Lecture 8
DC choppers

Objectives

- To consider operation of Class A Step-up and Class B Step-down DC choppers
- To combine Class A and Class B choppers to form Class C chopper
- To combine two Class C choppers in a bridge structure to form Class E chopper
- To consider classification for DC choppers in terms of operating envelopes

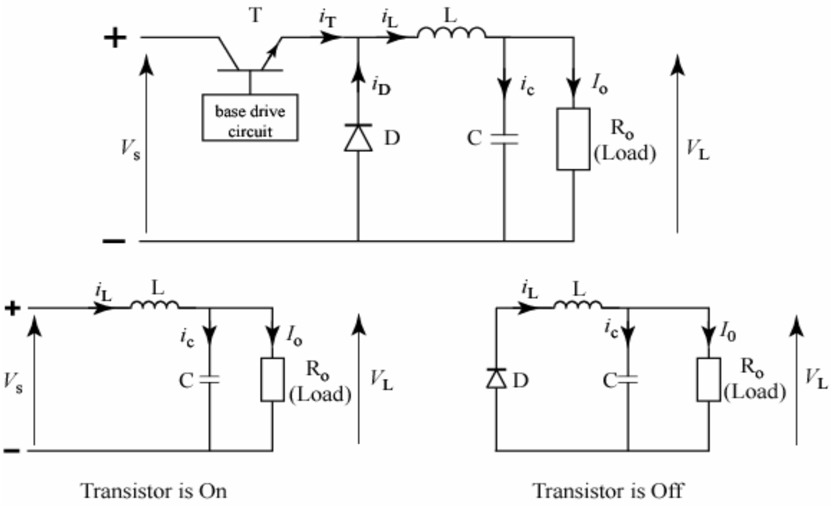
Introduction

- DC chopper:
  - Provides link between fixed DC source and load requiring controllable DC voltage
- Control achieved by activating switching devices placed between source and load
- Load voltage control by:
  - Vary mark-space ratio at constant frequency
    Or
  - Vary switching frequency with constant on-period
- Begin by considering basic class A, or step down chopper

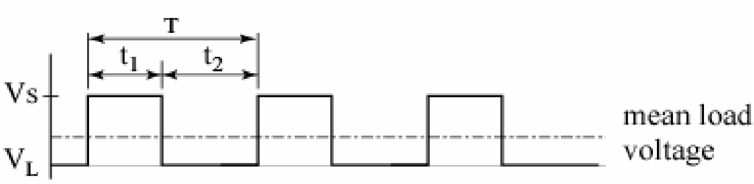
- First with highly inductive load; then with more resistive load
- Then consider class B chopper
- Finally, general classification for choppers

Class A step-down chopper

- Basic class A step-down chopper circuit:



  - GTO thyristor, MOSFET or BJT could be used for <u>low/medium power</u>
  - Thyristor turns off – load current continues to flow in diode



  - Voltage effectively 'chopped' between supply voltage V_s and 0 V
  - Mean load voltage:

$$V_L = V_s \frac{t_1}{T}$$

  - T is <u>period</u> , t_1 <u>on-interval</u> and t_2 is <u>off-interval</u>
  - RMS load voltage:

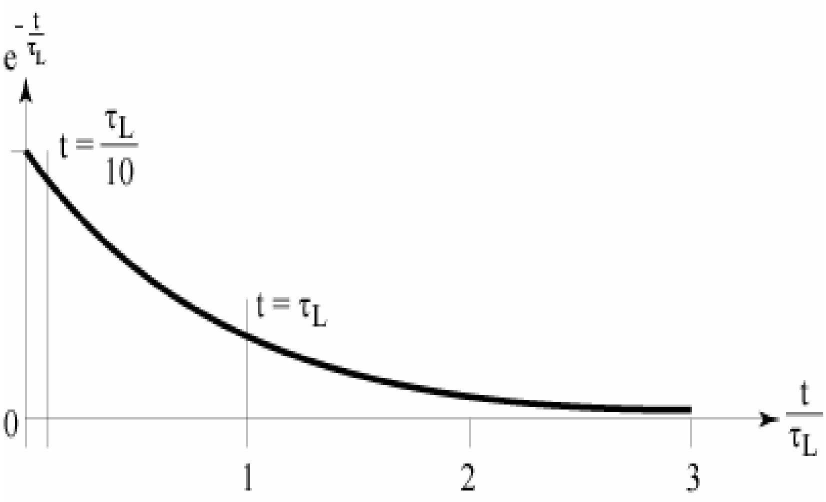
$$V_{L,RMS} = V_s \sqrt{\frac{t_1}{T}}$$

  - Load time constant:

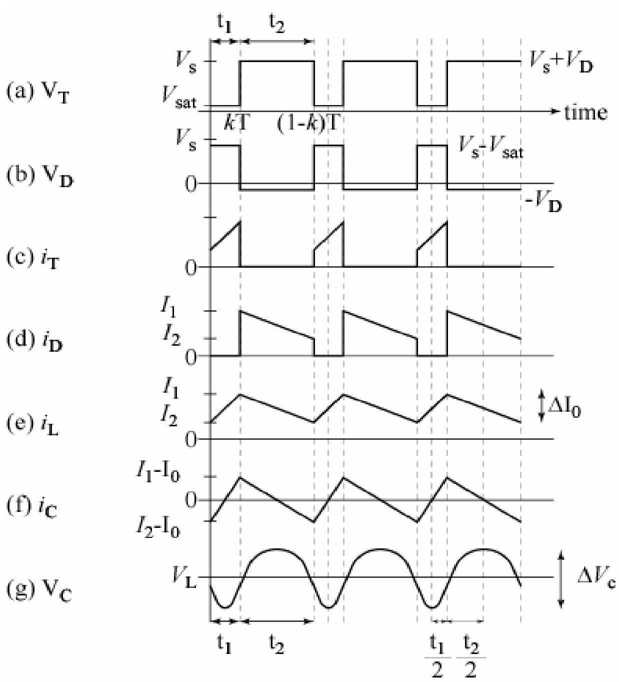
$$\tau_L = L / R$$

  - L – load inductance; R – load resistance

- Due to inductive and resistive elements, currents will rise and fall exponentially during switching cycle
- Assume load is highly inductive
- Load time constant >> switching period (T) e.g. $\tau_L > 10T$
- Load current variation ≈ linear over switching period $T < \tau_L/10$



- Load current, thyristor current and diode current waveforms,



- When thyristor conducts load current rises
- When diode conducts load current falls

- Using linear current approximation:

$$V_s - V_L = L\frac{di}{dt} = L\frac{\Delta I}{\Delta t}$$

- L is load inductance, V_L is voltage across load resistor
- During thyristor conduction interval:

$$\Delta I = I_1 - I_2 \qquad \Delta t = t_1$$

- Hence

$$\Delta I = I_1 - I_2 = \frac{(V_s - V_L)}{L} t_1$$

$$t_1 = \frac{\Delta I \cdot L}{(V_s - V_L)}$$

- During thyristor off-interval: $V_s = 0$

$$\Delta I = I_2 - I_1 \qquad \Delta t = T - t_1 = t_2$$

$$\Delta I = I_2 - I_1 = \frac{-V_L}{L} t_2$$

$$t_2 = \frac{\Delta I \cdot L}{V_L}$$

$$\Delta I = \frac{(V_s - V_L)}{L} t_1 = \frac{V_L}{L} t_2$$

- Putting $t_1 = kT, \quad t_2 = (1-k)T$

$$\frac{(V_s - V_L)}{L} kT = \frac{V_L}{L}(1-k)T$$

$$\Rightarrow V_L = kV_s$$

- Where k is the duty cycle

$$\frac{1}{f} = T = t_1 + t_2 = \frac{\Delta I \cdot L}{V_s - V_L} + \frac{\Delta I \cdot L}{V_L} = \frac{\Delta I \cdot L_s}{V_0\left(V_s - V_L\right)}\left(V_0 + \left(V_s - V_L\right)\right)$$

$$= \frac{\Delta I \cdot L \cdot V_s}{V_L\left(V_s - V_L\right)}$$

$$\Rightarrow \Delta I = \frac{V_L\left(V_s - V_L\right)}{f \cdot L \cdot V_s} = \frac{kV_s\left(V_s - kV_s\right)}{f \cdot L \cdot V_s} = \frac{V_s k\left(1 - k\right)}{f \cdot L}$$

- Instantaneous ripple current:

$$i_r = I_L - I_{mean}$$

for $0 < t < t_1$

$$i_r = I_2 + \left(I_1 - I_2\right)\frac{t}{t_1} - \frac{1}{2}\left(I_1 + I_2\right)$$

$$= \left(I_1 - I_2\right)\left(\frac{t}{t_1} - \frac{1}{2}\right)$$

for $t_1 < t < T$

$$i_r = I_1 - \left(I_1 - I_2\right)\frac{t}{t_2} - \frac{1}{2}\left(I_1 + I_2\right)$$

$$= \left(I_1 - I_2\right)\left(\frac{1}{2} - \frac{\left(t - t_1\right)}{t_2}\right)$$

- RMS ripple current:

$$i_{r,RMS} = \left\{ \frac{(I_1 - I_2)^2}{T} \left[\int_0^{t_1} \left(\frac{t}{t_1} - \frac{1}{2} \right)^2 dt + \int_{t_1}^{T} \left(\frac{1}{2} - \frac{(t - t_1)}{t_2} \right)^2 dt \right] \right\}^{1/2}$$

$$= \frac{I_1 - I_2}{2\sqrt{3}}$$

Example On Class A Chopper

- A class A step-down DC chopper is operating at a frequency of 2 kHz from a 96 V DC source to supply a load of resistance 8 Ω. The load time constant is 6 ms and the mean load voltage is 57.6 V
- (1) Find the mark-space ratio of the voltage waveform

Period = T = 1/f = 1/2000 = 0.5 ms

- Load time constant τ_L= 6 ms; Switching period T = 1/2000 = 0.5 ms

- τ_L = 12T > 10T; therefore assume linear load current variation

$$V_L = V_s \frac{t_1}{T} \qquad \therefore \frac{t_1}{T} = \frac{V_L}{V_s} = \frac{57.6}{96} = 0.6$$

$$t_1 = 0.6T$$

$$t_2 = T - t_1 = 0.4T$$

$$mark - space\ ratio = \frac{\mathrm{t}_1}{t_2} = \frac{0.6}{0.4} = 1.5$$

- (2) Find the mean load current

$$I_{mean} = \frac{V_L}{R} = \frac{57.6}{8} = 7.2\ A$$

- (3) Find the magnitude of the ripple current
  - First determine the value of the inductance

$$L = \tau R = 6 \times 10^{-3} \times 8 = 48\ mH$$

  - Then, we use

$$I_1 - I_2 = \frac{(V_s - V_L)t_1}{L} = \frac{(96 - 57.6)0.3 \times 10^{-3}}{48 \times 10^{-3}} = 0.24\ A$$

- (4) Find the RMS value of the ripple current
  - We have

$$i_{r,RMS} = \frac{I_1 - I_2}{2\sqrt{3}} = \frac{0.24}{2\sqrt{3}} = 69.3\ mA$$

- If needed, the minimum and maximum load current values can be determined as follows:

$$I_1 = I_{mean} + \frac{t_2 V_L}{2L}$$

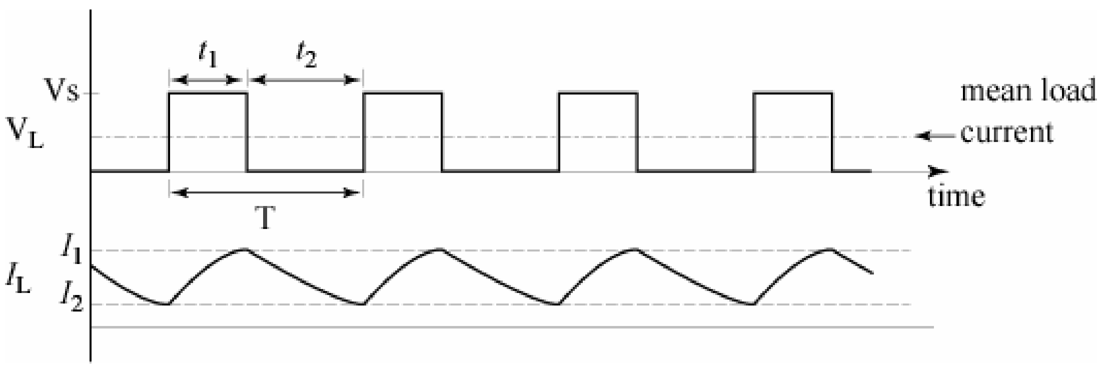
$$= 7.2 + \frac{0.2 \times 10^{-3} \times 57.6}{2 \times 48 \times 10^{-3}} = 7.32A$$

$$I_2 = I_{mean} - \frac{t_2 V_L}{2L}$$

$$= 7.2 - \frac{0.2 \times 10^{-3} \times 57.6}{2 \times 48 \times 10^{-3}} = 7.08A$$

Relaxing the linearity approximation

- If switching period T is of order of load time constant
  - Variation of load current can no longer be assumed to be linear
- Load current waveform:



- During thyristor conduction interval:

$$i_L = I_2 + \left(\frac{V_s}{R} - I_2\right)\left(1 - e^{-t/\tau}\right)$$

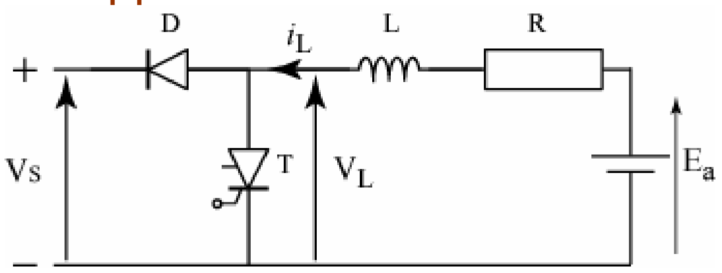
  - Where $\tau = L/R$
- During thyristor off-interval:

$$i_L = I_1 e^{-t/\tau}$$

- Equations may be solved to determine performance parameters of interest, such as magnitude and RMS value of current ripple
- Step-down chopper only allows power flow from supply to load

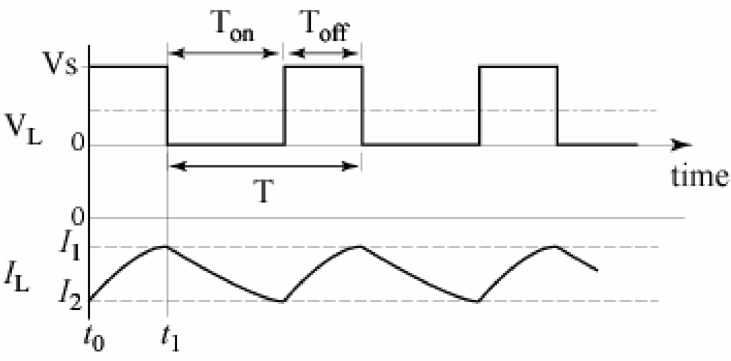
Class B step-up chopper

- Class B chopper circuit:



  - Power is transferred from load to supply:
  - Load acts as generator with back EMF E_a
  - Load could be DC motor in regenerative braking mode
  - When thyristor turned on, back EMF of load (E_a) drives current through inductor L
  - When thyristor is turned off, sudden reduction in load current causes voltage across inductor ($v = L\, di/dt$) which allows energy to be returned to supply via diode D

- Steady state load voltage and load current waveforms:



  - For interval $0 > t > t_1$: diode is conducting:

$$L\frac{dI_L}{dt} + i_L R = V_L - E_a$$

  - Solving this equations and applying boundary conditions:

$$i_L = \frac{V_L - E_a}{R}\left(1 - e^{-t/\tau}\right) + I_2 e^{-t/\tau}$$

where $\tau = L/R$

  - For interval $t_1 < t < T$: thyristor is conducting:

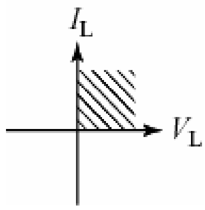
$$L\frac{dI_L}{dt} + i_L R = -E_a$$

$$i_L = -\frac{E_a}{R}\left(1 - e^{-(t-t_1)/\tau}\right) + I_1 e^{-(t-t_1)/\tau}$$

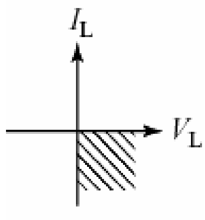
  - Equation may be solved to determine parameters of interest, e.g. peak and RMS current ripple

Class C and other classes of chopper

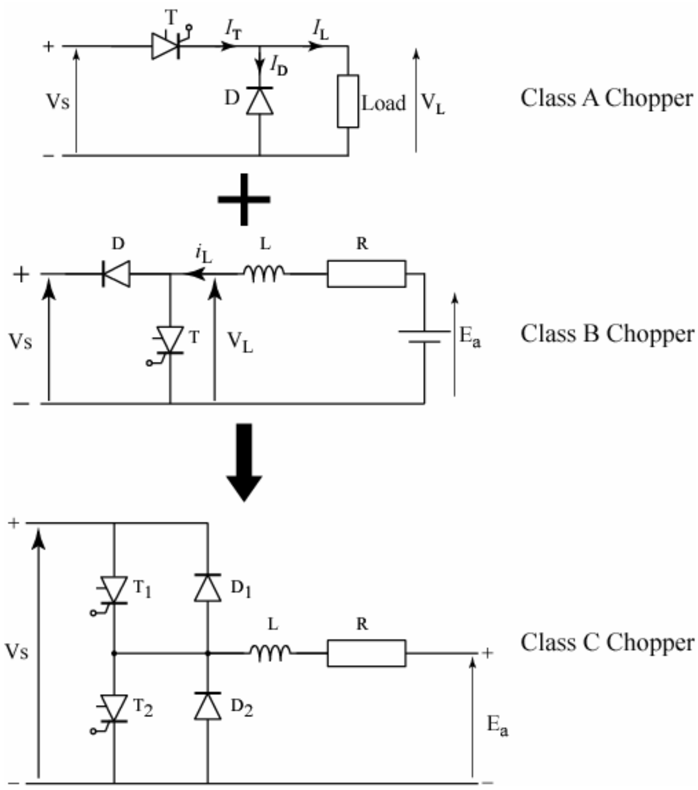
- Chopper classification in load current/load voltage (I_L/ V_L) plane:
  - Class A chopper – I_L *and* V_L > 0; i.e. only in 1st quadrant



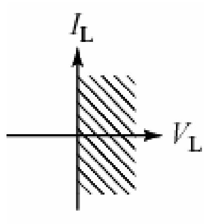
  - Class B chopper – V_L > 0 and I_L < 0; i.e. only in 4th quadrant



- Combine circuit elements of class A and class B chopper circuits:

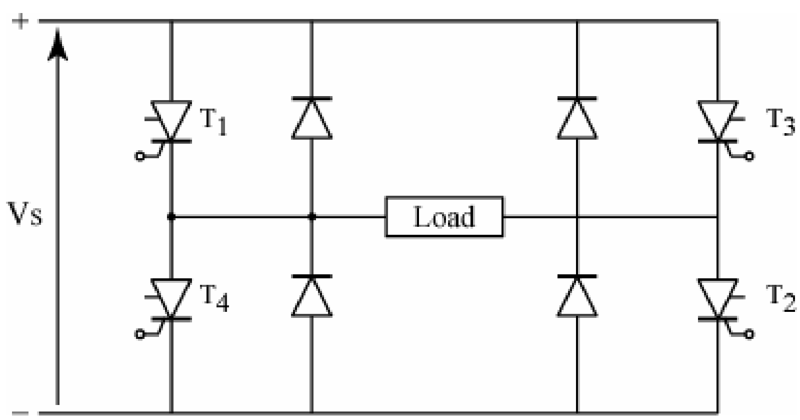


- Class C 2-quadrant chopper operates in either quadrant depending on which thyristor is fired:



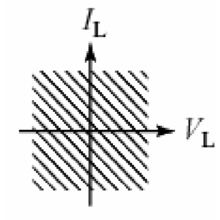
- Thyristors T_1 and T_2 are not fired together as this would short circuit the supply

- Further extend class C chopper into bridge structure:



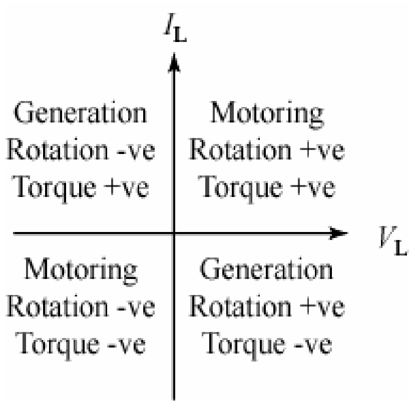
  - When T_1 is fired, we have class A chopper; when T_3 is fired, we also have class A chopper, but load voltage is reversed

- Firing T_4 gives us class B operation; T_2 gives us class B with load voltage reversed
- Circuit provides class A and class B operation with reversing action and can thus operate in all four quadrants of the V_L - I_L plane



- Such a chopper is called a class E chopper

- Different modes of operation of choppers can be related to different modes of operation for a motorised vehicle
- Such a vehicle can motor forwards and backwards and provide regenerative braking when travelling in the forward or backwards directions:
- When rotation and torque are in the same direction, speed is increasing
- When rotation and torque are in the opposite direction, speed is decreasing



Summary

- Have considered operation of DC chopper, starting with class A step-down chopper assuming highly inductive load
- Relaxed this condition on load impedance and then looked at class B step-up chopper
- Considered class C chopper which combines class A and class B operation in a single circuit
- Finally, the class E chopper combines two class C choppers allowing reversed operation
- This led to classification for DC choppers in terms of the polarity of the load voltage and load current