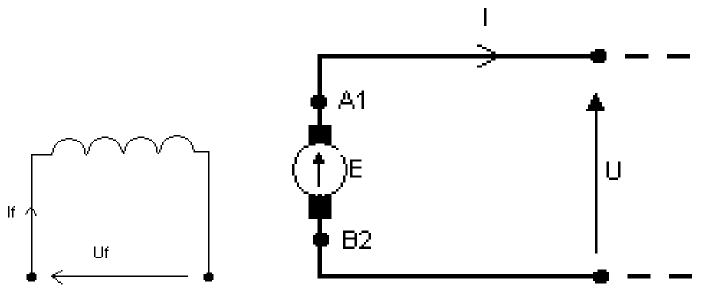
DIRECT CURRENT MACHINES 3

DC GENERATORS

a) Separately excited generator



Basic equations describing generator circuit and machine's torque:

$E = c\Phi n$

$I = I_a$

$U = E - IR_{at}$

$T = c_E \Phi I$

R_{at} - total resistance of armature circuit (armature winding resistance, brush-commutator contact resistance, interpole winding resistance)

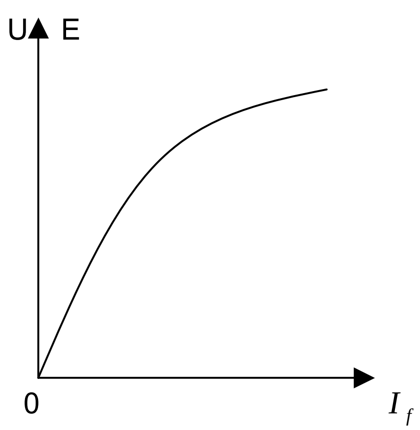
$R_{at} = R_A + R_B + R_c$

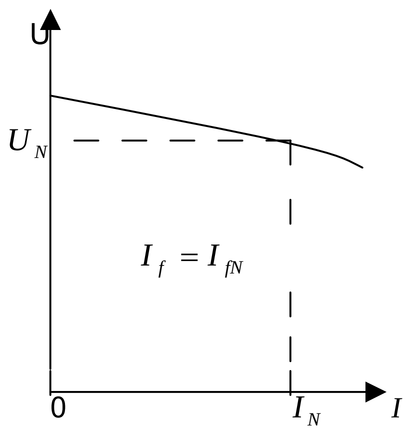
Open-circuit characteristic:

$U = E = f(I_f), \quad n = n_N$

Voltage-current characteristic; Load (external) characteristic

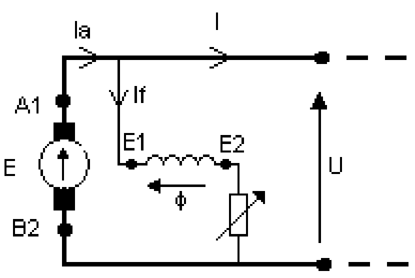
$U = f(I) \quad \begin{matrix} n = const \\ I_f = const \end{matrix}$





Voltage regulation: $\Delta U_r = \dfrac{U_0 - U_N}{U_N}$

b) Self-excited (shunt) generator



Relations:

$E = c\Phi n$;

$I_a = I + I_f$; $\quad (I_f = \dfrac{U}{R_f})$;

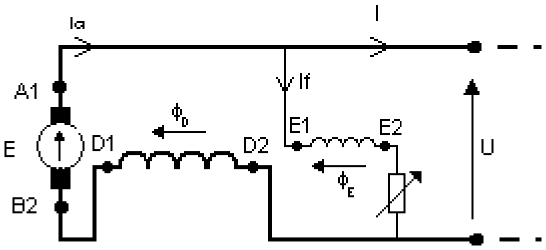
$U = E - I_a R_{at}$;

$T = c_E \Phi I_a$;

Very important and interesting problem: process (phenomenon) of self-excitation ⇔ RESIDUAL FLUX IN MAGNETIC CORE MATERIAL REQUIRED.

Load characteristic – see next page: curve (b).

c) Self-excited compound generator



(long-shunt connection)

Relations:

$$E = c\Phi n\,;\ (\Phi = \Phi_E + \Phi_D)$$

$$I_a = I + I_f\,;\quad (I_f = \frac{U}{R_f})\,;$$

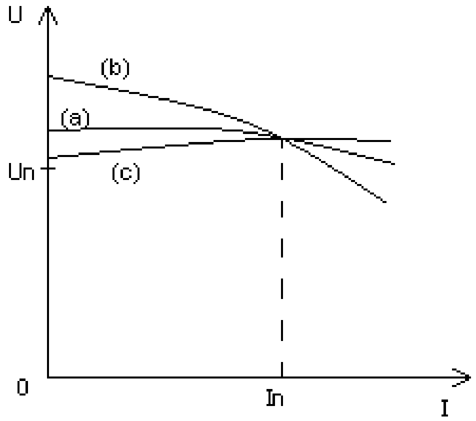
$$U = E - I_a R_{at}\,;$$

$$T = c_E \Phi I_a\,;$$

Here:

$$R_{at} = R_A + R_B + R_c + R_D$$

Characteristics



(a)-separately excited generator
(b)-shunt generator
(c)-compound generator

$I\uparrow \quad I_a\uparrow \quad \Phi_D\uparrow \quad \Phi\uparrow \quad E\uparrow$

ΔU_r can be small

ΔU_r : for separately excited generator $<$ 10%
for shunt generator 25 $\div$ 35%
for compound generator $<$ 5%

d) Series generator – no practical applications.

How the output voltage can be controlled?

$$U = E - I_a R_{at} \qquad U \approx E$$

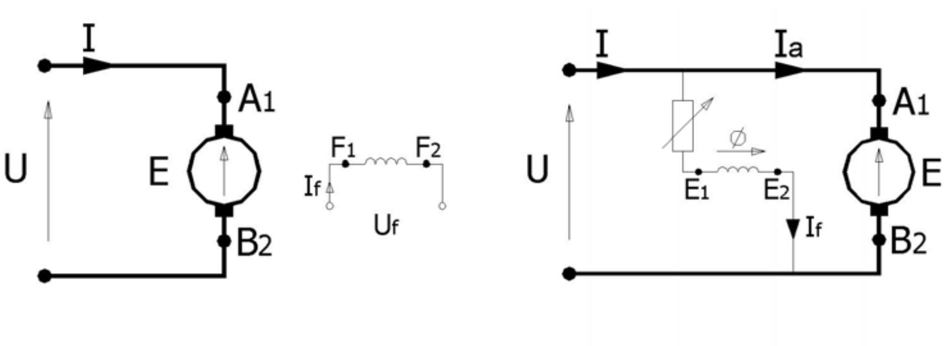
If the speed of generator is kept constant $U \approx E = cn\Phi = k\Phi$.
For unsaturated machine $\Phi \sim I_f$, therefore:

$$\boxed{U \approx const \times I_f}$$

In all kinds of connection (separately excited, shunt, compound) the best and simplest method of generator's output voltage control is to regulate its field current.

DC MOTORS

a) Separately excited or shunt motor



Relations for steady-state operation:

$U = E + IR_{at}$ $\qquad$ $U = E + I_a R_{at}$ $\qquad$ $(I = I_a + I_f)$

$E = c\Phi n$ $\qquad$ $E = c\Phi n$

$T = c_E \Phi I$ $\qquad$ $T = c_E \Phi I_a$

For U_f = const or U = const (in shunt motor) and with armature reaction neglected:

I_f = const $\quad\Rightarrow\quad$ Φ= const

Important assumption is made here: Φ is independent on load, is independent on I or I_a

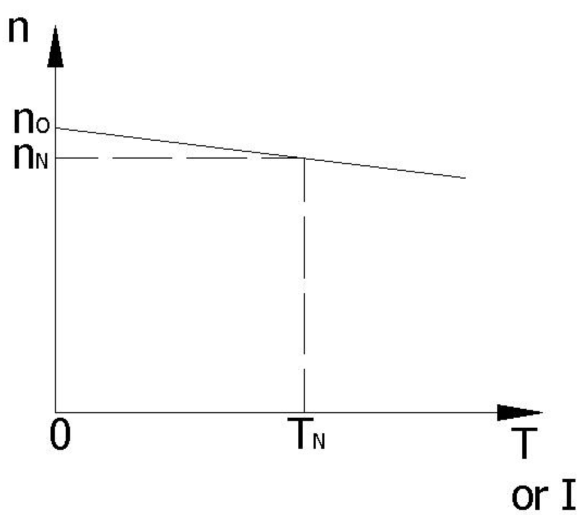
and characteristics of separately excited and shunt motors are similar (or even the same).

The most important relation for shunt motor is: $n = f(M)$ or $n = f(I)$ for U = const, I_f = const and Φ = const

$$n = \frac{E}{c\Phi}; \qquad n = \frac{U - R_{at} I_a}{c\Phi} = \frac{U}{c\Phi} - \frac{R_{at}}{c\Phi} I_a$$

$\boxed{n = n_o - kI_a}$ or taking into account that $T = c_E \Phi I_a$

$\boxed{n = n_0 - k'T}$ where n_o is no-load speed of shunt or separ. exc. motor.

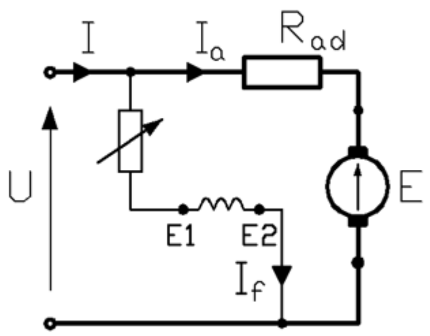


n = f(T) is called "mechanical characteristic" of the motor or "speed-torque characteristic.

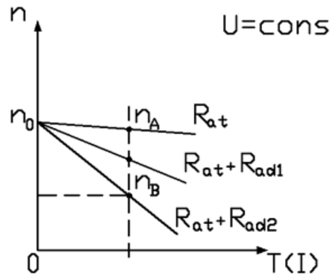
This characteristic is drawn for:
$U = U_N$ = const
$I_f = I_{fN}$ = const

How to control the speed of shunt motor?

1) - *by means of additional resistance connected in armature circuit*:



$$n = \frac{U}{c\Phi} - \frac{R_{at} + R_{ad}}{c\Phi} I_a$$



The method allows to reduce the speed into its lower values than for R_{ad}=0.
When we compare n_A and n_B speeds for the same T = const (I_a = const), we see that:

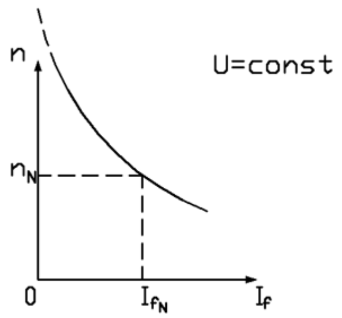
$P_{1A} = UI_A = UI_B = P_{1B}$ INPUT POWER IS THE SAME FOR A AND B

$$\begin{matrix} P_B = cTn_B \\ P_A = cTn_A \end{matrix} \Rightarrow \frac{P_B}{P_A} = \frac{n_B}{n_A} \Rightarrow \frac{\eta_B}{\eta_A} = \frac{n_B}{n_A}$$

When the speed is reduced significantly, the efficiency of power conversion is reduced in the same rate!

The method of speed control is **uneconomic** (compare with corresponding method for slip-ring induction motor speed control).

2) – *by means of exciting current control*



$$n = \frac{E}{c\Phi} \approx \frac{U}{c\Phi} \approx \frac{const}{I_f}$$

The method allows to increase the speed above its nominal value to infinite value! Practically – to its permissible value corresponding to mechanical strength (mechanical withstand) of the rotor (centrifugal forces ~ n^2). In practice the maximum permissible speed is of (1.2÷1.3)n_N.

The method is practically not applicable for lowering the speed below n_N. Why?

What happens when in the running shunt motor its field circuit is suddenly broken and field current becomes zero?

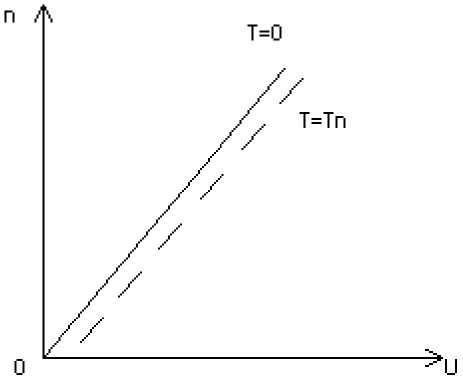
[Try to answer these two questions]

What would be the best solution for speed control of DC shunt motor?

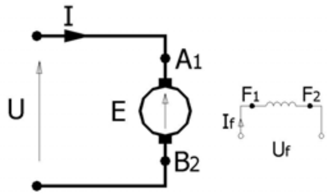
$$n = \frac{E}{c\Phi} \approx \frac{U}{c\Phi} \text{ let } \Phi = \text{const. and } U \text{ is variable: } \Rightarrow \; n = \text{const} \times U$$

If Φ is to be constant, the field current must be constant. Hence, the field winding cannot be supplied from variable voltage source.

To realize that, <u>the motor must be separately excited</u> or with PM:

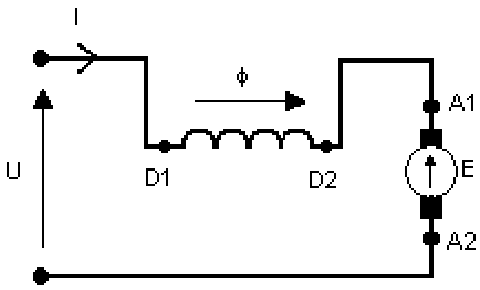


Φ = const



Very good proportional relation of the speed against armature supply voltage.

b) **<u>Series motor</u>**

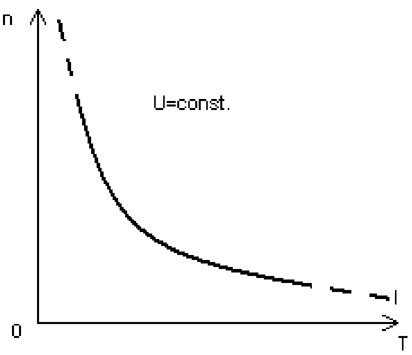


The basic relations are the same. Here:

$I = I_a = I_f$;

also:

$T = c_E \Phi I \approx c'_E I^2$;



Typical "series" speed-torque characteristic.

Therefore:

$$n = \frac{E}{c\Phi} = \frac{U - R_{at} I}{c' I} = \frac{A}{I} - B$$

or:

$$n = \frac{A'}{\sqrt{T}} - B$$

Applications? Yes – ELECTRICAL TRACTION!

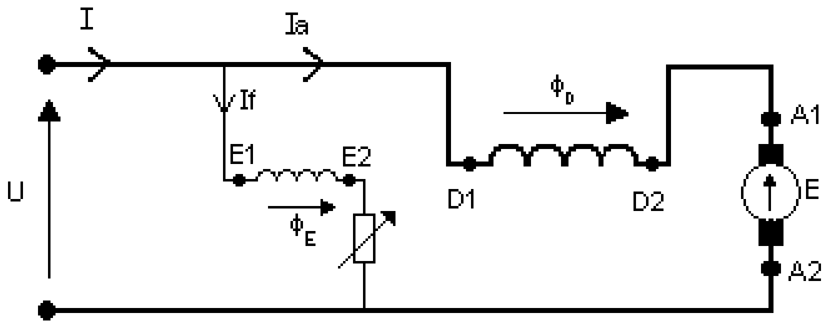
How to control the speed?

For T = const $\Rightarrow$ I = const, therefore:

$$n \sim U$$

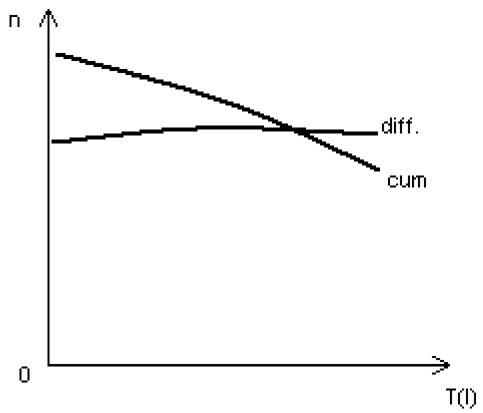
It is very easy to control the speed by means of supply voltage regulation.

c) **Series-shunt motor**



$\xrightarrow{\phi_E}\ \xrightarrow{\phi_D}$ - cumulative connection.

$\xrightarrow{\phi_E}\ \xleftarrow{\phi_D}$ - differential connection.

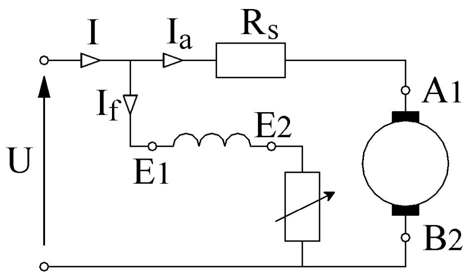


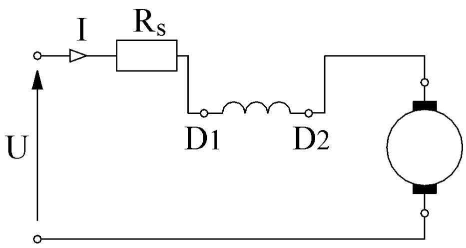
$$\frac{\phi_D}{\phi_E} = 2 \div 10\%$$

STARTING OF DC MOTORS

Armature circuit resistance is as small as possible (several Ω in small motors, a fraction of Ω in large motors).
Let us consider the following example: 220 V DC motor of 3 kW rated power. Its rated current I_N = 20 A, $R_{at} \approx 1\ \Omega$. Let consider both: shunt and series motors of such ratings:

It is designed to be small to avoid high I^2R losses in armature circuit.





At $n = 0$ $\quad$ $E = 0$

Starting current for both cases:

$$I_{as} = \frac{U}{R_{at} + R_s} \qquad \text{for } R_s = 0 \qquad I_{as} \approx \frac{220}{1} = 220 \text{ A}; \quad \frac{I_{as}}{I_N} = 11 \quad \textbf{(!)}$$

DC motor cannot start and operate with so heavy current because of commutation. Let us allow doubled rated current at starting: $\frac{I_{as}}{I_N} = 2$ and compare starting torques for shunt and series motors in such circumstances:

Shunt motor $\qquad$ Series motor

$$T_s = c_E \Phi_N \times 2I_{aN} = 2T_N \qquad T_s = c_E \times 2\Phi_N \times 2I_{aN} = 4T_N$$

Effect of saturation is neglected here.

Series motor has starting torque 50÷100% higher than comparable shunt motor (of the same size & similar parameters).

What happens when in shunt or series DC motor the polarity of supplying voltage U is changed (reversed)?

I_a is reversed

$\Rightarrow T = c_E \Phi I_a$ is of the same direction

Φ is reversed

Can we supply DC motor with alternating (for example sinusoidal) voltage?

AC COMMUTATOR MACHINES

AC series motor (universal motor) – most popular in household equipment: vacuum cleaners, hair dryers, coffee grinders, meat grinders, small electrical tools – hand drills, polishers, etc.)

[Figures for this part of DC Machines Theory were drawn with the help of 2002/03 academic year students:
at page 1,2,5,6 – Marcin Wesołowski,
page 3 – Bogdan Kapusta,
page 4 – Przemysław Nawrocki,
page 7 – Stefan Korzeniowski]