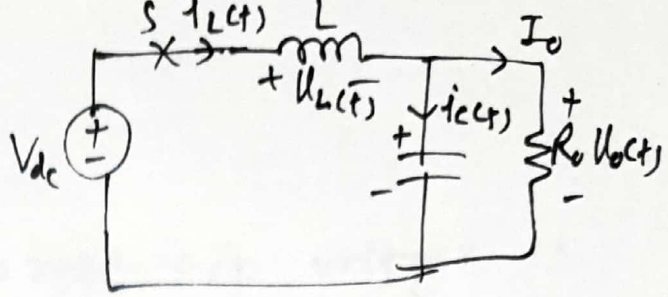
$\therefore$ During t_{ON} (0 to DT_s period), S is ON & $v_{s(t)} = V_{dc}$

During t_{OFF} (DT_s to T_s period), S is OFF & $v_s(t) = 0$.

Now, in addition to desired DC component V_s, the switch o/p voltage, $v_s(t)$ contains undesirable harmonics of switching frequency (due to rectangular nature of $v_s(t)$). To remove the harmonics and make load voltage, $v_o(t)$ essentially equal to DC component, V_s (i.e., $V_o = V_s$), a low-pass L-C filter is connected across load which makes load voltage equal to DC component of switch voltage,

i.e., $\boxed{V_o = V_s = DV_{dc}}$

Now, During first Sub-interval (0 to DT_s), Which is also called Duty interval, S is Closed and equiv. ckt. of DC-DC converter is,



Inductor current rises as inductor stores energy and inductor voltage is,

~~During~~

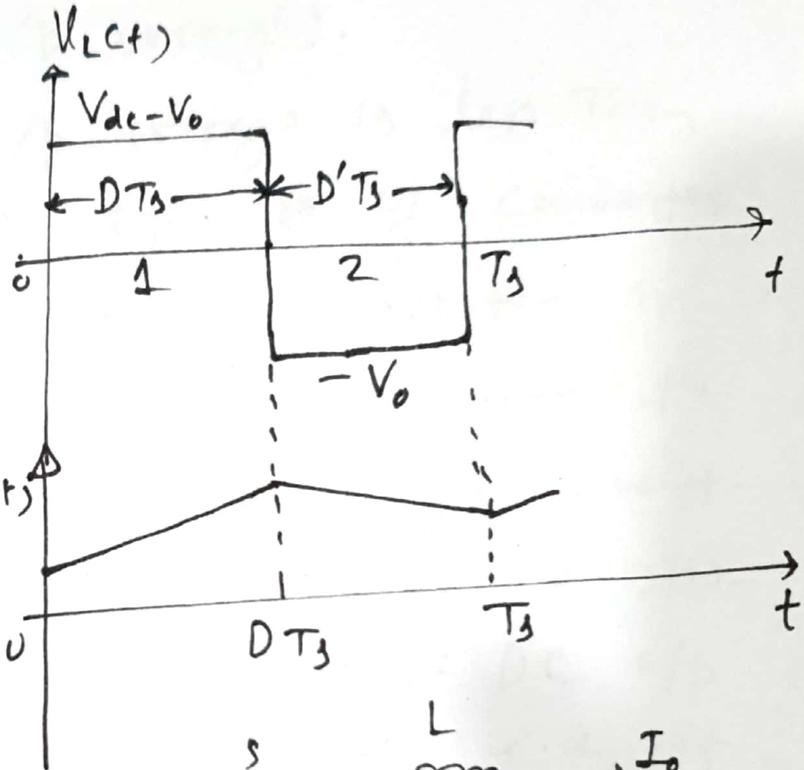
$$V_L = V_{dc} - V_o(t)$$

$$\Rightarrow V_L = V_{dc} - V_o$$

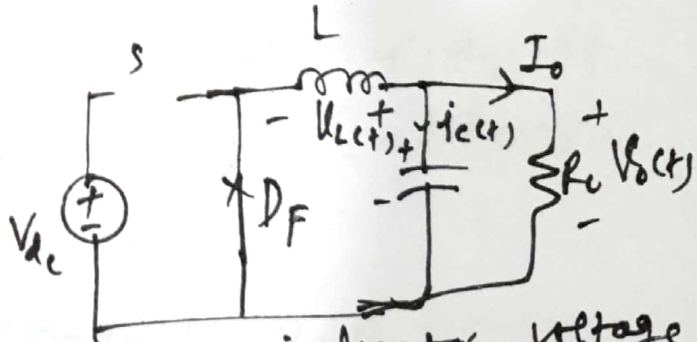
$$V_L = L\frac{di_L(t)}{dt}$$

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

$$\frac{di_L}{dt} = \frac{V_{dc}-V_o}{L} \text{ (+ive slope)}$$



During Sub-interval, 2 (FreeWheeling interval), equiv. ckt. is as shown.



Now, S is OFF & L releases energy and as per volt-sec. balance, The inductor voltage now becomes negative and $i_L(t)$ falls.

$$\therefore V_L(t) = -V_o(t) = -V_o$$

$$\text{As } \frac{di_L(t)}{dt} = \frac{V_L(t)}{L} = -\frac{V_o}{L} \text{ (-ive slope)}$$

Again, DC-DC converter average o/p voltage is,

$$V_o = D V_{dc}$$

As $D < 1$

$V_o < V_{dc}$ (i.e., Average o/p voltage is always less than i/p voltage).

Since average DC o/p voltage is less than
DC i/p voltage, this type of converter
is called DC-DC Buck converter or
Step-down chopper. It is also equiv. to
a step-down transformer of DC circuit.
Just like a step-down transformer, a step-down chopper produces an average DC o/p voltage less than DC i/p voltage, i.e., it steps down the DC i/p voltage (although it is not a transformer).

Also, $P_{dc} = P_o$ (i/p power = o/p power for a lossless converter).

$$\Rightarrow V_{dc} \cdot I_{dc} = V_o \cdot I_o$$

$$\Rightarrow \boxed{\frac{I_o}{I_{dc}} = \frac{V_{dc}}{V_o} = \frac{1}{D}}$$

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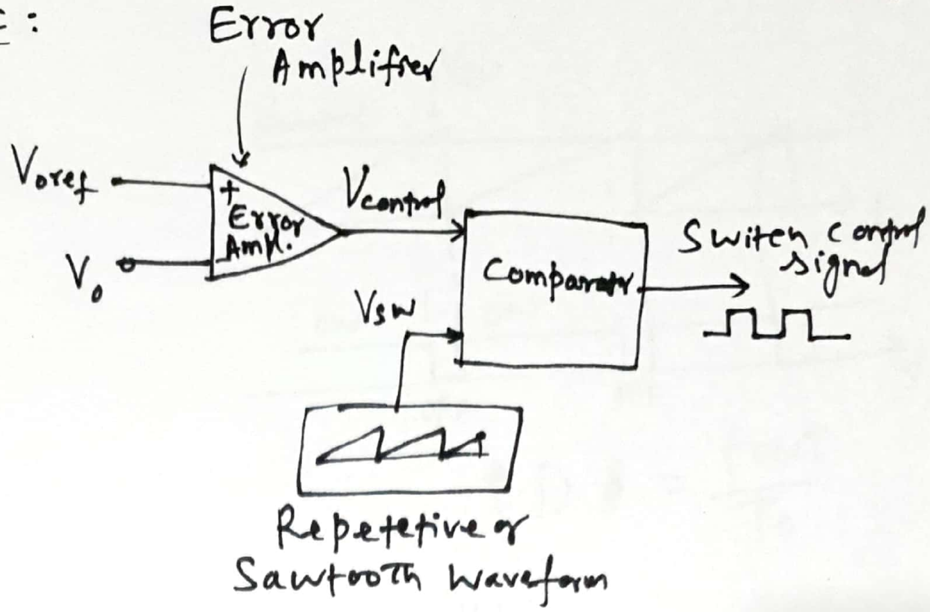
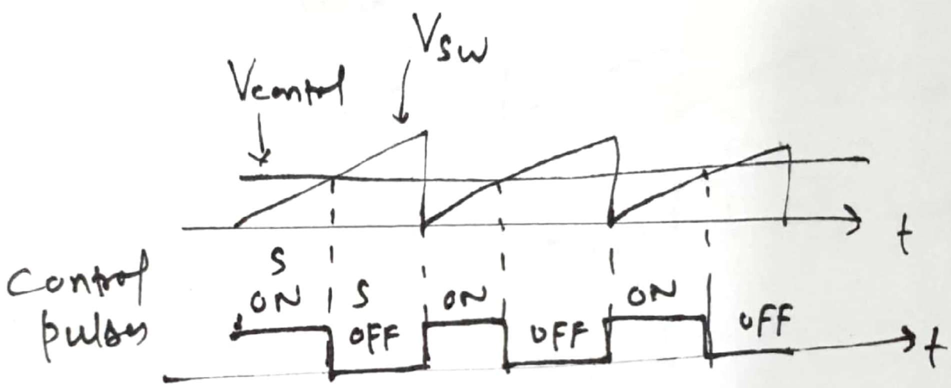
Control Logic:





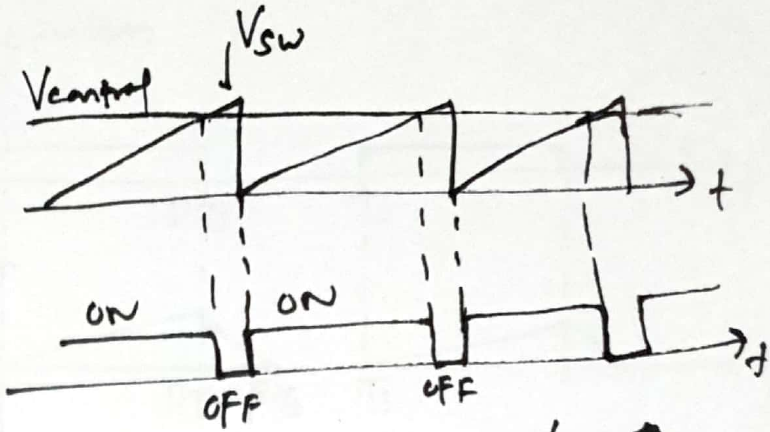
In terms of control signal,

$$\boxed{D = \frac{t_{ON}}{T_s} = \frac{V_{control}}{V_{sw}}}$$

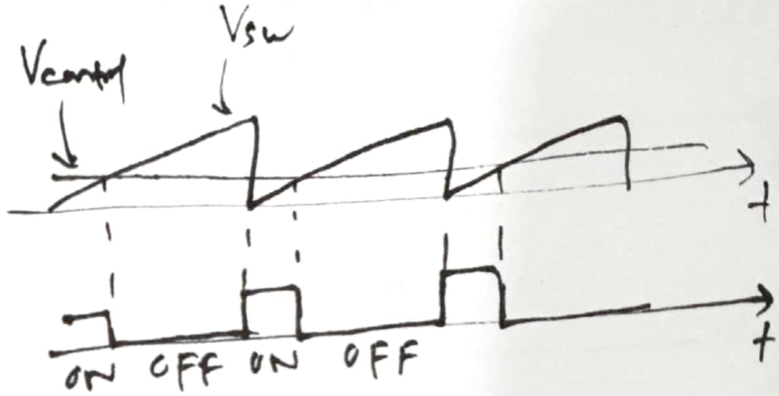
$V_{control}$ is a variable control voltage.

As $V_{control}$ increases, ON time of pulse increases & OFF time decreases $\Rightarrow$ D increases and $V_o = DV_{dc}$ also increases.

As $V_{control}$ decreases, ON time decreases and OFF time increases and D decreases and hence $V_o = DV_{dc}$ decreases.



$$\uparrow D = \frac{t_{on}\uparrow}{T_s}$$



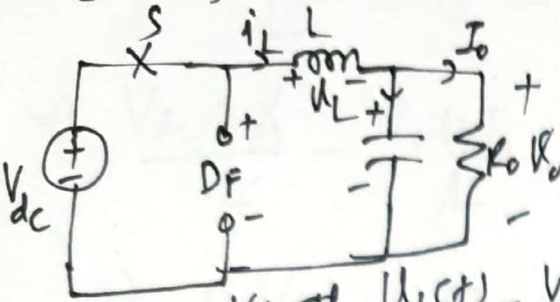
$$\downarrow D = \frac{t_{on}\downarrow}{T_s}$$

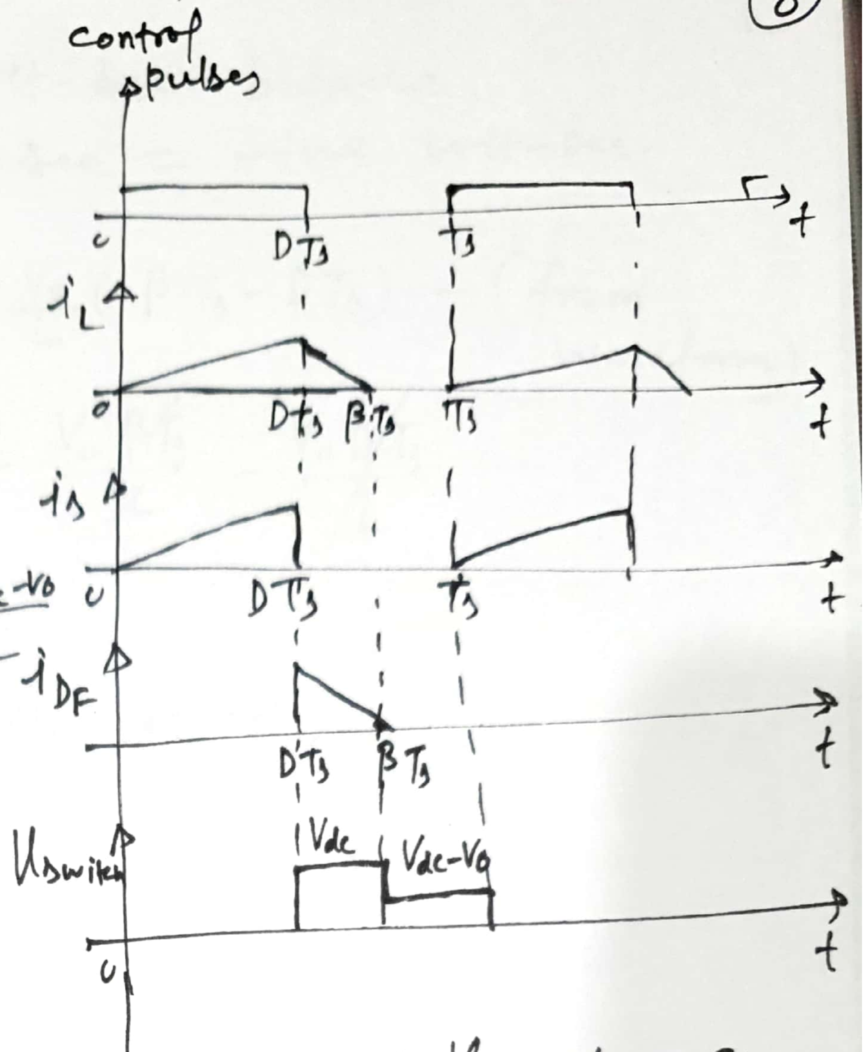
$V_o = D V_{dc}$ is valid for continuous Conduction Mode (CCM), i.e., inductor current, I_L is continuous.

Now, let us consider operation of Buck converter for Discontinuous Conductor Mode (DCM) i.e., when I_L is discontinuous.

Waveforms for DCM are as following:

Equiv. ckt. for $0 \le t \le DT_s$ (0 to DT_s) when S is ON:





$$\frac{di_L}{dt} = \frac{v_L(t)}{L} = \frac{V_{dc}-V_o}{L}$$

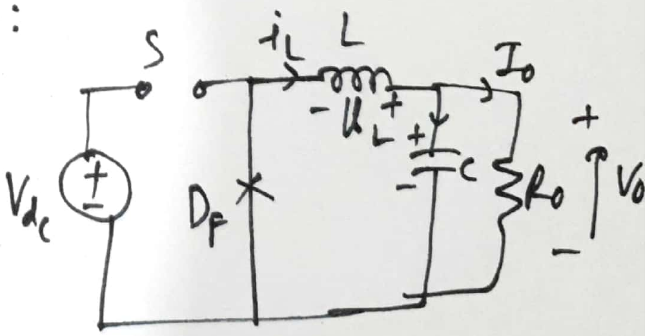
(+ive)

$\Rightarrow$ i_L rises as shown in waveforms.

Since 'S' conducts during this period, switch voltage, $v_{switch} = 0$.

Equiv. ckt. during freewheeling interval ($DT_s \le t \le \beta T_s$) i.e., DT_s to βT_s is as:

$$\frac{di_L}{dt} = \frac{v_L(t)}{L} = \frac{-V_o}{L} \quad (\text{-ive})$$



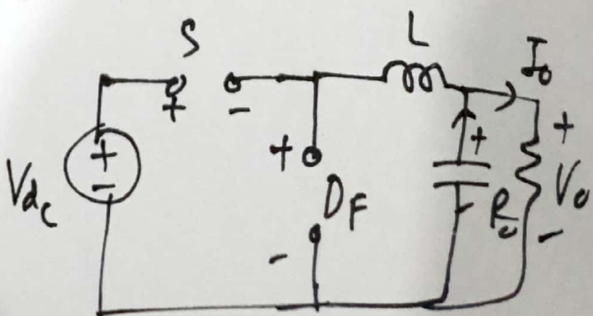
$\Rightarrow$ i_L falls.

Switch voltage, $v_{switch} = V_{dc}$.

Equiv. ckt. during coasting period ($\beta T_s \le t \le T_s$) i.e., βT_s to T_s is as:

Switch voltage,

$$v_{switch} = V_{dc} - V_o$$



Now, as per volt-sec. balance,
+ive volt-sec = -ive volt-sec.

$$\Rightarrow \frac{V_{dc}-V_o}{L} \cdot DT_s = \frac{V_o}{L}(\beta T_s - DT_s) \quad - \text{(from waveform)}$$

$$\Rightarrow \frac{V_{dc} D \cancel{T_s}}{\cancel{L}} - \cancel{\frac{V_o D T_s}{L}} = \frac{V_o \beta \cancel{T_s}}{\cancel{L}} - \cancel{\frac{V_o D T_s}{L}}$$

$$\Rightarrow D V_{dc} = \beta V_o$$

$\Rightarrow$ Average o/p voltage,

$$\boxed{V_o = \frac{D V_{dc}}{\beta}} \quad (\beta < 1)$$

$\Rightarrow$ For CCM, $\boxed{V_o = D V_{dc}}$

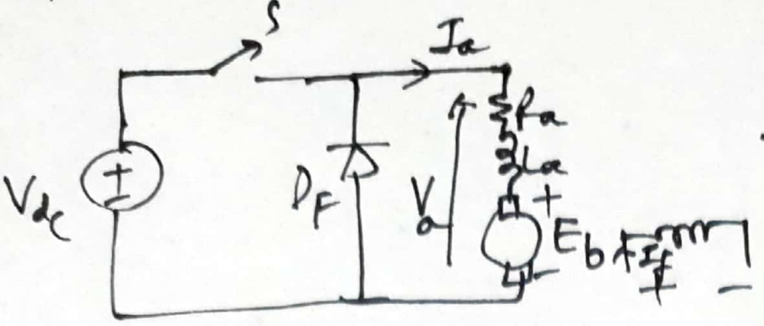
For DCM, $\boxed{V_o = \frac{D V_{dc}}{\beta}}$

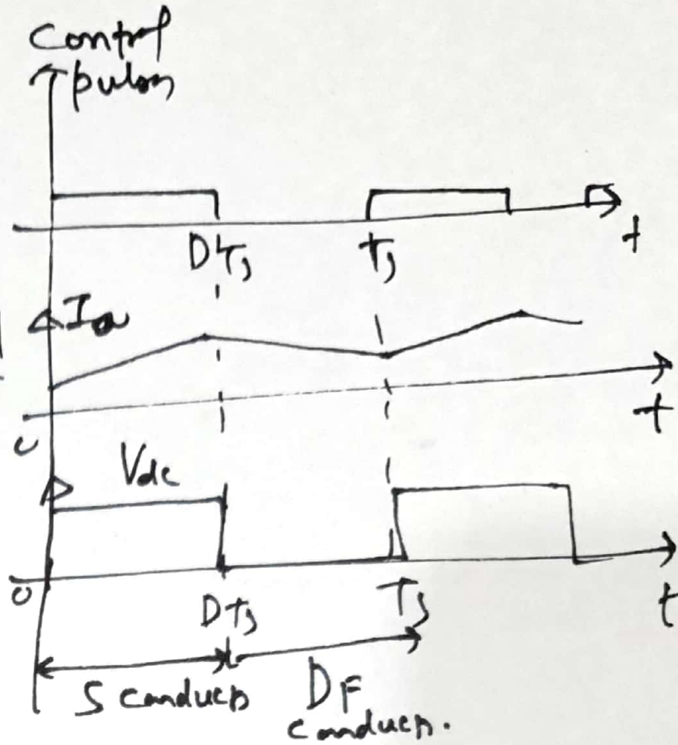
As $\beta < 1$,

$$V_{o\,DCM} > V_{o\,CCM}$$

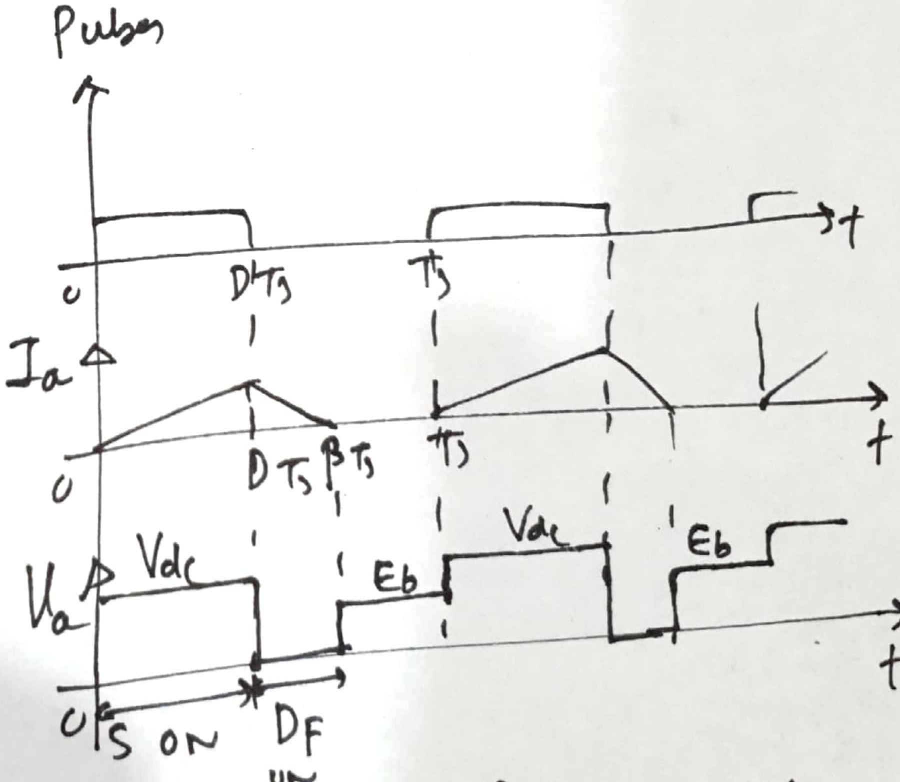
If load is a DC Motor,

for CCM:





For DCM:



Back Emf, E_b of motor shows it's presence in DCM as shown above.