Tribhuvan University
Institute of Engineering
Pulchowk Campus

Unit: III- Control Strategies

Class-11:
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Presented by
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Subject Name
EE: Modelling and Control of Electric Drives

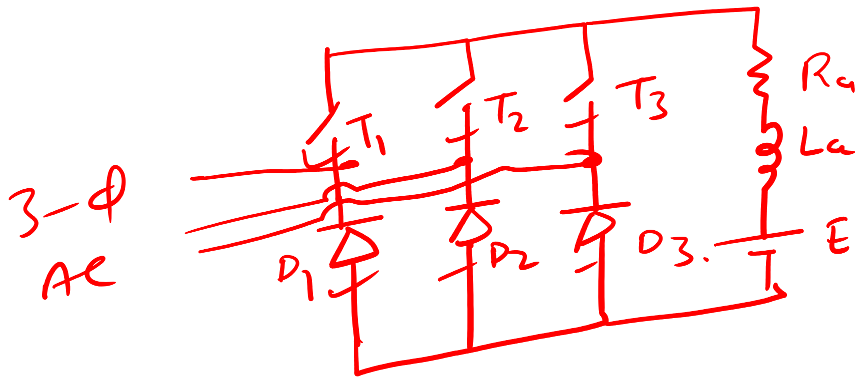
Discussed in the Previous Class

In the previous class discussed the following topics:

- ❖ Single Phase Half Controlled Rectifier Control of DC Motor
- ❖ Three Phase Fully Controlled Rectifier Control of DC Motor

Lecture Outcomes

- ❖ Three Phase Half Controlled Rectifier Control of DC Motor
- ❖ DC Motor Reversing Switch Diagram
- ❖ Dual Converter Control of DC Separately Excited Motor
- ❖ Drawbacks of Rectifier Fed DC Drives
- ❖ Chopper Control of Separately Excited DC Motor
- ❖ Lecture remarks: Key points of today's class



Three Phase Half Controlled Rectifier Control of DC Separately Excited Motor

Three Phase Half Controlled Rectifier Control of DC Separately Excited Motor

For the rectifier circuit, shown in Fig. 1, under continuous conduction

$$V_a = \frac{3V_m}{2\pi}(1 + \cos\alpha) \qquad (1)$$

From fundamental drive equations

$$\omega_m = \frac{3V_m}{2\pi K}(1 + \cos\alpha) - \frac{R_a}{K^2}T \qquad (2)$$

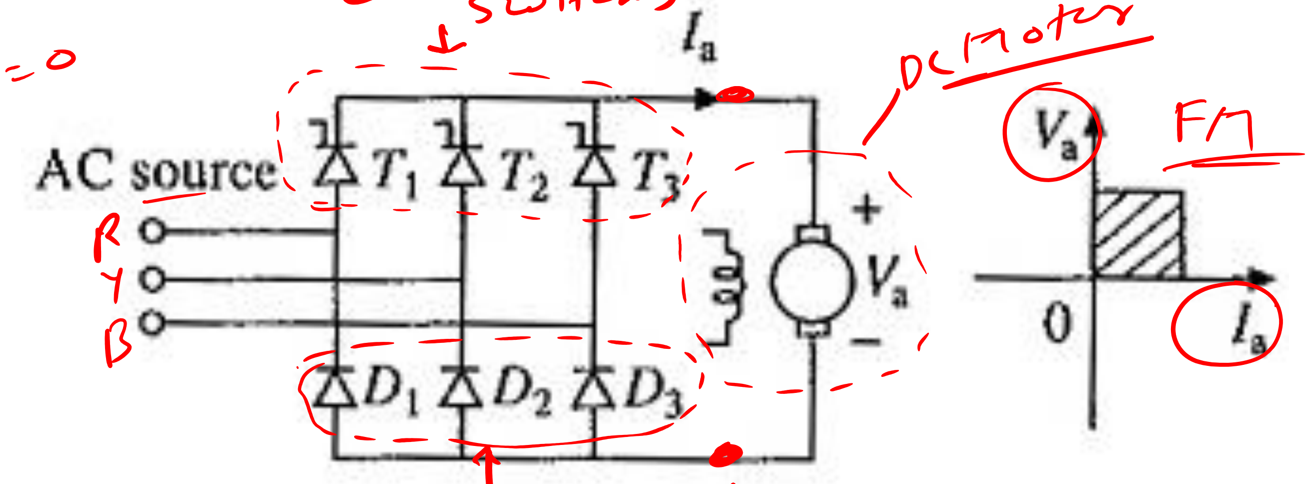


Fig. 1. Three-phase half-controlled rectifier fed DC motor.

DC Motor Reversing Switch Diagram

DC Motor Reversing Switch Diagram

- DC Motor Reversing Switch Diagram is shown in Fig. 1.

- A fully-controlled rectifier feeds the motor through a reversing switch RS which is used to reverse the armature connection with respect to the rectifier.

- A fully-controlled rectifier is capable of providing operation in quadrants I and IV.

- The reversal of the armature connection provides operation in quadrant III and II.

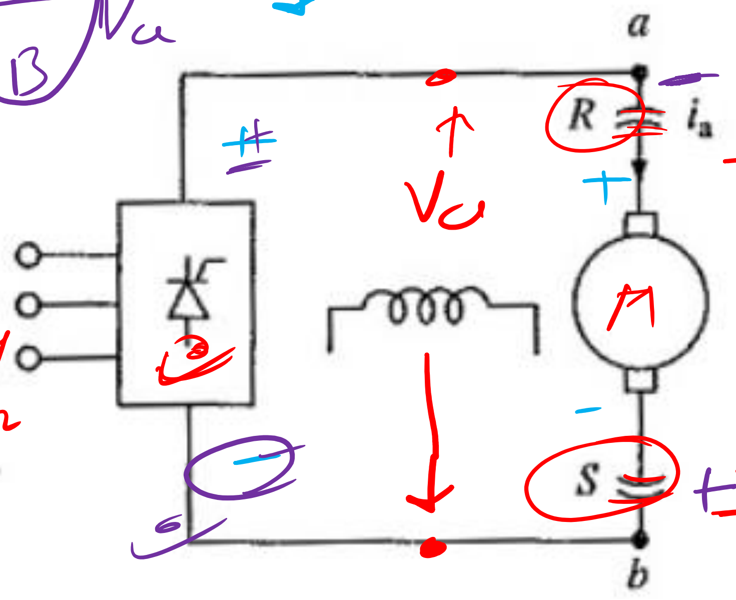


Fig. 1. Four quadrant drive employing single converter and reversing switch.

DC Motor Reversing Switch Diagram

The DC Motor Reversing Switch Diagram may consist of a relay-operated contactor with two normally open and two normally closed contacts as shown in Fig. 2.

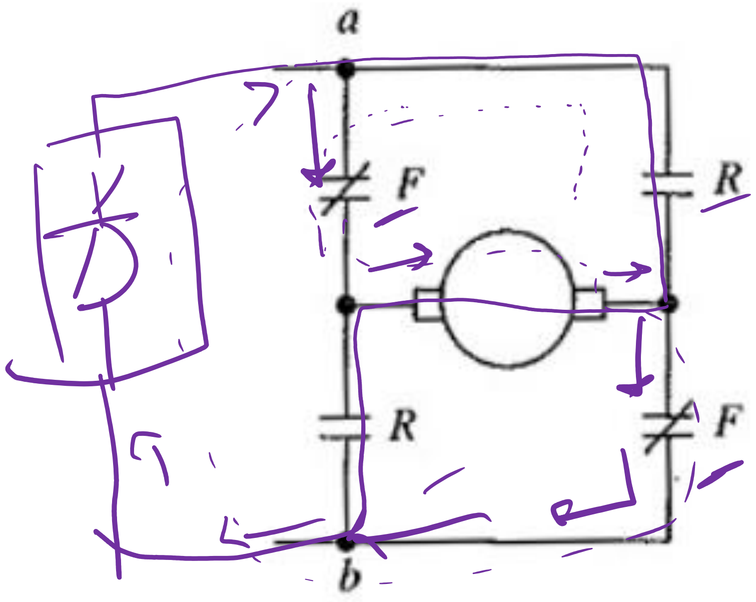


Fig. 2. Four quadrant drive employing single converter and reversing switch.

F → open terminal

R ⇒ closed terminals

DC Motor Reversing Switch Diagram

- When slow operation and frequent maintenance associated with the contactor is not acceptable, reversing switch is realized using four thyristors as shown in Fig. 3.

- With thyristor pair T_F on (and pair T_R off) operation is obtained in quadrants I and IV and with pair T_R on (and T_F off) the operation is provided in quadrants III and II.

- In both the configurations of RS, the switching is done at zero current in order to avoid voltage spikes and to reduce its rating.

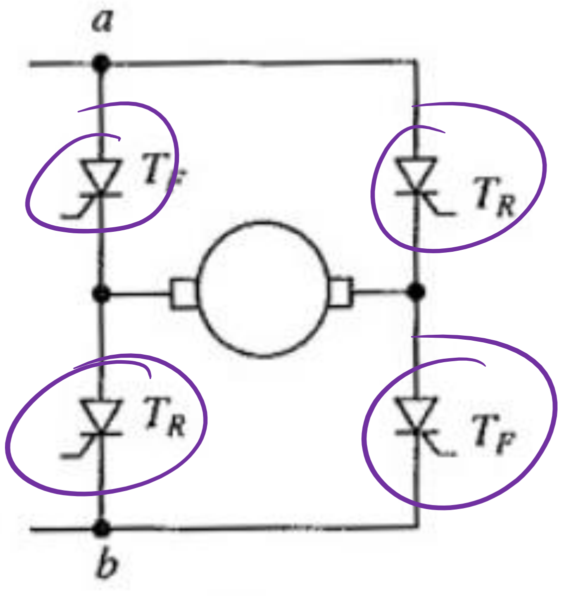
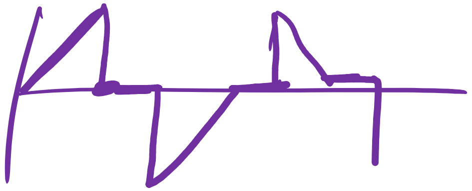


Fig. 3. Four quadrant drive employing single converter and reversing switch.

DC Motor Reversing Switch Diagram

- The speed reversal (transfer of operation from quadrant I to III or from quadrant III to I) is done as follows:
- The firing angle of the rectifier is set at the highest value. It works as an inverter and reduces armature current to zero.
- After the zero current is sensed, firing pulses are stopped.



- A delay time of 2 to 10 ms is provided to ensure that the thyristors conducted have all fully turned off.
- Such long delay (compared to thyristor turn-off time which is of few hundred micro-seconds) is required in order to take care of errors in zero current sensing.
- Now the armature connection is reversed and firing pulses are released with the firing angle set at the highest value.

DC Motor Reversing Switch Diagram

- The current control adjusts the firing angle continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates the motor (again at the maximum allowable current) to the desired speed in the reverse direction.

- The operation at the maximum current during speed reversal ensures braking and acceleration at the maximum motor torque ensuring fast reversal.

Dual Converter Control of DC Separately Excited Motor

Dual Converter Control of DC Separately Excited Motor

Fig. 1 shows a Dual Converter Control of a DC Separately Excited Motor consisting of two fully-controlled rectifiers connected in anti-parallel across the armature.

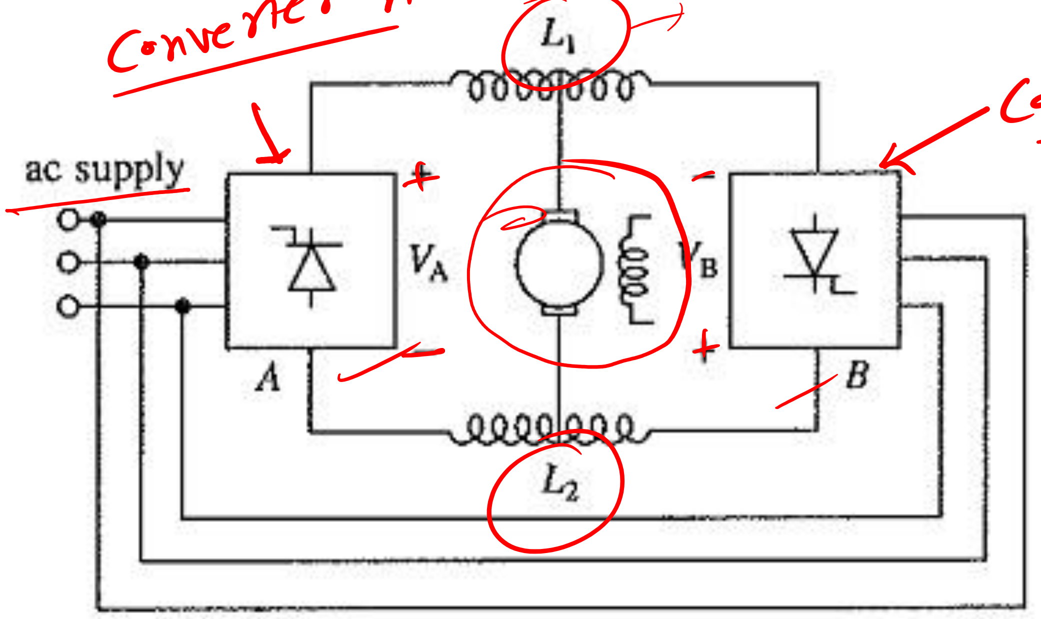


Fig. 3. Dual converter of DC separately excited motor. A and B are fully controller rectifiers. L1 and L2 are used with simultaneous control.

Dual Converter Control of DC Separately Excited Motor

- For power ratings up to around 10 kW, single-phase fully-controlled rectifiers can be used.

- For higher ratings, three-phase fully controlled rectifiers are employed.

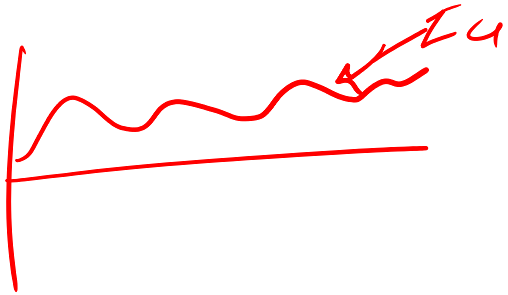
- Rectifier A, which provides positive motor current and voltage in either direction, allows motor control in quadrants I and IV,

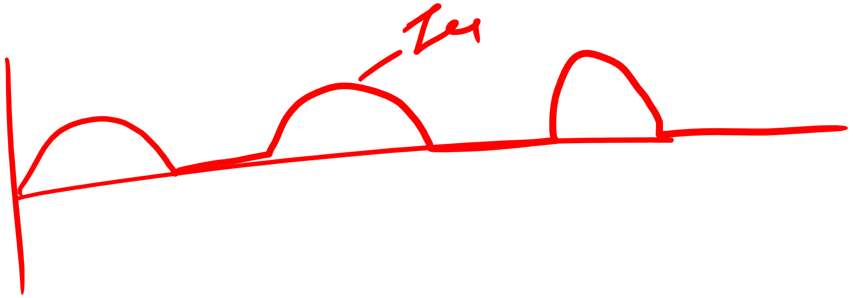
- Rectifier B provides motor control in quadrants III and II, because it gives negative motor current and voltage in either direction.

Dual Converter Control of DC Separately Excited Motor

There are two methods of control for the Dual Converter Control of DC Separately Excited Motor:

1. Circulation Conduction Mode
2. Non-Circulation Conduction Mode





Dual Converter Control of DC Separately Excited Motor

Circulation Conduction Mode

- In circulation control both the rectifiers are controlled together.
- In order to avoid DC circulating current between rectifiers, they are operated to produce the same dc voltage across the motor terminals. Thus
- $V_A + V_B = 0$ (1)
- Substituting from Eq. (2), yields

$$V_a = \frac{3}{\pi}\int_{\alpha+\pi/3}^{\alpha+2\pi/3} V_m \sin \omega t \, d(\omega t) = \frac{3}{\pi} V_m \cos \alpha \quad (2)$$

$$\cos \alpha_A + \cos \alpha_B = 0$$

$$\alpha_A + \alpha_B = 180^\circ \quad (3)$$

Dual Converter Control of DC Separately Excited Motor

- Although control of firing angle according to relation (3) prevents DC circulating current, AC does circulate due to the difference between instantaneous output voltages of the two rectifiers.
- Inductors L_1 and L_2 are added to reduce ac circulating current.
- Because of the flow of ac circulating current, simultaneous control is also known as circulating current control.
- In a three-phase dual converter, inductors are chosen to allow a circulating current of 30% of full load current. — How to select L_1 and L_2
- This completely eliminates discontinuous conduction, and therefore, gives good speed regulation in the complete range of the drive.

Dual Converter Control of DC Separately Excited Motor

The speed reversal is done as follows:

$\alpha_A + \alpha_B = 180^\circ$

- When operating in quadrant I, rectifier A will be rectifying ($0 < \alpha_A < 90°$) and rectifier B will be inverting ($90° < \alpha_B < 180°$).

- For speed reversal α_A is increased and α_B is decreased to satisfy eqn. 5.101. The motor back emf exceeds magnitudes of V_A and V_B.

  eqn. (3)

- The armature current shifts to rectifier B and the motor operates in quadrant II.

0 to 90° → First qua
90° to 180° → 2nd quadrant

Dual Converter Control of DC Separately Excited Motor

- The current control loop adjusts the firing angle α_B continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerate to the desired speed in the reverse direction.

- As α_B is changed, α_A is also changed to satisfy equation (3).

- The inductances L_1 and L_2 increase the weight, volume, cost and reversal time. The circulating current increases the losses.

- A sudden drop in source voltage can cause large current to flow through the rectifier working as inverter, blowing its thyristors.

Dual Converter Control of DC Separately Excited Motor

2. Non-circulation mode:

L_1 and L_2 not present in the circuit

- In a non-simultaneous or non-circulating current control method, one rectifier is controlled at a time.
- Consequently, no circulating current flows and inductors L_1 and L_2 are not required.
- This eliminates losses associated with circulating current and weight and volume associated with inductors.
- But then discontinuous conduction occurs at light loads and control is rather complex.

Dual Converter Control of DC Separately Excited Motor

The speed reversal is carried out as follows:

- When operating in quadrant I rectifier A will be supplying the motor and rectifier B will not be operating.
- The firing angle of rectifier A is set at the highest value.
- The rectifier works as an inverter and forces the armature current to zero. After zero current is sensed, a dead time of 2 to 10 ms is provided to ensure the turn-off of all thyristors of rectifier A.
- Now firing pulses are withdrawn from rectifier A and transferred to rectifier B. The firing angle α_B is set initially at the highest value.

Dual Converter Control of DC Separately Excited Motor

- Now onwards the current control loop adjusts the firing angle α_B continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the reverse direction.

- The dead time, and therefore, the reversal time can be reduced by employing methods that can sense the current zero accurately.

- When this is done non-simultaneous control provides faster response than simultaneous control.

- Because of this and the advantages stated above non-simultaneous control is widely used.

Drawbacks of Rectifier Fed DC Drives

Drawbacks of Rectifier Fed DC Drives

1. **Distortion of Supply:**

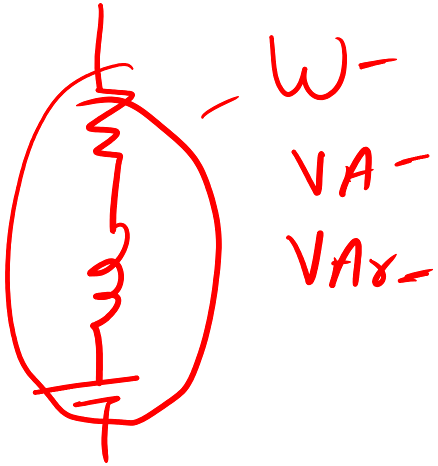
- The source current of a rectifier has harmonics. In a weak AC source, with high internal impedance, current harmonics distort source voltage.
- Furthermore, temporary short circuit of lines during the commutation of thyristors, causes sharp current pulses, which further distort source voltage.
- Source voltage and current distortions have several undesirable effects including interference with other loads connected to the source and radio frequency interference in communication equipment.

Drawbacks of Rectifier Fed DC Drives

2. Low power factor:

Assuming sinusoidal supply voltage, power factor (PF) of a rectifier can be defined as

$$PF = \frac{\text{Real Power}}{\text{Apparent Power}} = \frac{V I_1 \cos \phi_1}{V I_{rms}} \qquad (1)$$



where

V = rms source voltage in V

I_{rms} = rms source current in A

I_1 = fundamental component of source current in A

Φ_1 = phase difference between V and I_1, in rad

Therefore

$$PF = \frac{I_1}{I_{rms}} \cos \phi_1 = \mu \cos \phi_1 \qquad (2)$$

Drawbacks of Rectifier Fed DC Drives

- where μ is called the distortion factor and cos Φ_1 is the displacement factor.
- The distortion in source current makes μ lower than 1.
- When motor current is assumed to be perfect dc, Φ_1 has a value of α for fully controlled single-phase and three-phase rectifiers and α/2 for single phase half controlled rectifiers, thus giving displacement factors of cos α and cos α/2 respectively.
- Therefore, the supply power factor is low when the drive operates at low speeds.

Drawbacks of Rectifier Fed DC Drives

- Pulse width modulated rectifiers are being built using insulated gate bipolar transistors (IGBT) and gate turn-off thyristors (GTO) as they have high power factor and low harmonic content in source current but then their efficiency is low because of high switching losses.

Drawbacks of Rectifier Fed DC Drives

3. Ripple in Motor Current:

- The rectifier output voltage is not perfect dc but consists of harmonics in addition to dc component.
- Therefore, motor current also has harmonics in addition to dc component.
- The presence of harmonics, makes rms and peak values of motor currents higher than average value (dc component).
- Since flux is constant, torque is contributed only by the average value of current. The harmonics produce fluctuating torques, the average value of which is zero.

Drawbacks of Rectifier Fed DC Drives

- The presence of harmonics increases both copper loss and core loss.
- Hence for an allowable temperature rise, the torque and power outputs have lesser values than rated values.
- Due to the presence of harmonics, the peak value of the current increases and commutation condition deteriorates.
- Hence, the current that the motor can commutate without sparking at the brushes has a lower dc component than the rated motor current. Thus the derating of motor occurs due to this also.
- On the whole the motor output (power and torque) has to be restricted considerably below rated value in order to avoid thermal overloading and sparking at brushes.

DC to DC converter

Chopper Control of Separately Excited DC Motor

Chopper Control of Separately Excited DC Motor

Motoring Control:

- A transistor Chopper Control of Separately Excited DC Motor drive is shown in Fig. 1.

- Transistor T_r is operated periodically with period T and remains on for a duration t_{on}. Present-day choppers operate at a frequency that is high enough to ensure continuous conduction.

Buck converter Vo < Vin
Boost converter Vo > Vin
Buck-Boost converter Vo > Vin > Vo
Cuck converter

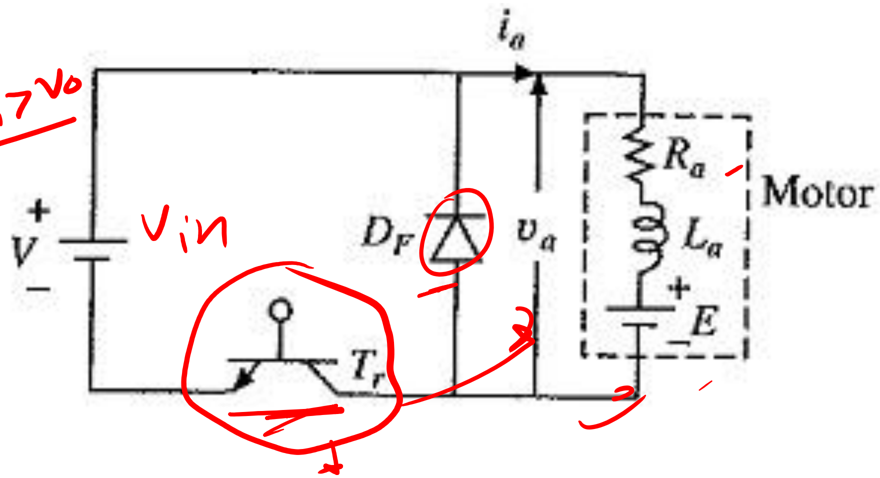


Fig. 1. Circuit diagram of chopper control of the separately excited motor.

Chopper Control of Separately Excited DC Motor

- Waveforms of motor terminal voltage v_a and armature current i_a for continuous conduction are shown in Fig. 2.

- During on-period of the transistor, $0 \leq t \leq t_{on}$, the motor terminal voltage is V.

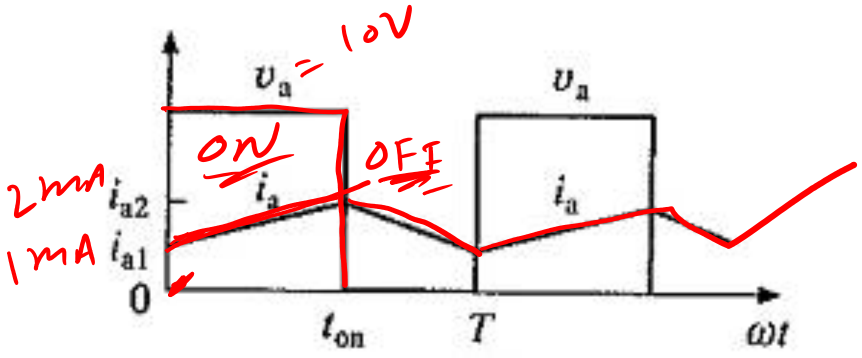


Fig. 1. Waveform of chopper control of the separately excited motor.

Chopper Control of Separately Excited DC Motor

The operation is described by

$$R_a i_a + L_a \frac{di_a}{dt} + E = V, \quad 0 \le t \le t_{on} \qquad (1)$$

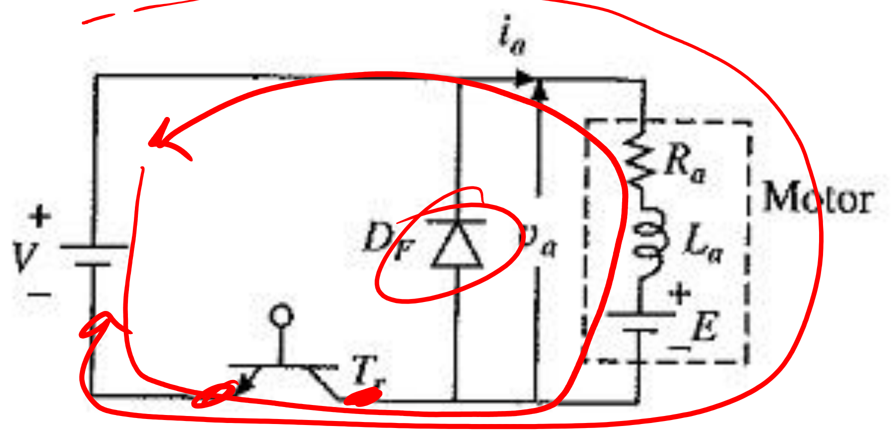


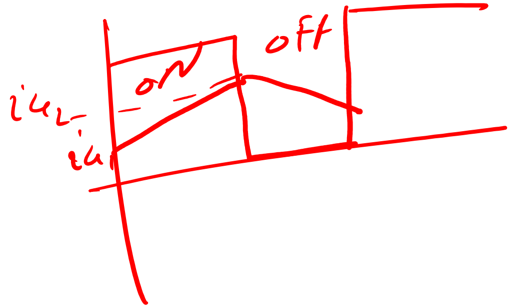
Fig. 1. Circuit diagram of chopper control of the separately excited motor.

- In this interval, the armature current increases from i_{al} to i_{a2}.
- Since the motor is connected to the source during this interval, it is called **Duty Interval**.

Chopper Control of Separately Excited DC Motor

- At $t = t_{on}$, T_r is turned-off.
- Motor current freewheels through diode D_F and motor terminal voltage is zero during interval $t_{on} \leq t \leq T$.
- Motor operation during this interval, known as freewheeling interval, is described by

$$R_a i_a + L_a \frac{di_a}{dt} + E = 0, \quad t_{on} \leq t \leq T \qquad (2)$$



Motor current decreases from i_{a2} to i_{a1} during this interval.

Chopper Control of Separately Excited DC Motor

Ratio of duty interval t_{on} to chopper period T is called **duty ratio or duty cycle** (δ). Thus

$$\delta = \frac{\text{Duty interval}}{T} = \frac{t_{on}}{T} \qquad (3)$$

$$V_a = \frac{1}{T}\int_0^{t_{on}} V\,dt = \delta V \qquad (4)$$

$$I_a = \frac{\delta V - E}{R_a} \qquad (5)$$

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2}T \qquad (6)$$

Key Points from Today's Class

- ❖ Three Phase Half Controlled Rectifier Control of DC Motor
- ❖ DC Motor Reversing Switch Diagram
- ❖ Dual Converter Control of DC Separately Excited Motor $\alpha_A + \alpha_B = 180^\circ$
- ❖ Drawbacks of Rectifier Fed DC Drives ① ② ③
- ❖ Chopper Control of Separately Excited DC Motor Buck Converter

Key Points from Next Class

In the next class, we will be discussing on the

- ❖ Regenerative Braking of Chopper fed DC Motor
- ❖ Speed Control of Three Phase Induction Motors

Boost converter

- ❖ Single Phase Half Controlled Rectifier Control of DC Motor

Thank you so much for your attentions

Q & A