Xi'an Jiaotong-Liverpool University

EEE108 Electromagnetism and Electromechanics

Lecture 18

DC Motors

Dr. Jinling Zhang

Dept. of Electrical and Electronic Engineering
University of Xi'an Jiaotong-Liverpool
Email: jinling.zhang@xjtlu.edu.cn

Today

DC Motors

- •Equivalent Circuit
- •Major Types
- •Terminal Characteristics
- •Losses
- •Power Flow

DC Machinery

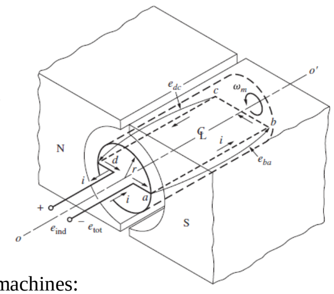
- ❖ DC power systems are not very common in the contemporary engineering practice.
- ❖ However, DC motors still have many practical applications, such as automobile, aircraft, and portable electronics, in speed control applications…
- ❖ An advantage of DC motors is that it is easy to control their speed in a wide region.
- ❖ Most DC machines are similar to AC machines: i.e. they have AC voltages and current within them. DC machines have DC outputs just because they have a mechanism converting AC voltages to DC voltages at their terminals. This mechanism is called a **commutator**; therefore, DC machines are also called **commutating machines**.

DC Machinery

DC motors convert DC electric energy to mechanical energy.

DC generators convert mechanical energy to DC electric energy.

The physical structure of the machine consists of 2 parts: the stator and the rotor.



There are two principal windings on a DC machines:

the armature windings and the field windings.

The armature windings: in which a voltage is induced, and located on the **rotor**

The field windings: produce the main magnetic flux, and located on the **stator**

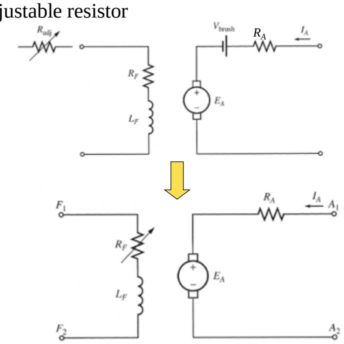
DC Machinery

For any DC machines:

The armature circuit is represented by an ideal voltage source E_A and a resistor R_A. This representation is the Thevenin equivalent of the entire rotor structure, including rotor coils, …

The field coils, which produce the magnetic flux in the machines are represented by inductor L_F and resistor R_F. The resistor R_{adj} represents an external variable resistor used to control the amount of current in the field circuit.

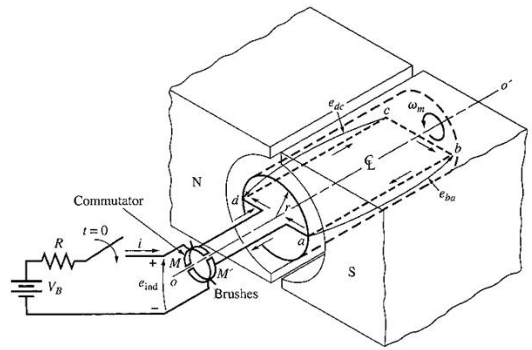
adjustable resistor



Field Circuit

Armature Circuit

DC Motors

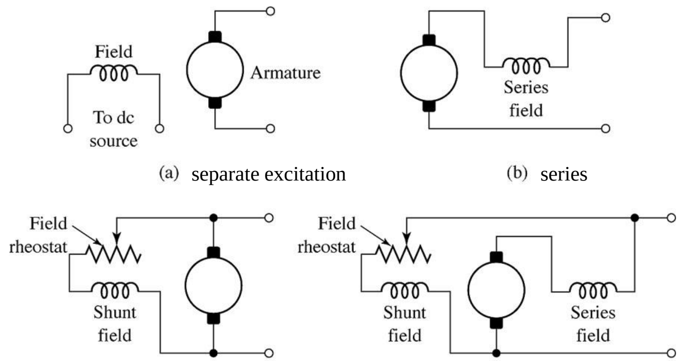


Five Major Types of DC Motors

There are five major types of DC motors in general use:

1. The separately excited DC motor
2. The shunt DC motor: the armature coils are connected in parallel with the field coils
3. The permanent-magnet DC motor
4. The series DC motor: the armature coils are connected in series with the field coils
5. The compounded DC motor: the armature coils are connected in series and parallel with the field coils

Field-circuit Connections of DC Motors



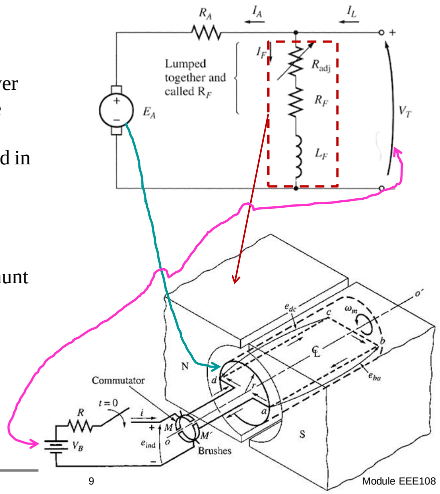
(a) separate excitation (b) series (c) shunt (d) compound

DC Shunt Motors

Equivalent Circuit

The shunt DC motors:

the field circuit gets its power directly across the armature terminals of the motor/ the armature coils are connected in ***parallel with the field coils***



The equivalent circuit of a shunt DC motor

$I_F = V_T/R_F$

$V_T = E_A + I_A R_A$

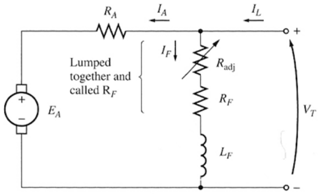
$I_L = I_A + I_F$

DC Shunt Motors

Terminal Characteristics

The terminal characteristic of a motor is a plot of its output torque versus speed.

Suppose that the load on the shaft of a shunt motor is increased. Then the load torque τ_{load} will exceed the induced torque τ_{ind} in the machine, and the motor will start to slow down.



When the motor slows down, its internal generated voltage drops ($E_A = K\Phi\omega\downarrow$), so the armature current in the motor $I_A = (V_T - E_A\downarrow)/R_A$ increases.

As the armature current rises, the induced torque in the motor increases ($\tau_{ind} = K\Phi I_A\uparrow$), and

finally the induced torque will equal the load torque at a lower mechanical speed of rotation.

DC Shunt Motors

Terminal Characteristics

The output characteristic of a shunt DC motor can be derived from the induced voltage and torque equations of the motor plus Kirchoff's voltage law (KVL).

From KVL: $V_T = E_A + I_A R_A$

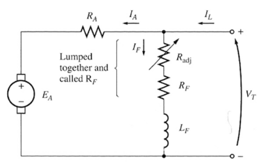
The induced voltage: $E_A = K\Phi\omega \quad \Rightarrow V_T = K\Phi\omega + I_A R_A$

The induced torque: $\tau_{ind} = K\Phi I_A \quad \Rightarrow I_A = \dfrac{\tau_{ind}}{K\Phi}$

$$\Rightarrow V_T = K\Phi\omega + \frac{\tau_{ind}}{K\Phi} R_A$$

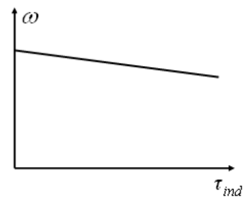
Then we can have the motor's speed:

$$\boxed{\omega = \frac{V_T}{K\Phi} - \frac{R_A}{(K\Phi)^2}\tau_{ind}}$$



DC Shunt Motors

Terminal Characteristics



$$\omega = \frac{V_T}{K\Phi} - \frac{R_A}{(K\Phi)^2}\tau_{ind}$$

This equation is a straight line with a negative slope.

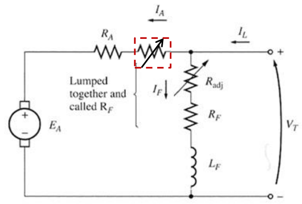
The terminal voltage supplied by the DC power source is assumed to be constant - if it is not constant, then the voltage variations will affect the shape of the torque-speed curve.

It is important to realize that, in order for the speed of the motor to vary linearly with torque, the other terms in this expression must be constant as the load changes.

DC Shunt Motors

Speed Control

$$\boxed{\omega = \frac{V_T}{K\Phi} - \frac{R_A}{(K\Phi)^2}\tau_{ind}}$$



Two common methods:

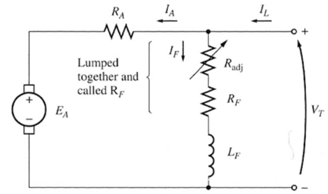
•Adjusting the field resistance R_F (and thus the field flux)
•Adjusting the terminal voltage applied to the armature.

Less common method:

Inserting a resistor in series with the armature circuit.

DC Shunt Motors

Speed Control - Changing the Field Resistance

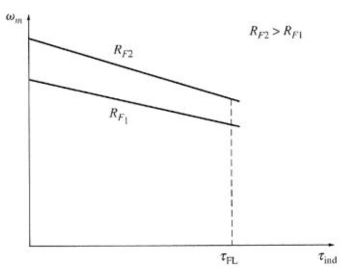


1. Increasing the field resistance R_F, → the field current I_F decreases ($I_F\downarrow = V_T/R_F\uparrow$).
2. As the field current I_F decreases, the flux Φ decreases as well.
3. A decrease in flux Φ causes an instantaneous decrease in the internal generated voltage $E_A\downarrow$ ($= K\,\Phi\downarrow\omega$).
4. Decreasing E_A causes a large increase in the machine's armature current $I_A\uparrow\uparrow$ ($= V_T - E_A\downarrow)/R_A$
5. Increasing I_A increases the induced torque τ_{ind} ($= K\,\Phi\downarrow I_A\uparrow\uparrow$)
6. Increasing τ_{ind} makes $\tau_{ind} > \tau_{load}$, and the speed ω increases.
7. Increasing speed ω causes the increasing $E_A = K\Phi\,\omega\uparrow$ again.

DC Shunt Motors

Speed Control - Changing the Field Resistance

8. Increasing E_A decreases I_A.
9. Decreasing I_A decreases τ_{ind} until $\tau_{ind} = \tau_{load}$ at a higher speed.



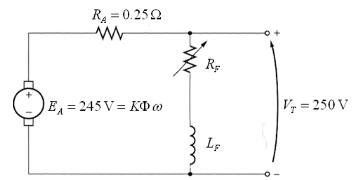
(a)

The effect of field resistance R_F speed control on a shunt motor's torque-speed characteristics over the motor's **normal operating range**

DC Shunt Motors

Speed Control - Changing the Field Resistance

Figure shows a shunt DC motor with an internal resistance of 0.25Ω. It is currently operating with a terminal voltage of 250V and an internal generated voltage of 245V. Therefore, the armature current flow is I_A = (250-245)/0.25= 20 A.



What happens in this motor if there is a 1% decrease in flux?

If the flux decrease by 1%, then E_A must decrease by 1% too, as $E_A = K\,\Phi\omega$
Therefore, E_A will drop to: $E_{A2} = 0.99\,E_{A1} = 0.99\,(245) = 242.55$ V

The armature current must then rise to
I_A = (250-242.55)/0.25 = 29.8 A

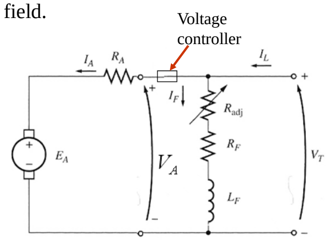
$$\boxed{\frac{29.8-20}{20}\times 100\% = 49\%}$$

A 1% decrease in flux produced a 49% increase in armature current.

The increase in current predominates over the decrease in flux. so $\tau_{ind} > \tau_{load}$, and the speed ω increases.

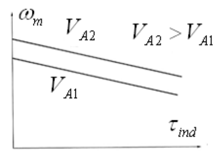
DC Shunt Motors
Speed Control - Changing the Armature Voltage

This method involves changing the voltage applied to the armature of the motor without changing the voltage applied to the field.



If the voltage V_A is increased, then the I_A must rise [$I_A = (V_A\uparrow - E_A)/R_A$].
As I_A increases, the induced torque τ_{ind} ($= K\Phi I_A\uparrow$) increases,
making $\tau_{ind} > \tau_{load}$, and
the speed of the motor increases.

As the speed increases, the E_A ($= K\,\Phi\omega\uparrow$) increases,
causing the armature current I_A to decrease.
This decrease in I_A decreases the induced torque,
causing $\tau_{ind} = \tau_{load}$ at a higher rotational speed.



Separately Excited DC Motors

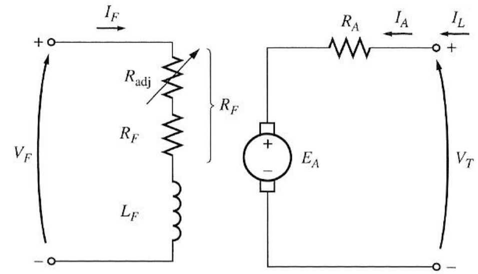
A separately excited DC motor is a motor whose field circuit is supplied from a separate constant-voltage power supply.

$$I_F = \frac{V_F}{R_F}$$

$$V_T = E_A + I_A R_A$$

$$I_L = I_A$$

The equivalent circuit



When the supply voltage to a motor is assumed constant, there is no practical difference in behaviour between a shunt DC motor and a separately excited DC motor.

Permanent-Magnet DC Motors

A permanent magnet DC motor (PMDC) is a DC motor whose poles are made of permanent magnets.

Advantage: Since the motors do not require an external field circuit, they do not have the field circuit copper losses. Because no field windings are required, they can be smaller than corresponding shunt DC motors.

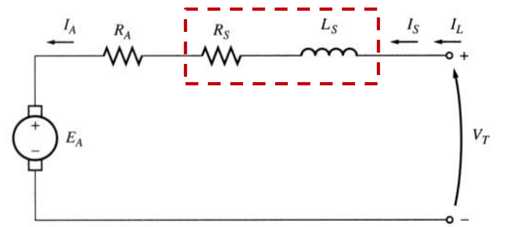
Disadvantages: Permanent magnets cannot produce as high flux density as an externally supplied shunt field, so a PMDC motor will have a lower induced torque per ampere of armature current than a shunt motor of the same size. Also, PMDC motors run the risk of demagnetization.

A PMDC motor is basically the same machine as a shunt DC motor, except that the flux of a PMDC motor is fixed. Therefore, it is not possible to control the speed of the PMDC motor by varying the field current or flux. The only methods of speed control available for a PMDC motor are armature voltage control and armature resistance control.

Series DC Motors

A series DC motor is a DC motor whose field windings are connected in series with the armature circuit.

The equivalent circuit of a series DC motor.



$$I_A = I_S = I_L$$

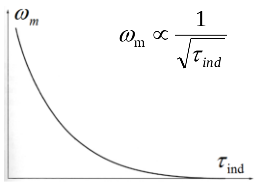
$$V_T = E_A + I_A\,(R_A + R_S)$$

The armature current, field current, and line current are all the same. The relationship of the voltages is: $V_T = E_A + I_A(R_A + R_S)$

Series DC Motors

Induced Torque

The induced torque is: $\tau_{ind} = K\Phi I_A$



The flux in this machine is directly proportional to its armature current (at least until metal saturates). Therefore, the flux in the machine can be given by $\Phi = cI_A$, where c is a constant of proportionality.

Thus the induced torque in a series DC motor:

$$\tau_{ind} = K\Phi I_A = KcI_A^2$$

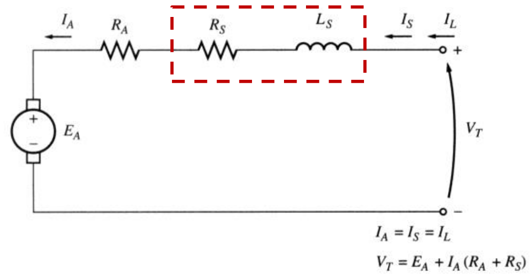
A series motor gives more torque per ampere than any other DC motor.

A series motor has the highest starting torque and tends to over speed at no load. It is used for very high-torque applications where speed regulation is not important, such as a car starter.

Series DC Motors

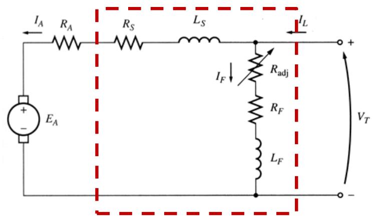
Speed Control

Unlike with the shunt DC motor, there is only one efficient way to change the speed of a series DC motor: to change the terminal voltage of the motor since the motor speed is directly proportional to its terminal voltage for any given torque.



Compounded DC Motors

A compounded DC motor is a motor with both a shunt and a series field. The equivalent circuits are:



The KVL for a compounded DC motor is:

$V_T = E_A + I_A (R_A + R_S)$

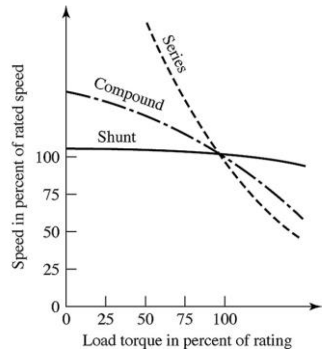
and the currents are:

$I_A = I_L - I_F$

$I_F = V_T/R_F$

Compounded DC Motors

Torque-Speed Characteristic



The compounded motor combines the best features of both the shunt and series motors. Like a series motor, it has extra torque for starting; like a shunt, it does not over speed at no load.

The torque-speed characteristic of a compounded DC motor compared to series and shunt motors with the same full-load rating.

Compounded DC Motors

Speed Control

The technique available for the control of speed in a compounded DC motor are the same as those available for a shunt motor:

1. Change the field resistance R_F
2. Change the armature voltage V_A
3. Change the armature resistance R_A

DC Motors

Speed Regulation

DC motors are often compared by their speed regulation.

The speed regulation is defined by:

$$SR = \frac{\omega_{m,nl} - \omega_{m,fl}}{\omega_{m,fl}} \times 100\% \quad \omega : \text{rad/sec}$$

or

$$SR = \frac{n_{m,nl} - n_{m,fl}}{n_{m,fl}} \times 100\% \quad n : \text{r/sec or r/min}$$

SR roughly reflects the shape of a motor's torque-speed characteristic.

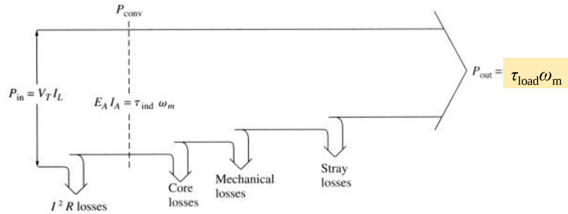
SR = 3 ~ 8%

Losses in DC Machines

The Losses in DC Machine:

1. **Electrical or Copper Losses** (I^2R Losses): the resistive losses in the armature and field windings of the machine:
   Armature loss: $P_A = I^2_A R_A$
   Field loss: $P_F = I^2_F R_F$
2. **Brush Losses**: the power lost across the contact potential at the brushes of the machine:
   $P_{BD} = V_{BD} I_A$
3. **Core Losses**: hysteresis and eddy current loss.
4. **Mechanical Losses**: losses associated with mechanical effects: friction and windage.
5. **Stray Loss**: losses that cannot be classified in any of the previous categories. For many machines, stray losses are assumed as 1% of full load.

DC Motor Power-flow Diagram



Electrical power is input to the machine, and the electrical and brush losses must be subtracted. The remaining power is ideally converted from electrical to mechanical form at the point labeled as P_{conv} : $P_{conv} = E_A I_A$

And the resulting mechanical power is $P_{conv} = \tau_{ind}\ \omega_m$

$$E_A I_A = \tau_{ind}\omega_m$$

After the power is converted to mechanical form, the stray losses, mechanical losses, and core losses are subtracted, and the remaining mechanical power is output to the load.

DC Motor Summary

•There are five types of DC motors: separately excited, shunt, permanent-magnet, series, and compounded.

•A shunt or separately excited DC motor has a torque-speed characteristic whose speed drops linearly with increasing torque. Its speed can be controlled by changing its field current, its armature voltage, or its armature resistance.

•A permanent-magnet DC motor is the same machine as above except that its flux is derived from permanent magnets. Its speed can be controlled by any of the above methods except varying the field current.

•A series DC motor has the highest starting torque and tends to over speed at no load. It is used for very high-torque applications where speed regulation is not important.

•A compounded DC motor is a compromise between the series and the shunt motor, having some of the best characteristics of each.

•There are five(four) categories of losses occurring in DC machines.

•Speed regulation roughly reflects the shape of a motor's torque-speed characteristic.

Next

- DC Generators
- Tutorial:
  Lab 2 Single-phase Transformers

Thanks for your attendance