EEP 225 : Electric Machines

Lecture 4
DC Machines IV

Available on GitHub

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1 Classification of DC Machines

1.1 Separately Excited DC Motor

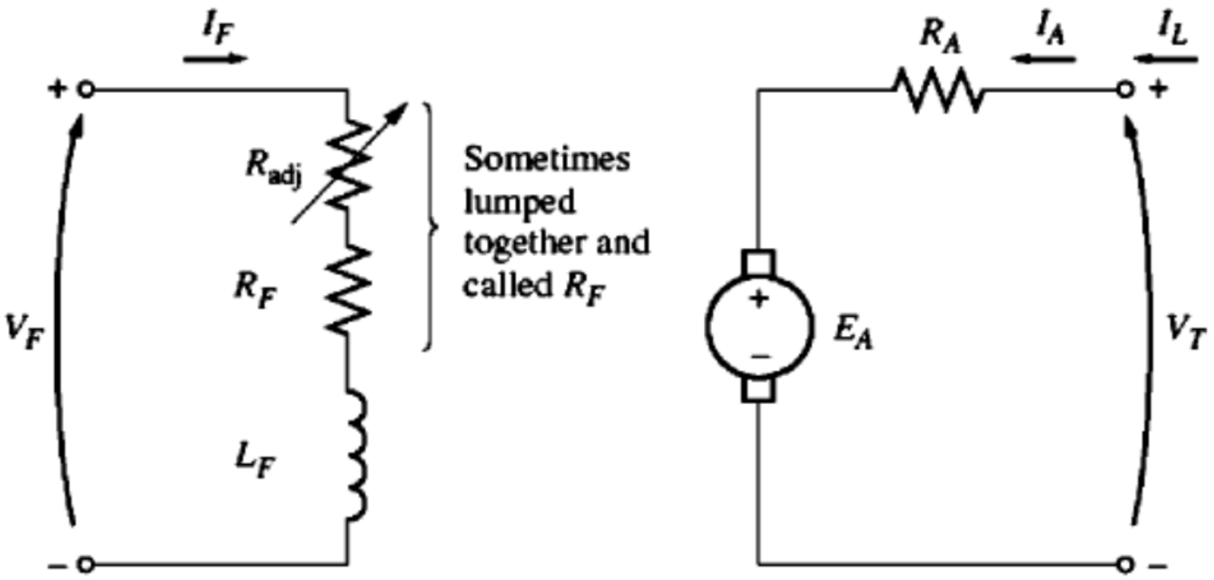

Figure 1: Separately excited DC motor model

Apply KVL

$$V_t = E_a + I_a\,R_a$$

$$V_f = I_f\,R_f \qquad I_a = I_L \qquad V_t = k_a\,\phi\,\omega_m + I_a\,R_a \qquad E_a = k_a\,\phi\,\omega_m$$

1.2 Self Excited DC Motor

1.2.1 Shunt motor

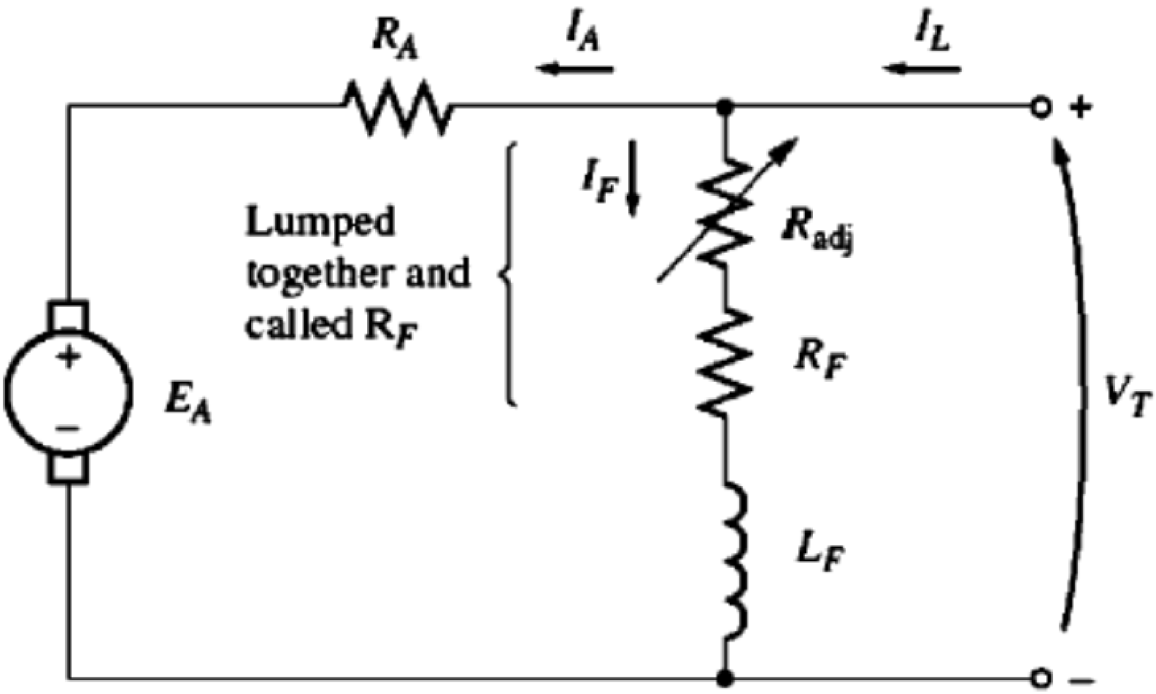

Figure 2: Shunt DC motor model

Apply KVL

$$V_t = E_a + I_a\, R_a$$

$$V_f = I_f\, R_f \qquad I_a = I_L - I_f \qquad V_t = k_a\, \phi\, \omega_m + I_a\, R_a \qquad E_a = k_a\, \phi\, \omega_m$$

1.2.2 Terminal Characteristics of DC Shunt Motor

Terminal characteristics always cares about the output, in the case of DC generator, we plotted V_t vs I_L, here in DC motor, we plot Torque T_d vs speed ω_m

We know that:

$$\begin{aligned} V_t &= E_a + I_a\, R_a \\ V_t &= K_a\, \phi\, \omega_m + I_a\, R_a \\ \omega_m &= \frac{V_t - I_a\, R_a}{K_a\, \phi} \end{aligned} \tag{1}$$

We notice the speed is directly proportional with the volt, which is intuitive, but unlike DC generator, the speed is *inversely proportional* with the field, at the first glance it seems counterintuitive, but it leads to many interesting characteristics in DC motors.

$$\frac{T_2}{T_1} = \frac{\phi_2}{\phi_1} \times \frac{I_{a2}}{I_{a1}}$$

Neglecting saturation:

$$\frac{T_2}{T_1} = \frac{I_{f2}}{I_{f1}} \times \frac{I_{a2}}{I_{a1}}$$

From mechanics we know:

$$T_d = \frac{P_d}{\omega_m}$$

P_d : Developed power

$$\begin{aligned} \therefore T_d &= \frac{E_a\, I_a}{\omega_m} \\ &= \frac{K_a\, \phi\, \omega_m\, I_a}{\omega_m} \\ &= K_a\, \phi\, I_a \end{aligned} \tag{2}$$

Note : In all machines, $T \propto I^2$, is it true in $T_d = K_a\, \phi\, I_a$? Yes. Since ϕ (flux) is a function in current (I_f), $T \propto I^2$

From (1) and (2):

$$\omega_m = \frac{V_t - I_a\, R_a}{K_a\, \phi}$$

$$\omega_m = \frac{V_t}{K_a\, \phi} - \frac{I_a\, R_a}{K_a\, \phi}$$

from (2):

$$I_a = \frac{T_d}{K_a\, \phi}$$

Substitute in (1) :

$$\omega_m = \frac{V_t}{K_a\,\phi} - \frac{R_a}{(K_a\,\phi)^2}\,T_d$$

What happens at no load ?
T_d is approximately zero, so $\dfrac{V_t}{K_a\,\phi}$ is called **no load speed**

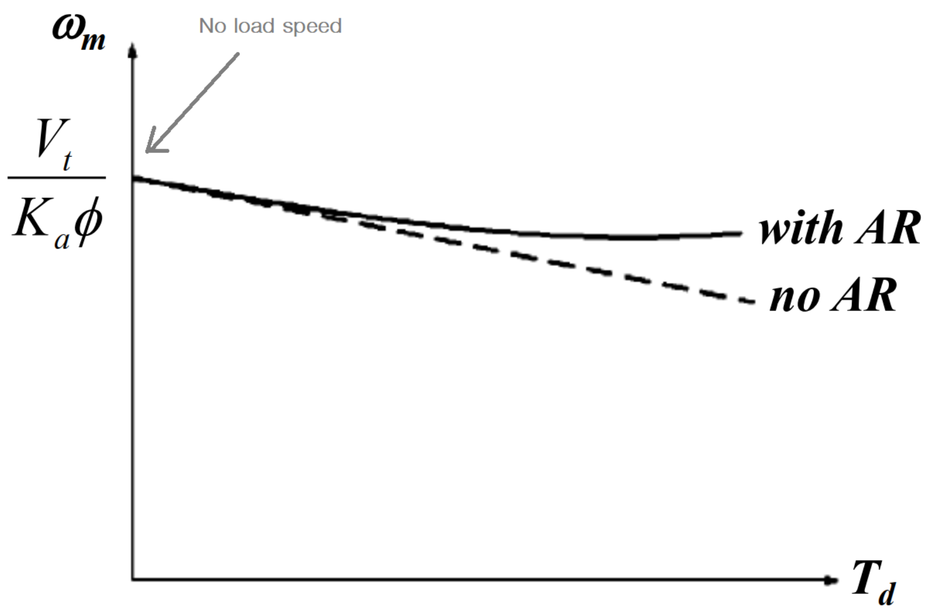

Figure 3: Terminal characteristics of DC shunt motor. note the armature reaction increases the speed because it reduces the field

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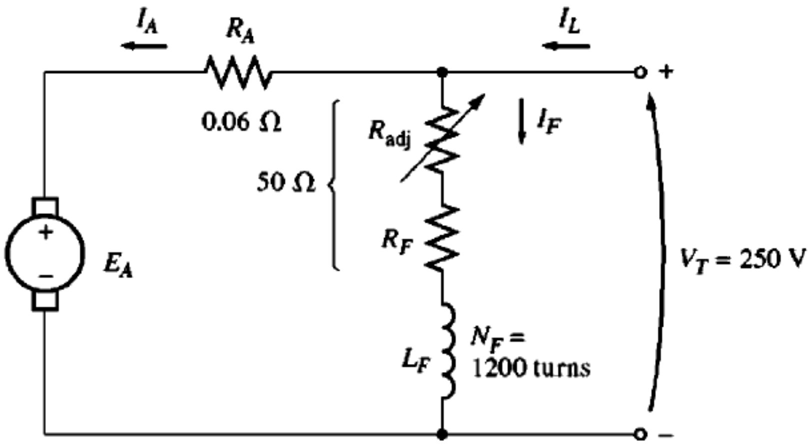
$\boxed{\text{1. Q}}$ — A 50 hp[1], 250 V, 1200 rpm DC shunt motor has an armature resistance of 0.06 Ω. Its field circuit has a total resistance of 50 Ω, which produces a no load speed of 1200 rpm

1. Find the speed of this motor when its input current is 100 A, 200 A, and 300 A.
2. Plot the torque-speed characteristic of this motor.

A —

[1]Output power for motor, note in DC generator output power is in Kilo-watts and in transformer output power is in volt



1.

At $I_L = 100$ A:

$$I_f = \frac{250V}{50\Omega} = 5 \text{ A}$$
$$I_a = 100 - 5 = 95 \text{ A}$$
$$E_a = V_t - I_a R_a = 250 - 95 \times 0.06 = 244.3 \text{ V}$$

Recall from lecture 2

$$\boxed{E_a = K\,\phi\,N}$$

$$\phi \,\propto\, I_f$$
$$\therefore E_a \propto I_f\,N$$
$$\boxed{\frac{E_2}{E_1} = \frac{I_{f2}}{I_{f1}} \times \frac{N_2}{N_1}}$$

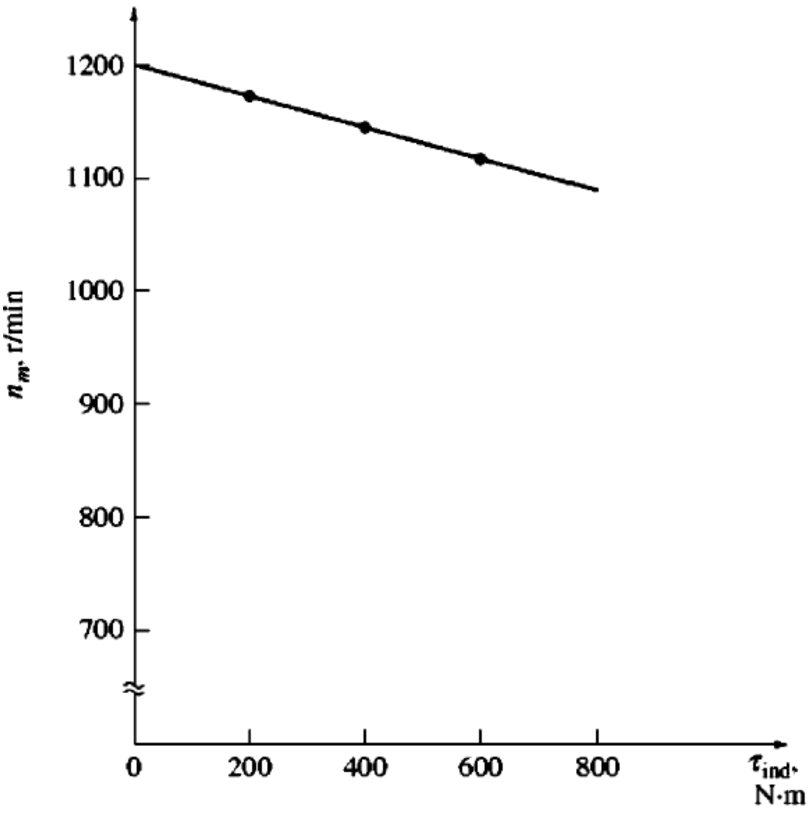
$$N_2 = \frac{E_2}{E_1} \times N_1 = \frac{244.3}{250} \times 1200 = 1173 \text{ rpm}$$
$$T_d = \frac{E_a I_a}{\omega_m} = \frac{244.3 \times 95}{\frac{2\pi}{60} \times 1173} = 190 \text{ N.m.}$$

At $I_L = 200$ A:

$$I_f = \frac{250V}{50\Omega} = 5 \text{ A}$$
$$I_a = 200 - 5 = 195 \text{ A}$$
$$E_a = V_t - I_a R_a = 250 - 195 \times 0.06 = 238.3 \text{ V}$$

$$N_3 = \frac{E_3}{E_1} \times N_1 = \frac{238.3}{250} \times 1200 = 1144 \text{ rpm}$$
$$T_d = \frac{E_a I_a}{\omega_m} = \frac{238.3 \times 195}{\frac{2\pi}{60} \times 1144} = 190 \text{ N.m.}$$

At $I_L = 300$ A: Try it yourself



2.

1.2.3 Series Motor

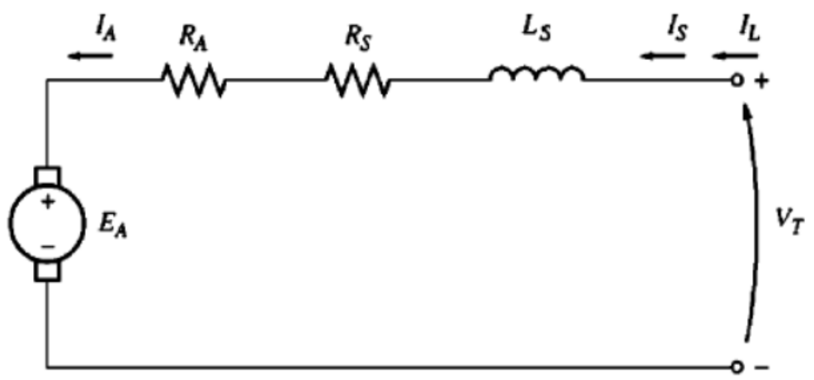


Figure 4: Series DC motor model

$$I_a = I_f = I_L$$

$$E_a = V_t - I_a(R_a + R_s)\ (1) \qquad E_a = K_a\phi\omega_m = k_s I_a \omega_m\ (2)$$

Substitute (2) in (1) and divide by $K_s I_a$

$$\omega_m = \frac{V_t}{K_s\, I_a} - \frac{R_a + R_s}{K_s}$$

How to get speed as a function of torque ? note that I_a is a function of T_d

$$T_d = K_a\,\phi\, I_a \qquad \because \phi \propto I_f \qquad \therefore \phi = K I_f = K I_a$$

$$\therefore T_d = K_a K I_a^2 = K_s I_a^2$$

$$\boxed{\omega_m = \frac{V_t}{\sqrt{K_s\, T_d}} - \frac{R_a + R_s}{K_s}}$$

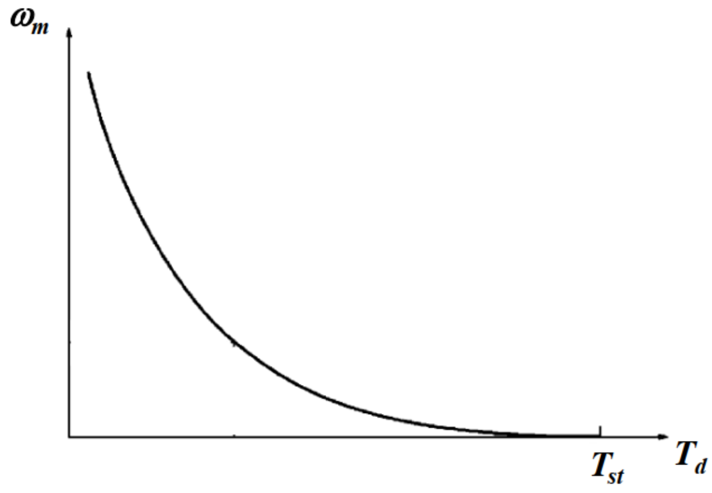


Figure 5: Series DC motor terminal characteristics

$\boxed{\text{2. Q}}$ — What is advantages and disadvantages of series DC motor

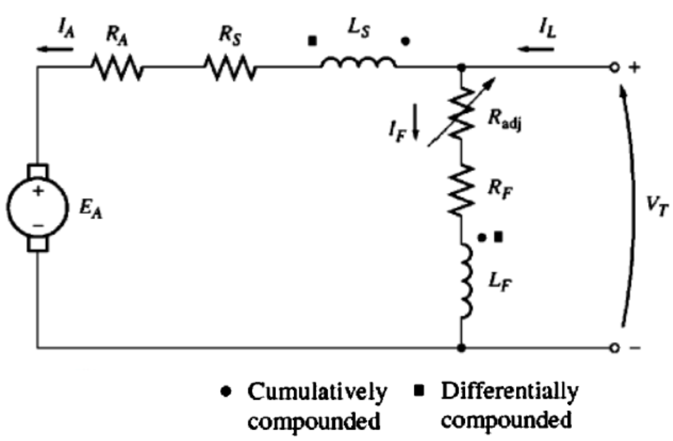
A —

- Disadvantage : series DC motor cannot be used at no load, because it will operate at dangerous high speed so it will be destroyed.

  Therefore it is only used in applications in which load always exists, e.g. Traction loads, Trolley, Electric Locomotive, Cranes, hoists

- Advantages : starting load (at zero speed) the torque is very high

1.2.4 Compound Motor



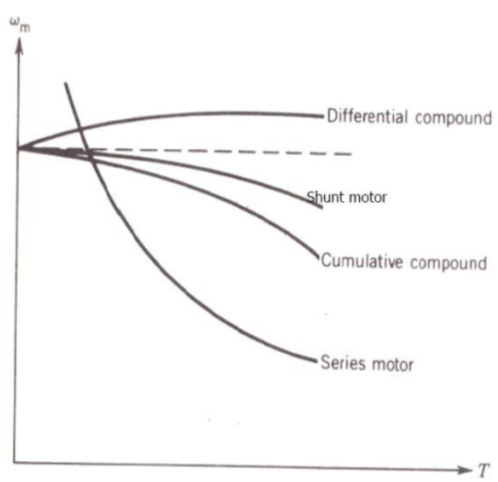


Figure 6: Compound DC motor

$$I_L = I_a + I_f \qquad V_t = I_f\, R_f$$

$$V_t = E_a + I_a(R_s + R_s)$$

$$\phi_t = \phi_{sh} \pm \phi_s$$

$$\omega_m = \frac{V_t}{K_a\,\phi} - \frac{R_a}{(K_a\,\phi)^2}\,T_d$$

$$AT_{\text{effective}} = AT_{sh} \pm AT_s - AT_{AR}$$
$$I_{f(\text{effective})} = I_f \pm \frac{N_s}{N_f} I_a - \frac{AT_{AR}}{N_f}$$

2 Applications

1. **Separately Excited Motor**
   - Machine tools.
   - Fans.
   - Pumps.
   - Blowers.
   - Lathers.
2. **Shunt Motor**
   - Machine tools.
   - Fans.
   - Pumps.
   - Blowers.
   - Lathers.
3. **Compound Motor**
   (a) Cumulative Compound:
      - High torque loads.

- Shearing and punching machines.
- Conveyors.
- Elevators.
- Rolling mills.
- Planers.
- Printing presses.

(b) Differential Compound:
Rarely used due to instability in its increasing speed with field weakening.

3 Speed Control of DC Motors

Why speed control ? Applications with variable speed motors have more efficiency than constant speed application

$$\because \omega_m = \frac{V_t - I_a R_a}{K_a \phi}$$

Therefore, the speed of DC motors can be controlled by controlling V_t, R_a or ϕ.

3.1 Armature Voltage Control

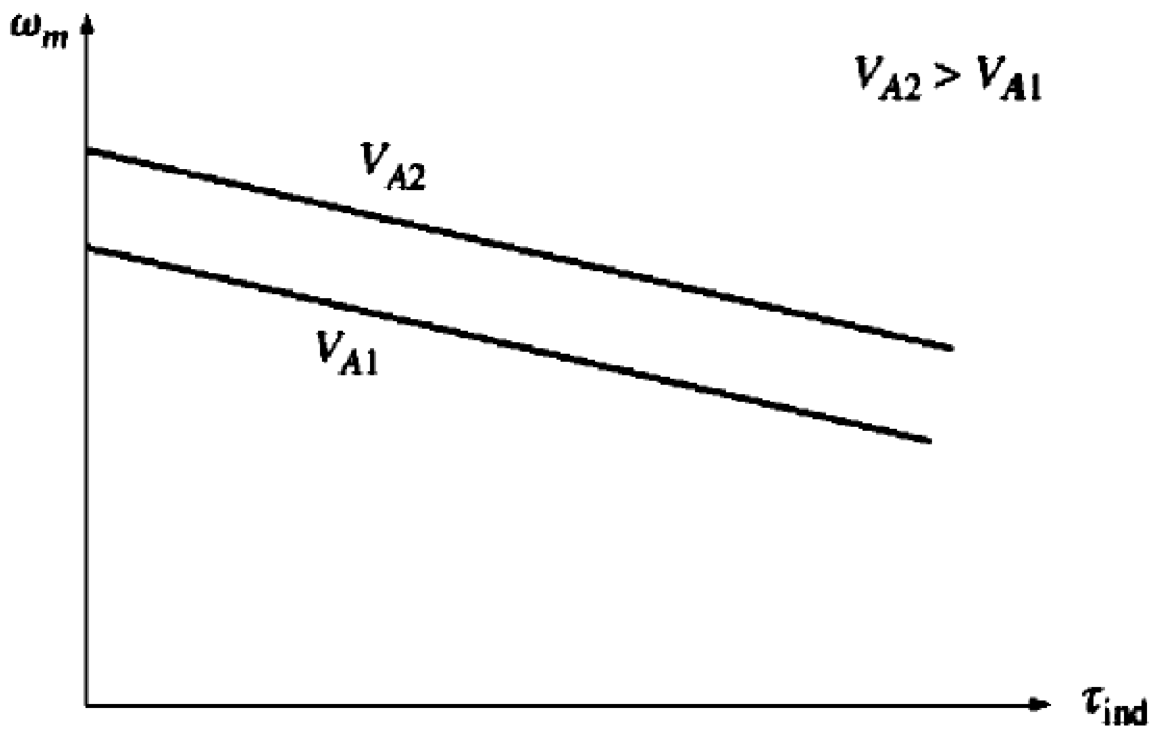


Figure 7: Armature voltage control

- In this method R_a and I_f (i.e. ϕ) are kept constant, and V_t is varied to change the speed.
- The motor must be separately excited to use armature voltage control.
- Armature voltage control can control the speed of the motor from zero to speeds below rated speed but not for speed above rated speed.
- This method is expensive because it requires a variable DC supply for the armature circuit.
- If you operate at speeds above rated speed, the motor will burn out, because the motor will absorb a large amount of active power, the current will increase sharply and so the temperature, insulation melts and wires will be shorted

3.2 Field Current Control

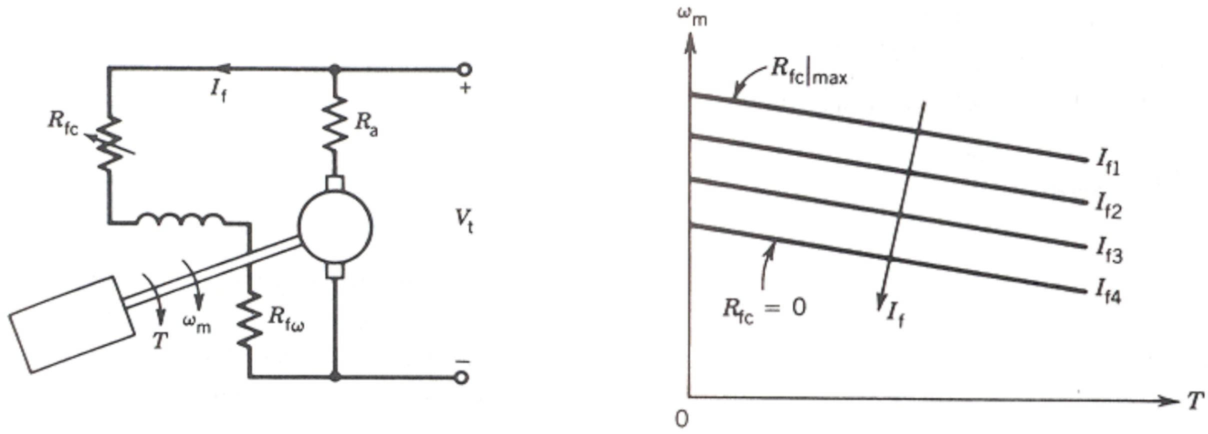


Figure 8: Field current control

- In this method V_t and R_a are kept constant, and I_f is varied to change the speed.
- This is normally achieved by using a field rheostat.
- Field control can control the speed of the motor for speeds above base speed but not for speeds below base speed.
- This method is simple to implement and less expensive, because the control is at the low power level of the field circuit.
- Can be used at all types of DC motors *except* series motors.

3.3 Armature Resistance Control

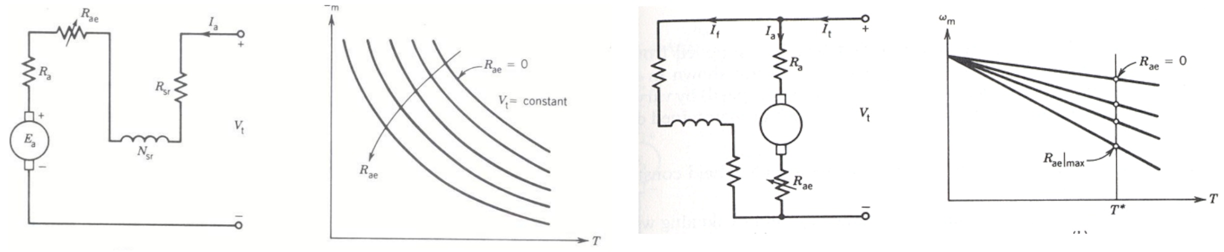
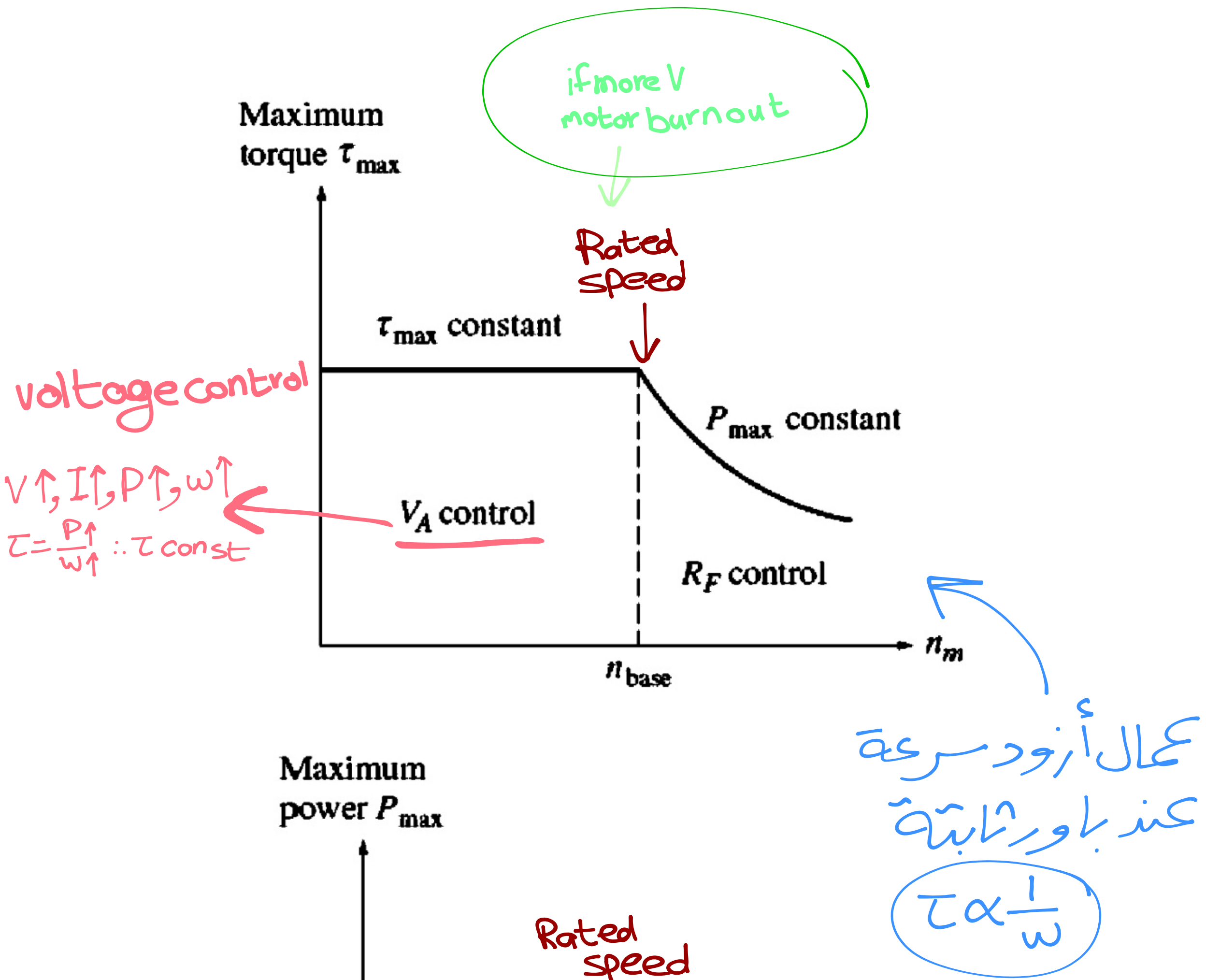
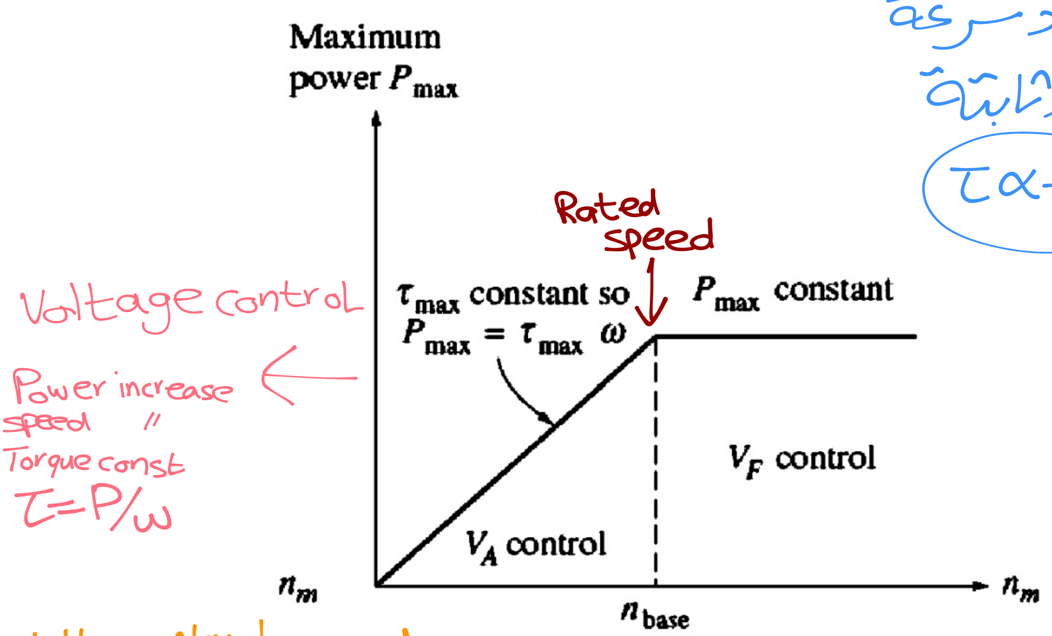


Figure 9: Armature resistance control

- In this method V_t and I_f are kept constant, and R_a is varied to change the speed.
- The speed is controlled by changing the resistance in the armature circuit.
- Armature resistance control is simple to implement
- However, this method is less efficient because of losses in the resistance.
- Armature resistance control can control the speed of the motor for speeds below base speed.
- Can be used at all types of DC motors

3.4 Power and Torque Limits as a Function of Speed for a Shunt Motor Under Armature Voltage and Field Resistance Control





Volt control used below rated speed at contant torque

Field control used above rated speed at constant power

3.5 Solid State Control

In Recent years, solid-state control have been used as a replacement of conventional methods. Both armature control and field control can be achieved using controlled rectifier(if AC supply) or choppers(if DC supply).

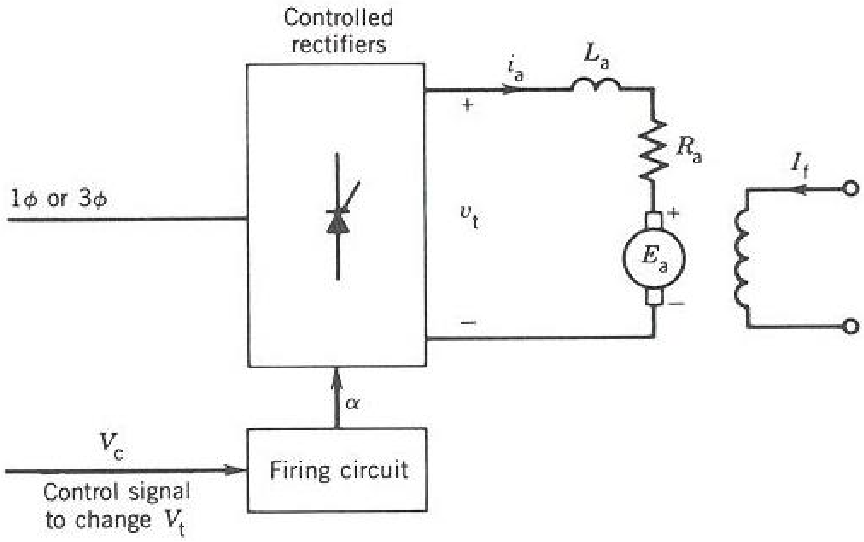


Figure 10: If the supply is AC, controlled rectifiers can be used to convert it to a variable voltage dc supply by changing the firing angle α of the rectifier thyristors.

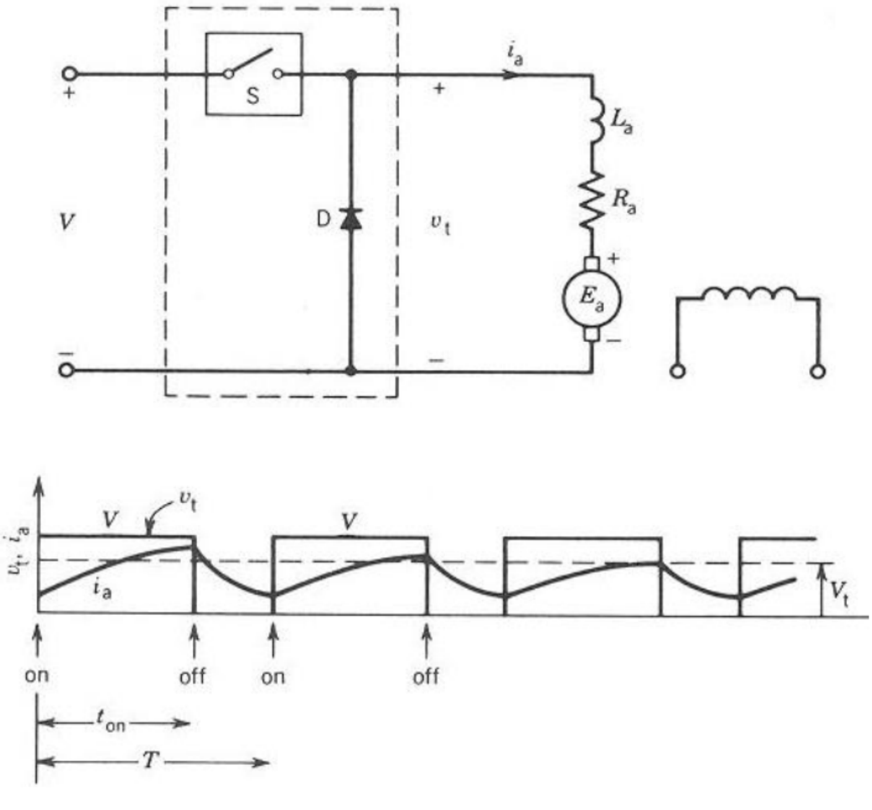


Figure 11: A chopper converts a fixed-voltage DC supply into a variable voltage DC supply, by controlling the *duty cycle* of the chopper.

$\boxed{3.\ Q}$ — Any drive system can do four things. Explain.

A — Any drive system can do four things:

1. Soft starting.
2. Speed control.
3. Inverting.
4. Electrical breaking.[2]

Not all drive systems can do these four things, but at least, each drive systems must be able to soft start and speed control.

4 Starting of DC Motors

Why we care about starting of DC motors?

$$\because I_a = \frac{V_t - E_a}{R_a}$$

At starting, $N = 0$, therefore $E_a = 0$.

$$\therefore I_{st} = \frac{V_t}{R_a}$$

If the rated voltage is applied to the DC motor[3], the current will be over 20 times the motor's rated full load current. That will damage the motor even if it lasts for a moment.

A solution to the problem of excess current during starting is to insert a starting resistor in series with the armature to limit the current flow until E_a can build up to do the limiting.

[2] Apply opposite torque on the motor. It is faster and more efficient than mechanical breaking

[3] This is called DOL (Direct online starter)

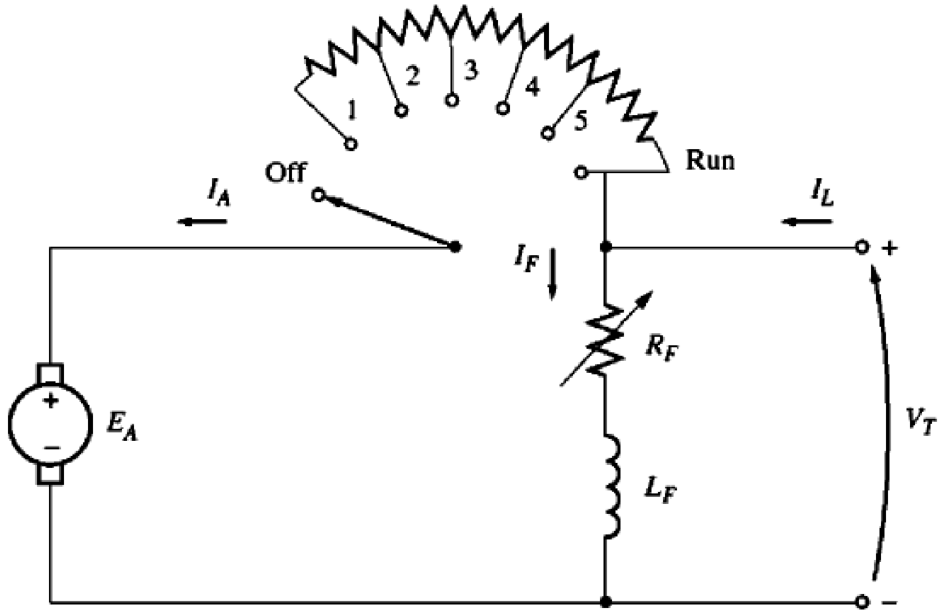


Figure 12: Starting resistor

This type of starter had problems, as it largely depended on the person starting the motor not to move its handle too quickly or too slowly. If the resistance were cut out too quickly (before the motor could speed up enough), the resulting current flow would be too large. On the other hand, if the resistance were cut out too slowly, the starting resistor could burn up.

Since they depended on a person for their correct operation, these motor starters were subject to the problem of human error. They have almost entirely been displaced in new installations by automatic starter circuits.

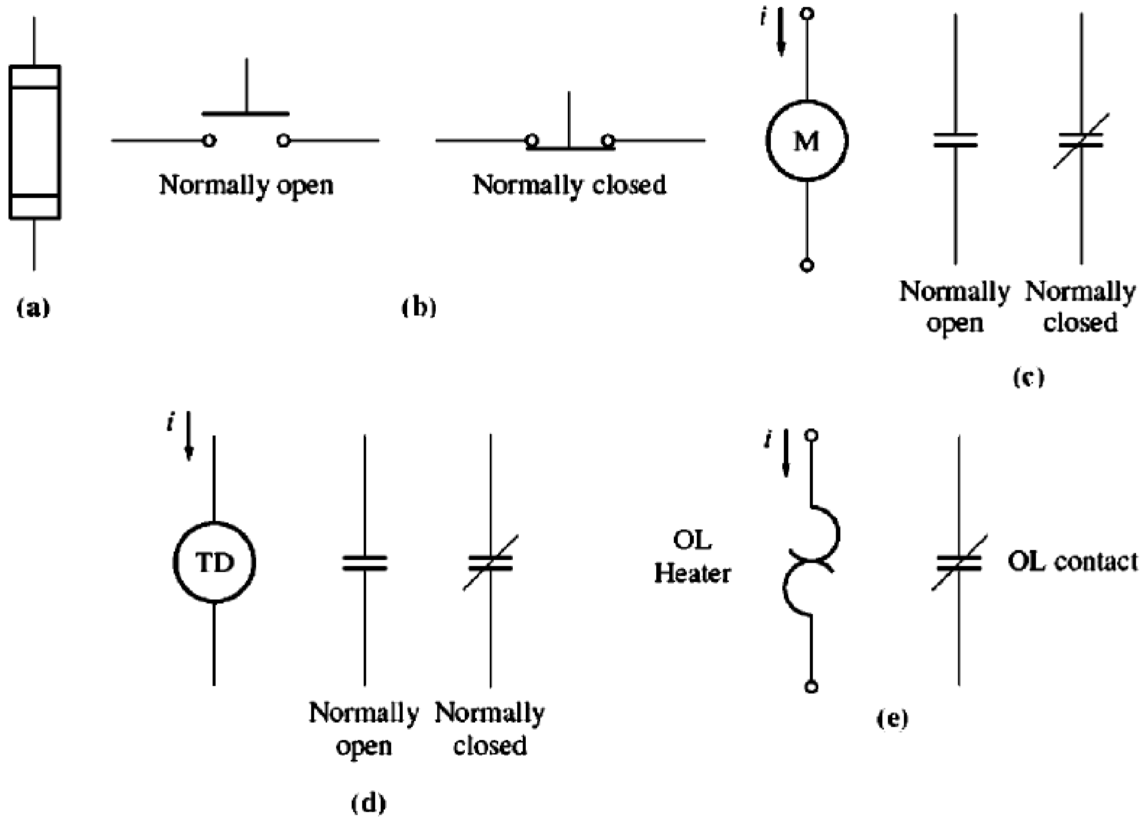


Figure 13: (a) A fuse. (b) Normally open and normally closed push button switches. (c) A relay coil and contacts. (d) A time delay relay and contacts. (e) An overload and its normally closed contacts

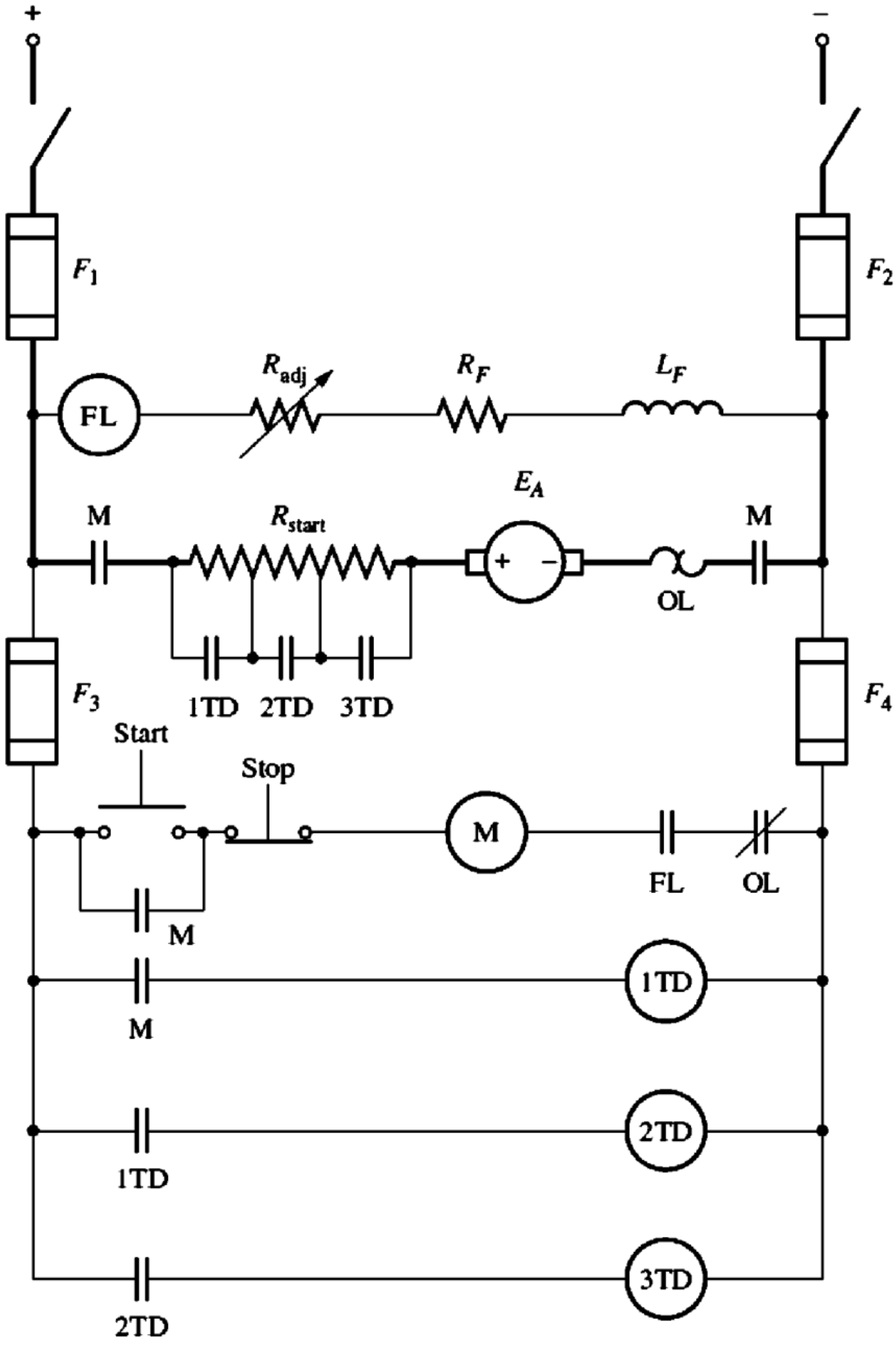


Figure 14: Automatic starter

5 Power Flow, Losses and Efficiency

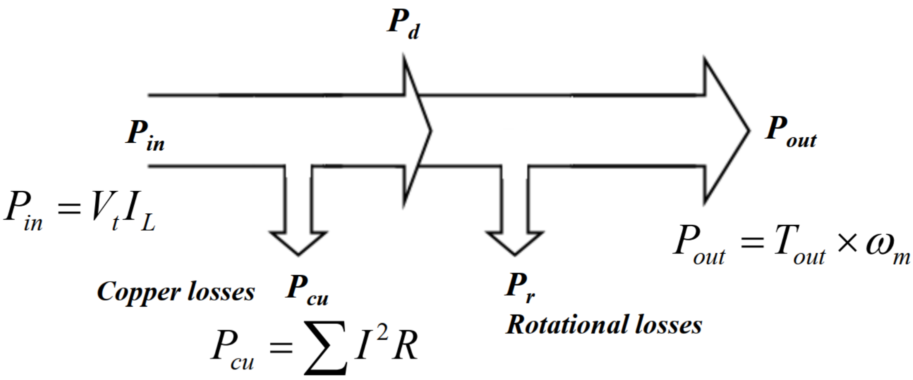


Figure 15: Power flow

$$P_{\text{in}} = V_t \, I_L$$

$$P_d = E_a I_a = P_{\text{in}} - P_{cu}$$

P_d : Developed power

$$P_{\text{cu}} = \sum I^2 R$$

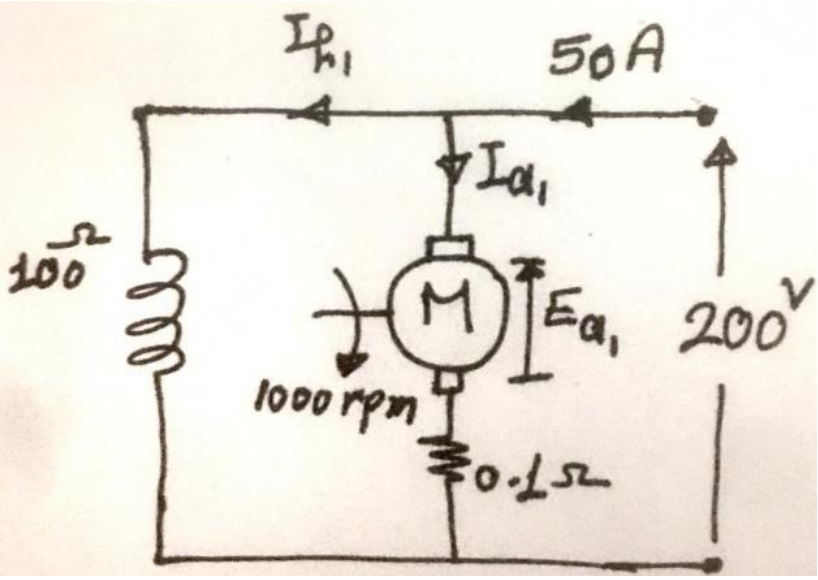
P_{cu} : Copper losses

$$\boxed{\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{out}}}{P_{\text{out}} + P_r + P_{\text{cu}}}}$$

$\boxed{\text{4. Q}}$ — A DC shunt motor drives a centrifugal pump whose torque varies as the square of the speed. The motor is fed from 200 V supply and takes a 50 A when running at 1000 rpm.

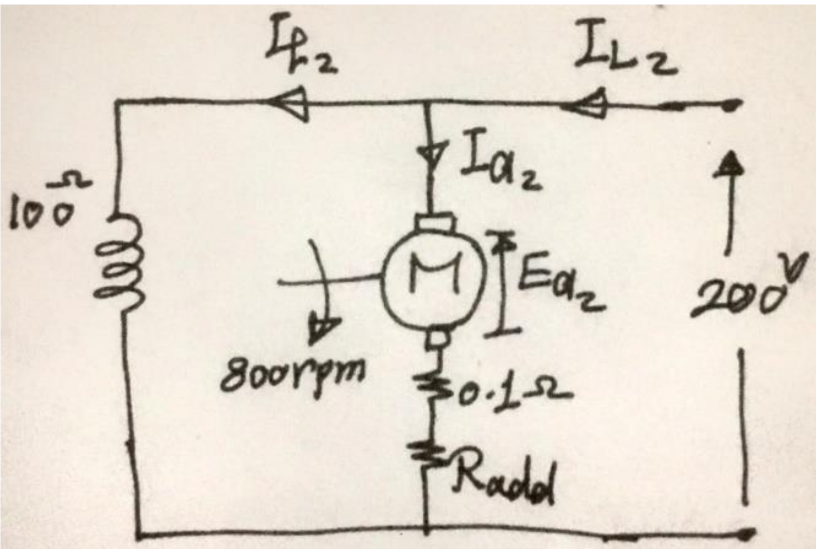
1. What resistance must be inserted in the armature circuit in order to reduce the speed to 800 rpm? The armature and field resistances of the motor are 0.1 Ω and 100 Ω respectively. Neglect saturation.
2. Find the starting resistance required to limit the starting current to 1.5 line current.

A — Note : If DOL, the current will be 2000 A!



1.

$$
\begin{aligned}
I_{f_1} &= \frac{200V}{100\Omega} = 2A \\
I_{a_1} &= 50 - 2 = 48A \\
E_{a_1} &= 200 - 48 \times 0.1 = 195.2V
\end{aligned}
$$



$$
\begin{aligned}
I_{f_1} &= I_{f_2} = \frac{200V}{100\Omega} = 2A \\
\frac{E_2}{E_1} &= \frac{I_{f2}}{I_{f1}} \times \frac{N_2}{N_1} \\
\frac{E_{a_2}}{195.2} &= \frac{800}{1000} \\
\therefore E_{a_2} &= 156.16V
\end{aligned}
$$

2.

$$50 \times 1.5 = 75 = \frac{200V}{0.1\Omega + R_{\text{add}}}$$

$$\therefore R_{\text{add}} = 2.566\Omega$$