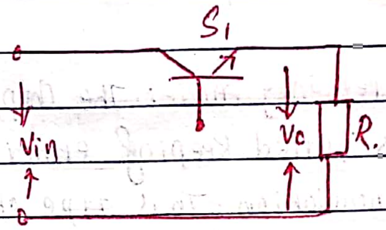
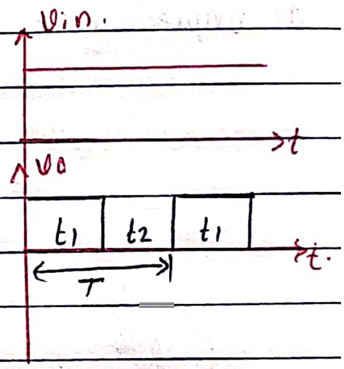
Chopper:

A dc chopper converts dc to dc by changing the effective value. It can be step-up or step-down dc voltage. The main principle is to chop a constant dc voltage (input) for a particular time interval and by changing the chopping time, output dc voltage can be controlled. Generally power transistors are used as switch for these purpose.

Step down chopper:



When transistor switch S_1 is closed for a time t_1, the input voltage V_i appears across the load R.



If the transistor switch S_1 is kept open for a time t_2 the voltage across the load is zero. The average value of V_0 over a time period of T will be definitely less than Vin.

The average O/P voltage is given by

$$V_0 = \frac{1}{T}\int_0^{t_1} V_{in} \cdot dt.$$

$$V_0 = \frac{V_{in}}{T} \times t_1$$

$$V_0 = \frac{t_1}{t_1+t_2} \times V_{in}.$$

$$\therefore V_0 = K * V_{in}$$

Where, t_1 = transistor on time.
t_2 = transistor off-time
T = time period (t_1+t_2)
$K = \frac{t_1}{t_1+t_2}$ = duty cycle.

Assuming loss less transistor switch then,

Input power = Output power

$$P_0 = \frac{1}{T}\int_0^{t_1} V_0 \, i_0 \cdot dt.$$

$$= \frac{1}{T}\int_0^{t_1} \frac{V_0^2}{R} dt. = \frac{1}{T}\int_0^{t_1} \frac{V_{in}^2}{R} \cdot dt = \frac{t_1}{T}\frac{V_{in}^2}{R}$$

$$= K \frac{V_{in}^2}{R}$$

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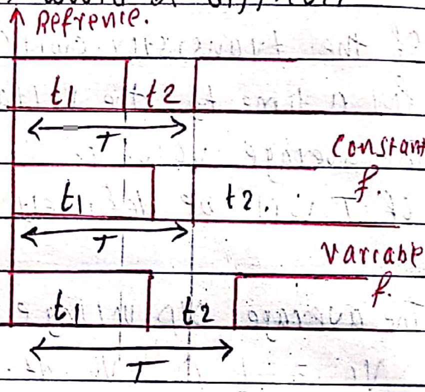
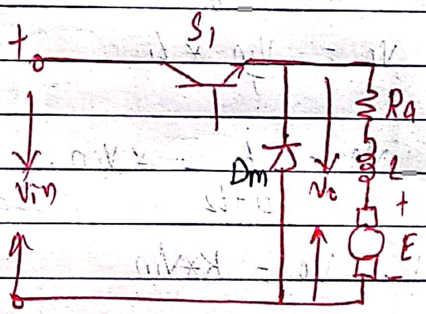
The duty cycle can be varied from 0 to 1 by varying t_1 with constant T or by varying T with constant t_1 or t_2.

Constant frequency mode:- The chopper period T (or chopping frequency $f = 1/T$) is kept constant and on time t_1 is varied. The width of the pulse is varied and this type of control is known as pulse width modulation (PWM) control.

Variable frequency mode:- The chopping period T (or chopping frequency $f = 1/T$) is varied keeping either t_1 or t_2 constant. This is called frequency modulation. This is type of control would generate harmonics at unpredictible frequencies and filter design would be difficult.



Chopper with dc motor as load: (RLE load)



Let, $V_{in} = V_m$ = dc input voltage.

V_o = dc output voltage (which is applied across the armature of dc motor)

R_a = armature resistance.

L = Inductance of armature winding.

E = Back emf generated by the motor.

Mode-I:- Switching on, current flows through the load.

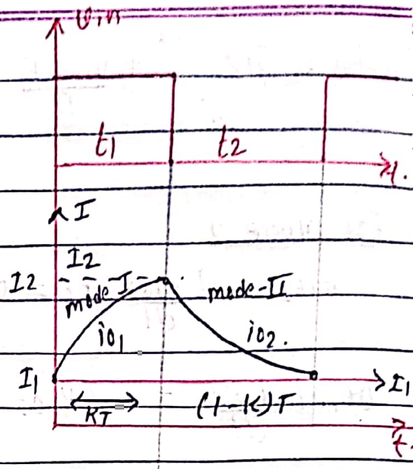
Mode-II:- Switch off, the load current continues to flow through free wheeling diode Dm due to energy stored in the inductor L.

For mode I :-

$$V_{in} - Ri_{01} - L\frac{di_{01}}{dt} - E = 0$$

or, $V_{in} - E - Ri_{01} = L\frac{di_{01}}{dt}$

or, $\frac{V_{in}-E}{R} - i_{01} = \frac{L}{R}\frac{di_{01}}{dt}$



Let, $y = \frac{V_{in}-E}{R}$

or, $y - i_{01} = \frac{L}{R}\frac{di_{01}}{dt}$

or, $\frac{R}{L}dt = \frac{di_{01}}{(y-i_{01})}$

Integrating both sides,

$$\int \frac{R}{L}dt = \int \frac{di_{01}}{(y-i_{01})}$$

or, $\frac{Rt}{L} + K_1 = -\ln(y-i_{01}) + K_2$

or, $\frac{R}{L}t = -\ln(y-i_{01}) + K$ ---- ①

At, $t=0$, $i_{01} = I_1$

Then, $K = \cancel{\ln(I_1)}\ \ln(y-I_1)$

Now, equation ① becomes.

$$\frac{R}{L}t = -\ln(y-i_{01}) + \ln(y-I_1)$$

or, $\frac{R}{L}t = \ln\left(\frac{y-I_1}{y-i_{01}}\right)$

$\therefore \frac{y-I_1}{y-i_{01}} = e^{\frac{R}{L}t}$

or, $y - i_{01} = (y-I_1)\cdot e^{-\frac{R}{L}t}$

or, $i_{01} = y - (y-I_1)e^{-R/L\,t} = \frac{V_{in}-E}{R} - \left(\frac{V_{in}-E}{R_1} - I_1\right)e^{-\frac{R}{L}t}$

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$$i_{01} = I_1 e^{-R/L\, t} + \frac{V_{in} - E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \quad \text{— (a)}$$

For mode 2.

$$R i_{02} + L\frac{di_{02}}{dt} + E = 0$$

or, $L\frac{di_{02}}{dt} = -(R i_{02} + E)$

or, $\frac{L}{R}\frac{di_{02}}{dt} = -\left(i_{02} + \frac{E}{R}\right)$

or, $\frac{di_{02}}{-\left(i_{02} + \frac{E}{R}\right)} = \frac{R}{L}\,dt.$

Integrating both sides, we get.

$$\int \frac{di_{02}}{-(i_{02} + E/R)} = \frac{R}{L}\int dt$$

or, $\ln(i_{02} + E/R) + K_1 = -\frac{R}{L}t + K_2$

or, $-\frac{R}{L}t = \ln\left(i_{02} + \frac{E}{R}\right) + K \quad \text{--- (2)}$

At, $t = 0$, $i_{02} = I_2$.

$\therefore K = -\ln\left(I_2 + \frac{E}{R}\right)$

Then, equation (2) becomes.

$$-\frac{R}{L}t = \ln\left(\frac{i_{02} + E/R}{I_2 + E/R}\right)$$

or, $\frac{i_{02} + E/R}{I_2 + E/R} = e^{-R/L\, t}$

or, $i_{02} = \left(I_2 + \frac{E}{R}\right)e^{-R/L\, t} - \frac{E}{R} \quad \text{— (b)}$

For calculating I_2, put $t = KT$ at equation (a) and for calculating I_1, put $t = (1-K)T$ at equation (b).

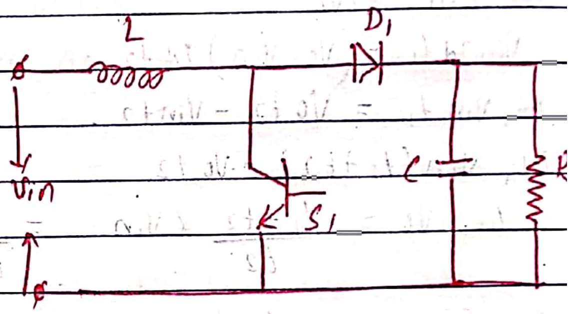
i.e, $i_{01} = I_2$ at $t = KT$

$i_{02} = I_1$ at $t = (1-K)T$

Then, $$I_{max} = \frac{V_s}{R}\left[\frac{1-e^{-Kz}}{1-e^{-z}}\right] - \frac{E}{R}$$

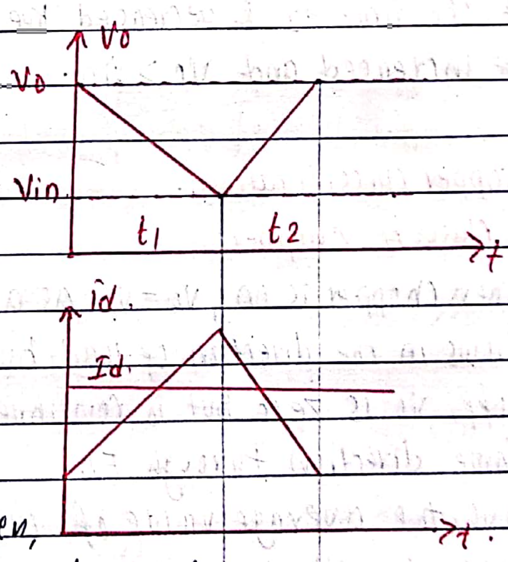
$$I_{min} = \frac{V_s}{R}\left[\frac{e^{Kz}-1}{e^{z}-1}\right] - \frac{E}{R}$$

Step up chopper:



When the transistor switch is closed an inductor current build up exponentially.

During this period, Inductance L stores energy and the capacitor C, (which was charged during the previous off period) discharges through load resistance R. Therefore, load voltage decreases during this period as shown in figure. The diode D_1 prevents the capacitor discharge back through the switch.



When the transistor switch S_1 is open, the inductor current id flows through D_1, thus by charging capacitor C. The energy releases during this and voltage across capacitor increases. Therefore load voltage Vo also increases during this period.

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let, I_d = Average value of inductor current.
V_o = Average value of output voltage.

Then,

Energy input to the inductor during on-time is given by.

$E_{in} = V_{in} I_d t_1$

Energy delivered by inductor during off time is given by.

$E_{out} = (V_o - V_{in}) I_d t_2$

If the system has no power loss than,

$E_{in} = E_{out}$

$V_{in} I_d t_1 = (V_o - V_{in}) I_d t_2$.

or, $V_{in} t_1 = V_o t_2 - V_{in} t_2$.

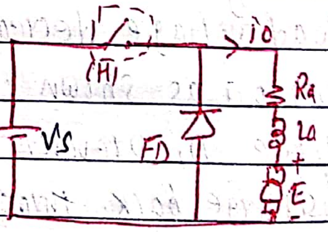
or, $V_{in}(t_1 + t_2) = V_o t_2$

or, $V_o = \frac{t_1 + t_2}{t_2} \times V_{in} = \frac{T}{t_2} V_{in}$.

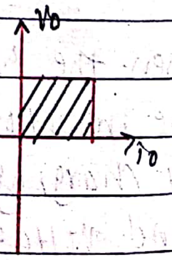
If off time t_2 is decreased keeping $(t_1 + t_2)$ = constant, then V_o will be increased and $V_o > V_{in}$.

Chopper Classification:

① Class A chopper:



When chopper is on, $V_o = V_s$ as a result the current flows in the direction of load but when the chopper is off, V_o is zero but i_o continues to flow in the same direction through FD.



Thus, the average value of output voltage and current will always be positive and output will be seen only in first quadrant. In class A chopper, power will always flow from source to load as average voltage V_o is less than dc input voltage V_s

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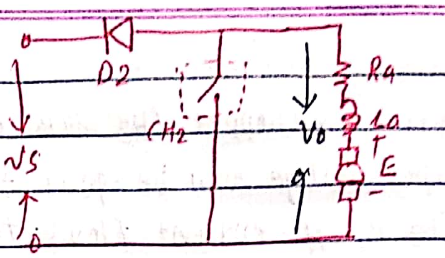
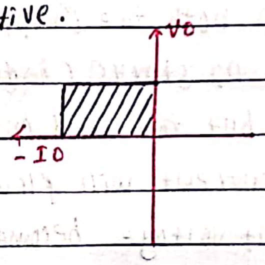
② Class B - Chopper:

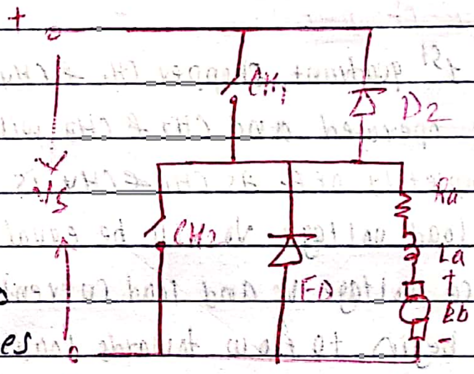


When the chopper is ON, V_0 is zero but the load voltage E drives the current through the inductor L. Inductor stores energy during ON time of the chopper i.e $E > V_s$ and during OFF time current stored in inductor flows through diode D2 to the source. No matter the chopper is ON or OFF, current will always flow through the load so the current always treated as negative.

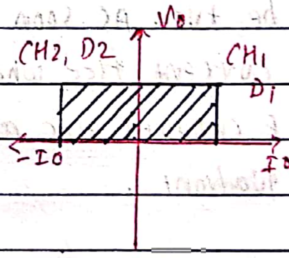


Since, V_0 is +ve and I_0 is -ve, power will flows from load to source. Since load voltage is more than source voltage such choppers are step up chopper.

③ Class-C Chopper:

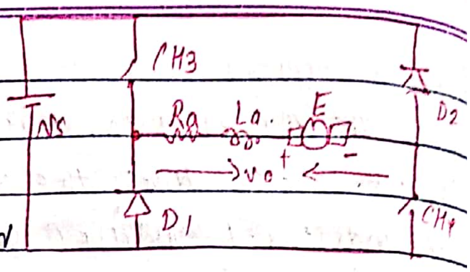


In 1st quadrant operation, CH_1 is turned ON keeping CH2 OFF, the current will flow in the path $V_s - CH_1 - Load - V_s$. Here V_0 and i_0 are +ve therefore motor operates in 1st quadrant. During ON period of CH_1 the armature current will flows through FD. In this 1st quadrant operation, chopper CH2 is completely turned OFF.

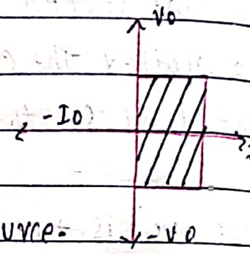


In 2nd quadrant, CH2 is turned ON keeping CH_1 turned OFF. During ON time of CH2, E drives the current through inductor and when CH2 is OFF, current flows towards source and current is negative and hence dc motor operates in 2nd quadrant.

④ Class D chopper:

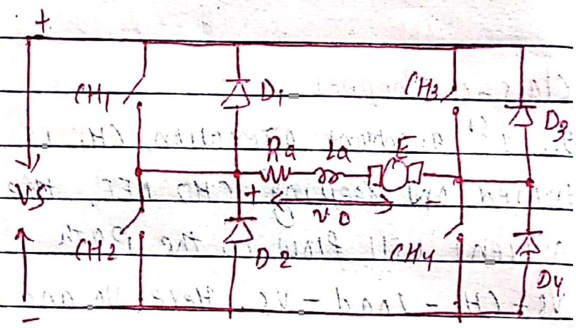


When both chopper CH3 & CH4 are ON, the output voltage will be equals to Vs and when CH3 is off current flows through D1 and hence average value of output current and voltage is always positive. i.e 1st quadrant operation.

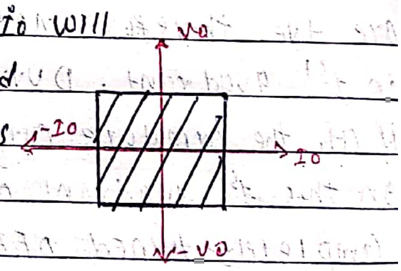


When both the chopper CH3 & CH4 are OFF, the diode D1 and D2 starts conducting. Here E is greater than Vs. but the load current is +ve that charges the source. The current will flow in the path D2 - Vs - D1 - E - D2 and hence output voltage becomes -ve. So, the dc motor operates in a 4th quadrant.

⑤ Class E chopper:



During 1st quadrant, chopper CH1 & CH4 will be operated and CH2 & CH3 will be completely OFF. As CH1 & CH4 is ON, the load voltage Vo will be equal to source voltage Vs and load current Io will begin to flow towards load. Here Vo & Io will be +ve. As soon as CH1 is turned off +ve load current free wheels through CH4 & D2. The class E chopper acts as step down chopper in 1st quadrant.



During 2nd quadrant, CH2 is operated and other 3-choppers are kept off. As CH2 is ON, -ve current starts to flow from E. Energy is stored in inductor L, when CH2 is ON.
When CH2 is OFF, current move back to the source through D1 to produce second quadrant operation of DC motor. The class E acts as step-up chopper in 2nd quadrant.

In 3^{rd} quadrant operation CH_2 & CH_3 is operated and CH_4 & CH_1 are kept OFF. For this quadrant working polarity of load should be reversed. As chopper CH_3 is ON load gets connected to source in the path $V_S - CH_3 - E - CH_2 - V_S$ and hence V_0 and i_0 will be -ve. In this case chopper acts as step down chopper.

CH_4 will be completely OFF. When CH_4 is ON, current will starts to flow $CH_4 - D_2 - E$ and inductor will store the energy. As CH_4 is turned OFF current is feedback to the source through D_2 and D_3 and the operation will be in 4^{th} quadrant.