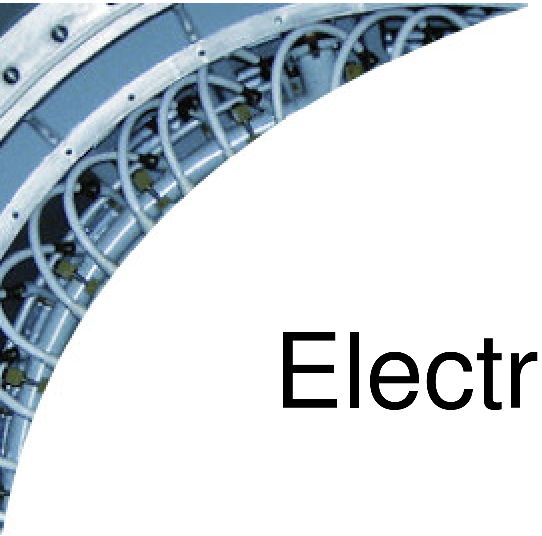
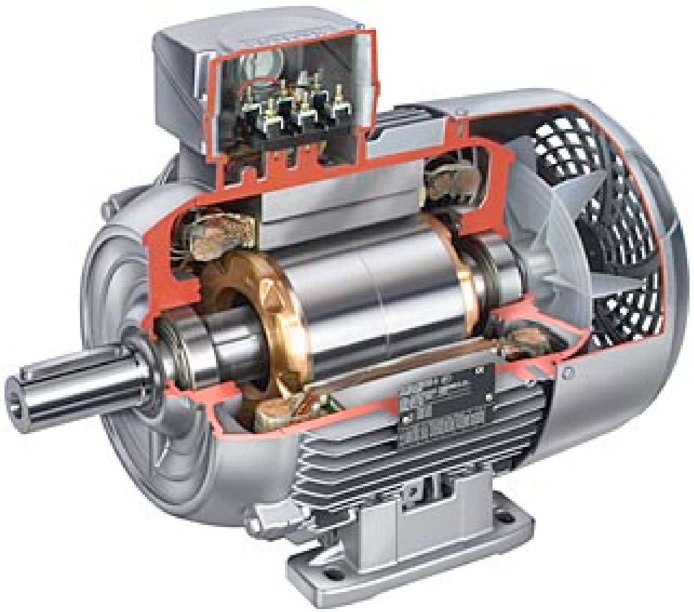


EEE 3352

Electromechanics & Electrical Machines



Lecture 6: DC machines

Dr A Zulu

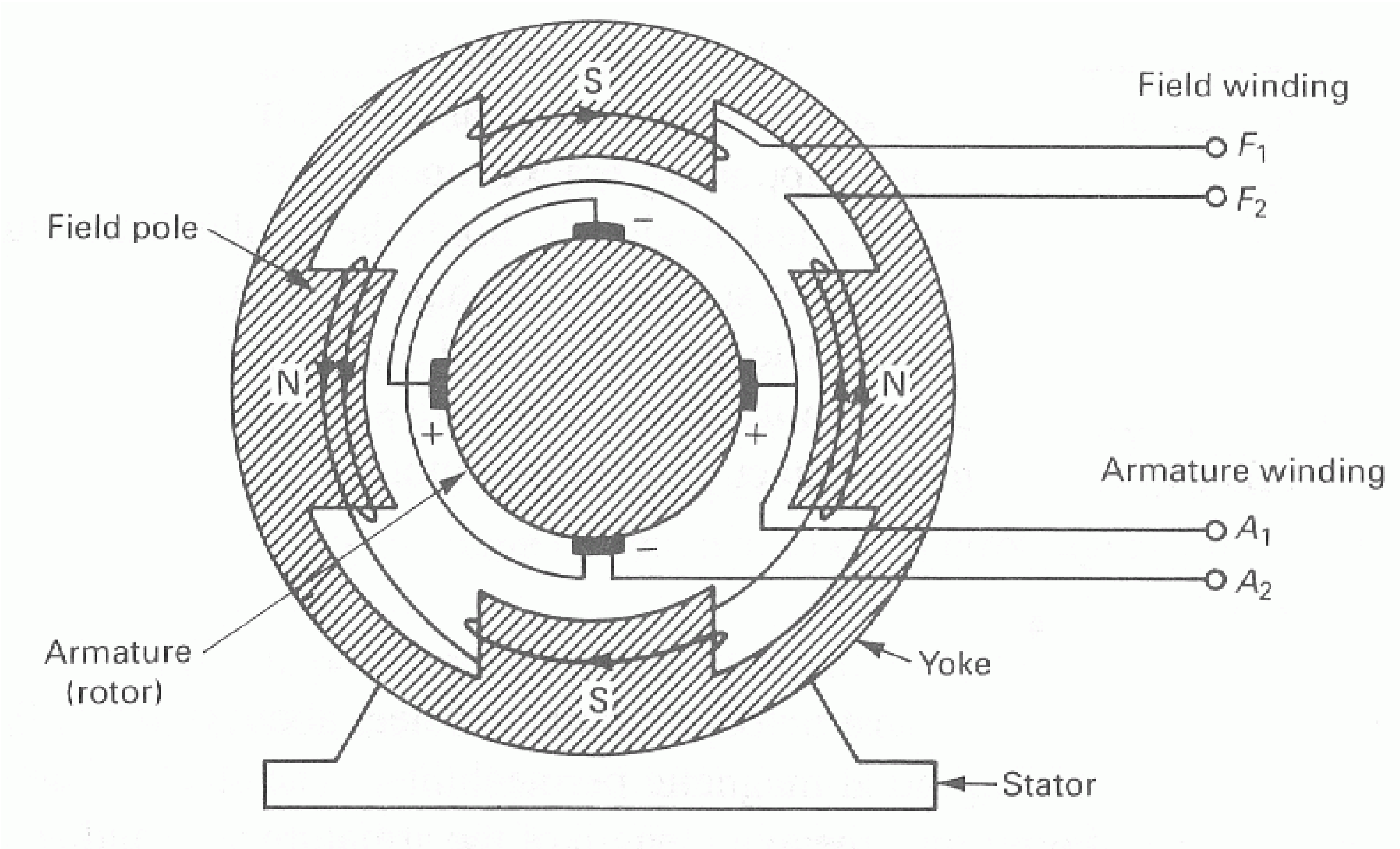
DC Machines

1. Introduction
2. Equivalent circuit
3. Production of flux
4. Power flow diagrams
5. DC machine configurations
6. DC generator
7. DC motor
8. Starting of DC motors

Objectives:

- at the end of the lecture, students should be able to
  - explain the equivalent circuit of the dc machine
  - develop power balance positions for generating and motoring
  - describe configurations that produce different types of dc machines
  - evaluate the performance of the dc separate and shunt generator
  - derive torque-speed characteristics of dc motor: separate, shunt & series
  - evaluate performance of dc separate, shunt and series motor
  - explain the starting dc motors

6.1 Introduction



4-pole dc machine

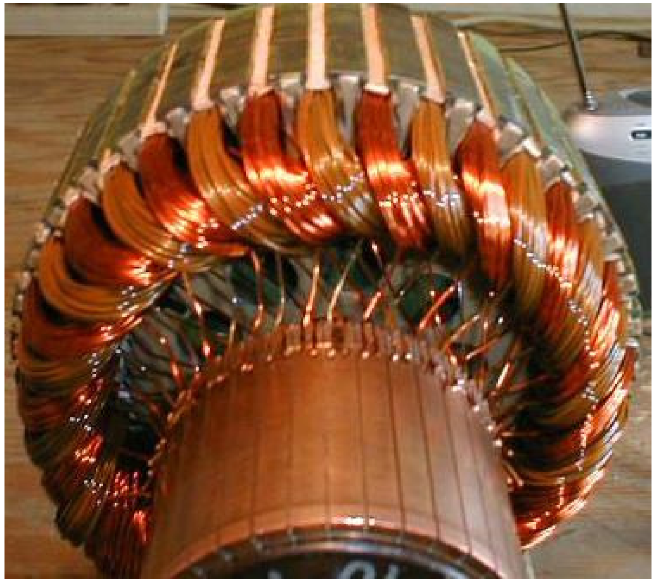
- dc machines have $\geq$ 2 sources of magnetic excitation
- magnetic sources interact in a magnetic system
- 2 principal excitations, i.e.
  - field
  - armature
- hence dc machine are called doubly-excited machine

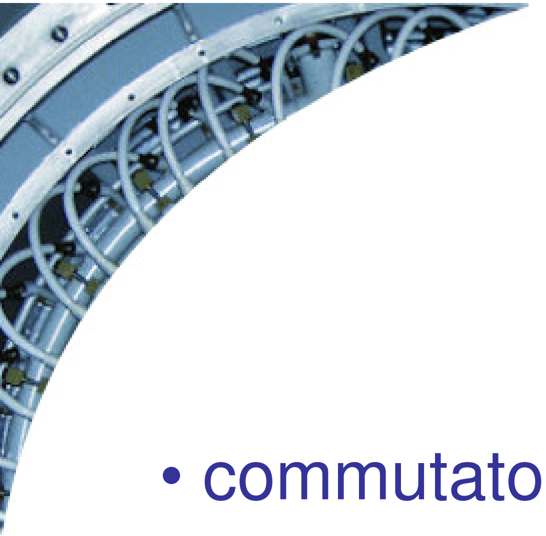
Field System

- creates a magnetic field in the magnetic circuit
- 2 methods used for a creating a field
    - electrical field winding
        - gives diversity and variety of performance characteristics that typify dc machines
    - permanent magnet excitation may be employed
        - ↑ is often less costly & occupies less space
        - ↑ eliminates need for separate source of energy
        - ↓ limited power for large machines (limited to few 100 W, until recently)

Armature System

- is the power winding of a dc machine
  - the machine's electromagnetic torque is a function of armature current
  - armature terminals are connected to the external power source/use through commutator / brush system



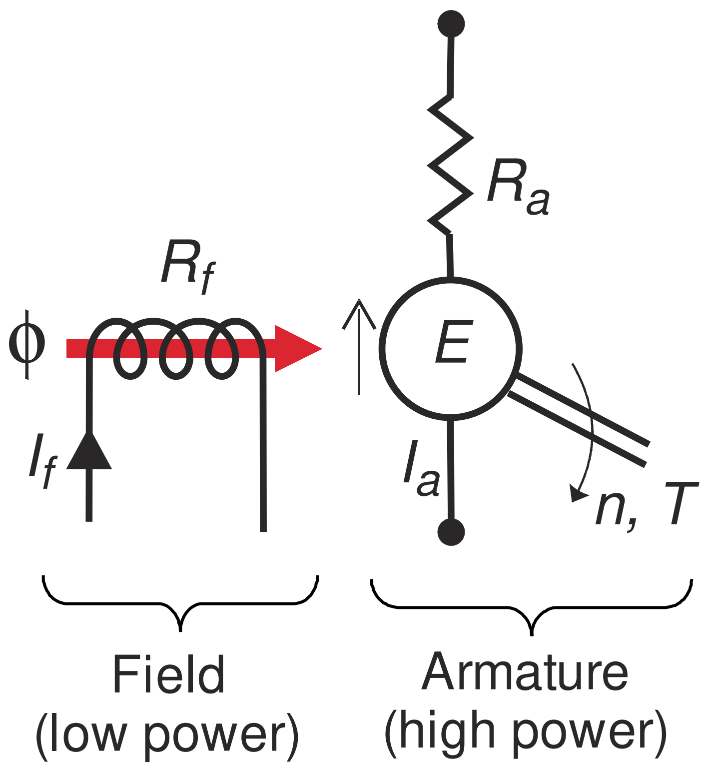


- commutator / brush system acts a mechanical switching device
    - between the external circuit and the armature winding
- external connection of the armature winding are made through the brushes resting on the commutator
    - brushes are held in stationary fixed positions
    - commutator rotates with the rotor
    - brushes are one pole-pitch apart

- In lap winding:
  - # of brush positions equal to # of poles is required
  - half the positions are +ve, half are –ve;
    - +ve and –ve groups are paralleled through external electrical connections

- In wave winding
  - only two brush position are required: one +ve and one –ve
- difference between lap and wave concerns electrical performance:
  - the number of parallel electrical paths through the winding between +ve and –ve terminals of the armature
- designate c for number of parallel paths between armature winding terminals
  - lap: $c = 2p$
  - wave: $c = 2$

6.2 Equivalent circuit of DC machine



Power Losses

1. Copper Loss

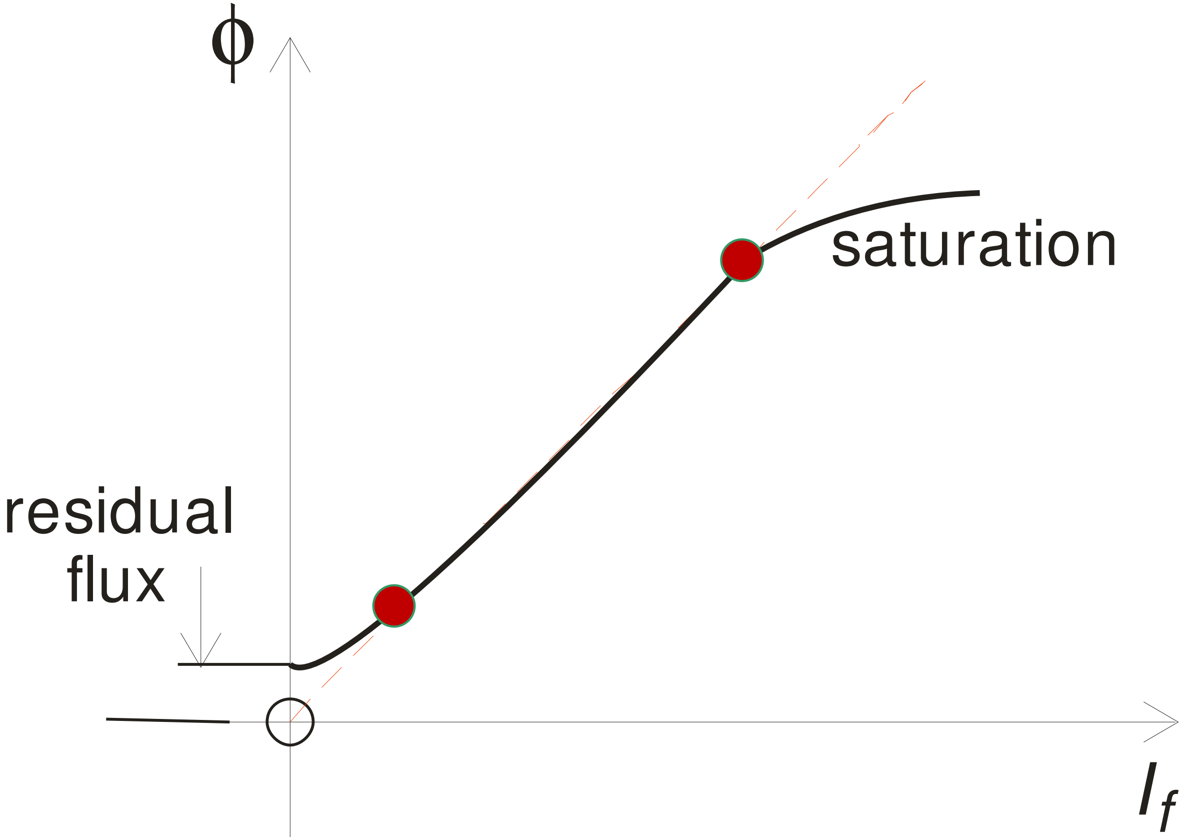
- armature $\longrightarrow \quad I_a^2 R_a$

- field $\longrightarrow I_f^2 R_f = V_f I_f = \dfrac{V_f^2}{R_f}$

2. Mechanical loss

- iron loss
- friction
- windage

6.3 Production of flux



$$\phi = \frac{F}{S} = \frac{N_f I_f}{S}$$

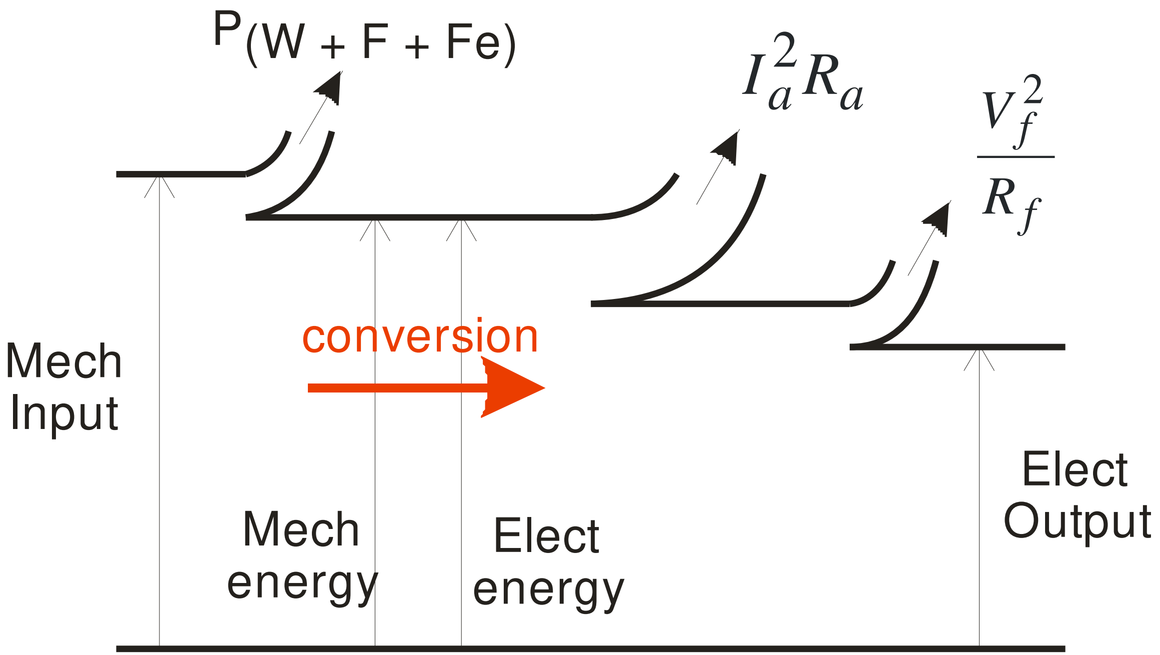
$$\phi = k_f I_f$$

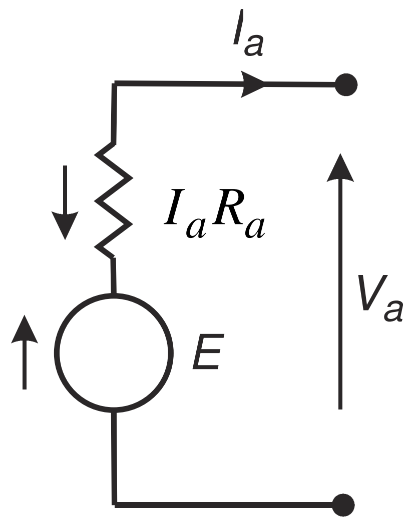
magnetisation curve

- a linear relationship between ϕ and I_f, if S is assumed constant
- deviation occurs because of saturation when ϕ increases

6.4 Power flow diagrams

Generator



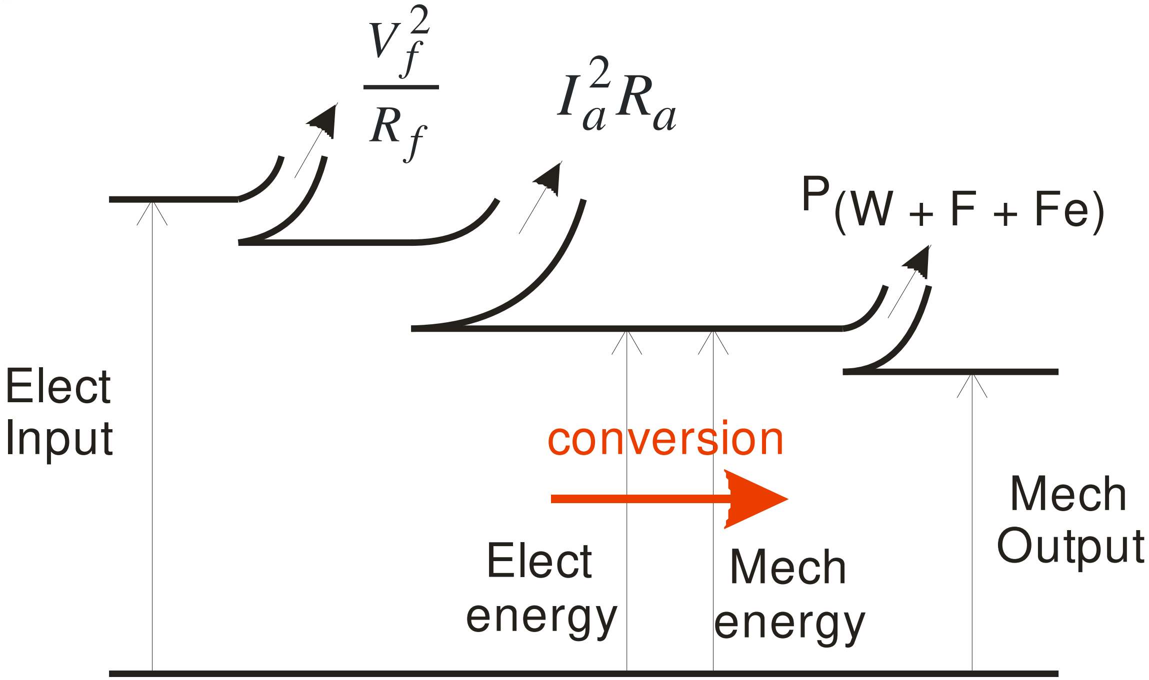


$$\eta = \frac{\text{elec. output}}{\text{mech. input}}$$

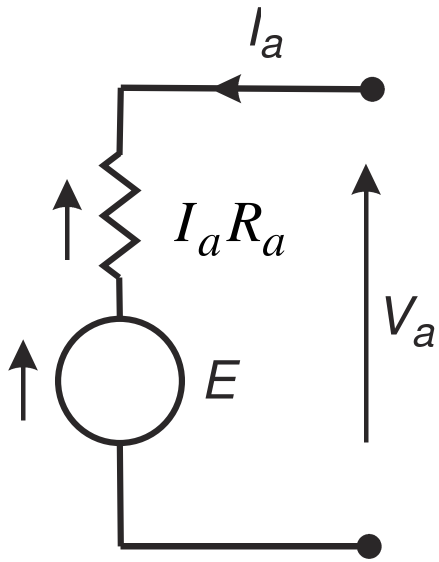
$$V_a = E - I_a R_a$$

$$E = \left(\frac{2pZ}{c}\right) n\phi$$

Motor



$$\eta = \frac{\text{mech. output}}{\text{elec. input}}$$



$$V_a = E + I_a R_a$$

$$E = \left(\frac{2pZ}{c}\right) n\phi$$

6.5 DC machine configurations

- field winding connection
  - determines the type of dc machine arrangement
  - can either be in
    - separate
    - series
    - shunt
    - compound

dc machine windings designation

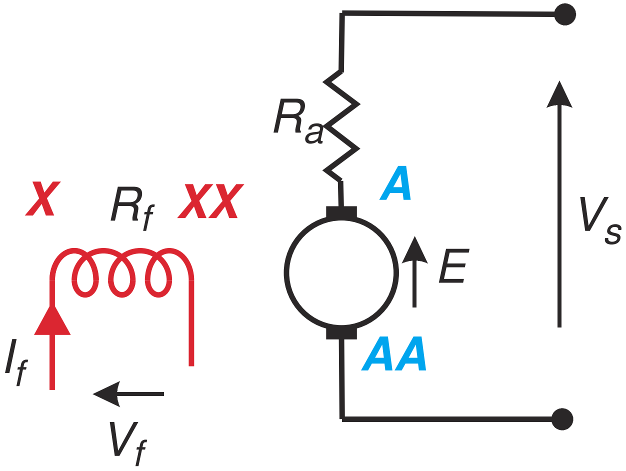
winding	BS 4999 pt3 (1977)	BS 8222 pt 6 (1964)
	+ −	+ −
armature	A1 – A2	A – AA
separate	F1 – F2	X – XX
series	D1 – D2	Y – YY
shunt	E1 – E2	Z – ZZ

- total mmf on the direct-axis is

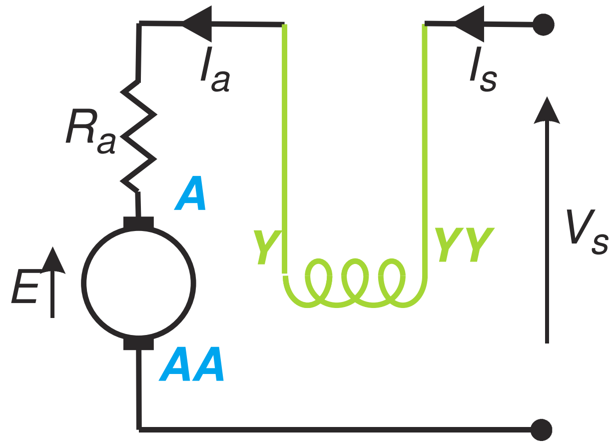
$$\sum NI = \pm N_X I_X \pm N_Y I_Y \pm N_Z I_Z$$

Field	$\sum NI$	
separate	$\pm N_X I_X + 0 + 0$	
series	$0 \pm N_Y I_Y + 0$	
shunt	$0 + 0 \pm N_Z I_Z$	
Compound (cumulative)	$0 + N_Y I_Y + N_Z I_Z$	$0 - N_Y I_Y - N_Z I_Z$
Compound (differential)	$0 + N_Y I_Y - N_Z I_Z$	$0 - N_Y I_Y + N_Z I_Z$

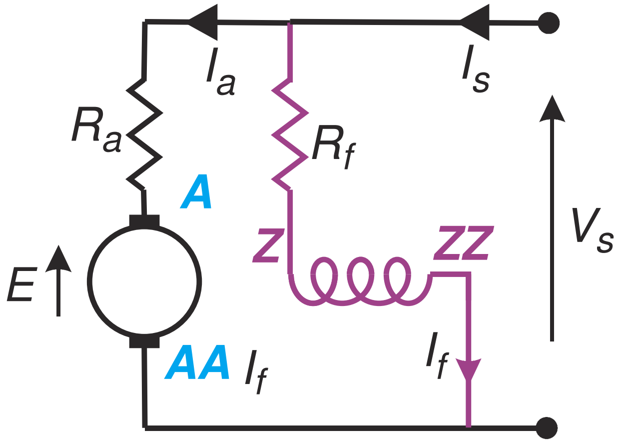
separate



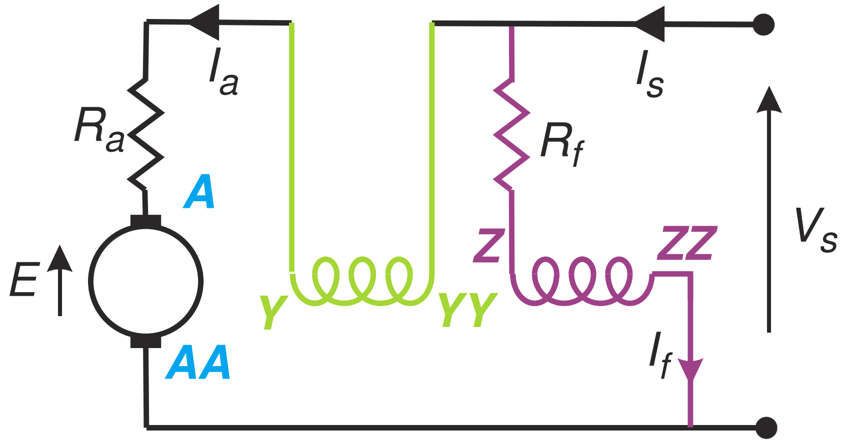
series



shunt



compound

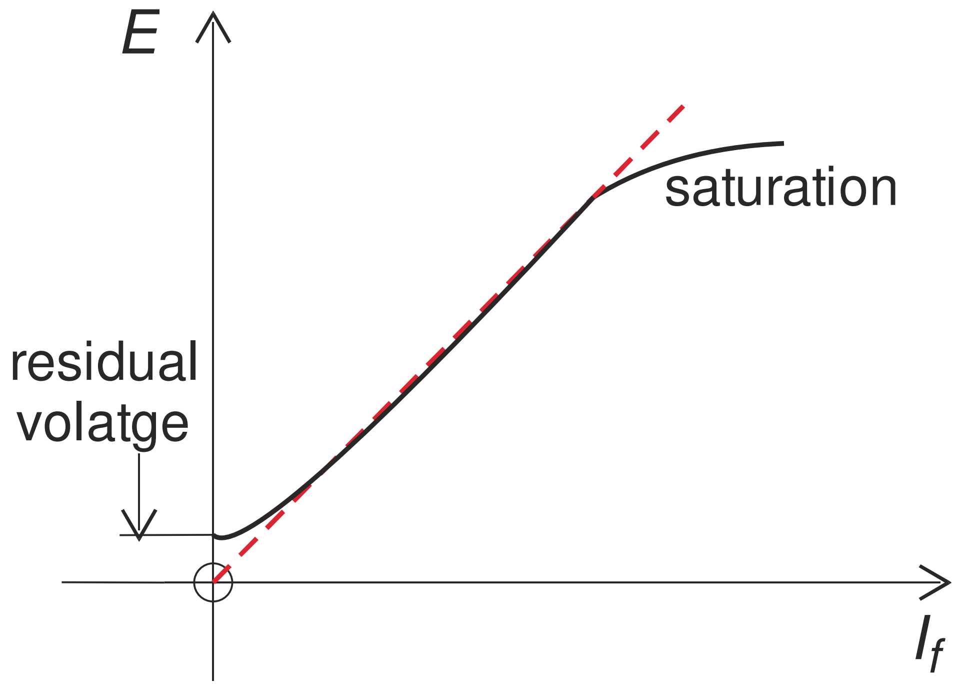


6.6 DC Generator

- dc supplies are commonly derived from ac supplies by rectification
- dc generators are built with outputs of a few W to several MW
- dc generators applications in

1) electrochemical plants for electro deposition and metal refining [√] + [**X**]
2) battery charging for standby or emergency supply [**X**]
3) diesel-electric locomotives [√] [**X**]
4) synchronous machine excitation [√]
5) automatic control systems [√] + [**X**]
6) hybrid electric vehicles [√]

6.6.1 Saturation curve

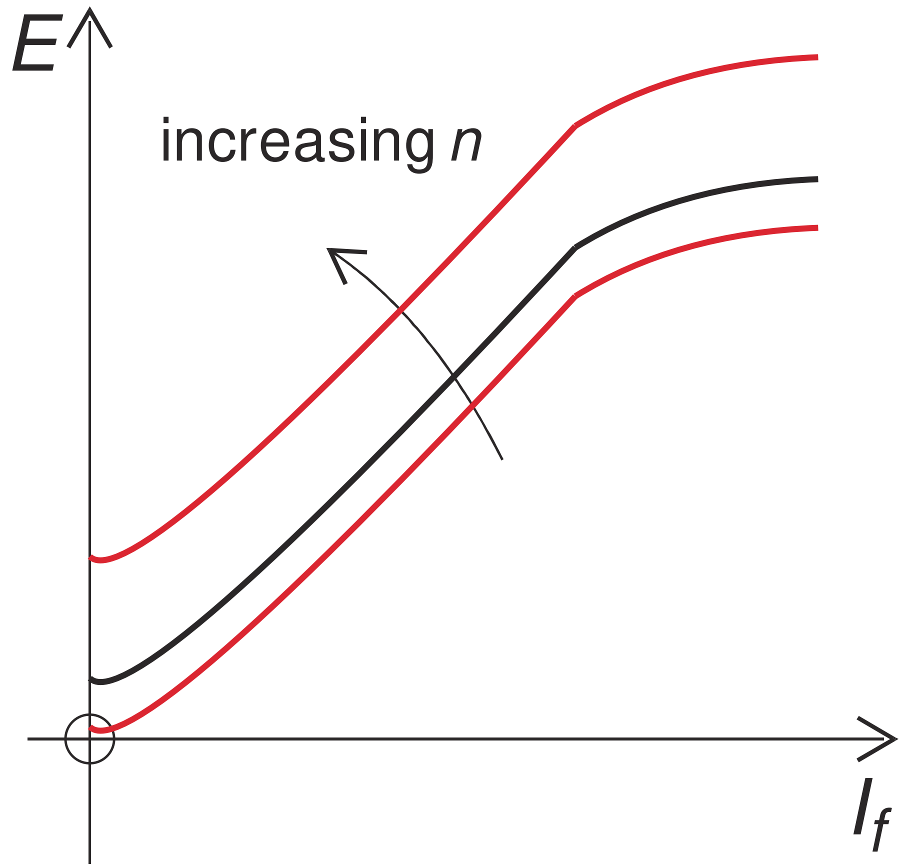


$$E = \left(\frac{2pZ}{c}\right) n\phi$$

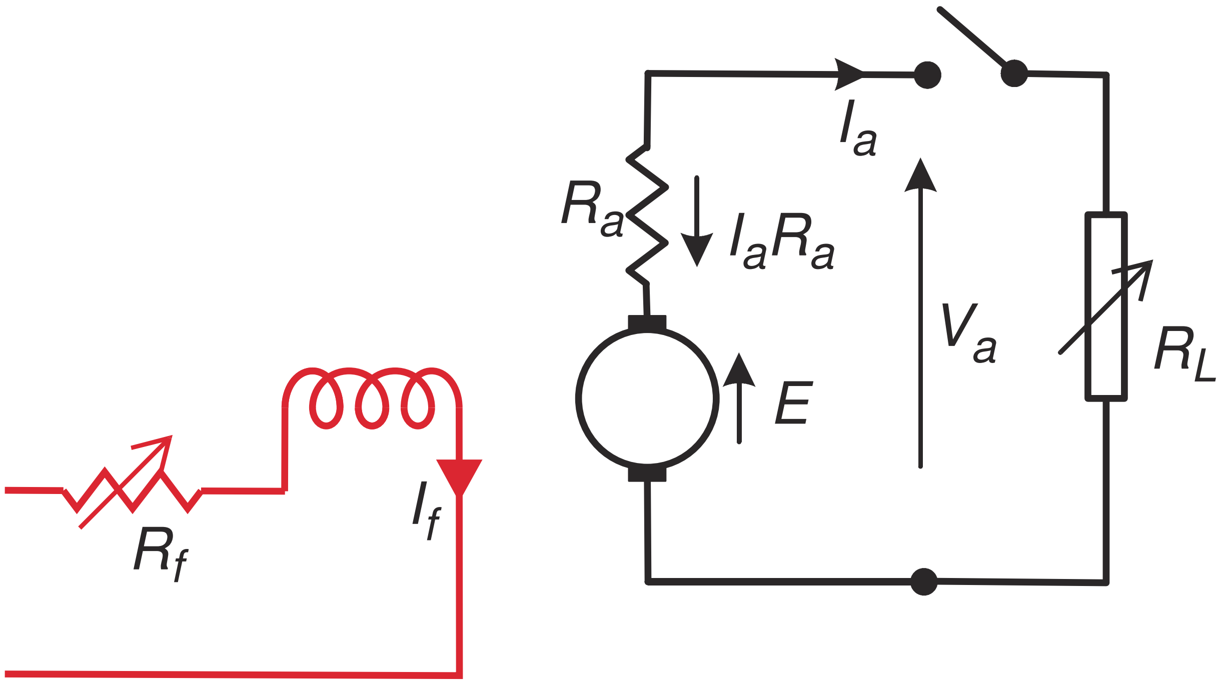
$$E \propto \phi \quad (n \ \text{const.})$$

$$E \propto n \quad (I_f \ \text{const.})$$

- the no-load saturation curve of a dc machine
- curve of emf *E* versus field current I_f for the machine running at rated speed on no-load
- a.k.a. open-circuit characteristic or magnetisation curve


E
increasing n
I_f

6.6.2 DC generator equivalent circuit

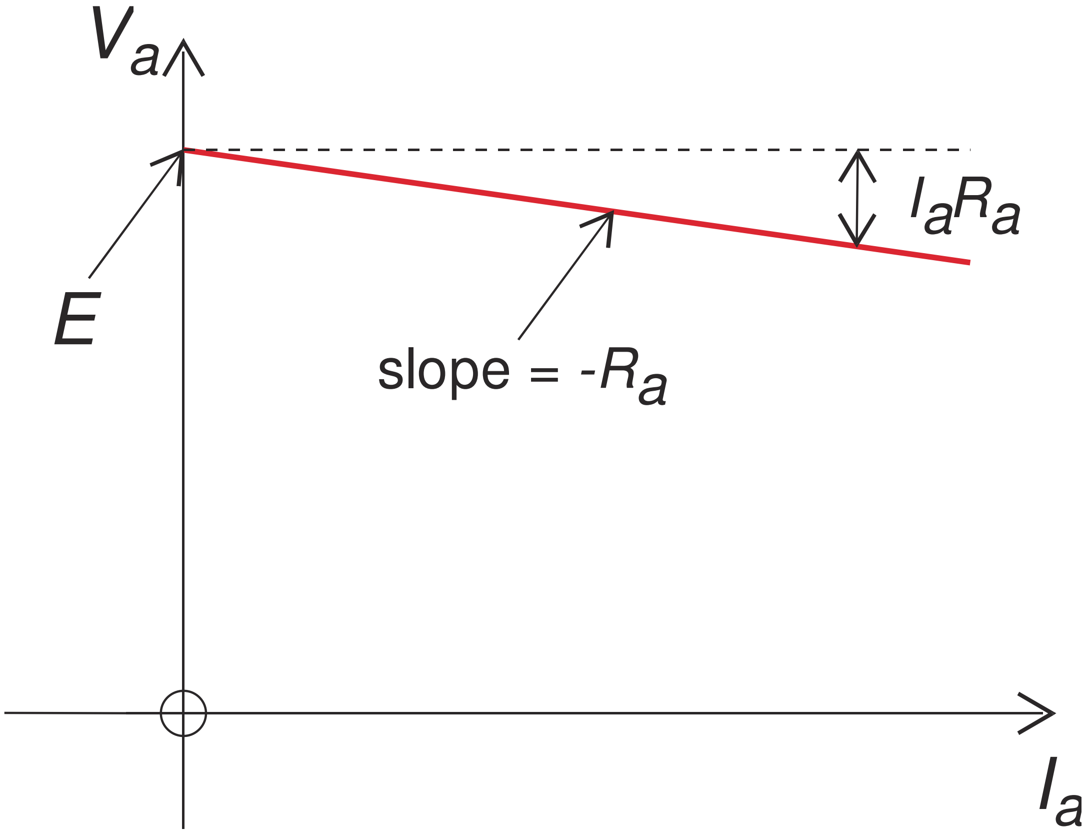


$$V_a = E - I_a R_a$$

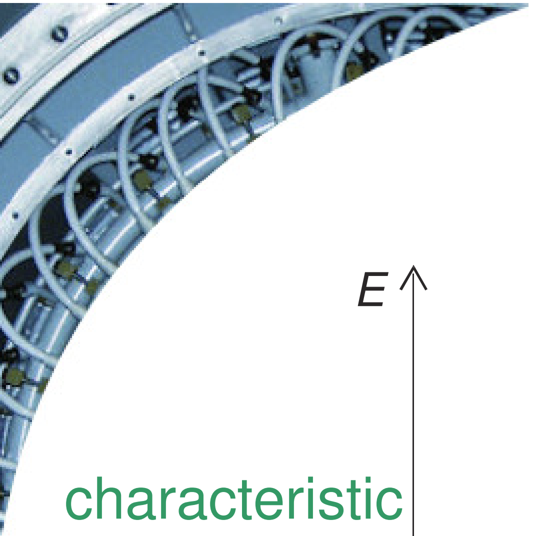
$$E = \left(\frac{2pZ}{c}\right) n\phi$$

6.6.3 Separate excitation

- I_f is from a separate source (external)



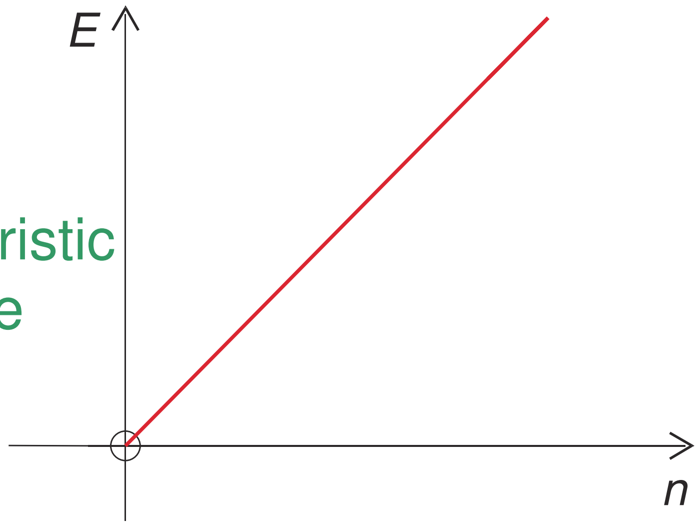
$$V_a = E - I_a R_a$$

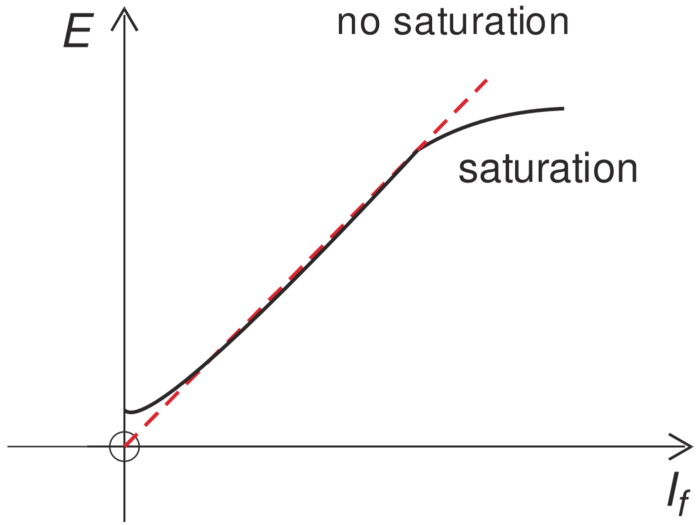


Vary n

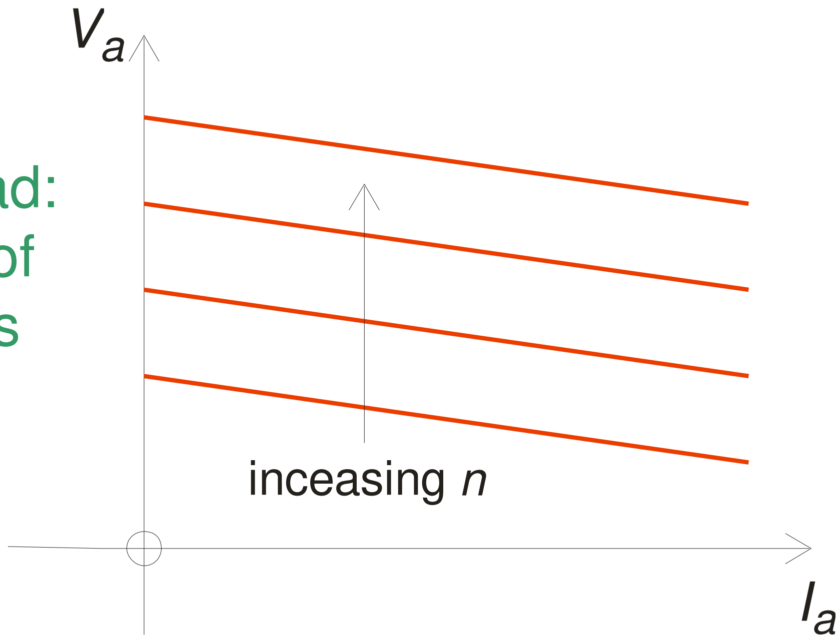
Vary I_f

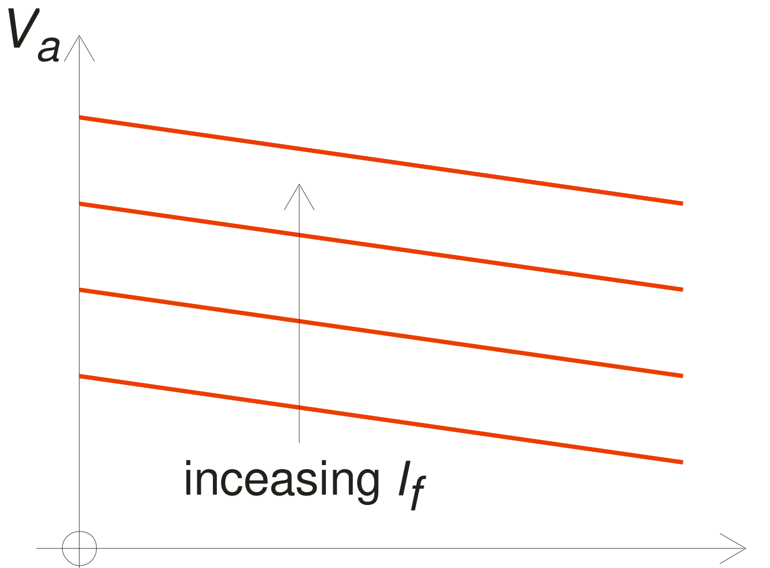
characteristic curve



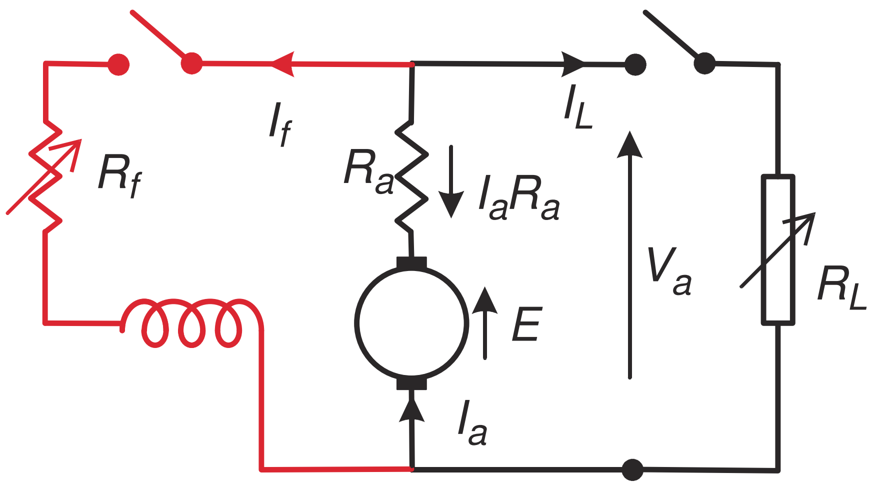


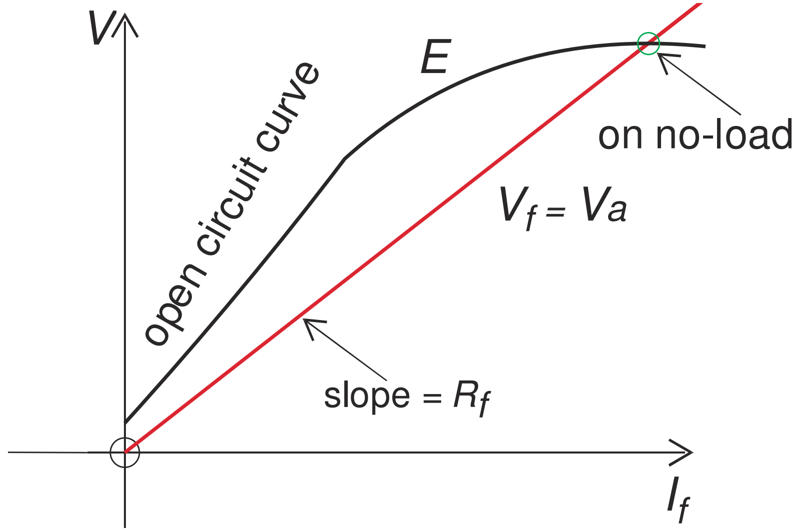
with load: family of curves





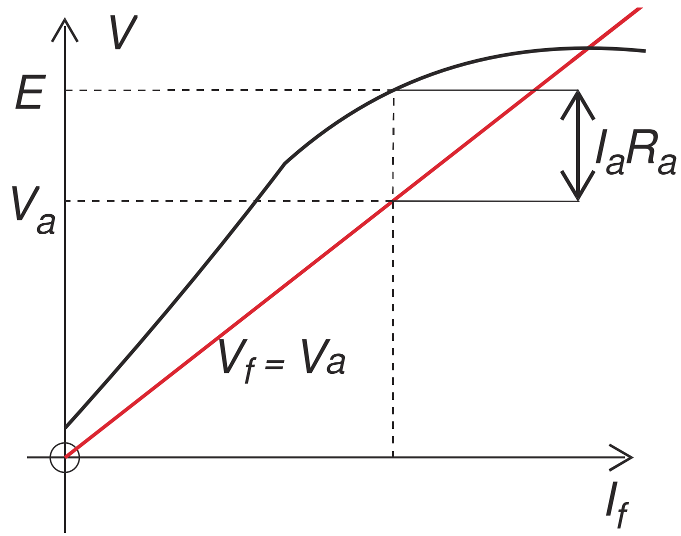
6.6.4 Shunt excitation





1) close field switch, then

$$V_f = V_a$$



1) on load with load switch closed

- on load with load switch closed, I_L flows and I_a is significant

- when I_a is increased, V_a reduces (due to I_aR_a drop), as in the case of separate excitation

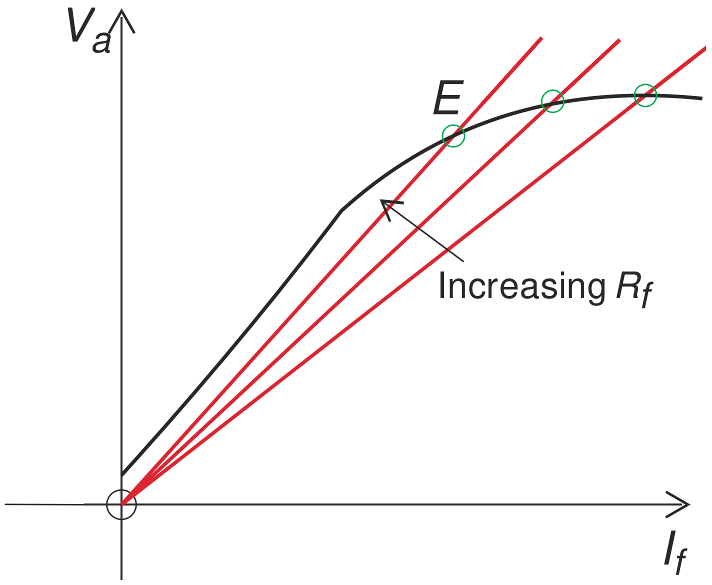
- V_f reduces, I_f reduces, ϕ reduces (unlike in separate excitation

- $\therefore$ E reduces

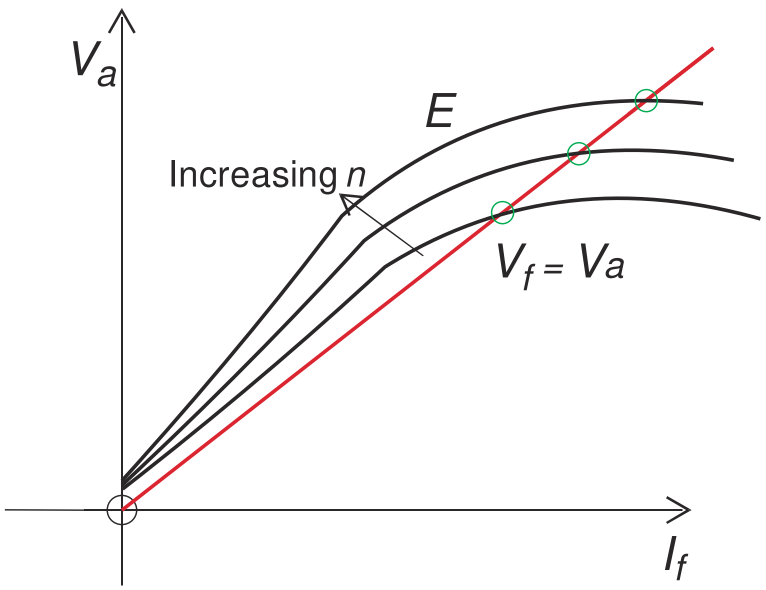
- V_a reduces even further


V_a
sep. exc.
shunt exc.
I_a

6.6.5 Why shunt generator may fail to self-excite



R_f is too high

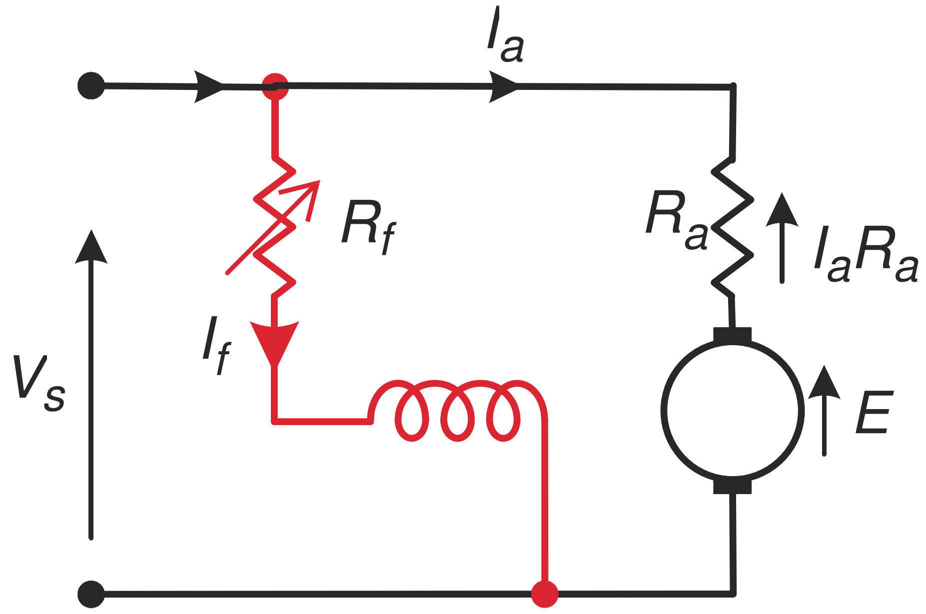


n is too low

6.7 DC Motors

- most common industrial workhorse is ac cage induction motor
- dc motor is more complex and more costly
- dc motor has advantage of
  - a wide variety of torque-speed [*T*-*n*] characteristics
  - economical speed control
- relationship between n and T corresponds to relationship between V and I_a for a generator
- n at which motor runs depends on the balancing point of the electromagnetic torque T_e and the mechanical load torque T_m

6.7.1 DC shunt motor



$$E = \left(\frac{2pZ}{c}\right)n\phi$$

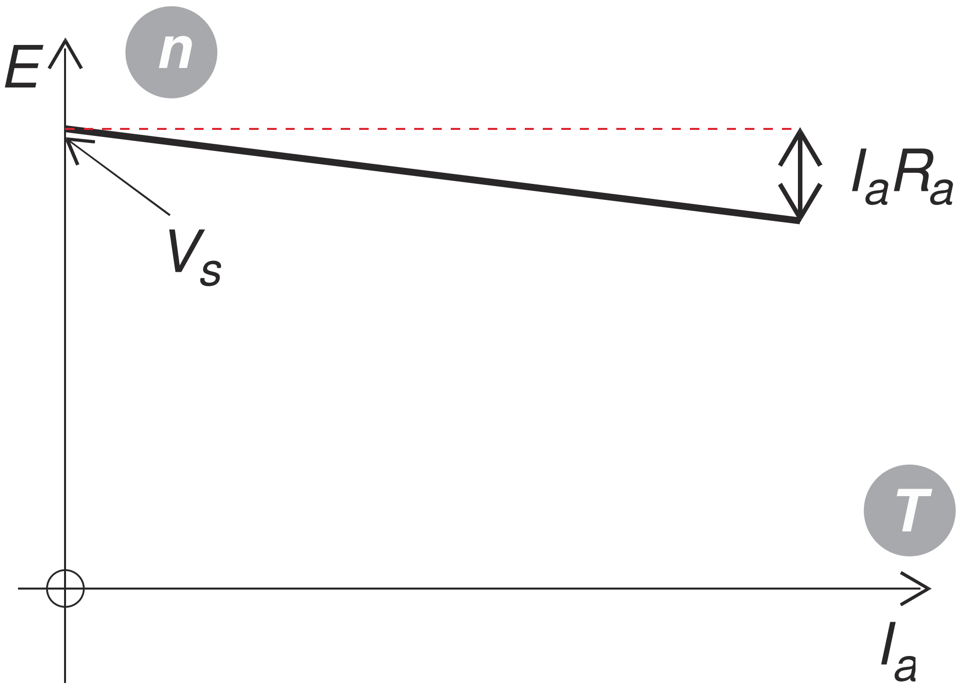
$$T = \frac{1}{2\pi}\left(\frac{2pZ}{c}\right)\phi I_a$$

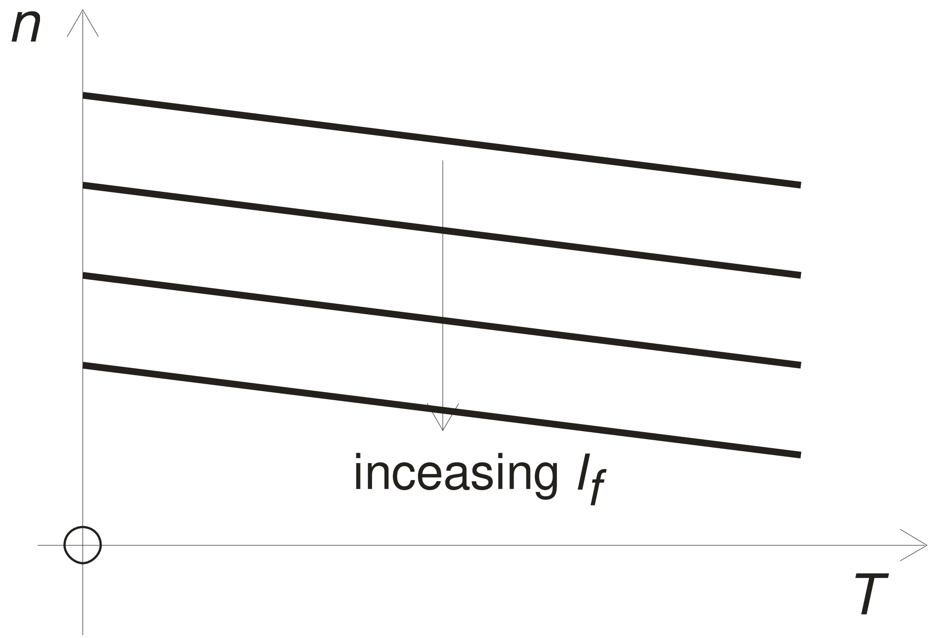
$$E = V_s - I_a R_a$$

- at constant I_f ($\therefore$ constant ϕ, since V_s = const.)

$$E \propto n$$

$$T \propto I_a$$

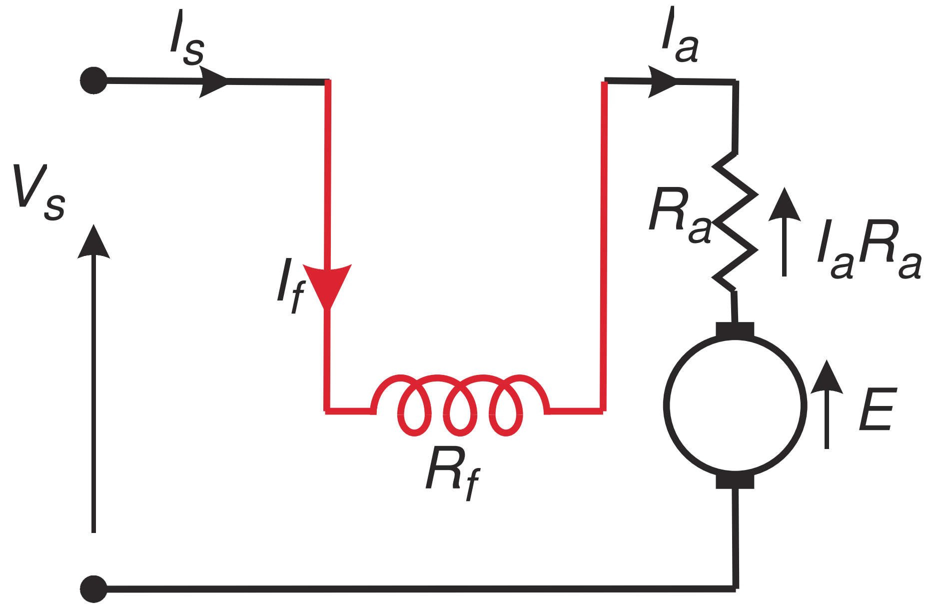




- characteristic behaviour is the same for separately-excited since

$$V_s = V_a = \text{ constant}$$

6.7.2 DC series motor



$$I_s = I_a = I_f = I$$

- 2 assumptions
  1) neglect "*IR*" drops
  2) neglect saturation, so $\phi \propto I$

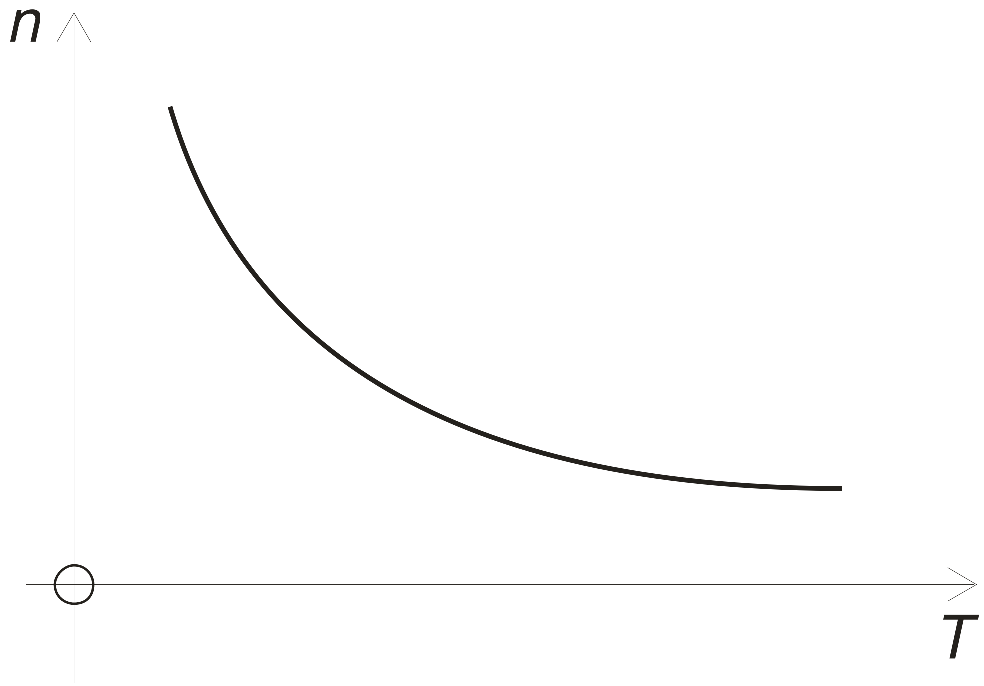
$$V_s = E = \left(\frac{2pZ}{c}\right) n\phi$$

$$\therefore n \propto \frac{1}{\phi} \propto \frac{1}{I}$$

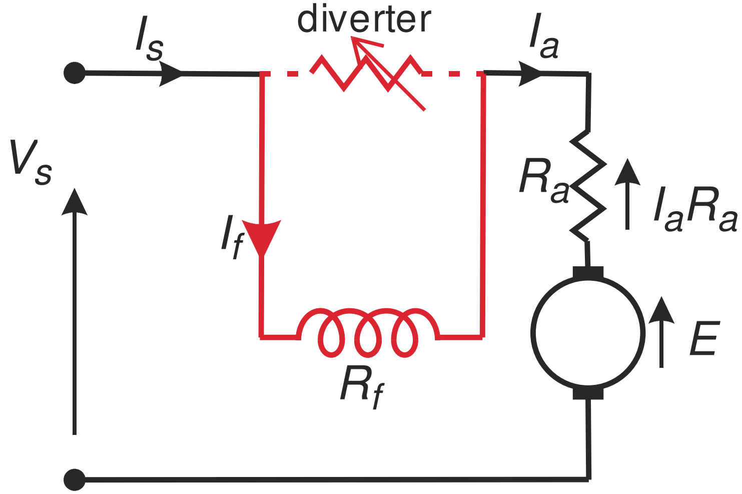
$$T = \frac{1}{2\pi}\left(\frac{2pZ}{c}\right)\phi I_a$$

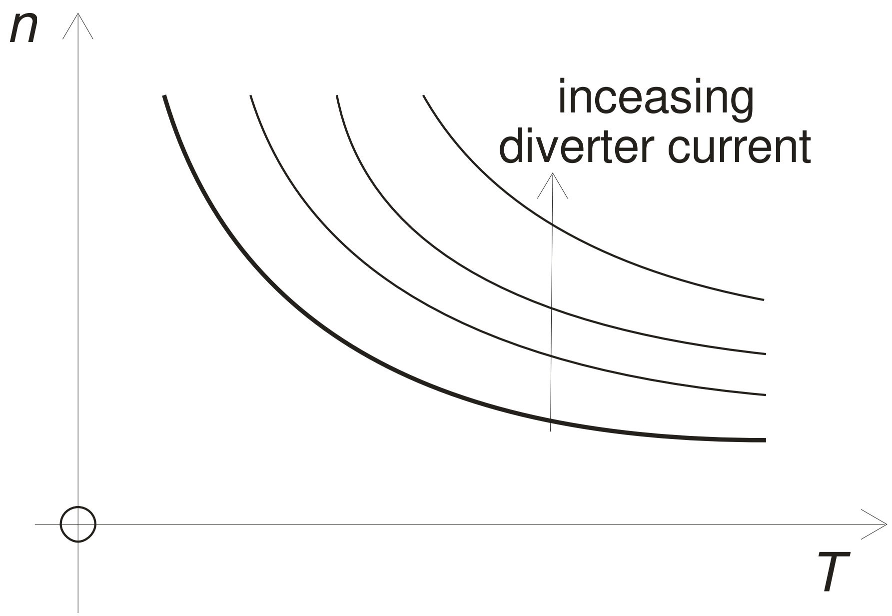
$$T \propto I^2$$

$$T \propto \frac{1}{n^2}$$



Using a current diverter





- gives a family of *T-n* curves

6.8 Starting DC motors

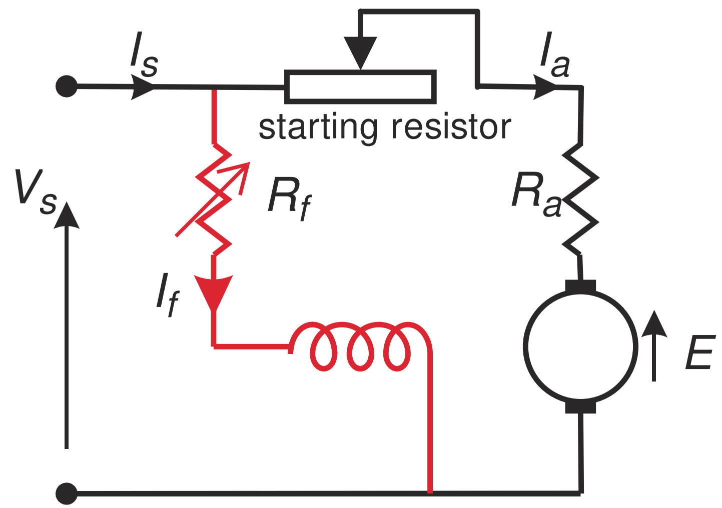
$$V_s = E + I_a R_a$$

- for V_s = 220 V, R_a = 1 Ω (e.g.)

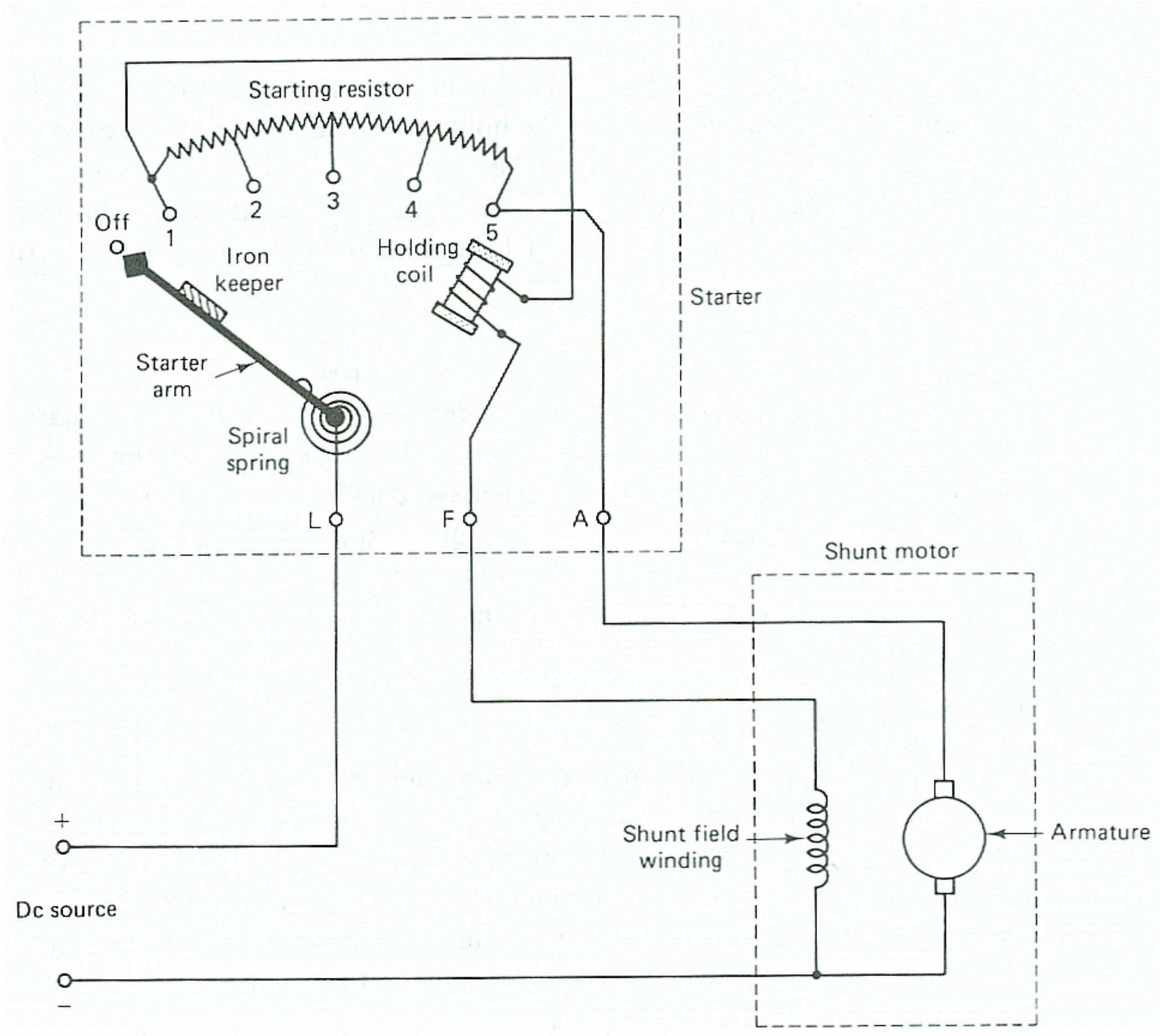
	I_a	V_s	=	E	+	$I_a R_a$
Full-load	10 A	220	=	210	+	10 x 1
No-load	1 A	220	=	219	+	1 x 1
Starting	?	220	=	0	+	? x 1

- for an assumed no-load I_a = 1 A and full-load I_a = 10 A,
  - starting current is 220 A!
- this is unacceptable

- to limit the starting current
    - include a temporary resistor in the armature
- this starting resistance is gradually reduced to zero as the machine speeds



A practical manual starter



Examples

1.

- A shunt generator has a field resistance of 60 Ω.
- when the generator delivers 6 kW, the terminal voltage is 120 V, while the generated EMF is 133 V.
- Determine
  - the armature circuit resistance and
  - the generated EMF when the output is 2 kW and terminal voltage is 135 V

2.

- A DC motor operates at 1680 r/min when drawing 28 A from a 230-V supply.
- If the armature resistance is 0.25 Ω, and assuming all losses are neglected, calculate
  - the no-load speed;
  - the developed power under loaded conditions;
  - the torque developed under the given load

3.

- A 240-V shunt motor has an armature resistance of 0.25 Ω
- Under load, the armature current is 24 A
- Suppose the flux is suddenly decreased by 2.5%
  - what would be the immediate effect on the developed torque?
  - if the motor was running at 640 r/min before the field was adjusted;
    - determine the new steady-state speed after the field has been decreased

4.

- A 240-V shunt motor runs at 800 r/min when the armature current at no-load
- the armature and field circuit resistance are 0.4 and 160 Ω, respectively
- calculate the required resistance to be placed in series with the field to increase the speed to 950 r/min when armature current is 20 A

- End of Lecture 6 -