25-Series DC Motors
Text Chapter 6.1-6.5

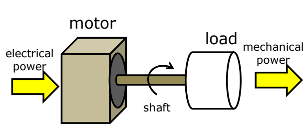
ECEGR 450
Electromechanical Energy Conversion

Overview

- Introduction
- DC Motor Operation
- Starting DC Motors
- Series Motor Model
- Torque vs Speed
- Speed Regulation

Introduction

- Motors: convert electrical energy into mechanical energy
- Physical construction of DC motors are the same as DC generators
  - Separately-excited DC motors are rare



Introduction

- DC motors are powered by a DC electrical system
- AC electrical systems are prevalent
  - AC/DC converters are available, but add cost
  - DC motors are used only when a specific application dictates their use

Introduction

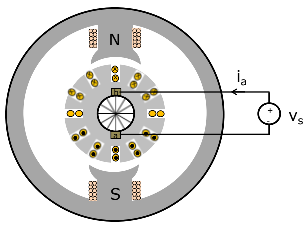
- Reasons to use DC motors
  - High starting torque
  - High speed operation
  - Easy to control the position of the shaft
- Applications:
  - Automobiles
  - Cranes
  - Subways
  - Computer printers

Operation of DC Motors

- Magnetic flux is established by permanent magnets or field windings (electromagnets)
- DC current is applied to the armature through brushes
- Interaction of the current in the armature and magnetic flux causes rotation

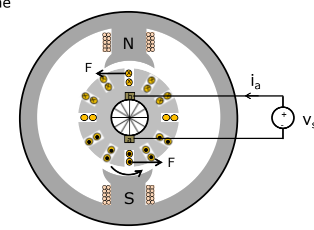
Operation of DC Motors

Which way does the rotor rotate?



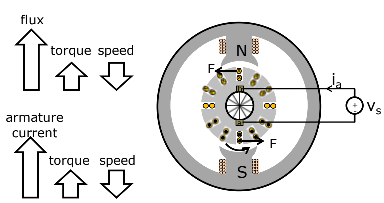
Operation of DC Motors

Which way does the rotor rotate?



Operation of DC Motors

Regardless of motor configuration, for a given power output:



Operation of DC Motors

- Recall developed torque is:

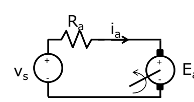
$T_d = K_a \phi_P i_a$

$K_a = \frac{PCN_c}{\pi a}$ (machine constant)

This is the same equation as the torque in a dc generator

- Recall back emf:

$E_a = K_a \phi_P \omega_m$



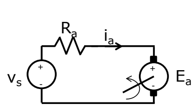
Operation of DC Motors

- Circuit equations:

$i_a = \frac{v_s - E_a}{R_a}$

$v_s = E_a + i_a R$

R_a is generally small, so v_s is slightly greater than E_a



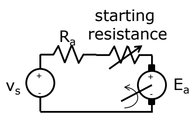
Starting DC Motors

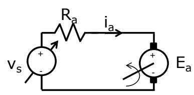
- Induced emf when motor is starting is zero
  $E_a = K_a \phi_P \omega_m$ (ω_m is 0)
- Large armature current will flow $i_a = \frac{v_s - E_a}{R_a}$
- Overheating and may damage the motor and/or dc source may occur
  - NEVER start a DC motor at its rated voltage!

How can we start a PM DC motor?

Starting DC Motors

- Insert a variable resistance in the armature circuit
  - Start at a high resistance and lower it as speed (and emf) increase
- Adjust v_s
  - Start at low value, and increase as speed increases





Armature Reaction

- Armature reaction for DC motors is nearly the same for DC generators
  - Important difference: current in the armature is in the opposite direction for given rotation direction

DC Motor Types

- There are several types of DC motors
  - Series
  - Shunt
  - Compound
- Different methods of connecting the field winding and armature winding

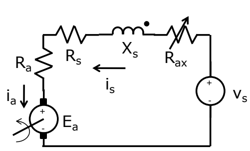
Series DC Motor

- Armature and field windings are connected in series to the same external source
- Flux is therefore related to the armature current
- An external variable resistance may be present to start or control the speed of the motor

Series Motor Model

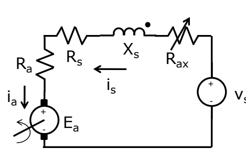
Field and armature windings are connected in series

- R_{ax}: variable starting/speed control resistance (Ohm)
- R_a: armature resistance (Ohm)
- R_s: field winding resistance (Ohm)
- X_s: series winding reactance (Ohm)
- v_s: voltage source (volts)
- E_a: armature back emf (volts)



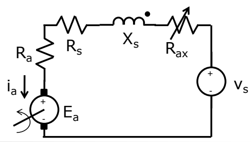
Series Motor Model

- Same current through the field winding and armature
  - $i_a = i_s$
- Armature current and flux increase and decrease together



Series Motor Model

- Analyzing the circuit
  $E_a = v_s - i_a(R_a + R_s + R_{ax})$
- Letting R be the total series resistance
  $E_a = v_s - i_a R$



Series Motor Model

- Pole flux and armature current relationship:
  $\phi_P = k_f i_a$
- From the dc motor equations:
  $E_a = K_a \phi_P \omega_m$
  $T_d = K_a \phi_P i_a$
- back emf:
  $E_a = K_a k_f i_a \omega_m$ Back emf is proportional to armature current
- torque:
  $T_d = K_a k_f i_a^2$

Question

Assume the power delivered by the motor is held constant. Qualitatively explain why increasing the armature current increases the torque and decreases the speed of the motor.

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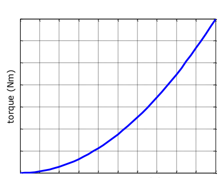
Increasing the armature current increases force on the armature conductors (Lorentz force), but it also increases the B field, so the force further increases. (Hence, the torque increase is proportional to the square of the current.) Since power is held constant, but torque is increased, the speed must decrease.

Series Motor Torque

Torque developed is proportional to the square of the armature current (assuming operation in linear permeability region) $T_d = K_a k_f i_a^2$



Series Motor Speed

Speed decreases as armature current increases:

$E_a = K_a k_f i_a \omega_m$

$\omega_m = \frac{E_a}{K_a k_f i_a} = \frac{V_s - i_a R}{K_a k_f i_a}$

Note: it is possible for a series motor to rotate so fast that it self destructs if operating without a load

Series Motor Power

Power developed by the motor is:

$$\omega_m = \frac{E_a}{K_a k_f i_a} = \frac{V_s - i_a R}{K_a k_f i_a}$$

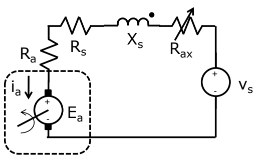
$$T_d = K_a k_f i_a^2$$

$$P_d = \omega_m T_d = \frac{V_s - i_a R}{K_a k_f i_a} K_a k_f i_a^2 = (V_s - i_a R) i_a = E_a i_a$$

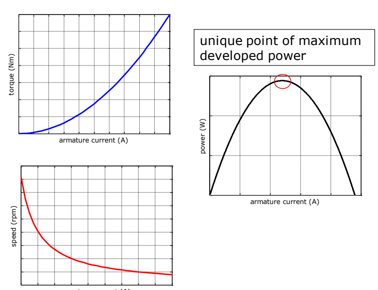
Series Motor Power

Power consumed by back emf voltage source = power developed by the motor

$$P_d = \omega_m T_d = E_a i_a$$



Series Motor Power



Series Motor Power

- What is the maximum power of the motor?

  $$P_D = E_a i_a = (v_s - i_a R) i_a$$

- Let the applied voltage be constant
- The maximum occurs when

  $$\frac{dP_d}{di_a} = 0$$

  $$\Rightarrow i_{a,max} = \frac{v_s}{2R}$$

- So the theoretical maximum power occurs when

  $$P_{d,max} = \frac{v_s^2}{4R}$$

Generally motors are operated below their maximum power point

Series Motor Torque vs Speed

- We can rewrite $\omega_m = \frac{v_s - i_a R}{K_a k_f i_a}$ as $i_a = \frac{v_s}{K_a k_f \omega_m + R}$
- Write an expression that relates the torque developed as a function of the speed of the rotor and applied voltage v_s

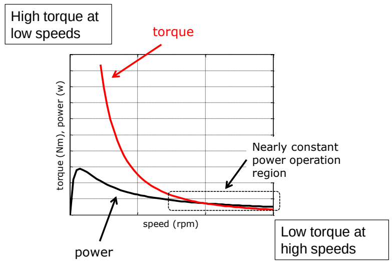
Series Motor

$$T_d = K_a k_f i_a^2$$

$$i_a = \frac{V_s}{K_a k_f \omega_m + R}$$

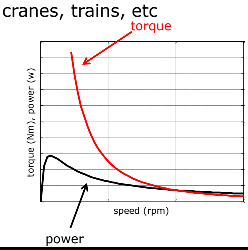
$$T_d = \frac{K_a k_f v_s^2}{[K_a k_f \omega_m + R]^2}$$

Series Motor



Series Motors

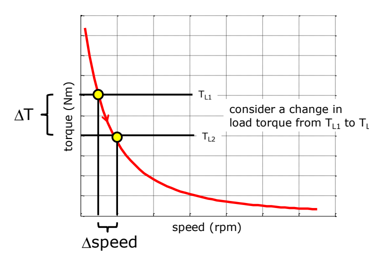
- Series motors are appropriate for loads with large starting torque
  - Hoists, cranes, trains, etc



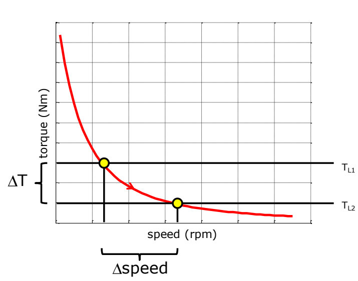
Speed Regulation

- What happens as the load torque on the motor increases?
- Is there a large change in speed, or is it nearly constant?

Speed Regulation



Speed Regulation



Speed Regulation

- Speed regulation is computed as:

$$SR = 100 \times \frac{\omega_{mnL} - \omega_{mfL}}{\omega_{mfL}} = 100 \times \frac{N_{mnL} - N_{mfL}}{N_{mfL}}$$

  - SR: speed regulation (%)
  - ω_{mnL}: speed under no load (rad/s)
  - ω_{mfL}: speed under full load (rad/s)
  - N_{mnL}: speed under no load (rpm)
  - N_{mfL}: speed under full load (rpm)

Speed Regulation

- Series DC motors are variable speed (large speed regulation)
- Shunt DC motors are nearly constant speed (small speed regulation)
- Compound DC motors: in between series and shunt motors

Example

A compound DC motor operates at 600 rpm under no load. At rated load the motor operates at 570 rpm. Compute the speed regulation.

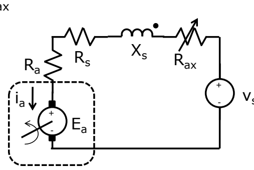
Example

A DC motor operates at 600 rpm under no load. At rated load the motor operates at 570 rpm. Compute the speed regulation.

$$SR = 100 \times \frac{N_{mnL} - N_{mfL}}{N_{mfL}} = 100 \times \frac{600 - 570}{570} = 5.26\%$$

Series Motor Control

- What are ways of controlling the speed of a series DC motor?
  - Adjust v_s
  - Adjust R_{ax}



Series Motor Control

- We can control the torque by adjusting the source voltage in accordance with:

$$T_d = \frac{K_a k_f V_s^2}{[K_a k_f \omega_m + R]^2}$$

- For a given speed, what happens to the torque if we double the applied voltage?

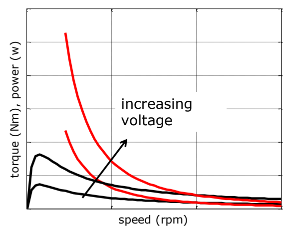
Series Motor Control

- We can control the torque by adjusting the source voltage in accordance with:

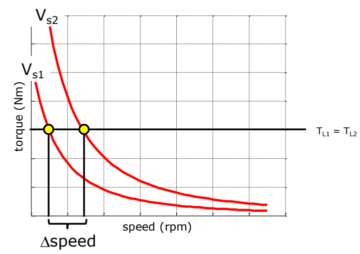
$$T_d = \frac{K_a k_f V_s^2}{[K_a k_f \omega_m + R]^2}$$

- For a given speed, what happens to the torque if we double the applied voltage?
  - Torque quadruples

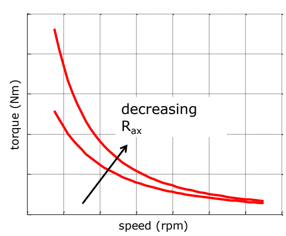
Series Motor Control



Series Motor Control



Series Motor Control



Summary

- Flux and armature current are directly related in series DC motors
- Series DC motors have high starting torque, but torque decreases with speed (near-constant power operation)
- DC motors should not be operated under no load, and should not be started at rated voltage