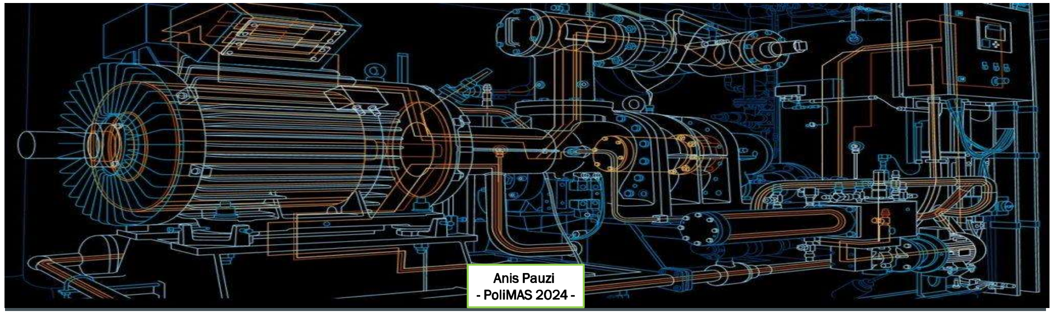
DET50063 MOTOR CONTROL AND DRIVES

CHAPTER 2 – SPEED CONTROL OF DC MOTOR



COURSE LEARNING OUTCOMES (CLO):

Upon completion of this course, students should be able to:

CLO 1 – Evaluate the various control methods based on the concept and principle of motor control and drives by considering energy efficiency (C5, PLO2)

CLO 2 – Display ability to conduct the various methods of motor control and drives using appropriate electrical equipment (P4, PLO5)

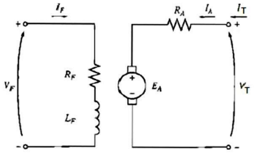
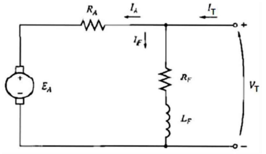
CLO 3 – Demonstrate the ability to communicate effectively in the assigned tasks (A3, PLO10)

OUTLINES

- 2. 1 Speed control methods of DC shunt/separately excited motors
- 2.2 Principles of controlling speed by adding resistance
- 2.3 Principles of controlling speed by adjusting armature voltage
- 2.4 Principles of controlling speed by adjusting field voltage
- 2.5 Principles of solid state control (thyristor controlled)
- 2.6 Principles of solid state control (chopper)
- 2.7 Analysis of principles of solid state control (chopper)
- 2.8 Evaluation of the motor efficiency using different control methods related to energy saving

2.1 SPEED CONTROL METHODS OF DC SHUNT/SEPARATELY EXCITED MOTORS

RELATED FORMULA (SEPARATELY EXCITED/ SHUNT MOTORS):

<table>
<tr><th>Separately Excited Motors</th><th>DC Shunt Motors</th></tr>
<tr><td>- is a motor whose field circuit is supplied from a separate constant-voltage power supply.</td><td>- is a motor whose field circuit gets its power directly across the armature terminals of the motor</td></tr>
<tr><td colspan="2">*When the supply voltage to a motor is assumed constant, there is no practical difference in behavior between these two machines.</td></tr>
<tr><td colspan="2">*When the load increases, the output torque required to drive the load will increase. Hence, the motor speed will slow down. Consequently, the internal generated voltage drops ($E_A = K\emptyset\omega_m \downarrow$), increasing the armature current (I_A) in motor $I_A = (V_S - E_A \downarrow)/R_A$. As the I_A increases, the developed (T_d) increase ($T_d = K\emptyset I_A \uparrow$) and finally the T_d will be equal the load torque at a lower mechanical speed of rotation ω_m.
Mechanical Load $\uparrow$ $\boldsymbol{\omega_m \downarrow, I_A \uparrow, T_d \uparrow} \longrightarrow$</td></tr>
<tr><td>
$I_a = \dfrac{V_t - E_a}{R_a}$
$I_t = I_a$ (line current)
$I_f = \dfrac{V_f}{R_f}$</td><td>
$I_a = \dfrac{V_t - E_a}{R_a}$
$I_t = I_a + I_f$ (line current)
$I_f = \dfrac{V_t}{R_f}$</td></tr>
</table>

RELATED FORMULA (SEPARATELY EXCITED/ SHUNT MOTORS):

Conversion of angular speed from radians per second (rad/s) to revolutions per minute (rpm):

$$rpm = \frac{(rad/s)}{2\pi} \times 60$$

$$V_t = E_a + I_a R_a$$

$$T_d = K\Phi I_a$$

$$T_d = K\Phi\left(\frac{V_t - E_a}{R_a}\right)$$

$$T_d = K\Phi\left(\frac{V_t - K\Phi\omega}{R_a}\right)$$

$$Power\ developed, P_d = E_a I_a = T_d \omega$$

$where;\ T_d = Torque\ developed$

To calculate speed, consider these two equations:

$$E_a = K\Phi\omega = V - I_a R_a$$

or

$$\frac{\Phi_1}{\Phi_2}\frac{n_1}{n_2} = \frac{V - I_{a_1} R_a}{V - I_{a_2} R_a}$$

$$\frac{E_{a_1}}{E_{a_2}} = \frac{\omega_1}{\omega_2} = \frac{n_1}{n_2} = \frac{V - I_a R_a}{V - I_a(R_a + R_{add_1})}$$

Motor Losses:

$$Losses = field\ losses + armature\ losses + rotational\ losses$$
$$= I_f^2 R_f + I_a^2 R_a + rotational\ losses$$

Where;

$Field\ losses = I_f^2 R_f$

$Armature\ losses = I_a^2 R_a$

SPEED CONTROL METHODS OF DC SHUNT/SEPARATELY EXCITED MOTORS

3 ways to speed control the DC shunt/separately excited motors:

- By adding resistance
- By adjusting armature voltage
- By adjusting field voltage

2.1.1 THE EFFECT OF EACH METHODS ON DC MOTOR SPEED

By adding resistance

- This method involves **adding external resistance** in **series with the armature circuit.**
- Resistance $\uparrow$, the armature current $\downarrow$, the torque $\downarrow$ and speed of the motor $\downarrow$.
- This method is **simple** and **inexpensive**, it's **highly inefficient.**
- Adding resistance results in **power dissipation**, leading to **energy loss in the form of heat.** This **reduces the overall efficiency of the motor system.**
- Additionally, the **speed control range is limited**, and the **motor may suffer from reduced torque capability**, especially at lower speeds.

By adjusting armature voltage

- Adjusting the armature voltage directly **affects the electromagnetic torque produced by the motor**, allowing for **smooth speed control over a wide range.**
- This method is **more efficient** than adding resistance since it doesn't result in significant power loss. However, it **requires sophisticated control circuitry** to implement PWM effectively.
- It provides **better torque control** compared to resistance control and is often preferred in applications where efficiency and precise speed control are crucial.
- The armature voltage Vt of the motor $\downarrow$, the motor speed $\downarrow$.

By adjusting field voltage

- This method involves adjusting the voltage applied to the motor's field winding. **By changing the field flux, the back EMF and hence the motor speed can be controlled.**
- Similar to armature voltage control, adjusting the field voltage provides **smooth speed control** and allows for **efficient operation over a wide range.**
- However, this method is generally **less common** compared to armature voltage control, especially in DC motor applications, due to factors such as **complexity** and the need for **additional control circuitry.**
- The field voltage $\downarrow$, the flux f $\uparrow$, and the motor speed $\uparrow$.
- It may be more suitable for specific applications where precise control of speed and torque characteristics is required, such as in certain industrial processes or specialized machinery.

All three methods can be used to control the speed of a DC motor, speed control by **adjusting armature voltage** is often preferred due to its efficiency, effectiveness, and wide range of control but only suitable for speed reduction. Speed control by **adding resistance** is less efficient and provides limited control range, while speed control by adjusting field voltage, though effective, is less common and may be more complex to implement but suitable for speed increase. For a full range of speed control, more than one of the three methods must be employed.

In summary;

a) By adding resistance to armature circuit	• The **speed drop Δω** is increases and the **motor speed ω** **decreases.**
b) By adjusting armature voltage (terminal voltage)	• Reducing the **armature voltage V_t** of the motor reduces the **motor speed ω.**
c) By adjusting field voltage (field flux)	• Reducing the **field voltage V_f** reduces the **flux Φ** and the **motor speed ω** increases.

THE SPEED-TORQUE CHARACTERISTICS OF A DC, SEPARATELY EXCITED (OR SHUNT) MOTOR CAN BE EXPRESSED BY THE FORMULA

- The speed-torque characteristics of a dc, separately excited (or shunt) motor can be expressed by the formula:

$$\omega = \frac{V_t}{K\Phi} - \frac{R_a}{(K\Phi)^2} T_d = \omega_0 - \Delta\omega \qquad \text{(Eq. 1)}$$

$$\omega = \frac{V_t}{K\Phi} - \frac{R_a}{K\Phi} I_a = \omega_0 - \Delta\omega \qquad \text{(Eq. 2)}$$

Where;

ω_0= no-load speed (The no-load speed is computed when the torque and current are equal to zero.)

$\Delta\omega$ = speed drop (The speed drop is a function of the load torque)

2.2 PRINCIPLES OF CONTROLLING SPEED BY ADDING RESISTANCE

2.2.1 – 2.2.4 CONTROLLING SPEED BY ADDING RESISTANCE

Figure 1 shows a dc motor setup with resistance added in the armature circuit

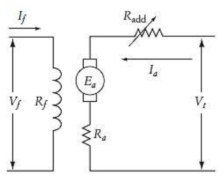


Figure 1

Note: The no-load speed ω_0 is unchanged regardless of the value of resistance in the armature circuit. The second term of the speed equation is the speed drop Δ_ω, which increases in magnitude when Radd increases. Consequently, the motor speed is reduced.

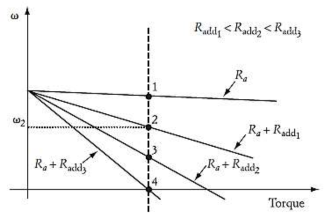


Figure 2 The corresponding speed-torque characteristics.

Example: Let us assume that the load torque is unidirectional and constant. Also, assume the field and armature voltages are constant. At point 1, no external resistance is in the armature circuit. If a resistance R_{add1} is added to the armature circuit, the motor operates at point 2, where the motor speed ω_2 is

$$\omega_2 = \frac{V_t}{K\Phi} - \frac{R_a + R_{add1}}{(K\Phi)^2} T_d = \omega_0 - \Delta\omega_2 \quad \text{or}$$

$$\omega_2 = \frac{V_t}{K\Phi} - \frac{R_a + R_{add1}}{K\Phi} I_a = \omega_0 - \Delta\omega_2$$

EXERCISE 1:

- A 150V, DC shunt motor drives a constant-torque load at a speed of 1200rpm. The armature and field resistances are 1Ω and 150Ω, respectively. The motor draws a line current of 10A at the given load.

a) Calculate the resistance that should be added to the armature circuit to reduce the speed by 50%. (**Ans:** $R_{add} = 7.83\Omega$)

b) Assume the rotational losses to be 100W. Calculate the efficiency of the motor without and with the added resistance. (**Ans:** $Efficiency, \eta\ motor\ without\ the\ added\ resistance = 77.93\%$ and $Efficiency, \eta\ motor\ with\ the\ added\ resistance = 35.65\%$)

c) Calculate the resistance that must be added to the armature circuit to operate the motor at the holding condition.

(**Ans:** $R_{add} = 15.67\Omega$)

2.3 PRINCIPLES OF CONTROLLING SPEED BY ADJUSTING ARMATURE VOLTAGE

2.3.1 – 2.3.4 CONTROLLING SPEED BY ADJUSTING ARMATURE VOLTAGE

This method is highly efficient and stable and is simple to implement. The circuit of **Figure 3** shows the basic concept of this method. The only controlled variable is the armature voltage of the motor, which is depicted as an adjustable-voltage source.

Note that we are assuming the field voltage is unchanged when the armature voltage varies.

Electric holding can be done if the armature voltage is reduced until $\Delta\omega$ is equal to ω_0. This operating point is shown in **Figure 4** at an armature voltage equal to V_4.

$$\omega_4 = \frac{V_4}{K\phi} - \frac{R_a}{(K\phi)^2} T_d = 0$$

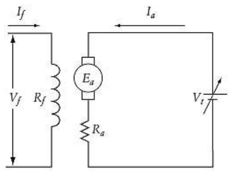


Figure 3

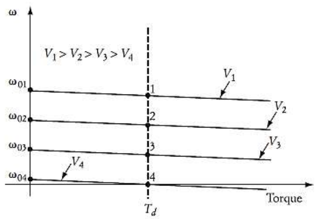


Figure 4: Motor characteristics when armature voltage changes

EXERCISE 2

A 150 V, dc shunt motor drives a constant torque load at a speed of 1200 rpm. The armature and field resistance are 1 Ω and 150 Ω , respectively. The motor draws a line current of 10 A . Calculate the motor speed if the terminal voltage is reduced by 25%.

(**Ans**: Motor speed, $n_2 = 900rpm$)

2.4 PRINCIPLES OF CONTROLLING SPEED BY ADJUSTING FIELD VOLTAGE

2.4.1 – 2.4.3 CONTROLLING SPEED BY ADJUSTING FIELD VOLTAGE

Figure 5 shows a setup for controlling speed by adjusting the field flux. If the field voltage is reduce, the field current and consequently the flux are reduced.

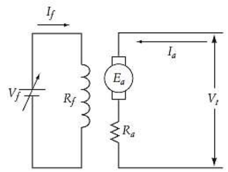


Figure 5

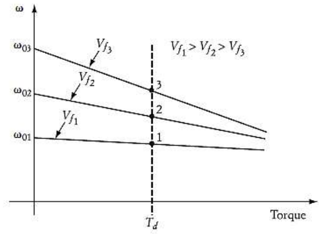


Figure 6: Effect of field voltage on motor speed

Figure 6 shows a set of speed-torque characteristics for three values of field voltages.

- ✓ When the field flux, Φ is ↓, the no-load speed ω_0 is ↑ in inverse proportion to the flux, and the speed drop $\Delta\omega$ is also ↑.
- ✓ The characteristics show that because of the change in speed drops $\Delta\omega$, the lines are not parallel. Unless the motor is excessively loaded, the motor speed ω ↑ when the field is ↓.

EXERCISE 3:

- A 150V, DC shunt motor drives a constant-torque load at a speed of 1200rpm. The armature and field resistances are 2Ω and 150Ω, respectively. The motor draws a line current of 10A. Assume that a resistance is added in the field circuit to reduce the field current by 20%. Calculate the armature current, motor speed, value of added resistance, and extra field losses.

(**Ans:** Armature current, $I_{a_2} = 11.25A$, Motor speed, $n_2 = 1448.86rpm$, Value of added resistance, $R_{add} = 37.5\Omega$, and Extra field losses, $P = 24W$.)

2.5 PRINCIPLES OF SOLID STATE CONTROL (THYRISTOR CONTROLLED)

PRINCIPLES OF SOLID STATE CONTROL (THYRISTOR CONTROLLED)

- Solid-state control is used for enhanced efficiency and for versatile operation of electric drive systems. For dc machines, converters are often used in the armature circuit to control the terminal voltage of the motor. In some cases, the converter is also used to control the field voltage.
- Two types of Solid State Control (Thyristor Controlled):
  1. Single Phase Half Controlled Converter
  2. Single Phase Fully Controlled Converter

2.5.1 – 2.5.2 SINGLE PHASE HALF CONTROLLED CONVERTER

The circuit of Figure 6 shows the armature loop. The converter in this case is a simple SCR triggered by a control circuit not shown in the figure. The waveforms of the circuit are shown in Figure 7.

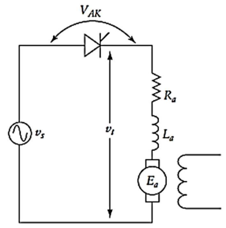


Figure 6: A single-phase half-wave SCR drive

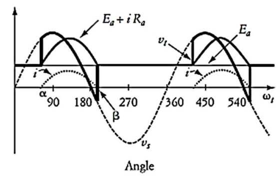


Figure 7: Waveforms of circuit in Figure 6

γ = conduction period
β = Extinction angle; its the angle at which the load current falls to zero
α = Triggering/Firing angle; the angle in the AC cycle at which the thyristor starts conducting at the application of positive voltage to gate

$$\gamma = \beta - \alpha$$

$$V_{max} = \sqrt{2}\, V_{rms}$$

For continuous armature current;

$$V_t = \frac{V_{max}}{2\pi}(1 + \cos\alpha) = k\Phi\omega + R_a I_a$$

$$\frac{V_{max}}{2\pi}[\cos(\alpha) - \cos(\beta)] = \frac{\gamma}{2\pi} E_a + R_a I_a$$

Replacing E_a with $K\Phi\omega$ yields;

$$\frac{V_{max}}{2\pi}[\cos(\alpha) - \cos(\beta)] = \frac{\gamma}{2\pi} k\Phi\omega + R_a I_a$$

EXERCISE 4:

A 1 hp, dc shunt motor is loaded by a constant torque of 10 Nm. The armature resistance of the motor is 5Ω, and the field constant $K\Phi = 2.5Vsec$. The motor is driven by a **half-wave SCR converter**. The power source is 120 V, 60 Hz. The triggering angle of the converter is 60°, and the conduction period is 150°. Calculate the motor speed and the developed power.

(**Ans:** Motor speed $\omega = 16.22\ rad/s$ or $n = 154.89 rpm$, Developed power $P_d = 162.2W$)

EXERCISE 5:

A 1hp, shunt dc motor is loaded by a constant torque of 10Nm. The armature resistance of the motor is 2Ω and the field constant $K\Phi = 2.5Vsec$. The motor is driven by a **half-wave SCR converter**. The power source is 240 Vrms, 50Hz. The triggering circuit angle of the converter is 30° and the conduction period is 240°. Calculate the motor speed and the developed power delivered to the load.

(**Ans:** Motor speed $\omega = 23.26\ rad/s$ or $n = 222.12rpm$, Developed power $P_d = 232.6W$)

EXERCISE 6:

A 1HP, DC separately excitation motor is loaded by a constant torque of 10Nm. The armature resistance of the motor is 2Ω and the field constant $K\Phi = 2.5Vsec$. The motor is driven by a **half-wave converter.** The power source is 240V, 50Hz. The triggering angle of the converter is 60°. The viscous friction and no-load losses are negligible. The inductances of armature and field circuits are sufficient enough to make the armature and field currents continuous and ripple free. Calculate the motor speed in rpm and the developed power delivered to the load.

(**Ans:** Motor speed $n = 290.41rpm$, Developed power $P_d = 304.12W$)

2.5.3 – 2.5.4 SINGLE PHASE FULL CONTROLLED CONVERTER

A full-wave drive can be realized by using one of the two circuits shown in Figures 8 and 9. The circuit in Figure 8 consists of four SCRs connected in a full-wave bridge. The switching of the SCRs is dependent on the polarity of the source voltage Vs.
The circuit in Figure 9 shows another alternative where two SCRs and a center-tap transformer are used. The secondary of the transformer should have double the voltage rating of the motor; that is,

$$V_1 = V_2 = rated\ armature\ voltage$$

When the source voltage V_s is in the positive half of its cycle and S_1 is triggered, I_1 flows in negative part and S_2 is closed, I_2 flows in the lower half of the secondary windings.

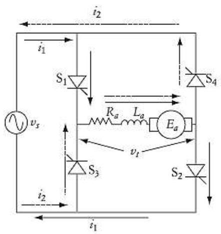


Figure 8: Full-wave drive using four-SCR bridge

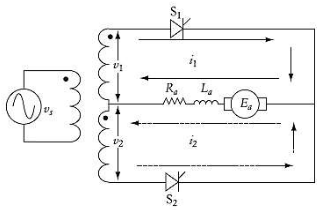


Figure 9: Full-wave drive using two SCRs and a center-tap transformer

The waveforms of the circuit in Figure 9 are shown in Figure 10. The figure shows V_1 and V_2 in reference to the center point of the transformer. When V_1 is in the positive part of its cycle and S1 is triggered at a, the terminal voltage of the motor V_t is equal to V_1 and the motor current is I_1.
Again, the average terminal voltage of the motor is calculated by

$$\boxed{V_t = E_a + I_a R_a}$$

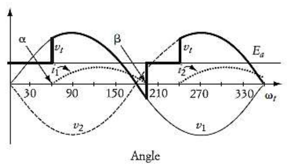


Figure 10: Waveforms of circuit in Figure 9

For continuous armature current;

$$\boxed{V_t = \frac{2V_{max}}{\pi}(\cos\alpha) = K\Phi\omega + R_a I_a}$$

The equation of the armature circuit is;

$$\boxed{\frac{V_{max}}{\pi}[\cos(\alpha) - \cos(\beta)] = \frac{\gamma}{\pi}E_a + R_a I_a}$$

Replacing E_a with $K\Phi\omega$ yields;

$$\boxed{\frac{V_{max}}{\pi}[\cos(\alpha) - \cos(\beta)] = \frac{\gamma}{\pi}k\Phi\omega + R_a I_a}$$

EXERCISE 7:

A 1HP, DC separately excitation motor is loaded by a constant torque of 10Nm. The armature resistance of the motor is 5Ω and the field constant $K\Phi = 2.5Vsec$. The motor is driven by a **full-wave converter.** The power source is 120V, 60Hz. The triggering angle of the converter is 60° and the conduction period is 150°. Calculate the motor speed and the developed power delivered to the load.

(**Ans:** Motor speed $\omega = 25.82\ rad/s$ and $n = 246.56rpm$, Developed power $P_d = 258.2W$)

EXERCISE 8:

A DC separately excitation motor has a constant torque of 60Nm. The motor is driven by a **full-wave converter** connected to a 120V, AC supply. The armature resistance of the motor is 2Ω and the field constant $K\Phi = 2.5Vsec$. Calculate the triggering angle α if the armature current is continuous and the speed is 200rpm.

(**Ans:** Triggering angle, $\alpha = 21.73°$)

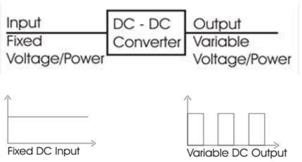
EXERCISE 9:

A 1 hp, DC separately excitation motor is loaded by a constant torque of 10Nm. The armature resistance of the motor is 2Ω and the field constant $K\Phi = 2.5Vsec$. The motor is driven by a **full-wave converter.** The power source is 240V, 50Hz. The triggering angle α of the converter is 60°. The viscous friction and no-load losses are negligible. The inductances of armature and field circuits are sufficient enough to make the armature and field currents continuous and ripple free. Calculate the motor speed in rpm and the developed power delivered to the load.

(**Ans:** n= 382.16rpm, Pdev = 400.2W)

2.6-2.7 PRINCIPLES OF SOLID STATE CONTROL (CHOPPER)

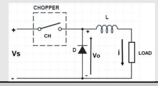
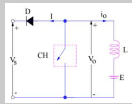
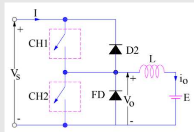
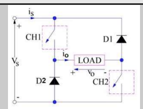
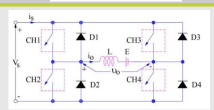
- A **chopper** is a device that converts **fixed DC input** to a **variable DC output** voltage directly.



Two (2) control techniques are utilized in DC chopper:

- **1. Time ratio control**
  The value of $\frac{T_{ON}}{T}$ varies. It can be done in two ways: with variable frequency operation or with fixed frequency operation.
  a) T_{ON} or T_{OFF} is kept constant.
  b) T_{ON} or T_{OFF} are varied.

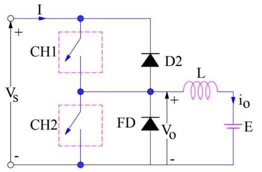
2. Current limit control
- The chopper is switched ON and OFF, so that the current in the load is maintained between two limit.
- When the current exceed upper limit, the chopper switched OFF.
- When the current reached lower limit, the chopper switched ON.
- During the OFF period the load current freewheels and decreases exponentially.

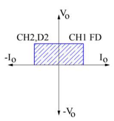
Class A chopper	• 1st-quadrant chopper. • Is a step down chopper in which power always flows from source to load.	
Class B chopper	• 2nd-quadrant chopper. • Used for regenerative braking of dc motor. • Is a step up chopper.	
Class C chopper	• 2 quadrant chopper • Is obtained by connecting class-A and class-B choppers in parallel. • Can be used both for DC motor control and regenerative braking of dc motor. • Can be used as a step-up or step-down chopper.	
Class D chopper	• 2 quadrant chopper	
Class E chopper	• 4 quadrant chopper	

2.6.1 & 2.7.1 SKETCH THE CIRCUIT DIAGRAM & ILLUSTRATE THE TWO QUADRANT OPERATION OF DC MOTORS USING CHOPPER DRIVES

<u>CLASS-C CHOPPER</u>

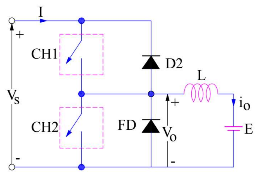
- Class-C Chopper is a category of chopper which can operate in first as well as second quadrant.
- This basically means that, the power can either flow from source to load or load to source in this chopper.
- As we know that, a Class-A and Class-B chopper operates in 1st and 2nd quadrant respectively. Therefore, if we connect both these types of chopper in parallel then it is possible to have chopper operation in 1st as well as 2nd quadrant.
- In fact, Class-C chopper is obtained by the parallel connection of Class-A and Class-B chopper.

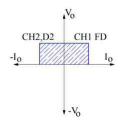




- Carefully observe the circuit diagram. You will notice that chopper CH1, free-wheeling diode (FD) and load are forming Class-A Chopper whereas chopper CH2, D2 and Load are forming Class-B chopper.
- Both these choppers are connected in parallel.
- To obtain 1st quadrant operation we should switch ON chopper CH1 and for getting 2nd quadrant operation we should switch ON chopper CH2.

CONT…. 2.6.1 & 2.7.1





1st Quadrant

- When CH1 is switched ON, source *Vs* directly gets connected to the load and hence, *Vo=Vs*. The direction of Io is from source to load as shown in the circuit diagram which is assumed positive.
- When CH1 is switched OFF, the FD comes into the circuit as it gets forward biased and hence shorts the load. Therefore, the *Vo*=0. However, the *Io* continues to die down through the FD and L in the same direction as shown in circuit diagram.
- Thus, the *Vo* and *Io* are positive and hence operation of chopper is in 1st quadrant.

- **2nd Quadrant**
- When CH2 is switched ON, load DC source E drives current through CH2 and load. The direction of this current Io will be opposite to that shown in circuit diagram and hence is assumed negative. Vo=0 during this time.
- When CH2 is made OFF, diode D2 gets forward biased and hence the current into the source from the load. The Vo=Vs in this time as the load is connected to the source through D2 during OFF time of chopper CH2.
- Thus, the load current is always negative i.e. operation of chopper is within 2nd quadrant.

CONT…. 2.6.1 & 2.7.1

From the above two quadrant explanation, we can conclude the following points:

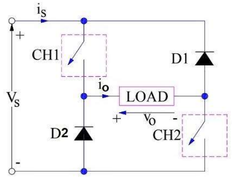
- The Vo=0 when CH2 is ON or FD conducts.
- The Vo=Vs when CH1 is ON or diode D2 conducts.
- The load current flows in the direction shown in circuit diagram (Io is positive when CH1 is ON or FD conducts).
- The load current flows opposite to the direction shown in circuit diagram (Io is negative when CH2 is ON or D2 conducts).
- The Vo(avg) is always positive but the Io(avg) may be positive or negative. Therefore, power flow may be from source to load (1st quadrant operation) or load to source (2nd quadrant operation).

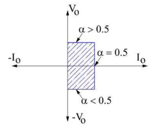
Caution: CH1 and CH2 should not be ON simultaneously as this would lead to direct short circuit on the supply lines.

CONT…. 2.6.1 & 2.7.1

CLASS-D CHOPPER

- Class-D chopper is a circuit configuration of chopper in which power can flow in either direction from source to load or load to source.
- The operation of this chopper is confined in 1st and 4th quadrant.
- The necessary condition for this chopper is that load should be inductive.





1st Quadrant

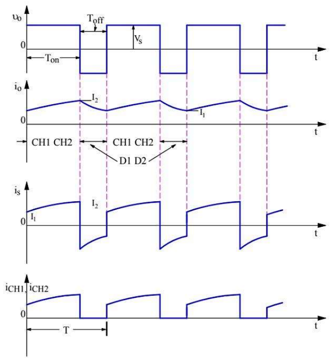
- When both the choppers are switched ON, the load is directly connected to source and hence the Vo=Vs. The current flows from source to load. Thus, both the Io and Vo are positive in this case.
- It should be noted that diode D1 and D2 are reversed biased in this case and hence they can be treated as an open switch.

4th Quadrant

- When both the choppers are made OFF simultaneously, the current through the load doesn't suddenly drops to zero due to inductive load. However, it decays gradually and hence a huge amount of voltage is induced in the inductor in the reverse direction (opposite to the direction of vo).
- This makes D1 and D2 forward biased. Thus, D1 and D2 starts conducting and connects the load to source again. But this time, the current flows from load to source.
- It shall be noted that, the direction of load current has not changed. The current is still flowing as shown by the direction of Io in the diagram but the polarity of Vo has changed.
- Thus, Io is positive but Vo is negative. The power flows from load to source.

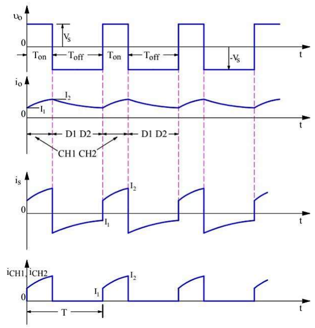
CONT…. 2.6.1 & 2.7.1

- Figure below represents waveforms during the time **both the chopper are ON.**



- During the ON time of CH1 & CH2, Vo=Vs (positive). When both the choppers are made OFF, the Vo= -Vs (negative).
- It may be noticed that, the Vo (average) may either be positive or negative. It depends on TON and TOFF time. If TON>TOFF time, average value of Vo will be positive.
- If TOFF>TON time, average value of Vo will be negative.

CONT…. 2.6.1 & 2.7.1



- Thus, the average Vo of Class-D chopper may either be positive or negative depending upon whether TON>TOFF.

- Average output voltage Vo is given as below.
- $V_o = V_S\left(\frac{T_{ON}-T_{OFF}}{T}\right)$ where, $T = T_{ON} + T_{OFF}$
- From the above formula, following points can be concluded:
  - In case TON>TOFF , duty cycle α>0.5, Vo is positive.
  - In case TON<TOFF , duty cycle α<0.5, Vo is negative.
  - In case of TON = TOFF, α = 0 and hence, Vo = 0.
- Load current (Io) is always positive irrespective of CH1 & CH2 are ON or OFF. Thus, the average value of Io will always be positive.
- Source current (Is) is negative when both CH1 and CH2 are OFF or diode D1 and D2 conducts. Negative source current means, current is flowing into the source.

EXERCISE 10:

A dc separately excitation motor is loaded by a constant torque of 50 Nm. The armature resistance is 1.2 Ω, the field current is 2.5 A and the field constant, KΦ is 3.2 V sec. The power source is 220 V. The motor is driven by a chopper drive. Analyze on the speed of the dc motor when the duty cycle are 25% and 75%. Based on the analysis, determine the effect of duty cycle on the dc motor speed.

(**Ans:**
For duty cycle 25%; n = 108 rpm
For duty cycle 75%; n = 436 rpm
Analysis: the larger the duty cycle, the faster the motor speed)

EXERCISE 11:

A dc separately excitation motor is loaded by a constant torque of 100 Nm. The armature resistance is 1.5 Ω, the field current is 2.0 A and the field constant, KΦ is 3.2 V sec and the power source is 240 V. The motor is driven by a chopper drive. Analyze the speed and the effects of the duty cycle towards the dc motor when the duty cycle is 25% and 75%.

(**Ans:**
For duty cycle 25%; n = 39 rpm
For duty cycle 75%; n = 397 rpm
Analysis: the larger the duty cycle, the faster the motor speed)

EXERCISE 12:

A dc separately excitation motor is loaded by a constant torque of 20 Nm. The armature resistance is 3 Ω and the field constant, KΦ is 2.5 V sec. The power source is 240 V. The motor is driven by a chopper drive. Determine the effect of duty cycle on dc motor speed based on the analysis that has been made to the speed of the dc motor when the duty cycle is 30% and 60%.

(**Ans:**
For duty cycle 30%; n = 183 rpm
For duty cycle 60%; n = 458 rpm
Analysis: the larger the duty cycle, the faster the motor speed)