Chapter 5: The DC Motor
Introduction

- DC motors transform electrical energy into mechanical energy
  - dc motors are found in many special industrial environments
- Motors drive many types of loads from fans and pumps to presses and conveyors
  - many loads have a definite torque-speed characteristic
  - other loads have a highly variable torque-speed characteristics
  - motors must be adapted to the type of loads to be driven
- Motor types
  - shunt, series, and compound connections
Motor Operation

• DC motors are built the same way as generators
  – Armature of a motor connected to a dc power supply
  – Current flows through the armature winding
  – Armature is within a magnetic field
  – A force is exerted on the windings

\[ F = B l I \]

  – The force causes a torque on the shaft
  – The shaft rotates
Counter EMF

- Rotating armature cuts through the magnetic field
- Voltage is induced in the armature windings
  \[ E = B l v \]
- The voltage opposes the flow of current
  \[ E_0 = \frac{Zn\Phi}{60} \]
- Power is taken from the electrical system
  \[ P_{arm} = E_0 I_{arm} \]
Acceleration of the Motor

- The net voltage acting on the armature circuit is: $E_S - E_0$

- The resulting armature current $I$ is limited only by the armature resistance
  \[
  I_a = \frac{(E_S - E_0)}{R_a}
  \]

- At rest, the induced voltage is zero: $E_{0,rest} = 0\, \text{V}$
  - the large current produces a large torque
    \[
    I_{a,rest} = \frac{E_S}{R_a}
    \]

- As speed increases, the counter *emf* increases and the voltage difference diminishes
  - resulting in a reduced current
Acceleration of the Motor

Example

- Separately excited dc motor has a resistance of 1 ohm and generates 50V at a speed of 500 rpm. If the armature is connected to a 150V supply, find:
  - the starting current
  - the counter-emf when the motor runs at 1000 rpm
  - the armature current at 1000 rpm
  - the counter-emf when the motor runs at 1460 rpm
  - the armature current at 1460 rpm
Machine Power and Torque

- Power and torque characteristics can be determined over various shaft speeds
  - calculate the counter emf
    \[ E_0 = \frac{Z n \Phi}{60} \]
  - calculate the armature power
    \[ P_{in} = P_a = E_s I_a \]
  - calculate the voltage drop (IR losses)
    \[ E_s = E_0 + I_a R_a \]
  - separate air gap power and losses
    \[ P_a = E_s I_a = E_0 I_a + I_a^2 R \]

- The mechanical power
  \[ P_m = E_0 I_a \]

- The developed torque
  \[ P_m = \frac{nT}{9.55} = E_0 I_a \]
  \[ E_0 = \frac{Z n \Phi}{60} \]
  \[ \frac{nT}{9.55} = \frac{Z n \Phi}{60} I_a \]
  \[ T = \frac{Z I_a \Phi}{6.28} \]
Machine Power and Torque

- Example
  - a 225 kW motor operates at 1200 rpm at 250 V
  - calculate the rated armature current and developed torque
Speed of Rotation

- We know that
  \[ E_0 = \frac{Z n \Phi}{60} \]
- The voltage drop across the armature resistance is always small compared to the supply voltage
  - even as the load varies from no-load to full-load
  - \( E_0 \) is approximately equal to \( E_S \)

\[ n = \frac{60 E_0}{Z \Phi} \approx \frac{60 E_S}{Z \Phi} \]
Armature Speed Control

• Speed is controlled by varying the armature voltage $E_S$

\[ n \approx \frac{60E_S}{Z \Phi} \]

• Motor speed changes proportionally to the armature voltage

• The armature voltage is controlled by an external variable power supply
  – the field winding is separately excited by a constant voltage source
Field Speed Control

- Speed is controlled by varying the field flux
  \[ n \approx \frac{60E_S}{Z\Phi} \]
  - assuming a constant armature supply voltage \( E_S \)

- Motor speed changes in inverse proportion to the flux
- The flux is controlled by a series rheostat \( R_f \) in the field circuit
Shunt Motor Under Load

• Consider a motor at no-load
• The application of a large mechanical load
  – the small armature current does not produce enough torque to carry the load
  – lacking torque the shaft speed decreases
  – the counter *emf* diminishes, causing the armature current to increase
  – higher armature current develops a larger torque
  – when the load and motor torques are equal, speed is constant

• Speed of a shunt motor stays relatively constant from no-load to full-load

• Example
  – find the armature current, counter emf, and mechanical power for a shunt motor running at 1500 rpm at 51A with a 120 V source, 120 ohm field winding, and 0.1 ohm armature resistance
Series Motor

- A series motor is identical in construction to a shunt motor except for the field windings
  - the field is connected in series with the armature and must carry the full armature current
- the performance is completely different
  - in a series motor the flux per pole depends upon the armature current (and the load)
  - the flux is proportional to the current
- At full-load the flux per pole is the same as that of the shunt motor
  - when the series motor starts, the armature current is higher than normal
  - the flux per pole is greater
  - the starting torque is considerably greater than for a shunt motor
Series Motor Speed Control

- Under light loading
  - the armature current and flux per pole are small
  - the weak field causes the speed to rise (over speed)
  - too small of loads may cause excess (run-away) speeds that can destroy the rotor (centrifugal force)

- Speed can be controlled by the current in the field winding
  - increase speed by placing a low resistance in parallel, reducing the field winding current
  - decrease speed by adding a series resistance, increasing the $IR$ drop
Series Motor Speed Control

• Example
  – a 15 hp, 240 V, 1780 rpm DC series motor has a full-load rated current of 54 A
  – its operating characteristics are given by the per-unit curves
  – find the current and speed when the load torque is 24 Nm
  – the efficiency under these conditions
Compound Motor

- Compound motors have both a series and shunt field windings
  - the shunt field is always stronger than the series field
  - in a cumulative compound motor the mmf of the two fields add
  - in a differential compound motor the series field is connected so the mmf opposes the mmf of the shunt field
Cumulative Compound Motor

- **Under no-load conditions**
  - the series field has a low current and the \( mmf \) is negligible
  - the shunt field is fully excited by \( I_X \), and the motor behaves like a shunt machine

- **As load increases**
  - the armature current passing through the series field generates a larger \( mmf \)
  - the shunt field remains constant, and the total \( mmf \) is greater than at no-load
  - the motor speed falls with increasing load
  - The motor speed changes from maximum at no-load to a 10%-30% minimum at full load
Homework

- 5-9, 5-10, 5-11, and 5-12