НАВЧАЛЬНО-МЕТОДИЧНА ЛІТЕРАТУРА

Ministry of Education and Science of Ukraine

Ternopil Iivan Pul'uj National Technical University

Department systems of power consumption and computer technologies in power industry

COURSE OF LECTURES

from discipline " Fundamentals of the electric drive"

for full-time and part-time students

of directly 6.050701 “Electrical engineering and electrotechnologies ”

Ternopil, 2017

COURSE OF LECTURES from discipline " Fundamentals of the electric drive" for full-time and part-time students of directly 6.050701 “Electrical engineering and electrotechnologies ”.

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CONTENTS

Lecture 1
A motor controller as the main part of automated production

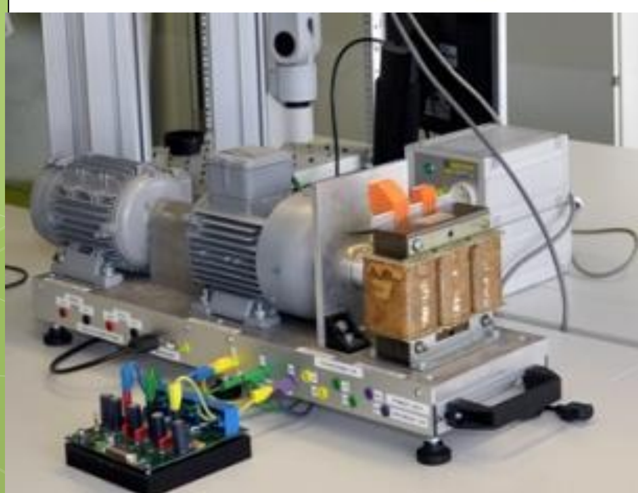
- 1. A brief historical overview and trends of the motor controller
- 2. Classification of motor controllers

1. A brief historical overview and trends of the motor controller

For modern production, transportation and other fields of the economy, mechanization and automation of production is carried out by means of **motor controller** and automatic control of the production process by **motor controller of the production mechanism** using programmable logic controller - PLC (controlled electronic computers).

Programmable Logic Controller (PLC)

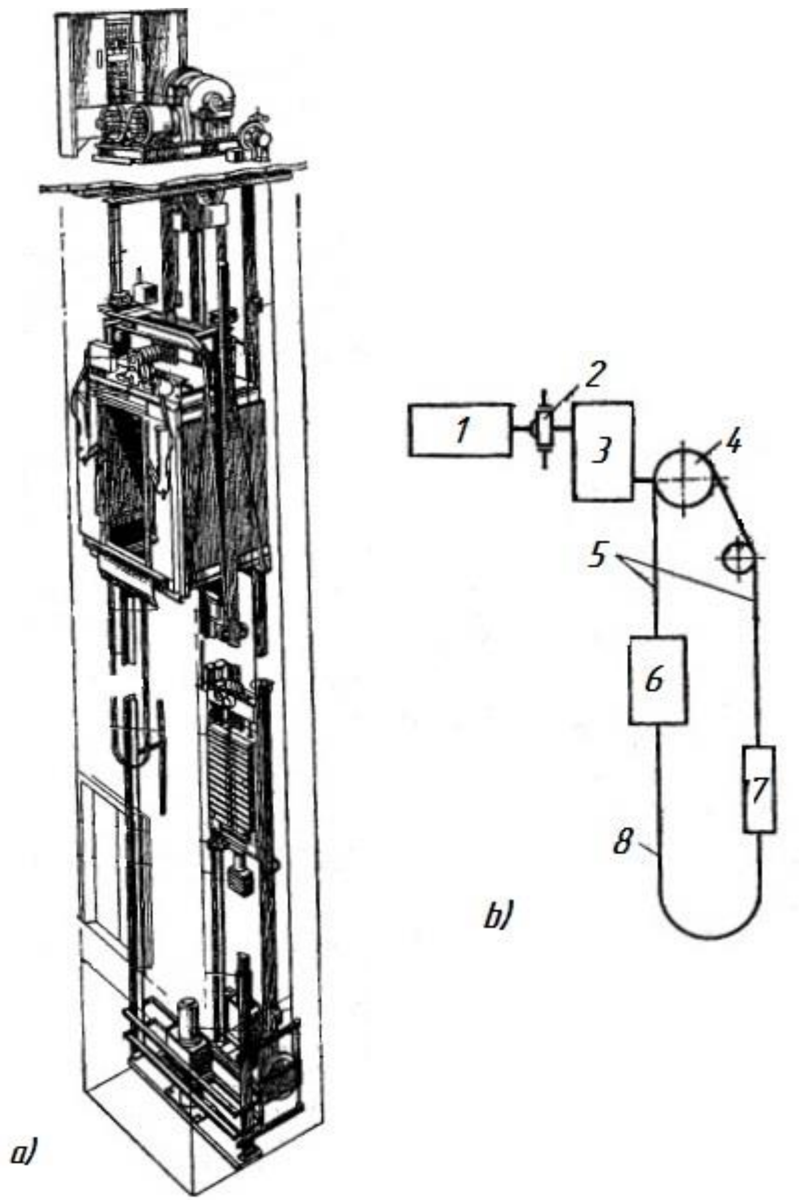
With the help of motor controller (electric drive control) is carried out by the **movement of industrial mechanism** to ensure **uninterrupted technological process**.



A motor controller is a machine device that performs the conversion of electrical energy into mechanical energy and provides **electrical control** by converted mechanical energy.

The main elements of the motor controller are the following:

- **electric motor;**
- **kinematic transmitter;**
- **electrical (or electronic) control system.**



General view of the motor controller of a industrial mechanisms (passenger elevator):

a) an elevator;

b) a kinematics scheme of a lift:

1 - electric motor;

2 - clutch;

3 – gear (reducer or gearbox);

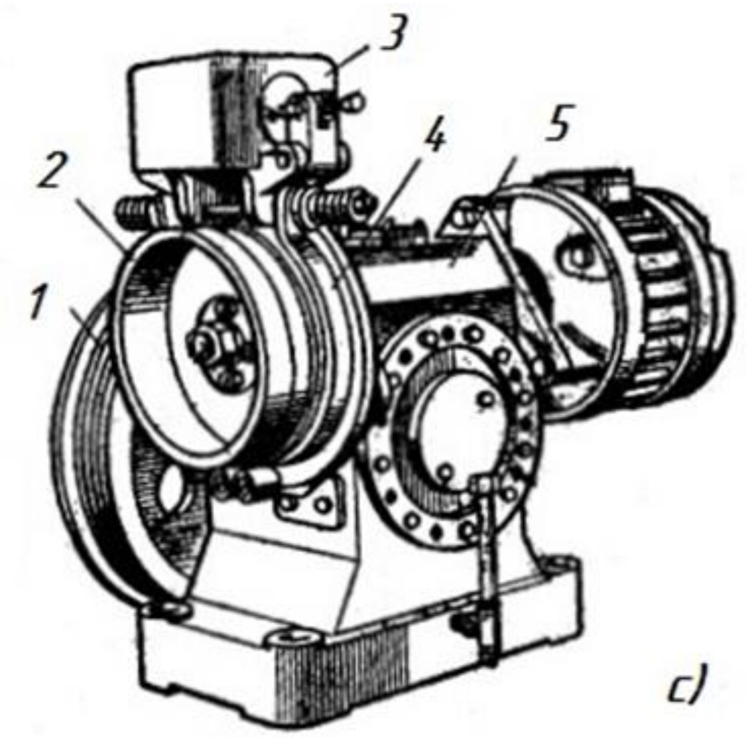
4 - traction sheave;

5 - main rope;

6 - cab;

7 - counterweight;

8 - rope for balance;



c) a motor controller with gear lifting mechanism:

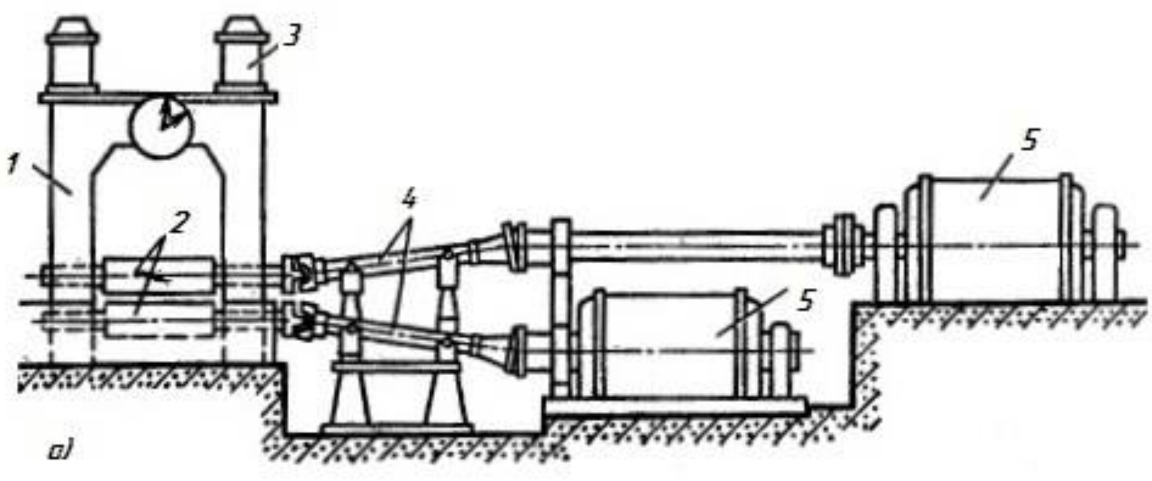
1 - traction sheave;

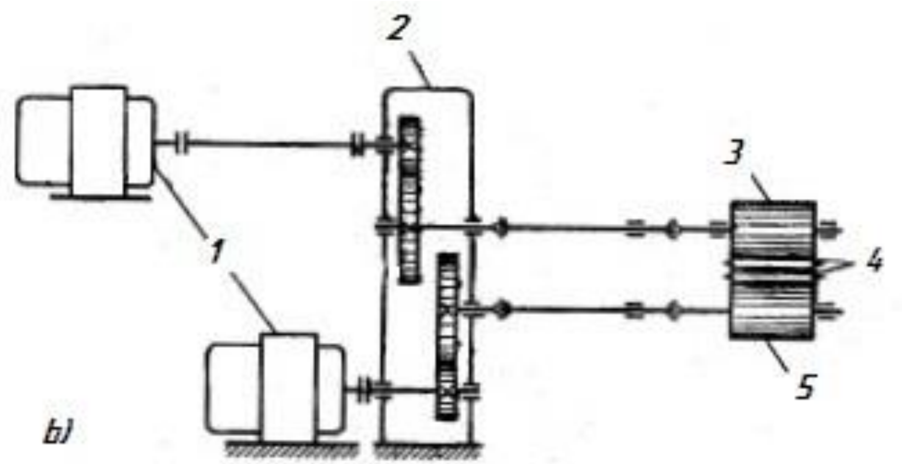
2 - braking sheave;

3 - brake electromagnet;

4 - brake pads;

5 - electric engine.





A motor control of shafts at two-shaft rolling for rolled rails, channels, beams:

a) a general view:

1 - bed frame;

2 - working shafts;

3 - a device for adjusting the distance between the shafts;

4 - spindles;

5 - electric engine;

b) kinematic scheme:

1 - electric engine;

2 – gear (reducer or gearbox);

3 - shafts.

The development of techniques for a motor controller was started with the **first electric motor** in the world created **in 1834**.

It was made and produced by Russian scientist **B.S. Jacobi** in St. Petersburg.

The main trends of a modern motor controller development are:

- **Efficiency** - reduction of specific material capacity of electric motor;
- **Creation of new types of electric motors** with a reduced specific gravity and lower losses on heating cores and windings;
- **Replacement** of **DC motors** in variable drive by **induction motors** with power and control of thyristor converters.

All mentioned above **trends** are embodied in **a modern energy efficient** motor controller, which is the **motor controller with:**

- the induction motor with squirrel cage rotor;

- **thyristor converters of frequency**;

- and **programmable logic controller**

(the motor controller as alternating current -thyristor converters of frequency-programmable logic controller **IC-TCF-PLC**).

2. Classification of motor controllers

The classification of motor controllers is due to the following criteria:

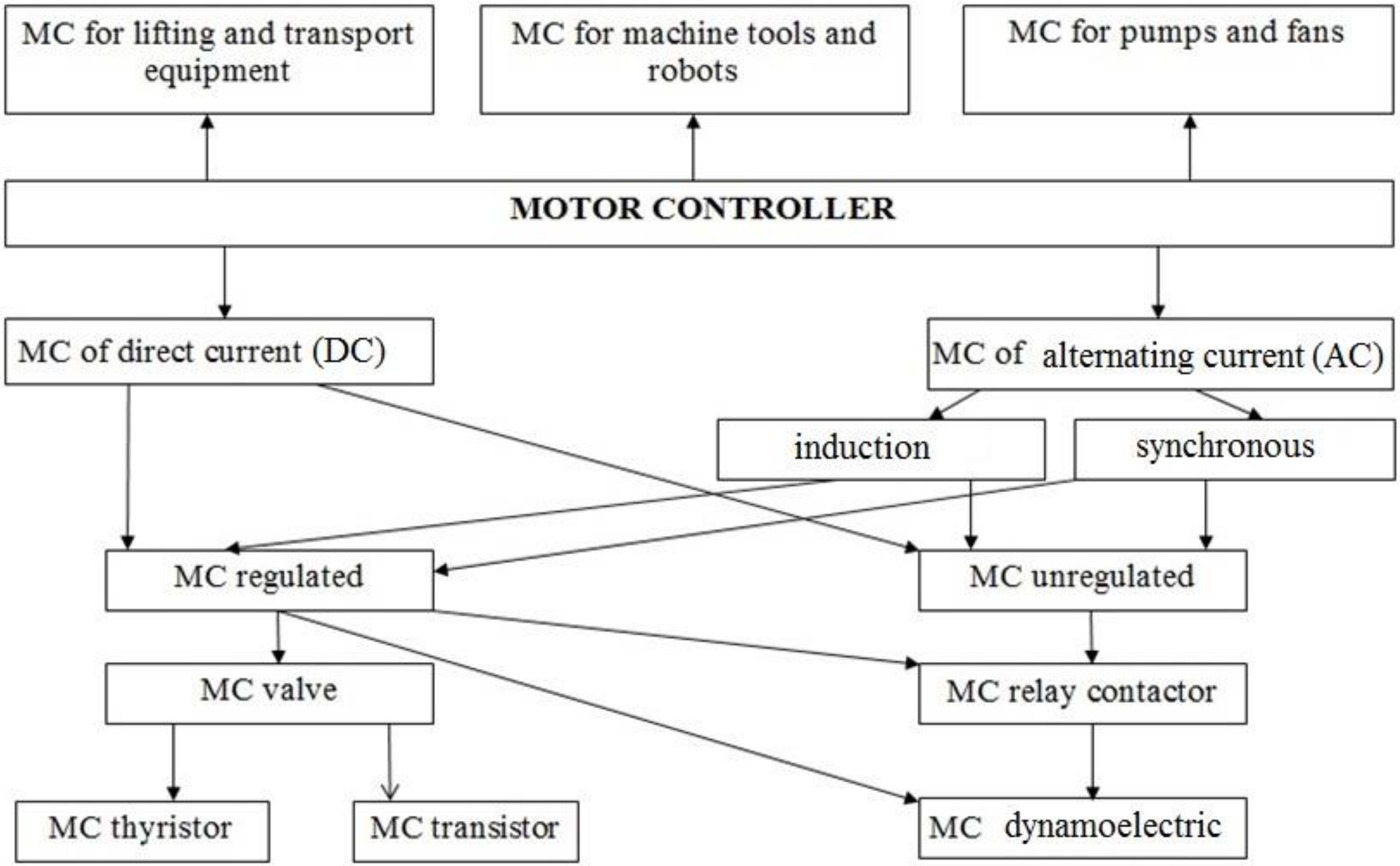
1. Type of current power of motor and type of motor - MC of alternating current (AC) motor (induction and synchronous) and MC of direct current (DC);

2. The possibility and capability of the system to control the speed and other variables - unregulated and regulated;

3. Type of voltage conversion:
- dynamoelectric;
- valve;

4. Element base of system regulation:
- relay contactor MC;
- thyristor MC;
- transistor MC ;

5. A group of industrial mechanisms, for which the motor controller is designed:
- MC for lifting and transport equipment,
- MC for machine tools and robots,
- MC for pumps and fans etc.



MC for lifting and transport equipment
MC for machine tools and robots
MC for pumps and fans
MOTOR CONTROLLER
MC of direct current (DC)
MC of alternating current (AC)
induction
synchronous
MC regulated
MC unregulated
MC valve
MC relay contactor
MC thyristor
MC transistor
MC dynamoelectric

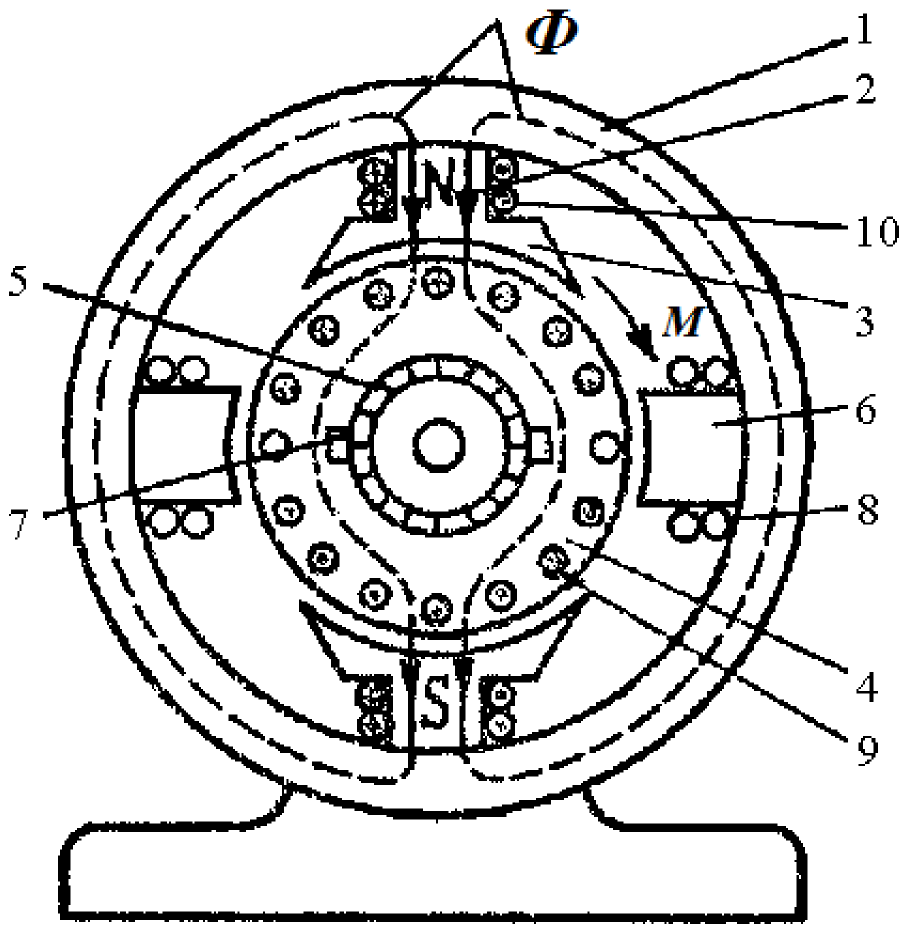
Lecture 2

ELECTRIC MOTORS OF DIRECT CURRENT (DC), THEIR CHARACTERISTICS AND METHODS OF REGULATION

- 1. Direct current (DC) electric motors
- 2. The ways of control (drive) of DCM

1. Direct current electric motors

The structure of DC motor (DCM)



collector 5
brushes 7

1 engine mouth piece
2 the main poles
10 the main winding poles
3 pole piece
6 additional poles
8 windings of poles
4 an engine armature (anchor)
9 conductors of engine armature winding

Fixed part, formed the core of the main poles of the winding and additional poles with windings called the **stator** and moving - an **anchor**.

There are **drive windings** to create a **magnetic field** between the poles at the poles of motors.

When you cut off the voltage on this winding (**drive windings**), current flows through it drive winding that **magnetize poles** and creates between the **magnetic field** induction vector *B*.

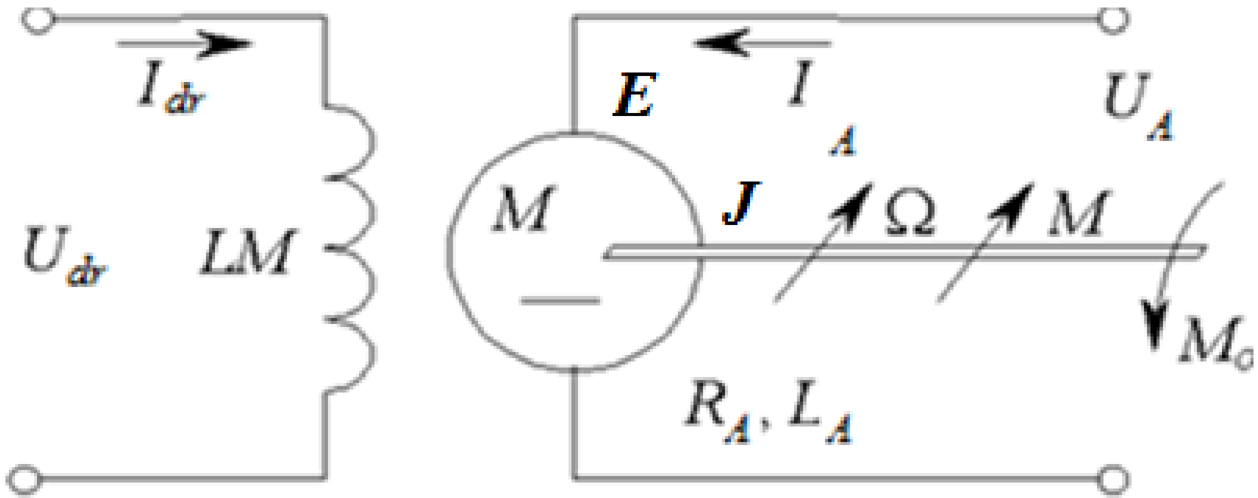
On the shaft of engine armature (anchor) is put a **collector** made of copper segments separated by an insulating gasket. To the each collector plate to a certain order are connected the beginning and the end of winding conductors.

Voltage to the collector lead with **two graphite brushes** placed in nests and oppression to the collectors with **springs**.

When you switch on the **supply voltage** to the windings the current I_A flows, that around windings **creates a magnetic field** of engine anchor.

From the **interaction** of magnetic fields - **fields anchor** and **field between the poles of the stator** creates a **rotating moment of anchor M**.

The electrical scheme of DCM with independent excitation



E - the electromotive force of the anchor winding,
J - moment of inertia of the anchor,
***M*o** - moment of resistance of the working mechanism,
M - electromagnetic moment of the engine,
Ω - frequency (angular velocity) of rotation.

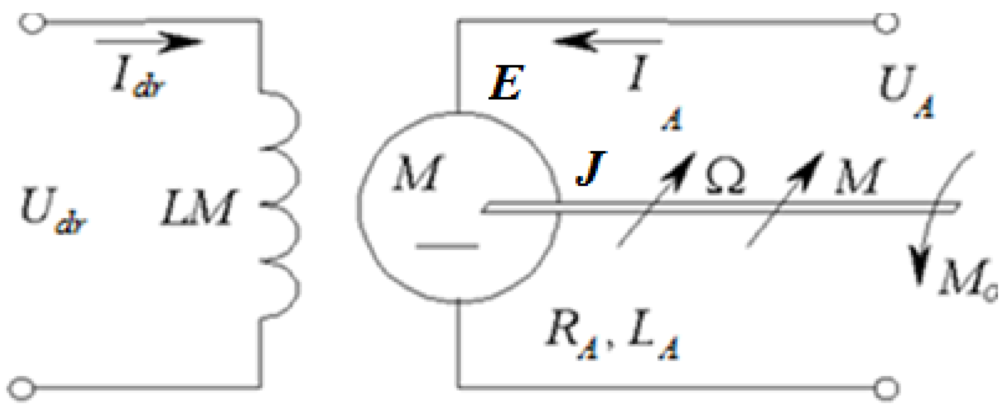
The working condition of the engine is described by **two equations:**

- **voltage balance equation** at engine anchor

$$U_A = I_A R_A + L_A \frac{dI_A}{dt} + E, \qquad (1)$$

- **equation of balance moments on the shaft** .

$$J \frac{d\Omega}{dt} = M - M_O, \qquad (2)$$



So, if we consider the electric motor **DC** as an **object of control**, its state is determined by **three following coordinates**:

1. Leading or output coordinate **Ω**,
2. Input or leading coordinate $\boldsymbol{U_A}$,
3. The second input or disturbing coordinate $\boldsymbol{M_o}$.

These coordinates are linked by the **equation of motion of the electric motor** and it is usual differential equation of the second order

$$T_м T_A \frac{d^2\Omega}{dt^2} + T_м \frac{d\Omega}{dt} + \Omega = K_d U_A - K_м M_o \qquad (3)$$

K_d - transfer coefficient of output voltage $K_d = \frac{1}{K\Phi}$

K_M - transfer ratio engine due to the moment $K_м = \frac{R_A}{(K\Phi)^2}$

T_M - electromechanical time constant of the motor;
T_A - electromagnetic time constant of the motor.

After the increase of current value to the motor shaft appears appropriate **winging moment** and **anchor begins to rotate**.

There is a **mechanical** transition process **acceleration** of the engine speed to the **default values**.

Duration of mechanical transient **longer for the** duration electromagnetic is

$$T_M > T_A$$

In practice, the duration of the process of acceleration of the engine ranges from **0,05 s to 0,5 s** and for high power engines it can be higher too.

Let's examine the characteristics of the engine in the **steady state**, with **Ω = const**, i.e. **static characteristics**.

In this case, the first and second components of equattion (3) are zero and it becomes

$$K_d = \frac{1}{K\Phi} \qquad K_м = \frac{R_A}{(K\Phi)^2}$$

$$\underbrace{T_м T_A \frac{d^2\Omega}{dt^2}}_{=0} + \underbrace{T_м \frac{d\Omega}{dt}}_{=0} + \Omega = K_d U_A - K_м M_o \qquad (3)$$

$$\Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot M_o}{(K\Phi)^2} \qquad (4)$$

In the steady state $\boldsymbol{M = M_o}$, then

mechanical characteristics

$$\Omega = \frac{U_A}{K\Phi} - \frac{R_A M_o}{(K\Phi)^2} \rightarrow \Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot M}{(K\Phi)^2} \quad (5)$$

This equation determines **the dependence of the motor** from the **moment** and it is called the equation of **mechanical characteristics.**

Given that

$$M = K\Phi I_A$$

Φ - the flow of excitation;

I_A – anchor current;

K – constructive constant of engine, which takes into account the number of pole pairs of the excitation system and the design parameters of the anchor winding

$$K = \frac{pN}{2\pi a}$$

we can write **mechanical characteristics**

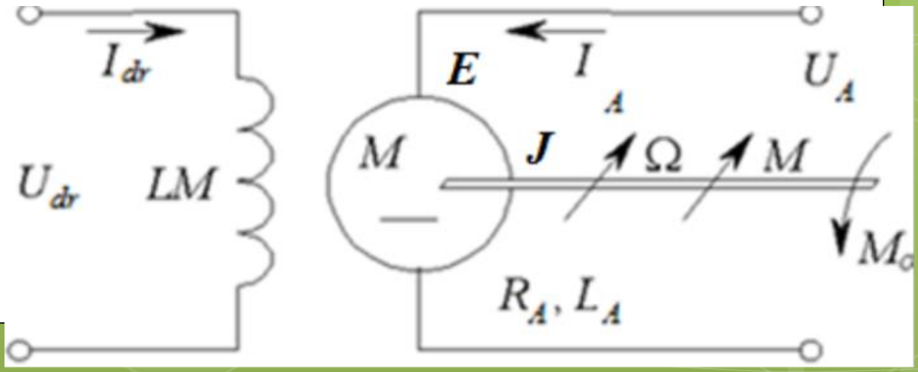
$$\Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot M}{(K\Phi)^2} \longrightarrow \boxed{\Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot I_A}{K\Phi}} \qquad (6)$$

$$\Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot I_A}{K\Phi}$$

This equation establishes a relationship between the **current** and **the speed** of the engine, it is called the equation of **electromechanical** or **high-speed characteristics.**

The analysis of this equation shows that the output coordinate **Ω** can be controlled by **changing one** or **two** of the three input coordinates:

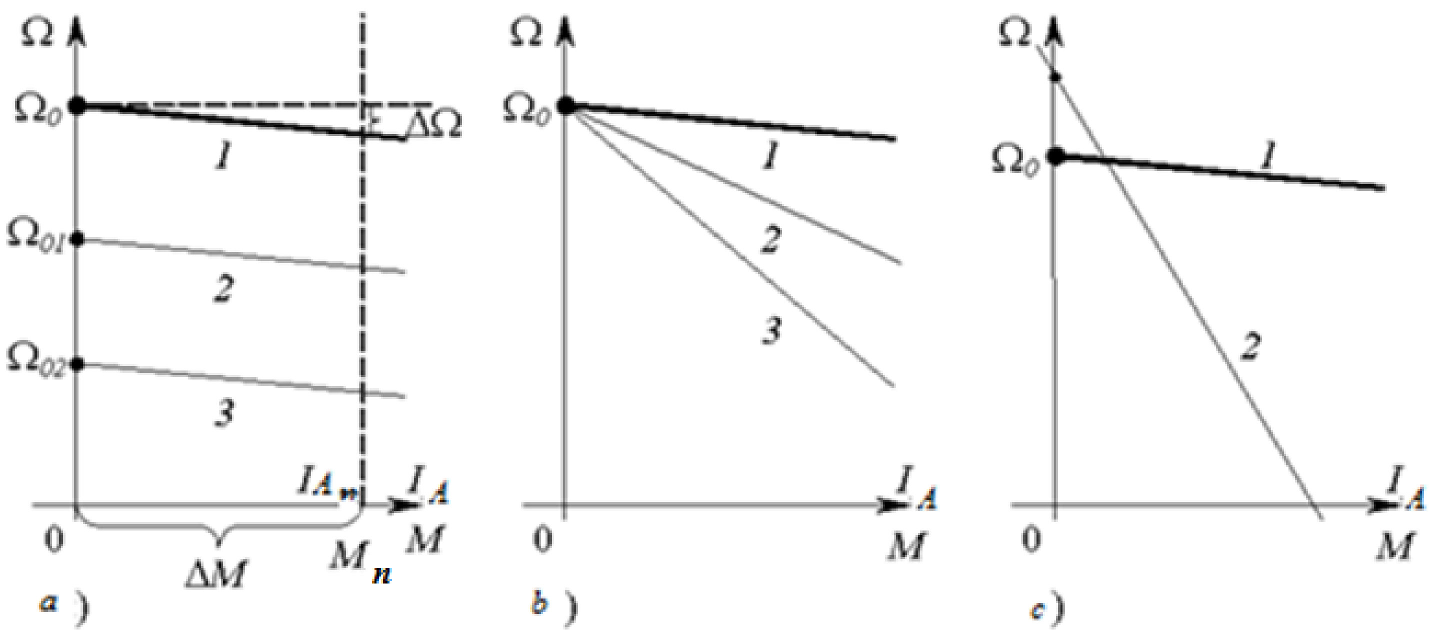
- the voltage at anchor winding U_A,
- anchor current I_A,
- the flow of excitation Φ.

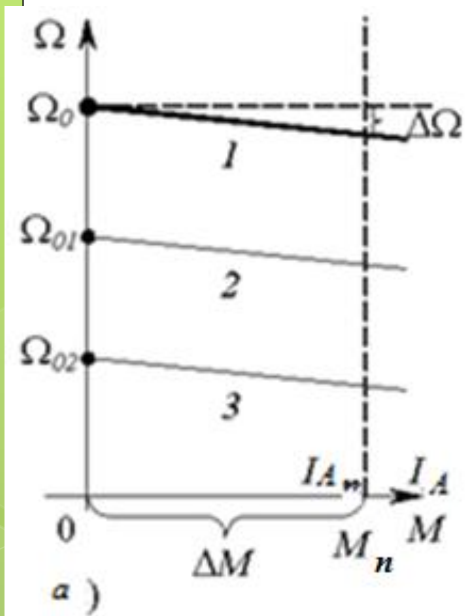


2. The ways of control (drive) of DCM

1. **Anchor voltage** control (a)
2. The regulation with **change of anchor current** (b)
3. The regulation with **change of the flow of excitation** (c)

The characteristics of DCM at different ways of control (drive)





1. Anchor voltage control is carried out by **change of voltage on anchor winding**.

This mode of regulation is **the main**, because it is most convenient for **automation**.

To implement this method, you must supply anchor to carry on regulated sources - **thyristor voltage converter** or electric machine generator.

Regulation of voltage change U_A should be carried out at **nominal value of the excitation flow** $\Phi = \Phi_n$.

Characteristic 1, based on at the nominal value of $U_A = U_H$, $\Phi = \Phi_n$ is called **natural.** Other characteristics (2, 3) are called **regulatory**.

Frequency Ω_0 is called the **ideal frequency of rotation**

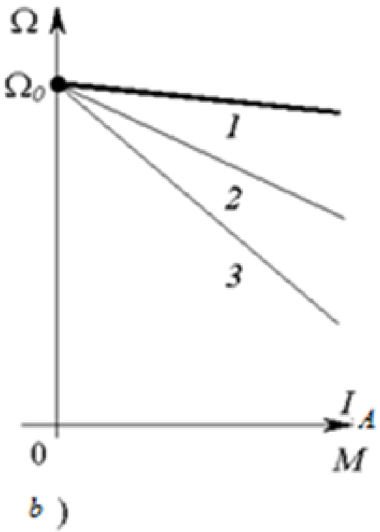
$$\Omega_o = \frac{U_A}{K\Phi_n} = \frac{U_A}{c} \quad \text{, where} \quad c = K\Phi_n \qquad (7)$$

c - **feedback factor for EMF engine**

Point with coordinates $M = M_n$, $\Omega = \Omega_n$ on natural characteristic (1) is **point of the nominal operating mode of the engine**. When regulating voltage the **speed changes** at a **constant moment on the shaft**.

So, the **equation of natural mechanical characteristics** of the engine, is written through his passport data, is

$$\Omega = \frac{U_n}{c} - \frac{R_A \cdot M}{c^2} \qquad (8)$$



2. The regulation with change of anchor current is carried out the **introduction** of the circle anchor **additional resistor (rheostat)** R_r. By varying the rheostat resistance, we change the stiffness characteristics

rheostat

$$\Omega = \frac{U_n}{c} - \frac{(R_A + R_r)\cdot M}{c^2} \qquad (9)$$

While $R_r = 0$ we have a **natural characteristic (1)**, which has the highest stiffness.

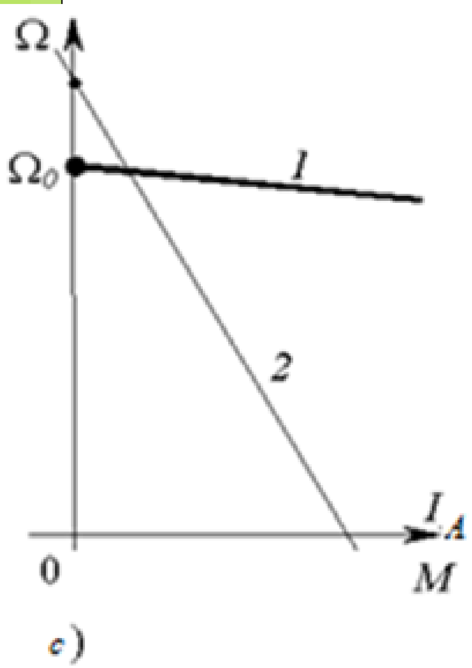
If $R_r > 0$ we obtain **regulatory characteristics (2,3).**

Adjusting with the rheostat is used for **automatically starting** of the engine with **starting current limitation**.

To start can be used a rheostat with **multiple** sections.

Start begins with a **fully switched on rheostat**, and with increasing speed, sections of the rheostat are **closed automatically** at short contacts magnetic contactors.

When reaching the steady speed of engine as Ω_n the rheostat **fully derived** from the circle of the anchor.



3. The regulation with change of the flow of excitation used when it is necessary to have a speed **greater than nominal**.

From formulas (4,5)

$$\Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot M_o}{(K\Phi)^2} \quad (4)$$

$$\Omega = \frac{U_A}{K\Phi} - \frac{R_A \cdot M}{(K\Phi)^2} \quad (5)$$

we can see that the **decrease of flow Φ** will increase the speed of Ω_o.

You can **only adjust** downward flow from **Φ_n** to **$0,5\Phi_n$**.

Controlling the flow of excitation should be at the **nominal voltage Un**.

The disadvantage of this method of regulation is the **dependence motor moment M on the speed** of the engine and a significant decrease the moment due to the $\Omega > \Omega_n$.

Therefore, this method is **used with the first one** when you need a **wide range** of adjustment.

This method implements with the winging power from a separate thyristor converter.

Lecture 3

Asynchronous (or induction) motors, their structure, principle of operation, the mechanical characteristics

Asynchronous motors (AM) are used mainly for the **unregulated** motor controller.

AM are easy for use and reliable because they do not have the brush-collector node, and they have less specific consumption of materials in 1,5 ... 2 times.

Due to these advantages **asynchronous motor controller** is the **main type** of motor controllers.

The disadvantage of AM is that it is **difficult** to **control**.

However, with the development of **semiconductor** transforming technology this disadvantage is persisted and now **AM with squirrel cage motor is the best variant** for both unregulated and regulated energy-saving motor controller.

According to the **construction of rotor AM** can be divided into **two** types:

1. AM with short circuit rotor ;

2. AM with phased rotor (AM with contact circuit).

Asynchronous motors with higher capacity than 0,18 kW are manufactured as **three phases**.

The construction of three-phased AM is on the fig. 1b.

The general look of three-phased AM and construction elements are on the fig. 1.

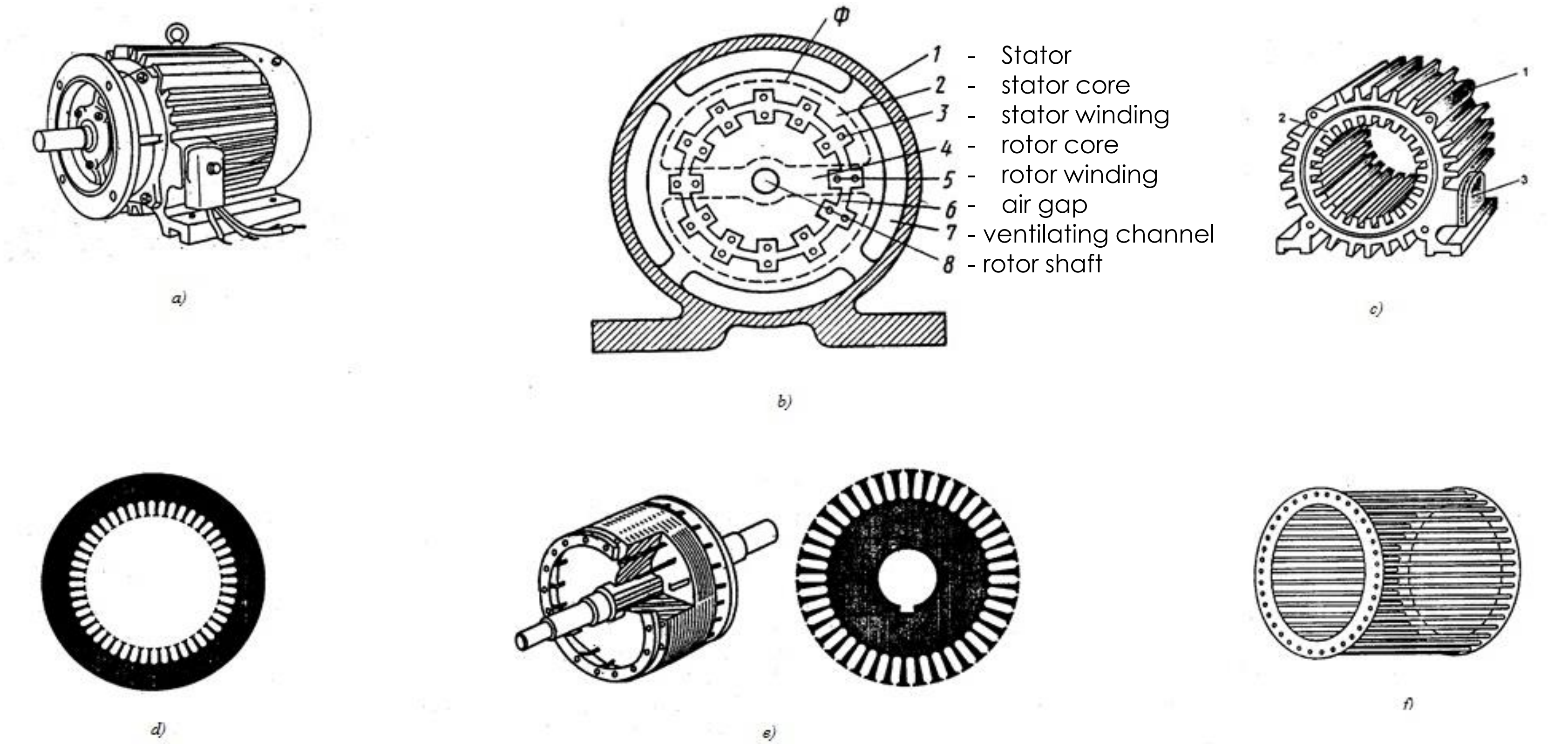


Figure 1 - General view of the structure of AM with SC (short circuit) rotor: **a)** general view of AM-SC; **b)** structure of AM-SC; **c)** stator and bedframe; **d)** stator lamination; **e)** rotor and rotor lamination; **e)** winding of a rotor as for "squirrel wheel".

The winding in AM with short circuit rotor consists of copper or aluminum windings placed in the rotor slots.

If you can imagine it separately out of main body, it looks like a **squirrel wheel** shown on fig. 1.

In schematic diagrams we use symbols AM with short circuit rotor, as shown in Fig. 2.

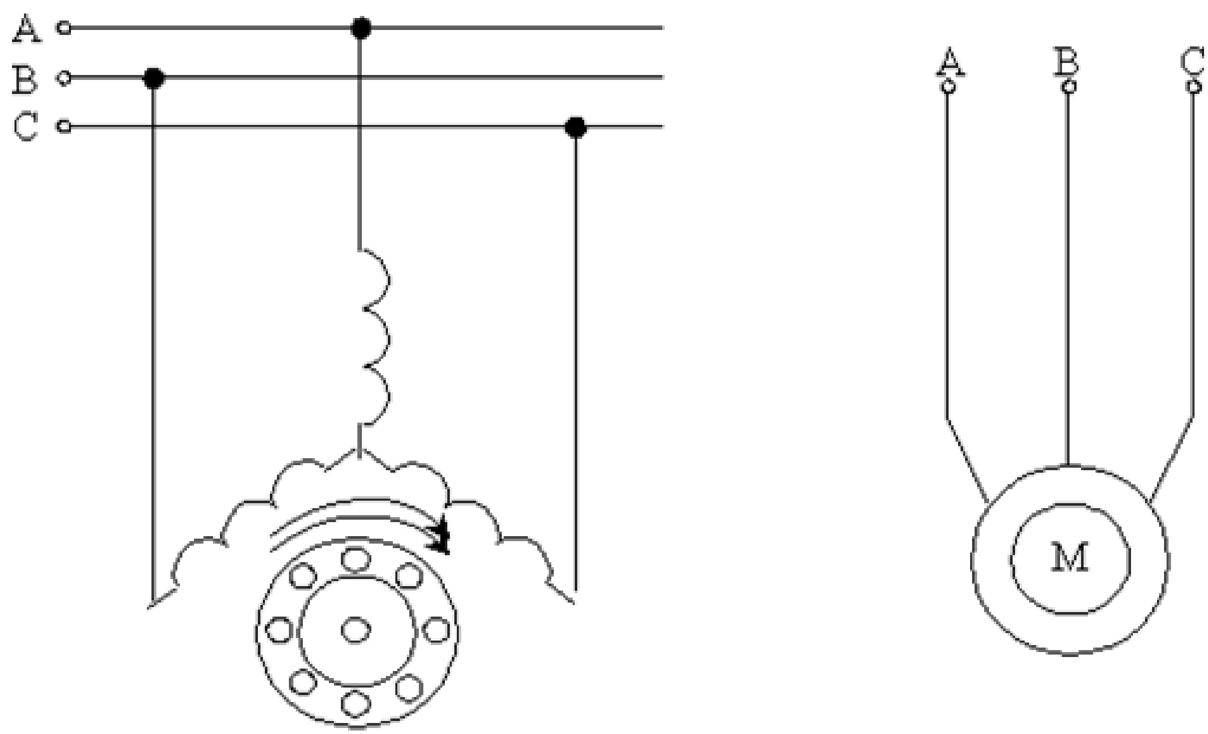
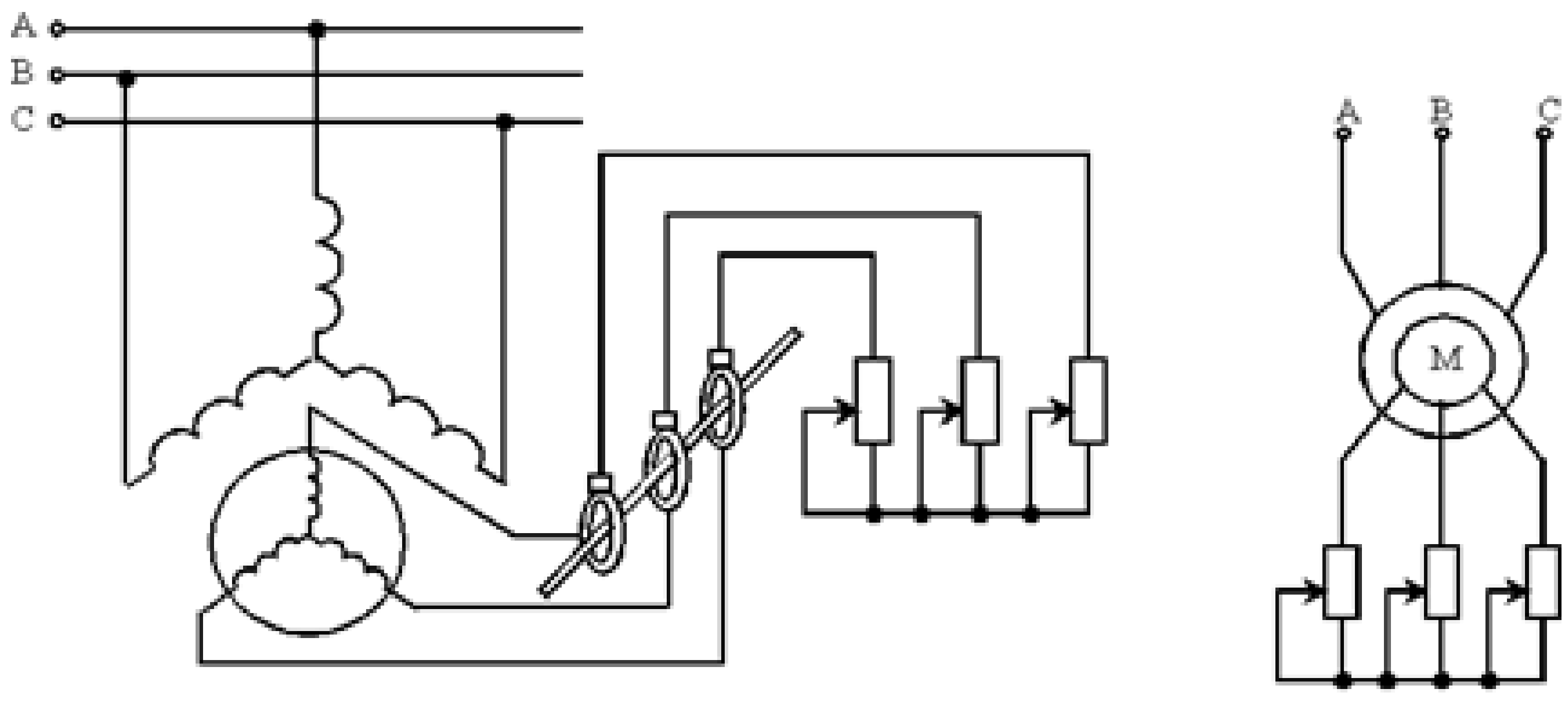


Figure 2 - The conventions of AM with squirrel cage rotor



The conventions of AM with phase rotor

The principle of operation of asynchronous motor is based on the **interaction** of the **magnetic field created by the stator currents** with the **magnetic field of the rotor**.

The current flowing through the stator windings forms a three-dimensional magnetic field.

This magnetic field is called a **three-phase rotating field**.

The process of rotation of the magnetic field induction is synchronized with the **frequency of the stator current**.

Therefore, the frequency of rotation of the field in the AM is called **synchronous frequency** and marked by ω_0 **rad/s** or n_0 **rev/min**.

If a stator has **p** pole pairs, then

$$n_0 = \frac{60 \cdot f}{p}$$

Rotating magnetic field created by the stator currents permeating winding of rotor gives it **EMF** (**electromotive force**), from which current flows to the closed rotor winding.

A rotor current creates a **magnetic field of a rotor**, which interacts with the rotating magnetic field and generates **rotating moment of the rotor.**

The frequency of rotation the rotor **Ω** (or **n**) is **less** than the frequency of the rotating field at some $\Delta n = n_0 - n$, which depends on the parameters of the rotor and stator windings.

The value **s** is called the **sliding of AM**.

$$s = \frac{n_0 - n}{n_0} = \frac{\omega_0 - \Omega}{\omega_0}$$

In engines

- **of low power** (to 10 kW) s_n = **5 – 10 %** ,
- **of high power** (20 – 200 kW) s_n = **2 – 5 %**

Example:

- number of pole pairs of AM ***p* = 1;**
- sliding **s = 5%**

then synchronous frequency of fields (stator) n_0

$$n_0 = \frac{60 \cdot f}{p} = \frac{60 \cdot 50}{1} = 3000 \text{ rev. / min.}$$

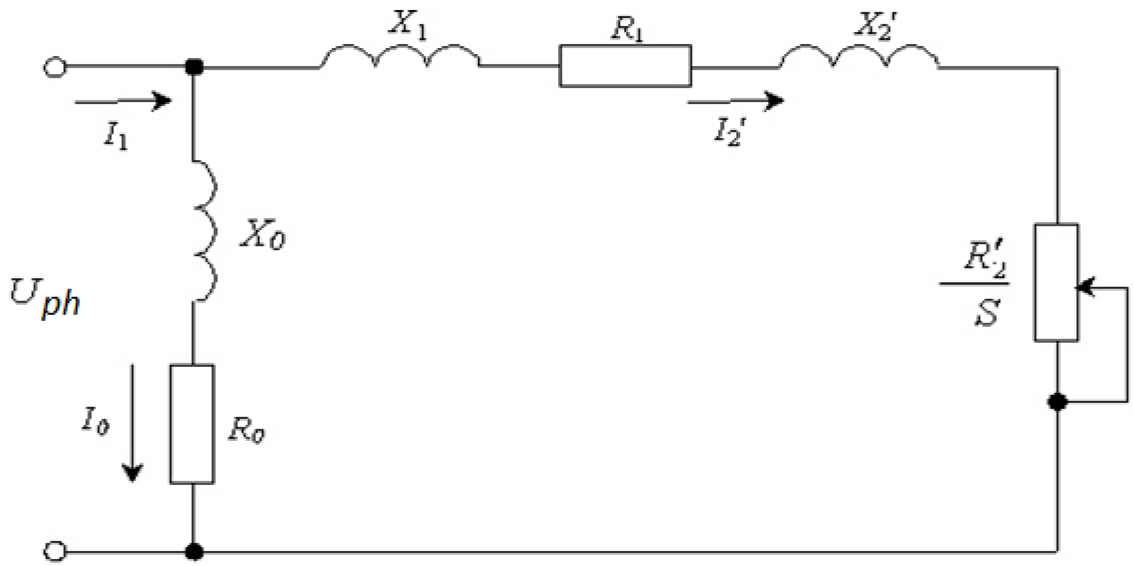
and rotor speed

$$s = \frac{n_0 - n}{n_0}$$

:

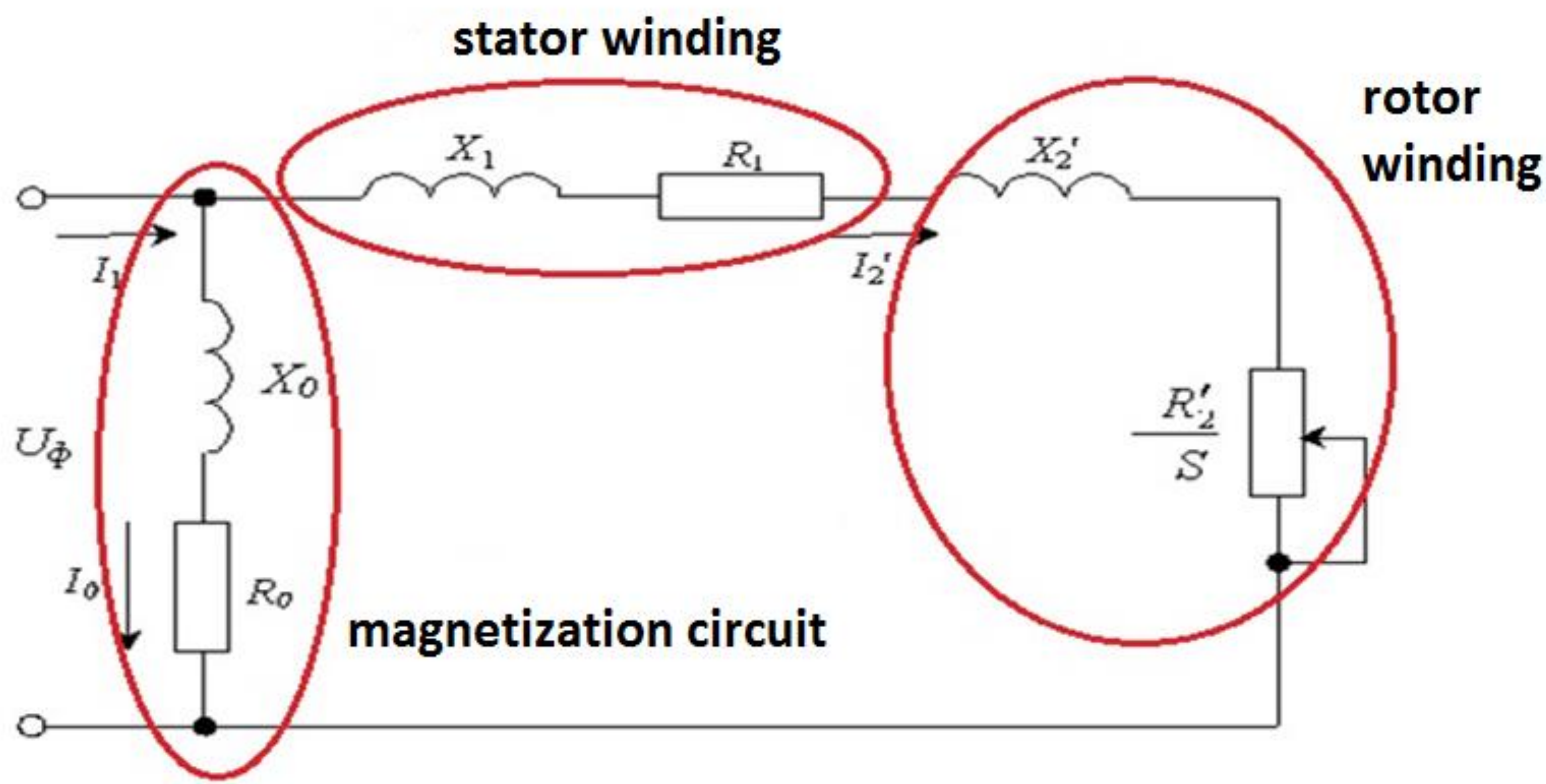
$$n = n_0 - s \cdot n_0$$

$$n = 3000 - 0,05 \cdot 3000 = 3000 - 150 = 2850 \text{ rev. / min.}$$



Equivalent scheme of AM (one phase) :

U_{ph} - voltage on phase stator winding,
I_1 - phase stator current,
I'_2 - consolidated rotor current,
I_0 - current idle (magnetization current),
R_1, x_1 - active and reactive resistance of the stator winding,
R_2', x_2' - consolidated active and reactive resist of rotor winding,
R_0, x_0 - active and reactive resist of circuits magnetization


stator winding
rotor
winding
X_1
R_1
X_2'
I_1
I_2'
X_0
U_Φ
I_0
R_0
$\frac{R_2'}{S}$
magnetization circuit

According to the **equivalent scheme** of consolidated rotor current (**Ohm's law**)

$$I_2' = U_{ph} \Big/ \sqrt{\left(R_1 + R_2'/s\right)^2 + \left(x_1 + x_2'\right)^2}$$

The equation of balancing losses.

Electromagnetic power is transmitted from the stator to rotor

$$P_1 = M\omega_0$$

$$P_1 = P + \Delta P$$

the mechanical power of the rotor shaft	power losses during the heating
$P = M\Omega$	$\Delta P = P_1 - P =$ $= M\omega_0 - M\Omega =$ $= M(\omega_0 - \Omega) = M\omega_0 s$ $\Delta P = M\omega_0 s$

Power losses in the heating is proportional to the **square** of the rotor current

$$\Delta P = M\omega_0 s = 3(I'_2)^2 R'_2$$

Whence the **rotating moment** of engine

$$M = 3(I_2')^2 R_2' \Big/ \omega_0 s$$

Inserting in this expression the rotor current

$$I_2' = U_{ph} \Big/ \sqrt{\left(R_1 + R_2'/s\right)^2 + \left(x_1 + x_2'\right)^2}$$

we obtain an expression for the **mechanical characteristics of AM**, which connects all the parameters: moment **M**, voltage **U**, resistance (**R**,**x**), sliding **s**, frequency ω_0

$$M = \frac{3U_{ph}^{2}R_{2}^{'}}{\omega_0 \cdot s[\left(R_1 + R_2^{'}/s\right)^2 + \left(x_1 + x_2^{'}\right)^2]}$$

Moment on the shaft of AM is proportional the voltage to the square

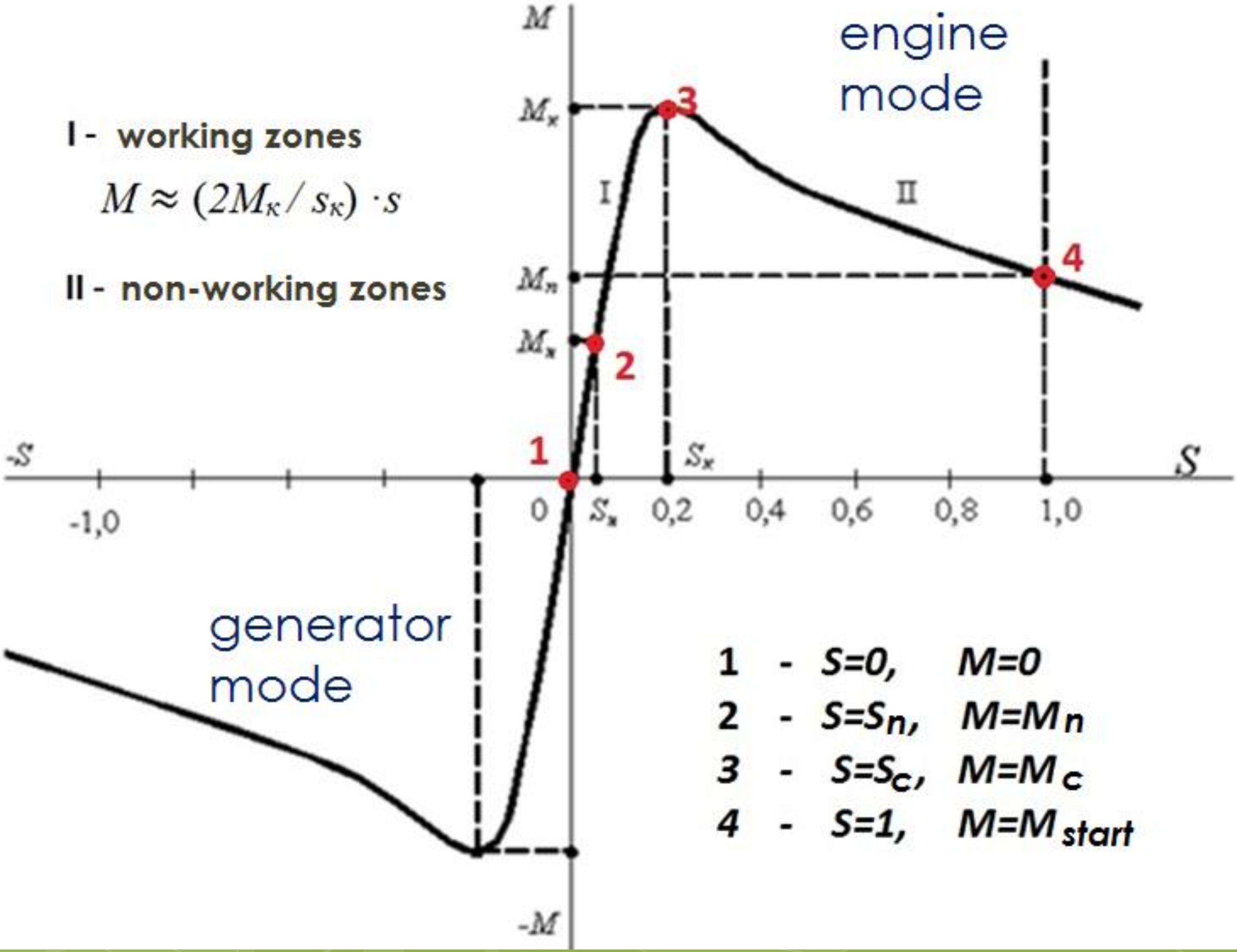
$$M = \frac{3U_{ph}^{2} R_2'}{\omega_0 \cdot s[\left(R_1 + R_2'/s\right)^2 + \left(x_1 + x_2'\right)^2]}$$

therefore AM is **very sensitive** to **fluctuations** the networks voltage

If you draw the graphic function ***M = f(s)***, changing ***s*** at the parameters from **-1** to **0** and from **0** to **1**, we obtain the curve as on the Fig.

The curve has two extremes, in which $M = M_{max} = M_c$, one is in engine mode, the second is in generator mode.

Mechanical characteristics of AM *M=f(s)*



Analysis of mechanical characteristics shows that it consists of two zones - **working *I*** and **non-working - *II***.

In the working area the sliding changes in the range $0 < s < s_c$, passing through $s = s_n$. This area has almost **linear part**, which is **the working area of characteristic**. In this part the characteristic equation has the form

$$M \approx (2M_c / s_c) \cdot s$$

So, when working in this part the speed **depends linearly on the motor torque (moment).** There are the points in this part of characteristic corresponding to the nominal motor data – M_n , I_{1n}, n_n , s_n.

The value of the nominal sliding depends on rotor winding resistance.

Equating the derivative of expression

$$M = \frac{3U_{ph}^{2} R_{2}^{'}}{\omega_{0} \cdot s[\left(R_{1} + R_{2}^{'}/s\right)^{2} + \left(x_{1} + x_{2}^{'}\right)^{2}]}$$

to zero ***dM/ds* = *0***

find critical points (or extremes) ***s*$_c$** i ***M*$_c$**

- critical moment *M*$_c$

$$M_{C} = \frac{3U_{ph}^{2}}{2\omega_{0}[R_{1} \pm \sqrt{R_{1}^{2} + (x_{1} + x_{2}')^{2}}]}$$

- critical sliding *s*$_c$

$$s_{C} = \pm \frac{R_{2}^{'}}{\sqrt{R_{1}^{2} + (x_{1} + x_{2}^{'})^{2}}}$$

If we divide the expression

$$M = \frac{3U_{ph}^2 R_2'}{\omega_0 \cdot s[\left(R_1 + R_2'/s\right)^2 + \left(x_1 + x_2'\right)^2]}$$

on expression

$$M_C = \frac{3U^2_{ph}}{2\omega_0[R_1 \pm \sqrt{R_1^2 + (x_1 + x_2')^2}]}$$

we get the **simplified expression** for the **mechanical characteristics of AM**

$$M = \frac{2M_c(1 + as_c)}{s/s_c + \frac{s_c}{s} + 2as_c}$$

where $a = R_1/R'_2$.

for engines **of** **high power** (more than 5 kW)

$$R_1 \approx 0$$

$$a = R_1/R'_2 \approx 0$$

$$M = \frac{2M_c(1+as_c)}{s/s_c + \frac{s_c}{s} + 2as_c} \longrightarrow M = \frac{2M_c(1+as_c)}{s/s_c + \frac{s_c}{s} + 2as_c}$$

$as_c = 0$, $2as_c = 0$

Klos formula:

$$M = \frac{2M_c}{\frac{s}{s_c} + \frac{s_c}{s}}$$

From **Klos formula**

$$M = \frac{2M_c}{s/s_c + s_c/s}$$

we obtain

$$s_c = s_n\left(\lambda \pm \sqrt{\lambda^2 - 1}\right)$$

де λ - **the multiplicity of maximum moment**

$$\lambda = M_c / M_n$$

For engines
- with phase rotor $\lambda \geq$ ***1,8***
- with squirrel cage $\lambda \geq$ ***1,65***

The **initial starting moment**

$$M_{start} = \frac{2M_c(1+as_c)s_c}{1+s_c^2(1+2a)}$$

sliding at start

$$s = \frac{n_0 - n}{n_0}$$

0

1

s =1

Lecture 4
Ways of asynchronous motor (AM) controlling

1. Rheostat control
2. Stepwise regulation
3. Frequency regulation of AM

1. Rheostat control

Let us analyze the formula (1) and (2) concerning speed control capabilities of asynchronous motor (AM).

$$M = \frac{3U_{ph}^{2} R_2^{'}}{\omega_0 \cdot s[\left(R_1 + R_2^{'}/s\right)^2 + \left(x_1 + x_2^{'}\right)^2]} \quad (1)$$

$$M_C = \frac{3U_{ph}^{2}}{2\omega_0[R_1 \pm \sqrt{R_1^2 + (x_1 + x_2')^2}]} \quad (2)$$

The adjusting with voltage at the stator windings $\boldsymbol{U_{ph}}$ is **possible in a very narrow range (1,1 –1,2) *U_n*,** because when you change the voltage (**U_{ph}**) at point ***k*** moment (**M)** decreases ***κ^2*** times.

So, if you can not regulate voltage induction motor stator, ***it seems as unregulated***.

But if you analyze the formulas (3), (4) we can see an alternative to uncontrolled AM-SC.

linear dependence

$$s_C = \pm \frac{R_2^{'}}{\sqrt{R_1^2 + (x_1 + x_2^{'})^2}} \qquad (3)$$

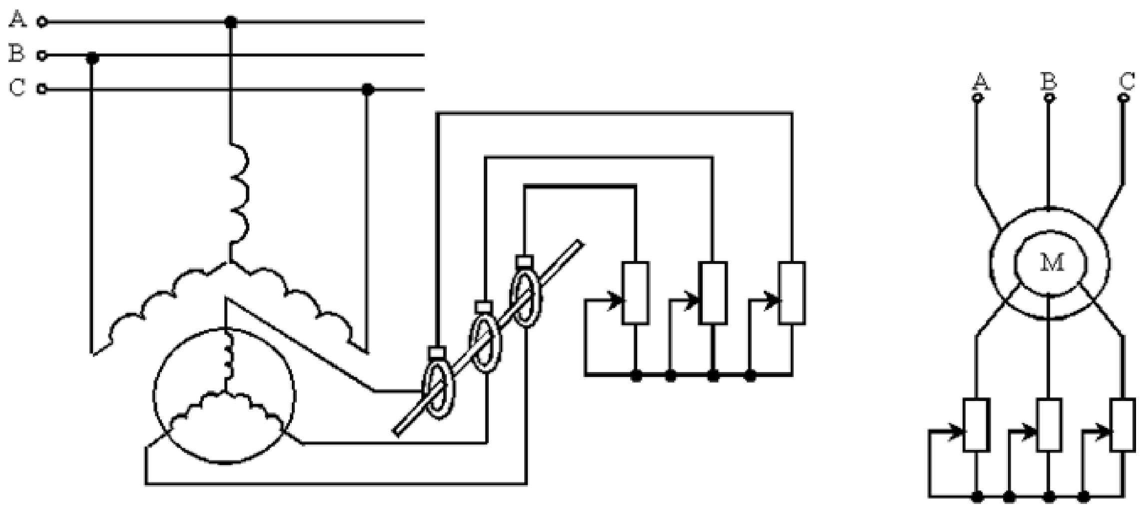
$$s = \frac{n_0 - n}{n_0} = \frac{\omega_0 - \Omega}{\omega_0} \qquad (4)$$

Using the formula (3) we see that the **critical sliding s_c** of AM linearly depends on the **resistance** $R_2^{'}$ of the rotor windings.

If we make the resistance of the winding rotor $R_2^{'}$ regulated, then **adjusting the resistance with** a **rheostat** we **can adjust the sliding s_c** , i.e. **rotor speed n**.

This possibility is realized by creating an **AM with phase rotor.**

In practice, this rheostat is produced of **two-** or **three-levels**, these levels of a rheostat are switched over with push-button device called **command instruction controllers**.



Adjusting the sliding with a rheostat is **energy-consuming**, approximately reduction of **ECE** (**energy conversion efficiency**) can be estimated by formula (6).

$$\eta = \frac{P_{mechenical}}{P_{magnetic}} = \frac{M\omega_0}{M\omega_0}(1-s) = 1-s \qquad (5)$$

Example:

The crane motor with two degrees of frequency

- 300 rev./min. $s_1 = 0,7$
- 900 rev./min. $s_2 = 0,1$

Synchronous frequency AM n_0=*1000 rev./min.*

ECE (**energy conversion efficiency**) is

$$\eta = \frac{P_{mechenical}}{P_{magnetic}} = \frac{M\omega_0}{M\omega_0}(1-s) = 1-s$$

$$\eta_1 = 1-s = 1-0,7 = 0,3 = 30\ \%$$

$$\eta_2 = 1-s = 1-0,1 = 0,9 = 90\ \%$$

While it work with the speed 300 rev./min., **the losses are equal** to **70%.**

2. Stepwise regulation

Analysis of the formulas

$$s = \frac{n_0 - n}{n_0}$$

$$n = n_0 - s \cdot n_0$$

$$n_0 = \frac{60 \cdot f}{p}$$

indicates that the synchronous frequency of AM and rotor speed depends on the **number of pole pairs** of the stator.

Factories produce AM series 4A which have 1, 2, 3, 4 pairs of poles.

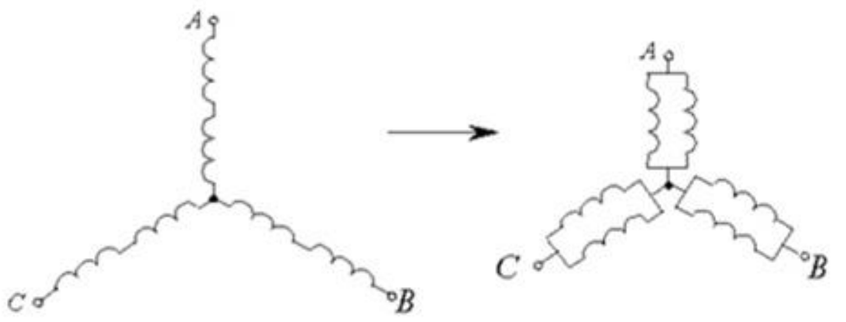
Changing the rotor speed is done **by switching over the stator windings**, which changes the number of pole pairs.

Let's examine a three-phase AM with two pairs of poles. It has 2 windings for each phase of the stator. Possible winding connection are shown in Fig.

The most common are used the circuit switching from the "**star**" to the **double "star"** and from the **triangle** to the **double "star."**

Switching three-phase windings of AM (p=2)

з "зірки" на подвійну "зірку"

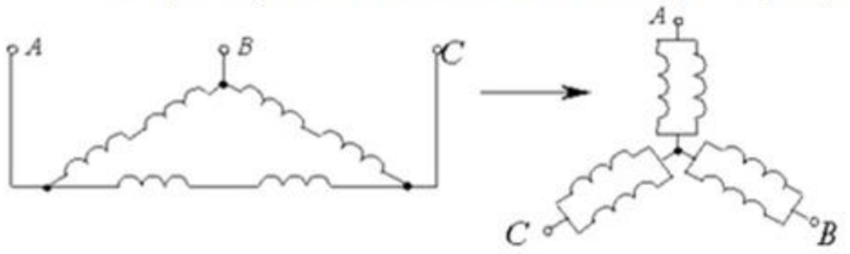


$$\frac{P_{YY}}{P_{Y}} = \frac{(1/\sqrt{3})\,U_{\text{л}}\cdot 2I_{\text{ф}}\cdot\cos\varphi}{(1/\sqrt{3})\,U_{\text{л}}\cdot I_{\text{ф}}\cdot\cos\varphi} = 2$$

$$\frac{M_{YY}}{M_{Y}} = \frac{P_{YY}\cdot\Omega_{Y}}{P_{Y}\cdot\Omega_{YY}}$$

Ω: increases in 2 times
P: increases in 2 times
M: unchanged

з трикутника на подвійну "зірку"



$$\frac{P_{YY}}{P_{\Delta}} = \frac{(1/\sqrt{3})\cdot U_{\text{л}}\cdot 2I_{\text{ф}}\cdot\cos\varphi}{U_{\text{л}}\cdot I_{\text{ф}}\cdot\cos\varphi} = 1{,}5$$

$$\frac{M_{YY}}{M_{\Delta}} = \frac{P_{YY}\cdot\Omega_{\Delta}}{P_{\Delta}\cdot\Omega_{YY}} = 2$$

Ω: increases in 2 times
P: increases in 1,5 times
M: decreases in 2 times

3. Frequency regulation of AM

As it is found, AM r**egulation with voltage for a wide range is impossible**.

Except voltage, the parameters of current power, which can be changed, is the **frequency of current *(f)*** and **magnetic flow (*Φ*) of stator's field**. If in the formula

$$M_C = \frac{3U_{ph}^2}{2\omega_0[R_1 \pm \sqrt{R_1^2 + (x_1 + x_2')^2}]}$$

we take into consideration that $R_1 \ll x_1 + x_2'$,then **Mc** can be written as

$$M_c = 3U_{ph}^2 / 2\omega_0 X_c$$

where X_c - short-circuit reactive resistance ($X_c = \omega_0 L_c$)

Since

$$\omega = 2\pi f$$

then

$$M_c = 3U_{ph}^2 \Big/ 2\omega_0 X_c$$

can write

$$M = \frac{3U_{ph}^2}{2\omega_0 \cdot \omega_0 L_c} = \frac{3U_{ph}^2}{2 \cdot 4\pi^2 f^2 \cdot L_c} \approx A\frac{U_{ph}^2}{f^2}$$

ω_0^2 X_c ω_0^2

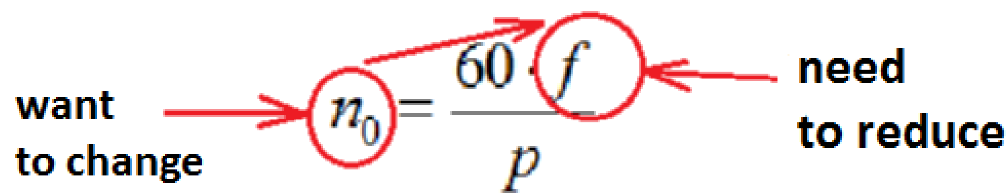
so the critical moment **Mc is** proportional to $\left(\frac{U_{ph}}{f}\right)^2$

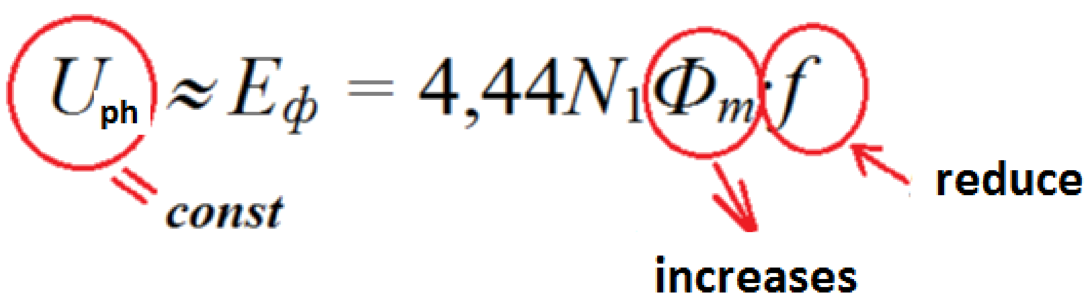
The **voltage U**, **frequency f** and **stator magnetic flow Φ** are joined in the following way

$$U_{ph} \approx E_{ph} = 4{,}44 N_1 \Phi_m \cdot f$$

where N_1 - number of turns of the stator winding.

Let U_{ph} = $const$, reducing **motor speed Ω** is reached with decreasing the **current frequency** f.





This leads to saturation of the magnetic system, increasing of **hysteresis losses** and **eddy currents**, **reducing ECE** (energy conversion efficiency).

Increasing of the frequency leads to **decreasing flow Ф** and the motor moment ***M***, which is also **unwanted**.

we want to increase

$$n_0 = \frac{60 \cdot f}{p}$$

need to increase

$$U_\phi \approx E_\phi = 4{,}44 N_1 \Phi_m \cdot f$$

U_ϕ = *const*

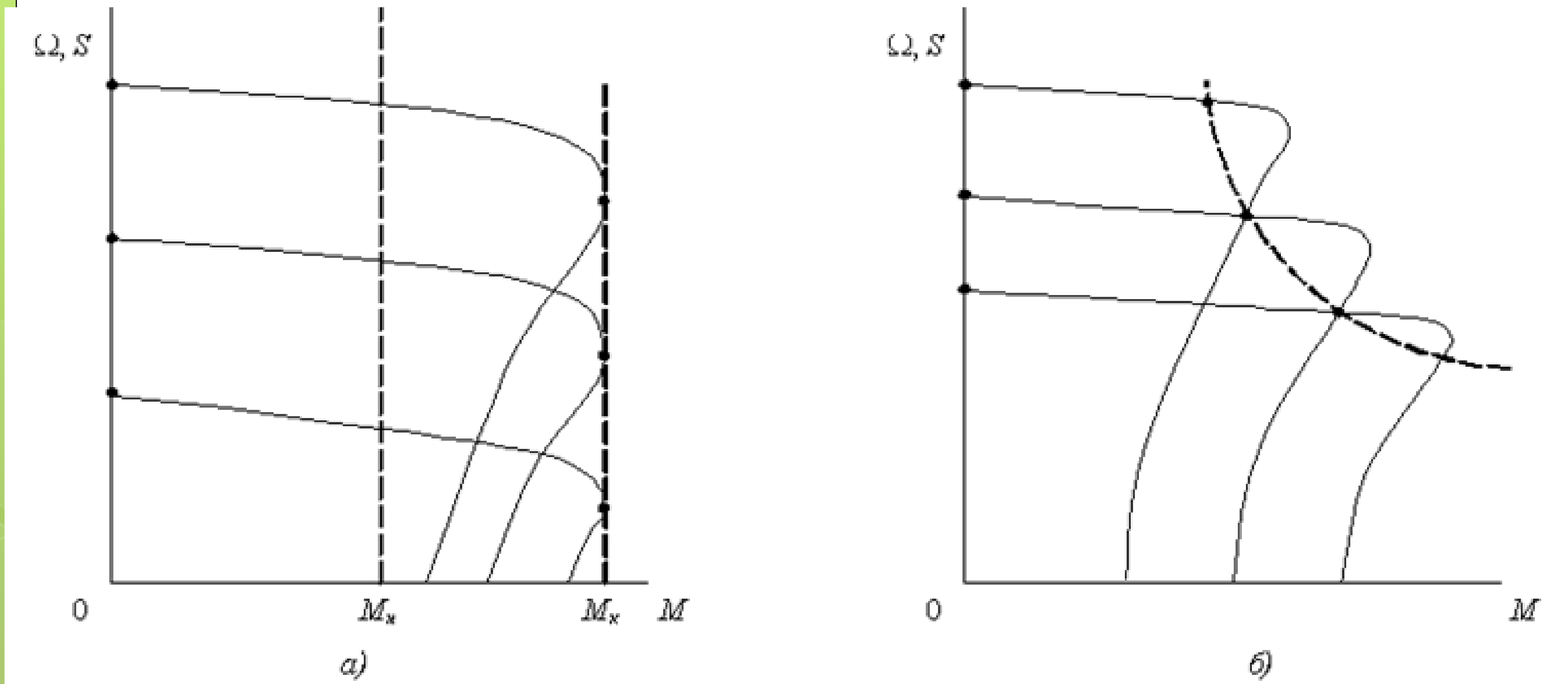
Φ_m decreases

f increase

So you need to **adjust both the voltage and frequency**, performing the formula

$$\frac{U}{f} = \Phi = const$$

Mechanical characteristics of AM-SC



a) while driving the law

$$U_{ph}/f = const$$

b) while driving the law

$$U_{ph}/\sqrt{f} = const$$

From Fig. a) we can see that due to the regulation of AM by law

$$U_{ph}/f = const$$

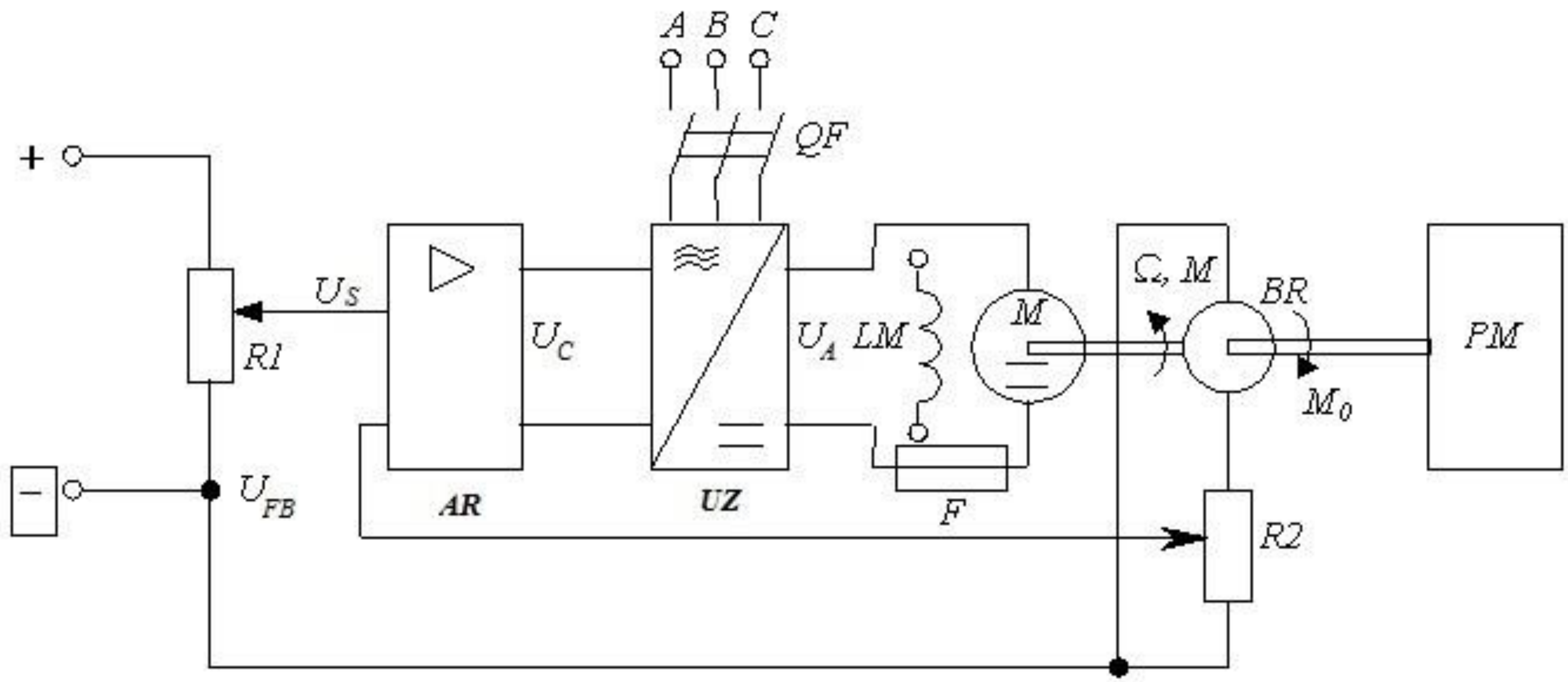
it **does not lose load capacity** at the feasibility of **simultaneous regulation of voltage and frequency current induction motor is regulated**.

Lecture 5
Elements of automatic motor controller (AMC)

- 1. Functional scheme of automatic motor controller
- 2. Functional elements of automatic motor controller (AMC)

1. Functional scheme of automatic motor controller

The functional scheme of **the system of automatic control of an electric motor of direct current**, built on principle of control after a rejection, on principle of feed-back.



M - an engine anchor; **LM** – drive winding; **PM** - productive mechanism; **AR** - a regulator; **UZ** - thyristor voltage transformer; **BR** – a feeding device of frequency of rotation; **QF** - a circuit breaker; **R1** – a driving element; **F** - safety cutoff.

- **The scheme works in the following way:**

1. The system maintains **constant frequency Ω of rotation of the motor shaft**.

2. The frequency control is performed through voltage regulation U_A by engine anchor.

3. The necessary frequency is adjusted with setting element R1, from which the voltage signal of U_S specified action is taken.

This signal **is compared with the feedback signal** U_{FB} which is taken from the **feeding device frequency (speed)** **BR** and is proportional to the current value of the rotation frequency **Ω**;

4. At the **time of starting the engine U_{FB} = *0***,

$$U_C = U_S - \overset{0}{U_{FB}} > 0$$

the control signal **U_C increases to the set one**, the **output voltage U_A** at thyristor voltage transformer **increases** to the nominal value, **the engine accelerates**, the frequency **Ω increases**, achieving a given value.

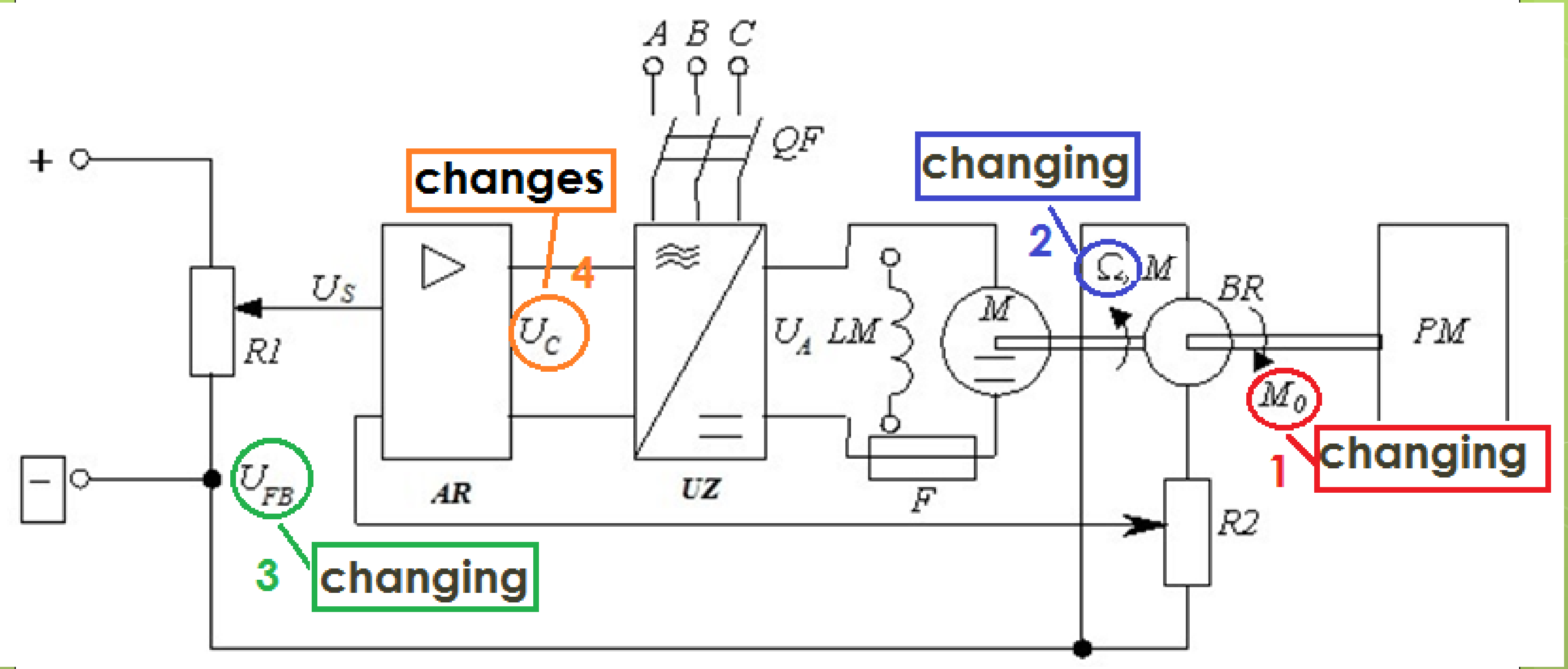
At the same time **U_{FB} increases** and the **control signal U_C**, reaches its constant mean,

$$U_C = U_S - U_{FB} = const$$

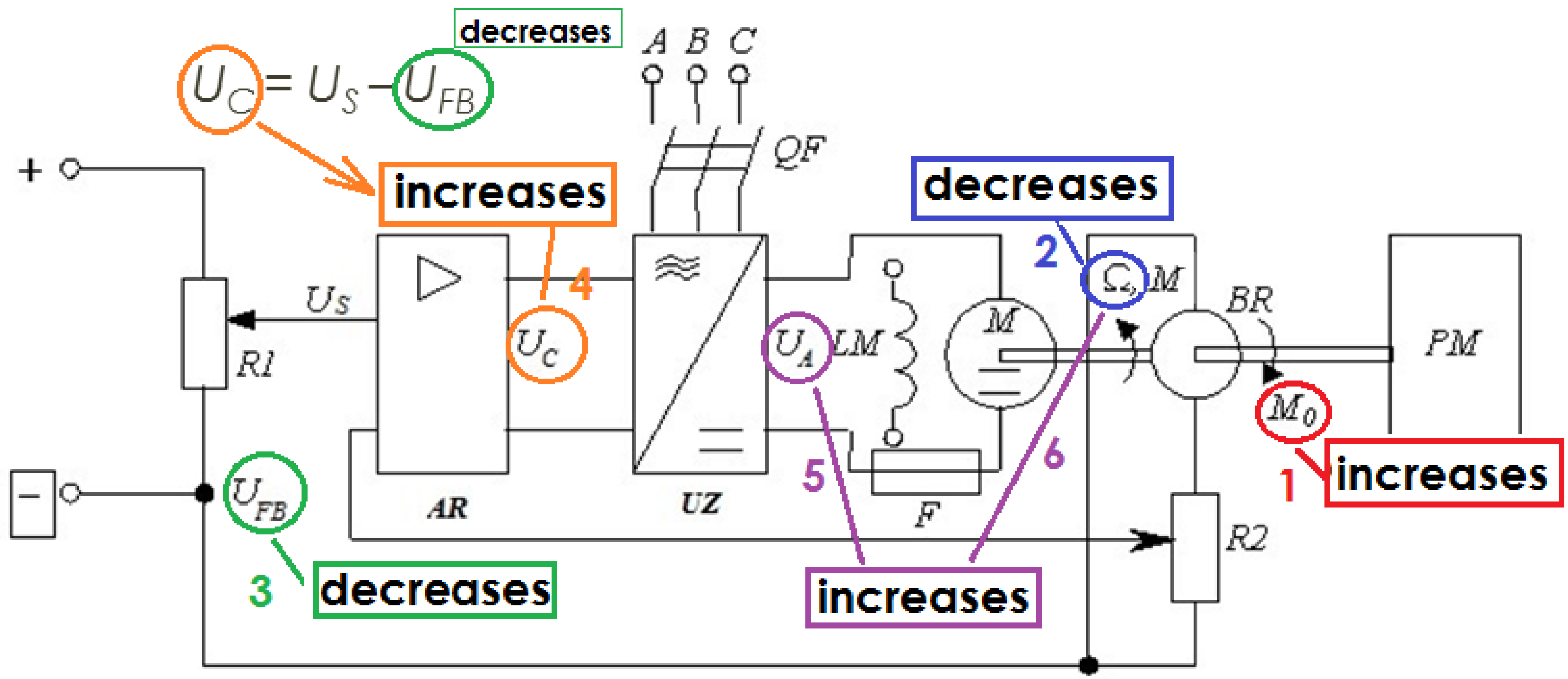
where the frequency is equal to a given value with a permissible error.

5. In **the constant mode $U_{FB} = U_S$**, a control signal **U_C = *const***, frequency **$\Omega = \Omega_S$** .

6. When the **load moment** M_0 on the production mechanism **is changing** the **frequency** Ω **changes** and the **changing feedback signal** U_{FB}. The **controller AR** immediately **changes** the **control signal** U_C by thyristor converter UZ



7. If moment of resistance M_0 increases, then the frequency Ω decreases, the controller AR increases the U_C signal, the voltage at the anchor U_A increases and as a result the frequency increases too and the signal at the output of the regulator Uc decreases;



8. As only the frequency Ω reaches the set mean then the increasing signal U_C stops and the constant mode is set;

9. When the voltage of a production machine decreases, the control process is in the opposite direction.

2. Functional elements of automatic motor controller (AMC)

The main functional elements of AMC:

1. Electric motor (EM):

- direct current motor (**DCM**),

- alternating current motor (asynchronous motor(**AM**) and synchronous motors (SM)),

- electric motors for specific constructions (step, valve);

2. Thyristor converters of voltage (TCV) and **thyristor converters of frequency (TCF)** which convert electrical energy into the electricity for supplying motor.

3. Sensor of controlled measurement:

- sensor of rotation frequency - **tachometer generator;**

- a sensor of angular and linear motion – **selsyn**;

- current sensors and **voltage** sensors;

4. Regulators, amplifiers and adjustment fixed elements

5. Specifying the elements (R1, selsyn)

6. Elements of commutation and protection (QF).

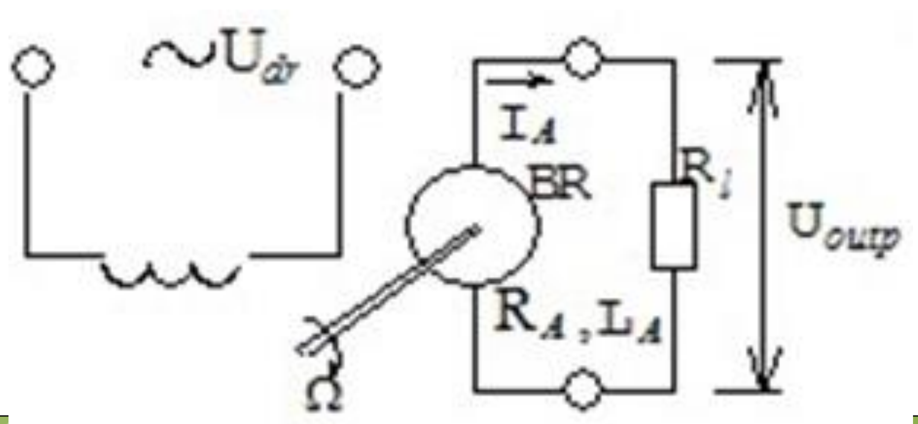
SENSOR OF ROTATION FREQUENCY - TACHOMETER GENERATOR

A tachometer generator (TG) is called a low-power electric machine, which is used **to convert the frequency of rotation** of the motor shaft **into an electrical signal**.

A tachometer generator has almost linear characteristic, which can be expressed by the equation

$$U_{tg} = \frac{K \cdot \Omega}{1 + \frac{R_A}{R_l}} = K_{tg} \cdot \Omega$$

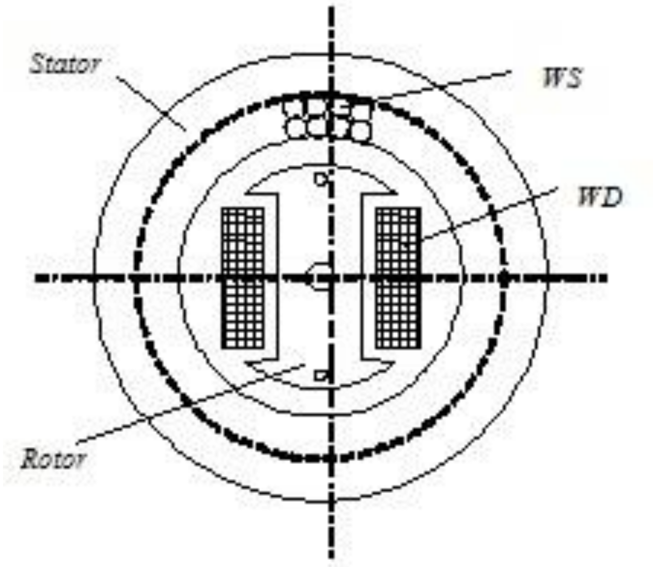
where **K** - constructive parameter, $\boldsymbol{R_A}$ - anchor winding voltage of TG, $\boldsymbol{R_l}$ - load resistance of TG, $\boldsymbol{K_{tg}}$ - transfer coefficient of TG .

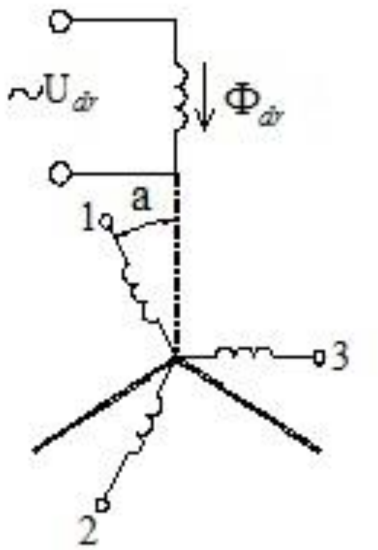


A SENSOR OF ANGULAR AND LINEAR MOTION - SELSYN.

Selsyn is used **to convert to electrical signal of angle of shaft rotation** and the angle of divergence of two shafts.

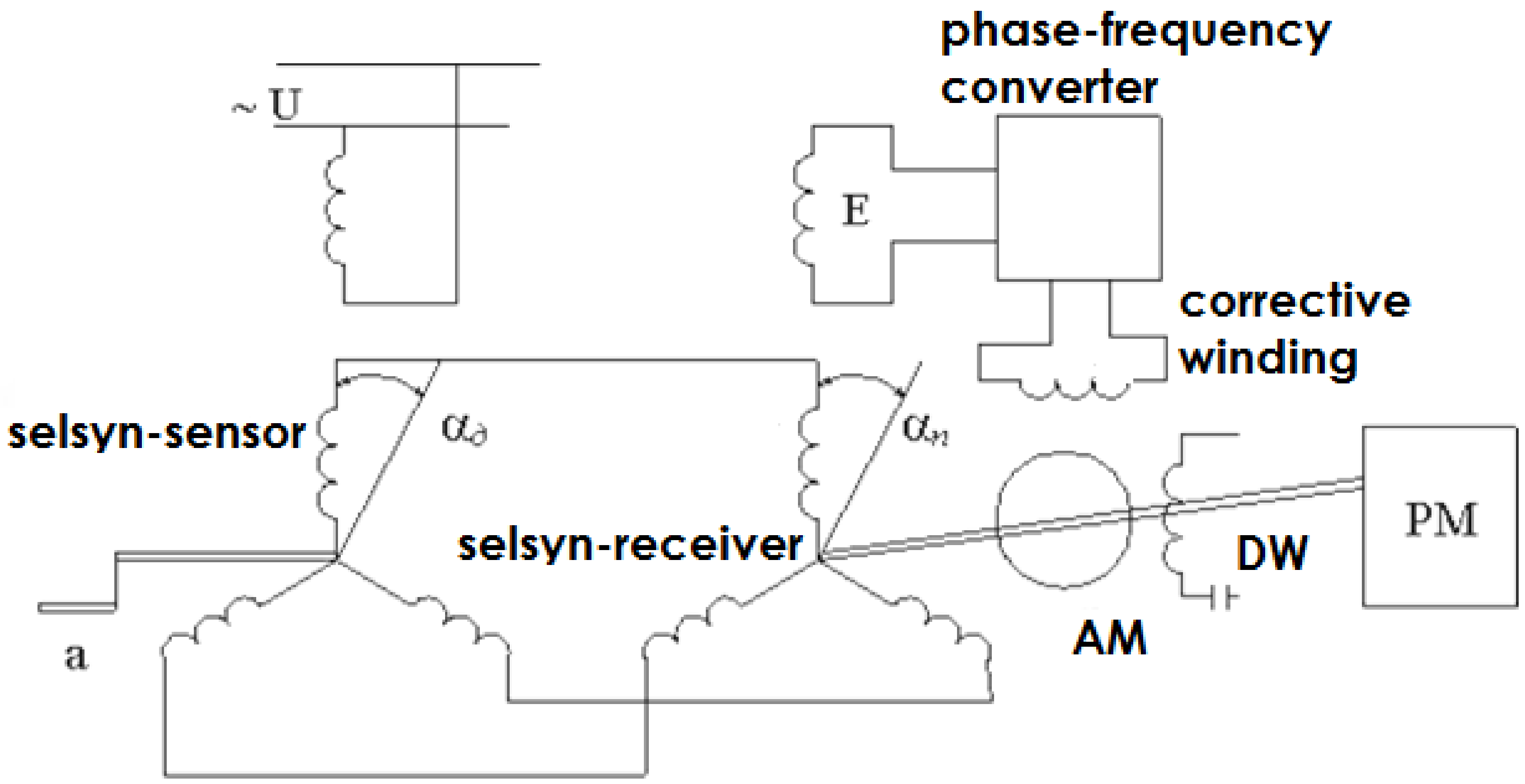
A selsyn is a small electric machine with changeable voltage, which **can self-synchronizing.**





Construction and the scheme of contact selsyn

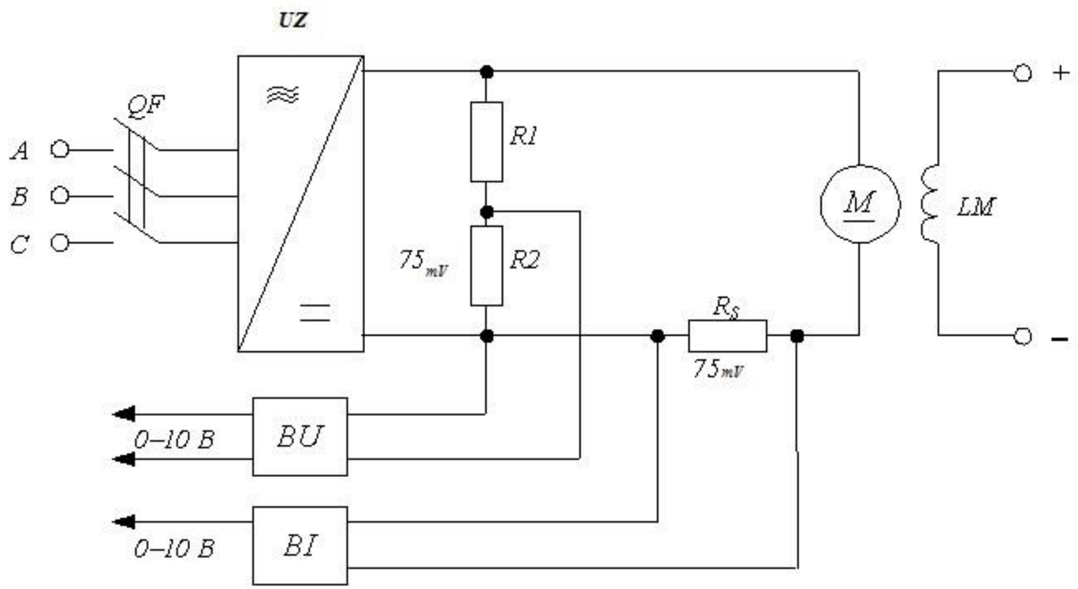
In electric drives of industrial and other mechanisms selsyn used in transformer mode.



CURRENT SENSORS AND VOLTAGE SENSORS

Current sensors are used to regulate and stabilize the anchor current.

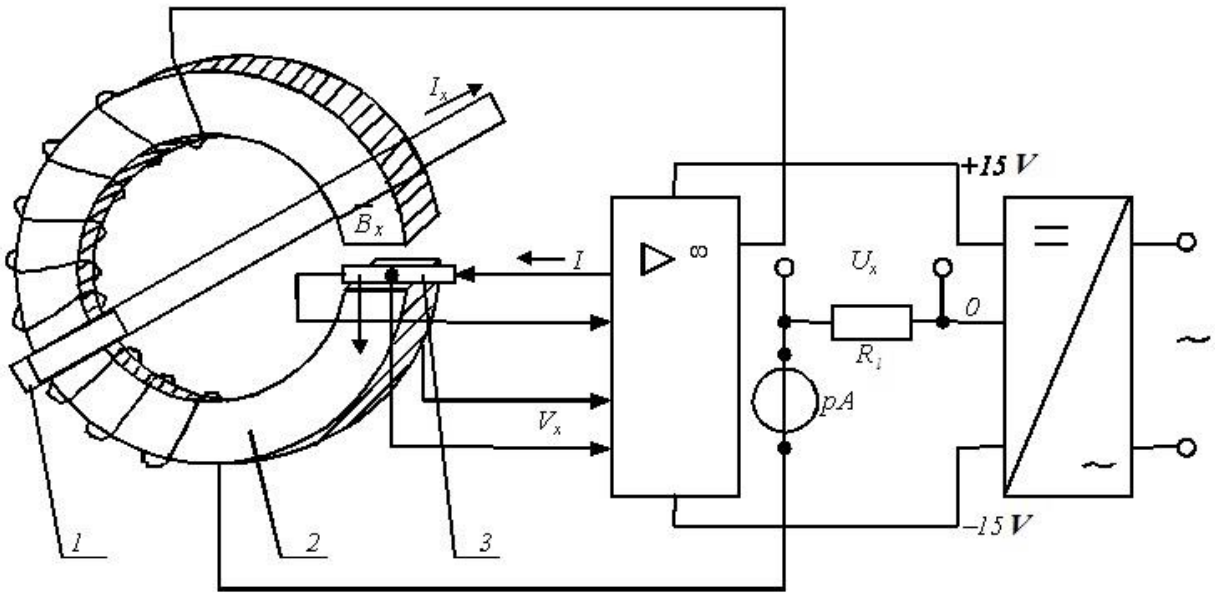
Voltage sensors are used for speed control systems instead of tachometer generator with drives, which are not required high precision of frequency control.



A scheme of electrical switching current sensors and voltage sensors in the circuit of MC armature:

UZ – thyristor converter; **BU** – signal converter of voltage; **BI** – signal converter of current; **R_S** – electric shunt resistor; **R1+ R2** – voltage divider.

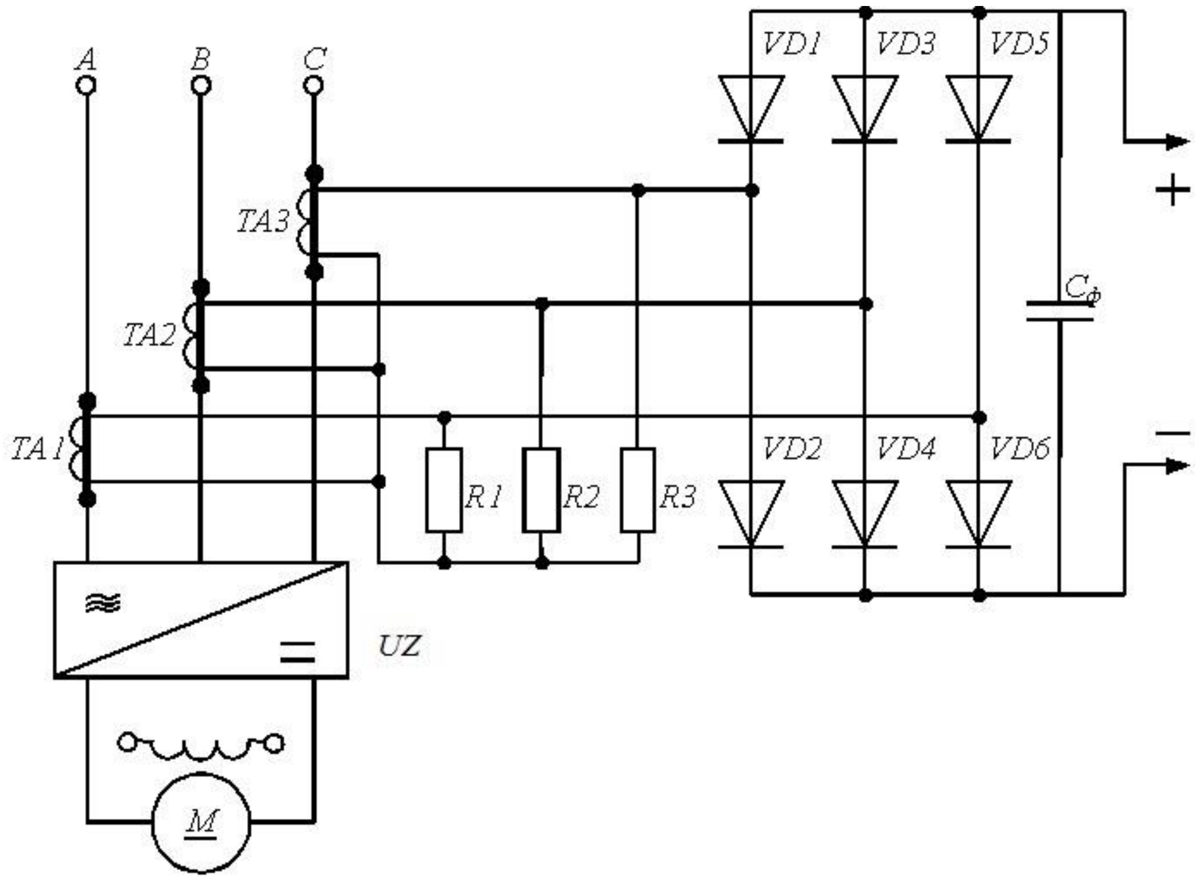
A **modern** progressive method of measurement **without electric shunt resistor** of direct current is a method implemented by **Hall effect**.



A scheme of electrical current sensor with the Hall's sensor: 1 - conductor of the measured current; **2** - toroidal core with permalloy; **3** – Hall's sensor; $\mathbf{I_x}$ – measured current 10 ... 10000 A; $\mathbf{U_x}$ - standardized output signal 0 ... 10 V.

To measure AC power we use sensors with **current transformers (TA)**.

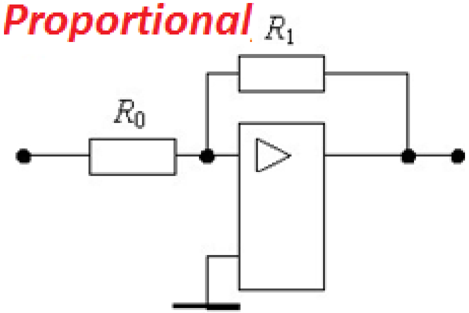
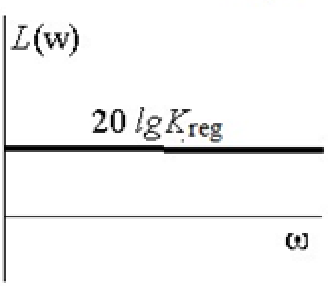
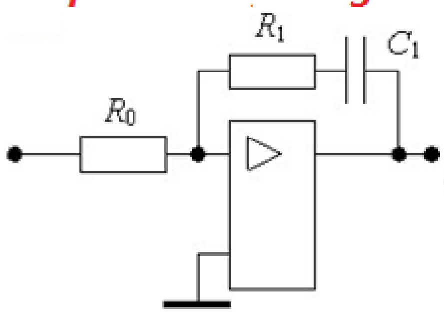
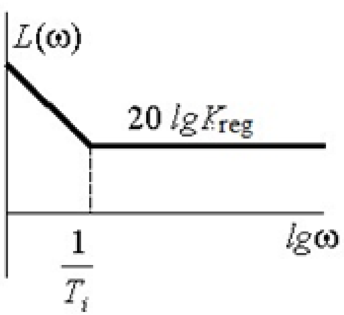
Measuring current transformers TA1-TA3 with primary winding plug in phase conductors, as it is shown in the scheme

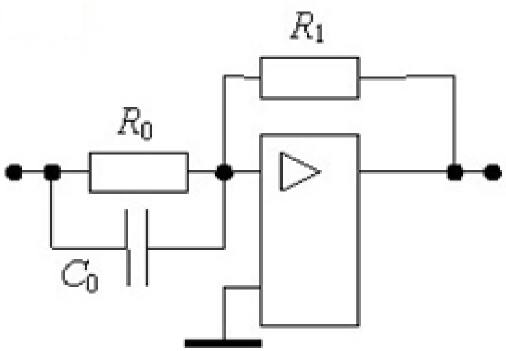
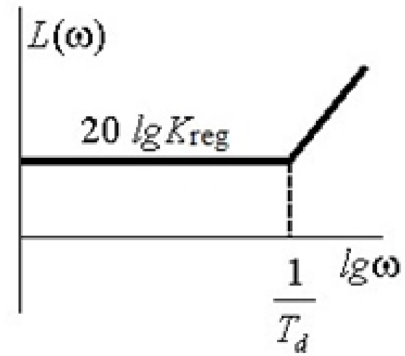
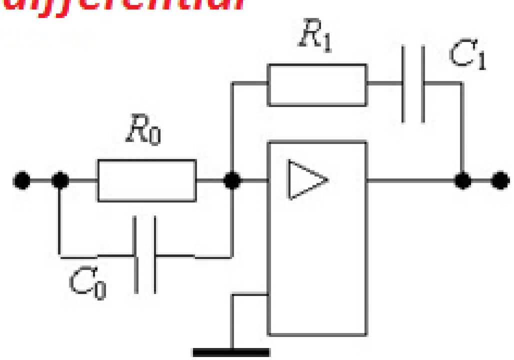
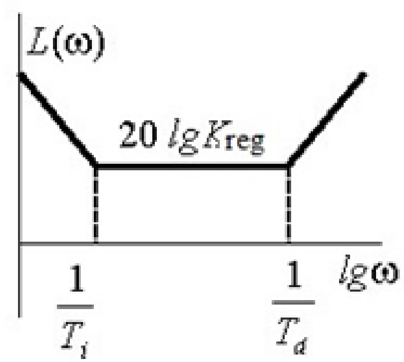


REGULATORS, AMPLIFIERS AND ADJUSTMENT FIXED ELEMENTS

In an automated electric drive use **standard amplifiers of signals and regulators** made on **operational amplifiers (OA).** For modern motor controllers with digital control systems typical control rules are implemented through programmable logic controllers (PLC).

Types, schemes, transfer function and frequency response of regulators for systems of automatic motor controller

Kind and scheme of regulators	Transfer function	Parameters	Logarithmic frequency response
P-regulator ***Proportional*** 	$W_{reg}(p) = K_{reg}$	$K_{reg} = \frac{R_1}{R_0}$	$K_{reg} > 0$ 
PI-regulator ***Proportional-integral*** 	$W_{reg}(p) = \frac{K_{reg}(1 + pT_i)}{pT_i}$	$K_{reg} = \frac{R_1}{R_0}$ $T_i = R_1 C_1$	

Kind and scheme of regulators	Transfer function	Parameters	Logarithmic frequency response
PD-regulator *Proportional-differential* 	$W_{reg}(p) = K_{reg}(1 + pT_d)$	$K_{reg} = \frac{R_1}{R_U}$ $T_d = R_U C_U$	
PID-regulator *Proportional-integral-differential* 	$W_{reg}(p) = \frac{K_{reg}(1 + pT_i)(1 + pT_d)}{pT_i}$	$K_{reg} = \frac{R_1}{R_0}$ $T_i = R_1 C_1$ $T_d = R_U C_U$	

Lecture 6
Mechanics of motor controller

1. Static characteristics of typical industrial mechanisms

2. Mechanics of a motor controller. Summary of moments of resistance and inertia moments to the motor shaft

1. Static characteristics of typical industrial mechanisms

One of the most important characteristics of motor controller is **the energy conversion efficiency (ECE)**, which is the **greatest** when the mechanical characteristics of the electric motor are **consistented with the mechanical characteristics of the production mechanism**.

Due to the type of rotational speed quantity from the moment of mechanism resistance of the whole set of production mechanisms can be divided into **four groups** for which we can write a general **empirical relationship**, which is the **equation of the mechanical characteristics of the mechanism**

$$M_{st.(static)} = M_0 + (M_{st.nom} - M_0) \cdot \left(\frac{\Omega}{\Omega_{nom}} \right)^n \qquad (1)$$

where **Ω** is reduced to the motor shaft angular velocity of the performance body (PB) of a mechanism,

M_{static} - reduced to the motor shaft static moment of resistance of the PB of a mechanism;

M_0 - moment of static resistance of mechanism to overcome **friction** in the moving parts of machine;

$M_{st.nom}$ - static moment of resistance of the mechanism at nominal angular velocity Ω_{nom};

n – exponent that characterizes the change of moments of resistance by changing the angular velocity.

The value of index ***n*** is the same parameter that **influences to the type of mechanical characteristics** and determines the mechanism of belonging to that particular group (class).

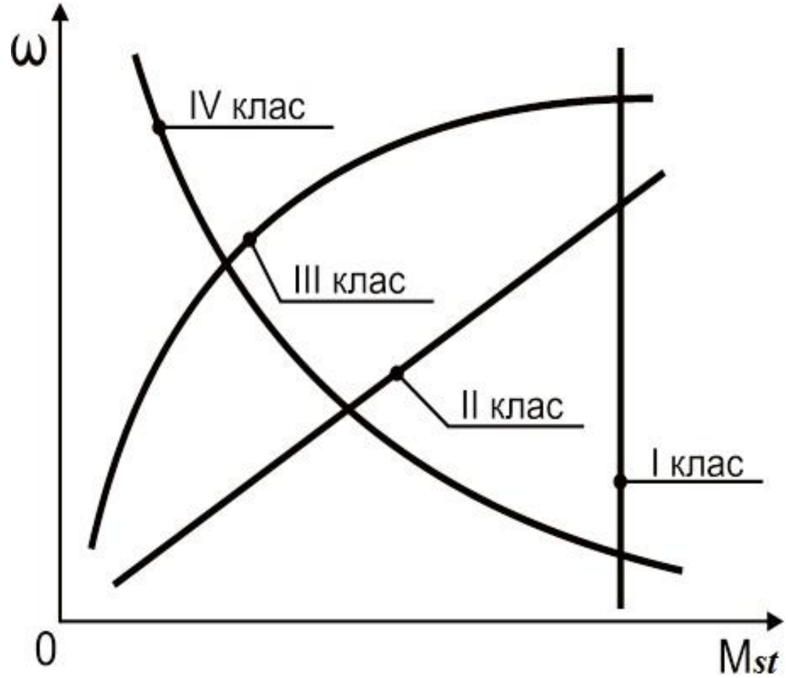


Figure 1 – Mechanical characteristics of industrial mechanisms

I class. This class includes all the mechanisms for which the static moment of resistance ***(M_{static})* is independent of velocity (speed).**

Mechanical characterization of these mechanisms is a **straight line** parallel to the axis of ordinates (Fig. 1).

According to equation (1) $n = 0$.

Equation (1)

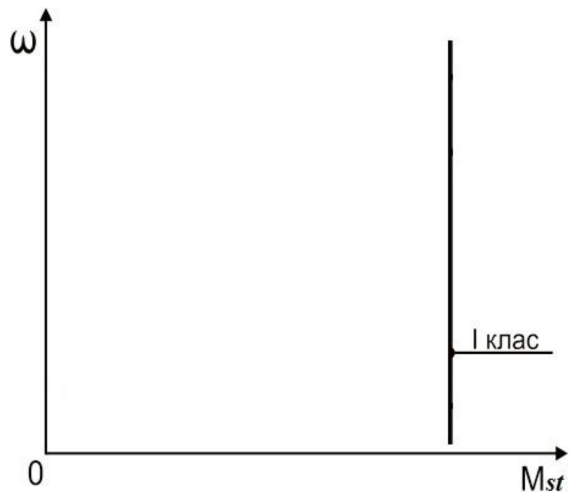
$$M_{st.(static)} = M_0 + (M_{st.nom} - M_0) \cdot \left(\frac{\Omega}{\Omega_{nom}} \right)^n$$

has the form

$$M_{st} = M_{st.nom} \quad (2)$$

These characteristics have the following mechanisms:

- lifting machines,
- hoists,
- feeder machines,
- the performance body of most robots,
- assembly line with a constant mass of material that moves.



II class. The second class includes all the mechanisms for which the static moment of resistance **increases with increasing speed (velocity) linearly (inclined line** $y = k \cdot x + b$**).**

According to the equation (1) $n = 1$.

The equation (1)

$$M_{st.(static)} = M_0 + (M_{st.nom} - M_0) \cdot \left(\frac{\Omega}{\Omega_{nom}} \right)^n$$

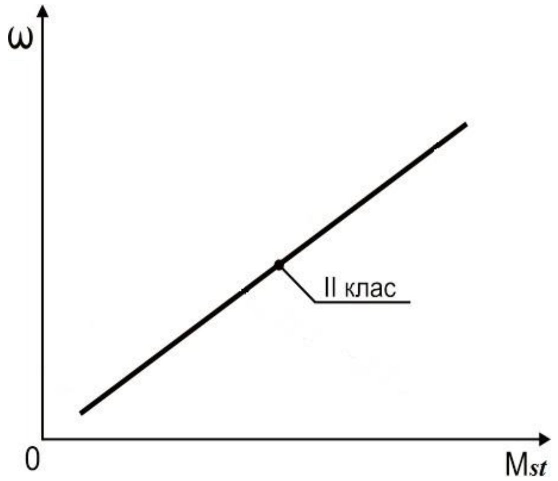
has the form

$$M_{st.} = M_0 + \frac{\left(M_{st.nom} - M_0\right) \cdot \Omega}{\Omega_{nom}} \qquad (3)$$

$$M_{st} = M_0 + M'_{st} \cdot \omega \qquad (4)$$

where $M'_{st} = \frac{\left(M_{stnom} - M_0\right)}{\Omega_{nom}}$ - a constant.

There is **a little number** of such mechanisms (DC generator with separate excitation, which operates at constant external resistance).



III class. This class includes all the mechanisms for which the static moment of resistance **increases nonlinearly with increasing velocity**, i.e. the mechanical characteristic is nonlinearly increasing (parabola).

According to the equation (1) n = 1,8…2,2 .

The equation (1)

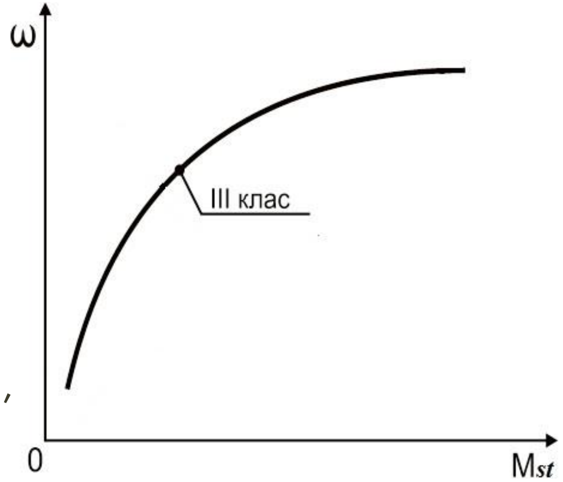
$$M_{st.(static)} = M_0 + (M_{st.nom} - M_0)\cdot\left(\frac{\Omega}{\Omega_{nom}}\right)^n$$

has the form

$$M_{st} = M_0 + \frac{M_{st_{nom}} - M_0}{\Omega_{nom}}\cdot\Omega^n \qquad (5)$$

$$M_{st} = M_0 + M''_{st}\cdot\Omega^n \qquad (6)$$

where $M''_{st} = \dfrac{\left(M_{st.nom} - M_0\right)}{\Omega_{nom}}$ - a constant.



Example of the mechanisms:

- fan,
- centrifugal pumps,
- compressors, propellers of air and water vessels,
- centrifuges, separators and others.

Their feature is that at **low speeds - load is small**, **while the velocity grows, the resistance increases too**.

IV class. This class includes all the mechanisms for which the static moment of resistance **decreases nonlinearly with increasing velocity**, i.e. mechanical characteristic is nonlinear decreasing (hyperbole). According to equation (1) *n* = -1.

The equation (1)

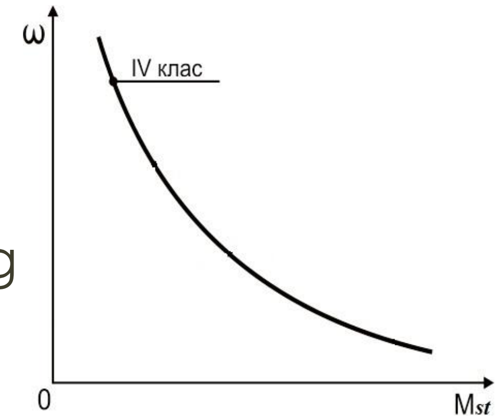
$$M_{st.(static)} = M_0 + (M_{st.nom} - M_0)\cdot\left(\frac{\Omega}{\Omega_{nom}}\right)^n$$

has the form

$$M_{st} = M_0 + \frac{M_{st_{nom}} - M_0}{\Omega_{nom}}\cdot\Omega^{-1} \qquad (7)$$

$$M_{st} = M_0 + \frac{M'}{\Omega} \qquad (8)$$

where $M' = \frac{\left(M_{stnom} - M_0\right)}{\Omega_{nom}}$ - a constant.



An example: mechanisms of cutting machine tools (lathes, milling machines and others).

Here, **the higher velocity of the mechanism is, the less it should be supply – the less resistance moment** and vice versa.

2. Mechanics of a motor controller. Summary of moments of resistance and inertia moments to the motor shaft

When projecting a motor controller of industrial mechanism, **parameters of the rotating or translational motion of the production mechanism reduce to the rotational motion parameters of the engine**. This reduction is carried out by means of **kinematic transmission (reductor)**. Examples of kinematic gear are shown in Fig. 2.

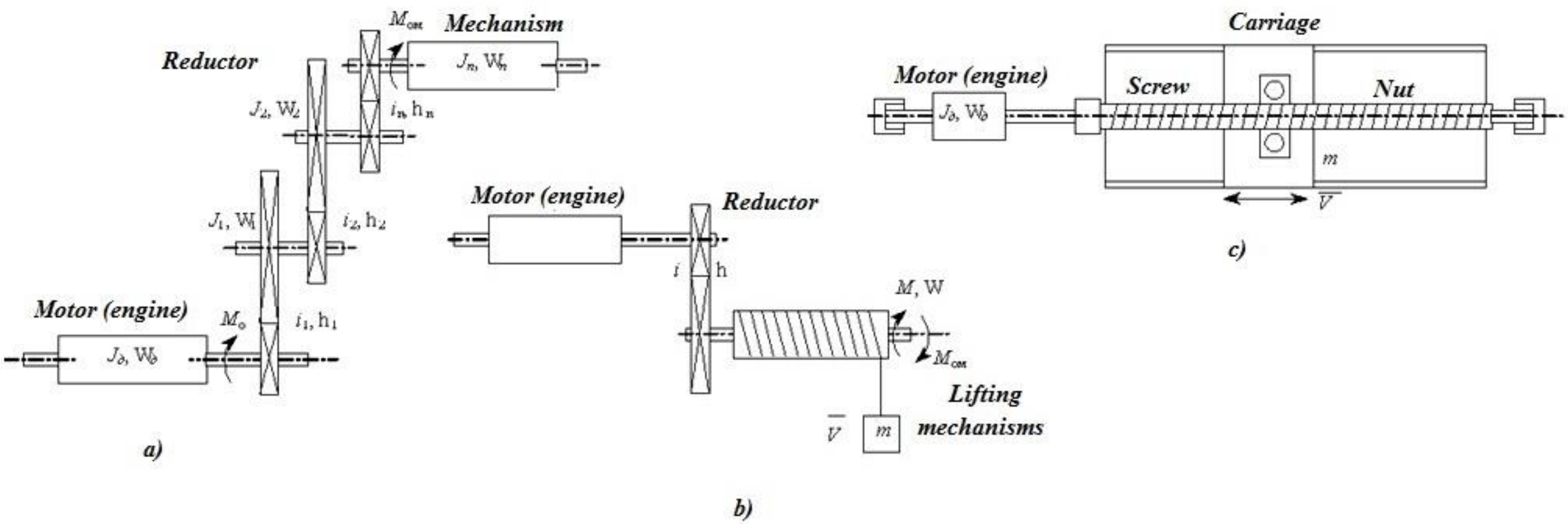


Figure 2 - Examples of kinematic schemes of motor controllers:
a) MC of main motion machine-tools; b) MC of lifting mechanism;
c) MC of feeding cutting machine

When selecting a motor for a particular production mechanism generally, motion parameters of the engine **do not match** the parameters of the production mechanism.

In order to accommodate the motor with a production mechanism selects the appropriate kinematic device, for example

- **gear reductor** (Fig. 2a)
- **reductor - drum** (Fig. 2b),
- **screw - nut** (Fig. 2c).

Kinematic device of **"reductor-drum"** type is used in hoisting machines where the motor **rotary motion is converted into forward movement of cargo**.

Devices such as **"screw-nut**" and **"rack-gear"** are used in controllers for **supplying** at machine tools.

While using for electric drives kinematic devices **forces** and **moments of resistance *working mechanisms*** must be **reduced** to the **moment of resistance** on the ***motor shaft***.

To calculate the required torque and motor power moment of resistance and the rotational speed of the mechanism are reduced to the moment and the rotational speed of the engine.

The reduction of points to the axis of rotation resistance mechanism to the axis of rotation of the engine is done according to the **law of energy balance**: ***power on the output shaft of the motor is the sum of the shaft power of the working mechanism and power losses due to friction in the kinematic transmission***.

The power losses are taken into account through the **energy conversion efficiency (ECE) kinematic transmission** η_{kt}.

For the scheme (Fig. 2a) we can write down

$$M_0 \cdot \Omega_{motor} = M_{o mec.(mechanism)} \cdot \Omega_{mec.} / \eta_{kt} \quad (9)$$

$$M_0 = M_{o mec.} \cdot \frac{\Omega_{mec.}}{\Omega_{motor}} \cdot \frac{1}{\eta_{kt}} = M_{o mec.} \cdot \frac{1}{i \cdot \eta_{kt}} \quad (10)$$

where $i = \frac{\Omega_{motor}}{\Omega_{mechanism}}$ - gear ratio of kinematic transmission.

If there are several mechanical transmission between the motor and mechanism

$$M_{0(motor)} = M_{o mec.} \frac{1}{(i_1 \cdot i_2, ..., i_n) \cdot (\eta_1 \cdot \eta_2, ..., \eta_n)} \quad (11)$$

The equations **of motion of the engine** has the form

$$J \frac{d\Omega}{dt} = M - M_o, \quad (12)$$

Moment of resistance M_0 is balanced with motor torque and inertia (dynamic) moment $J \frac{d\Omega}{dt}$.

For most industrial mechanisms mass and moment of inertia are constant. The **moment of inertia of the controller** can be shown as

$$J = m\rho^2 = \frac{GD^2}{4g} \qquad (kg \cdot m^2) \tag{13}$$

where ***m*, *ρ*** and ***D*** - weight, radius and diameter of inertia, respectively,
G - gravitational force,
g = 9,81 m/c^2 - acceleration of free falling.

The size ***GD*²=4*gJ*** is called **flywheel moment**.

If bodies rotate with moments of inertia j_1, j_2, …, j_n, and angular velocity Ω_1, Ω_2,…,Ω_n, their dynamic performance is replaced with dynamic performance with one moment of inertia reduced to the motor shaft speed

$$J\frac{\Omega_{motor}^2}{2} = \frac{J_{motor}\Omega_{motor}^2}{2} + \frac{J_1\Omega_1^2}{2} + \frac{J_2\Omega_2^2}{2} + \ldots + \frac{J_n\Omega_n^2}{2} \tag{14}$$

From (14) **moment of inertia of the motor shaft**

$$J = J_{motor} + J_1\left(\frac{\Omega_1}{\Omega_{motor}}\right)^2 + J_2\left(\frac{\Omega_2}{\Omega_{motor}}\right)^2 + \ldots + J_n\left(\frac{\Omega_2}{\Omega_{motor}}\right)^2 \tag{15}$$

$$GD^2 = GD_{motor}^2 + G_1D_1^2\left(\frac{n_1}{n_{motor}}\right)^2 + G_2D_2^2\left(\frac{n_2}{n_{motor}}\right)^2 + \ldots + G_nD_n^2\left(\frac{n_n}{n_{motor}}\right)^2 \tag{16}$$

If you replace $n_1/n_{motor} = 1/i_1$, $n_2/n_{motor} = 1/i_2$, etc. in (16), then

$$J = J_{motor} + J_1 \, 1/i_1^2 + J_2 \, 1/i_2^2 + \ldots + J_n \, 1/i_n^2 \qquad (17)$$

In kinematic gears of lifting mechanisms, machine tools and other mechanisms, it is necessary **to reduce of forces and moments translational motion of *PB* to rotational motion of *motor shaft***.

For this case the ***energy balance equation*** has the form

$$F_{o\,mec.} \cdot V \cdot 1/\eta_{kt} = M_0 \Omega_{motor} \qquad (18)$$

where ***F*_o mec_** - the resistance force of mechanism,
V - velocity of translational motion.

From (18) the resistance moment is equal to the motor shaft

$$M_0 = \frac{F_{o\,mec.} \cdot V}{\Omega_{motor} \cdot \eta_{kt}} \qquad (19)$$

Reduction of mass moving in turn is carried out on the basis of equality **supply of kinetic energy**

$$\frac{mV^2}{2} = J\frac{\Omega^2}{2} \qquad (20)$$

The last one shows, the moment of inertia of mass moving in turn, reduced to the motor shaft, is equal to

$$J = m\left(\frac{V}{\Omega_{motor}}\right)^2 \quad (21) \qquad GD^2 = \frac{365V^2}{n_{motor}^2} \quad (22)$$

Lecture 7
Energy losses in the motor and in other electric elements of a motor controller. A thermal mathematical model of an electric motor.

Power losses in electric motors are divided into **constant losses** and **variable losses**

$$\Delta P = \Delta P_{const} + \Delta P_{var.} \qquad (1)$$

Constant losses does not depend on the **load**, i.e. it does not depend on the electric motor (EM) **current**. These include:

- loss on magnetization and eddy currents in the magnetic steel $\Delta P_{st.}$,

- mechanical friction losses in the bearings and friction of the brushes on the collector, ventilation losses $\Delta P_{mec.}$.

In DC motors and synchronous EM with electromagnetic excitation to the constant losses are added losses in the excitation winding ΔP_{exc}. Besides that, to the constant losses are added **additional losses** (1...2% from P_{nom}) .

The **variable losses** are those that **depend on the load current**.

In a **DC motor** this is a loss in the anchor winding, and **asynchronous motors (AM)** it is lost in the windings of the stator and rotor.

These losses depend on the current squared, which is changed by changing the load.

For **DC motor**

$$\Delta P_{\mathrm{var}} = R_a I_a^2 = \Delta P_{\mathrm{var.nom}} \left(\frac{I_a}{I_{anom}} \right)^2 \qquad (2)$$

For **AM**

$$\Delta P_{\mathrm{var}} = 3R_1 I_1^2 + 3R_2'(I_2')^2 \qquad (3)$$

Value of variable losses in the average load to losses when P_{nom} is

$$\frac{\Delta P_{\text{var}}}{\Delta P_{\text{var.nom}}} = \left(\frac{I'_2}{I'_{2\ \text{nom}}}\right)^2 \cdot \frac{R_1(I_1/I'_2)+R'_2}{R_1(I_{1\ \text{nom}}/I'_{2\ \text{nom}})^2+R'_2} \tag{4}$$

If the resistance of the stator is $R_1 \approx 0$, then

$$\Delta P_{\text{var}} \approx \Delta P_{\text{var.nom}}(I'_2 / I'_{2\text{nom}})^2 \tag{5}$$

Thus, the power losses in the motors of direct current and alternating current can be expressed by the general formula

$$\Delta P = \Delta P_{const} + \Delta P'_{\text{var.nom}} x^2 = \Delta P_{\text{var.nom}}(\alpha + x^2) \tag{6}$$

where $\alpha = \dfrac{\Delta P_{const}}{\Delta P_{\text{var.}nom}}$ - loss coefficient, which, depends on the

type of engine is in the range of 0,5 ... 2;

$\boldsymbol{x}$ - load coefficient:

- for DC motor $\boldsymbol{x = I_a / I_{a\ nom}}$,
- for asynchronous motor (AM) $\boldsymbol{x = I'_2 / I'_{2\ nom}}$.

When the engine works due to the natural characteristic at constant voltage load coefficient

$$x = \frac{P}{P_{nom}} \tag{7}$$

The efficiency of the motor depends on the load

$$\eta(x) = \frac{x}{x + \frac{\Delta P_{\text{var.nom}}}{P_{nom}}(\alpha + x^2)} \tag{8}$$

Full face of loss of EM is determined by $\boldsymbol{P_{nom}}$ i $\boldsymbol{\eta_{nom}}$

$$\Delta P_{nom} = P_{nom}\frac{1-\eta_{nom}}{\eta_{nom}}$$

$$\Delta P_{\text{var.nom}} = P_{nom}\frac{1-\eta_{nom}}{\eta_{nom}} \cdot \frac{1}{1+\alpha} \tag{9}$$

$$\eta(x) = \frac{\eta_{nom}(1+\alpha)x}{(1-\eta_{nom})x^2 + \eta_{nom}(1+\alpha)x + (1-\eta_{nom})\alpha} \tag{10}$$

The dependence of the **energy conversion efficiency (ECE)** on the **load coefficient** is shown on Fig. 1.

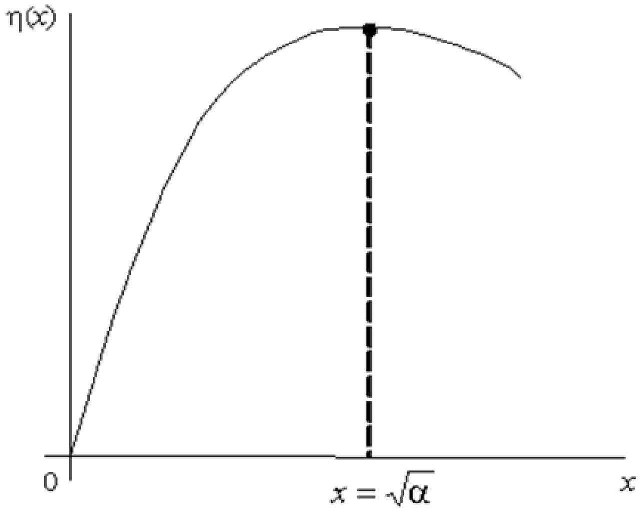


Figure 1 - The dependence of the efficiency coefficient on the load coefficient

The **maximum efficiency** is at $x = \sqrt{\alpha}$, when variable losses are equal to a constant losses.

At low load engine, efficiency decreases and reaches zero at idle.

Operating the engine at loads smaller than the nominal, is ineffective.

In a regulated motor controller, power losses depend on the speed.

It is believed that the losses in steel and mechanical losses are proportional to the square of the speed.

At low speeds the energy conversion efficiency **(ECE)** of electric motor **drops to zero**. Therefore, **the continuous work of the engine at a speed less than the nominal, is also ineffective**.

Loss of electrical power in the electric motor is converted into **thermal energy, which heats it**.

The electric motor is a **complex thermodynamic system.** The system is heterogeneous in its thermal parameters, which complicates its mathematical description and analysis that is performed on the basis of the **differential equations of mathematical physics** and the **theory of non-stationary processes**.

Approximate analysis and calculation of the thermal state of the motor can be done due to the simplified mathematical model, compiled on the basis of the **heat balance equation**

$$dQ_1 = dQ_2 + dQ_3 \qquad (11)$$

where dQ_1 - heat losses is proportional to the power losses

$$dQ_1 = \Delta P \cdot dt$$

dQ_2 - part of the heat energy absorbed by the body of the engine and raises its temperature

$$dQ_2 = C \cdot d\theta$$

dQ_3 - part of the heat energy emitted into the environment

$$dQ_3 = A \cdot \theta \cdot dt$$

Thus, the heat balance equation has the form

$$\Delta P dt = C d\theta + A\theta dt$$

or

$$C\frac{d\theta}{dt} + A\theta = \Delta P \qquad (12)$$

where **C** - heat capacity (Joules/Kelvin) of the engine body, taken into consideration as constant and homogeneous;

A - heat transfer, W/K;

$\boldsymbol{\theta}$ - temperature excess of the engine above the environment temperature.

At steady thermal regime

$$d\theta/dt = 0,\ A\theta = \Delta P,$$

all the thermal energy released in the electrical motor is transferred to the environment.

The steady excess temperature can be found in accordance with the formula

$$\theta_{steady} = \Delta P / A \qquad (13)$$

Then ***the heat balance equation*** can be written as the following one

$$\frac{C}{A} \cdot \frac{d\theta}{dt} + \theta = \theta_{steady} \qquad (14)$$

where $C/A = T_\theta$ - **time constant heating** or heat constant of the engine.

While the initial conditions $t = 0$ i $\theta(0) = 0$ we will have

$$\theta(t) = \theta_{steady} + (\theta_0 - \theta_{steady})e^{-t/T_\theta}$$

$$\theta(t) = \theta_{steady}\left(1 - e^{-t/T_\theta}\right) \qquad (15)$$

Thus, in a first approximation the **transitional process of heating** the engine can be considered as exponential, as in a typical aperiodic link of 1-st order.

If the value of thermal constant $\boldsymbol{T_\theta}$ is known, it is easy to calculate how much time the engine warms up to the maximum permissible temperature at nominal operation. This heat process of the engine is shown on Fig. 2.

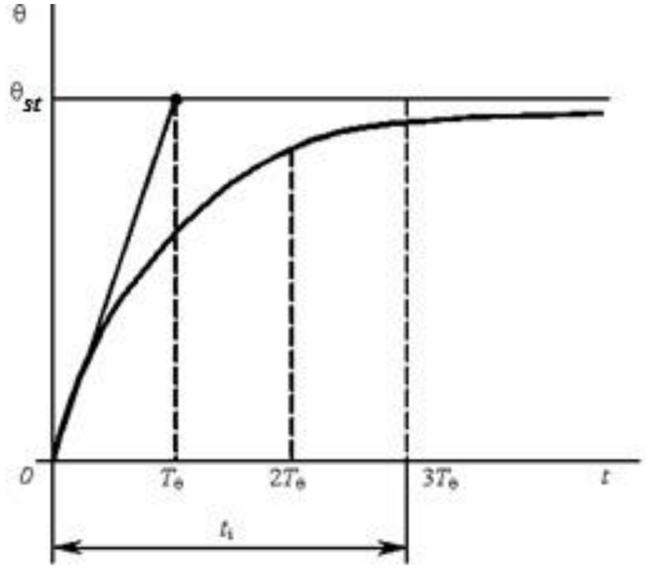


Figure 2 - Graphic picture of the process of the engine heating

Lecture 8
Open-loop control systems of the unregulated motor controller

1. Control system of start-up of DC motor
2. Scheme of power supply and control of asynchronous motor (AM)
3. Transient processes in open-loop systems

1. Control system of start-up of DC motor

Open-loop control system of the DC motor with parallel excitation is shown on Fig. 1.

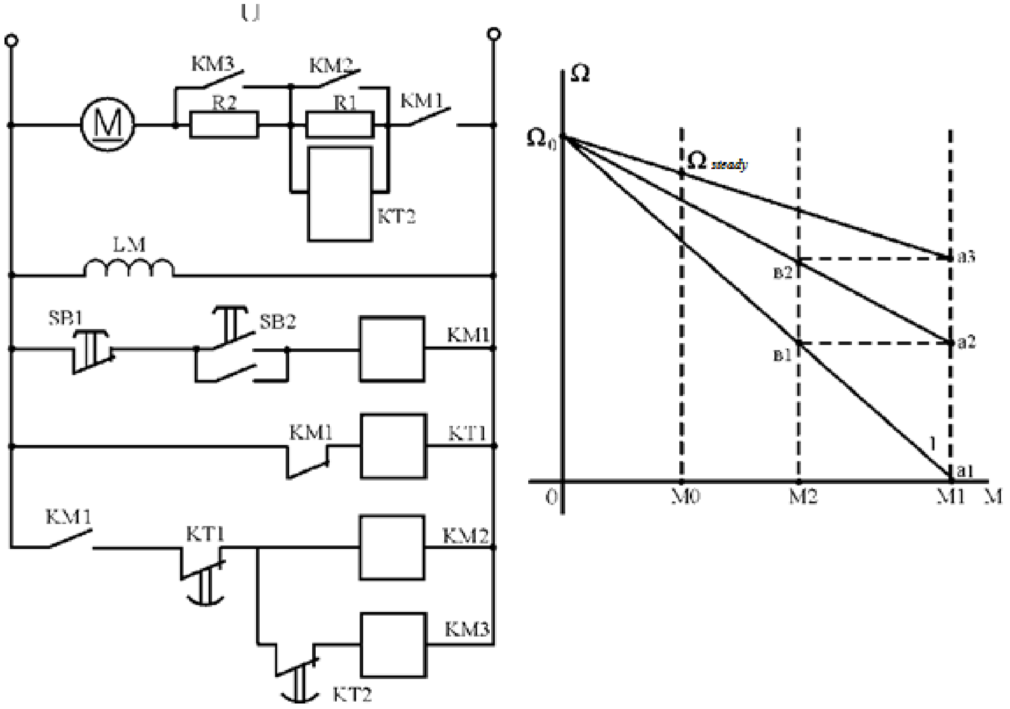


Figure 1 - Scheme of start-up of the DC engine and starting mechanical characteristics of the DC engine

When the engine is starting the voltage balance equation on armature has the following form

$$U_a = I_a R_a + L\frac{dI_a}{dt} + E \qquad (1)$$

At the time of start the engine $\Omega = 0$, $E = k\Phi\Omega = 0$, the self-induced electromotive force (EMF) is also equal to zero, then appears and disappears in a very short time.

Therefore, at the time of start the engine

$$I_a \approx \frac{U_a}{R_a}$$

current is in 5-7 times higher than the nominal meaning of current.

When the engine is accelerated, it’s speed and EMF increase gradually, applied to the armature winding voltage equals to EMF and the current decreases to the nominal (at nominal load).

Great value a current at the start-up moment the motor is dangerous for the **engine collector**.

To reduce the starting current in the motor armature circle **to connect successively the rheostat** (on the scheme R1+R2)

Acceleration of the engine occurs at reduced current and to preserve the necessary rate of the acceleration, the rheostat withdraws gradually, i.e. **to reduce its resistance**.

In practice, the resistor is performed **partitioned** and during the start-up, the partition are closed for a short time and removed from the circle. This act is **done automatically** by relays and magnetic contactors.

The most popular are start-up schemes **with a function of time** (Fig. 1).

The scheme works as follows:

- when you turn on voltage ***Ua*** through the drive winding LM flows drive current;
- start should be occured at a nominal flow of excitation Φ_{nom}, that's why at the moment of the start-up the condition should be performed $U_a = U_{nom}$;
- at the same time with the switching voltage on drive winding, the voltage is applied to the winding of **time switch *KT1*** that triggered and disconnects normally closed contact at the power circuit of contactor *KM2* and *KM3*;
- contacts of these contactors KM2 and KM3 are open-loop and **starting rheostat (R1+R2)**, switched in series with the armature winding **has full resistance**;

- the starting rheostat enacted fully, acceleration of the motor takes place according to the ***characteristics 1*** of point $\boldsymbol{a_1}$ to point $\boldsymbol{b_1}$.

- when the engine speed rises to the point $\boldsymbol{b_1}$, the relay ***KT1*** releases, closes the power circle ***KM2***, ***KM2*** contactor triggered and its contact makes short-circuit to the resistor ***R1***;

- the working point moves to the position $\boldsymbol{a_2}$ and the acceleration goes due to the ***characteristics 2*** to the point $\boldsymbol{b_2}$ and so on, until the engine operating point mode turns the natural characteristics and the following acceleration continues under **natural characteristics.**

2. Scheme of power supply and control of asynchronous motor (AM)

The simplest scheme of power supply AM is **non-reversible scheme** of power supply of unregulated asynchronous motor (AM), as it is shown on Fig. 2.

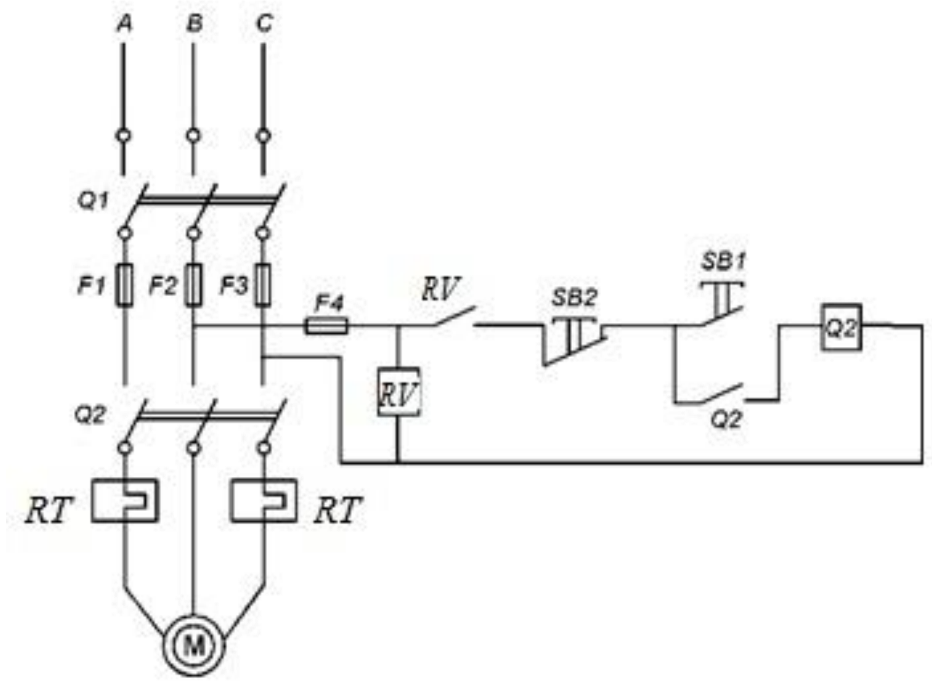


Figure 2 – scheme of start-up AM with short-circuit rotor (or squirrel cage rotor): *Q1* - packet switch, *Q2* - magnetic contactor, *RV* - under-voltage relay, *RT* - thermal relay, *F1-F4* – base fuses, *SB1* - "Start" button, *SB2* - "Stop" button

The start-up going on in the following order:

when you switch on the packet switch ***Q1*** the power goes to the under-voltage relay ***RV***.

If a linear voltage in the power circuit is not below the permitted meaning U_{min}, the relay is triggered and makes short-circuit of *PV* contact of power circuit at the contactor winding **Q2**.

When you click on the button **start *SB1***, the current flows through the contactor winding, the contactor will work and make short-circuit of power circuit at the engine ***M***.

At the same time with its contact **Q2** contactor will block the power circuit of winding.

Releasing the button ***SB1*** winding power circuit still to be closed.

To **turn off** the engine press the button ***SB2*** (**stop**).

The protection from the supply voltage dip in the supply power line below U_{min} is the **under-voltage relay RV**, broking down the contact ***RV*** of the power circuit **Q2**, the power circuit brakes down and the contactor turns off the voltage from the motor stator windings.

Overload protection of motor is performed by **thermal relay *RT***. With prolonged overload the current in the stator windings is increasing. Flowing through the heating element at the relay **RT**, the current heats it to the established temperature as the result, the relay operates and opens the power circuit.

The protection from short-circuit current is made with means of **base fuses *F1-F3***. In responsible motor controllers the protection should activated as soon as possible. In these cases, **instead of base fuses** is used the **over-current relay**. The functions of over-current relay and thermal relay are combined into a **circuit breaker** (a device that is turn on manually and turn off automatically).

3. Transient processes in open-loop systems

The analysis of transients in the simplest motor controller systems performs through the appropriate method and the move of the controller is described with the differential equation

$$J\frac{d\Omega}{dt}=M(\Omega)-M_0(\Omega) \quad (2)$$

where $M_0(\Omega)$ - moment of resistance as a function of speed.

In the simplest case $M_0=const$, and mechanical characteristics is linear as in a DC motor. In this case, the equation has the form

$$T_m\frac{d\Omega}{dt}+\Omega=\Omega_{\text{steady}} \quad (3)$$

The solution of this equation is

$$\Omega(t)=\Omega_{steady}(1-e^{-t/T_m}) \quad (4)$$

where $T_m=\frac{JR_a}{c^2}$ - mechanical time constant,

Ω_{steady} - the established speed.

A transfer characteristic of the acceleration of the motor has the following form (Fig. 3).

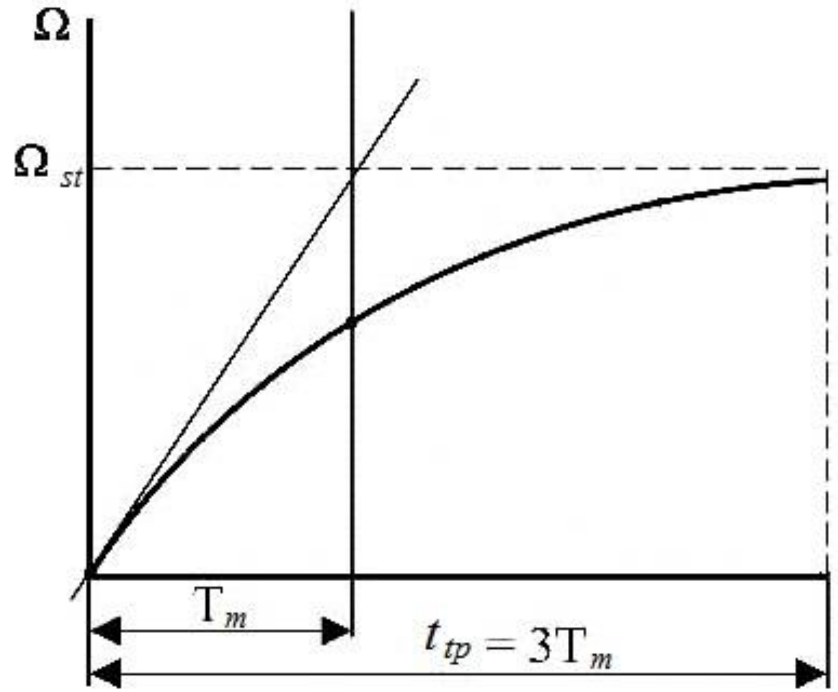


Figure 3 - A transfer characteristic of the acceleration of the motor

The duration of the transient processes can be determined from the equation (2) if to divide the variables

$$J\frac{d\Omega}{dt}=M(\Omega)-M_0(\Omega)$$

Dividing the variables, we get

$$dt=J\frac{d\Omega}{M(\Omega)-M_0(\Omega)} \tag{5}$$

Let's integrate (5) and get

$$t_{tp}=\int_0^{\Omega_{steady}} J\frac{d\Omega}{M_{start}(\Omega)-M_0(\Omega)} \tag{6}$$

In the simplest case the acceleration occurs

$$M_0=const,\ M_{start}=const,\ \Omega_1=0,\ \Omega_{steady}=\Omega_{nom}$$

The duration of the start

$$t_{start}=\frac{J\Omega_{nom}}{M_{start}-M_0} \tag{7}$$

We can see from this formula that for the start-up should be the following condition $M_{start}>M_0$.

The greater the **starting torque** than the **moment of resistance** $M_{start} > M_0$, whereby the **quicker motor accelerates** to the nominal speed.

While there is an electric braking, the motor moment changes its mark (or sign), so **braking time** is determined with the formula

$$t_{braking} = \frac{J\Omega_{nom}}{M_{braking} + M_0} \qquad (8)$$

For the asynchronous motor, the **start-up time** can be defined with the formula

$$t_{start} \approx \frac{J\omega_0}{4M_{critical}s_{critical}} \qquad (9)$$

Lecture 9
CHOICE ELECTRIC MOTOR FOR THE POWER

1. Choosing the type and motor power for production mechanism
2. General requirements to the choice the type of motor

1. Choosing the type and motor power for production mechanism

A motor controller in industry, construction and municipal sector consumes **about 60%** of energy which is produced by power stations.

Therefore the **choice of type and motor power** for production mechanism **is important** and very difficult task.

Correctly chosen motor **should provide** execution of technological process by production mechanism with the set indicators of quality for the **least energy and operating costs**.

If in the motor controller establish the electric motor **more power than the production mechanism needs**, that the engine will be **underloaded** and motor controller **will have low efficiency**.

With the **reduced power** of engine **increased energy losses to heat**, **decreases efficiency** and **accelerated the aging winding insulation** and engine life.

Therefore, when choosing the type of electric motor to drive the production mechanism **is necessary with sufficient accuracy to calculate the power mechanism** in all modes of the technological process.

The first of the requirements that must be made when choosing the type of engine is motor type must match the type of production mechanism.

Electrical industry produces motors of **general-series**, electric motors of the **machine tool series**, electric motors of the **crane series**, electric motors of **passenger lifts**, electric motors for **rolling mills.**

The second requirement - mode of operation of selected engine must meet the mode of mechanism.

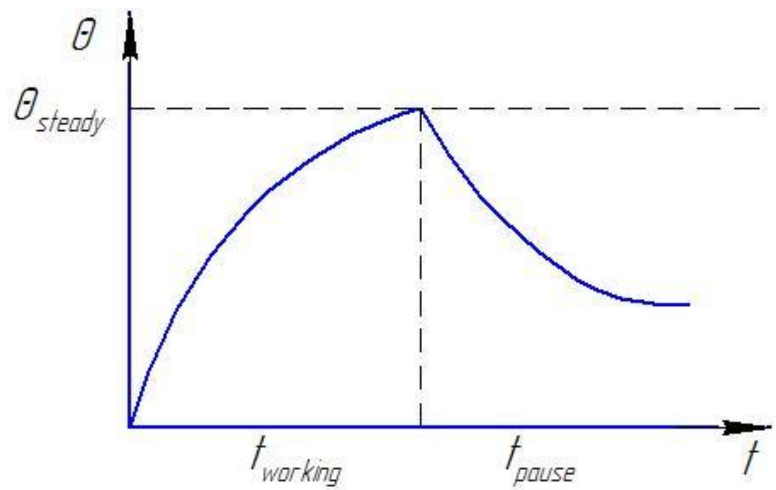
Modes of operation of production mechanisms are quite diverse. They **differ** in the **duration** and **nature of the load**, **duration of pauses**, **transient starting** and **braking.**

Industry produces motors are designed for a specific mode, which is called the **nominal.**

According to the **state standard** set **8 nominal mode** of electric motors, which denote the cipher S1, S2, ..., S8.

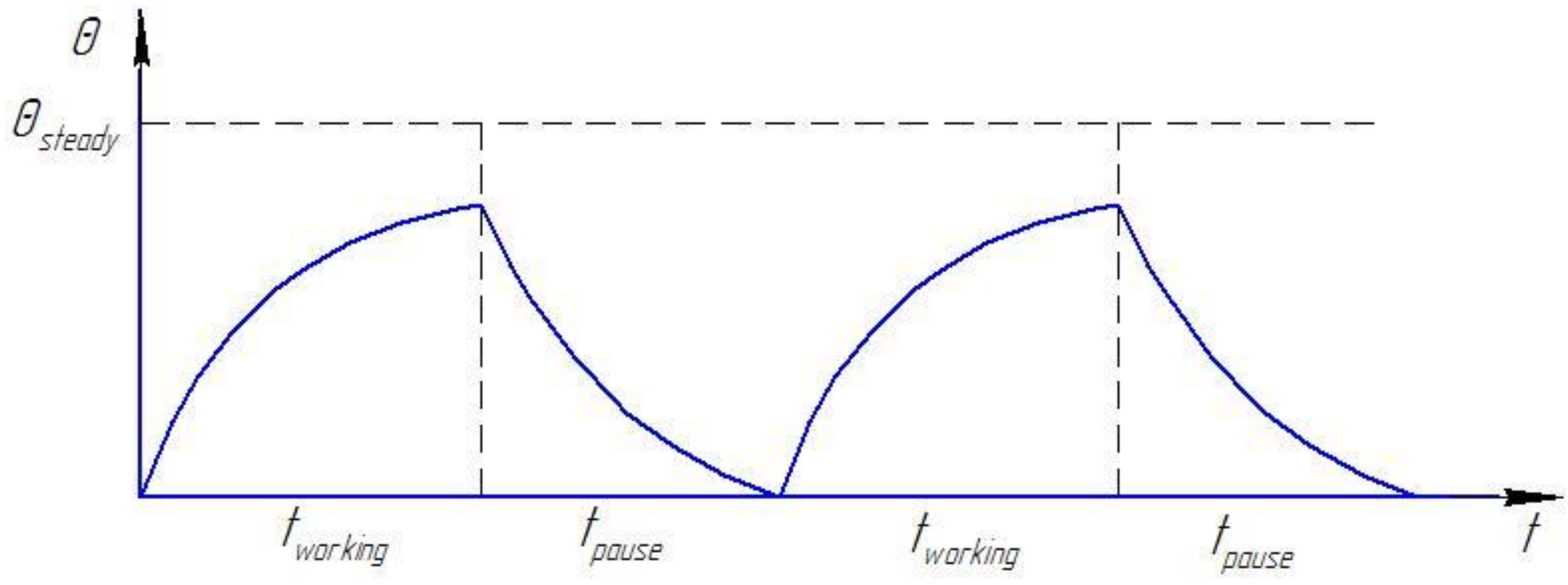
Prolonged nominal mode S1

This mode is characterized by a constant load which is applied to the engine at a time by which excess of temperature all parts of the engine reaches a steady value θ_{steady}



Short nominal mode S2

It is a mode in which the constant load which is applied to the engine at a time, which is not enough to achieve the steady value excess of temperature, then the engine turn off at a time that all its parts are cooled to ambient temperature.



Re-short mode S3

This is a mode in which the load has recurring character and consists of short periods of the unchanging load in which excess of temperature does not reach the steady value and short breaks during which the engine does not have time to cool down to ambient temperature.

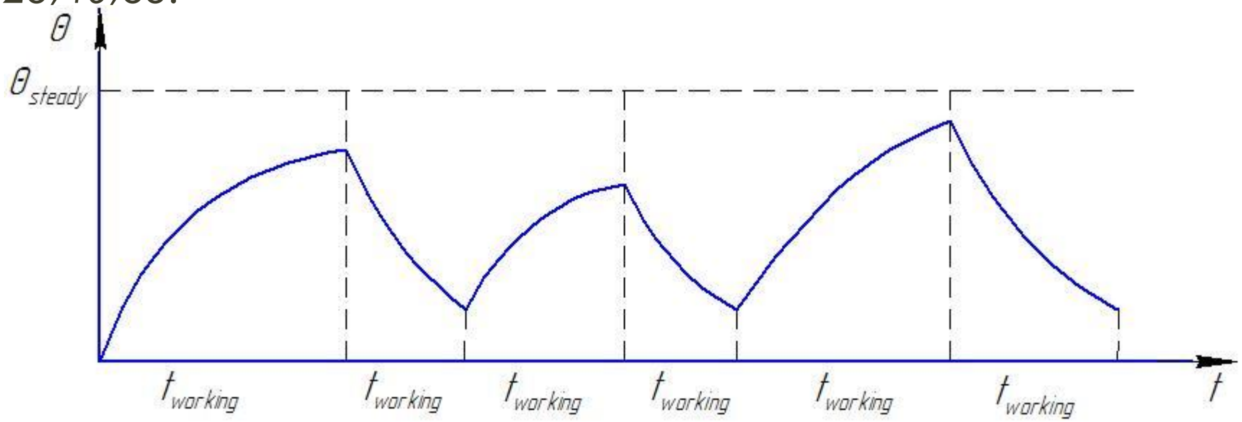
At the time of pauses the engine is switched off with network. This mode is characterized by the cycle duration t_{cycle}

$$t_{cycle} = t_{working} + t_{pause}$$

and relative duration of switch on – DS

$$\mathrm{DS\%} = \frac{t_{working} \cdot 100}{t_{cycle}}$$

A standardized value of maximum time of cycle duration t_{cycle} = *10 min; DS% = 15, 25,40,65.*



2. General requirements to the choice the type of motor

The main criterion for the choice of engine power is its **heating.**

Severe restrictions of heating electric machines associated with a decrease winding insulation resistance at heating. Nominal power is determined by the permitted heat of insulation.

If the motor is overloaded it quickly heats up, the temperature of isolation increases, breakdown voltage isolation decreases and isolation irreversibly loses its quality. **Reliability and service life of engine reduced.**

Insulation materials for stability to heat divided into **classes**, depending on the **maximum allowable temperature.**

Maximum temperature insulation depends not only on the load of EM, but also on the ambient temperature.

In calculating thermal management and choice of engine power ambient temperature is taken constant, so that is 40^0 C.

According to this temperature is set two parameters:

- maximum permissible excess of temperature θ_{max}
- permissible temperature $t_{permissible}$

Table 1 - Maximum permissible excess of temperature and permissible temperature for existing classes winding insulation electric machines

Temperature ^0C	Insulation class				
	E	B	F	H	C
$t_{permissible}$	120	130	155	180	180
θ_{max}	80	90	115	140	140

Besides limiting for the **heating**, the engine has limited by **overloading capacity** and limit by the **starting moment.**

Permitted **overload asynchronous motor** is determined by its maximum (critical) moment and the value is given in the catalogs.

Overload of **DC motors** limited of conditions the collector switching.

Limitation on the **starting moment** lies in the fact that at start-ED starting moment should be greater than the moment of loading otherwise the engine will not starts.