CAN102

Electromagnetism and Electromechanics

2023/24-S2

Lecture 17 DC Motors

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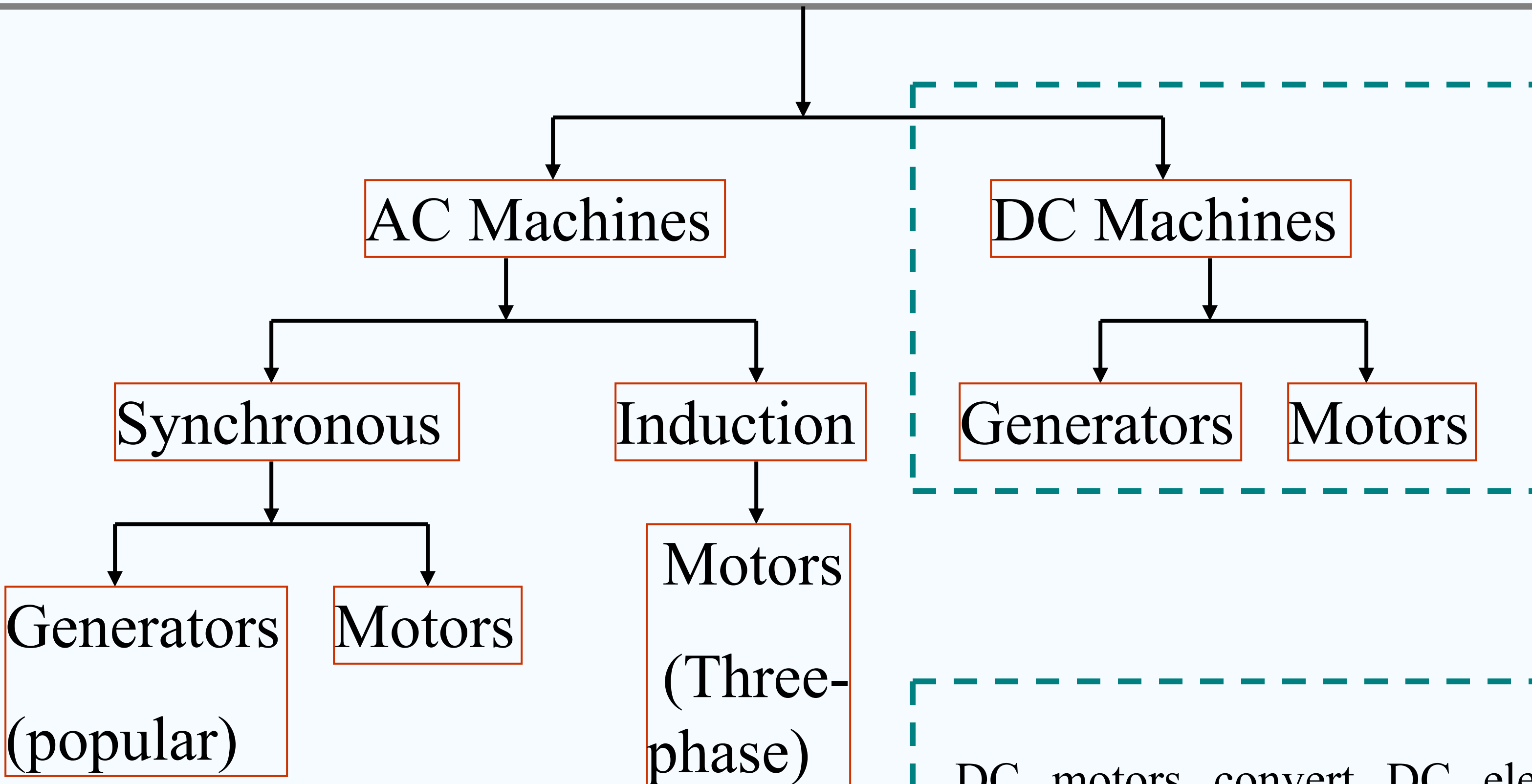
Electrical Machines

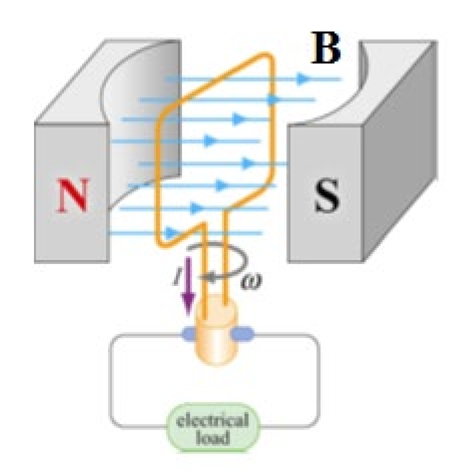


DC motors convert DC electric energy to mechanical energy.

DC generators convert mechanical energy to DC electric energy.

Introduction

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

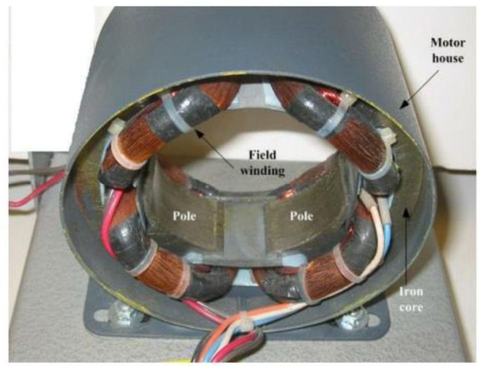


There are two principal windings on a DC machines:

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**

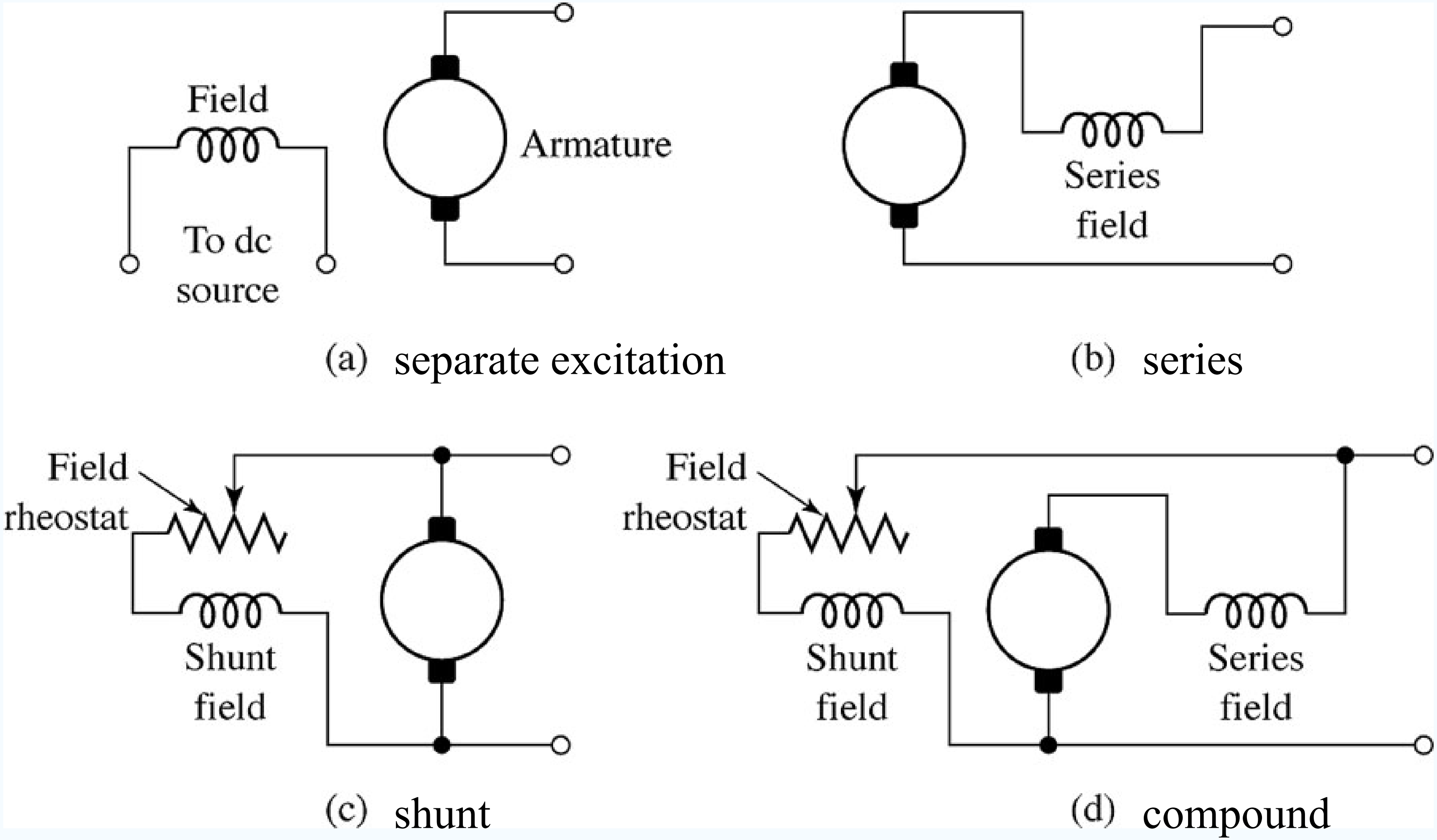


Five Major Types of DC Motors

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

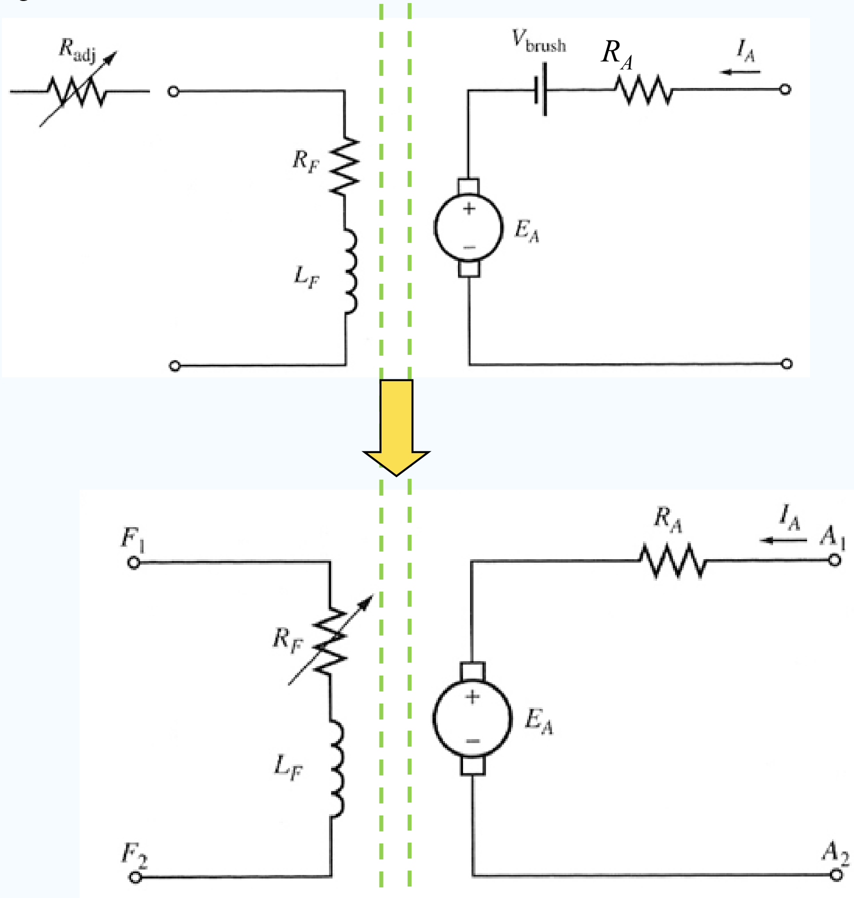
1. The separately excited (自励) DC motors
2. The shunt (并励) DC motors: the armature coils are connected in **parallel** with the field coils
3. The permanent-magnet (永磁) DC motors
4. The series (串励) DC motors: the armature coils are connected in **series** with the field coils
5. The compounded (复励) DC motors: the armature coils are connected in **series and parallel** with the field coils

Field-circuit Connections of DC Motors



General Equivalent Circuit

adjustable resistor



Field Circuit

Armature Circuit

For any DC machines:

armature circuit

E_A :an ideal voltage source (internal generated voltage)

R_A : a resistor of armature windings

I_A: armature current

V_{brush}: the brush voltage drop opposing the direction of the current flow in the machine

field circuit

L_F : an inductor produces the magnetic flux in the machine

R_F : a resistor of field windings

R_{adj} :an external variable resistor used to control the amount of current in the field circuit.

Summary (Recall)

The total induced voltage

$$e_{ind} = \begin{cases} 2rlB\omega & \text{under the pole face} \\ 0 & \text{beyond the pole edges} \end{cases}$$

$$e_{ind} = \begin{cases} \frac{2}{\pi}\Phi\omega & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

where $\Phi = \pi rlB = A_p B$

The induced voltage in any real machine will depend on the same 3 factors:
1. The flux in the machine
2. The speed of rotation
3. A constant representing the construction of the machine.

$$e_{ind} = K\Phi\omega$$

The total induced torque

$$\tau_{ind} = \begin{cases} 2rlBi & \text{under pole faces} \\ 0 & \text{beyond pole edges} \end{cases}$$

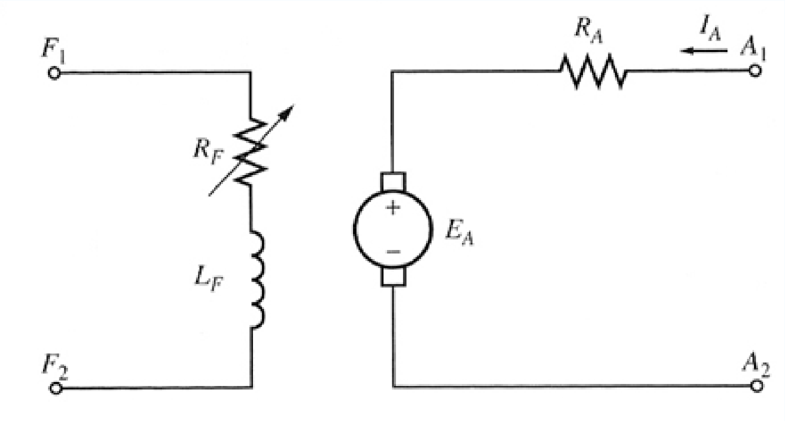
$$\tau_{ind} = \begin{cases} \frac{2}{\pi}\Phi i & \text{under pole faces} \\ 0 & \text{beyond pole edges} \end{cases}$$

where $\Phi = \pi rlB = A_p B$

The torque in any real machine will depend on the same 3 factors:
1. The flux in the machine
2. The current in the machine
3. A constant representing the construction of the machine.

$$\tau_{ind} = K\Phi i$$

Circuit Analysis



Field Circuit

Armature Circuit

- Internal generated voltage

$$E_A = K\Phi\omega_m$$

- Induced torque developed by the machine

$$\tau_{ind} = K\Phi I_A$$

- Kirchhoff's voltage law equation of armature circuit

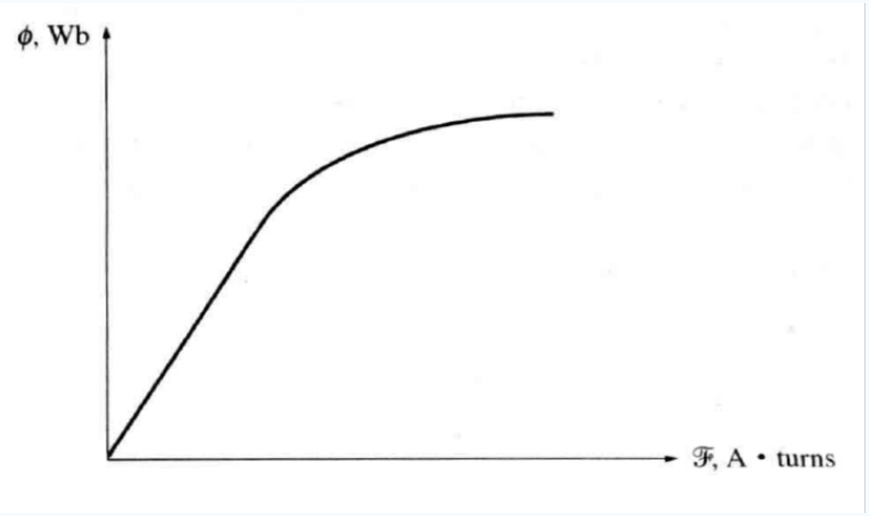
- Magnetization curve about E_A-I_F relation

Magnetization Curve

The filed current in a dc machine produces a field magnetomotive force is given by

$$F = N_F I_F = \Phi \Re_F$$

This magnetomotive force produces a flux in the machine in accordance with its magnetization curve



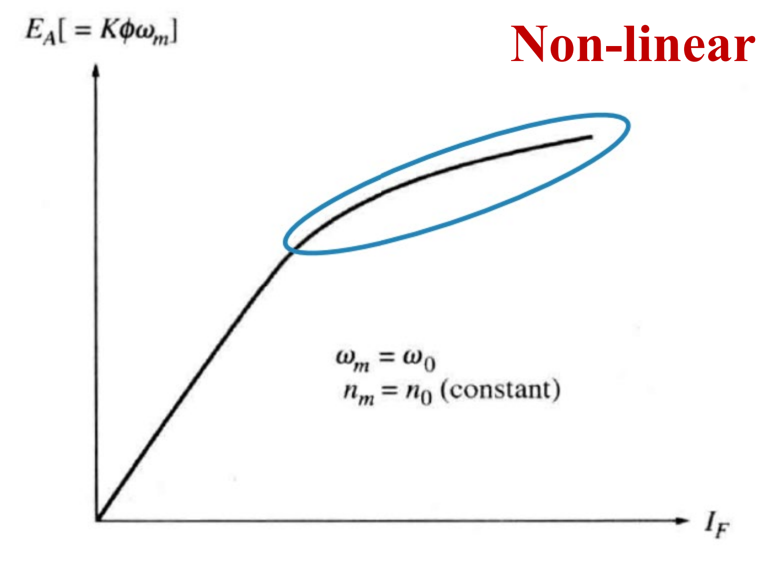
Non-linear

The magnetization curve of a ferromagnetic material

Magnetization Curve

$$(mmf)\ F = N_F I_F = \Phi \Re_F$$

$$E_A = K\Phi\omega_m = K\frac{F}{\Re_F}\omega_m = K\omega_m\frac{N_F}{\Re_F}I_F$$



The relationship between E_A and I_F

- In practice, however, E_A is nonlinear with respect to I_F due to magnetization curve. The magnetomotive force in a machine has a nonlinear effect on the internal generated voltage of the machine.
- To get the maximum possible power per pound of the weight, most motors and generators are designed to operate near the saturation point on the magnetization curve.
- A fairly large increase in the field current is often necessary to get a small increase in E_A near full load operation.

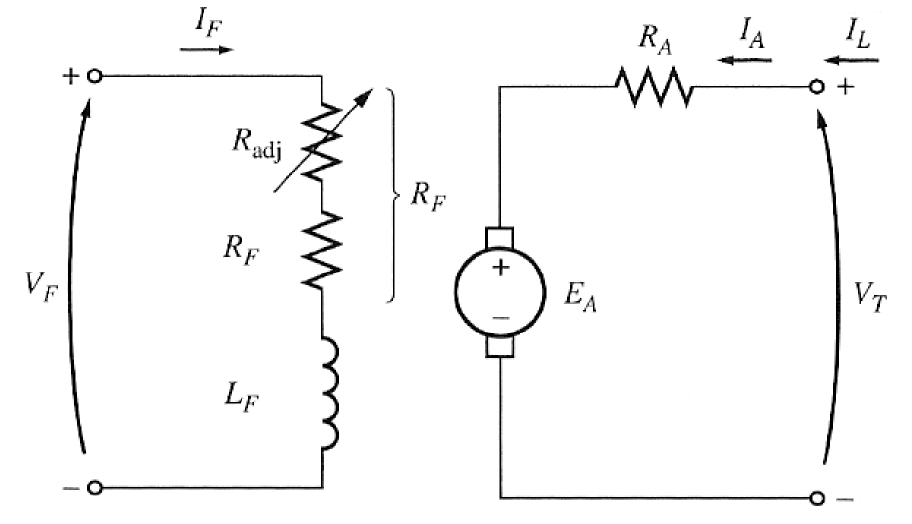
Separately Excited DC Motors

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

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

$$V_T = E_A + I_A R_A$$

line current $$I_L = I_A$$

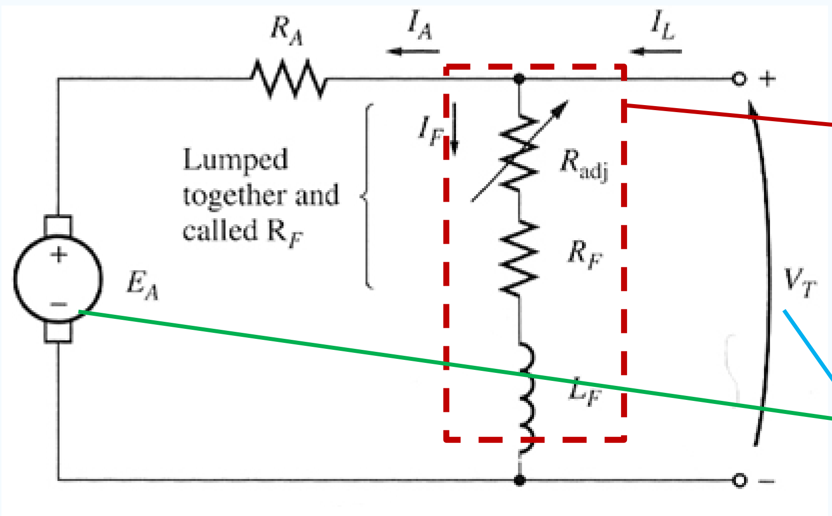


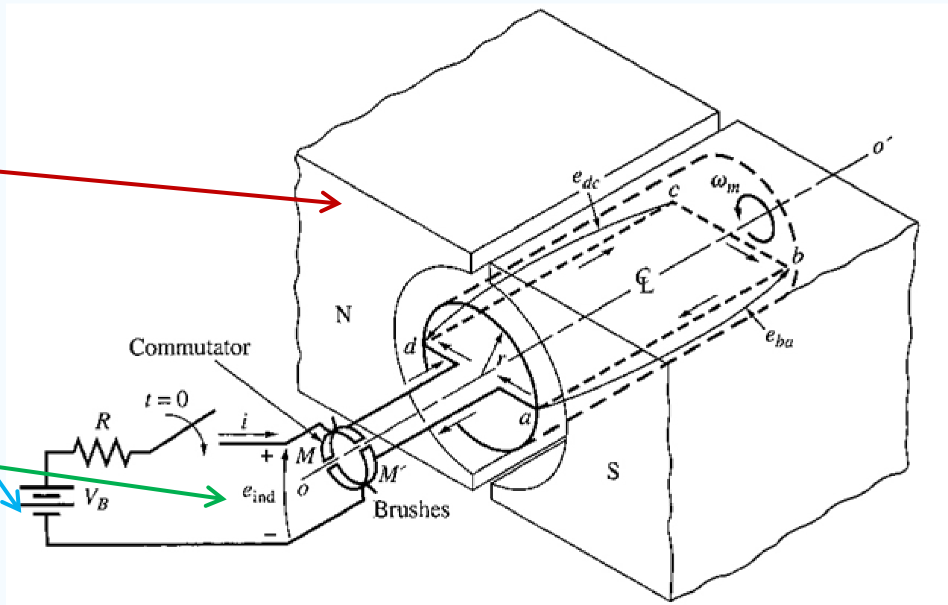
Line current is the total current flowing from the power source to the motor or from the motor back to the power source. It represents the sum of all currents flowing through the different windings and components of the motor.

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

Shunt DC Motors

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***





$$I_F = V_T/R_F$$

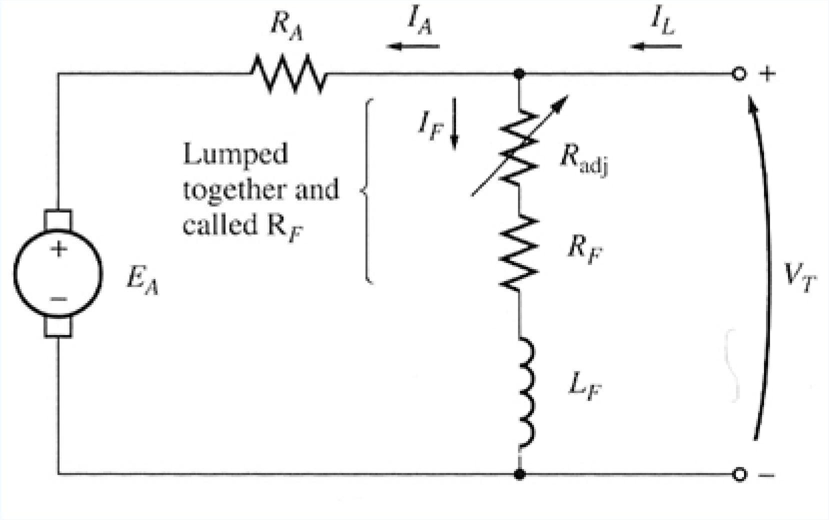
$$V_T = E_A + I_A R_A$$

$$I_L = I_A + I_F$$

Shunt DC 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.

Shunt DC 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: $V_T = E_A + I_A R_A$

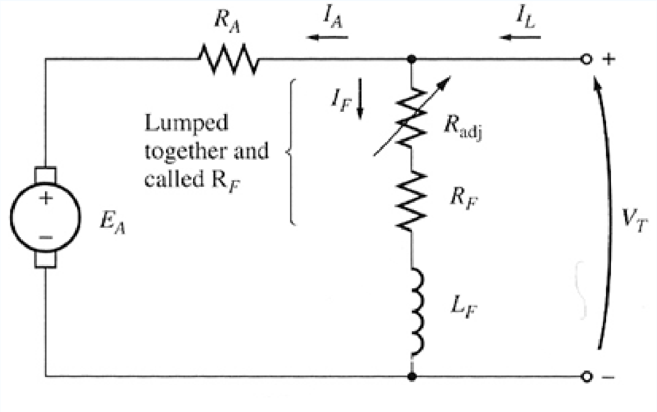
The induced voltage: $E_A = K\Phi\omega \quad \Rightarrow V_T = K\Phi\omega + I_A R_A$

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:

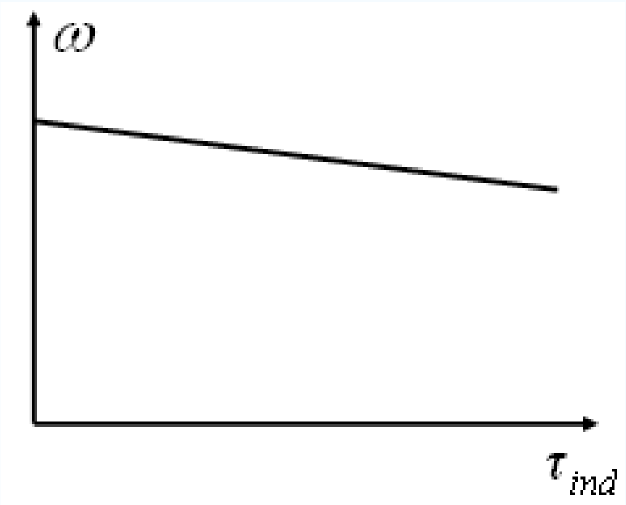
$$\boxed{\omega = \frac{V_T}{K\Phi} - \frac{R_A}{(K\Phi)^2}\tau_{ind}}$$



Shunt DC Motors-Terminal Characteristics

Torque-speed characteristics

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.

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

This equation is a straight line with a negative slope.

Shunt DC Motors-Nonlinear Analysis

The magnetomotive force or field current in a machine will have a nonlinear effect on the internal generated voltage of the machine.

If a machine has armature reaction, its flux will be reduced with each increase in load, causing E_A to decrease.

The total equivalent magnetomotive force in a shunt dc motor is the field circuit magnetomotive force less the magnetomotive force due to armature reaction (AR).

$$F_{total} = N_F I_F - F_{AR}$$

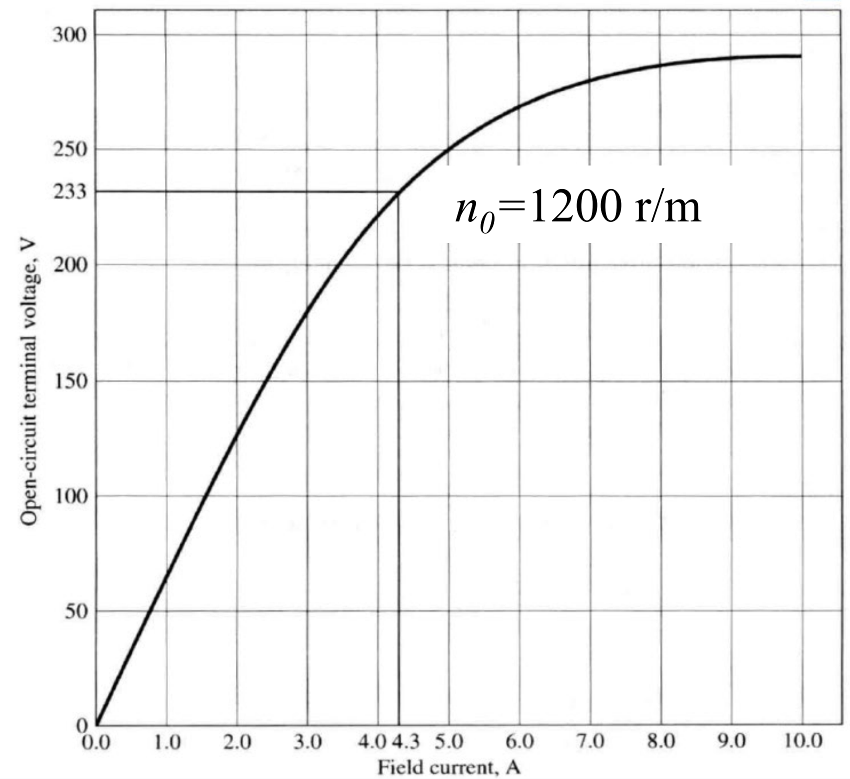
The equivalent actual field current is given by

$$I_F^{*} = I_F - \frac{F_{AR}}{N_F}$$

Shunt DC Motors-Nonlinear Analysis

- To accurately determine its EA for a given magnetomotive force, the magnetization curve of the machine must be used.
- For a given effective filed current, the flux in a machine is fixed, so the internal generated voltage is related to speed by

$$\boxed{\frac{E_A}{E_{A0}} = \frac{\omega_m}{\omega_0} = \frac{n_m}{n_0}}$$

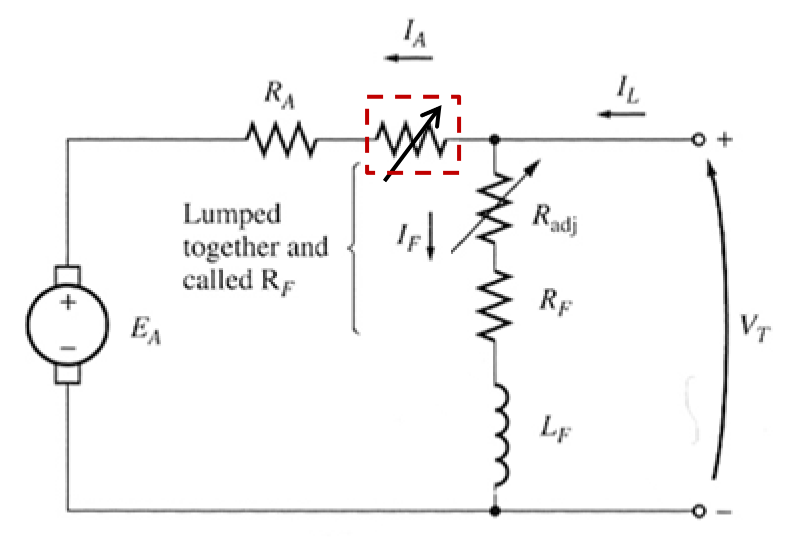


the magnetization curve is a direct plot of E_A versus I_F for a given speed.

Where E_{A0} and n_0 represent the reference values of voltage and speed, respectively

Shunt DC Motors-Speed Control

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



Two common methods:

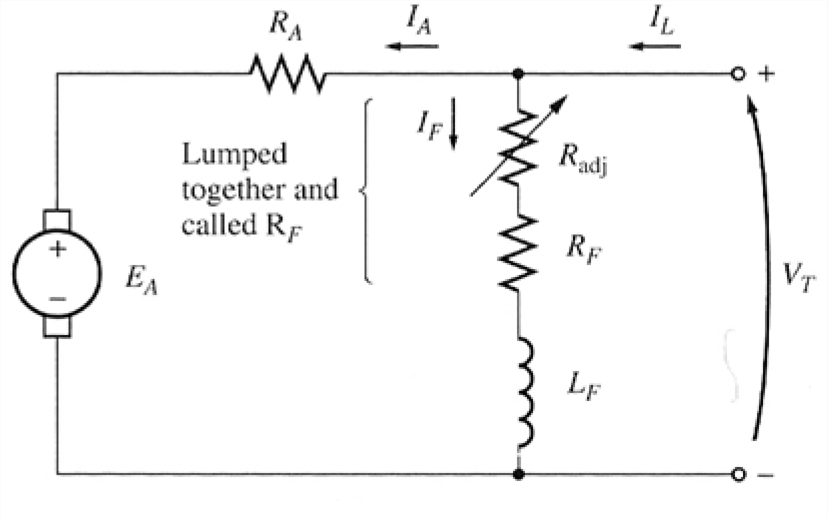
- Adjusting the field resistance R_F (and thus the field flux)
- Adjusting the terminal voltage applied to the armature.

Less common method:

Inserting a resistor in series with the armature circuit.

Shunt DC Motors

Speed Control - Changing the Field Resistance



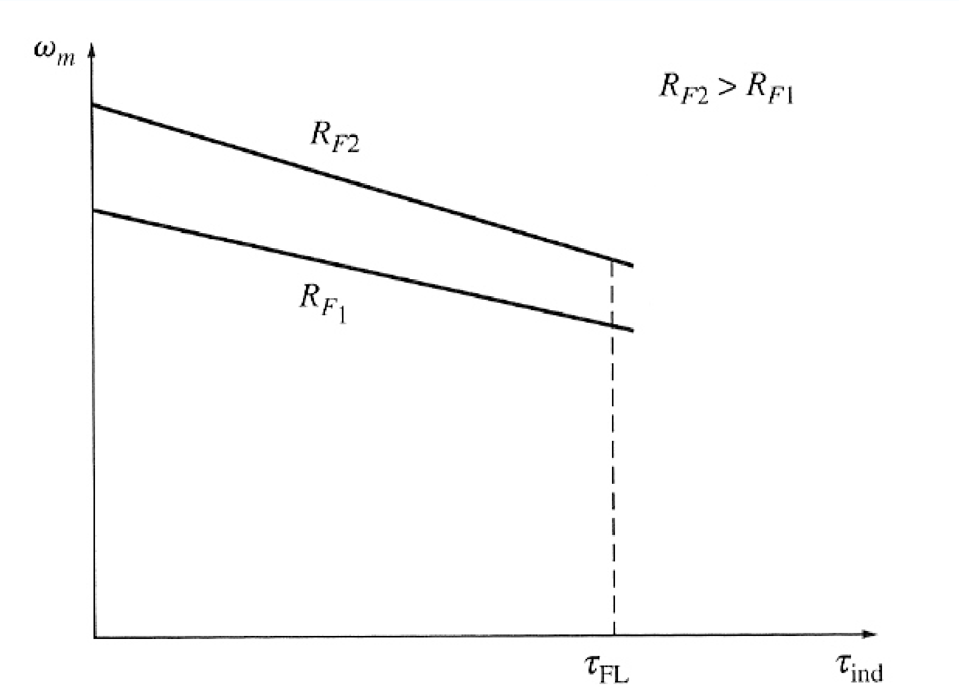
1. Increasing the field resistance R_F, → the field current I_F decreases ($I_F\downarrow = V_T/R_F\uparrow$).
2. As the field current I_F decreases, the flux Φ decreases as well.

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} ($= K\,\Phi\downarrow I_A\uparrow\uparrow$), with the change in dominant over the change in flux

Speed Control - Changing the Field Resistance

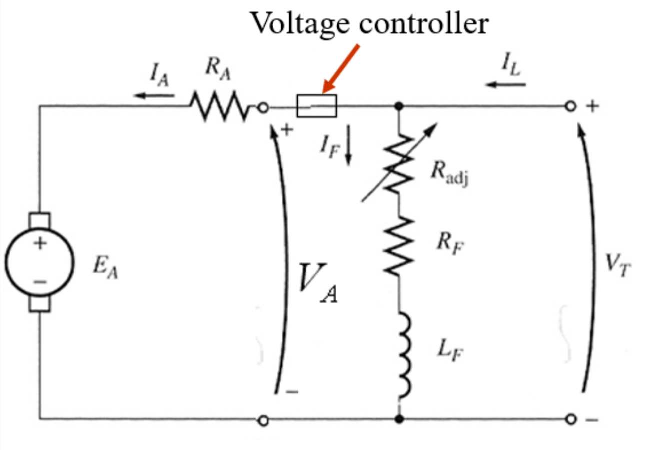
6. Increasing τ_{ind} makes $\tau_{ind} > \tau_{load}$, and the rotational speed ω increases.
7. Increasing rotational speed ω causes the increasing $E_A = K\Phi\,\omega\uparrow$ again.
8. Increasing E_A decreases I_A.
9. Decreasing I_A decreases τ_{ind} until $\tau_{ind} = \tau_{load}$ at a higher speed.



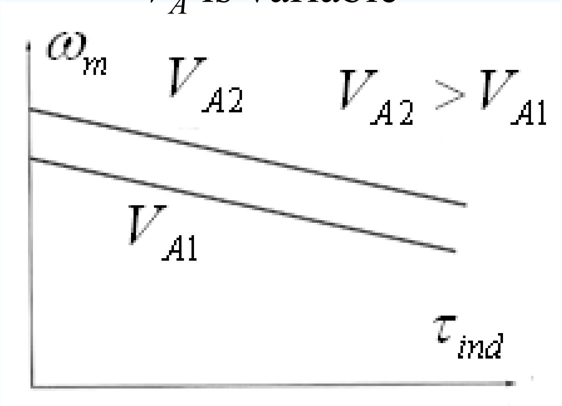
The effect of field resistance R_F speed control on a shunt motor's torque-speed characteristics over the motor's **normal operating range**

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.



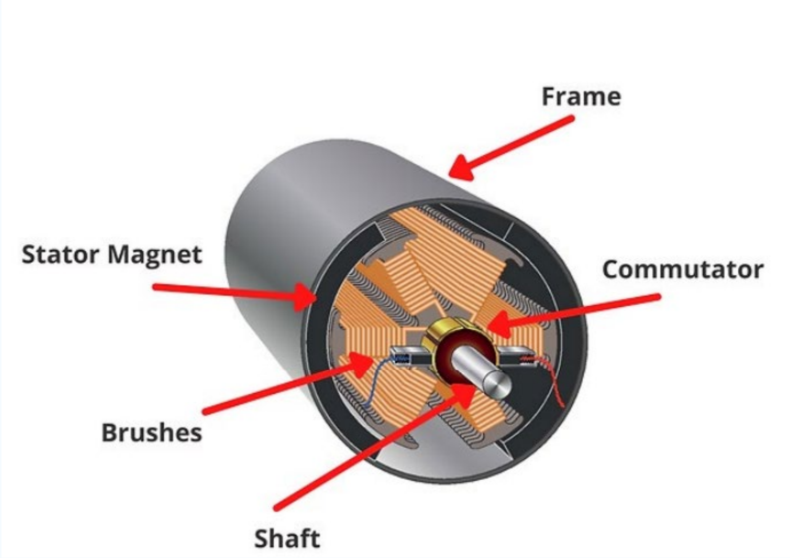
V_T is constant
V_A is variable



1. An increase in V_A increases I_A [$I_A = (V_A \uparrow - E_A)/R_A$].
2. As I_A increases, the induced torque τ_{ind} (= $K\Phi I_A\uparrow$) increases
3. Increasing τ_{ind} makes $\tau_{ind} > \tau_{load}$, increasing rotational speed ω.
4. Increasing speed ω increases E_A (= $K\,\Phi\omega\uparrow$)
5. Increasing E_A decreases I_A [$I_A = (V_A - E_A\uparrow)/R_A$]
6. This decrease in I_A decreases the induced torque, causing $\tau_{ind} = \tau_{load}$ at a higher rotational speed.

Permanent – Magnet DC motors

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



A PMDC motor is basically the same machine as a shunt DC motor, except that the flux of a PMDC motor is fixed.
Methods of speed control - **armature voltage** control and **armature resistance** control, not varying the field current or flux as shut DC motors.

Benefits:

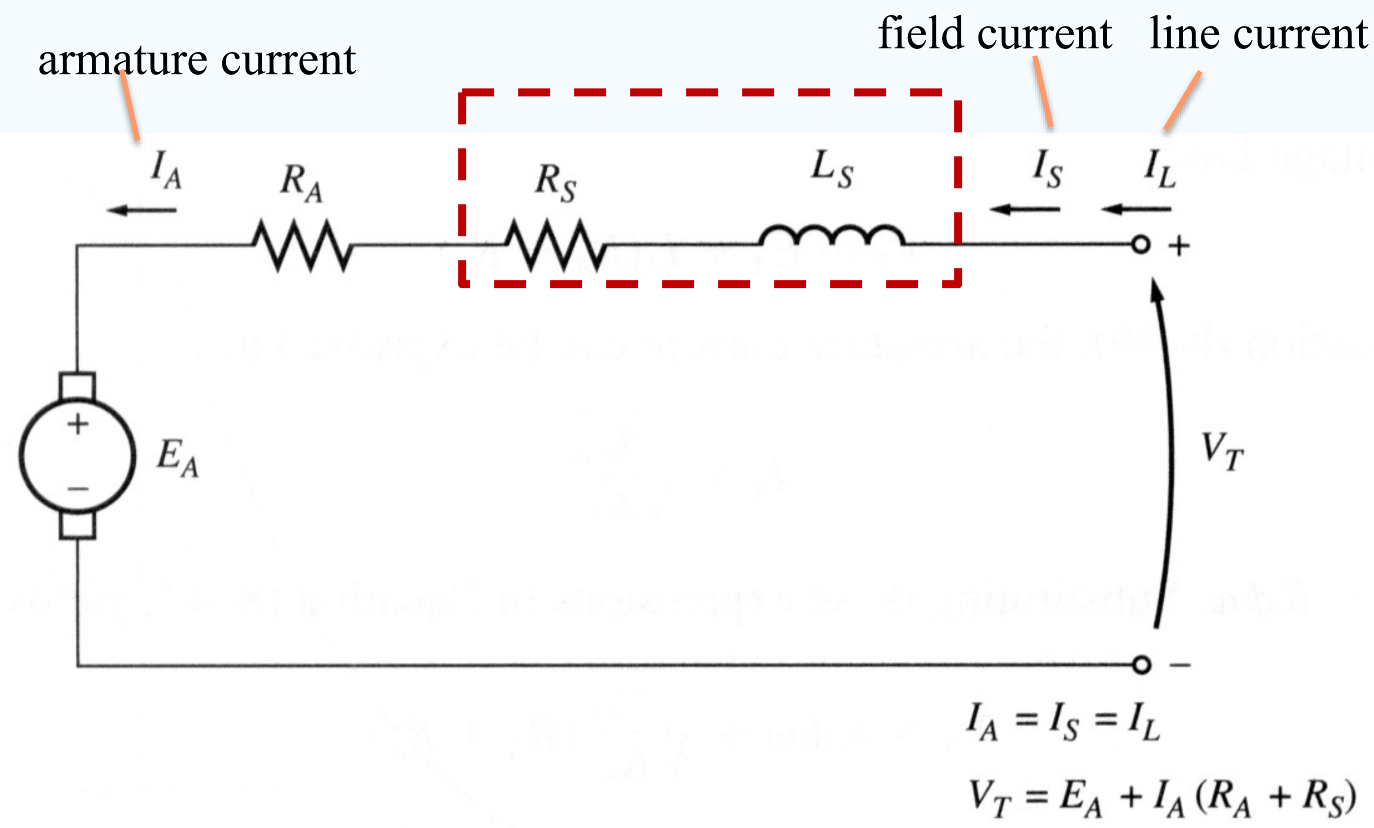
- ✓ do not require an external field circuit;
- ✓ do not have the field circuit copper losses;
- ✓ no field windings are required;
- ✓ be smaller than corresponding shunt DC motors.

Drawbacks:

- permanent magnets cannot produce as high flux density as an externally supplied shunt field,
- have a lower induced torque per ampere of armature current than a shunt motor of the same size.
- run the risk of demagnetization.

Series DC motors - Equivalent circuit

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



Series DC Motors-Terminal characteristic

The flux in this machine is directly proportional to its armature current (at least until metal saturates).

$$\Phi = cI_A$$

where c is a constant of proportionality.

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

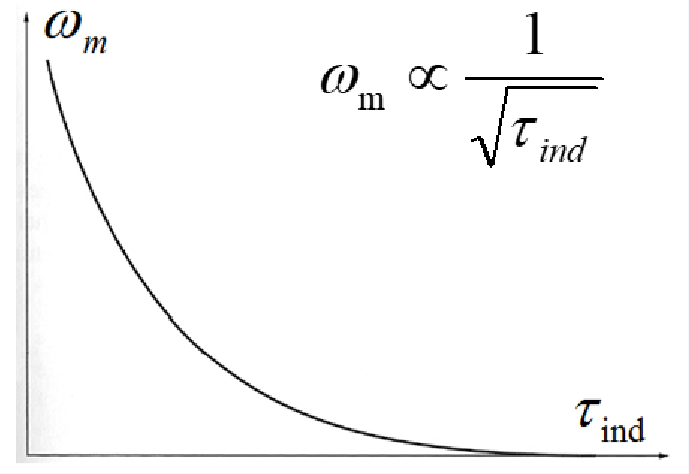
Thus the induced torque in a series DC motor: $\tau_{ind} = K\Phi I_A = KcI_A^2$

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

Series DC Motors-Terminal characteristic

The resulting torque-speed relationship

$$\omega_m = \frac{V_T}{\sqrt{Kc}} \frac{1}{\sqrt{\tau_{ind}}} - \frac{R_A + R_s}{Kc}$$



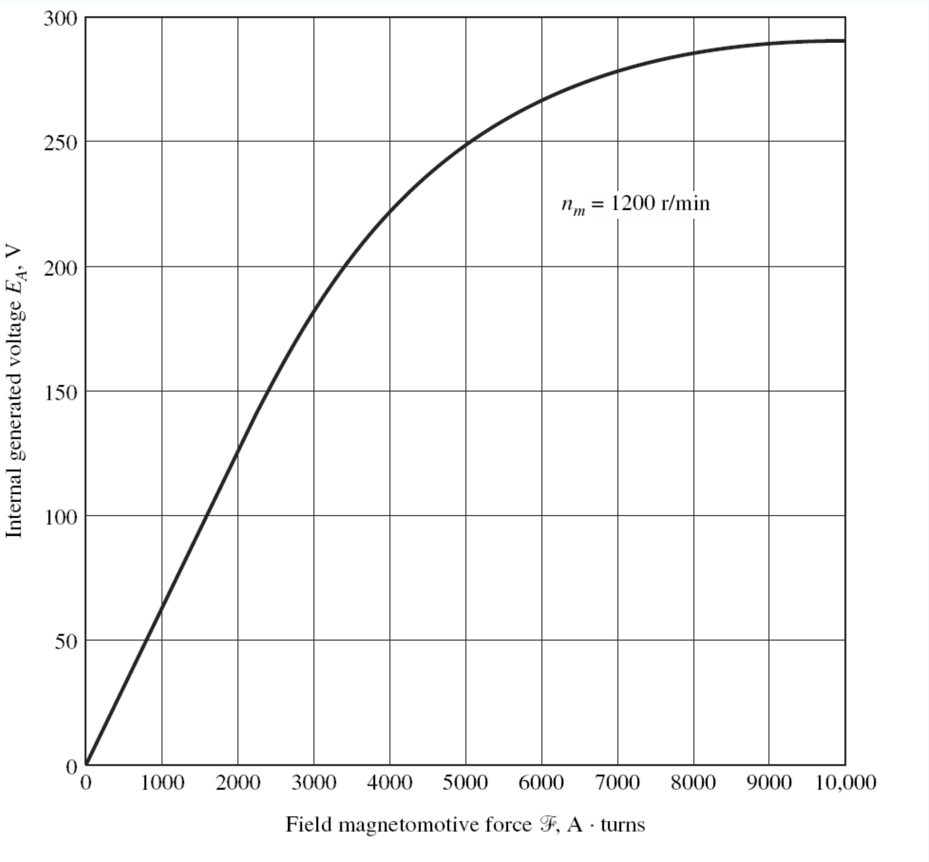
A series motor has the highest starting torque and tends to over speed at no load. It is used for very high-torque applications where speed regulation is not important, such as the starter motors in a car, elevator motors, and tractor motors in locomotives

Series DC Motors-Nonlinear Analysis

The nonlinear analysis of a series DC motor with magnetic saturation effects, the magnetization curve of the machine is used in units of magnetomotive force (ampere-turns) for a given speed.

- The ratio of the internal generated voltage at one speed to the internal generated voltage at another speed is given

$$\boxed{\frac{E_{A2}}{E_{A1}} = \frac{\omega_{m2}}{\omega_{m1}} = \frac{n_{m2}}{n_{m2}}}$$



Series DC Motors-Speed control

$$\omega_m = \frac{V_T}{\sqrt{Kc}} \frac{1}{\sqrt{\tau_{ind}}} - \frac{R_A + R_s}{Kc}$$

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:

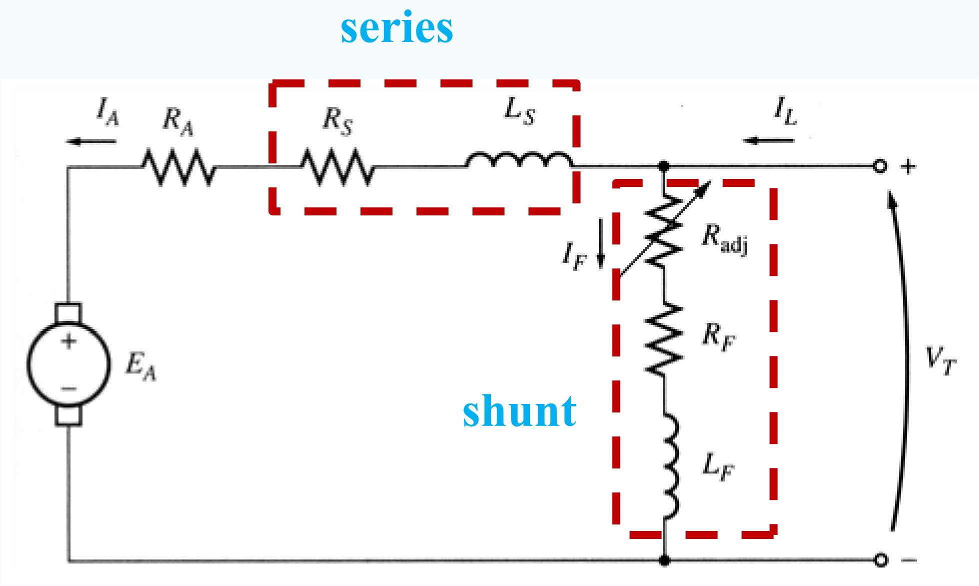
The KVL for a compounded DC motor is:

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

and the currents are:

$I_A = I_L - I_F$

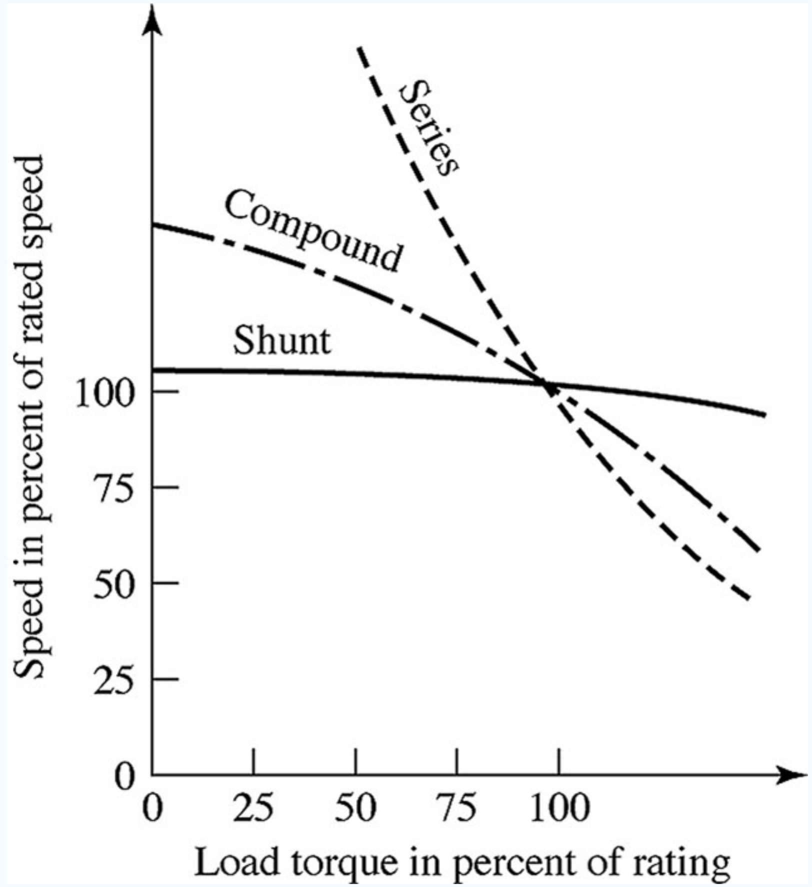
$I_F = V_T/R_F$



Compounded DC Motors –Terminal 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
3. Change the armature resistance R_A

Power Flow in DC Motors

The Losses in DC Machine:

$$\text{Efficiency}: \eta = \frac{P_{in} - P_{loss}}{P_{in}} \times 100\%$$

1. Electrical or Copper Losses (I^2R Losses)

   Armature loss: $P_A = I^2_A R_A$

   Field loss: $P_F = I^2_F R_F$

2. Core Losses

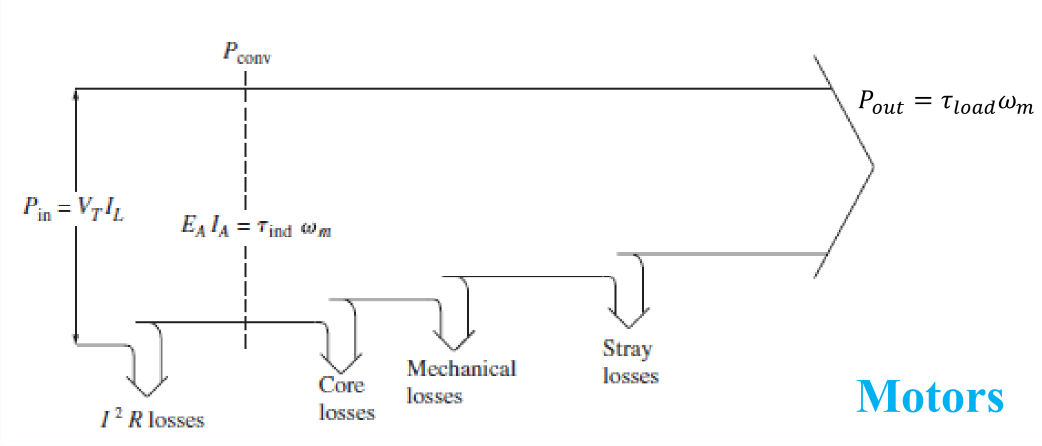
   Hysteresis losses

   Eddy Current Losses

3. Mechanical Losses

   Friction and windage losses

   Brush contact loss



4. Stray Losses

   Losses that cannot be placed in one of the previous categories, and are often accounted for 1 percentage of the total losses.

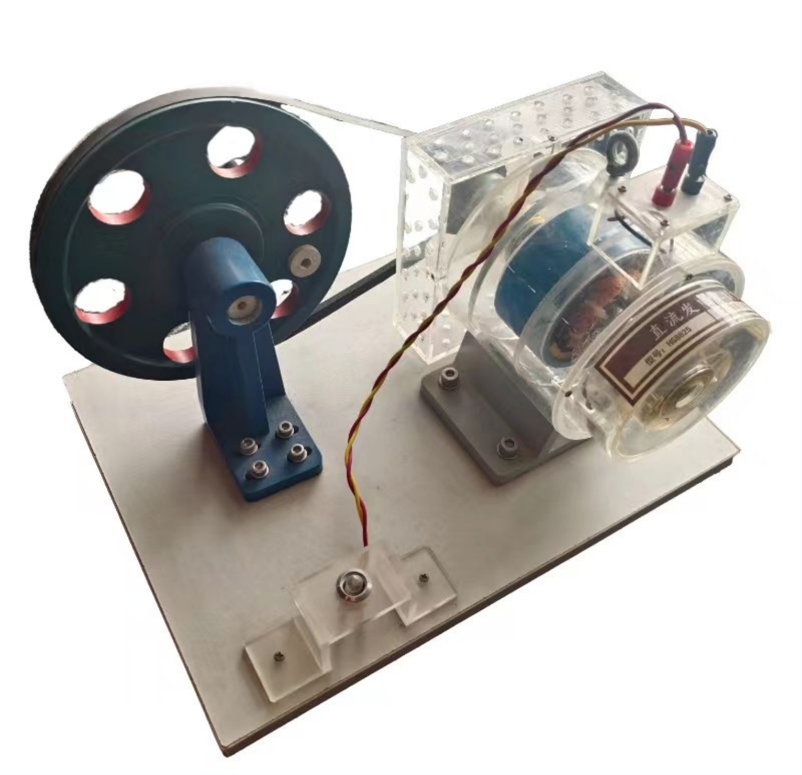
Summary

There are five types of DC motors:

separately excited （自励）, shunt （并励）, permanent-magnet（永磁）, series（串励）, and compounded（复励）.

- Equivalent Circuits
- Terminal Characteristic: torque-speed characteristic
- Non-linear Analysis
- Methods of Speed Control
- Power Flow

Next



DC Generators

Thanks for your attention