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ELECTRIC DRIVE

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Study guide contains four chapters for course "Electric drive". It is designed for students for all electromechanical and energy fields and for all forms of learning.

The tutorial sets out in summary form the theoretical questions about the electric drive. The drive is considered as a system, its structural diagrams, physical processes and principles of control and regulation of origin in electric drives with DC and AC motors in open and closed systems, as well as elements database and design principles of automated full drives.

The manual is intended for students studying in the field 140604 "Electric drive and automation of industrial installations and technological complexes", 140601 "Electromechanics", 140211, "Power supply", 140610 "Electrical equipment and electric economy of companies, organizations and institutions".

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INTRODUCTION

State Standard of the Russian Federation (50363-92) is set to the following definition of the drive:

The electric drive – electro-mechanical system consisting generally of interacting power converters, electro-mechanical and mechanical transducers, control and information devices and interfaces to external electrical, mechanical, control and information system designed to propel the executive bodies of the machine tools and control the movement of the technological process.

Electric drive consists of two channels: power channel and data channel. (fig. 1)

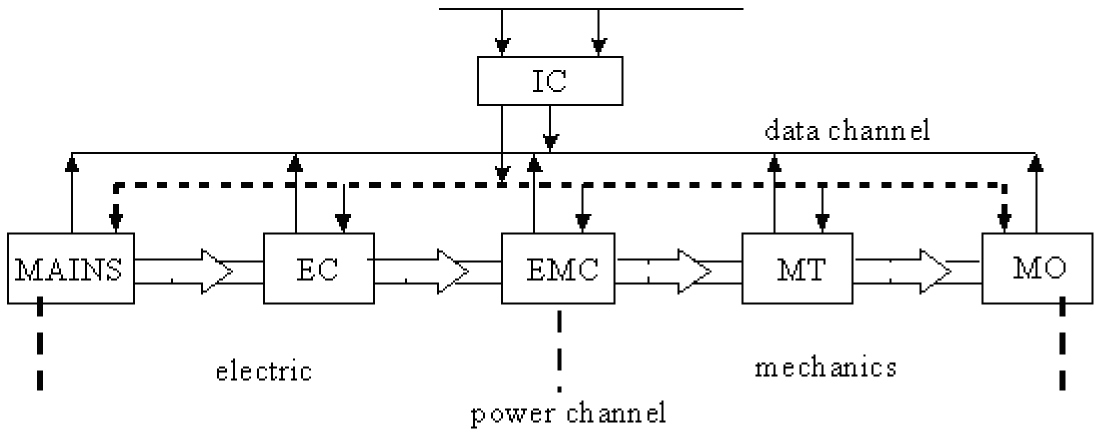


Fig. 1. Structure of electric drive

EC - electric converter;
EMC - electromechanical converter;
MT - mechanic transducer;
IC - informational converter;
MO - movable object of process installation.

By the power channel transformable energy is transported. According to information channel manages the flow of energy, the collection and processing of data on the status and functioning of the system, fault diagnosis.

Drive as technical system consists of certain elements itself as a subsystem included in other larger system (Fig. 2).

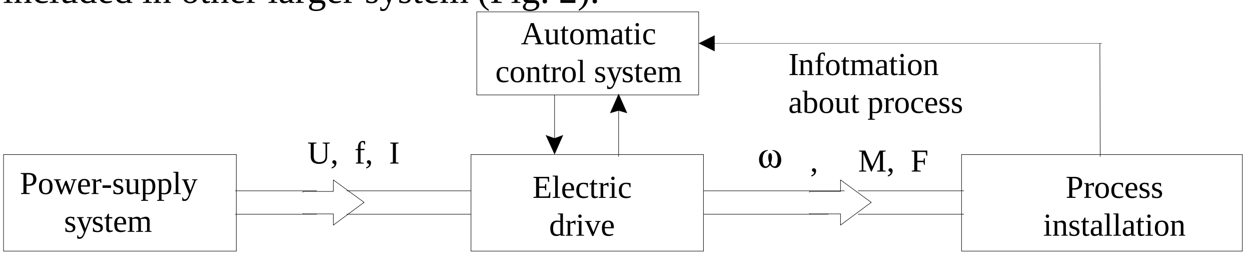


Fig. 2. The electric drive as a subsystem

All elements inside the drive are closely linked, for example, the power semiconductor technology affects the electricity supply system (electromagnetic compatibility). Examples of the integration of the movable operating element with an electromechanical transducer: motor - wheel transport systems, electric spindle lathes; magnetohydrodynamic pump in the foundry. The use of microprocessor-based equipment in the data channel affects on the quality of the functioning of the power channel.

The range of electric drives:

- the power:от 1 mcW до 100 MW;
- the frequency of rotation:от 1 rev/year до 500 000 rev/min;
- on the application: from the artificial heart to the flexible manufacturing systems.

There is a constant expansion of functionality drives.Types of drives on the physical principles of the converter of electric energy into mechanical energy:

1. Electromachine drive in which the conversion of electrical energy into mechanical energy by electric machines based on the interaction of the electromagnetic fields and current-carrying conductors.

2. The electromagnetic drive in which the conversion of electrical energy into mechanical energy by the device based on the interaction of electromagnetic fields and ferromagnetic materials.

3. The electrostatic drive, in which the energy conversion device is based on the interaction of the electrostatic field and electric charges (capacitive motors).

4. A piezoelectric drive, wherein the energy conversion device is based on the piezoelectric effect, which consists in that the deformation of certain crystals generates an electric charge and electrostatic interactions.

5. Magnetostrictive drive, wherein the energy conversion device is based on the magnetostrictive effect, which is that ferromagnetic materials are deformed under the influence of the magnetic field and change its magnetic properties.

Classification of electric drives

1. According to the type of movement:

a) rotational movement (There may be reversible and non- reversible, have continuous and discrete)

b) forward;

c) reciprocation

2.According to the principles of speed and position control:

a) fixed (constant velocity);

b) adjustable;

c) tracking (the transfer is made in accordance with the setting signal);

g) program-controlled (moving according to a given program);

d) adaptive (automatically provides optimal movement of the executive body with a change in his work);

e) position (provides position control of the executive body of the machinery).

3. By the nature of the mechanical transmission device:

a) reduction electric drive

b) reductor-free drive.

4. By the nature of the electric converter installation

a) controlled rectifier – motor (controlled rectifier - direct current motor);

b) frequency convertor - motor FC-M has alternating-current drive conversion device which is adjustable frequency converter;

c) system generator - motor (G-M);

d) system magnetic amplifier - motor (MA - M).

5. According to a method of transmitting mechanical power to the executive body:

a) an individual (each executive body of the machine tool driven by a separate motor) the main drive;

b) interconnected (two or more electrically or mechanically coupled motors);

c) a group (one motor driven multiple machines).

<u>Requirements to the drive:</u>

1. Reliability (reliability - the probability of failure).
2. Accuracy (required to carry out the controlled motion of a given accuracy).
3. Performance (the system's ability to respond to these pressures).
4. The quality of the dynamic processes (ensuring of requirements of the processes over time)).
5. Energy efficiency (specific power consumption for production of the final result and efficiency).
6. Compatible electrical drive with electric power supply systems and information.
7. Resource of capacity (materials consumption, duty, labor content during installation, operation, repair).

Dutys of motor:

– magnetic - 1 J/kg;
– classical capacitive - 0,1 J/kg;
– film - 10 J/kg;
– hydraulic internal combustion - 10 J/kg;
– human and animal muscle - 500 J/kg

1 MECHANICS OF ELECTRIC DRIVE

1.1 The equation of mechanical motion

From the electric motor (EM) to the movable object (MO) the mechanical energy is transmitted through the mechanic transducer (MT) (separate elements: couplings, gears, pulleys, ropes, shafts, etc.) that rotate or move steadily at different speeds, have different mass, moment of inertia. The mechanical motion of the drive elements described by the laws of Electromechanics. According to the second law of Newton's equation of motion for a rigid body rotating around a fixed axis is determined by:

$$\sum M = J\frac{d\omega}{dt}, \qquad (1.1)$$

where J - moment of inertia of the body;

$d\omega/dt = \varepsilon$ - the angular acceleration of a rotating body.

For translational motion of the body

$$\sum F = m\frac{dV}{dt}, \qquad (1.2)$$

where m - mass of a body;

dV/dt = a - acceleration translational of motion of the body.

In fact $\vec{M}$; $\vec{F}$; $\vec{\varepsilon}$; $\vec{a}$, are vector quantities but as directed along one axis can be used scalars. To find the dependence of the speed of the time $d\omega/dt$ and $\omega = f(t)$; and V = f (t) integration of the equations is performed at constant m и J.

M and F may depend on the body position, while integrating the differential rate equation $\omega = d\varphi / dt$ and $V = dS / dt$,

where $\varphi = f(t)$ - the angular position of the body;

S= f(t) - linear position of the body.

Only in exceptional cases, J and m may depend on the time and position of the body that occur rare.

If $\sum M \neq 0$; $\sum F \neq 0$, that the drive is accelerated.

If

$$\sum M = 0; \quad \sum F = 0, \qquad (1.3)$$

then the drive moves at a constant speed or established in a state of rest. (1.3) describes the conditions of steady motion.

Each element of drive has its speed, the moment of inertia and weight. For the calculations used to reduce torques, forces, moments of inertia and mass of each element, as a rule, to the shaft of the motor, to this is a real cinematic scheme replaced by the estimated energy equivalent circuit. For example, the real scheme of the mechanical part of the drive (Fig. 1.1) is replaced by the reduced design (Fig. 1.2).

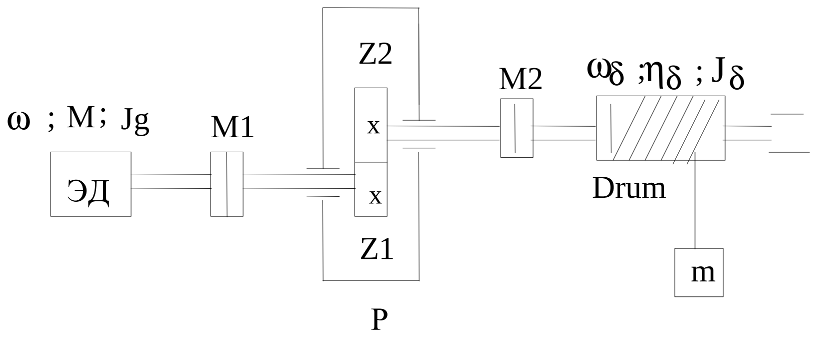


Fig. 1.1

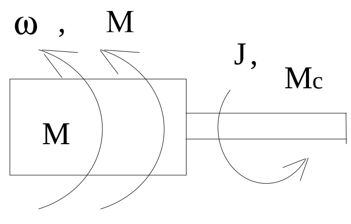


Fig. 1.2

The load of the drive: the power of gravity and friction of moving parts. It must define the values given load torques M_C (drag torque) and the moment of inertia J, based on the equality of the mechanical power of the load of motor in real and equivalent circuits.

1.1.1 Reducing torque:

a) For lifting the load the motor performs useful work and covers the friction loss in the kinematic scheme. The mechanical energy from the motor is sent to the executive device, while:

$$M_c \cdot \omega = F_{ио} V_{ио} / \eta_p \cdot \eta_Б$$

$$M_c = \frac{F_{ио} V_{ио}}{\eta_p \eta_Б \omega} = \frac{F_{ио} \cdot \rho}{\eta_p \eta_Б} \tag{1.4}$$

where: $\rho = \frac{V_{ио}}{\omega}$ - reducing radius;

b) For lowering of the load the potential energy is transmitted to the electric drive. Then the balance of power is determined by

$$M_c \omega = F_{ио} V_{ио} \eta_p \eta_б ,$$

whence:

$$M_c = F_{ио} V_{ио} / \omega \cdot \eta_p \eta_б = F_{ио} \cdot \eta_p \cdot \eta_б \cdot \rho , \tag{1.5}$$

because the frictional energy losses borne by the potential energy;

c) If the executive element performs rotational motion with speed $\omega_{ио}$ and creates a torque load $M_{ио}$, given to the motor shaft, then

$$M_c = M_{ио} \frac{\omega_{ио}}{\eta \omega} = M_{ио} / \eta \cdot i \tag{1.6}$$

in the direction of the energy from the motor to the executive element;

$$M_c = M_{ио} \frac{\omega_{ио}}{\omega} = M_{ио} \frac{\eta}{i}; \qquad (1.7)$$

when transferring power from the executive element to the motor,

where $i = \frac{\omega}{\omega_{ио}}$ - gear ratio of kinematic scheme.

1.1.2 Reduction of the moments of inertia and mass is produced, based on the equality of the reserve of the kinetic energy in the actual and the equivalent design circuit:

$$J\frac{\omega^2}{2} = J_д \frac{\omega^2}{2} + J_б \frac{\omega_\delta^2}{2} + \frac{mV_{ио}{}^2}{2},$$

whence:

$$J = J_д + J_б \frac{\omega_{ио}{}^2}{\overline{\omega}^2} = J_д + J_б / i^2 + m\rho^2 \qquad (1.8)$$

where J - reducing to the shaft of the motor moment of elements inertia;

$J_д$ - moment of inertia of the motor, clutch M1 and gearwheel Z1.

$J_Б$ - moment of inertia of gearwheel Z2, clutch M2 and drum.

Therefore:

a) to reduce the moment of inertia of the rotor to the shaft of the motor should be divided J by the square of gear portion of the kinematic scheme between the motor and this element, J/i^2;

b) to reduce the weight of linearly moving element should multiplied mass on the square of the radius of reducing plot of the kinematic scheme between the motor and this element, $m \cdot \rho^2$.

Finally, for the rotational movement equation of motion vector form is

$$\vec{M} + \vec{M}_c = J\frac{d\vec{\omega}}{dt}, \qquad (1.9)$$

where M – torque of the motor;

M_c - drag torque.

In scalar form can be written

$$M - M_c = J\frac{d\omega}{dt}, \qquad (1.10)$$

because sign M и M_c counteract each other.

$$M_{dyn} = J\frac{d\omega}{dt}, \qquad (1.11)$$

M_{dyn} - dynamic torque of the motor.

Considered design scheme called single-mass system has absolutely rigid elements and has no gaps.

1.2 Multimass mechanical systems

In the presence of elastic elements in the kinematic scheme it is difficult to obtain single-mass design scheme, therefore dual mass and three-mass mechanical system are produced. Thus the concept of the rigidity coefficient of the elastic element is introduced - the coefficient of proportionality between force and linear deformation or between the torque and angular deformity.

$$F_{\text{упр}} = C_1 \Delta L, \tag{1.12}$$

where ΔL - linear deformation;

$$M_{\text{упр}} = C_2 \Delta\varphi, \tag{1.13}$$

where $\Delta\varphi$ - angular deformation.

Coefficients C_1, C_2 determined by the geometrical dimensions of the elastic element and the material properties. For an elastic rod under tension

$$C_1 = \frac{SE}{L}, \tag{1.14}$$

where S, L - sectional area and length of the rod, mm^2, m;

E - coefficient of elasticity, Pa .

For shaft radius R under torsion:

$$C_R = J_s \frac{G}{L}, \tag{1.15}$$

where J_S - moment of inertia of the cross section of the shaft, m^4.

G - modulus of elasticity under torsion, Pa.

$$J_S = \pi R^4 / 2.$$

Then the rigidity C_1, C_2 is higher, the deformation is lower.

The reciprocal of the rigidity coefficient, called the coefficient of compliance $\left(\frac{1}{C} \quad , \frac{1}{C_2}\right)$.

In compiling design schemes of the mechanical part is carried by reducing the motor shaft rigidity coefficient of the elastic element.

For flexible shaft in torsion given coefficient is determined:

$$C = \frac{C_2}{i^2}. \tag{1.16}$$

For translational motion of the elastic element in tension and compression given coefficient:

$$C = C_1 \cdot \rho^2. \tag{1.17}$$

When connected in parallel elastic elements with the rigidities C_1, C_2, C_3, the equivalent rigidity is determined:

$$C_{eq} = C_1 + C_2 + C_3 + C_n . \quad (1.18)$$

In series the equivalent stiffness is:

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + ... + \frac{1}{C_n} . \quad (1.19)$$

Design model of a two-mass system is given by (Fig. 1.3):

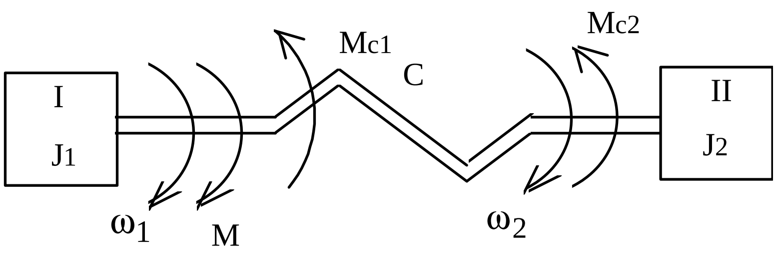


Fig. 1.3

Mass I - mass of the rotor of motor and components between the motor and the elastic element.

Mass II - mass of the executive body and the elements between it and an elastic element.

These masses are connected with the elastic element with a rigidity coefficient C and, in general, ω_1 and ω_2 and φ_2 are not equal. This system can be divided into separate elements, as shown in Fig. 1.4, where the M_{12} - the torque of the elastic element, φ_1 and φ_2 - angular position.

Then the equation of motion of the individual elements of the two-mass of the whole system will be:

$$\begin{cases} M - M_{12} - M_{c1} = J \dfrac{d\omega_1}{dt} \\ M_{12} = C(\varphi_1 - \varphi_2) \\ M_{12} - M_{c2} = J_2 \dfrac{d\omega_2}{dt} \end{cases}$$

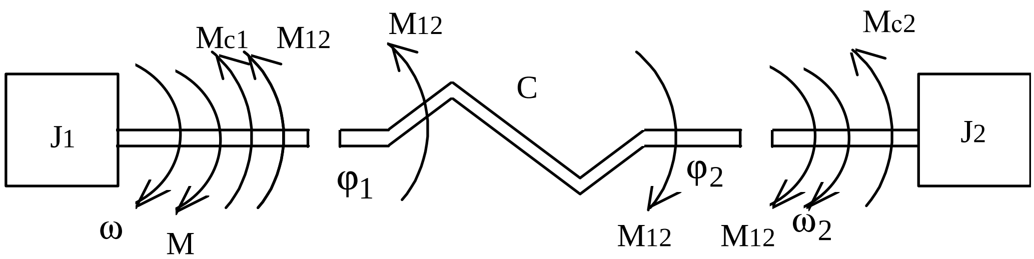


Fig. 1.4

Rewrite the system, taking:

$$\frac{d}{dt} = P; \qquad \frac{d\varphi_1}{dt} = \omega_1; \qquad \frac{d\varphi_2}{dt} = \omega_2;$$

$$\begin{cases} M - M_{12} - Mc_1 = JP\omega_1 \\ PM_{12} = C(\omega_1 - \omega_2) \\ M_{12} - Mc_2 = J_2 P\omega_2 \end{cases}$$

In these equations M_1; M_{12}; Mc_1; Mc_2; ω_1; ω_2 - variables, a C ; J_1; J_2 - parameters.

If the variables are indicated by arrows, the parameters enclosed in the frame, and for adding variables to use circles, the equation can be represented graphically by structural schemes:

$$M - M_{12} - Mc_1 = JP\omega_1$$

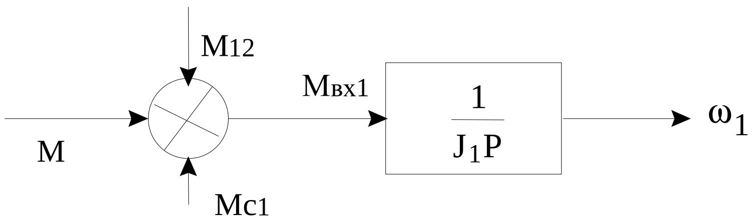


Fig. 1.5

The output variable ω_1 is calculated by multiplying the input variable

M - Mc_1 - M_{12}

on the expression in the frame $\left(\frac{1}{J_1 P}\right)$, which is called a transfer function.

Equation $M_{12} - Mc_2 = J_2 P\omega_1$ is presented by structural scheme:

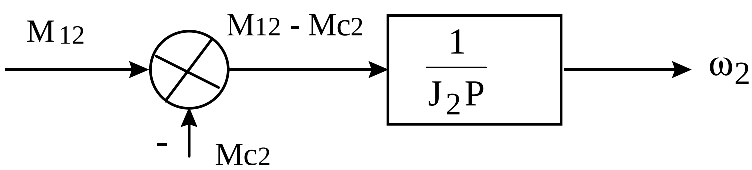


Fig. 1.6

Equation $PM_{12} = C(\omega_1 - \omega_2)$ presents by structural scheme

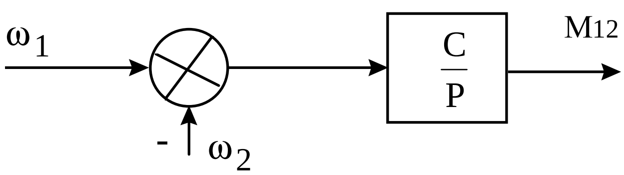


Рис. 1.7

Now combine the structural scheme of separate units in the block diagram of the system (three equations). For this node, or branching is denoted by point in the diagram; all exhaust of the node arrows corresponds the same variable. Obtain:

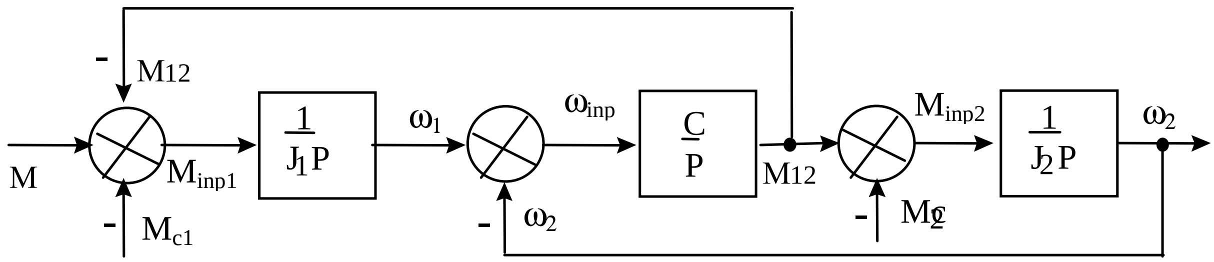


Fig. 1.8

Structural diagram of the mechanical system consists of 3 parts of integrators:

$$X_{out} = K\frac{X_{inp}}{P} \quad \text{and} \quad X_{out} = K\int X_{inp}$$

You can get a different configuration structural diagrams, solving the basic equations with respect to other values: for example, solving the equation:

$$M - M_{12} - Mc_1 = J_1 P\omega_1$$

relatively M_{12} and equation

$$pM_{12} = C(\omega_1 - \omega_2)$$

relatively ω_1, we obtain structural diagram:

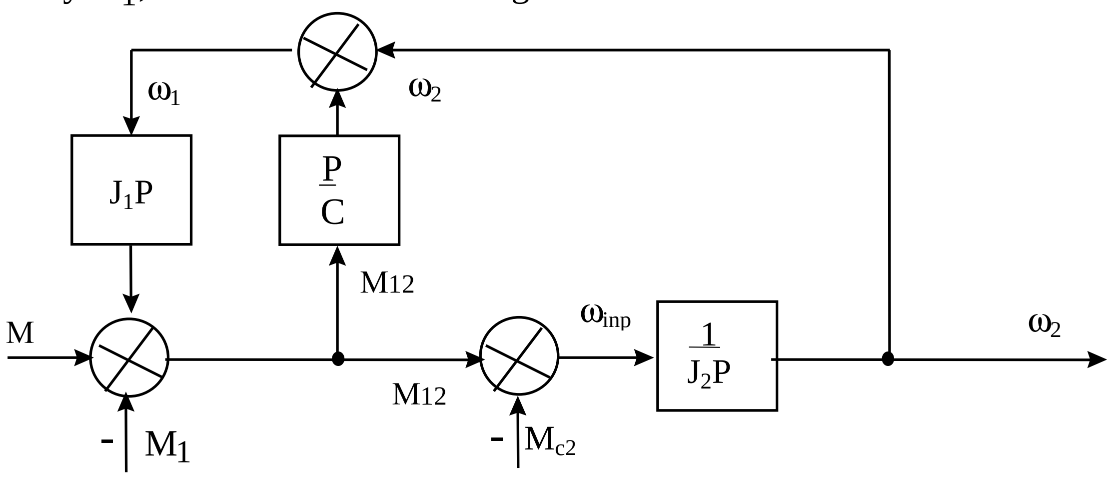


Fig. 1.9

If the input is considered M_1, M_{C1}, M_{C2}, and the M_{12} exit, then structural scheme:

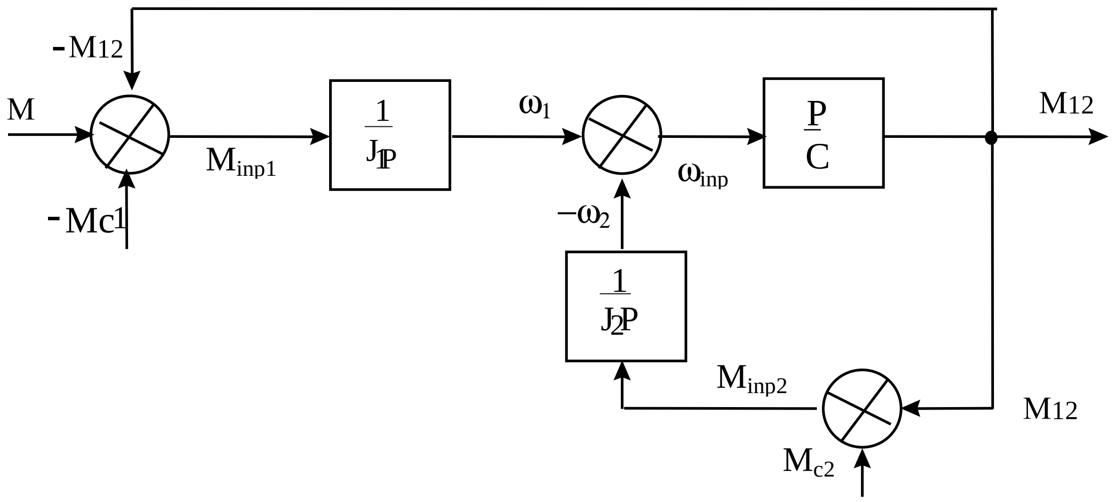


Fig. 1.10

The transfer functions of links - the expression in rectangular framework for structural schemes are defined:

$$\omega_1(P)=\frac{1}{J_1P}=\frac{\omega_1(P)}{M_{inp1}(P)},$$

$$\omega_2(P)=\frac{C}{P}=\frac{M_{12}(P)}{\omega_{inp}(P)},$$

$$\omega_3(P)=\frac{1}{J_2P}=\frac{\omega_2(P)}{M_{inp2}(P)}.$$

Three-mass system is obtained taking into account the 2-elastic elements or clearances between elements are taken into account (the calculations are carried out on a computer).

Reducing clearance is carried out on the following rules:

1) For an element to the rotational motion and angular clearance δ_1 (rad) reduced value of clearance δ is determined by: $\delta_1 \cdot i_1$ (rad).

2) For an element with translational or linear motion a clearance δ_2 (m) is the reduced value clearance: $\delta = \delta_2 / \rho$ (rad).

1.3 The steady movement of the drive

In this mode ω = const, M_{dyn} = 0, so the condition of steady motion can be formulated as follows: motor torque is equal for given the load torque M = Mc.

Checking this condition is carried out on the mechanical characteristics of the motor and the executive body. Mechanical characteristics are called dependence $\omega = f(M)$ for rotary motion and $V = f(F)$ - for translational.

Mechanical characteristics of the motor may be natural (produced at nominal motor operation $U = U_n$) and artificial (adjusting) obtained by $U \neq U_n$.

Fig. 1.11 presents naturally mechanical characteristics of different types of motors:

1) direct current motor (DCM) of separate excitation;
2) DCM of series excitation;
3) induction motor;
4) synchronous motor;
5) DCM compound excitation with subtractive polarity;
6) DCM which powered by source of current .

Fig. 1.12 presents the mechanical characteristics of $\omega_{ed} = f(M_{ed})$ the executive devices of different mechanisms:

1) lifting-gears Mc = const (active torques);
2) machinery conveyors, transfers, feed machinery, movement of cranes, the torque of resistance which is caused by the friction forces (reactive torques);
3) fans, compressors and pumps (ventilatory);
4) mechanisms of the main motion lathes and milling machines, winding and rewinding devices.

The steepness of the mechanical characteristics of the motor is characterized by rigidity:

$$\beta = \frac{dM}{d\omega} = \frac{\Delta M}{\Delta\omega} .$$

From Fig. 1.11 implies that the characteristic 4 (synchronous motor) is absolutely rigid $\beta = \infty$; characteristic 1 (direct current motor ыузфкфеу excitation) is rigid $\beta < 0$; characteristic 2 (direct current motor of series excitation) - soft $\beta \ll 0$; characteristic 3 (IM) has variable-rate: in the work area is negative rigidity $\beta < 0$; at the inflection $\beta = 0$, then $\beta > 0$.

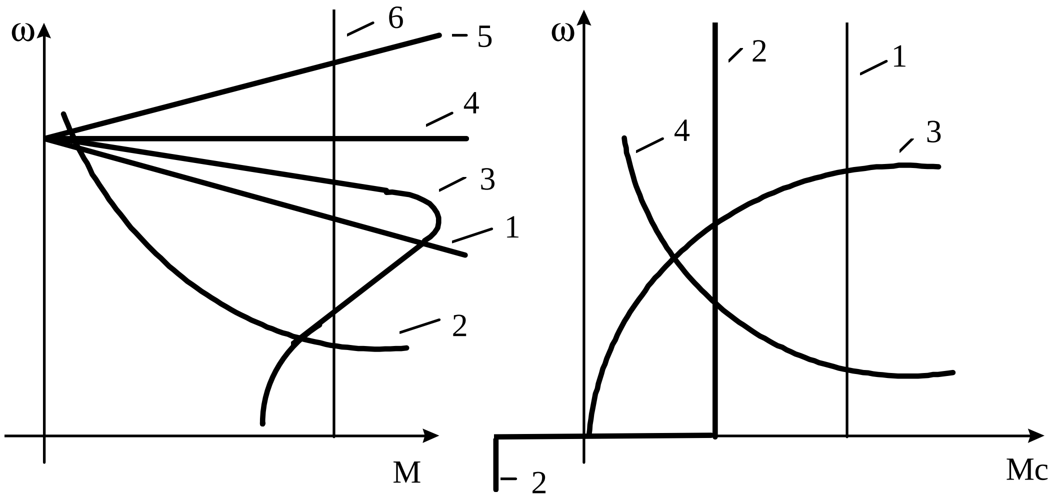


Fig. 1.11 Fig. 1.12

To determine the condition of steady motion it is necessary to correlate the mechanical characteristics of the motor and drive M = f(ω) and M_c = f(ω) (Fig. 1.13).

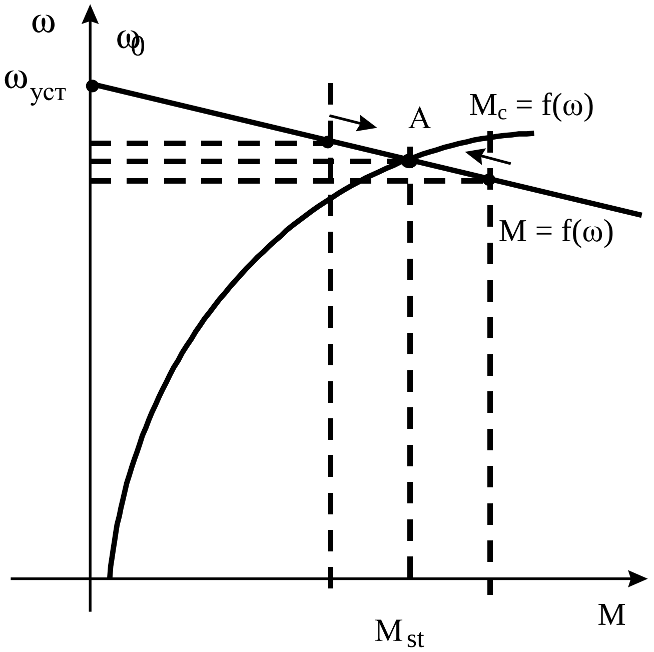


Fig.1.13

Point A, in which M = M_c - the point of the steady motion.

Stable is a steady motion, which, being derived from the steady-state returns to him again.

Fig. 1.14 presents the mechanical characteristics of the induction motor and the mechanism having M_c = const. At points 1 and 2 motor torque is equal to the torque of resistance, that is, there is a steady motion. Let's check the stability of the mode. If at point 1 speed $\omega_{1\,уст}$ increases, then motor torque will be less than M_c, the negative dynamic torque will be appear $M_{dyn} = J\frac{dw}{dt}$ and the drive will decelerate to a speed ω_{1st}. With a decrease ω_{1st} $M_1 > M_c$ positive torque M_{dyn} appears, which will increase the speed to ω_{1st}. Consequently, the point 1 - point of stable motion. If the speed ω_{2st} at point 2 is increased, then $M_{motor} > M_c$, occurrence of positive M_{dyn} will further increase the speed to the point of curve flection. With a decrease of the ω_{2st} there is a negative M_{dyn}, which will further reduce the speed to zero. Consequently, the point 2 - point of unstable motion.

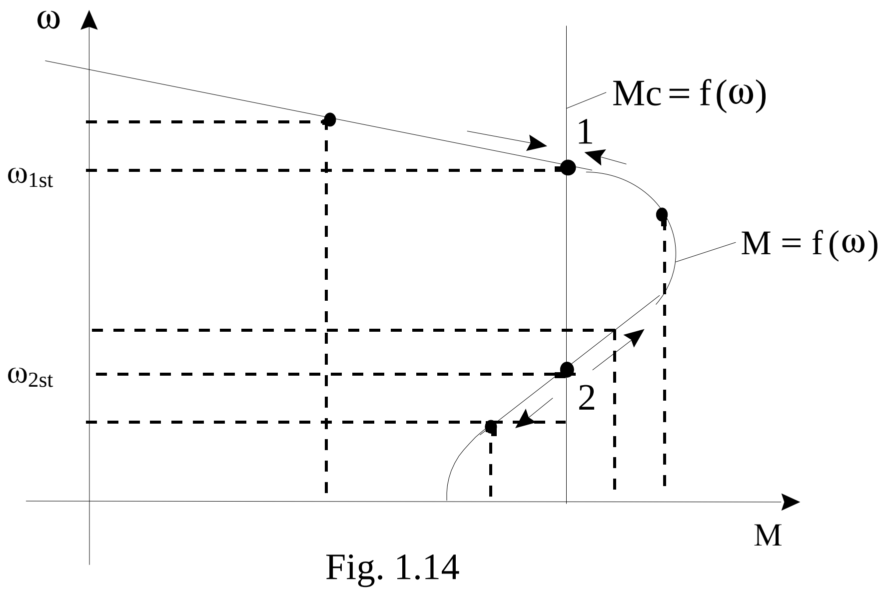


Fig. 1.14

Thus, the stability condition can be expressed by the inequalities:

$$\frac{\Delta M_{dyn}}{\Delta\omega} < 0 \quad \text{or} \qquad \beta - \beta_c < 0\,, \quad \text{or} \qquad \beta < \beta_c\,.$$

1.4 Unsteady motion of drive

The condition unsteady motion is the presence of dynamic torque $M_{dyn} \neq 0$, which can be constant or random depending on the speed. Unsteady motion is a transient process electric drive, so its analysis is necessary to determine the transition time of process and dependence of the torque, the speed and position of the motor shaft from time to time.

1.4.1. Consider the unsteady movement of the drive at a constant dynamic torque (M_{dyn} = const; M - M_c = const). Assume set the mechanical characteristics of the motor powered by a current source, and the executive lifting mechanism:

$$\omega = f(M) \qquad \text{or} \qquad \omega = f(M_c),$$

presented at Fig. 1.15, which correspond to M_{dyn} = M - M_C = const.

The basic equation

$$M - Mc = J\frac{d\omega}{dt},$$

Whence $\qquad d\omega = \frac{M - Mc}{J}dt. \qquad$ If M - Mc = const, then

$$\omega = \frac{M - Mc}{J}t + C_1.$$

The integration constant C_1 is determined by the initial conditions:

$$\text{if} \qquad t = 0 \qquad \omega = \omega_{init}$$

$C_1 = \omega_{init}$, then

$$\omega = \frac{M - M_c}{J} t + \omega_{init}. \qquad (1.20)$$

Therefore, the speed is a linear function of time. Transient-process time t_{tt} determined:

$$t_{tt} = \frac{J(\omega_{fin} - \omega_{init})}{M - Mc}, \qquad (1.21)$$

Integrating the speed of expression, we obtain

$$\varphi = \int \omega dt = \frac{M - Mc}{J} \int t dt + \omega_{init} \int dt,$$

$$\varphi = \frac{M - Mc}{J} \cdot \frac{t^2}{2} + \omega_{init} t + C_2.$$

Constant of integration C_2 determined from two initial conditions:
at $t = 0$, $\varphi = \varphi_{init}$, whence $C_2 = \varphi_{init}$, then:

$$\varphi = \frac{M - Mc}{J} \cdot \frac{t^2}{2} + \omega_{int} t + \omega_{int}. \qquad (1.22)$$

The dependence $\varphi = f(t)$ has a parabolic character. Fig. 1.16 shows the dependence:

$$\omega = f(t); \qquad M = f(t); \qquad \varphi = f(t).$$

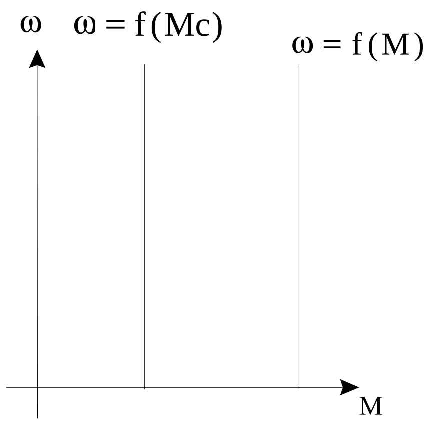


Fig. 1.15

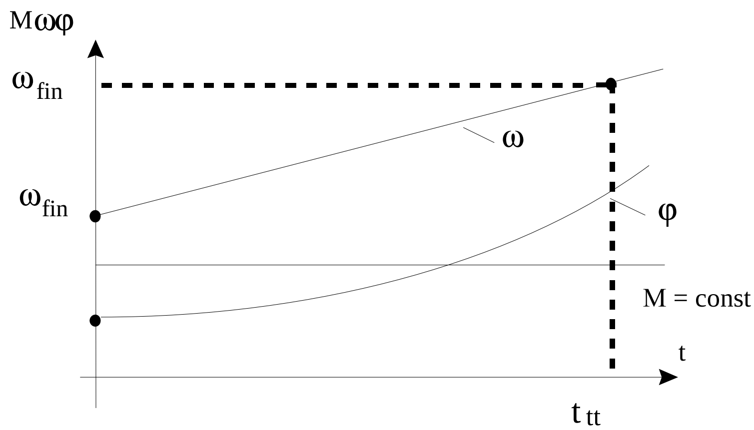


Fig. 1.16

1.4.2 Unsteady drive motion for linear dependence torque motor and torque mechanism on the drive speed.

The equation of the mechanical characteristics of the motor and the mechanism have the form:

$$M = M_{SC} - \beta\omega,$$

$$Mc = Mc_0 + \beta_c \omega.$$

Fig. 1.17 presents mechanical characteristics of the motor and mechanism.

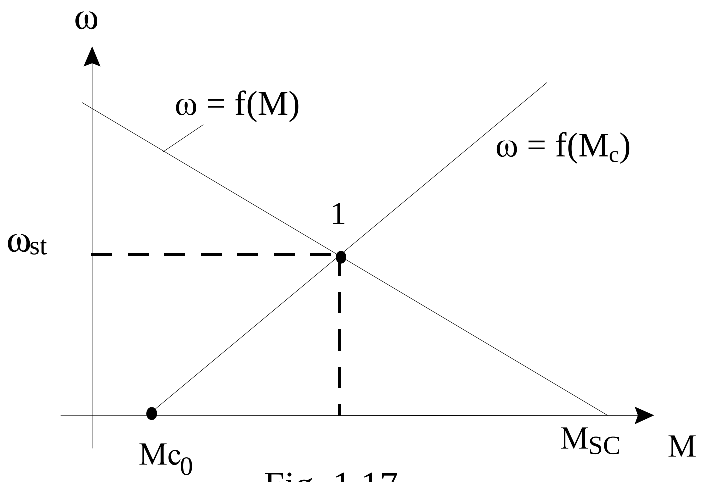


Fig. 1.17

Expressing M or Mc via ω, get:

$$J\frac{d\omega}{dt}+(\beta+\beta_c)\cdot\omega=M_{SC}-Mc_0.$$

Dividing by $(\beta+\beta_c)$ get:

$$T_M\frac{d\omega}{dt}+\omega=\omega_{st},$$

where $T_M=\dfrac{J}{\beta+\beta_c}$ – electro-mechanical time constant of the transition process;

$\omega_{st}=\dfrac{M_{SC}-Mc_0}{\beta+\beta_c}$ – steady speed of motion.

The solution of inhomogeneous differential equation is the sum of the general solution of the homogeneous linear equation (free component of the movement).

$$T_M\frac{d\omega}{dt}+\omega=0,$$

and a particular solution of the inhomogeneous equation (compulsory component of the motion):

$$\omega=\omega_{free}+\omega_{comp}.$$

Free component of speed is determined by:

$$\omega_{free}=Ae^{-\frac{t}{T_M}}, \tag{1.23}$$

Forcing component is found from the condition $\dfrac{d\omega}{dt}=0$ in equation:

$$T_M \frac{d\omega}{dt} + \omega = \omega_{st},$$

then $\omega_{comp} = \omega_{st}$.

In general, the solution has the form:

$$\omega = \omega_{st} + Ae^{-\frac{t}{T_M}}. \quad (1.24)$$

A constant A finding in the initial conditions: at t = 0, $\omega = \omega_{init}$, $A = \omega_{init} - \omega_{st}$.

Then:

$$\omega = (\omega_{init} - \omega_{st})e^{-\frac{t}{T_M}} + \omega_{st} \quad (1.25)$$

Since M and ω are linear, then:

$$M = (M_n - M_{st})e^{-\frac{t}{T_M}} + M_{st}. \quad (1.26)$$

Differentiating equation $d\varphi = \omega(t)dt$, obtain dependence the angle of rotation on the time and speed:

$$\varphi = \varphi_n + T_M(\omega_{init} - \omega_{st})(1 - e^{-\frac{t}{T_M}}) + \omega_{st} \cdot t. \quad (1.27)$$

Transient time - the time of speed change or torque from the initial value to ω_i or M_i:

$$t_{tt} = T_M \ln\frac{\omega_{st} - \omega_0}{\omega_{st} - \omega_i} = T_M \ln\frac{M_0 - M_{st}}{M_i - M_{st}}. \quad (1.28)$$

Idealized mechanical motor characteristic (rectangular) defines the run-up to the motor idling ω_0 at $M = M_{SC}$; $\omega_{init} = 0$. (Fig. 1.18):

$$t_{tt} = t_{acc} = \frac{J\omega_0}{M_{SC}} = T_M. \quad (1.29)$$

Therefore, T_M is numerically equal to the run-time the motor without load to the idle speed under the action of torque M_{SC}. T_M can determined if it draw a tangent to the speed or torque $\omega = f(t)$ or $M = f(t)$ at point t = 0.

Dependence $\omega = f(t)$ and $M = f(t)$ are presented in fig. 1.19.

The transient time is 3-4 T_M.

1.4.3 If random time dependce the dynamic mechanical caracteristics on the speed the $\omega = f(M)$ or $\omega = f(Mc)$ must be given by analytic expressions. To determine the dependencies $M = f(t)$; $\omega = f(t)$; $\varphi = f(t)$ it is necessary integrate the data of expression.

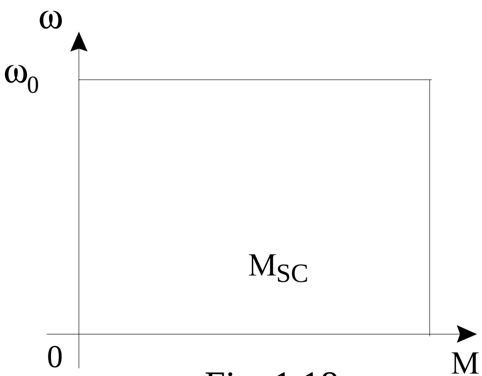


Fig. 1.18

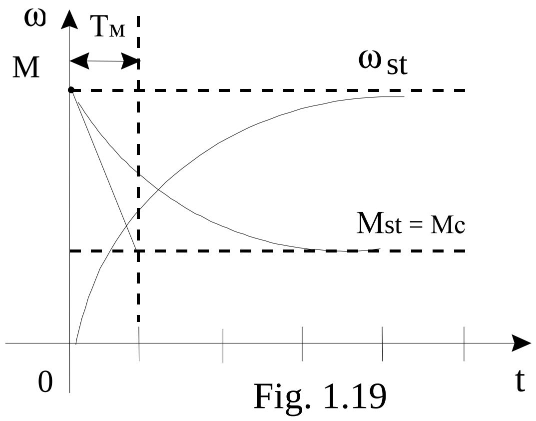


Fig. 1.19

If the exact solution is not possible, use the approximate methods of integration: graph-analytic or numerical. When using numerical methods (the methods of Euler, Runge-Kutta), the derivatives are replaced by increments (Fig. 1.20) and with given mechanical properties $\omega = f(M)$ or $\omega = f(Mc)$ the values:

$$\omega_1 = \Delta\omega_1; \quad \omega_2 = \omega_1 + \Delta\omega_2; \quad \omega_i = \omega_{i-1} + \Delta\omega_i,$$

for which the calculated $\Delta t_1;\ \Delta t_2;\ \Delta t_i$ on expression:

$$\Delta t = \frac{J\Delta\omega}{M - Mc}.$$

Fig. 1.20 presents the mechanical characteristics ω = f(M) or ω = f_1(Mc) and dependence of transition process ω = f(t) or M = f(t).

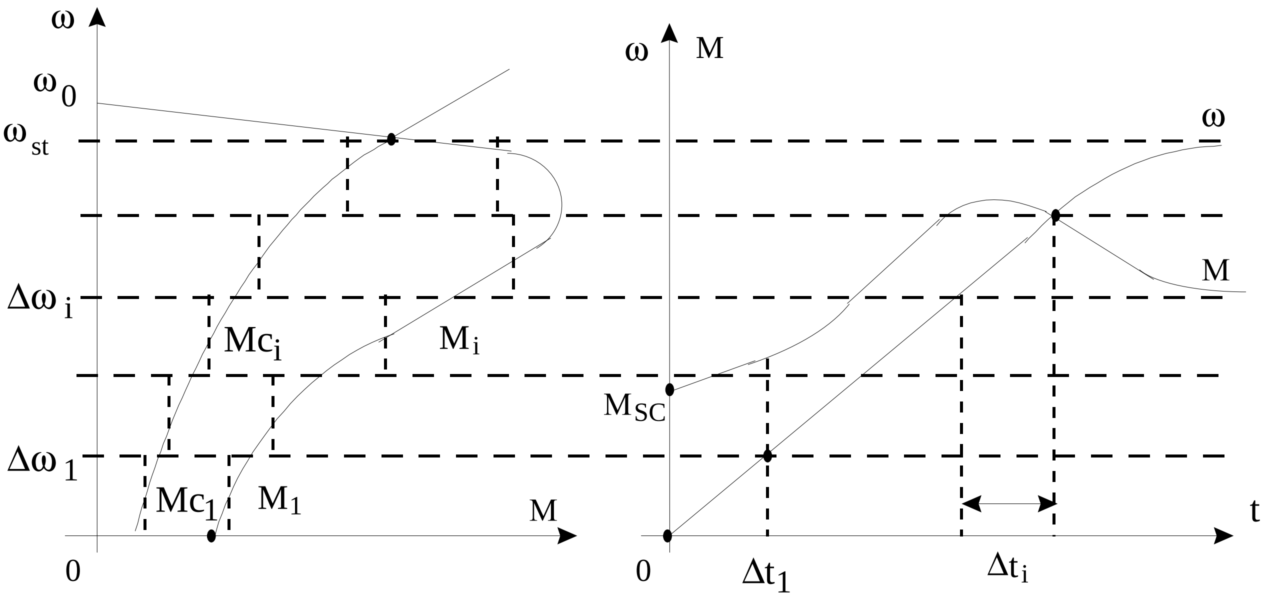


Fig. 1.20

1.4.3 Optimization of gear ratios

The optimal value of the gear ratio i_g allows you to get the greatest acceleration or deceleration of the drive, which improves the performance of working machines. In the case of M_c = const and $\eta_{gear} = 1$ equation of motion of the drive:

$$M \cdot i_g - M_{ed} = \left(J_m i_g^2 + J_{ed}\right) \cdot \frac{d\omega_{ed}}{dt},$$

where: M_{ed} – torque of executive device, J_m - inertia moment of motor, J_{ed} - inertia moment of executive device,

whence:

$$\frac{d\omega_{ed}}{dt} = \varepsilon_{ed} = \frac{M i_g - M_{ed}}{J_m i_g^2 + J_{ed}},$$

ε_{ed} - acceleration of the executive device should be the maximum, take the derivative and equate it to zero (finding the max of the function), and then convert:

$$i_{g.opt} = \frac{M_{ed}}{M} + \sqrt{\left(\frac{M_{ed}}{M}\right)^2 + \frac{J_{ed}}{J_m}}. \qquad (1.30)$$

This expression is valid for a maximum deceleration of the executive device. While ensuring maximum deceleration and acceleration is much more difficult to obtain $i_{g.opt}$.

Provided $M_{ed} = 0$:

$$i_{g.opt} = \sqrt{\frac{J_{ed}}{J_m}}. \qquad (1.31)$$

Optimization i_g can be done not only to the maximum ε_{ed}, but also from the ratio of the rates specified conditions, the maximum path executive device or a minimum time to complete a given path.

1.5 Principles of construction automated electric drive

1.5.1 Regulation of the coordinates of electric drive

The mechanical part of electric drive in the form of a block diagram have form:

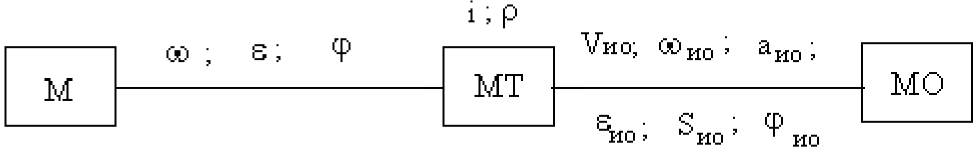


Fig. 1.21

Typically, on conditions the process by the angular ω_{ed} or linear velocity V_{ed} are regulated:

$$\omega_{ed} = \frac{\omega}{i}; \qquad V_{ed} = \omega\rho,$$

where i - reduction ratio of MT;

ρ - reduction radius of MT.

Speed regulation can be in the following ways:

a) the regulation i or ρ at ω = const , (mechanical way: transmission gear, variators);

б) the regulation ω at i, ρ = const, (electric way);

c) the combined method.

Regulation of linear $a_{ио}$ or angular ε_{ed} acceleration, linear S_{ed} or angular φ_{ed} position of executive device $a_{ed} = \rho \cdot \varepsilon$; $\varepsilon_{ed} = \frac{\varepsilon}{i}$; $S_{ed} = \rho \cdot \varphi$; $\varphi_{ed} = \frac{\varphi}{i}$ called regulation of coordinates.

For motor control current, voltage, flow control is also called regulation of variables or the coordinates of motor. Sometimes required to get simultaneously regulation the speed, acceleration and position of the executive device (for example, when moving the elevator).

1.5.2. Speed regulation of electric drives, as well as maintaining speed at a given level can be done in two ways:

a) parametric (changing the parameters of the circuit switching resistors, capacitors, inductors);

b) in closed loop system (changing by supplied voltage or frequency, or both simultaneously by the transducers).

Speed regulation is characterized by the following parameters:

– control range (from one to 10, 000)

$$D = \frac{\omega_{max}}{\omega_{min}};$$

– control direction - up from the basic, down from core speed or two-zone regulation;

– smoothness of the speed regulation - speed ratio for the next two characteristics $K_{smooth} = \frac{\omega_i}{\omega_{i-1}}$;

– rate stability is characterized by its change by the changing the load on the shaft;

– economy of speed regulation is characterized by a capital costs, as well as η, $\cos\varphi$;

$$\eta = \frac{P_2}{P_2 + \Delta P'} ,$$

where P_2 - useful power on the shaft ;

$P_1 = P_2 + \Delta P'$ - input power.

When the regulation is determined the weight-average η_{av}, $\mathrm{Cos}\varphi_{av}$ for adjusting the cycle:

$$\eta_{av} = \sum_{7}^{n} P_{2i} \cdot t_i \,/\, \sum_{1}^{n} (P_{2i} + \Delta P_i) t_i ,$$

$$\mathrm{Cos}\varphi_{av} = \sum_{1}^{n} P_i t_i \,/\, \sum_{1}^{n} \sqrt{P_i^2 + Q_i^2} \cdot t_i ,$$

where n - number of speeds.

1.5.3 Regulation of current and torque motors

Regulation of speed by varying the torque or force electric drive by changing the current of the motor armature.

Current limit and torque motors is made due to overload in the stop mode of the actuator in short circuit mode.

Current regulation and torque. Parametric methods (resistors) does not provide the accuracy and efficiency. In closed systems, at the introduction of feedback of current achieved a high accuracy, efficiency and ability to provide the vertical site ofmechanical characteristics.

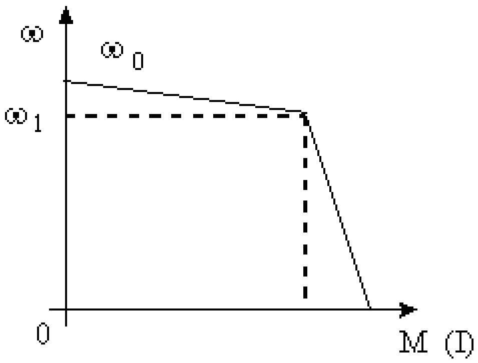


Fig. 1.22

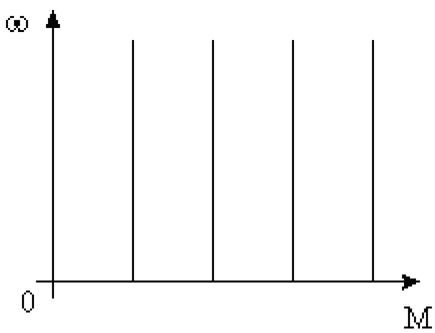


Fig. 1.23

According to this characteristic (Fig. 1.22) is provided the current regulation and torque in range changing speed from 0 до ω_1.

Supply the motor from the power converters with the properties of the current source provides vertical mechanical properties (Figure 1.23). The current source has a constant time at every step when the speed is changing (vertical characteristics in a wide range).

1.5.4 Adjusting the position of electric drive

Adjusting the position of the executive body in space - positioning - is used in the feed mechanism of machine tools, lifting-and-shifting machines, robots, manipulators, plotters. The main requirement - high accuracy. In open-loop control motor drives regulation is executed by means of limit switches, position switch (lifts, etc.).

For high accuracy of the position control, for example, when testing printed circuit boards, microprocessor unit, etc. is used electric drive with electric position feedback. It is used for tracking and program-controlled drives.

1.6 Principles of construction the control systems of the electric drives

Motion control is carried by control system, which has a converter (power) and the control unit. Control systems: manual and automated, in the latter operator gives a command only at the beginning and end of the workand, the whole process is provided by the control system.

At the open-loop control (Figure 1.24) setting signal X_{def} determines output signal level X_{out}. X_{dist} – disturbance action determined by interference (voltage fluctuations, emergency, the load of the drive. X_{dist} influence reflected on X_{out}, ie X_{out} dependent on external perturbations, which is the basic drawback of open-loop system.

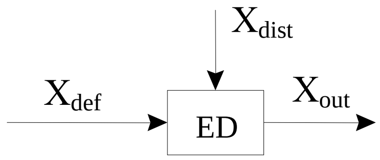


Fig. 1.24

Closed systems allow to eliminate the influence of external disturbances on the output value. They can be constructed on the principle of feedback (Fig. 1.25). X_{fb} signal proportional X_{out} is input to the electric drive, compared with X_{def} and the resulting signal X. The error signal or rejection is input control signal to the drive.

If the speed electic drive (ED) X_{out} of the load changed, then changed X that lead to the restoration speed.

<u>Feedback (FB)</u> can be positive when X_{fb} is directed according to the X_{def} and negative (X_{oc} back-to-back X_{def}). Tough FB - signal operates in steady-state and transient conditions. Flexible FB - the signal is only operate under transient conditions. Linear FB described by linear equations, nonlinear FB - Non-linear.

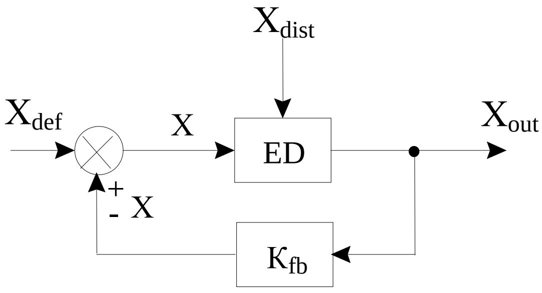


Fig. 1.25

Feedback can be for speed, position, current, voltage. Feedbacks on torque and effort reporting are rarely used, since sensors of these variables are complex. Closed systems may be constructed on the principle of compensation for disturbance (Figure 1.26). The input signal X_{inp}, proportional X_{dist} is fed into the system along with X_{def}, the resulting signal X controls the ED, compensating for the disturbance. It is used less often as sophisticated load sensors.

Combined control system using both principles (Fig. 1.27).

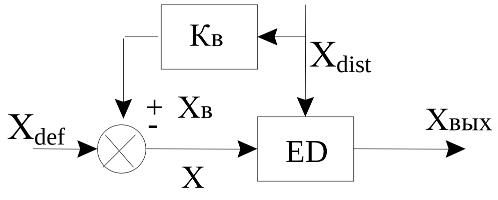


Fig. 1.26

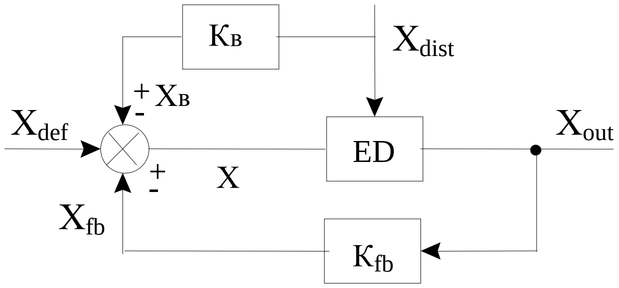


Fig. 1.27

The greatest application gets a closed system with feedback.

In the management of several coordinates ED (speed, position - a way, acceleration, current, voltage) circuits are used:

a) with a total amplifier (A) (Fig. 1.28), where EC - electrical converter X_{fb1}, X_{fb2}, X_{fb3} – feedback signals in different coordinates. The main disadvantage of the scheme: it can not regulate the coordinates independently of each other; EPM - electric part of motor; MPM - mechanical part of motor.

b) in a scheme with general amplifier and nonlinear feedback effect of feedback is split (Figure 1.29).

Nonlinearity of the feedback provided by the additional signals cutoff (X_{COFF_1}, X_{COFF_2} , X_{COFF_3}) and valve elements. Disadvantage - independent adjustment of all the coordinates can not be done.

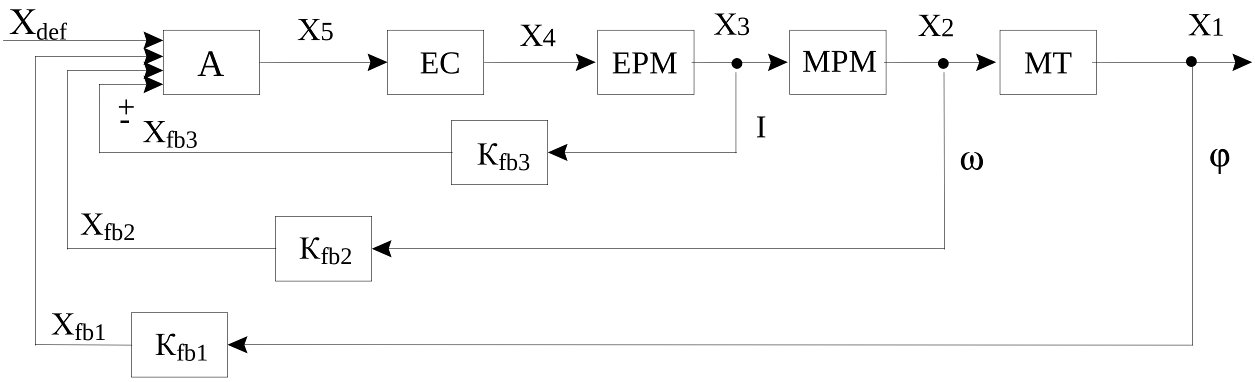


Fig. 1.28

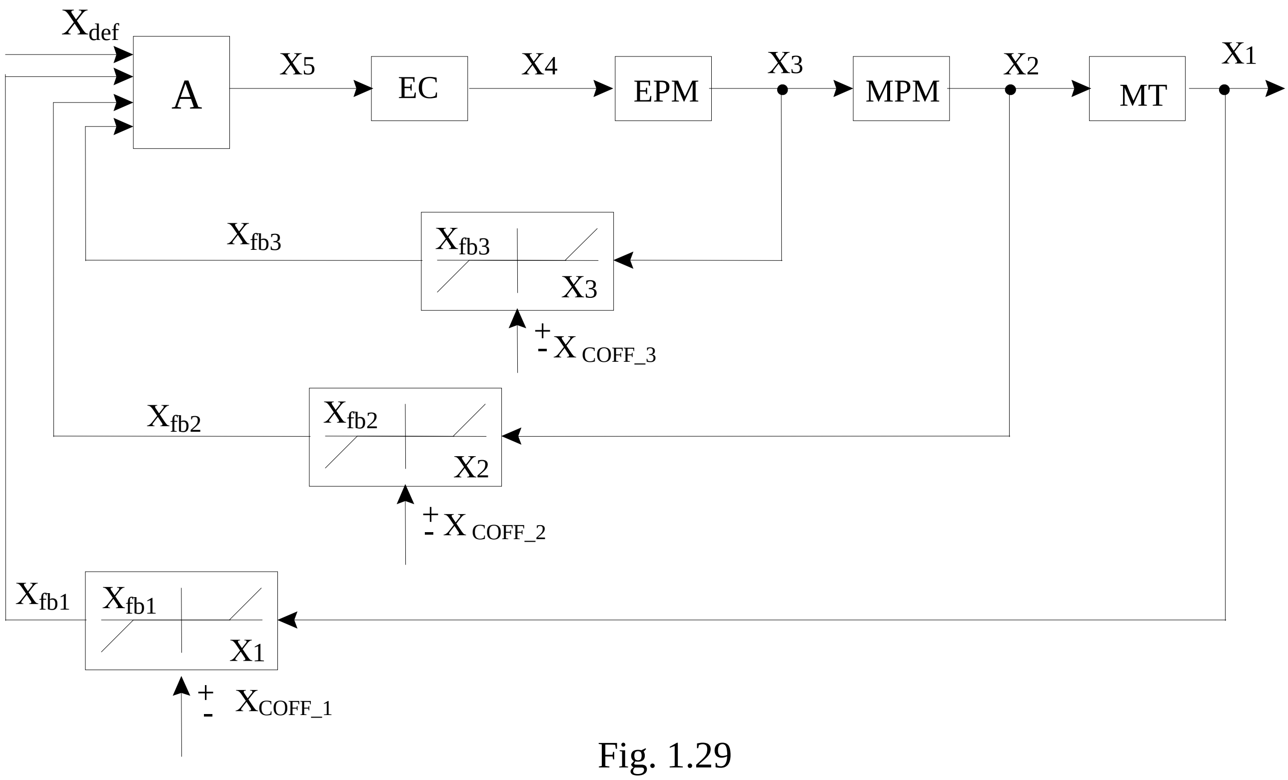


Fig. 1.29

This disadvantage is devoid the scheme of slave coordinate control with consistent correction (Figure 1.30). Here the output of the outer loop is defining signal of the inner loop, that is, each internal submitted to its external circuit. X_3 - loop current and torque; X_2 - the speed loop, X_1 - the position loop.

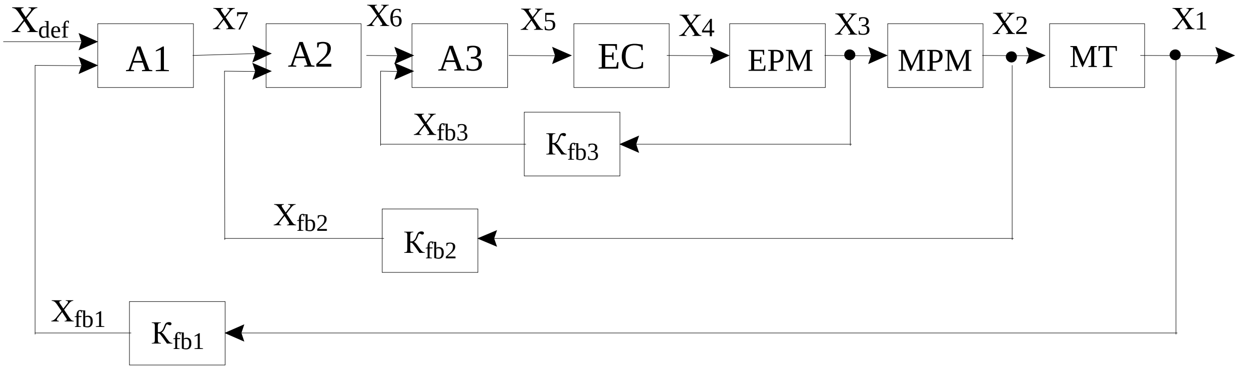

X_def
A1
X7
A2
X6
A3
X5
EC
X4
EPM
X3
MPM
X2
MT
X1
X_fb3
K_fb3
X_fb2
K_fb2
X_fb1
K_fb1

Fig. 1.30

2 ELECTRIC DRIVES WITH DC MOTOR

2.1 The generalized electric machine

Electromechanical converter EMC in the motor drive system is regarded as an idealized electric motor having n pairs of electrical terminals and a pair of mechanical pins in the form of electro-mechanical multi-pole (Fig. 2.1) with the input variables (U_1, i_1, U_2 , U_n , i_2 , i_n) and output variables (M, ω).

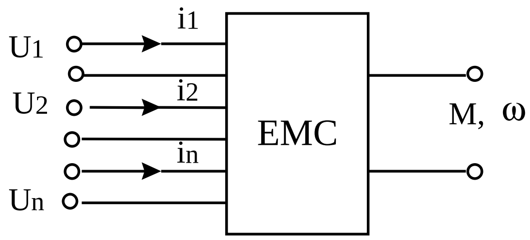


Fig. 2.1

When using polyphase motors it is considered several inputs corresponding to the number of phases. Any multiphase electric machine with n-phase stator winding and the m-phase rotor winding can be a two-phase model, if the equality of the impedances of stator and rotor phase. Such a machine is called a generalized electrical machine, which is a simplified model of the real, as the following assumptions: the distribution of winding is complete, the absence of non-sinusoidal magnetomotive force, no air gap eccentricity, the magnetic circuit is unsaturated, and the influence of the saliency accounted for by introducing a variable radial magnetic permeability:

$$\mu_{rad} = \mu - \Delta\mu = \mu - \Delta\mu_{max}\cos 2\varphi_{el}$$

$$\varphi_{el} = P_n \varphi \ ,$$

where φ_{el} - electric, φ - geometric rotation angle of the rotor relative to the stator, P_n - the number of pairs of poles.

Then the scheme of generalized two-pole machines can be represented (Fig. 2.2), where the coordinate system for the stator: α, β, the rotor: d, q.

Generalized machine in dynamic mode is described by the system of equations in accordance with the second law of Kirchhoff:

$$
\begin{cases}
U_{1\alpha} = R_1 i_{1\alpha} + d\psi_{1\alpha} / dt; \\
U_{1\beta} = R_1 i_{1\beta} + d\psi_{1\beta} / dt; \\
U_{2d} = R_2 i_{2d} + d\psi_{2d} / dt; \\
U_{2q} = R_2 i_{2q} + d\psi_{2q} / dt; \\
M = \frac{1}{2} \cdot \frac{d}{dt} \sum_{i=1\alpha}^{2q} i_i \psi_i ,
\end{cases}
\tag{2.1}
$$

where $\psi_{1\alpha}$, $\psi_{1\beta}$; ψ_{2d} ; ψ_{2q} ; $i_{1\alpha}$; $i_{1\beta}$; i_{2d} ; i_{2q} - currents and the flux linkages of stator and rotor windings along the corresponding axes, which are determined by:

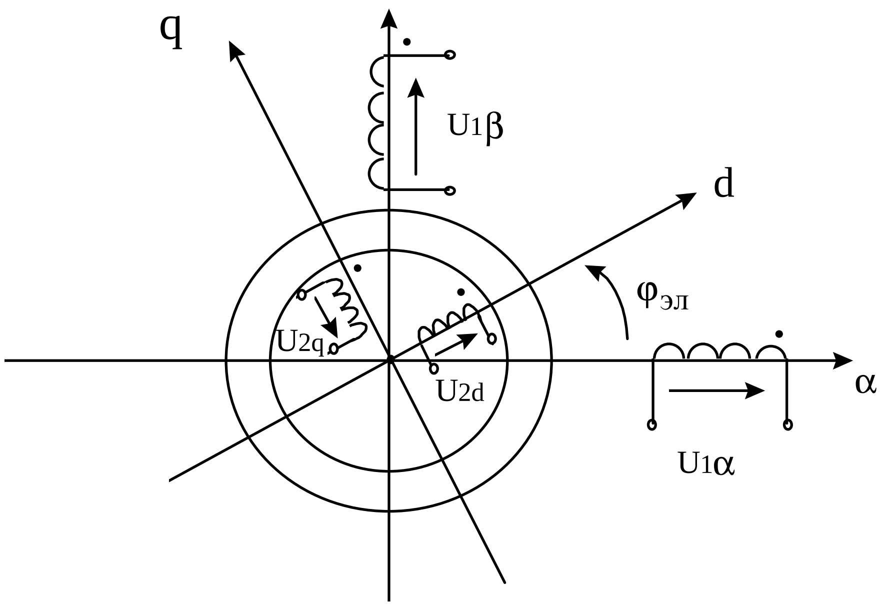


Fig. 2.2.

$$
\begin{aligned}
\psi_{1\alpha} &= L_{1\alpha 1\alpha} \cdot i_{1\alpha} + L_{1\alpha 1\beta} \cdot i_{1\beta} + L_{1\alpha 2d} \cdot i_{2d} + L_{1\alpha 2q} \cdot i_{2q} ; \\
\psi_{1\beta} &= L_{1\beta 1\alpha} \cdot i_{1\alpha} + L_{1\beta 1\beta} \cdot i_{1\beta} + L_{1\beta 2d} \cdot i_{2d} + L_{1\beta 2q} \cdot i_{2q} ; \\
\psi_{2d} &= L_{2d1\alpha} \cdot i_{1\alpha} + L_{2d1\beta} \cdot i_{1\beta} + L_{2d2d} \cdot i_{2d} + L_{2d2q} \cdot i_{2q} ; \\
\psi_{2q} &= L_{2q1\alpha} \cdot i_{1\alpha} + L_{2q1\beta} \cdot i_{1\beta} + L_{2q2d} \cdot i_{2d} + L_{2q2q} \cdot i_{2q}
\end{aligned}
$$

or in the general form:

$$
\psi_i = \sum_{j=1\alpha}^{2q} L_{ij} \cdot i_j , \tag{2.2}
$$

where L_{ij} - inductances of the corresponding windings.

The relative position of stator and rotor changes, therefore

$$L_{ij} = f(\varphi_{el}),$$

while the self-inductance of the windings are:

$$L_{1\alpha 1\alpha} = L_{1\beta 1\beta} = L_1 = const,$$

$$L_{2d2d} = L_{2q2q} = L_2 = const.$$

The mutual inductance between the stator and rotor windings are equal to 0 because $\alpha_{el} = 90^0$,

$$L_{1\alpha 1\beta} = L_{1\beta 1\alpha} = L_{2d2q} = L_{2q2d} = 0.$$

The mutual inductances of stator and rotor depend on $\varphi_{эл}$ that varies from 0 to 2π:

$$L_{1\alpha 2d} = L_{2d1\alpha} = L_{12}Cos\varphi_{el};$$

$$L_{1\alpha 2q} = L_{2q1\alpha} = L_{12}Cos(\varphi_{el} + 90^0) = -L_{12}Sin\varphi_{el};$$

$$L_{1\beta 2q} = L_{2q1\beta} = L_{12}Cos\varphi_{el};$$

$$L_{1\beta 2d} = L_{2d1\beta} = L_{12}Sin\varphi_{el}.$$

So, the equation of electric equilibrium of the generalized machine is expressed by the:

$$U_i = R_i i_i + \frac{d}{dt}\sum_{j=1\alpha}^{2q} L_{i,j} \cdot i_i. \tag{2.3}$$

The differential equation of electromechanical energy conversion is of the form:

$$M = \frac{1}{2}\sum_{i=1\alpha}^{2q} \frac{dL_{i,j}}{d\varphi} \cdot i_j \cdot \sum_{i=1\alpha}^{2q} i_i. \tag{2.4}$$

After the conversion, entering depending on time and differentiating, if $\omega = \frac{d\varphi}{dt}$, when get:

$$U_i = R_i i_i + \sum_{j=1\alpha}^{2q} L_{i,j}\frac{di_j}{dt} + \omega \sum_{j=1\alpha}^{2q} \frac{dL_{i,j}}{d\varphi} i_j, \tag{2.5}$$

where $\omega \sum_{j=1\alpha}^{2q} \frac{dL_{i,j}}{d\varphi} i_j = e_i$,

e_i - resultant electromotive force induced in the winding by a mechanical movement of the rotor,

$R_i i_i$ - voltage drop on the active circuit resistance of each winding,

$\sum\limits_{j=1\alpha}^{2q} L_{i,j}\dfrac{di_j}{dt}$ - the resultant EMF of self-induction and mutual induction caused by varying the current in the windings.

Therefore, the currents in the windings and the electromagnetic torque of the machine depend on the speed ω. Dependencies $\omega = f(i_i)$ and $\omega = f(M)$ are called electromechanical and mechanical characteristics, and the equations:

$$\begin{cases} U_i = R_i i_i + \sum\limits_{j=1\alpha}^{2q} L_{i,j}\dfrac{di_j}{dt} + \omega \sum\limits_{j=1\alpha}^{2q} \dfrac{dL_{i,j}}{d\varphi}\cdot i_j; \\ M = \dfrac{1}{2}\sum\limits_{j=1\alpha}^{2q} i_i \cdot \sum\limits_{j=1\alpha}^{2q} \dfrac{dL_{i,j}}{d\varphi}\cdot i_i; \end{cases} \tag{2.6}$$

called the equations of electro-mechanical and mechanical characteristics in the dynamic mode of the drive.

2.2 DC motor in the form of generalized machine

DC motor with separate excitation (DCM) can be represented by a two-phase model of generalized machine (Fig. 2.3), and is described by equations (2.7):

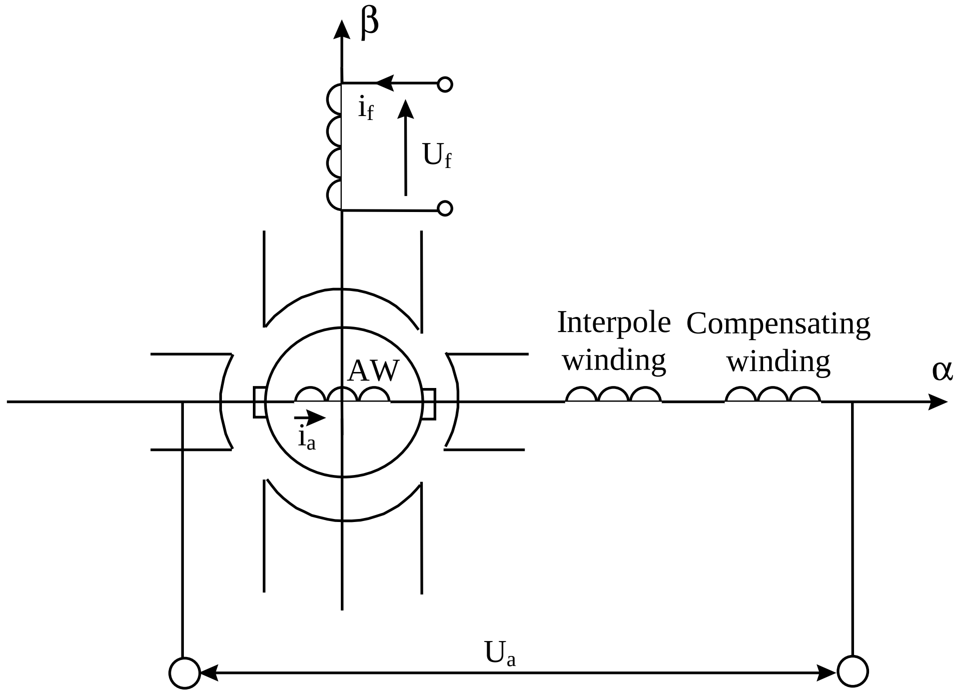


Fig. 2.3

$$\begin{cases} U_{1\alpha} = i_{1\alpha}R_1 + d\psi_{1\alpha} / dt; \\ U_{1\beta} = i_{1\beta}R_1 + d\psi_{1\beta} / dt; \\ U_{2\alpha} = i_{2\alpha}R_2 + d\psi_{2\alpha} / dt + \omega \cdot \psi_{2\beta}; \\ U_{2\beta} = i_{2\beta}R_2 + d\psi_{2\beta} / dt - \omega \cdot \psi_{2\alpha}; \\ M = P_n L_{12} (i_{1\beta} i_{2\alpha} - i_{1\alpha} \cdot i_{2\beta}), \end{cases} \tag{2.7}$$

where $U_{1\alpha} = 0$ $\quad i_{1\alpha} = 0$

$U_{1\beta} = U_в$ $\quad i_{1\beta} = i_f$

$U_{2\alpha} = U_я$ $\quad i_{2\alpha} = i_a$

$U_{2\beta} = 0$ $\quad i_{2\beta} = 0$

i_f – current of field winding;

i_a – current of armature winding.

Then, for the DCM with separate excitation system of equations will have the form:

$$\begin{cases} U_f = i_f R_f + L_f di_f / dt; \\ U_a = i_a R_a + L_a di_a / dt + \omega L_{12} i_f; \\ M = P_n L_{12} i_f i_a, \end{cases} \tag{2.8}$$

where rotating electromotive force E:

$$E = \omega L_{12} i_f = ж \cdot \Phi \cdot \omega, \tag{2.9}$$

$K = \frac{P_n N}{2\pi a}$ - DCM constructive factor that takes into account the number of pole pairs P_n; number of turns N and the parallel branches «a» of the armature winding.

The torque is determined by:

$$M = P_n L_{12} i_в i_я = K\Phi i_я. \tag{2.10}$$

The system of equations can be written:

$$\begin{cases} U_f = iR_f + L_f di_f / dt; \\ U_a = i_a R_{a\varepsilon} + L_a di_a / dt + K\Phi\omega; \\ M = K\Phi i_a. \end{cases} \tag{2.11}$$

At constant magnetic flux machine armature current:

$$i_a = \frac{M}{K\Phi}. \tag{2.12}$$

Voltage U_a is determined as:

$$U_a = \frac{M}{K\Phi} R_{a\varepsilon} + \frac{L_a}{K\Phi} \cdot \frac{dM}{dt} + K\Phi\omega, \qquad (2.13)$$

откуда уравнение механической характеристики ДПТ независимого возбуждения в динамике:

$$\omega = \frac{U_a}{K\Phi} - \frac{R_{a\varepsilon}}{K^2\Phi^2} M - \frac{L_a}{K^2\Phi^2} \cdot \frac{dM}{dt}. \qquad (2.14)$$

The equation of the electromechanical characteristics of the DCM separate excitation in the dynamic mode:

$$\omega = \frac{U_a}{K\Phi} - \frac{R_{a\varepsilon}}{K\Phi} i_a - \frac{L_a}{K\Phi} \cdot \frac{di_a}{dt}, \qquad (2.15)$$

If DC I_a and flux Φ are constant $\left(\frac{dM}{dt} = \frac{di_a}{dt} = 0\right)$ equations for DCM separate excitation take the form:

$$\omega = \frac{U_a}{K\Phi} - \frac{R_{a\varepsilon}}{K\Phi} I, \qquad (2.16)$$

$$\omega = \frac{U_a}{K\Phi} - \frac{R_{a\varepsilon}}{K^2\Phi^2} M, \qquad (2.17)$$

which represents static electro-mechanical and mechanical characteristics, which are linear and are characterized by two points:

1) if $I_a = 0$, $M = 0$; $\qquad \omega_0 = \frac{U_a}{K\Phi}$;

2) if $I_a = I_{SC}$, when $\omega = 0$; $\qquad I_{SC} = \frac{U_a}{R_{a\varepsilon}}$,

$$M_{CS} = K\Phi \frac{U_a}{R_{a\varepsilon}} = K\Phi I_{SC},.$$

Fig. 2.4 presents the electromechanical and mechanical characteristics of the DCM separate excitation.

Differentiating equation:

$$M = K\Phi \frac{U_a}{R_{a\varepsilon}} - \frac{K^2\Phi^2}{R_{a\varepsilon}} \omega,$$

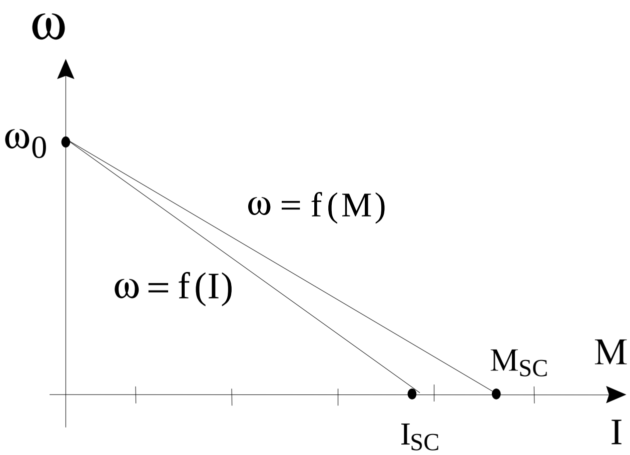


Fig. 2.4

then get:

$$\frac{dM}{d\omega}=\beta_{st}=\frac{K^2\Phi^2}{R_{a\varepsilon}}, \tag{2.18}$$

where β_{st} - static rigidity of mechanical characteristics.

The equations of static mechanical characteristics can be written as

$$M=\beta(\omega_0-\omega), \tag{2.19}$$

$$\omega=\omega_0-\frac{M}{\beta}, \tag{2.20}$$

$$M=M_{SC}-\beta\omega, \tag{2.21}$$

and static electromechanical characteristics:

$$\omega=\omega_0-\frac{R_{a\varepsilon}}{K\Phi}I_a, \tag{2.22}$$

$$I_a=I_{SC}-\frac{K\Phi}{R_{a\varepsilon}}\cdot\omega. \tag{2.23}$$

Let us go back to the equation of the mechanical characteristics of the DCM separate excitation in the dynamics:

$$\omega=\frac{U_a}{K\Phi}-\frac{R_{a\varepsilon}}{K^2\Phi^2}M-\frac{L_a}{K^2\Phi^2}\cdot\frac{dM}{dt},$$

and considering that

$$\omega_0=\frac{U_a}{K\Phi},$$

$$\beta_{st}=\frac{K^2\Phi^2}{R_{a\varepsilon}},$$

$$T_a = \frac{L_a}{R_{a\varepsilon}},$$

- electromagnetic time constant of the armature circuit, and then obtain a block diagram of a DC motor with separate excitation:

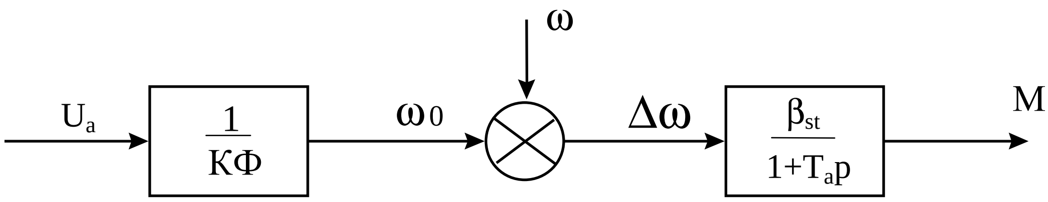


Fig. 2.5

Then dynamic rigidity is:

$$\beta_{dyn}(p) = \frac{M(p)}{\omega(p)} = -\frac{\beta_{st}}{(1 + T_a p)}. \tag{2.24}$$

Dynamic rigidity characterizes DCM in dynamics, it is differs from β_{st}, therefore, static and dynamic characteristics of the DCM are differ.

2.3 Modes of DCM separate excitation

Fig. 2.6 shows the scheme of DCM separate excitation in the armature circuit which included additional resistor R_{add}, and to change the excitation current is the resistance R_f.The impedance of the armature:

$$R = R_a + R_{add},$$

where $R_a = r_{aw} + r_{ap} + r_{cw} + r_b$,

r_{aw} - the resistance of the armature winding,

r_{ap} - winding resistance of additional poles,

r_{cw} - compensating winding resistance,

r_b - transfer resistance brush contact.

Equations of electro-mechanical amd mechanical characteristics:

$$\omega = \frac{U}{K\Phi} - \frac{MR}{(K\Phi)^2} = \omega_0 - \Delta\omega, \tag{2.25}$$

$$\omega = \frac{U}{K\Phi} - \frac{IR}{K\Phi} = \omega_0 - \Delta\omega, \tag{2.26}$$

For these equations following assumptions are existed: the reaction of the armature is not considered and the shaft torque is equal to the electromagnetic torque.

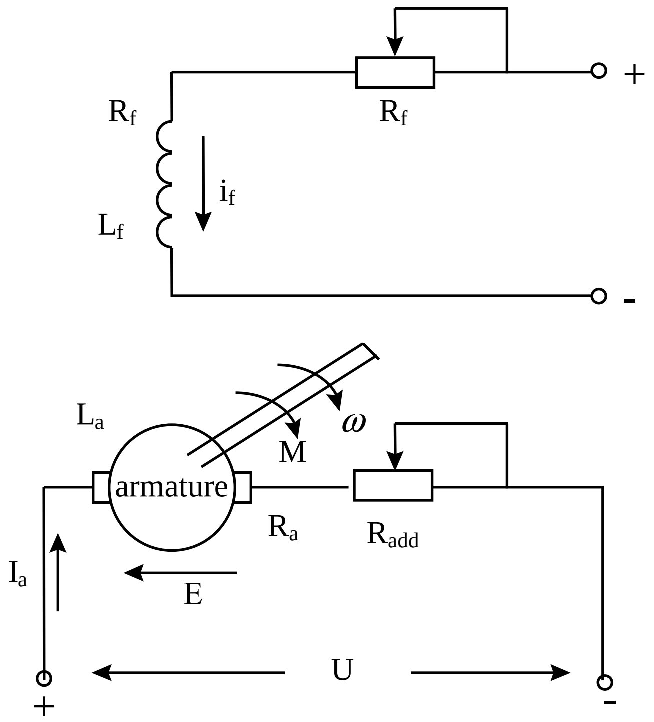


Fig. 2.6

Fig. 2.7 are electromechanical and mechanical characteristics of the DCM seperate excitation of different polarity power supply and of the absence of U = 0 and for constant current excitation (Φ = const).

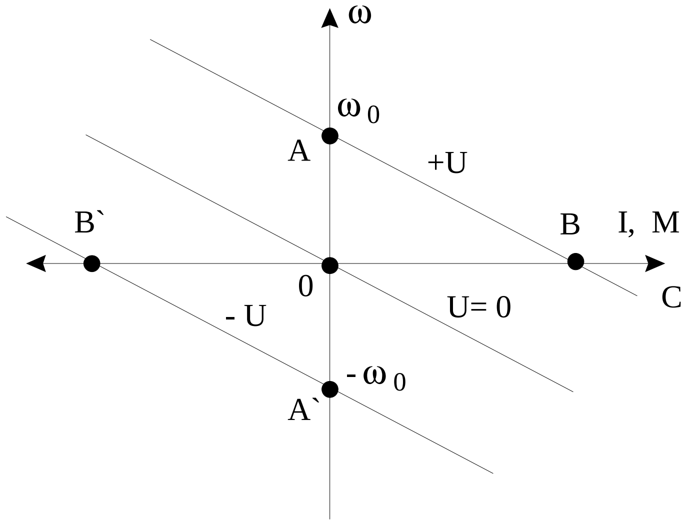


Fig.2.7

In this case, at a certain scale mechanical and electro-mechanical characteristics are the same.

Analysis of equations (2.25) and (2.26) allows to specify methods for controlling coordinates (ω, I, M, φ) of electric drive:

a) changing the resistance R_{add} in the armature circuit;

b) changing the excitation current, and as a result, magnetic flux Φ;

c) the change of the supplied armature voltage.

More these methods and their derivatives will be discussed later.

Consider modes DCM separate excitation in different parts of its characteristics.

1. Idling DCM. Point A or A' for different polarity of the applied armature voltage is characterized by the following parameters:

$i = 0$, $M = 0$, $\omega = \pm\, \omega_0$. The motor does not receive electrical power from the mains, except for losses due to excitation and friction, and doesn't gives mechanical energy.

2. Motor mode takes place on the section AB (forward), or A `B '(reverse), where the angular speed and torque M have the same direction. In this mode $|U| > |E|$; $0 < \omega < \omega_0$; armature current I coincides with the direction of U and is directed against E, the electric energy supplied from the mains, and the mechanical is given from motor shaft to working machine.

3. Mode short circuit of DCM. The point B or B` on the characteristics (Fig. 2.7) has the following parameters: $\omega = 0$, $E = 0$; $I = I_{K3} = U/R$. The electrical energy consumption from the mains is dissipated as heat in the resistors in the armature circuit. The mechanical energy is not given to a working machine.

4. Generator mode DCM parallel with the mains, which is called regenerative braking mode, takes place in the second and fourth quadrants mechanical characteristics. In this case, the angle speed ω is more than idle speed ω_0 for forward and backward. EMF is greater than the voltage applied to the armature, I, and M change its direction. The motor receives the mechanical power from the working machine and sends a (regenerating) it to the mains in the form of electrical energy produced by the generator.

5. Generator mode series with the mains, which is called the mode of plugging, will take place $\omega < 0$ (section B and C or B` A`). In this mode, the electromotive force coincides with the direction of voltage and DCM is sequentially switched with mains, armature current I coincides with the direction of E and U, and is defined:

$$I = \frac{U + E}{R}.$$

Electrical energy is supplied from the mains, and is also produced by working as a generator DCM and dissipated as heat in the resistors of armature circuit. This mode is the most severe because the high current is in the armature circuit.

6. Generator mode regardless of the mains, which is called dynamic braking mode, occurs when the armature circuit is disconnected from the mains (U = 0) and closed-circuit or series resistor. The armature current I flows under the action E and has the same direction. Electrical power is generated by converting mechanical energy from a motor shaft connected to the machine tool, then dissipated and converted into thermal energy in the resistances of the armature circuit. On the characteristics of this mode is characterized by a straight line passing through the origin of coordinates.

At start-up of the DCM inrush current exceeds rated in 10-50 times because when working on the natural characteristics at the time of the DCM start:

$$\omega = 0;\ E = 0,\ \text{then}\ I = \frac{U}{R} = I_{SC}.$$

Limitation of I_{SC} to acceptable I_{acc} = (2-2.5) I_n is realized by the introduction of additional start-up resistor R_{add} (starting resistors). The value of R_{add} is defined:

$$R_{add} = \frac{U}{I_{acc}} - R_a. \qquad (2.\ 27)$$

Natural characteristic of the DCM separate excitation (1) and artificial (2) are obtained by the inclusion R_{add} and presented on Fig. 2.8. At start-up as the speed increases and E increases and the armature current decreases - the characteristic (2). When the current I_2 = (1,1 - 1,2) I_n is switched to the natural response (1).

During dynamic braking, when the armature circuit of the DCM is disconnected from the mains and is closed on additional resistance R_{add2}, the braking process takes on the characteristics (3) to stop the motor. The value R_{add2} is determined

$$R_{add2} = \frac{E}{I_{acc}} - R_a \approx \frac{U}{I_{acc}} - R_a, \qquad (2.28)$$

since for ω_n close to ω_0, voltage value E is close to voltage U.

When the reverse of the motor or the plugging the polarity of the voltage at armature is changed while integrating into the armature circuit resistor R_{add3}. The motor goes to the response (4). The value is determined R_{add3}:

$$R_{add3} = \frac{U + E}{I_{acc}} - R_a \approx \frac{2U}{I_{acc}} - R_a. \qquad (2.29)$$

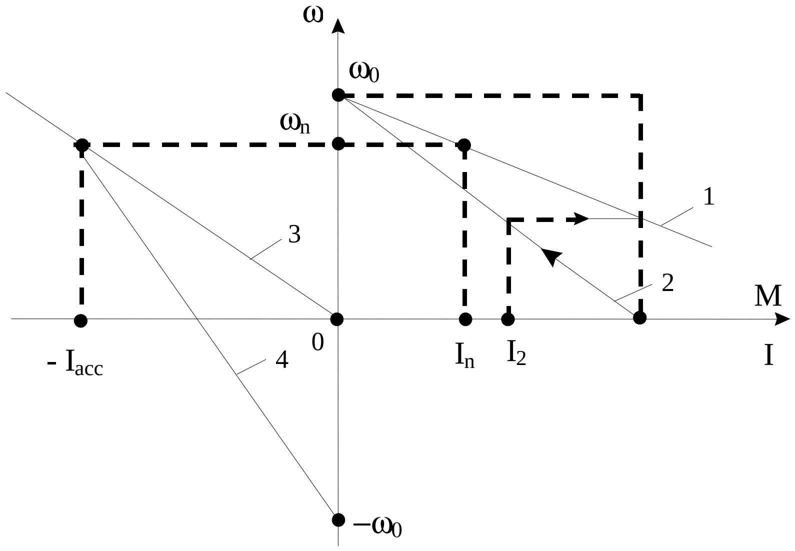


Fig.2.8

2.4 Calculation of the additional resistance

Calculation R_{add} at the start, speed control and braking of the DCM can be made using the following methods:

1. The permissible armature current, as shown in Section 2.3.
2. The method segments.
3. Method of proportions.

For the calculation of R_{add} must be specified motor data, the natural and artificial electro-mechanical or mechanical characteristics. From the electromechanical characteristics of the equation, it has:

$$\omega_{art} = \frac{U_n}{K\Phi_n} - \frac{I_n R}{K\Phi_n} = \frac{U_n}{K\Phi_n}(1 - \frac{I_n R}{U_n}), \tag{2.30}$$

where: $R = R_a + R_{add}$; $\omega_0 = \dfrac{U_n}{K\Phi_n}$; $R_n = \dfrac{U_n}{I_n}$,

then:

$$\omega_{art} = \omega_0 (1 - \frac{R}{R_n}) \tag{2.31}$$

or:
$$\frac{R}{R_n} = \frac{\omega_0 - \omega_n}{\omega_0} = \frac{\Delta\omega}{\omega_0} = \delta,$$

where: δ - the relative speed differential.

Consequently, the relative speed differential will determine the value of the relative resistance of the armature circuit $R_a + R_{add} / R_n$, where R_{add} is.

Let's set the natural and artificial features of the DCM separate excitation (Fig. 2.9). On the mechanical (electromechanical) characteristics of the DCM segments ab, ac, ad correspond to the speed differential $\Delta\omega$. ab segment corresponds to the differential speed at rated mode of the DCM without additional resistances:

$$ab = \Delta\omega_n = \omega_0 - \omega_n ;$$

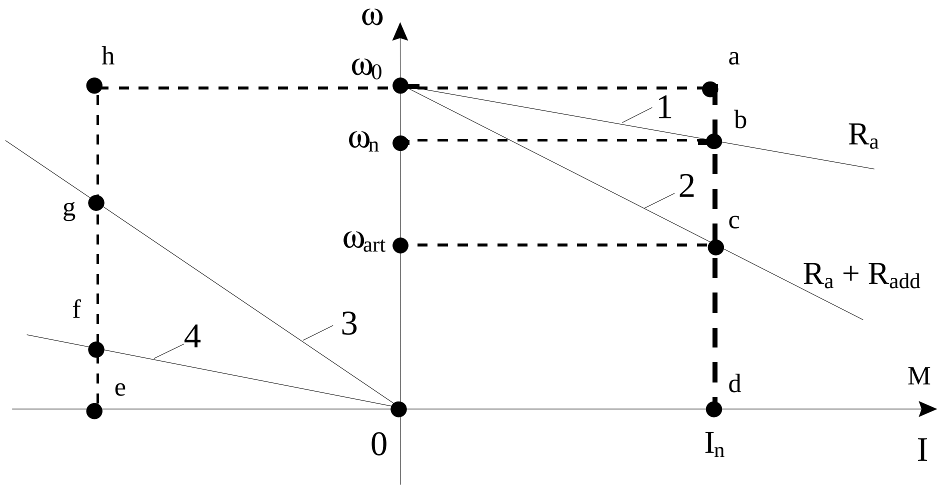


Fig.2.9

segment ac - artificial characteristic with switched resistor R_{add1};

$$ac = \Delta\omega_n = \omega_0 - \omega_n ;$$

segment ad $= \omega_0$.

Then, using the method of segments, define:

$$R_a = R_n \frac{ab}{ad}; \qquad R_{add1} = R_n \cdot \frac{bc}{ad}.$$

If characteristics of the motor working in dynamic braking mode are defined (line 3 at the additional resistance R_{add2}, line 4, with $R_{add} = 0$), the value of R_{add2} is:

$$R_{add2} = R_n \cdot \frac{fg}{eh}.$$

To determine the additional resistances by method of proportions sufficient to use the expression:

$$\frac{\Delta\omega_{nat}}{\Delta\omega_{art}} = \frac{R_a}{R_a + R_{add}},$$

where:

$$R_{add} = R_a\left(\frac{\Delta\omega_{art}}{\Delta\omega_{nat}} - 1\right). \qquad (2.32)$$

R_a is the value of from the empirical formula:

$$R_a \approx 0{,}5R_n(1-\eta_n). \qquad (2.33)$$

These methods are used in the calculation of resistances of starting resistors. In this case it is necessary to diagram starting chart identifying the number of switching stages:

$$m = \lg\left(\frac{I_2}{I_{acc}}\right) / \left(\frac{R_a I_{acc}}{U_n}\right),$$

using the following conditions: I_{acc} must not exceed (2-2.5) I_n; switching current I_2 = (1,2 - 1,2) I_n, with off-speed resistance inrush current must not exceed I_{acc}. Fig. 2.10 shows a diagram of the DCM separately excited when starting with three-stage acceleration.

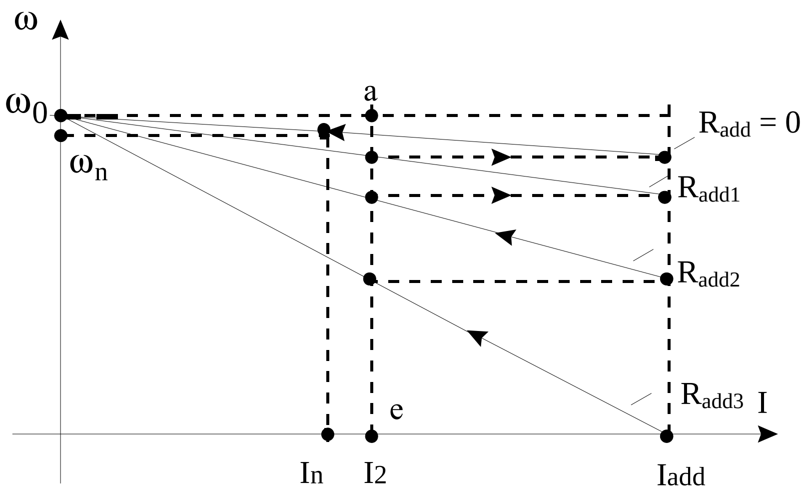


Fig. 2.10

2.5 Speed adjustment of DCM of separately excitation by variation of the magnetic flux

This method is possible only upward regulation of speed from the natural, attenuation of the magnetic flux because the nominal drive current is calculated on the optimum thermal conditions, and the magnetic system with DCM i_{fn} (Φ_n) is close to saturation.

From the electromechanical characteristics equation:

$$\omega = \frac{U}{K\Phi} - I\frac{R}{K\Phi},$$

it follows that the attenuation of the magnetic flux the idle speed ω_0 increases and slope characteristics also increases (Fig. 2.11). As the I_{SC} does not depend on Φ, electromechanical characteristics obtained for different values of the flow ($\Phi_2 < \Phi_1 < \Phi_n$), converge at one point. Torque M_{SC} in the short-circuit DCM mode changes with the changing flow:

$$M_{SC} = K\Phi I_{SC}.$$

The family of the mechanical characteristics of the DCM separate excitation at attenuation the flow $\Phi_n > \Phi_1 > \Phi_2$ is shown in Fig. 2.12.

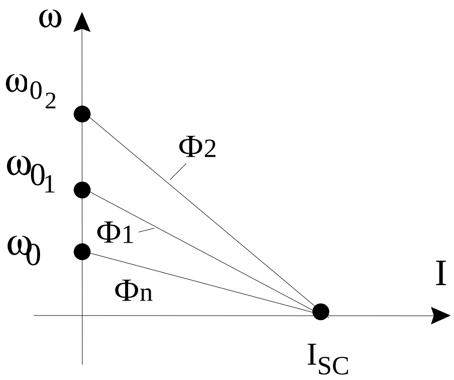


Fig. 2.11

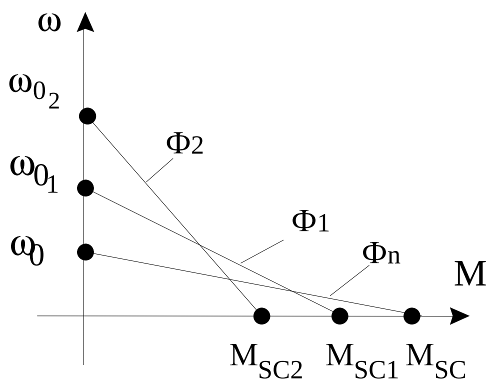


Fig. 2.12

From Fig. 2.12 it follows that at the attenuation of the flow when working on artificial characteristics the permissible load (torque) is reduced:

$$M_{acc} = K\Phi_{art} I_n \;\; ; \;\; M_{acc} < M_n .$$

The magnetic flux on the artificial mechanical characteristics are determined from the relations:

$$E_{nat} = K\Phi_n \omega_n = U_n - I_n R_a ,$$
$$E_{art} = K\Phi_{art} \omega_{art} = U_n - I_n R_a ,$$

then

$$\Phi_{art} = \Phi_n \frac{\omega_n}{\omega_{art}} . \qquad (2.34)$$

Useful power at the shaft of the DCM:

$$P_n = M_n \omega_n = P_{art} = M_{acc} \omega_n = \text{const} .$$

Therefore, regulation of the speed by this method is at constant power.

2.6 Adjustment of the coordinates of the DCM separate excitation by changing the armature supplied voltage

A smooth variation of the supplied voltage to the armature of the DCM is a converter having an internal resistance R_c and the gain K_c by changing the control signal U_{cont} (Fig. 2.13).

Adjusting the output voltage of the inverter $U = E_c - IR_c$ and the gain $K_c = \dfrac{E_c}{U_{cont}}$ substitute in the equations of the characteristics of the DCM separate excitation.

$$\omega = \frac{K_c U_{cont}}{K\Phi} - I\frac{R_a + R_c}{K\Phi} = \omega_0 - \Delta\omega; \qquad (2.35)$$

$$\omega = \frac{K_c U_{cont}}{K\Phi} - M\frac{R_a + R_c}{(K\Phi)^2} = \omega_0 - \Delta\omega. \qquad (2.36)$$

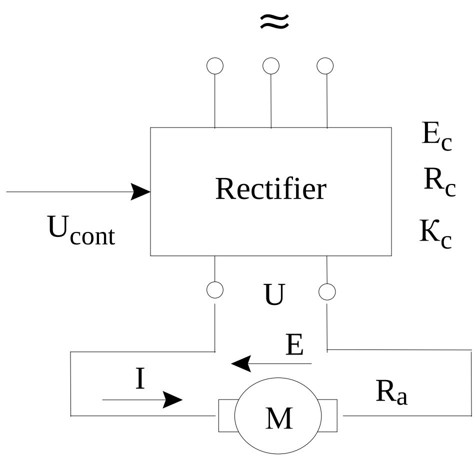


Fig. 2.13

Electrico-mechanical and mechanical characteristics of the DCM excitation with converter supply have a greater slope than natural due to the influence of the internal resistance of the converter R_c. Fig. 2.14 presents the natural and family of artificial characteristics of the DCM separate excitation at the regulation of the magnitude and polarity of the armature applied voltage.

If E_c = 0 DCM operates in dynamic braking. The converters used electric machines, in which the source is regulated voltage direct current generator, which forms together with the DCM system generator-motor (GD), shown in Fig. 2.15 and semiconductor forming the system thyristor converter - motor (TC-M), shown in Fig. 2.16.

Advantages of GD - great range and a very smooth control, rigidity and linearity characteristic, the ability to provide all modes of DCM.

The disadvantages of GD include large installed power and size, increased noise, inertia and operating costs.

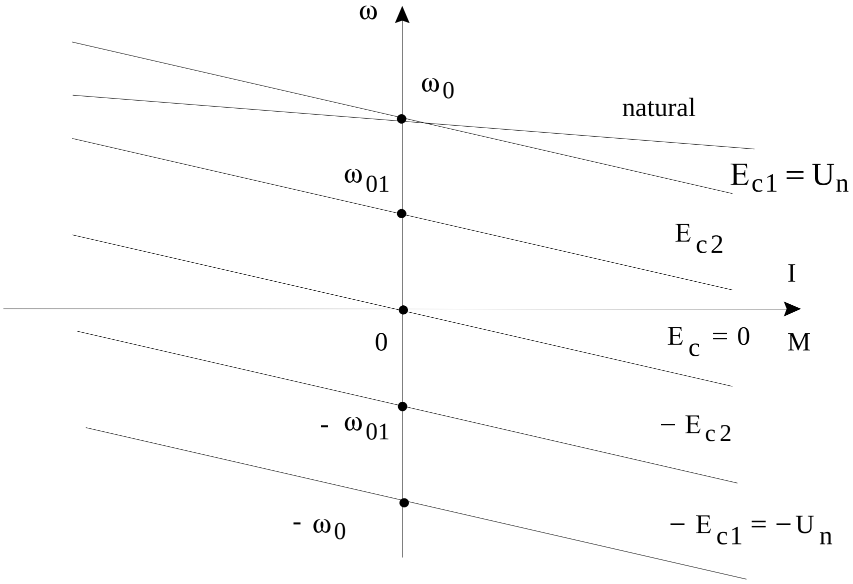


Fig. 2.14

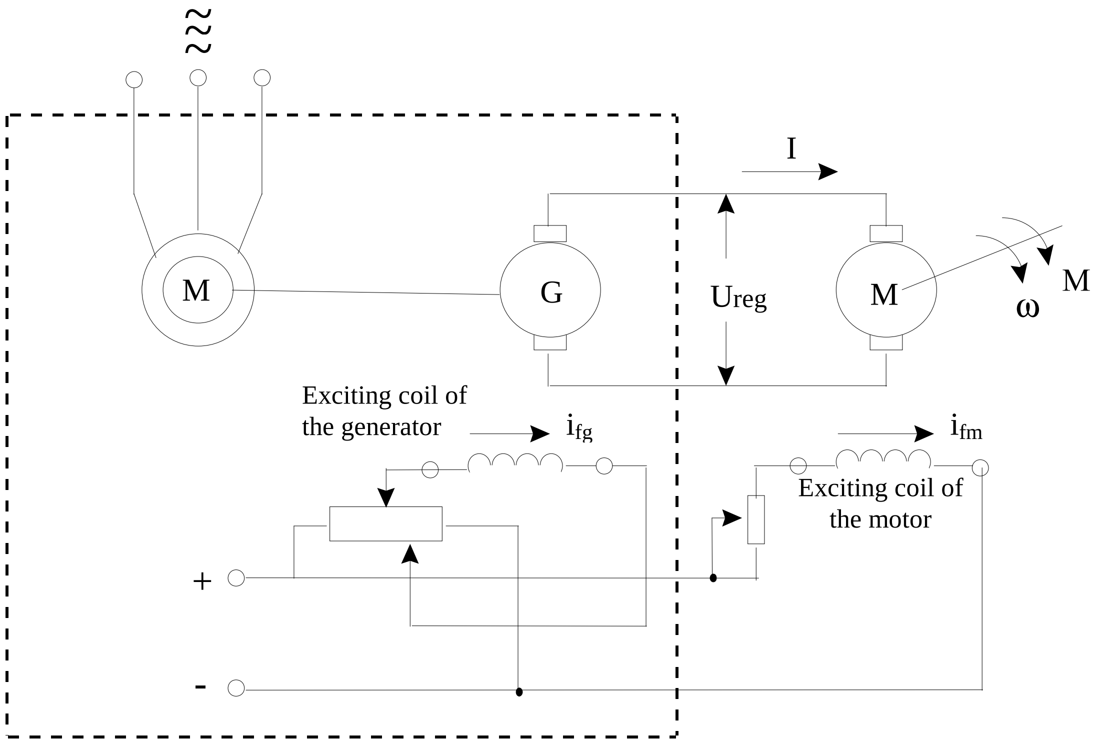


Fig. 2.15

Controllable semiconductor converters are typically thyristor or lower power transistor, may be one or three phase, reversible or irreversible, assembled by zero or bridge schemes. Fig. 2.16 presents single-phase full-wave irreversible thyristor rectifier assembled by zero scheme. Thyristor converter has a transformer (TR) with two secondary windings, two thyristors VS1 and VS2, smoothing reactor L and a system of pulse-phase control circuit (PPCC).

Regulation U of DCM is provided by changes the average value of E_c by changing the thyristor control angle α relative to the moment of their natural opening, when the anode potential is higher than the potential cathode.

If $\alpha = 0$, thyristors receive management impulses from the PPCC at the time of their natural opening, the converter provides full-wave rectification and DCM is applied to the total mains.

If create the control pulse of the PPCC with a shift the angle $\alpha \neq 0$, then the EMF E_c will decrease, and the average voltage is below:

$$E_{av} = \frac{E_{max} \cdot m}{\pi} \sin\frac{\pi}{m} \cos\alpha = E_{av.0} \cdot \cos\alpha,$$

where $E_{av.0}$ – EMF of converter at $\alpha = 0$.

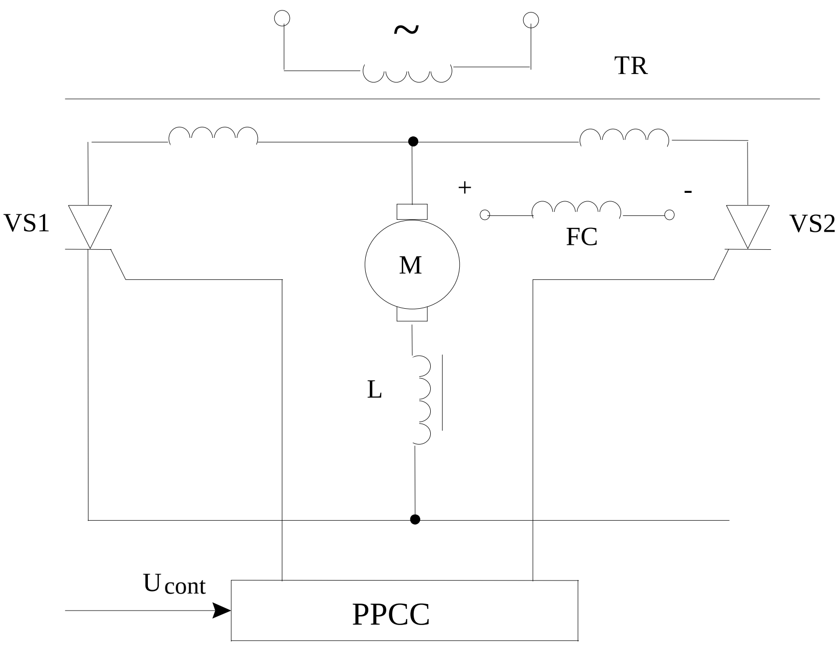


Fig. 2.16

Consequently, E_c and current I are pulsating. To reduce the ripple a smoothing reactor L is applied. Multi-phase rectifier circuit also reduces ripple.

When DCM separate excitation is powered by the thyristor converter equation of the electromechanical and mechanical characteristics are the form:

$$\omega = E_{av.0}\cos\alpha / K\Phi - I(R_n + R_c) / K\Phi;$$

$$\omega = E_{av.0}\cos\alpha / K\Phi - M(R_n + R_c) / (K\Phi)^2,$$

where $R_c = X_{tr} \cdot m / 2\pi + R_{tr} + R_L$;

X_{tr}, R_{tr} – reduced to the secondary winding inductance and active resistance of the transformer (TR);

R_L - resistance of the smoothing reactor.

Electromechanical and mechanical characteristics of the DCM separate excitation are shown on Fig. 2.17 when the changing control angle α from 0 to 180^0.

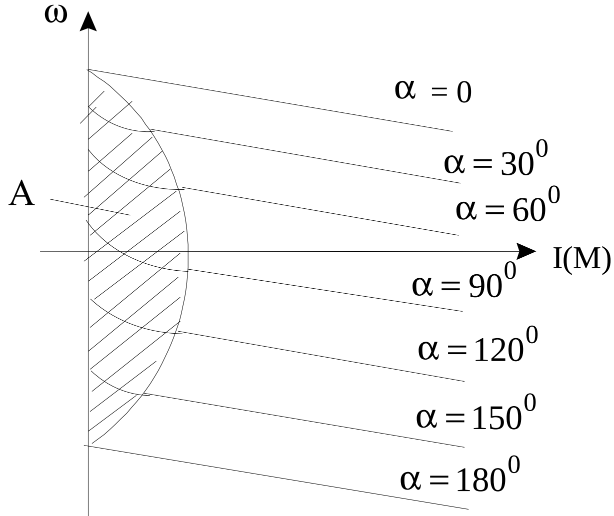


Fig. 2.17

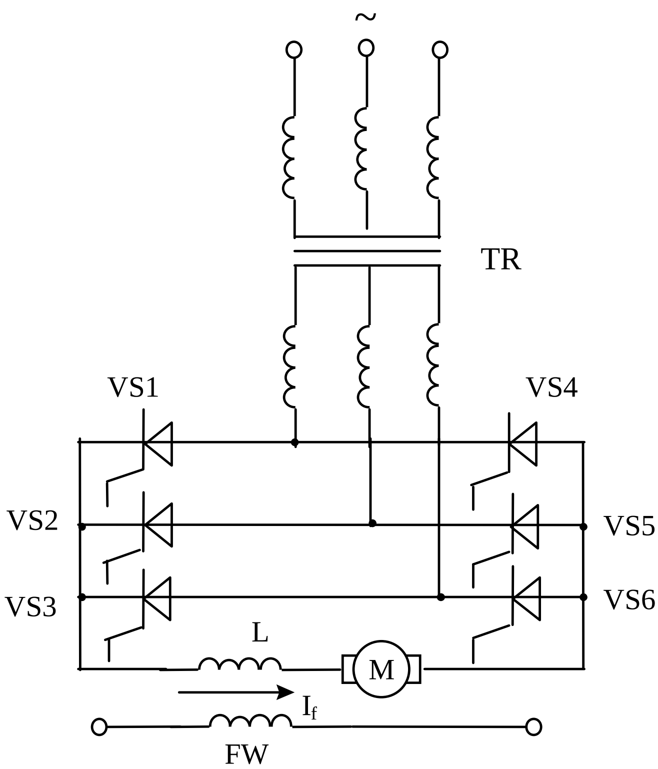
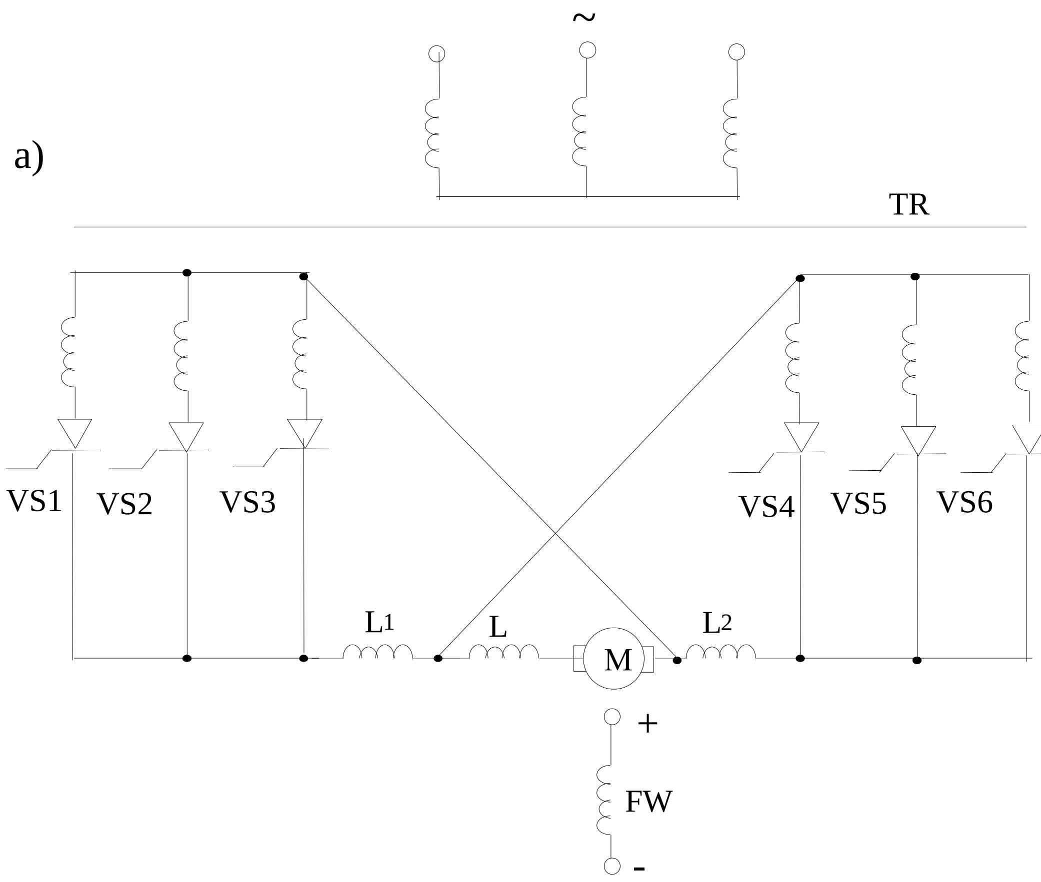


Fig. 2.18

a)


~
TR
VS1
VS2
VS3
VS4
VS5
VS6
L1
L
L2
M
+
FW
-

b)

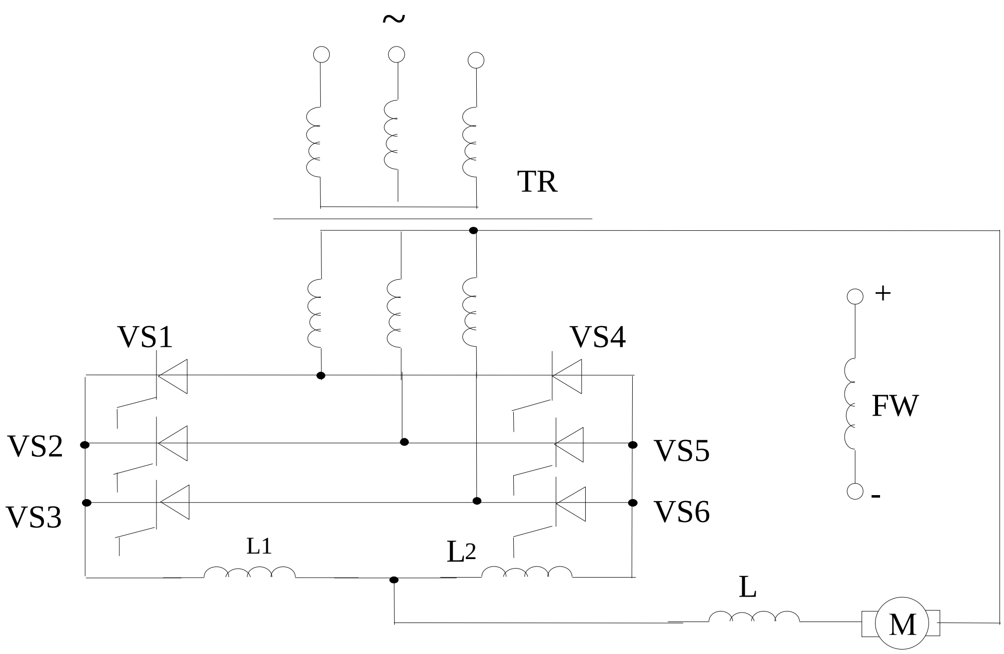

~
TR
VS1
VS4
VS2
VS5
VS3
VS6
L1
L2
L
M
+
FW
-

Fig. 2.19

The natural characteristics of the DCM are linear obtained when the direction of rotation at $\alpha = 0$ and $\alpha = 180^0$. At other angles of control at low loads linearity of characteristic breaks and the region of interrupted currents appears (A).

At $\alpha = 90^0$, $E_c = 0$ DCM operates in dynamic braking.

If a thyristor converter has a bridge circuit ripple is much lower.

The scheme of the electric drive with a bridge nonreversible thyristor converter is shown in Fig. 2.18.

Motor operation in all modes can be achieved when powered by reversing thyristor converters, which use joint or separate sets of control valves. The joint control of the valves control pulses from the PPCC are served simultaneously on both sets of valves.

Fig. 2.19 is a electric circuit of reversible electric drive TC-M with zero output, (a - cross, b - antiparallel), Fig. 2.20 - cross bridge.

In these circuits, one thyristors group is working in the rectifier mode, the other - in the inverter mode, with condition $E_{av.inv} \geq E_{av.rec}$, and the sum of angles control of rectifier α_1 and inverter α_2 is supported to 180^0.

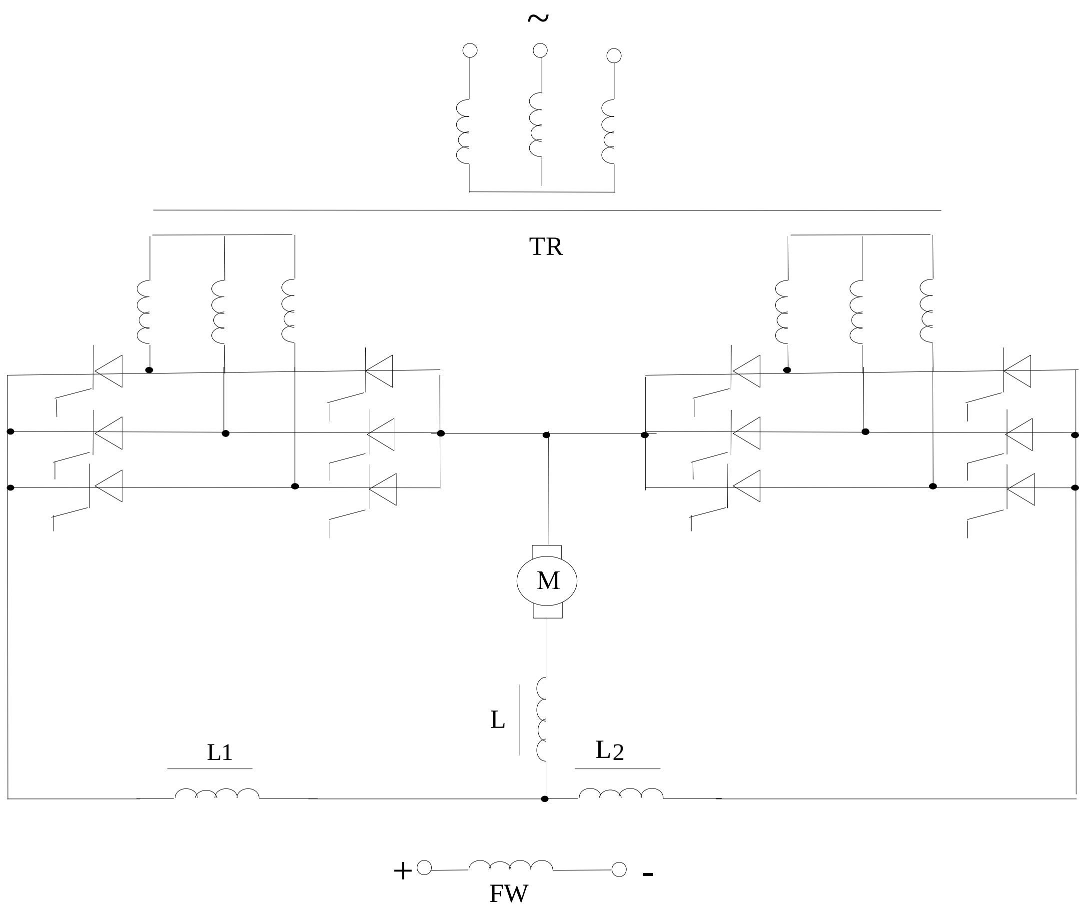


Fig. 2.20

Characteristics of the DCM with the joint linear coordination control angles are linear (Fig. 2.21).

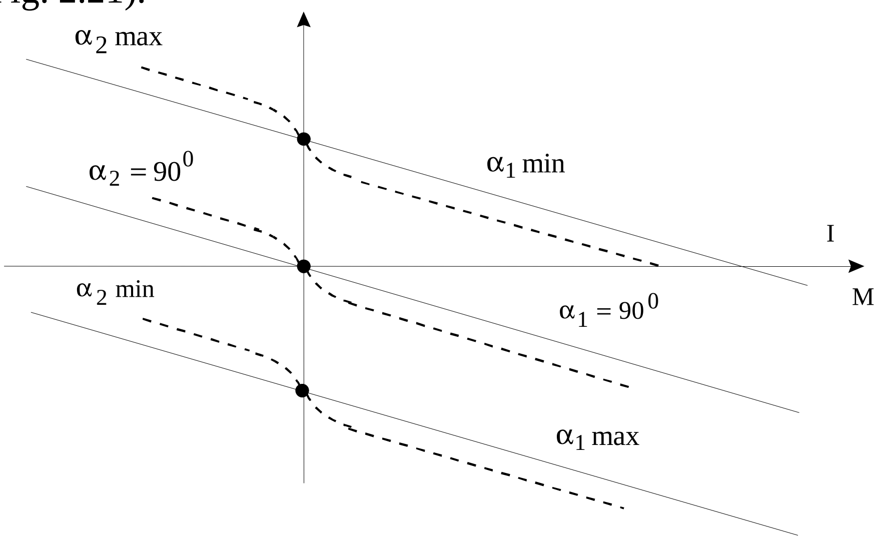


Fig. 2.21

In nonlinear coordination of control angles $\alpha_1 + \alpha_2 \neq \pi$ during the transition from motor mode to the generator mode angle speed increases and characteristics of DPT become non-linear (Fig.2.21) (dashed lines). To limit the circulating currents between groups of thyristors are used reactors L_1, L_2.

By separate thyristor control voltage pulses U_{cont} from the PPCC serves only to that group of valves which should work, another group of valves closed. The switching device switches on and off valves with a pause of 5÷10 ms. For this reason, interrupted currents occur in the low load mode, which impairs the working environment of the drive. The advantages of the system TC - M are smooth and significant speed range, high rigidity of artificial caracteristics, high motor efficiency, ease of maintenance and operation. The main disadvantages of this system should be noted current and voltage pulsating and decrease of power factor (Cosφ) with deep speed control.

2.7 Formation of the static characteristics of the drive in a closed system the converter - motor

In previously considered open-loop systems TC - M due to the influence R_c characteristics have low rigidity and doesn’t provides limiting of current and torque. And widely used closed control system of speed, power and torque with the aid of feedback.

2.7.1 The closed system of TC-M with a negative feedback on the speed is shown on Fig. 2.22.

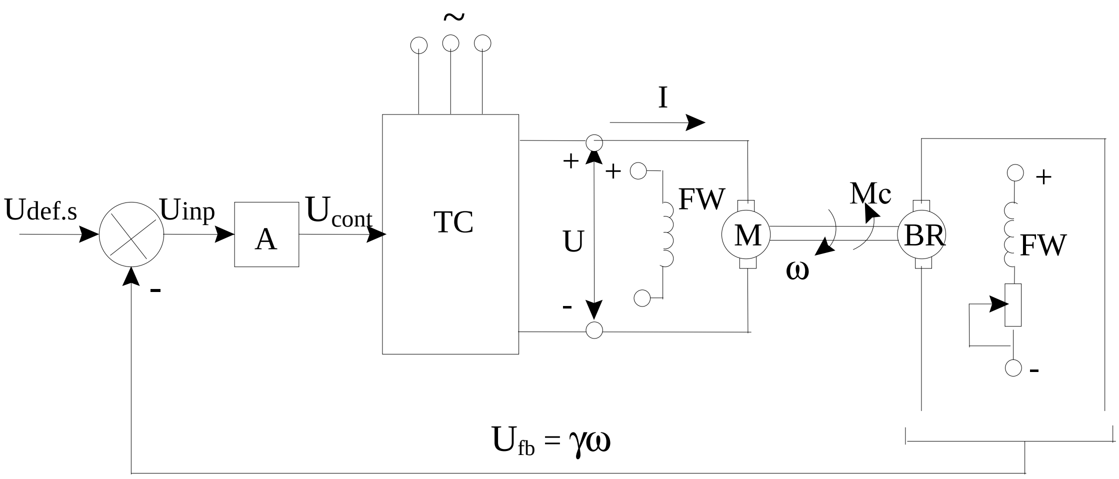


Fig. 2.22

BR - the speed sensor - tacho-generator;

A - amplifier;

$U_{fb} \equiv \omega$ - a feedback signal;

γ - gain of speed feedback.

The equations of the characteristics of the DCM separate excitation in open loop:

$$\omega = \frac{K_c U_{cont}}{K\Phi} - \frac{I(R_a + R_c)}{K\Phi} = \omega_0 - \Delta\omega,$$

$$\omega = \frac{K_c U_{cont}}{K\Phi} - \frac{M(R_a + R_c)}{(K\Phi)^2} = \omega_0 - \Delta\omega.$$

Insert $U_{inp} = U_{def.s.} - \gamma\omega$; $U_{cont} = K_{cont} U_{inp}$ obtain the characteristic equation in a closed system:

$$\omega = \frac{K_{cont} K_c U_{def.s}}{C(1+K_s)} - \frac{I(R_a + R_c)}{C(1+K_s)}, \tag{2.37}$$

$$\omega = \frac{K_{cont} K_c U_{def.s}}{C(1+K_s)} - \frac{M(R_a + R_c)}{C^2(1+K_s)}, \tag{2.38}$$

where $K_s = \frac{\gamma K_{cont} K_c}{C}$ - gain of the system,

$C = K\Phi_n$.

Fig. 2.23 shows the mechanical characteristics of DCM in a closed system (lines 2, 4, 5) for the various defining signals.

$U_{def.s1} > U_{def.s2} > U_{def.s3}$. For comparison the characteristic (line 3) in open loop is presented:

$$\Delta\omega_{op} = I(R_a + R_c) / C \ ,$$

$$\Delta\omega_{cl} = I(R_a + R_c) / C \cdot (1 + K_s) = \Delta\omega_{op} / (1 + K_s) \ .$$

where $\Delta\omega_{op}$ – speed differential in open system; $\Delta\omega_{cl}$ – speed differential in close system.

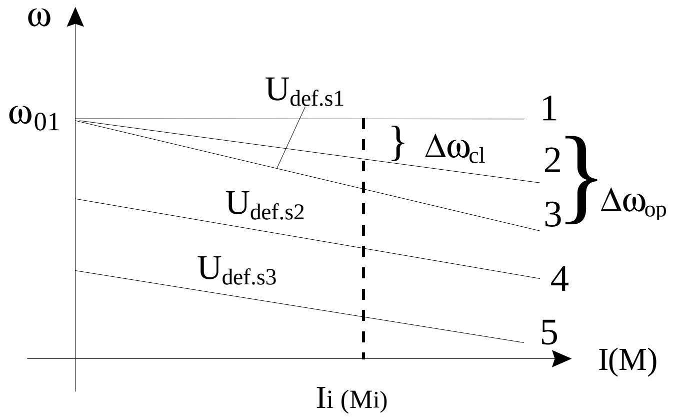


Fig. 2.23

Characteristics of the DCM at $K_s \to \infty$, $\Delta\omega \to 0$ – absolutely rigid (line 1). However, in practice it is not applicable due to deterioration of the drive dynamics.

Consequently, $\Delta\omega_{cl} < \Delta\omega_{op}$, characteristics rigidity of the DCM in a closed system more than characteristics rigidity in the open-loop system.

The work of the speed feedback.

If the motor is in steady state at angle speed ω and increase the load M_c, the speed will decrease and decrease the feedback signal U_{BR}. This will increase the U_{cont} E_c, and speed.

If the load torque is reduced, the speed increases and decrease signals $U_{inp} = U_{def} - \gamma\omega$, U_{cont} and U_{cont}, and then decrease speed. Thus, speed maintenance is carried out automatically when the load M_c changes.

2.7.2 The closed system of TC-M with a negative voltage feedback DPT. (Fig. 2.24)

Voltage sensor is a potentiometer R, from which from the voltage feedback signal is obtained $U_{fb} = \alpha \cdot U$, where α - the feedback factor. Then $U_{inp} = U_{def.s} - \alpha U$. In this case, the equations of mechanical and electro-mechanical characteristics of the DCM are:

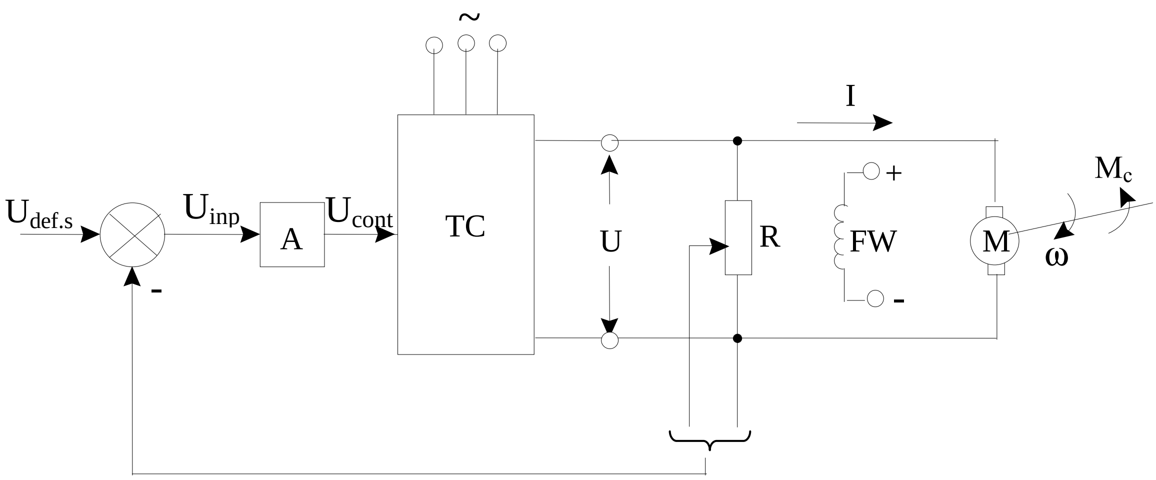


Fig. 2.24

$$\omega = \frac{K_{cont}K_c U_{def.s}}{C(1+K_S)} - \frac{I[R_c + R_a(1+K_S)]}{C(1+K_S)}, \tag{2.39}$$

$$\omega = \frac{K_{cont}K_c U_{def.s}}{C(1+K_S)} - \frac{M[R_c + R_a(1+K_S)]}{C^2(1+K_S)}, \tag{2.40}$$

where $K_s = K_{cont}K_c \cdot \alpha$ - overall gain of the system.

Let's compare the characteristics rigidity in open-loop and closed-loop systems.

$$\Delta\omega_{op} = \frac{I(R_a + R_c)}{C} > \Delta\omega_{cl} = \frac{I\left[R_a + \dfrac{R_c}{1+K_s}\right]}{C}$$

Consequently, the DCM characteristics in a closed system (fig. 2.25, lines 2, 4, 5) is more rigid than the open loop (3).

Finite rigidity of characteristics in a closed system at $K_s \to \infty$, then $\Delta\omega_{cl} \to \dfrac{IR_a}{C}$ – the natural characteristic (line 1).

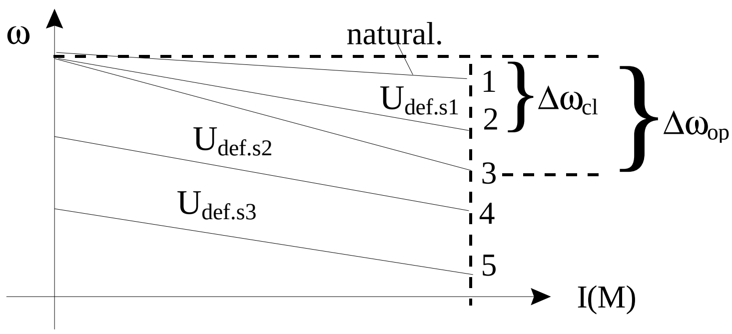


Fig. 2.25

Thus, the feedback voltage at $K_s \to \infty$ provides full compensation for the voltage drop across the internal resistance of the converter R_c.

The work of the voltage feedback: with increasing shaft load M_c increases the armature current I, increases the internal voltage drop of the converter, and then the armature voltage U reduces.

Then signal $U_{inp} = U_{def.s.} - \alpha U$ grows and U_{cont} also grows, what leading to an increase converter EMF and an increase the armature voltage U. Automatically regulation the converter EMF is occured.

2.7.3 The closed system of TC-M with positive feedback armature current (Fig. 2.26).

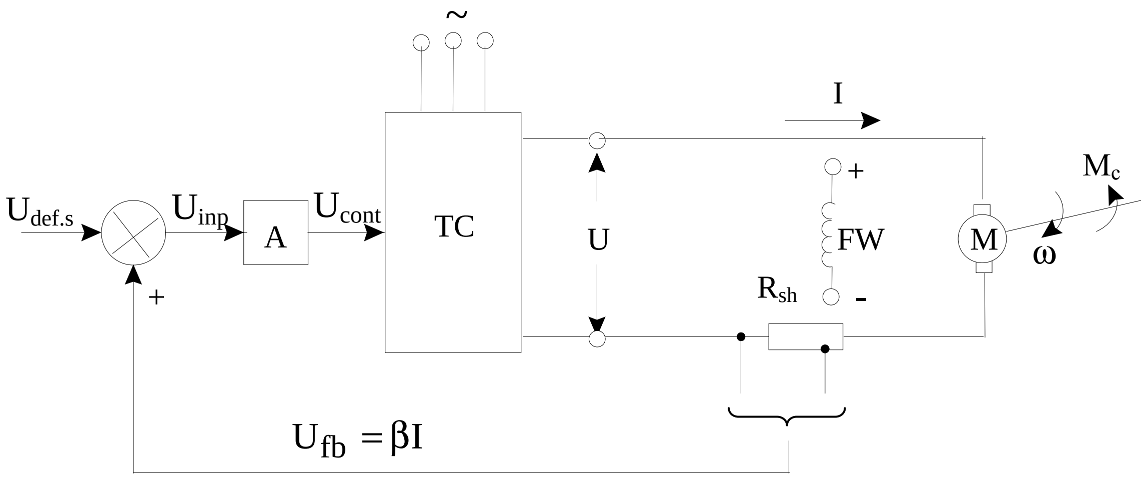


Fig. 2.26

Current sensor - shunt R_{sh} $\Delta U_{sh} = I \cdot R_{sh} \equiv I$,

The feedback current signal $U_{fb} = \beta I$

β - the coefficient of the current feedback (Ohms).

As R_{sh} can use motor commutating winding or compensatory winding. The signal at the input of the amplifier $U_{inp} = U_{def.s} + \beta I$.

Electromechanical and mechanical characteristics of the DCM in a closed system:

$$\omega = \frac{K_{cont} K_c U_{def.s}}{C} - \frac{I(R_a + R_c - K_s)}{C}, \tag{2.41}$$

$$\omega = \frac{K_{cont} K_c U_{def.s}}{C} - \frac{M(R_a + R_c - K_s)}{C^2}, \tag{2.42}$$

where $K_s = K_{cont} \cdot K_c \cdot \beta$ (Ом) - overall gain of the system.

Fig. 2.27 shows the characteristics of the DCM at different K_s.

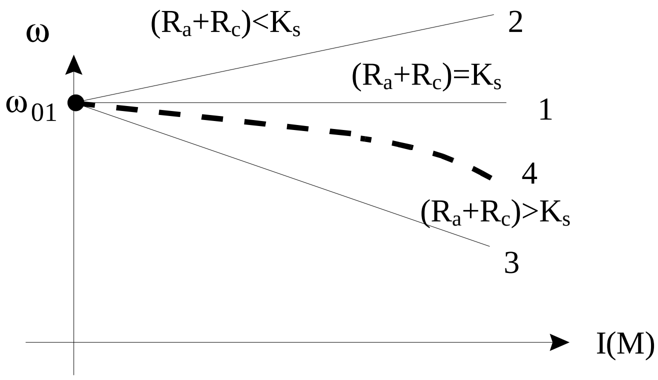


Fig. 2.27

Caracteristics analysis shows that at $(R_a + R_c) = K_s$ - absolutely rigid characteristic (line 1), $(R_a + R_c) < K_s$ - (line 2) - characteristics rigidity is positive; $(R_a + R_c) > K_s$ - (line 3) - characteristics rigidity is negative.

The actual characteristics are nonlinear due to variability K_s (curve 4). Therefore, this feedback is used in conjunction with others, such as the voltage.

2.7.4 Regulation (limitation) current and torque in a closed system TC-M by non-linear negative feedback of the current (Fig. 2.28). The feature of current cutoff (CCO) is added in the circuit.

Characteristic of CCO. $U'_{fb} = f(U_{fb})$ Up until the feedback signal $U_{fb} = \beta I$ is less than a predetermined reference voltage U_{ref}, signal $U'_{fb} = 0$. When $U_{fb} > U_{def}$ negative feedback signal U'_{fb} appears, which is input to the system.

U_{def} value is determined by a given current, from which begins regulation (current cutoff I X_{COFF}).

If $U_{def} = \beta I_{COFF} \geq \beta I$, $\quad U'_{fb} = 0$.

If $U_{def} = \beta I_{COFF} < \beta I$, $\quad U'_{fb} \neq 0$.

Fig. 2.29 are electromechanical and mechanical characteristics of the DCM seperate excitation at current limit with current cutoff.

On the section I $U`_{fb} = 0$, the system is open.

On the section II $U`_{fb} \neq 0$, the system is closed and is current and torque control.

The equation of section II electromechanical characteristics:

$$\omega = \frac{K_{cont} K_c U_{def.s}}{C} - \frac{(I - I_{COFF})(R_a + R_c + K_s)}{C}.$$

If ω = 0 current of stop I_{stop} is determined:

$$I_{stop} = I_{COFF} + K_{cont} K_c \frac{U_{def.s}}{R_a + R_c + K_s}.$$

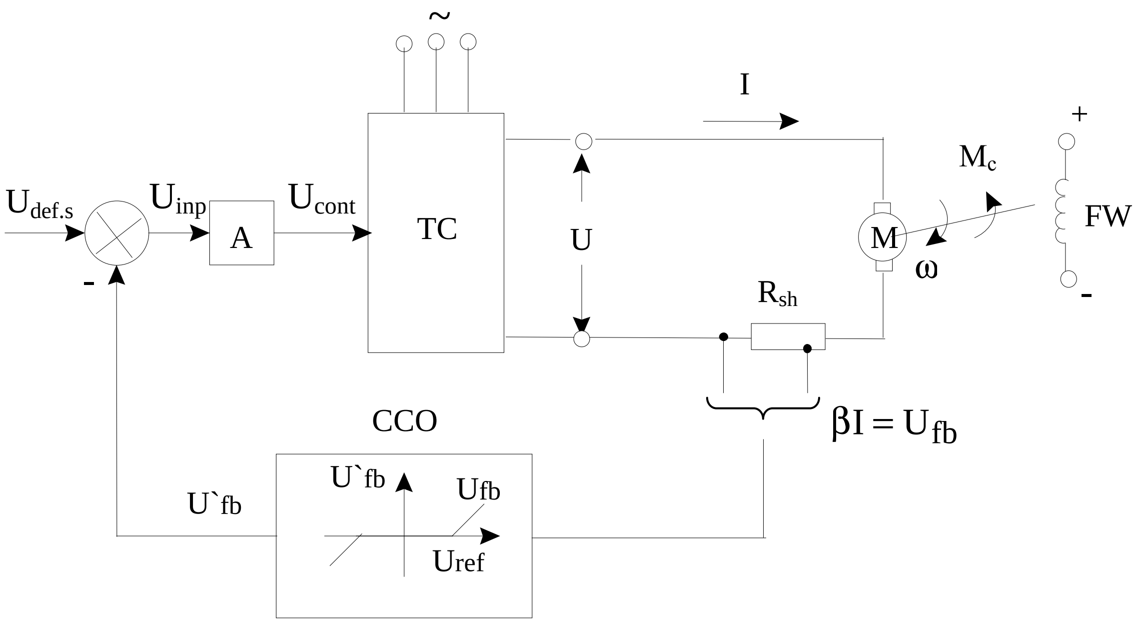


Fig. 2.28

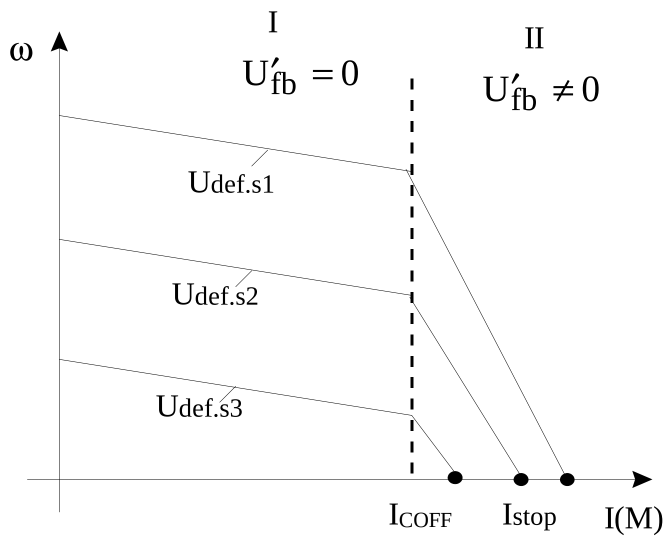


Fig. 2.29

When $K_s \to \infty$ - infinitely large increase of the system gain: $I_{stop} \to I_{COFF}$, ie characteristics are close to the vertical lines.

On the section II with $I > I_{COFF}$. signal $U`_{fb}$ increases and decreases U_{inp} and U_{cont}, converter EMF reduces and motor current and torque limite.

For very large K_s worsen the dynamic characteristics (time decay transient overshoot, oscillation).

2.8 Speed regulation of DCM separate excitation by shunting armature

Shown in Fig. 2.30 DCM separate excitation circuit with bypass armature produces rigid caracteristics for low speeds.

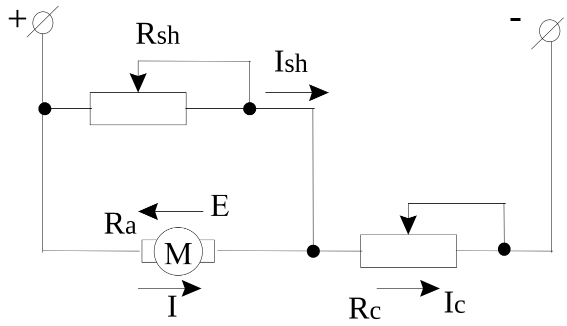


Fig. 2.30

Writing by the second Kirchhoff law of voltage equilibrium equations and EMF:

$$U = E + IR_a + I_c R_c;$$
$$U = I_{sh} R_{sh} + I_c R_c,$$

where $I_c = I + I_{sh}$, the equations of electromechanical and mechanical characteristics of DCM are obtained.

$$\omega = a\omega_0 - I\frac{R_a + aR_c}{K\Phi}, \tag{2.43}$$

$$\omega = a\omega_0 - M\frac{R_a + aR_c}{(K\Phi)^2}, \tag{2.44}$$

where $a = \dfrac{R_{sh}}{R_{sh} + R_c}$.

Analysis of (2.43, 2.44) indicates that the bypass armature angle speed of ideal idling decreases and falls rigidity of characteristics. Therefore, this method combines the speed control by varying the voltage (the first term of the equation) and the rheostat control in the armature circuit (the second term of equations) (2.43) (2.44).

Fig. 2.31 shows the characteristics of the DCM at armature shunting with the permanent shunt R_{sh} and changing R_c.

A_1 corresponds to the DCM mode when it does not consume the mains (motor operate in dynamic braking mode with the current I_1), in this case, the

EMF DCM balances voltage of mains and internal voltage drop in the armature $E = U + I R_a$.

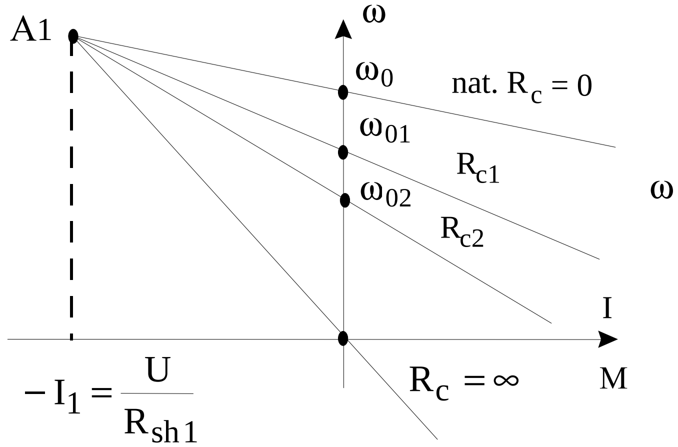


Fig. 2.31

If the value R_{sh} is changed, leaving unchanged R_c characteristics family of DCM separate excitation is obtained and presented at Fig.2.32.

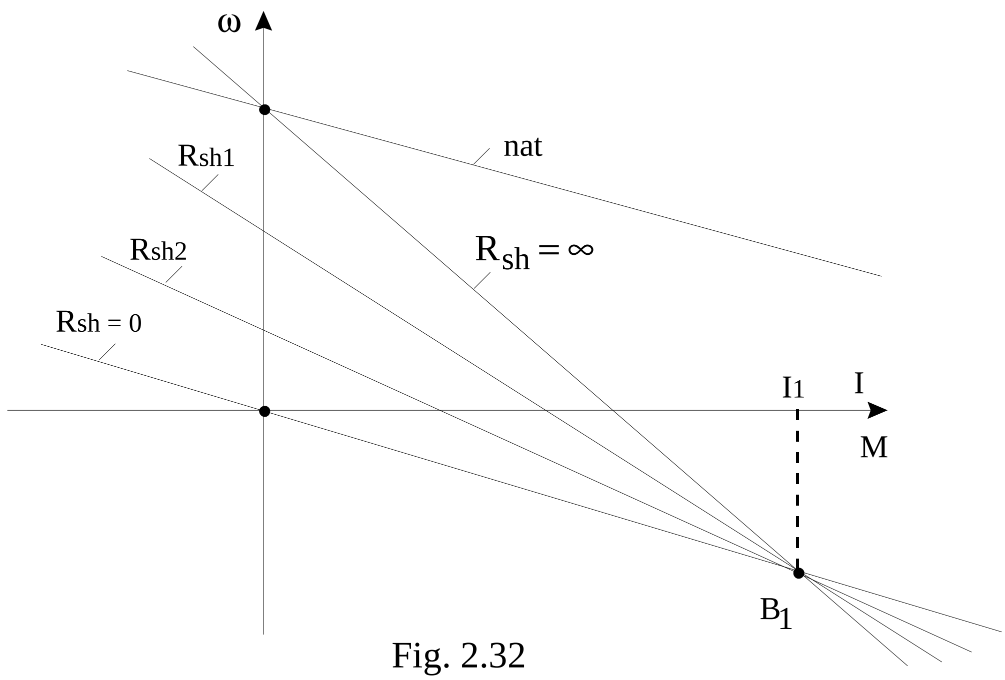


Fig. 2.32

Crossing artificial characteristics occurs at B_1, which is determined by the current $I_1 = \frac{U}{R_\Pi}$ flowing through the motor armature. In this case, the current through the shunt does not pass, because the EMF changing the sign, fully compensates for the internal voltage drop armature.

Speed control in this way is down from the basic, speed range D = 5 - 6, high characteristics rigidity of the DCM. Due to the significant loss of power in the resistors R_{sh} and R_c this method used to control the speed of the low power DCM at low speeds.

2.9 Drive coordinate regulation of the system current source - the motor (CS-M)

When the DCM is powered from the current source (CS), its value flowing on the armature is constant and independent of the source voltage, what determines the type of electromechanical and mechanical characteristics.

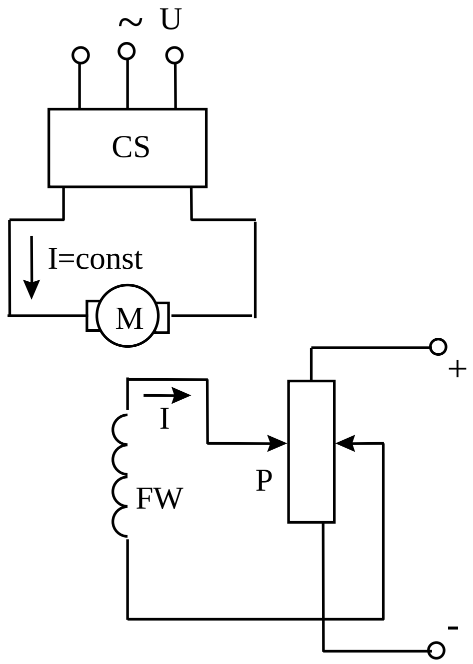


Fig. 2.33

Fig. 2.33 is a supply circuit of armature DCM from CS providing I = const. The current in the field winding (FW) can vary widely in value, but also in the direction of a potentiometer P.

Fig. 2.34, a represents by the electromechanical characteristics of the DCM, powered by CS, Fig. 2.34, b - the family of the mechanical characteristics of the DCM at different excitation current, and hence the magnetic flux (Φ_1, Φ_2, Φ_3).

These characteristics ensure consistent torque on the shaft of the DCM at any speed.

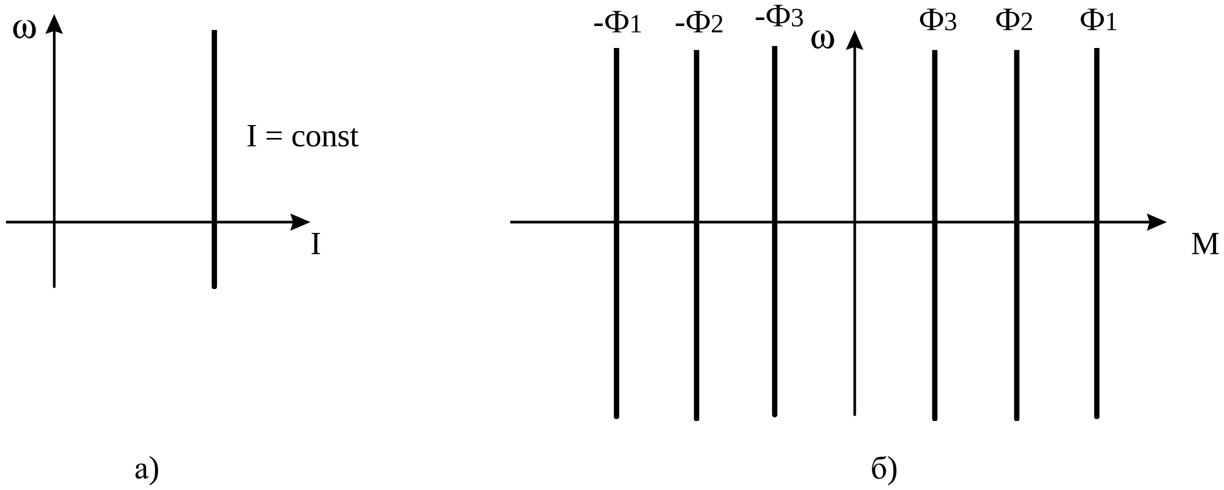


Fig. 2.34

If negative feedback on speed is introduced in this scheme, you can get sloping mechanical characteristics of the DCM separate excitation.

As shown in Fig. 2.35, the field winding of the DCM is powered by the operating coil of the magnetic amplifier (MA), magnetomotive force (MMF) is created by two control coils CWM (control winding of the torque), and CWS (control winding of the speed). Last included in the circuit of nonlinear feedback, which forms the tacho-generator BR, valve V and the speed defining potentiometer SDP.

The valve V starts to pass I_{sp} at a certain EMF tachometer, the corresponding angle speed ω_1. At this point, MDS of magnetic amplifier:

$$F_{cont} = F_{м} - F_{sp}$$

is reduced, field current I_f, magnetic flux Φ and torque are also reduced, and the mechanical characteristics at $\omega > \omega_1$ are inclined line as shown in Fig. 2.36.

Since at speeds $\omega < \omega_1$ tacho EMF less $U_{def.s}$, the current I_{sp} and MMF F_c equal to zero, the system is opened and the mechanical characteristics of the DCM - vertical lines.

When $\omega < \omega_1$, assuming linear dependences

$$\Phi = \alpha I_f ,$$

$$I_f = \beta F_{cont} ,$$

$$F_{sp} = K_{fb} \cdot \omega,$$

mechanical characteristics of the equation would be:

$$\omega = \frac{F_M}{K_{fb}} - \frac{M}{K_{fb} \cdot \alpha \cdot \beta \cdot K \cdot I}, \tag{2.45}$$

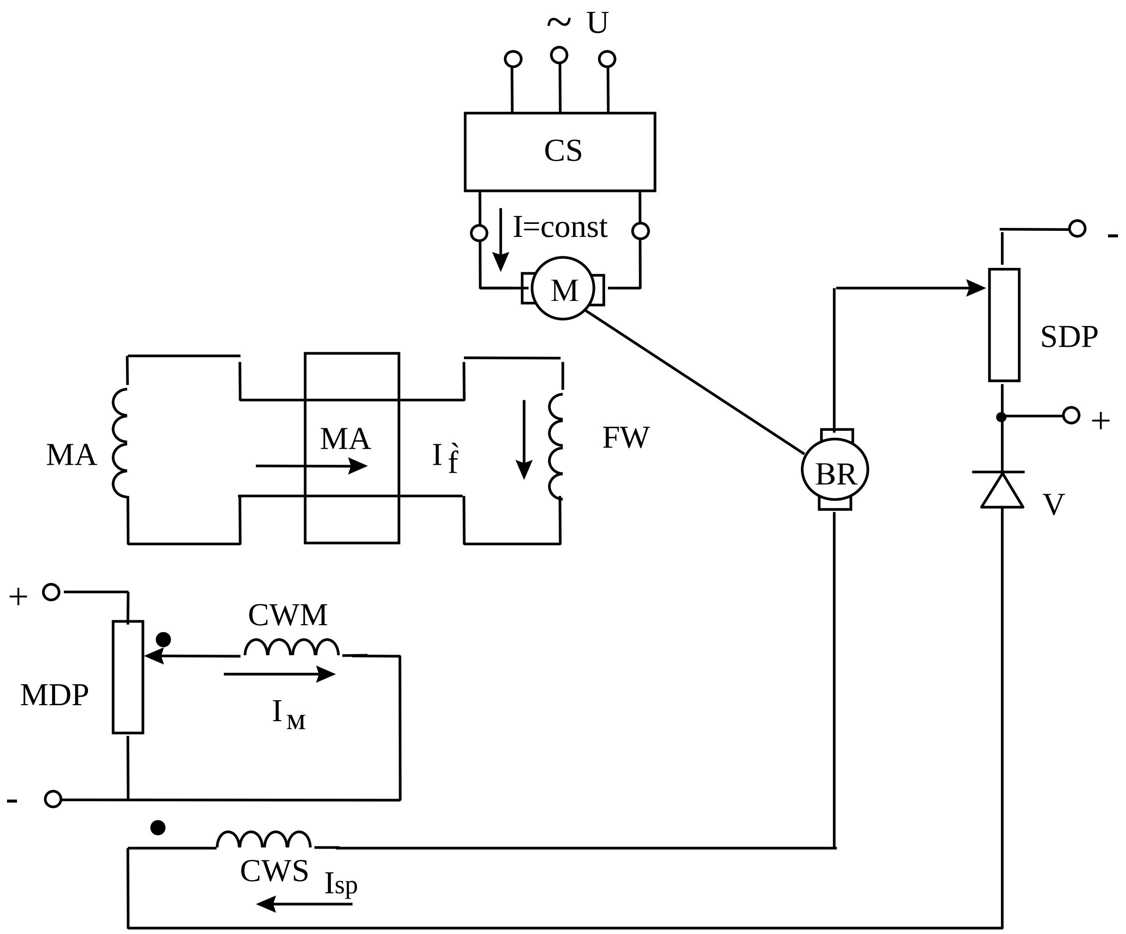


Fig. 2.35

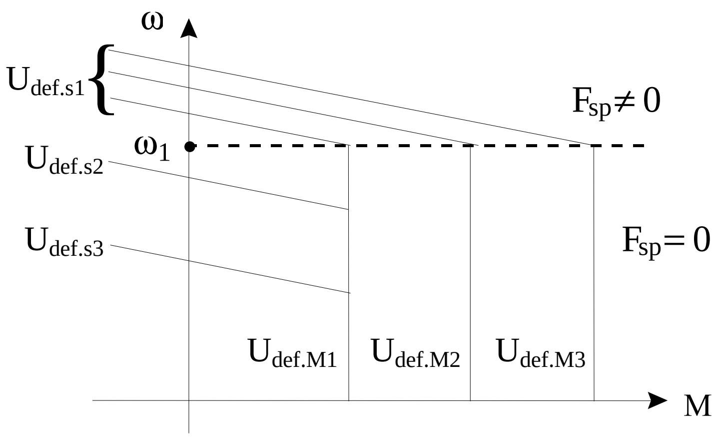


Fig. 2.36

where α, β, K_{fb} - transfer coefficients of the excitation circuit of the magnetic amplifier and a feedback circuit.

By changing the setting of the moment defining potentiometer (MDP), the torque could be adjust when $\omega < \omega_1$.

As a current source the inductive-capacitive circuits have received the greatest application (Fig. 2.37).

CS circuit formed by three capacitors with reactance X_c and three reactors X_L, which are equal to each other.

Neglecting the resistances of capacitors and reactors, we have:

$$\dot{U}_{line} = \dot{U}_c + \dot{U}_L,$$

$$\dot{I}_2 = \dot{I}_c - \dot{I}_L, \qquad \dot{I}_c = \frac{\dot{U}_c}{(-jX_c)}, \qquad \dot{I}_L = \frac{\dot{U}_L}{(jX_L)}.$$

where:

$$\dot{I}_2 = j\left(\frac{U_л}{X}\right).$$

Consequently, the current I_2, (load) is determined only by the circuit parameters and the mains voltage and independent from load. The system CS-M provides a large speed range (50 and above), has a high stability and smoothness control.

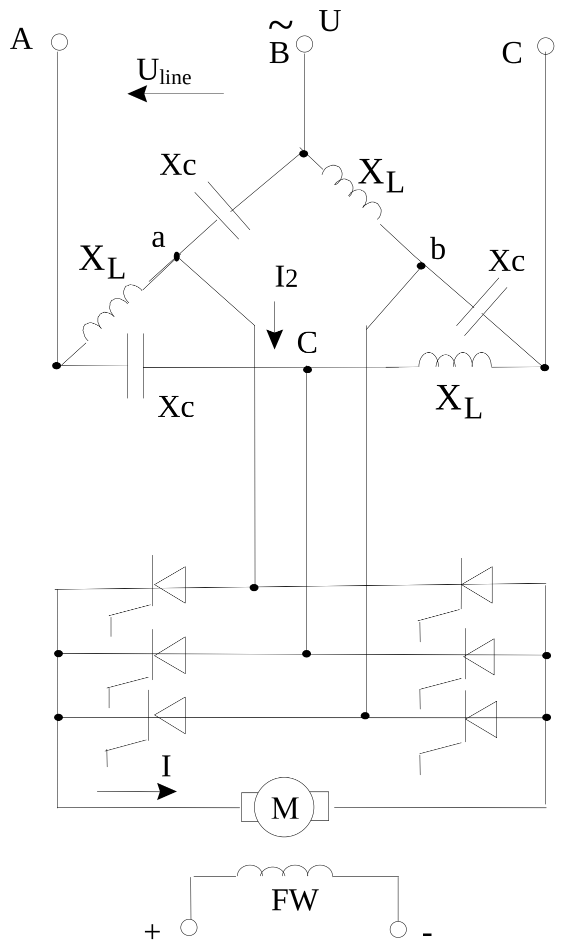


Fig.2.37

2.10 Pulse method of coordinates control

Pulse control method provides a periodic electric pulse parameters change: resistance or supply voltage. In particular, for the DCM can be applied pulse control resistance in the armature circuit, in the excitation circuit (the excitation current pulse change or flux change) or supply voltage.

2.10.1 Pulse control of resistance in the armature circuit

It occurs periodically switching (switching on - off) by a certain law switch K (Fig. 2.38).

There are two ways to control the switch:

a) pulse-width control;

b) pulse-frequency control.

When the pulse-width control the switching period key $T_к = t_{cl} + t_{op}$ remains constant and the ratio of t_{cl} to T_K changes.

$$\gamma = \frac{t_{cl}}{T_k} = \frac{t_{cl}}{(t_{cl} + t_{op})}, \tag{2.46}$$

which is called the duty factor γ.

When the pulse-frequency control t_{cl} = const, the commutation period $T_к$ of the switch changes, and consequently the frequency. Thus, γ - duty factor is indicative of the control mode. When the switch K is closed γ = 1 - the motor operates at the natural characteristic (Fig. 2.39) (line 1), when the switch K is opened γ = 0 - resistor R_{add} fully input - the artificial potentiometric response (line 2.) For intermediate values 0< γ < 1 mechanical caracteristics - lines 3-4.

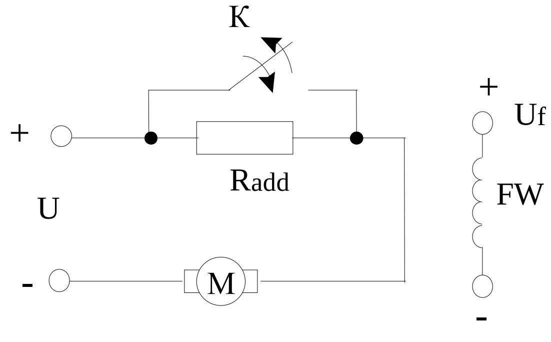


Fig. 2.38

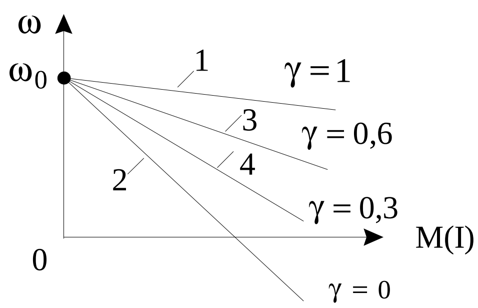


Fig. 2.39

The equation of the mechanical characteristics in pulse control

$$\omega = \frac{U}{K\Phi} - \frac{M}{(K\Phi)^2}[R_{add}(1-\gamma) + R_a]. \tag{2.47}$$

2.10.2 In pulsed magnetic flux regulation DCM separate excitation R_{add} and switch K are included in the field winding (Fig. 2.40)

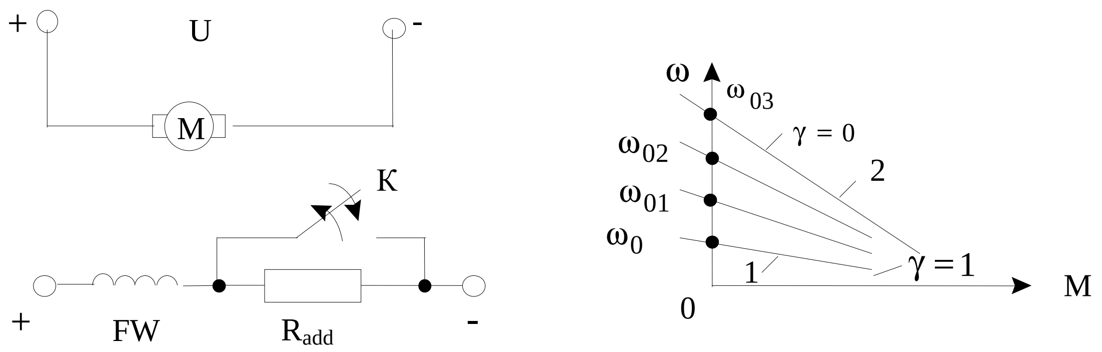


Fig. 2.40

The duty factor γ is adjustable $0 < \gamma < 1$. When $\gamma = 1$ R_{add} bypassed by switch K, which corresponds to the natural mechanical characteristics 1 presented on Fig. 2.40. When $\gamma = 0$ R_{add} constantly introduced in the circuit FW, I_f and Φ are reduced, and the speed ω_{03} increases - (artificial characteristic, line 2, Fig. 2.40).

Armature voltage U pulse control is presented by the scheme (Fig. 2.41), family of mechanical characteristics is shown in Fig. 2.41.

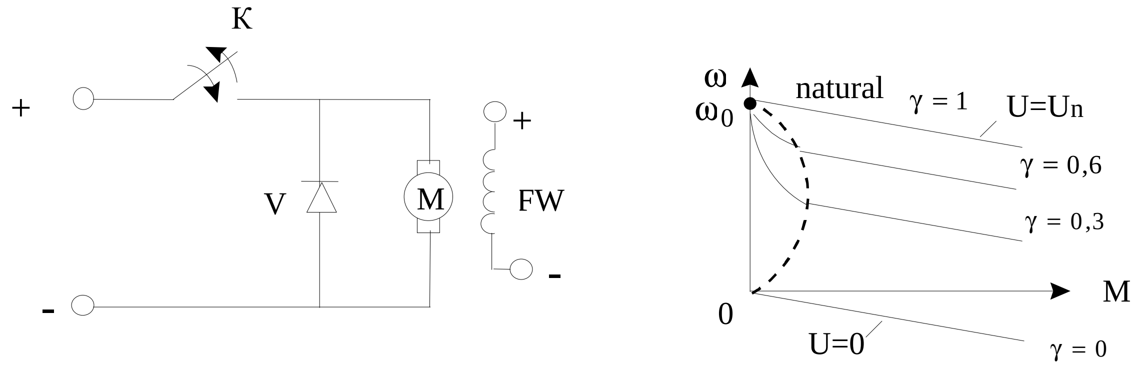


Fig. 2.41

When the switch K is permanently closed ($\gamma = 1$) the armature current flows under the influence of maince U (natural mechanical characteristics), the opened switch K - under the influence of EMF, closed in the diode V, while the current is pulsating. By adjusting the duty factor γ, it gets artificial characteristics, with $\gamma = 0$ - no voltage U is applied (circuit of dynamic braking mode) and the mechanical characteristic passes through the origin.

For small loads the interrupted current mode is possible, which occurs when the following boundary values of speed and power:

$$\omega_b = \omega_0 \gamma \left(1 - \frac{1-\gamma}{2T_a} \cdot T_k \right), \qquad (2.48)$$

$$I_b = I_{SC}\frac{\gamma(1-\gamma)}{2T_a}T_k, \tag{2.49}$$

where $T_a = \frac{L_a}{R_a}$ - electro-mechanical time constant of the armature circuit.

Only in the area of interrupted currents the mechanical characteristics are not straight, in the operating load range the mechanical characteristic equation is:

$$\omega = \frac{\gamma U}{K\Phi} - \frac{MR_a}{(K\Phi)^2}. \tag{2.50}$$

2.10.4 For pulse control various schemes of thyristor switches are used. The principle of thyristor switches operation for pulse control of resistance R is considered by the scheme (Fig. 2.42)

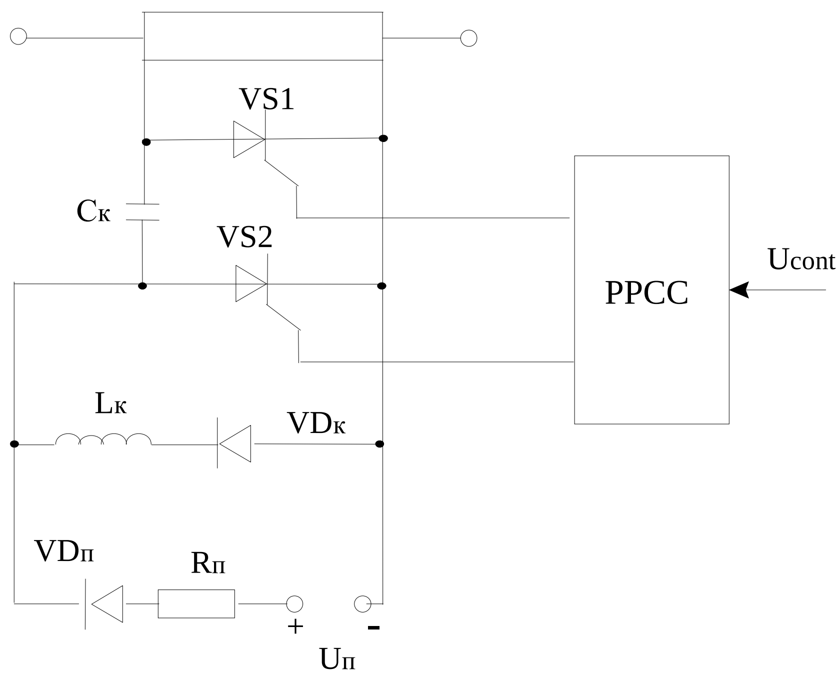


Fig. 2.42

Thyristor VS1 serves as a switch. Opening, VS1 shunts R, closing, enters in the circuit R. To close VS1 besides removing pulse of the control electrode (PPCC) the higher cathode potential than the anode potential must be provide. This is achieved by including an additional thyristor VS2 and switching elements $C_к$, $L_к$, diode $VD_к$, low-power DC power supply $U_п$ and a diode $VD_п$.

If the thyristor VS1 at initial position is opened, VS2 is closed and the capacitor $C_к$ is charged with the sign + on the lower plate, then to close the VS1 it’s need to remove impulse control from VS1 and submit it to the VS2, which will open, then cathode of VS1 is applied by plus of the voltage $C_к$ and the anode - minus and VS1 closes. Capacitor $C_к$ will charges through an open VS2 with plus of the upper plate.

If it removes the control pulse from VS2, it is closed to the end of the recharge $C_к$. Then, when a pulse on VS1 it will re-open bypassing R, and capacitor overcharging re-starts by the circuit $C_к$ - VS1 - $VD_к$ - $L_к$ until the potential of the lower plate $C_к$ becomes positive. For the initial charge $C_к$ is the source $U_п$, $VD_п$ or $R_п$.

For pulsed voltage control scheme of thyristor switch is applied shown in Fig. 2.43. Precharge the capacitor $C_к$ is made from U_c (+ on the upper plate).

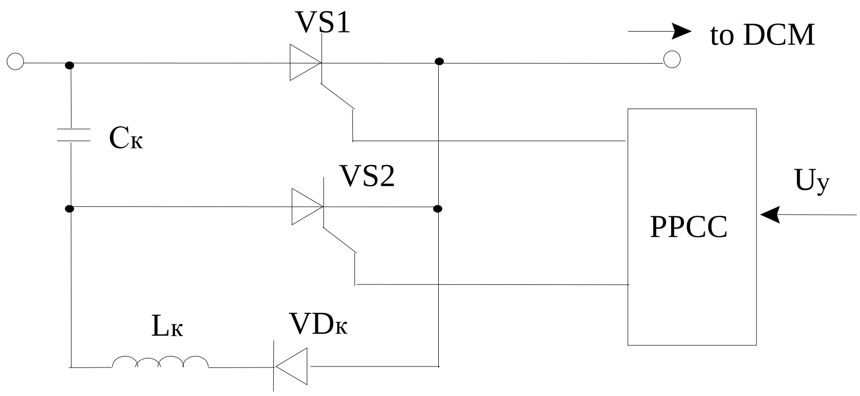


Fig. 2.43

If the VS1 is fed by a control pulse, VS1 will open and the motor is energized. At the same time through the VS1, $VD_к$, $L_к$ begins recharging the capacitor $C_к$ with + on the upper plate, so when a pulse on the VS2, VS1 closes. By varying the duty factor with the PPCC control pulses VS1, in concert with the pulse application VS2 a pulse voltage regulation is provided.

2.11 The drive of direct current motor series excitation

Circuit of the DCM is shown in Fig. 2.44.

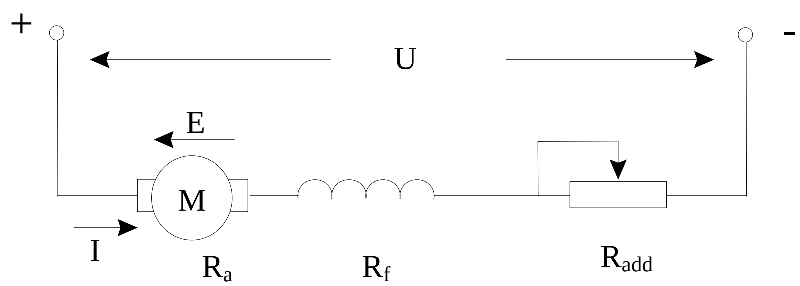


Fig. 2.44

DCM series excitation feature is the dependence of the magnetic flux Φ of the field current $I_f = I$, as shown in Fig. 2.45.

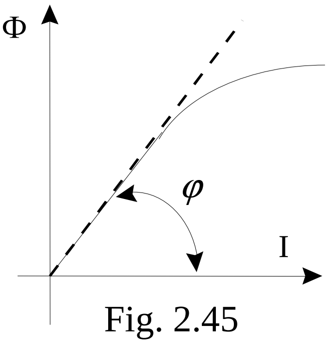


Fig. 2.45

To derive the equations of electromechanical and mechanical characteristics of the DCM series excitation, neglecting saturation, obtain:

$$\Phi = \alpha \cdot I,$$

where $\alpha = \mathrm{tg}\varphi$;

$M = K\Phi I = K\alpha I^2$, where $I = \sqrt{\dfrac{M}{K\alpha}}$. Then the equations of electro-mechanical and mechanical characteristics of the DCM series excitation can be

$$\omega = \frac{U}{K\alpha I} - \frac{R}{K\alpha}, \quad (2.51)$$

$$\omega = \frac{U}{\sqrt{K\alpha M}} - \frac{R}{K\alpha}. \quad (2.52)$$

Dependences $\omega = f(I)$ and $\omega = f(M)$ shown in Fig. 2.46 is a hyperbola with asymptotes: vertical – speed axis ω corresponding to the ideal mode of idling at $I \to 0$, horizontal asymptote - a straight line with $\omega_a = -\dfrac{R}{K\alpha}$ corresponding to the mode $I \to \infty$ and $M \to \infty$. The point of a short circuit on the characteristics (I_{SC}; M_{SC}) is determined by the condition $\omega = 0$:

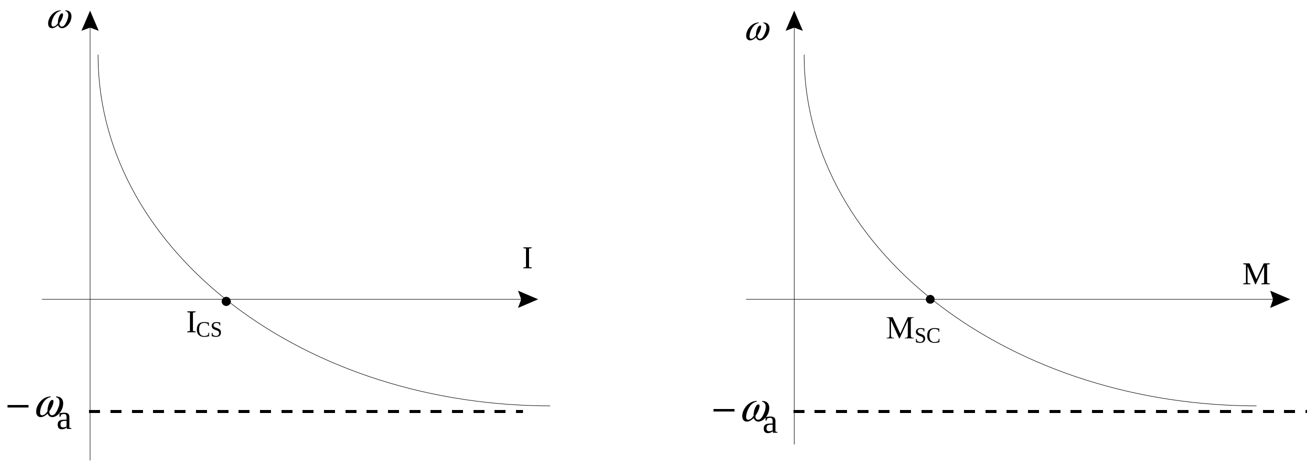


Fig. 2.46

$$\frac{U}{K\alpha I}-\frac{K}{K\alpha}=0,\ \text{where}\quad I_{SC}=\frac{U}{R};$$

$$\frac{U}{\sqrt{K\alpha M}}-\frac{R}{K\alpha}=0,\quad \text{where}\quad M_{SC}=\frac{U^2}{R^2}K\alpha\,.$$

Since the mechanical and electro-mechanical characteristics do not intersect the speed axis and do not pass in the second quadrant, DPT series excitation can not operate as a generator in parallel with the mains (during regenerative braking).

Ideal idle speed is determined by the residual magnetic flux Φ_{res}:

$$\omega_0=\frac{U}{K\Phi_{res}}$$

Equations (2.51) and (2. 52) have derived at the absence of saturation of the magnetic system, in fact DCM series excitation operate in nominal operation of the magnetization curve inflection, when Φ is much less and the speed ω - more, therfore as a rule characteristics do not pass region of negative speed and have the form (Fig. 2.47).

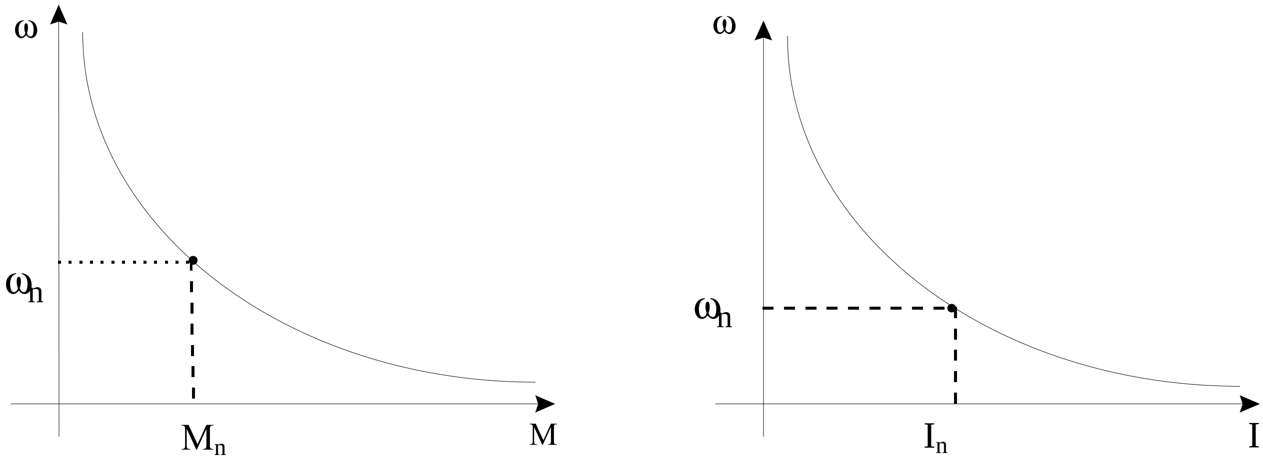


Fig. 2.47

Usually relative values of speed, torque and current are used and also universal characteristics (Fig. 2.49), where

$$\omega^*=\frac{\omega}{\omega_n};\ \ I^*=\frac{I}{I_n};\quad M^*=\frac{M}{M_n}\ .$$

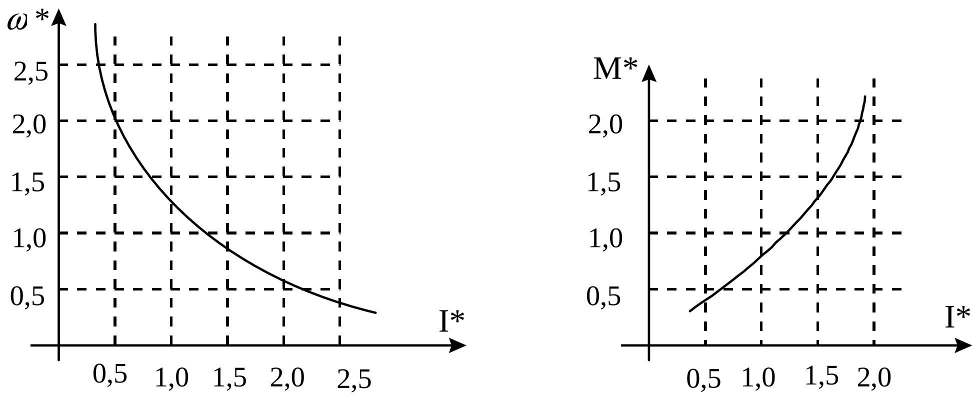


Fig. 2.48

2.12 Coordinates control methods of the DCM series excitation

2.12.1 Regulation of ω, I, M is made by the resistors in the armature circuit as shown in Fig. 2.44. Represent the equations of natural and artificial electromechanical characteristics as:

$$\omega_{nat} = \frac{U}{K\Phi} - I\frac{(R_a + R_f)}{K\Phi}, \tag{2.53}$$

$$\omega_{art} = \frac{U}{K\Phi} - I\frac{(R_a + R_f + R_{add})}{K\Phi}, \tag{2.54}$$

Speed ratio on the natural ($\omega_{nat.i}$) and artificial ($\omega_{art.i}$) is determined by the characteristics of a current I_i:

$$\omega_{art.i} = \omega_{nat.i}\frac{U - I_i(R_a + R_f + R_{add})}{U - I_i(R_a + R_f)}. \tag{2.55}$$

If the natural electromechanical characteristics and magnitude of additional resistors R_{add1}; R_{add2}; $R_{ap.}$ are given, then for a number of current values $I_1, I_2, ... I_i$ artificial characteristics (Fig. 2.49) are calculated by the expression (2.55).

The Universal electromechanical characteristics $\omega^* = f(I^*)$ and $M^*=f(I^*)$ are used to build mechanical natural and artificial characteristics, presented on Fig. 2.50.

The resistance value of the armature circuit for DCM series excitation is determined:

$$R_a + R_f \approx 0{,}75\frac{U_n}{I_n}(1 - \eta_y) = 0{,}75 R_n (1 - \eta_n). \tag{2.56}$$

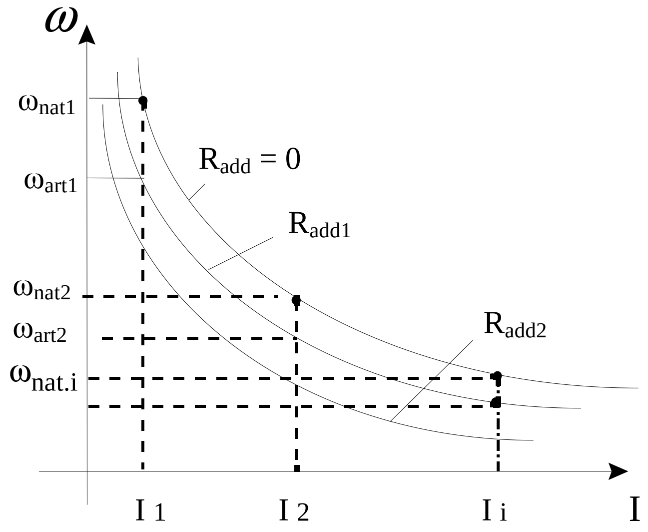


Fig. 2.49

If the value of R_{add} is needed to determine, by given electromechanical characteristics, calculation of R_{add} produced by the expression:

$$R_{add} = \left(1 - \frac{\omega_{n.i}}{\omega_{nat.i}}\right)\left(\frac{U}{I_i} - R_a - R_f\right). \qquad (2.57)$$

If a mechanical rheostat (artificial) characteristic is specified $\omega_{art} = f(M)$ then at the first by the universal characteristics $M^* = f(I^*)$ the value of the current I_i is determined and R_{add} is calculated by the expression (2. 57). In exceptional cases, to calculate R_{add} graphic analytical methods are used.

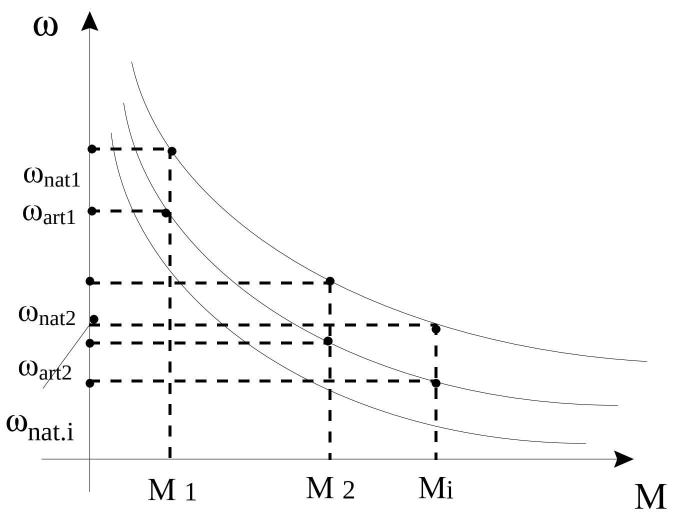


Fig. 2.50

2.12.2 Regulation of coordinates ω, I, M of the DCM series excitation by the variation of the magnetic flux (Φ).

Change F is effected by shunt the winding circuit resistor by the R_{sh} (Fig. 2.51).

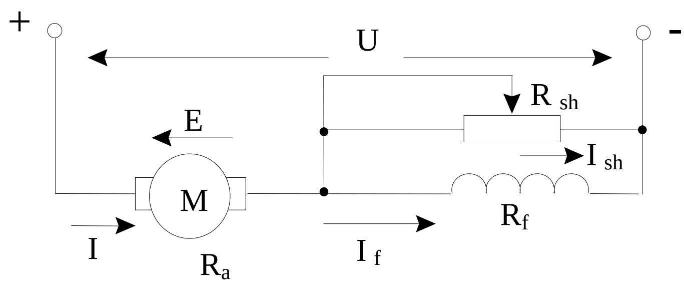


Fig. 2.51

Reduction R_{sh} leads to an increase of the current I_{sh} and reduce the magnetic flux Φ, consequently, high speed ω. Fig. 2.52 shows a family of mechanical characteristics of the DCM series excitation obtained at different values R_{sh} .

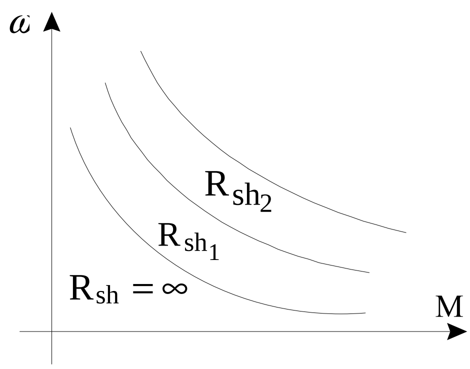


Fig. 2.52

Natural mechanical characteristics is corresponded to the mode of the open-circuit shunt resistor $(R_{sh} = \infty)$. Artificial mechanical characteristics of the attenuation of the magnetic flux are located above the natural, the speed axis is an asymptote of all characteristics.

2.12.3 Regulation of cordinates (ω, I, M) of the DCM series excitation by the voltage changes.

Control is performed as shown in Fig. 2.53, in which the controlled voltage source is a thyristor converter, the output voltage U is regulated by changing the input control signal U_Y.

Mechanical characteristics of the DCM series excitation at different output voltage U are shown in Fig. 2.54. Since the regulation is possible only below the basic speed, artificial characteristics are below the natural corresponding U_n. Characteristics rigidity is not reduced. Axis speed is an asymptote of characteristics. A special case of this method for controlling the speed of the

DCM is to switch the connection of the individual motors in multi-motor drive. Fig. 2.55 are diagrams enable the DCM series excitation at full voltage U_n (parallel connection) and $U_n/2$ (series connection), corresponding the speed $\omega_n / 2$. These schemes are used in the electric transport, iron and steel production.

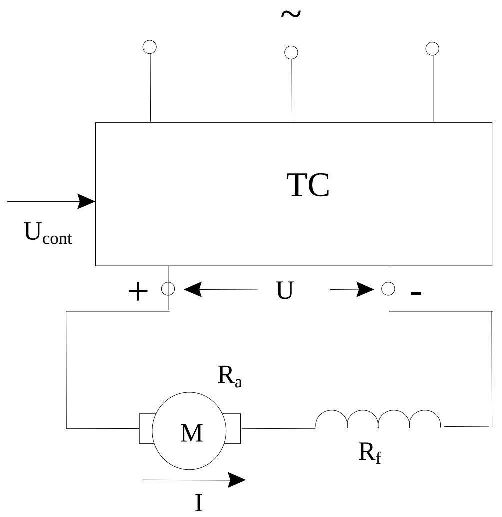


Fig. 2.53

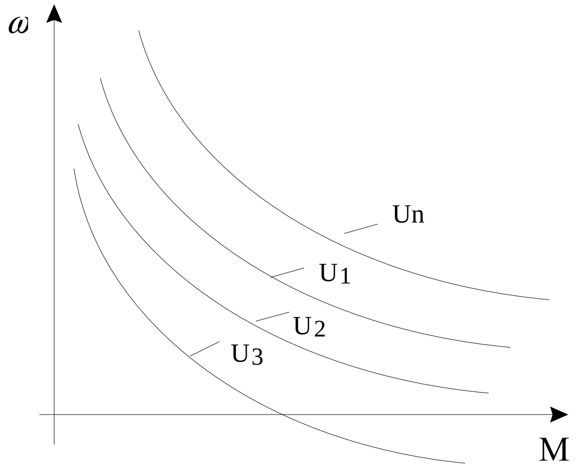


Fig. 2.54

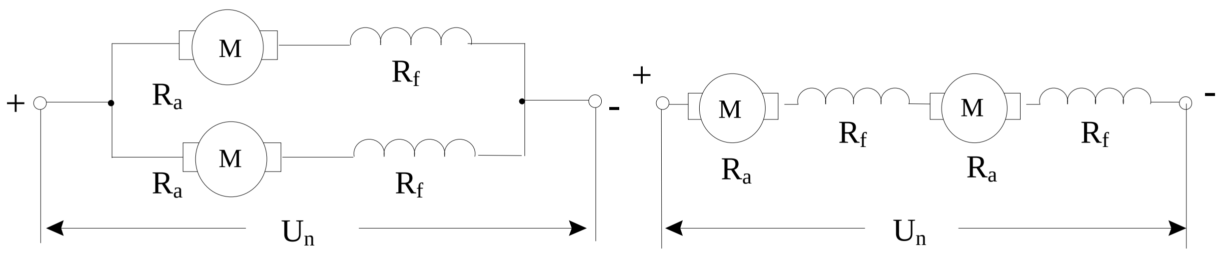


Fig. 2.55

2.12.4 Speed control of the DCM series excitation by shunting the armature.

In some cases, it’s required to obtain low-speed or fixed speed perfect idling of the motor series excitation. It uses a shunting armature winding scheme (Fig. 2.56).

The low voltage U feed the armature and the characteristics of the DCM are located below the natural. When $I = 0 \quad I_f = I_c \neq 0$, as $I_f = I_{sh}$, therefore $\Phi \neq 0$ and the motor has a ideal idling ω_0.

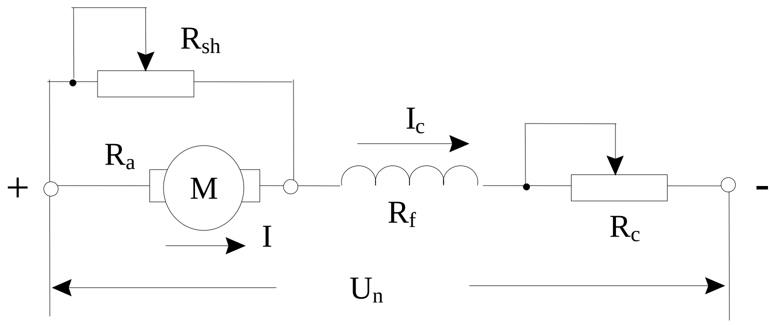


Fig. 2.56

At a speed $\omega > \omega_0$ the armature current changes direction and $I_f = I_c$ and the speed decreases. When $I = -\frac{U}{R_{sh}}$, then Φ tends to zero as well $\omega \to \infty$. Fig. 2.57 shows the electromechanical characteristics of the DPT series excitation, obtained by shunting the armature resistance, which implies that the vertical line with the abscissa is the asymptote of the electromechanical characteristics.

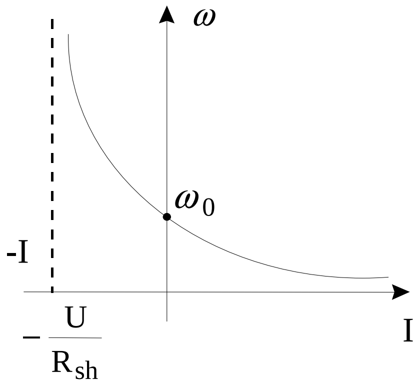


Fig. 2.57

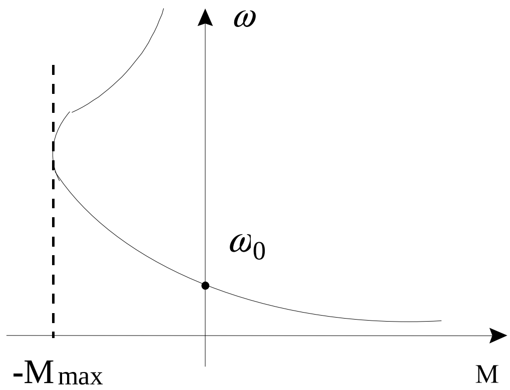


Fig. 2.58

Let’s analyze the mechanical characteristics of the DCM series excitation obtained by shunting the armature (Fig. 2.58). Since the torque M depends on the current I and the magnetic flux Φ, (M = KΦI), if the direction of the current changes the torque sign also changes which reaches a maximum value $-M_{max}$ and then begins to fall, since $I = -\frac{U}{R_{sh}}$ the excitation current and Φ tend to zero and $M \to 0$. Consequently, the speed axis is an asymptote of the mechanical characteristic of the DCM series excitation in the second quadrant.

The scheme of armature bypass is used to for low speeds for large torque (electric vehicles, lifting machinery).

2.13 Braking DPT series excitation

Plugging (work of generator in series with the mains).

There are two possible ways:

1. Changing the polarity of U at armature while maintaining the direction of the current in the field winding. Accompanied by a transition from the characteristic 1 (point a) on the characteristic 2 (point b). Fig. 2.59 presents the mechanical properties of the DCM series excitation (1) and operating mechanism M_C. On the site вс - mode of plugging.

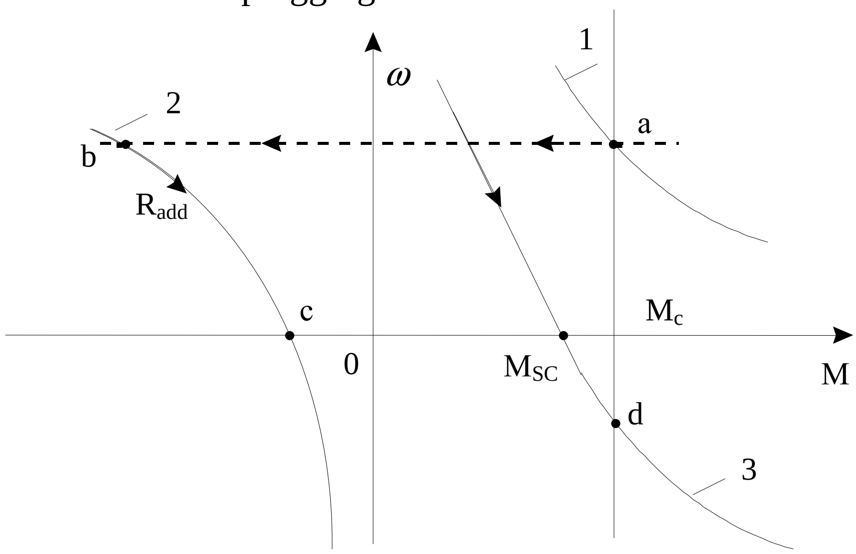


Fig. 2.59

2. If DCM operates in motor mode of characteristic 1 in point a and the R_{add} is introduced in the armature circuit DCM will work on the characteristic 3. Since in this case $M_{motor} < M_c$, the motor will brake and then accelerate in the opposite direction to the point d, when $M_{motor} = M_c$. This mode also applies to the mode of plugging.

Dynamic braking of the DCM series excitation.

There are two possible schemes include: separate excitation (Fig. 2.60, a) and a self-excited (Fig. 2.60, b).

In the first case, the mechanical characteristics shown in Fig. 2.61 correspond to the characteristics of the DCM separate excitation.

In the dynamic braking of the DCM series excitation (scheme 2.60, b) with self-excitation it is necessary that the residual magnetic flux Φ_{res} coincided with the flux of excitation Φ_f, and the speed $\omega \neq 0$. Fig. 2.62 presents the mechanical characteristics of the DCM series excitation in the mode of self-excitation.

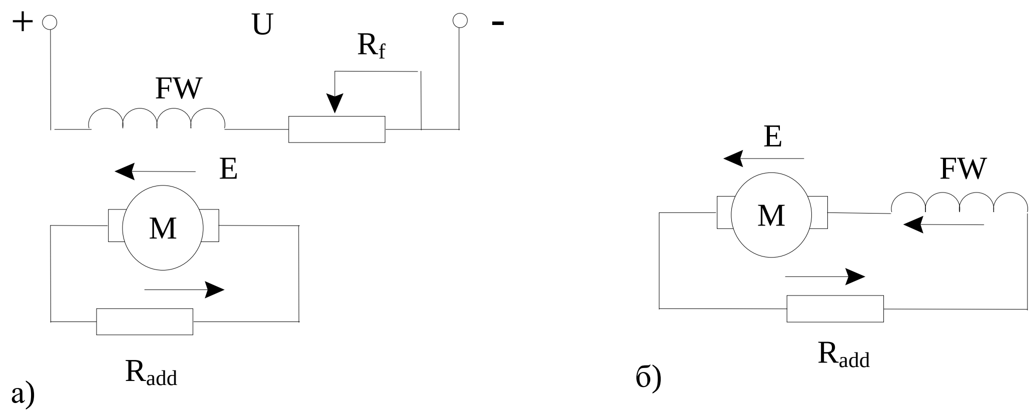


Fig. 2.60

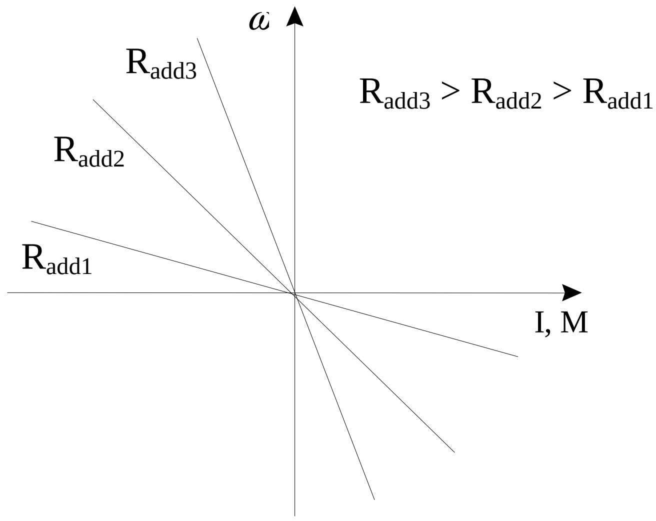


Fig. 2.61

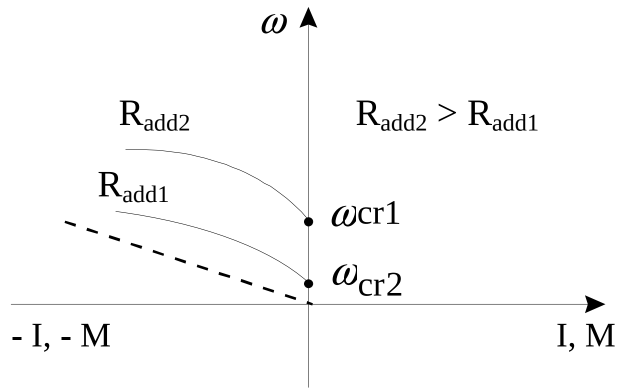


Fig. 2.62

Each resistance value R_{add} has its own critical speed ω_{cr}. For small values ω_{cr}, if $R_{add} < R_{add1}$ the self-excitation does not occur.

This mode of braking of the DCM series excitation is applied to heavy braking in electric vehicles and lifting mechanisms.

2.14 Features DCM mixed excitation

Circuit of the DCM mixed excitation is presented in Fig.2.63.

The motor has two windings of excitation: serial (SWE) and independent (IWE), which may be included as a parallel to a single voltage source U.

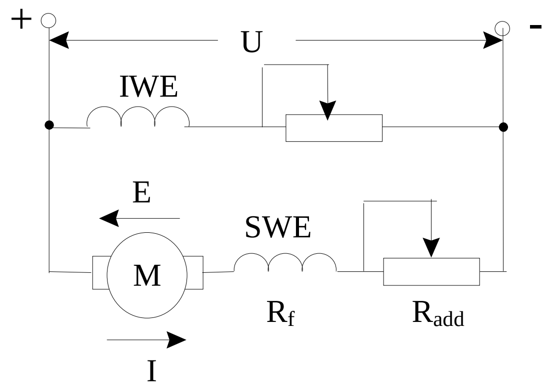


Fig. 2.63

The magnetic flux motor Φ is created by two components: Φ_{IWE} - independent of the load current and Φ_{SWE} - proportional to the load current I, as shown in Fig. 2.64.

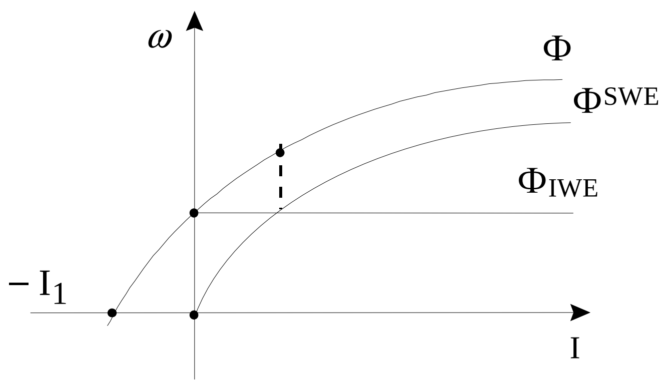


Fig. 2.64

When I =- I_1 magnetic flux Φ = 0, the magnetic system is demagnetized. The equations of electromechanical and mechanical characteristics are of the form

$$\omega = \frac{U}{K\Phi(I)} - I \cdot \frac{R}{K\Phi(I)}; \quad \omega = \frac{U}{K\Phi(I)} - M \cdot \frac{R}{[K\Phi(I)]^2}.$$

Electromechanical and mechanical characteristics are presented in Fig. 2.65 and Fig. 2.66. Performance of analysis has shown that the I = $-I_1$, Φ = 0 and the speed tends to ∞.

When $\omega = \omega_0$ the torque M = 0 when the speed is changed $\omega_0 < \omega < \infty$, and then torque changes to $-M_{max}$ and then decreases to zero.

DCM mixed excitation combines the properties of the DCM seperate and series excitation works in all modes discussed above: idle, short circuit, motor, generator, in series, in parallel with the mains and mains independent. Regulation is carried out by all means considered: changes in Φ, the armature current, voltage. The low technical and economic performance of the DPT mixed excitation (high weight, cost, size) lead to the fact that it is rarely used in electric drives.

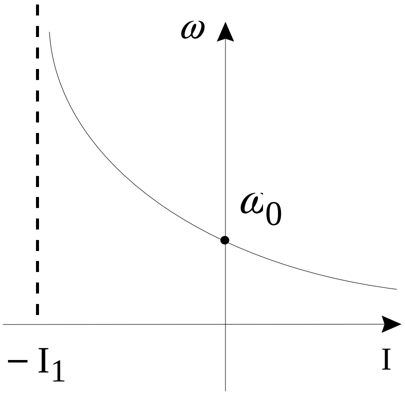


Fig. 2.65

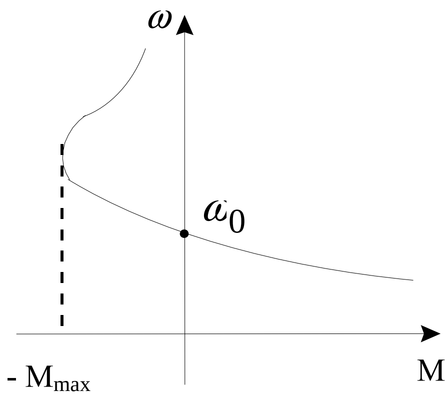


Fig. 2.66

3 ELECTRIC DRIVES WITH INDUCTION MOTORS

Three-phase induction motors (IM) were widely used in motor drives due to their simple design, operational reliability, low overall and cost indicators. With the development of power electronics (thyristor converters of frequency and voltage) IM are started to be used in regulated electric drives.

3.1 Mathematical description of the processes in the induction motor based on generalized electrical machine

Fig. 3.1 is a diagram of a three-phase induction motor with a wound rotor and the corresponding diagram of a general electric machine (two-phase model).

The equations of electromechanical and mechanical characteristics in the dynamic mode of the drive have the form:

$$\begin{cases} U_i = R_i i + \sum\limits_{j=1\alpha}^{2q} L_{i,j}\dfrac{di_j}{dt} + \omega \sum\limits_{j=1\alpha}^{2q} \dfrac{\alpha L_{ij}}{dt\rho}\cdot i_j, \\ M = \dfrac{1}{2}\sum\limits_{j=1\alpha}^{2q} i_i \cdot \sum\limits_{j=1\alpha}^{2q} \dfrac{dL_{ij}}{dt\rho}, \end{cases} \tag{3.1}$$

can be expressed for IM wound rotor in the form of:

$$\begin{cases} U_1 = \dfrac{R_1 L_2 \psi_1}{L_1 L_2 - L_{1,2}{}^2} - \dfrac{R_1 L_{1,2}\ \psi_2}{L_1 L_2 - L_{1,2}{}^2} + \dfrac{d\psi_1}{dt} + j\omega_0\psi_1; \\ O = \dfrac{R_{2\Sigma}^{`}\ L_{1,2}\psi_1}{L_1 L_2 - L_{1,2}^2} + \dfrac{d\psi_2}{dt} + j(\omega_0 - \omega)\psi_2; \\ M = \dfrac{P_n L_{1,2}}{L_1 L_2 - L_{1,2}^2}\sum \psi_1 \psi_2 . \end{cases} \tag{3.2}$$

For the analysis of static modes of induction motor will take:

$$\frac{d\psi_1}{dt} = 0; \qquad \frac{d\psi_2}{dt} = 0.$$

Then electromechanical characteristics equation of IM in static mode can be expressed:

$$U_1 = \dot{I}_1(R_1 + jX_1) + jI_\mu X_\mu,$$

$$O = I_2^{`}(R_{2\Sigma}^{`} + jX_2^{`}S) + jI_\mu X_\mu S. \tag{3.3}$$

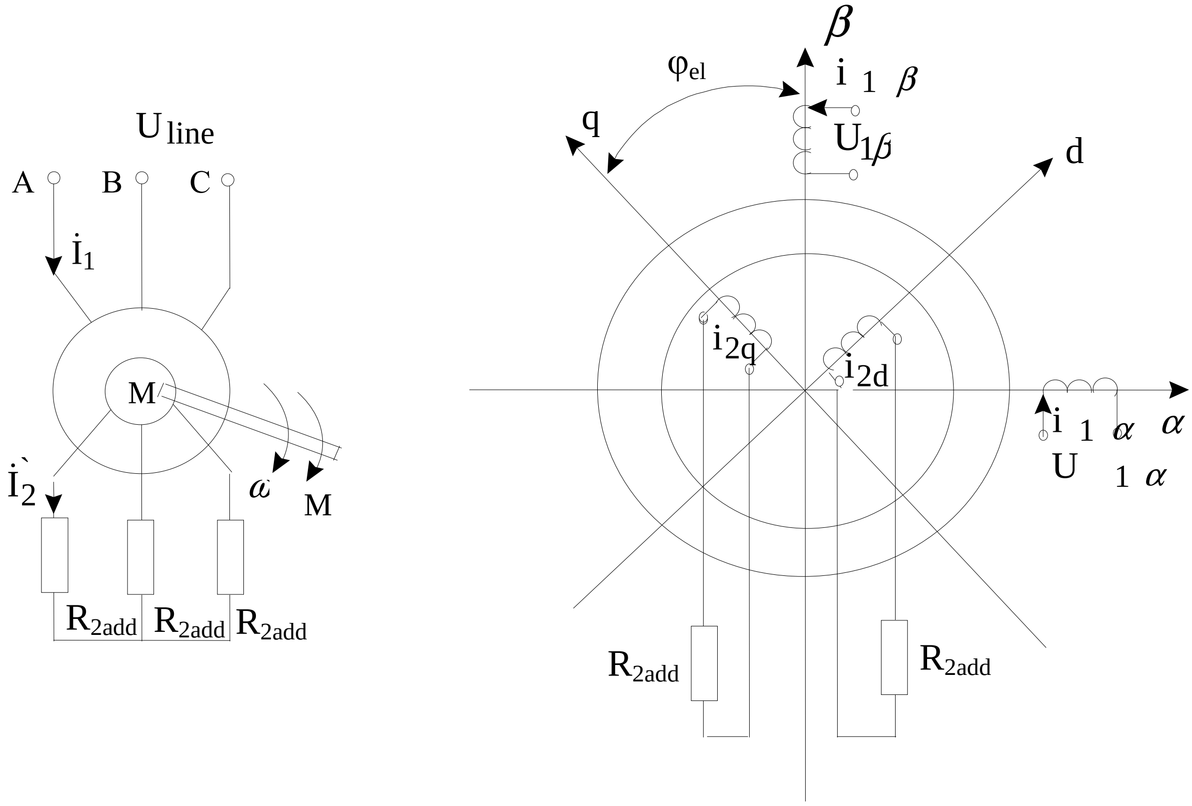


Fig. 3.1

These equations can be obtained on the basis of the phase equivalent circuit IM shown in Fig. 3.2.

In the equivalent circuit the magnetizing circuit put to the contacts of the supply voltage, and it does not take into account the voltage drop across the resistor R_1 from the magnetizing current $I\mu$. However, the error introduced by this assumption does not exceed 5%.

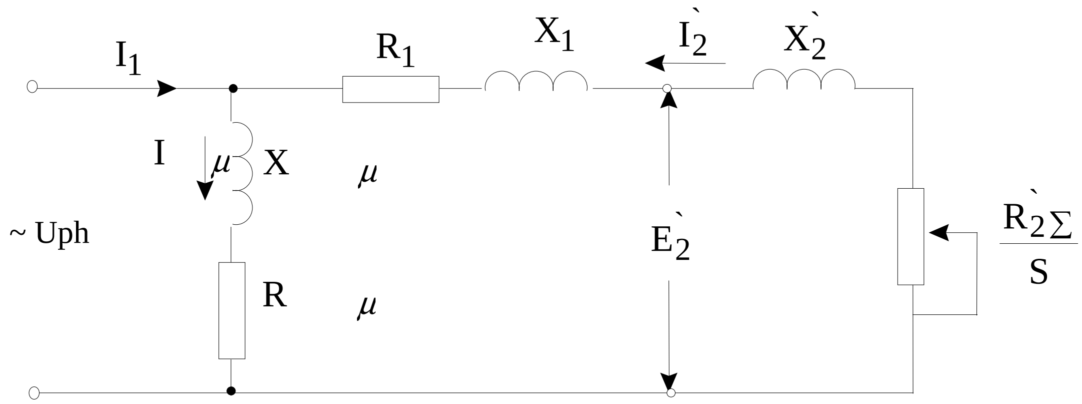


Fig. 3.2

In the equivalent circuit of the phase IM next symbols are accepted:

R_1 - the active phase resistance of the stator winding;

$R'_{2\Sigma} = R'_2 + R_{2add}$ - reduced resistance of the rotor phase, including the additional resistance of the resistor;

X_1 - phase stator inductance;

X'_2 - reduced inductance phase of the rotor;

$X_1 + X'_2 = X_{SC}$ - inductive phase impedance of short circuit;

X_μ, R_μ - respectively active and inductive resistance of magnetizing circuit, $R_\mu \approx 0$.

Slip of induction motor:

$$S = \frac{\omega_0 - \omega}{\omega_0},$$

where: $\omega_0 = \frac{2\pi f_1}{P_n}$ - angle speed of the rotating magnetic field (synchronous speed).

f_1 – the frequency of the voltage supply;

P_n - the number of IM pole pairs;

$\omega = \omega_0(1-S)$ - the angle speed of the shaft IM.

The equilibrium equations of the voltage and EMF on the equivalent circuit can be written:

$$U_{ph} = R_1\dot{I}_1 + jX_1 I_1 + E_1;$$

$$-E_2^{`} = \frac{R_{2\Sigma}^{`}}{S} I_2^{`} + jX_2^{`} I_2^{`};$$

$$E_1 = E_2^{`} = jI_\mu X_\mu,$$

and then the equation of electromechanical characteristics of IM can be written as:

$$I'_2 = \frac{U_{ph}}{\sqrt{\left(R_1 + \frac{R'_{2\Sigma}}{S}\right)^2 + \left(X_1 + X'_2\right)^2}} = \frac{U_{ph}}{\sqrt{\left(R_1 + \frac{R'_{2\Sigma}}{S}\right)^2 + X_{SC}^2}},$$

$$I_1 = I_2^{`} + I_\mu.$$

Fig. 3.3 presents the electromechanical characteristics of IM as dependences: $\omega = f(I_1)$, $\omega = f(I_2^{`})$, $S = f(I_2^{`})$.

Will analyze the characteristics.

1. At S = 0; $\omega = \omega_0$; $I_2^{`} = 0$; $I_1 = I_0$ - the point of ideal idling.

2. At S = 1; $\omega = 0$; $I_1 = I_{SC} = I_{start}$ - the point of short circuit.

3. At $S_1 = -\frac{R_2^`}{R_1}$; $\omega_1 = \omega_0(1 - S_1)$; $I_2^{'} = I_{max} = \frac{U_{ph}}{X_{SC}}$ - the point of maximum current of the rotor, which lies in the negative side of the slip.

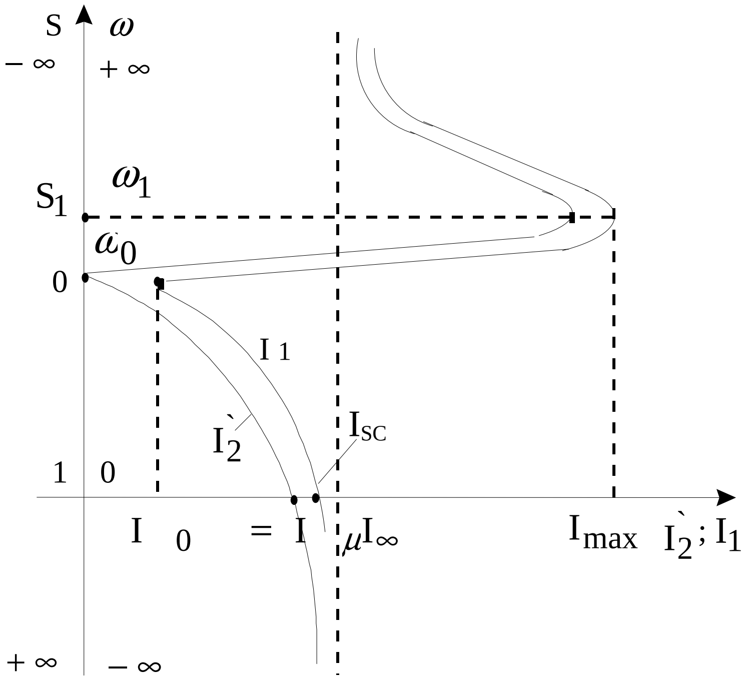


Fig. 3.3

4. At $S \to \pm\infty$, $\omega \to \mp\infty$ $I_2^{'} \to I_\infty = \frac{U_{ph}}{\sqrt{R_1^2 + X_{SC}{}^2}}$.

To construct the mechanical characteristics of IM consider the power balance in the rotor circuit.

Power losses in the rotor circuit:

$$\Delta P_2 = P_{em} - P_2 = M\omega_0 - M\omega = M\omega_0 S,$$

where P_{em} - electromagnetic power,

P_2 - useful mechanical shaft power.

Since the losses in the rotor ΔP_2 depends on S, they are called lossy slip.

On the other hand $\Delta P_2 = 3I_2^{'2}R_2^{'}$, then $M = \frac{3I_2^{`2} R_2^{`}}{\omega_0 \cdot S}$, substitute $I_2^{`}$, get:

$$M = \frac{3U_{ph}^2 R_2^{'}}{\omega_0 S\left[\left(R_1 + \frac{R_2^{'}}{S}\right)^2 + X_{SC}{}^2\right]}$$

- the equation of the IM mechanical characteristic. Analyzing the equation for max (finding the derivative $\frac{dM}{dS}$ and equating to zero), we get the extremes of the function defined by the critical torque and slip:

$$M_k = \frac{3U_{ph}}{2\omega_0\left[R_1 \pm \sqrt{R_1^2 + X_{SC}^2}\right]}; \quad S_k = \pm\frac{R_2^{'}}{\sqrt{R_1^2 + X_{SC}^2}};$$

+ - relates to sides where S > 0;

– - relates to sides where S < 0.

Dividing M by M_K and transforming, we obtain the mechanical characteristics of IM in the form of (specified Kloss formula):

$$M = \frac{2M_k\left(1 + \frac{R_1}{R_2^{`}} \cdot S_k\right)}{\frac{S}{S_k} + \frac{S_k}{S} + \frac{2R_1}{R_2^{`}} S_k}. \qquad (3.4)$$

If neglecting the stator resistance R_1, obtain the approximate equation of mechanical characteristics of IM:

$$M = \frac{2M_k}{\frac{S}{S_k} + \frac{S_k}{S}}; \qquad (3.5)$$

$$M_k = 3U_{ph}{}^2 / (2\omega_0 X_{SC});$$

$$S_k = \frac{R_2^{'}}{X_{SC}}.$$

Fig. 3.4 is a mechanical characteristic of IM in different modes of operation.

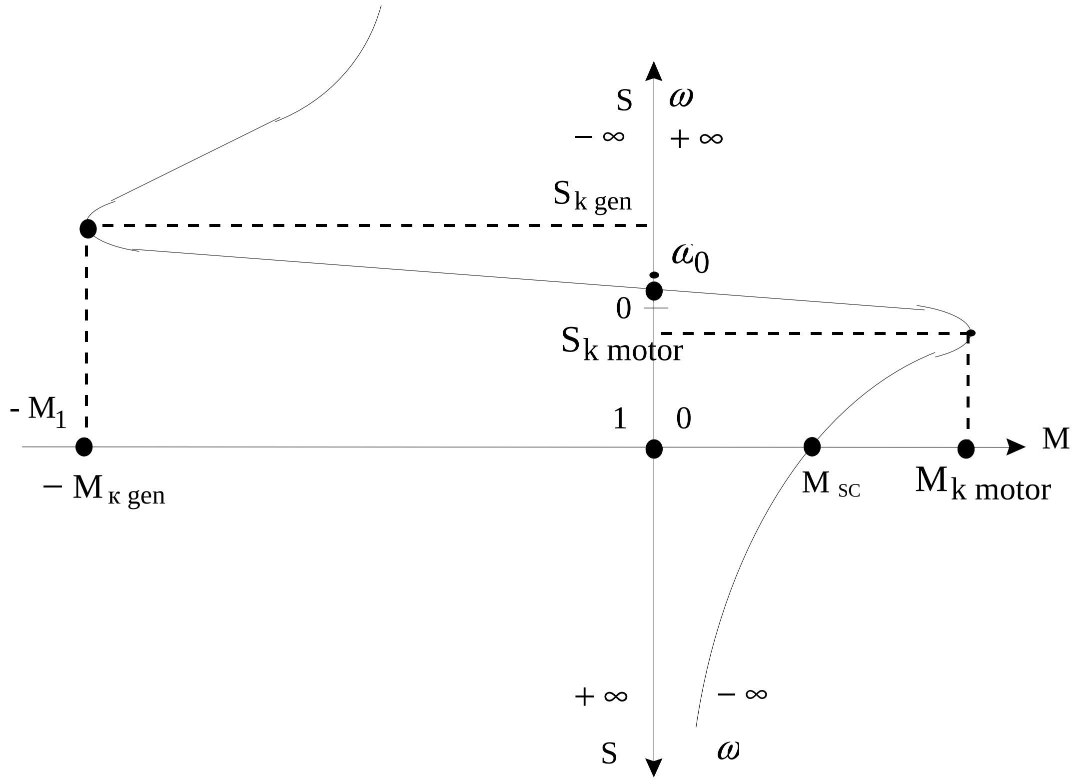


Fig. 3.4

Will analyze mechanical characteristics of IM:

At $S = 0$, $\omega = \omega_0$, $M = 0$ - the point of ideal idling IM.

At $S = 1$, $\omega = 0$, $M = M_{sc} = M_{start}$ - the point of short circuit IM.

At $S = S_{k(motor)}$, $M = M_{k(motor)}$, $S = -S_{k(gen)}$, $M = -M_{k(gen)}$, - extreme point (maximum M).

At $S \to \pm\infty$, $\omega \to \pm\infty$, $M \to 0$ - asymptote of mechanical characteristics.

Induction motor can operate in next modes:

1. Idling $S = 0$; $\omega = \omega_0$.
2. Short circuit (starting condition) $S = 1$; $\omega = 0$.
3. Motor mode $0 < S < 1$, $0 < \omega < \omega_0$.
4. Generator (regenerative) mode $S < 0$; $\omega > \omega_0$.
5. Generator (plugging) mode $S > 1$; $\omega < \omega_0$.
6. Generator (regardless of mains) mode, which is called dynamic braking. In this mode, the stator winding is disconnected from the mains of three-phase AC current and the two-phase stator windings connected to a DC source.

If in (3.5) substitute the values of M and S for the nominal mode and to name the maximum torque $M_k / M_n = \lambda_M$, which reflects the overload capacity of IM, then get:

$$S_k = S_n(\lambda_M \pm \sqrt{\lambda_M{}^2 - 1}.$$

This expression can be used to determine the critical slip on catalog data in IM.

Here is the procedure for calculating of mechanical characteristics of IM for the specified catalog data:

P_n, n_n, λ_M, f_1, P_n.

1. Determine the angular speed of the stator field ω_0 and the rotor in the nominal mode ω_n:

$$\omega_0 = \frac{2\pi f_1}{P_n}; \qquad \omega_n = \frac{2\pi n_n}{60}.$$

2. Determine the nominal torque:

$$M_n = \frac{P_n}{\omega_n}.$$

3. IM slips in the nominal mode:

$$S_n = \frac{\omega_0 - \omega_n}{\omega_n}.$$

4. Critical torque:

$$M_k = \lambda_M \cdot M_n.$$

5. Critical slip:

$$S_К = S_Н\left(\lambda_М + \sqrt{\lambda_М{}^2 - 1}\right).$$

6. By this equation:

$$M = \frac{2M_К}{\dfrac{S}{S_К} + \dfrac{S_К}{S}},$$

the current values of the torque M are defined in the range slips of motor mode
0 <S <1.

Fig. 3.5 presents the mechanical characteristic of IM S = f(M) in the motor mode.

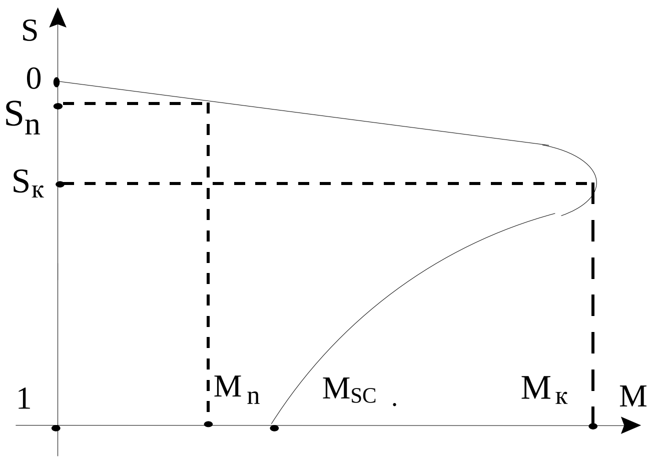


Fig. 3.5

3.2 Adjustment of speed, torque and current IM by the resistors in the circuit of the rotor

The introduction of the resistors R_{2add} in the rotor circuit of IM wound rotor, as shown in the diagram in Fig. 3.6, changes the nature of mechanical characteristics, the equation is of the form:

$$M = \frac{3U_{ph}{}^2(R_2^{'} + R_{2add})}{\omega_0 S\left[\left(R_1 + \frac{R_2^{'} + R_{2add}}{S}\right)^2 + X_{SC}^2\right]}. \qquad (3.6)$$

Fig. 3.7 presents the mechanical properties of IM with a wound rotor (natural – at $R_{2add} = 0$ and artificial – at $R_{2add2} > R_{2add1} > 0$).

Will analyze mechanical characteristics.

1. The speed of the stator field of IM (synchronous speed) of the regulation R_{2add} does not change, so all the mechanical characteristics are in the same point ω_0.

2. Critical (maximum) torque M_K remains constant therefore it does not depend on the value R_{2add}:

$$M_k = \frac{3U_{ph}}{2\omega_0\left[R_1 + \sqrt{R_1^2 + X_{SC}{}^2}\right]}.$$

3. Critical slip S_K increases if R_{2add} increases:

$$S_k = +\frac{R_2^{'} + R_{2add}}{\sqrt{R_1{}^2 + X_k{}^2}}.$$

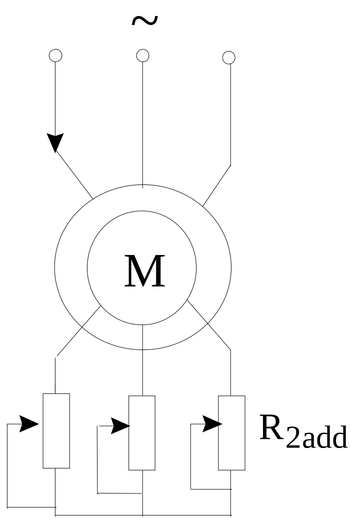


Fig. 3.6

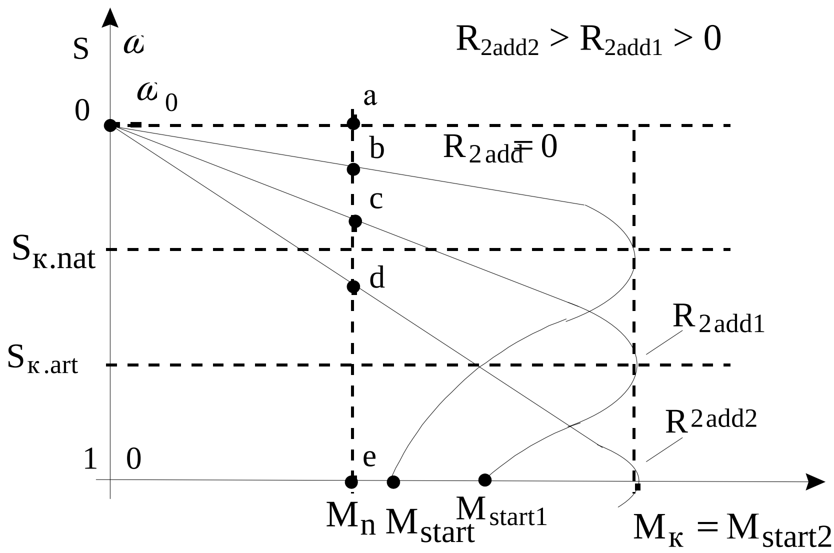


Fig. 3.7

Since power losses in the rotor circuit (slip loss):

$$\Delta P_2 = P_1 - P_2 = M\omega_0 - M\omega = M\omega_0 S = P_1 S,$$

depend on the slip, the speed range does not exceed 2-3. Speed control is just down from the main, smooth regulation is determined by the $\Delta R_{2add} = R_{2add2} - R_{2add1}$.

4. Starting torque $M_{start} = M_{SC}$ is increased with the increase R_{2add} up to the critical torque M_K, at S = 1:

$$M_{start} = M_{SC} = \frac{3U_{ph}^2 (R_2' + R_{2add})}{\omega_0 \left[(R_1 + R_2' + R_{2add})^2 + X_{SC}^2 \right]}.$$

Therefore, the introduction of R_{2add} is used during IM start-up with high load torque.

If both natural and artificial mechanical characteristics of IM are defined, the calculation of additional resistors R_{2add} is made on the basis of the relationship:

$$\frac{S_{k.nat}}{S_{k.art}} = \frac{R_r'}{R_r' + R_{2add}'} = \frac{R_r}{R_r + R_{2add}},$$

from which:

$$R_{2add} = R_r \left(\frac{S_{k.nat}}{S_{k.art}} - 1 \right), \tag{3.7}$$

where active rotor resistence: $R_r = \frac{E_{2k}S_{,}}{\sqrt{3} \cdot I_{2n}}$.

If only the operating points of the mechanical characteristics of IM are defined, the calculation of resistors R_{2add} is produced using the method of lines, according to which from Fig. 3.7:

$$R_{2add1} = R_{2n} \frac{bc}{ae},$$

$$R_{2add2} = R_{2n} \frac{bd}{ae},$$

$$R_r = R_{2n} \frac{bc}{ae},$$

where $R_{2n} = \frac{E_{2k}}{\sqrt{3} \cdot I_{2n}}$,

E_{2k} - rotor EMF if S = 1.

If any point on artificial characteristic is defined (S_{art}; M_{art}), and if $\frac{R_2^{`}}{S} = \text{const}$, then resistance $R_{2add.art}$ is defined by equation:

$$R_{2add.art} = R_r \left(\frac{S_{art}}{S_{nat}} - 1 \right).$$

3.3. Coordinate regulation of IM by the stator circuit resistors

This method may realize speed control of IM with squirrel-cage rotor (Fig. 3.8).
Perhaps inclusion of resistors R_{1add} in only one phase, which greatly reduces the loss of energy. Fig. 3.9 shows a family of mechanical characteristics of IM at different values $R_{1add} < R_{1add1} < R_{1add2}$.

The analysis shows the following mechanical characteristics:

1. Since ideal idling speed does not depend on R_{1add}, all the mechanical characteristics pass through the point ω_0.

2. Critical torque M_K and slip S_K inversely proportional, so they decreases if the R_{1add} increases.

3. By increasing R_{1add} the starting torque M_{start} decreases.

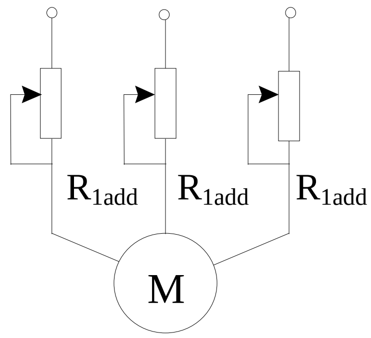


Fig. 3.8

Consequently, this method does not provide the desired properties regulating IM therefore it rarely used for speed control, more for current limiting during start-up, reverse or braking. Calculation of R_{1add} is similar of R_{2add} calculation, that discussed in 3.2.

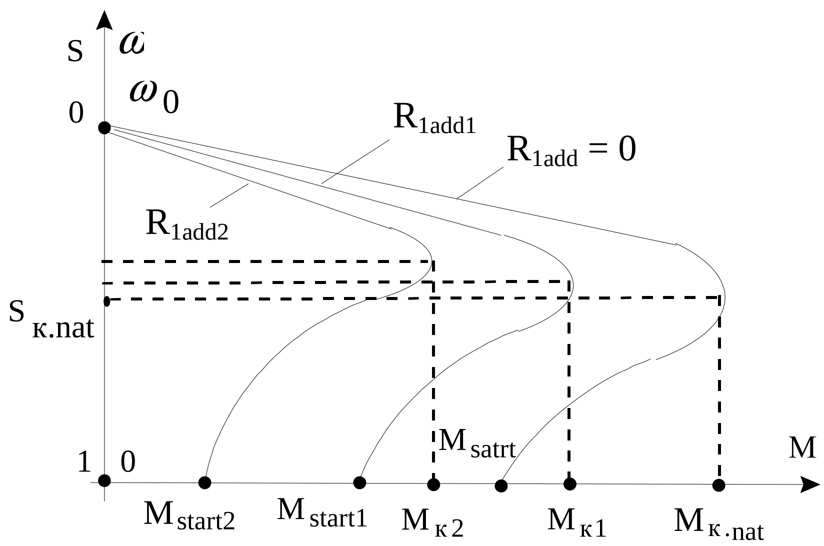


Fig. 3.9

3.4 Speed control of IM by changing the number of pole pairs

This method is used to regulate the speed of IM with a multi-speed squirrel-cage rotor. Thus there is a stepped change speed of the magnetic field

$$\omega_0 = \frac{2\pi f_1}{P},$$

where P - the number of pole pairs of the stator winding of IM. Changing P is possible if the stator has two independent windings with a different number of pole pairs (P_1 or P_2). Then:

$$\omega_{01} = \frac{2\pi f_1}{P_1}; \qquad \omega_{02} = \frac{2\pi f_2}{P_2};$$

and IM has different mechanical properties. These are called multi-speed IM, which are called multiwinding. Furthermore, changing the number of pole pairs can receive by branches shifting per winding. This is illustrated in Fig. 3.10.

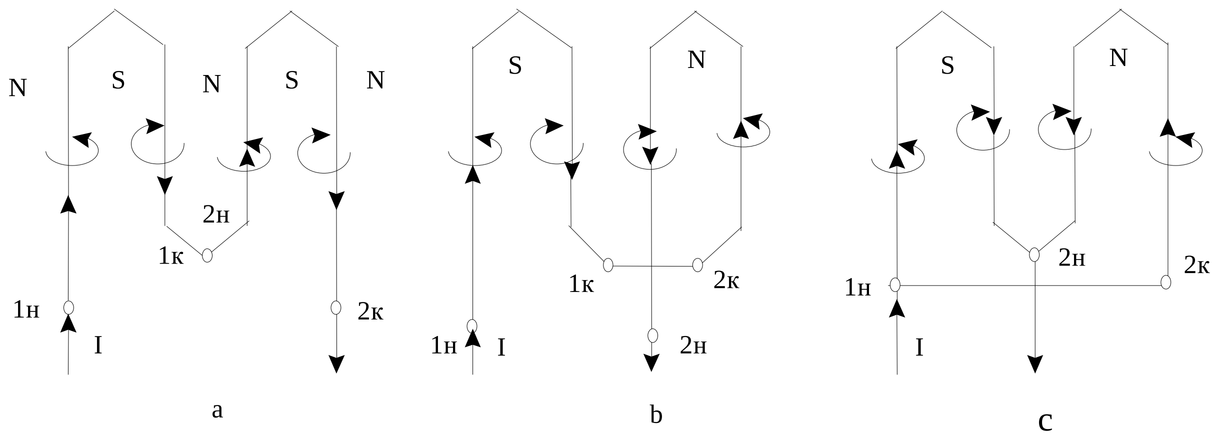


Fig. 3.10

Switching branches of phase stator windings from the serial series connection switching (a) on a serial opposite connection (b) or to the parallel opposite connection (c) are achieved the varying the number of poles pairs from $P_1 = 2$ to $P_2 = \frac{P_1}{2}$. These branches connection of each phase of a three phase system implemented in the form of switching windings from a triangle to a double star or from star to double star.

The switching circuit of the stator windings of IM from a triangle to a double star is shown in Fig. 3.11. When connected in a triangle it occurs serial series connection of the phase branches which corresponds to (Fig. 3.10, a) $P_1 = 2$, and when switching to a double star the parallel opposite branches connection (Fig. 3.10, c), which corresponds to $P_2 = \frac{P_1}{2} = 1$. Consequently, ω_{02} twice higher than ω_{01}. Power consumption in IM at rated load when connected to a triangle is equal to the

$$P_{1\Delta} = 3U_{1n}I_{1n}\cos\varphi_{1n},$$

when connected to a double star:

$$P_{1\lambda/\lambda} = \frac{3U_{1n}}{\sqrt{3}} 2I_{1n}\cos\varphi_{1n} = 3,46U_{1n}I_{1n}\cos\varphi_{1n}.$$

Consequently, the power consumption when switching the windings of a triangle on a double star varies slightly. Therefore, the mechanical properties of

IM when switching from a triangle to a double star corresponds to constant power regulation. In this case, an increase ω_0 in twice, the critical and start-up torques are reduced in two times (Fig. 3.12).

The switching circuit of the stator windings of IM from a star to the double star is shown in Fig. 3.13. When connecting on triangle the branches of winding phases are connected series, serial and formed two pairs of poles P_1 = 2. In this case, the power consumption is

$$P_{1\lambda} = 3\frac{U_{1n}}{\sqrt{3}} I_{1n} Cos\varphi_{1n} = \sqrt{3} U_{1n} I_{1n} Cos\varphi_{1n}.$$

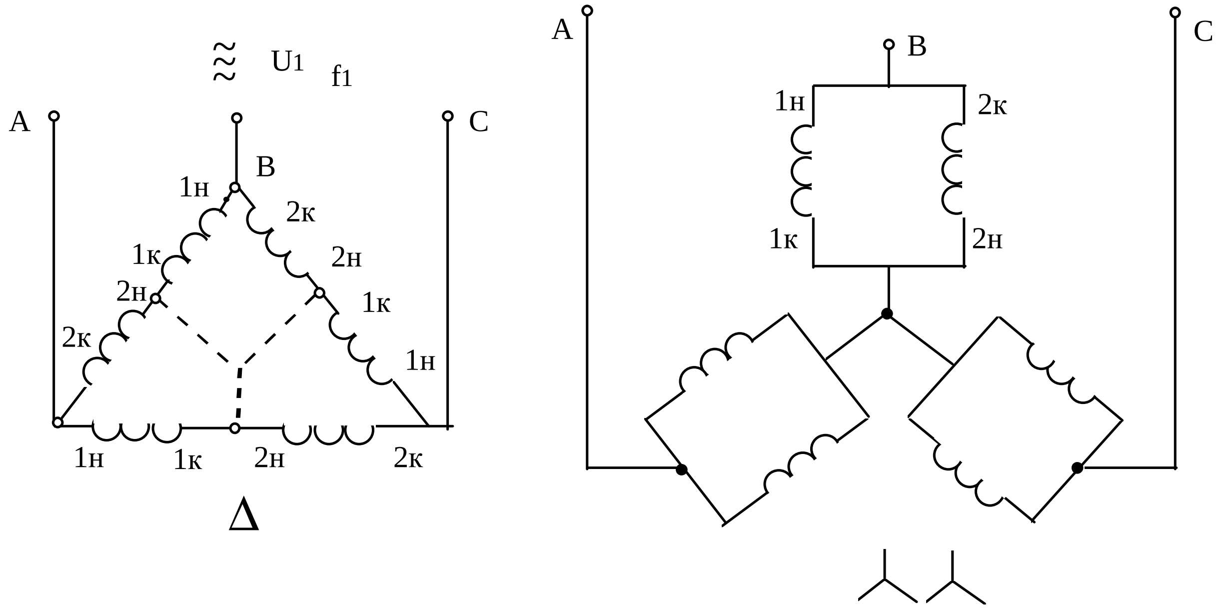


Fig. 3.11

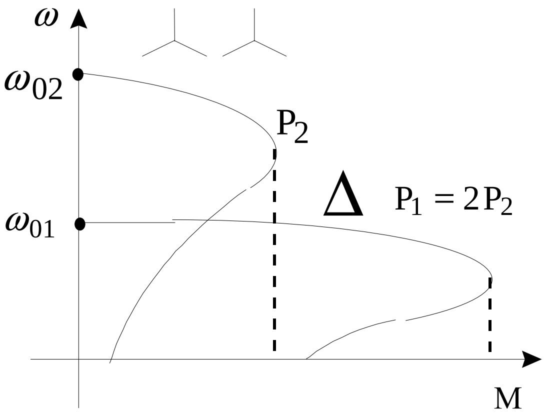


Fig. 3.12

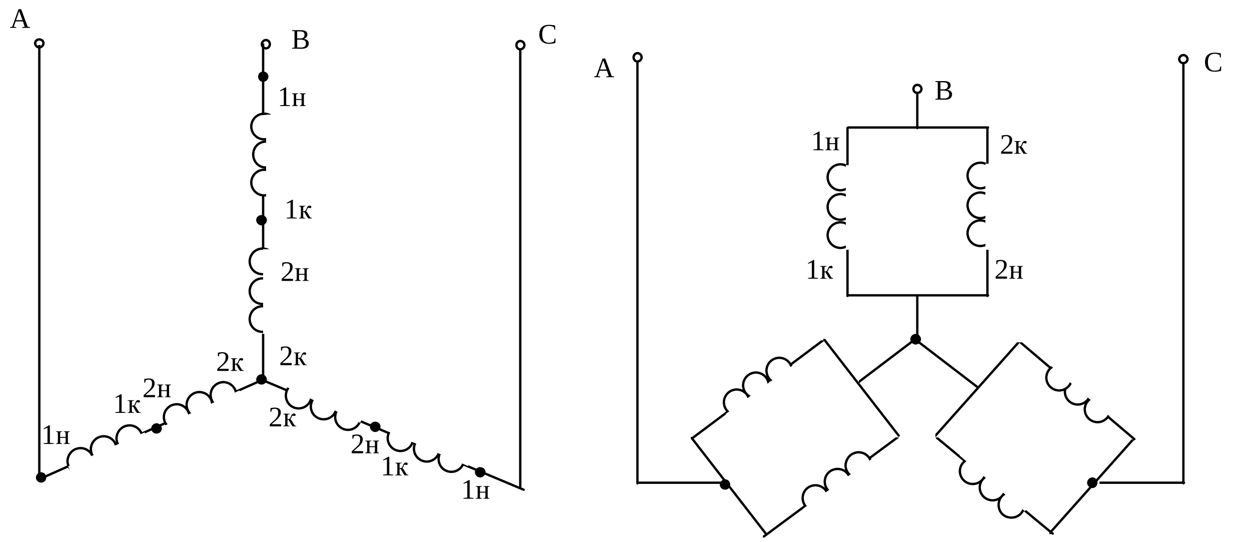


Fig. 3.13

Therefore, when switching from star to double star the speed and power consumption increased in 2 times. This means that in this case the regulation is carried out at a constant torque.

Mechanical characteristics shown in Fig. 3.14. Industry produces two-speed, three-and four-speed IM. The latter have two independent stator windings for different number of poles pairs, each of which is switched by the above scheme.

Discussed method of speed control of IM is quite economical, and mechanical properties have high rigidity and sufficient overload capacity.

The disadvantages include the step changes of IM speed and a small range of its regulation, not more than 6-8.

3.5 Drive coordinates regulation in the system Voltage Converter – Motor

When changing the voltage on the stator windings with voltage converter (Fig. 3.15), the values of M and the critical M_K change and synchronous speed ω_0 and the critical slip S_K remains unchanged, as it does not depend on U_{1ph}.

$$M = \frac{3U_{1ph}^{2}K_2^{'}}{\omega_0 S\left[\left(R_1 + \frac{R_2^{'}}{S}\right)^2 + X_{SC}^{2}\right]};$$

$$M_k = \pm\frac{3U_{ph}^{2}}{2\omega_0\left(R_1 \pm \sqrt{R_1^{2} + X_{SC}^{2}}\right)};$$

$$S_k = \pm \frac{R_2^Б}{\sqrt{{R_1}^2 + {X_{SC}}^2}}.$$

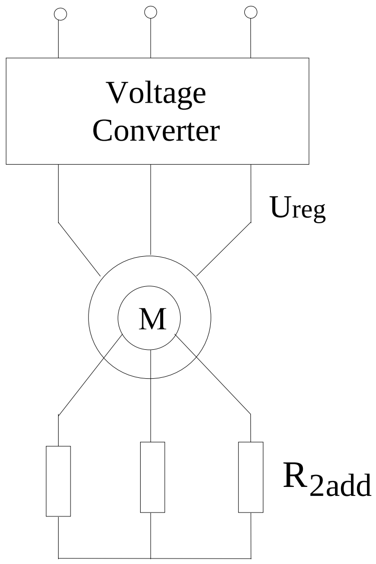


Fig. 3.15

Fig. 3.16 presents the mechanical characteristics with the U_{1ph} regulation.

To control the three-phase power frequency most widely - voltage thyristor converters VTC. Fig. 3.17 shows the power part of one phase of VTC for voltage regulation. The control electrodes of the thyristors from pulse-phase control circuit (PPCC) are fed by the control pulses, thyristors VS1, VS2 open.

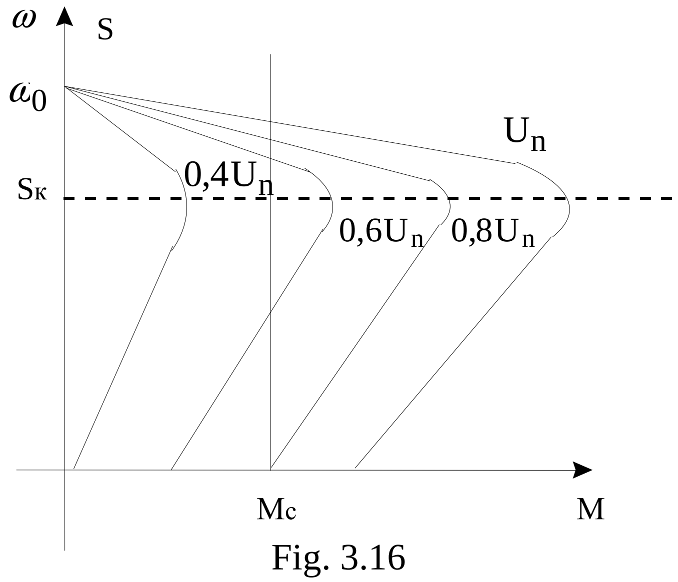


Fig. 3.16

If the absence of signals from the PPCC thyristors VS1, VS2 are closed and U_{load} = 0. By applying pulses to the thyristors of the PPCC at the time of their natural opening (control angle $\alpha = 0$), the thyristors are fully open and the voltage at the load $U_{load} = U_1$.

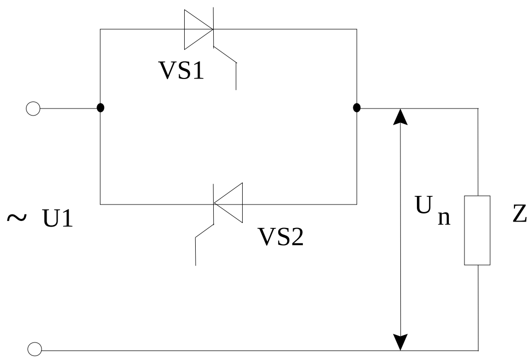


Fig. 3.17

If $\alpha \neq 0$, then the load is applied by the part of the U_1. When changing α from 0 to π the U_{load} varies from 0 to U_1.

An anti-parallel thyristor connection - provided work alternately each thyristor during one half cycle of mains (can be used instead of a pair of thyristors the single symmetric thyristor (triac). Open circuit three-phase power supply IM - VTC is shown in Fig. 3.18.

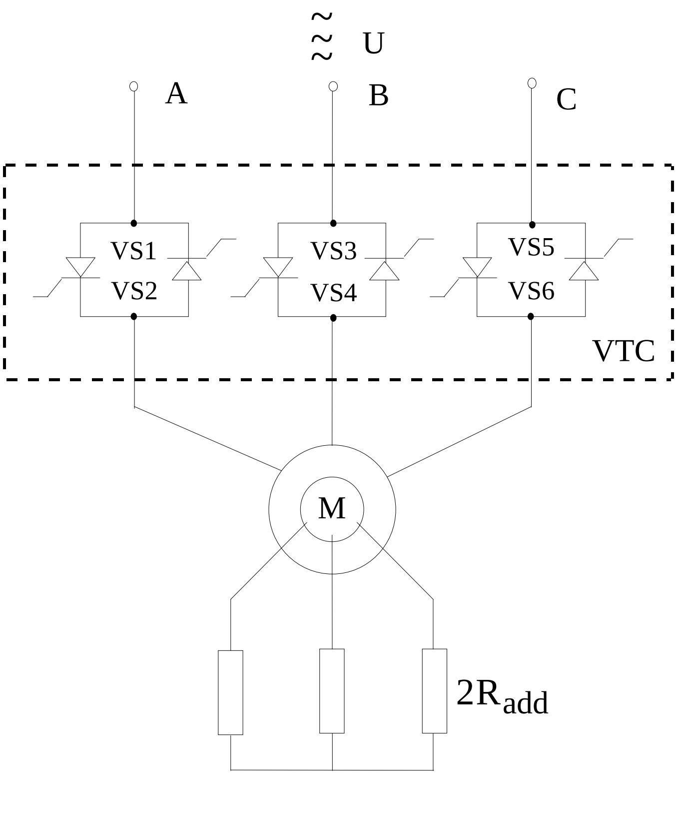


Fig. 3.18

As increase of the control angle α the amplitude of the first voltage harmonic U_{13p} decreases. Voltage (regulated) is non-sinusoidal, higher harmonics create additional losses (20-30%), although they have a little affect to the torque. Mechanical characteristics have low rigidity as M_K decreases with increasing control angle α and the speed changes sharply, as shown in Fig. 3.19.

If the motor is running at point 1, $\alpha = 75^0$, then the motor load is increased to M_{c2}, motor will slow down, because $M < M_{c2}$. In this case it is necessary to change the angle $\alpha = 60^0$ and the motor will operate at point 2, wherein $M = M_{c2}$ at speed ω_2.

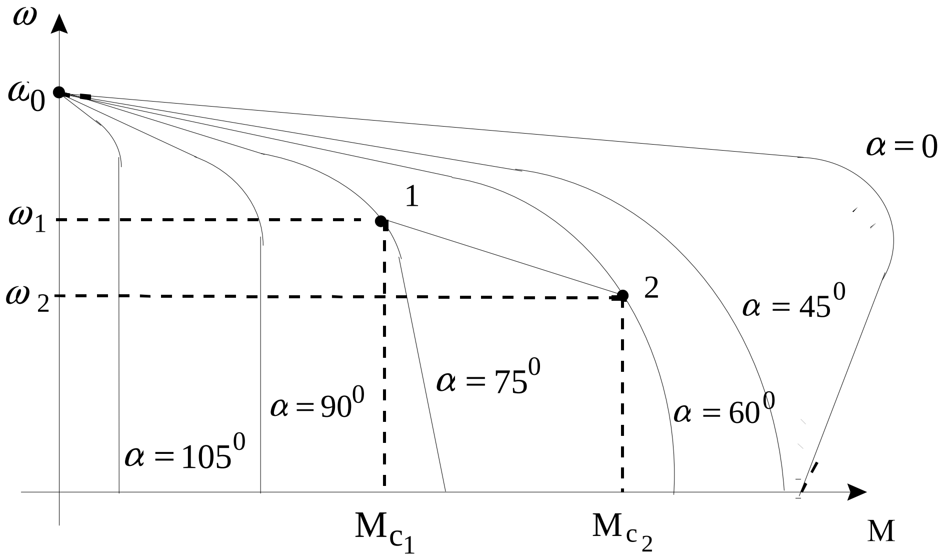


Fig. 3.19

This means that when the load M_c need to adjust α (the angle control). This is achieved in closed systems automatically with the aid of speed feedback. The scheme of the closed system VTC -IM is shown in Fig. 3.20.

In scheme there are 3 pair of anti-parallel connection of thyristors VS1-VS6, the electrodes control of which are connected to PPCC, which feeds the shift pulse depending on the control signal U_{cont}.

EMF of tacho-generator $e_{BR} = \gamma\omega$, defined signal voltage $U_{def.}$. Control signal $U_{cont} = U_{def} - \gamma\omega$ input to PPCC. If at speed ω_1 $e_{BR} = \gamma\omega_1$, then $U_{cont} = U_{def} - \gamma\omega_1$ and PPCC gives control angle $\alpha = 75^0$, then if torque is M_{C1} IM works in the point 1 on the mechanical characteristic (Fig. 3.19). If load torque M_{C2} increases the angle speed changes from ω_2, $e_{br} = \gamma\omega_{2,}$ $U_{cont} = U_{def} - \gamma\omega_2$ and PPCC creates control angle $\alpha = 60^0$, then IM will work in the point 2.

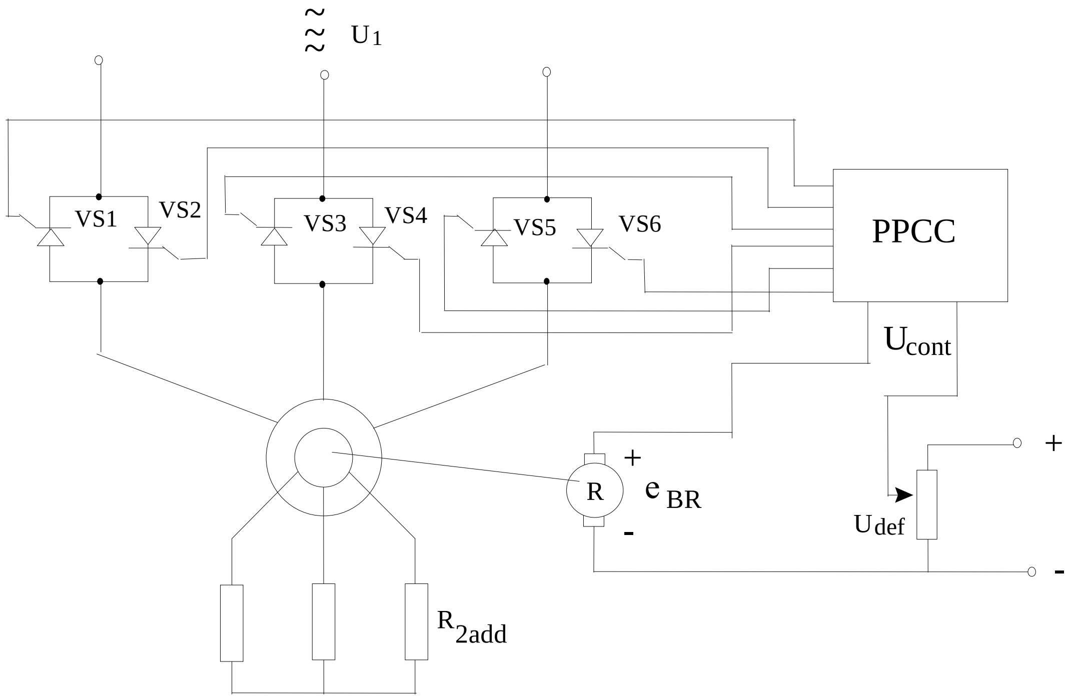


Fig. 3.20

By changing U_{def} can be quite hard to get a family of mechanical properties (Fig 3.21).

The system provides a large speed range, but does not allow the reversal of IM.

Reversible IM control system includes five pairs of anti-parallel connected thyristors (Fig. 3.22).

If PPCC creates control signals, which supplies the tyristors VS1-VS2, VS3-VS4, VS5-VS6, then the voltage with phase sequence ABC is applied to $C_1C_2C_3$ and IM rotates in the forward direction. If control signals supplies the tyristors VS7-VS8 and VS9-VS10, leave VS5-VS6, and remove control signals from VS1-VS2, VS3-VS4, then reverse is happened (phase sequence is BAC).

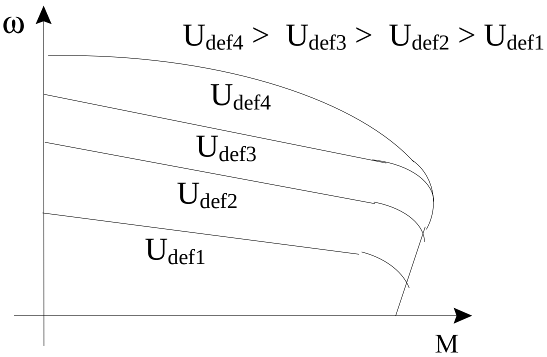


Fig. 3.21

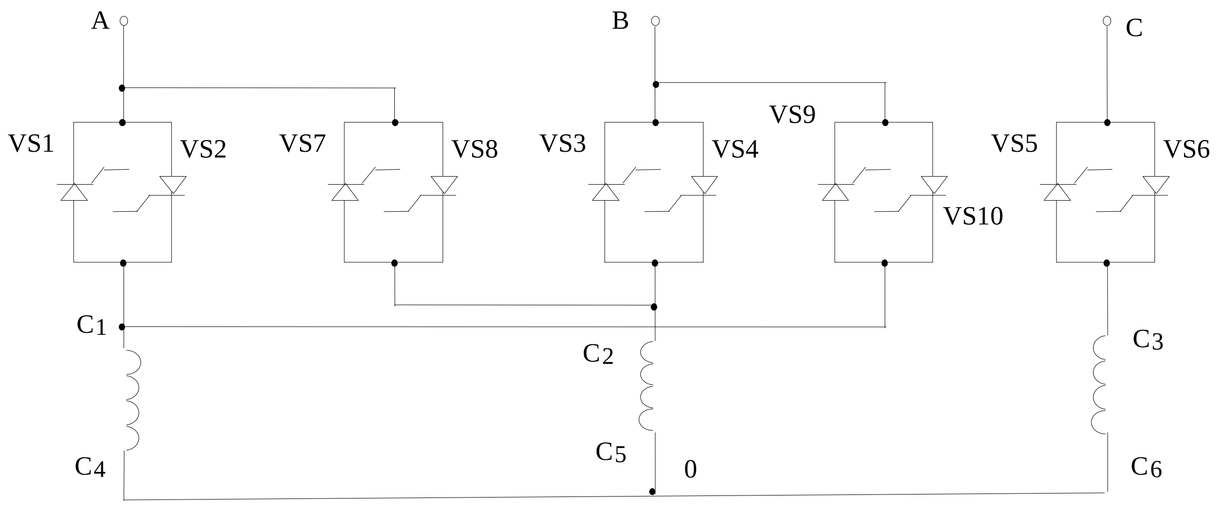


Fig. 3.22

By the reversing VTC the dynamic braking of IM is provided. For this IM is disconnected of AC mains and two phases are connected to DC source. This case achieved by work of tyristors VS1 = VS9 and VS8 - VS4 by scheme schown on Fig. 3.23.

The signals U_{cont} from the PPCC served on thyristors VS1, VS4; VS9, VS8, which open and form a single-phase controlled rectifier bridge, from which a constant (rectified) current flows through the two phases of the stator winding, providing dynamic braking. On the other thyristors U_{cont} of PPCC are not served and they are closed. Therefore, using the VTC can be carried out starting, reversing, braking and control of speed, current and torque.

Advantages of the system VTC - IM - high speed range (up to 10), rigid characteristic in the presence of the speed feedback. Disadvantages - heavy losses in the rotor winding when operating at low speeds, variable speed - down from the main one.

Mechanical characteristics of IM with supply it from VTC defined by the expression:

$$M(S) = \left(\frac{U_1}{U_{1n}} \right)^2 \cdot M_{cr}(S), \tag{3.8}$$

where $M_{cr}(S)$ - torque on the boundary characteristics of the slip S, corresponding to the control angle of thyristors $\alpha = 0$;

U_1 - 1st voltage harmonic.

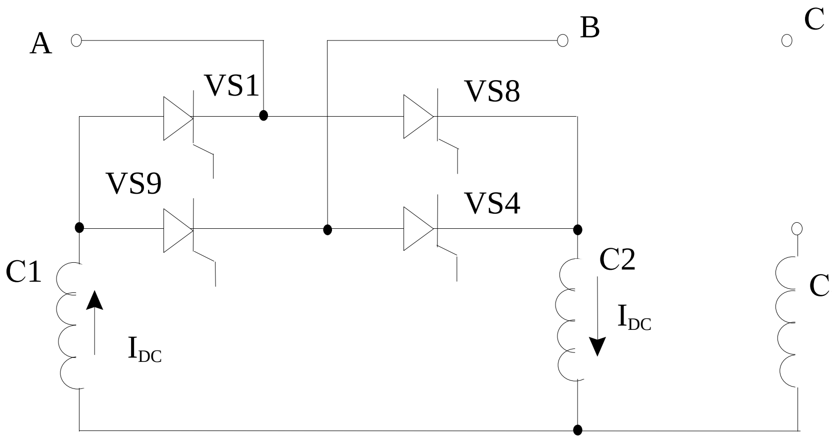


Fig. 3.23

Boundary characteristic at $R_{2add} = 0$ coincides with the natural as $R_{VTC} \approx 0$.

When $R_{2add} \neq 0$ - limiting characteristic coincides with the rheostat. U_1 depends on the control angle α and the load angle θ, which is defined by:

$$\theta = \mathrm{arctg}\frac{X_{mot.eq}}{R_{mot.eq}} = \mathrm{arctg}\frac{R_2'/X_\mu S^2 + X_{SC}}{R_1R_2'/(X_\mu S^2 + R_2'/S + R_1}, \qquad (3.9)$$

where $X_{mot.eq}$ and $R_{mot.eq}$ - the equivalent resistance of the stator phase.

Therefore, the load angle depends on slip, as shown in Fig. 3.24.

Calculation of mechanical caracteristic at its supply from VTC is as follows:

1. It is set of slip values S and on natural or artificial mechanical characteristics of IM is determined for each of M_{cr}.

2. In equation 3.9 to calculate the load angle for each value S.

3. For a given control angle VTC α and load angle θ the curves in Fig. 3.25 are determined by the relative value of of the first harmonic voltage U_1/U_{1n}.

4. According to the formula 3.8 the values of M(S) are determined and the mechanical characteristics of IM powered by the VTC are build.

3.6 Coordinates regulation in the electric system Frequency Converter – Induction Motor (FC-IM)

This method is widely used as a method of controlling the synchronous speed $\omega_0 = \frac{2\pi f_1}{P}$. The method provides variable speed over a wide range both up and down from the primary. Since there is no increase S, the loss of slip is small - cost effective way. However, for a better use of IM (high efficiency, Cosφ, overload capability), simultaneously with the change f_1 need to change and U_1. Law of the cange voltage depends on the nature of the load torque. The main criterion - to keep the overload capacity by regulating the voltage and frequency $\lambda = \frac{M_{cr}}{M_c} = \text{const}$.

Substituting M_K, neglecting R_1 and considering that $X_{SC} \cong f_1$; $\omega_0 \cong f_1$, get:

$$\lambda = \frac{3U_{ph}{}^2}{2\omega_0 X_{SC} M_c} = A\frac{U_{ph}{}^2}{f_1{}^2 M_c}, \tag{3.10}$$

Therefore, for any value of f_1 (i, k) the ratio must be maintained:

$$\frac{U^2_{ph_i}}{(f^2_{1i} M_{ci})} = \frac{U^2_{phk}}{(f^2_{1k} M_{ck})},$$

Where:

$$\frac{U_{ph}}{U_{phk}} = \frac{f_{1i}}{f_{1k}}\sqrt{\frac{M_{ci}}{M_{ck}}}. \tag{3.11}$$

If M_c=const then $\frac{U_{ph}}{f_1}$=const.

If M_c is a ventilatory characteristic, then $\frac{U_{ph}}{f_1^2} = \text{const}$.

If M_c is inversely of speed then $\frac{U_\phi}{\sqrt{f_1}} = \text{const}$.

. When adjusting the frequency f_{1n} of the up, it is impossible to increase both U_1 over U_{1n}, therefore can not be achieved $\lambda = \text{const}$ so critical point decreases as shown in Fig. 3.25.

The relation $U/f_1 = \text{const}$ is true if it neglects R_1, but for small f_1 resistance R_1 is comparable to $X_1 = 2\pi f_1 L_1$, and therefore not provided $\lambda = \text{const}$ and M_{cr}

decreases (Fig. 3.26). This is because at low f_1 the voltage drop $I \cdot R_1$ increases due to the influence of the R_1 and decreases EMF and field, and hence the M_{cr}.

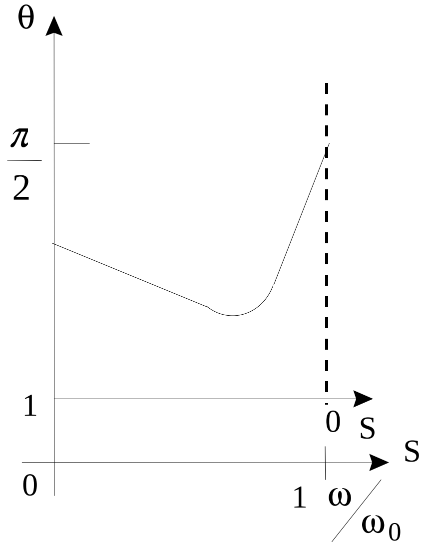


Fig. 3.24

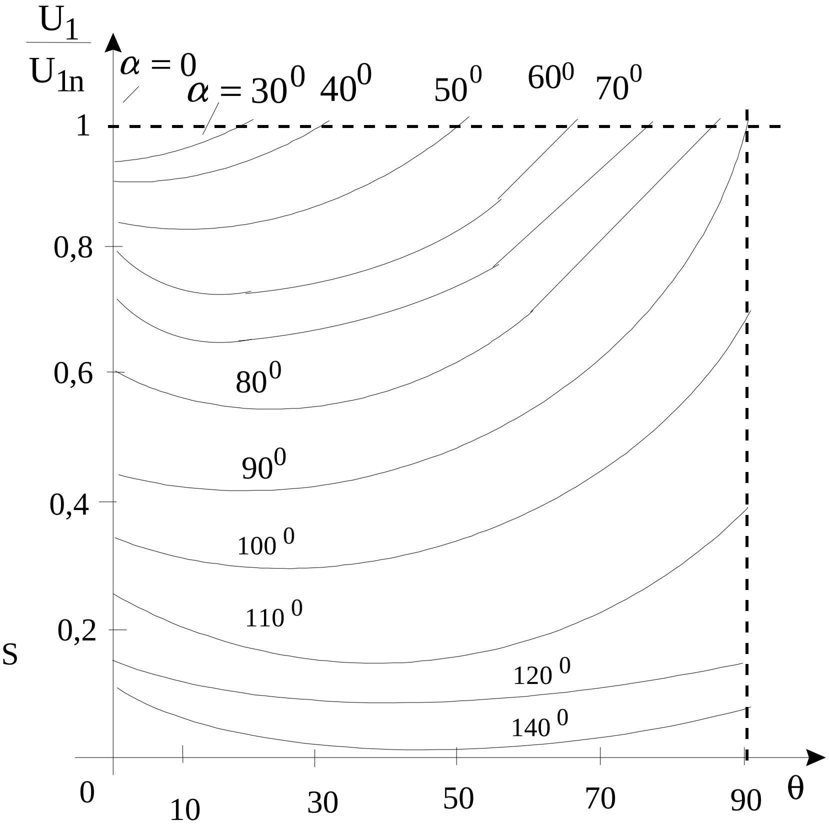


Fig. 3.25

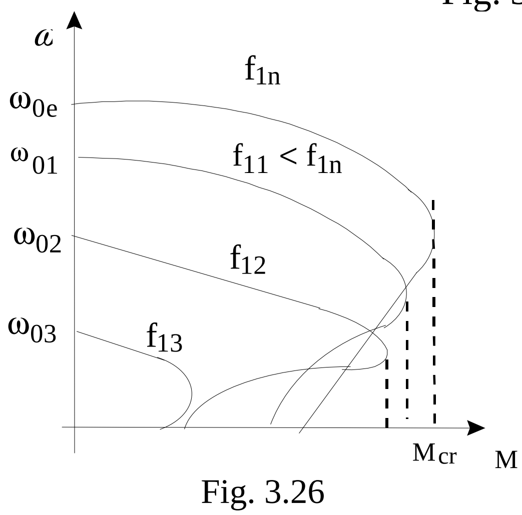


Fig. 3.26

To avoid this, you it needs with decreasing f_1 to reduce U_1 to a lesser extent, that is $\frac{U_1}{f_1} = \text{const}$.

Thus, for the coordinate regulation of IM in this manner required frequency and voltage converters. Frequency and voltage converters are divided into:

1) dynamoelectric (rotating)

2) static converters.

Fig. 3.27 presents an electromachine frequency converter with synchronous generator SG, which provides the regulation of frequency and voltage.

When changing $I_{F\ DCG}$ the voltage of DCM changes, when changing $I_{F\ DCM}$ magnetic flux of DCM changes therefore the speed of SG ω_{SG} regulated within wide limits and, as a consequence, the frequency f_{1reg}.

If the $I_{F\ SG}$ changes the U_{1reg} also changes.

The main disadvantage of this method is the double-conversion (AC to DC, then to AC adjustable), leading to large losses and provides a low efficiency of the system, the complexity, noise and mechanical inertia.

These disadvantages are deprived of static converters, which are divided into 2 groups:

1. Drive without the DC link with direct-coupled to the load supply.
2. FC with intermediate direct current section (two-tier FC).

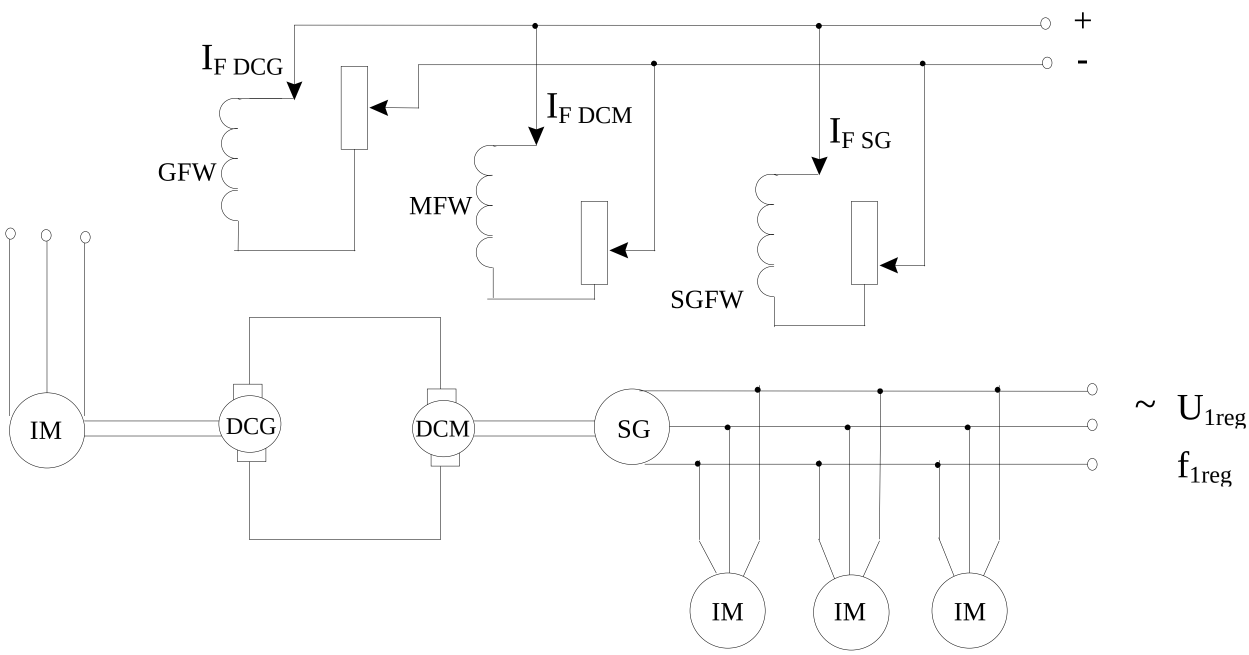


Fig. 3.27

3.7 FC without DC link

Block diagram of the inverter is shown in Fig. 3. 28.

PS - the power section;

CS - control scheme.

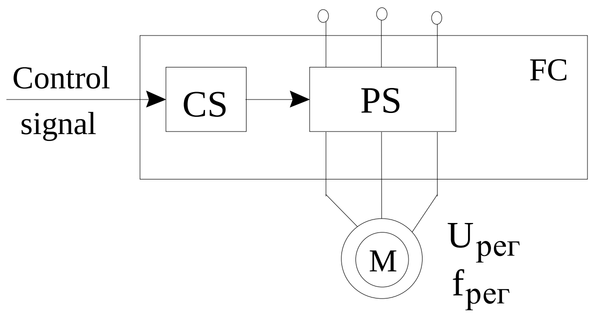


Fig. 3.28

PS includes thyristors and matching transformers.

Electric circuit of FC (Fig. 3.29) contains a three groups of thyristors, in each thyristor group are 6 thyristors, three of which are connected to the anodes, three - phase to the cathode of the secondary winding of transformer T. Each phase operates independently, connection phase load (IM) is made between the phase and neutral (zero scheme).

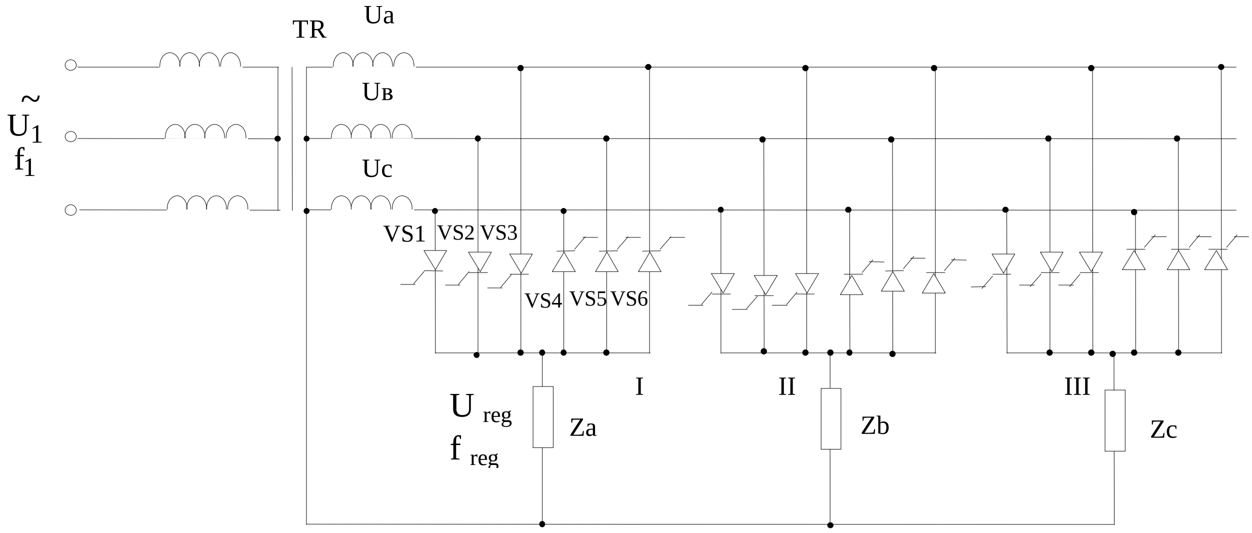


Fig. 3.29

Consider the work of a thyristors group I (phase A, Za). If the control pulses from the CS is not served, the thyristors are closed and the voltage at the load Za equel to zero.

If at the time t_1 to apply impulse to VS1 (at the moment of opening), at the time t_2 on VS2, a t_3 on VS3, then rectified voltage with the pulsations is applied at Za. If it removes the impulses and to apply at the time t_5 on VS6, at t_6 on VS4, at t_7 on VS5 the ripple voltage reverse polarity is applied at Za - as shown in Fig. 3.30.

Consequently, the load Za formed an AC voltage with a period of $T_{РЕГ}$ and frequency $f_{reg} = \dfrac{1}{T_{reg}}$, which is significantly less than the supply voltage f_1. Fig. 3.30 shows that

$$\frac{T_{reg}}{2} = \frac{T_1}{2} + h\frac{T_1}{3} \qquad \text{or} \qquad T_{reg} = T_1(3+2h)/3,$$

where h = 0, 1, 2, 3 …. - the number of opened thyristors in the group less than one.

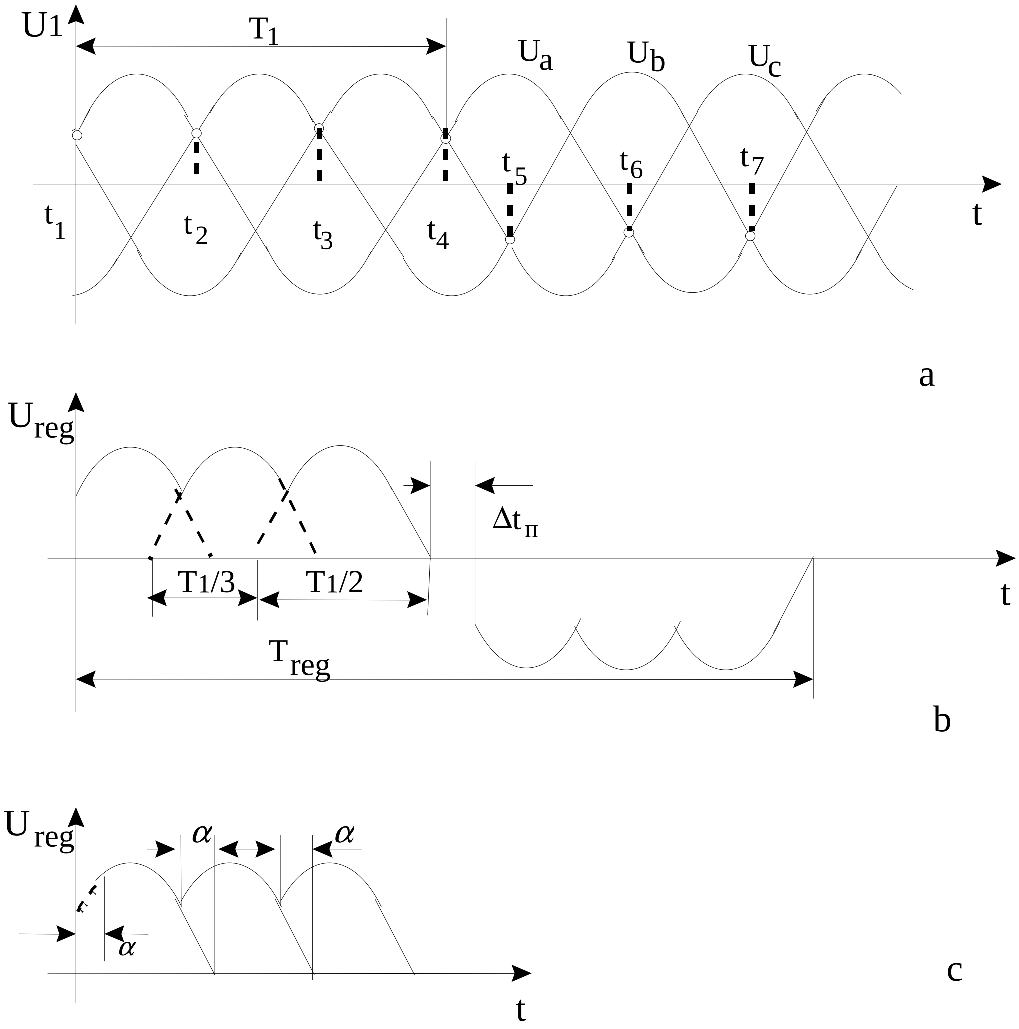


Рис.3.30

Then $f_{рег} = \dfrac{1}{T_{рег}} = \dfrac{3f_1}{3+2h}$ - for three-phase voltage;

$f_{рег} = m_1 f_1 / (m_1 + 2h)$ - for m-phase voltage.

For example, at f_1 = 50 Hz and at the number of opened thyristors less than one h:

h =	2	3	4	5	6	7	8
f_{reg} =	21,4 Hz	16,7	13,6	11,5	10	8,8	7,9 Hz

have a step change of the adjusted frequency. If between the time of removal of the control pulses to the thyristors VS1 - VS3 and serving thyristors VS4 - VS6 to introduce a time delay – pause $\Delta t_П$, the output frequency:

$$f_{reg} = \frac{m_1 f_1}{m_1 + 2h + \Delta t_п f_1}. \tag{3.12}$$

So, gradually adjusting the pause $\Delta t_П$, it can smoothly adjust the frequency f_{reg}.

If the control pulses to the thyristors do not apply at the time of their natural opening (t_1, t_2, t_3 ...), and apply with delay (control angle is not equal to zero ($\alpha \neq 0$)), it can adjust the voltage at the load U_{reg}. Effective value of the regulated voltage is dependent on the control angle α:

$$U_{reg} = \frac{\sqrt{2} m_1 U_{ph} \mathrm{Sin}\frac{\pi}{m_1}}{\pi} \cdot \mathrm{Cos}\alpha. \tag{3.13}$$

Maximum value U_{reg} at $\alpha = 0$ equal:

$$U_{reg.max} = \sqrt{2}\frac{m_1}{\pi}\mathrm{Sin}\frac{\pi}{m_1}U_{ph}.$$

Therefore, the above considered inverter allow to regulate voltage and frequency over a wide range.

Disadvantage of scheme - the presence of the neutral conductor.

3.8 FC with link DC

The block diagram is shown in Fig. 3. 31.

CR - controlled rectifier;

CI - controlled inverter;

CSCR - control scheme of CR;

CSCI - control scheme of CI.

With CSCR rectified voltage can be adjusted within wide limits. The rectified and regulated voltage E_0 is input to the inverter CI, which converts the DC voltage E_0 in a three-phase AC voltage U_{reg} controlled frequency f_{reg}, which is set by CSCI depending on the control signal. The principle of obtaining an adjustable rate CI look as shown in Fig. 3.32.

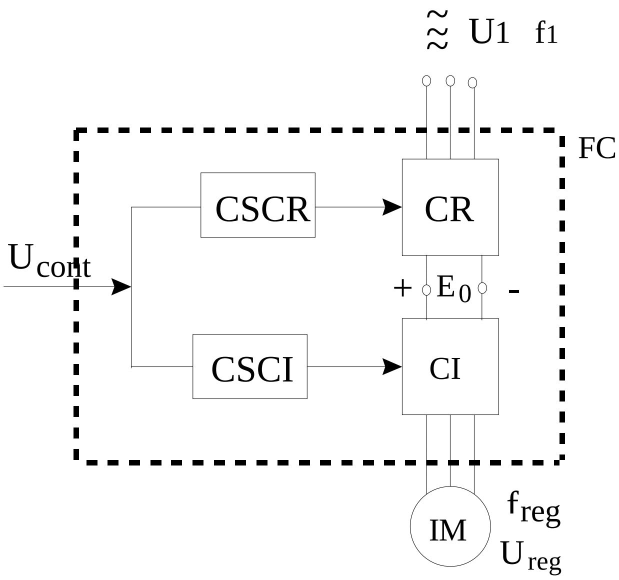


Fig. 3.31

Thyristors VS1 - VS6 collected in a bridge circuit, can be opened by the control circuit CSCR signals in the desired sequence and for any length of time.

Most often used cyclic duration factor of thyristors (duration factor of opened thyristors state)

$$\lambda = \frac{1}{2} T_{reg} \text{ and } \lambda = \frac{1}{3} T_{reg}.$$

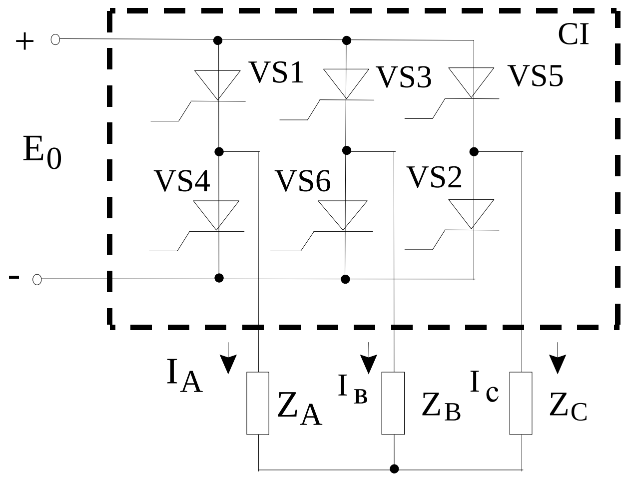


Fig. 3.32

The shift of the opening times of the thyristors in the circuit of Fig. 3.32 is $\frac{1}{6} T_{reg} = 60^0$. At each time point three of the 6 thyristors are opened. Let $\lambda = \frac{1}{2} T_{reg}$.

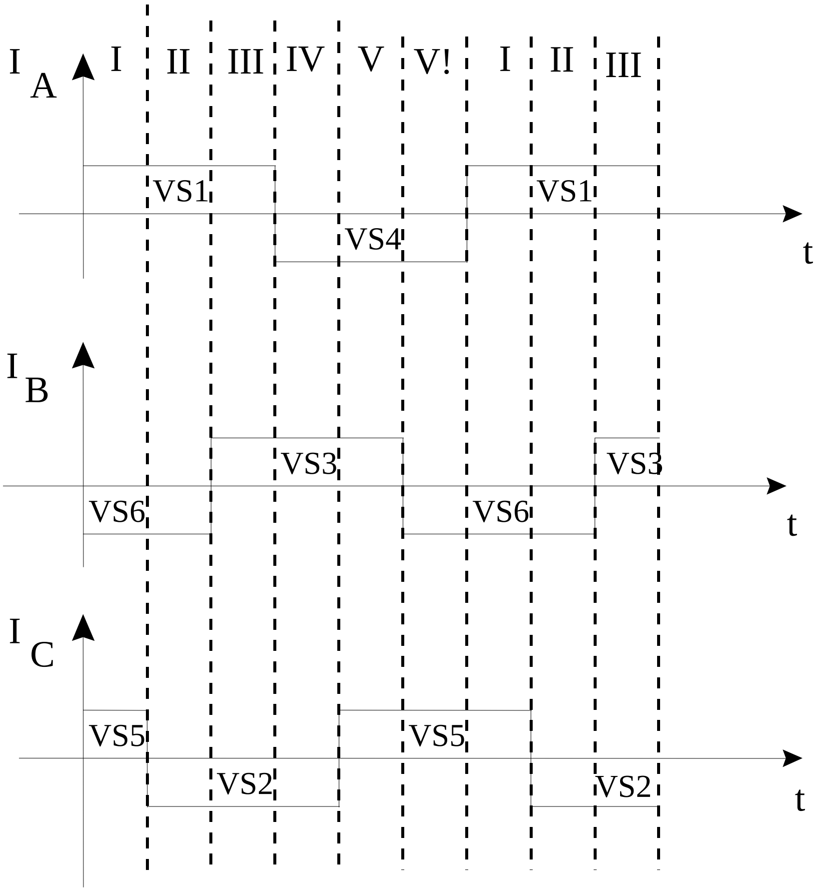


Fig. 3.33

Phase currents flowing through the Z_A, Z_B, Z_C are on the graph (Fig. 3.33). At intervals I, II, III currents pass through resistors Z_A, Z_B, Z_C, as shown in Fig. 3.34, and create a voltage drop $E_0/3$ or $2E_0/3$.

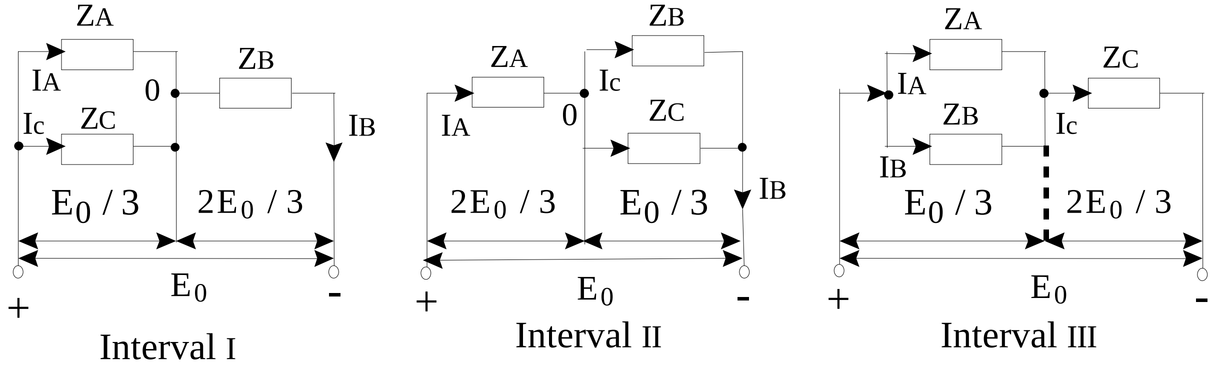


Fig. 3.34

Let's construct a graph of the voltage at the load phases of U_A; U_B; U_C (Fig. 3.35).

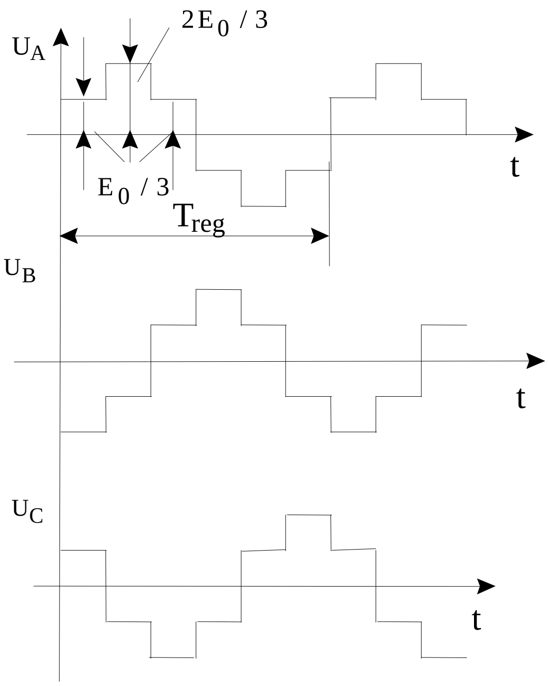


Fig. 3.35

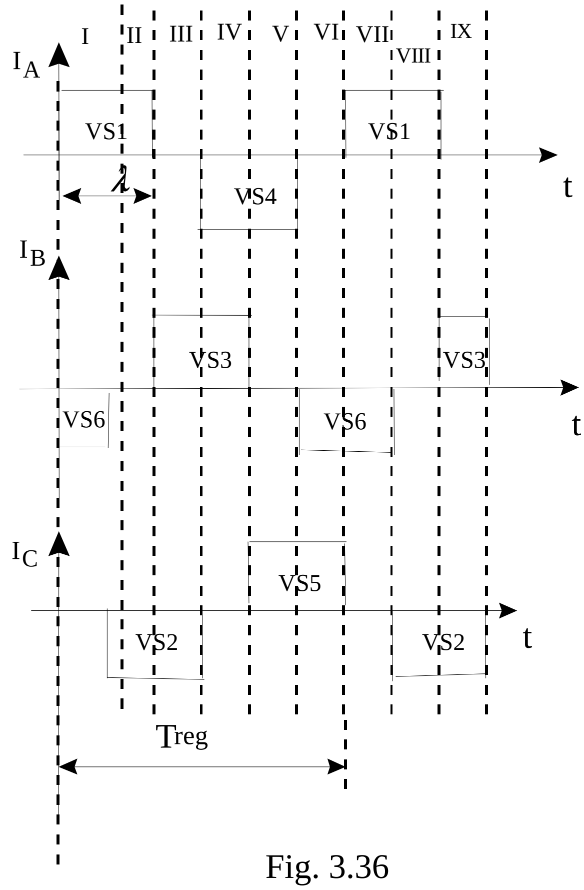


Fig. 3.36

Consequently, the load phases are fed alternating voltage, maxima U_{Amax}, U_{Bmax}, U_{Cmax} are shifted to 120^0 ($2x60^0$) (a third period of an adjustable frequency).

Thus, the output of the inverter managed an alternating three-phase non-sinusoidal voltage.

If the duration of the open state of each tyristor is $\lambda = \frac{T_{reg}}{3}$, in each time interval, only two thyristors are opened.

Diagram of phase currents shown in Fig. 3.36, from which implies that, at each time interval the two load phases connected to the voltage E_0 and the third phase is disabled. Then, the voltage of each of serially connected power phase is $E_0/2$, and the third E = 0. (Fig. 3.37).

Depending on the current switching valves all inverters are divided in mains-controlled inverter and self-commutated inverter. In the first switching current from valve to valve provides by AC voltage source. In self-commutated inverters are used in the scheme with L and C. In the electric drives with frequency control is used self-commutated inverters.

Self-commutated inverters are divided in voltage inverter SCVI and current SCCI.

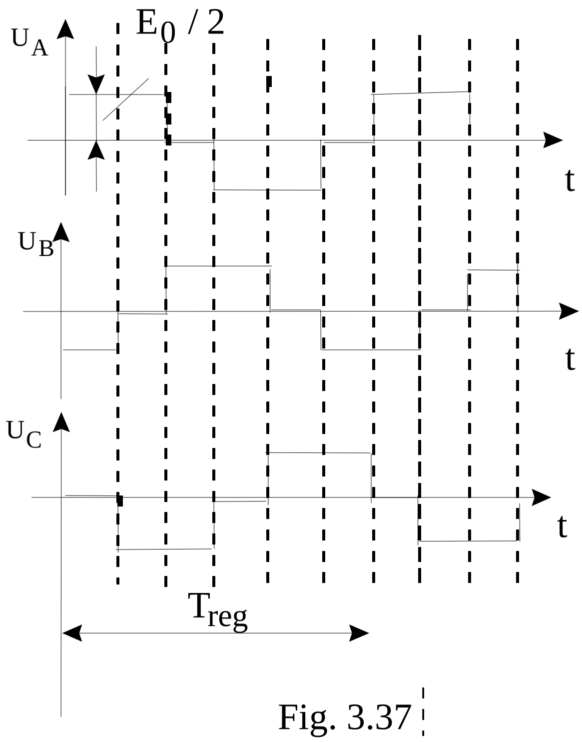


Fig. 3.37

FC with DC link and Self-commutated voltage inverter (SCVI)

The electric circuit is presented on Fig. 3.38.

SCVI has a supply voltage source. If SCVI is supplied from a controllable rectifier, the output is set to capacitor with large capacitance, then SCVI has rigid external characteristic, i.e. change load current doesn't change voltage. When using SCVI control actions on IM are the frequency and voltage.

Controlled rectifier CR is formed by thyristors VS7-VS12. The output of the CR is filter L_0 and C_0, which with the diodes VD7-VD12 provides circulation of reactive power. Thyristors VS1 - VS6 form a controlled inverter for speed control. Capacitors C and inductances L together with diodes VD1 - VD6 form a circuit of artificial switching, providing closing the main thyristors VS1 - VS6 at the right time. For rigid static and dynamic characteristics of the electric drive with SCVI apply feedback on speed, magnetic flux, or a combination thereof.

It is widely used frequency-current control of IM. It uses SCCI to regulate the stator current, and frequency.

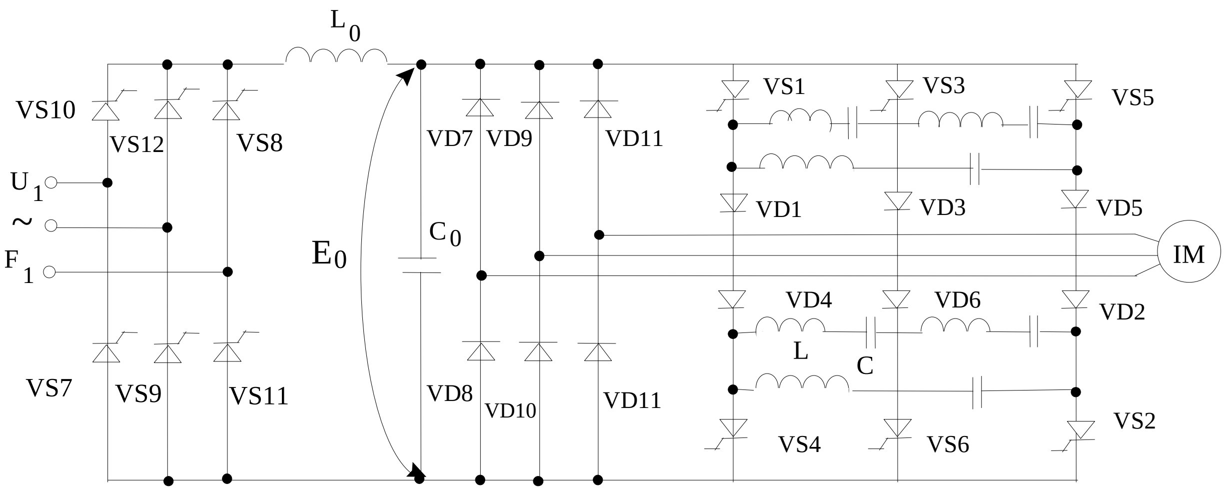


Fig.3.38

The circuit of induction motor with SCCI

SCCI have the properties of the current source, the power is provided from the power source. If SCCI is powered by the controlled rectifier, its output is set to reactor with a large inductance. When using the SCCI control actions on IM are the frequency and the stator current. Fig. 3.39 is a closed system-frequency current control of IM with the SCCI.

CSR – tyristors control scheme of CR;

CSI - tyristors control scheme of SCCI;

CC - stator current controller;

CS - stator current sensor;

SS - the speed sensor;

LA - limiting amplifier;

FG - function generator;

$U_{def\omega}$ – defining signal – defines switching frequency of tyristors SCCI VS7 - VS12 and stator current frequency of IM. From $U_{def\omega}$ subtrac speed feedback signal U_ω - then get signal $U_\beta = U_{def\omega} - U_\omega$, proportional to the relative frequency of the rotor $\beta = \frac{f_2}{f_{1n}}$ (β - absolute slip), $\beta = \frac{f_2}{f_{1n}} \cdot S$.

Signal U_β, pass through LA together with the signal U_ω, inputs to the CSR. The frequency of the CSR ouput is defined by the signal $U_{\omega s} = U_\omega + U_\beta$. CSR is adjusted so, that LA works in linear section, the frequency of the CSI output is constant and doesn’t depends on the load ($U_{\omega s} = U_{def\omega}$). The motor has rigit mechanical characteristics.

The signal U_β after passing through the FG is also setting signal to the control circuit current. Since U_β is proportional to the absolute slip, then the IM current at all frequencies will be proportional U_β.

When overloaded, or sudden changes $U_{def\omega}$ the LA enters in a output signal restricted zone U_β = const, limiting the current. The motor is operated at any speed in this mode at constant current and absolute slip, that is, the mechanical characteristic is absolutely soft (Fig. 3.40).

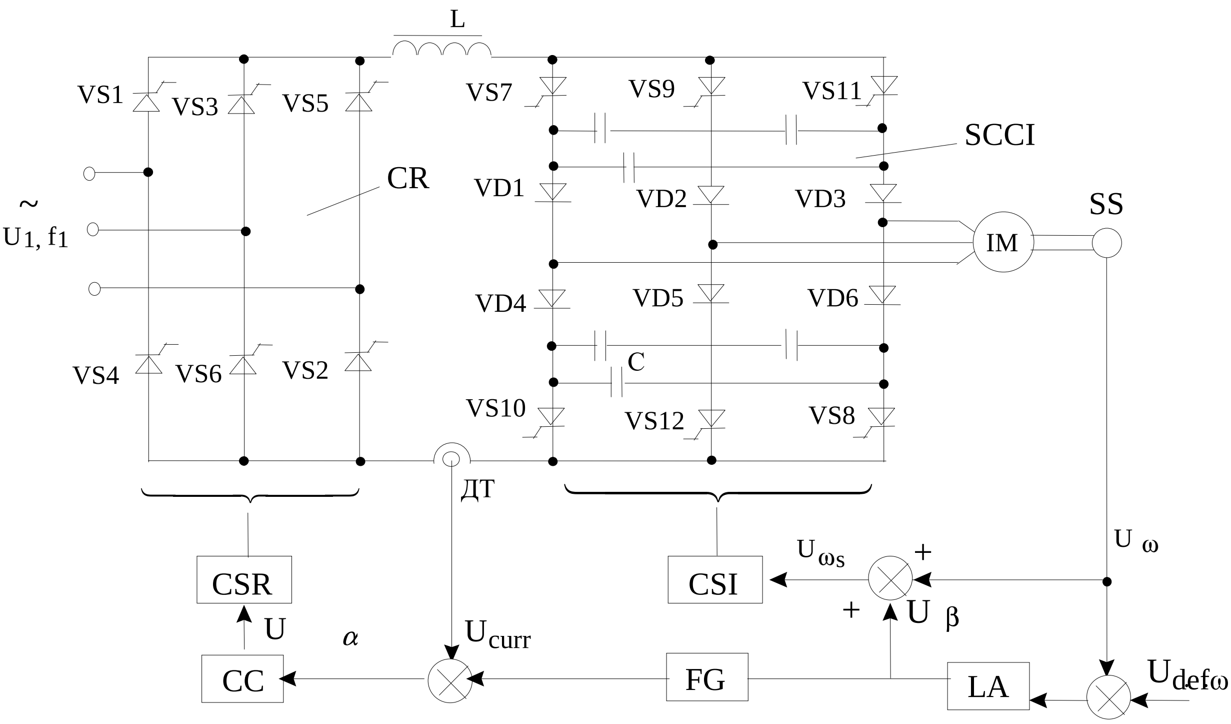


Fig. 3.39

When IM braking with power recuperation the SCCI switches to the rectifier mode, and CR in the mode of mains-controlled inverter.

In the inverter with DC link inverters are used with pulse-width modulation (PWM), which allow a wide voltage and frequency regulation and provide a sinusoidal output current. When using the inverter with PWM inverter circuit can be applied uncontrolled rectifier.

These are used as the drive pulse time-proportional control (TPC), which are installed between the DC power source and inverter. TPC scheme allows a wide range of voltage regulation across the entire range of frequency. TPC-voltage scheme shown in Fig. 3.41.

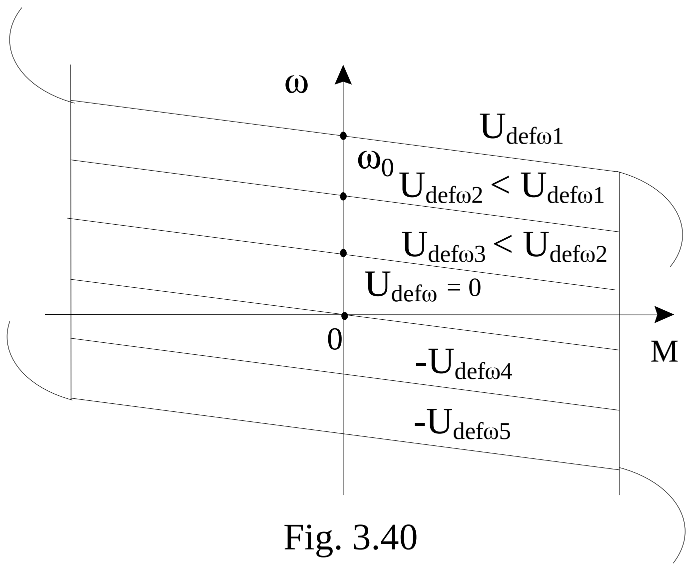


Fig. 3.40

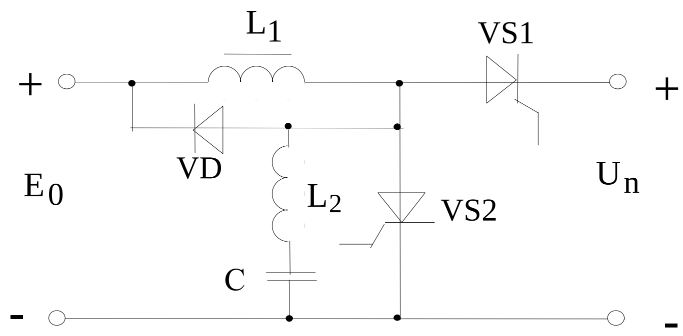


Fig. 3.41

VS1 - the main thyristor
VS2 - auxiliary thyristor;
L_1 - limiting the reactor;
L_2-C - switching circuit;
VD - uncontrollable diode.

When a control pulse from the PPCC to VS1, it opens and the load is applied supply voltage E_0. To disconnect the load from the power source pulse is applied to the VS2 and removed from VS1, then use circuit switching thyristor L_2 C the VS1 closed. The average voltage across the load is proportional to duty cycle switching thyristor VS1

$$U_{n.av} = \gamma E_0 .$$

Thus, a wide range voltage controlled.

In open-loop drive FC - IM the speed range is 5 - 10, and in the closed (with feedback) can reach 1000 or more. The use of the FC - IM: high-speed systems (electrospindles, fans aerotrub, etc.).

3.9 Speed control of IM in the cascade schemes

In high-power electric drives with IM losses of slip:

$$\Delta P_2 = M\omega_0 S,$$

significant, so it is necessary to use the energy of slip for useful work. The first schemes, where energy of slip is used, were circuits, where IM connected to other machines and called cascade. Currently power slip can be used without additional machinery, and with semiconductor circuits. They are also called cascade.

Cascading connection scheme allows with speed control to use the power slip energy. Distinguish circuit of electrical and electromechanical stages. In an electric stage (Fig. 3.42 a) transducer converts the slip power ΔP_2 at frequency $f_2 = f_1 \cdot S$ in power $P_{el.s}$ with f_1 and U_1 and sends it to the mains $P_{el.s} = \Delta P_2 - \Delta P_{2el} - \Delta P_n$.

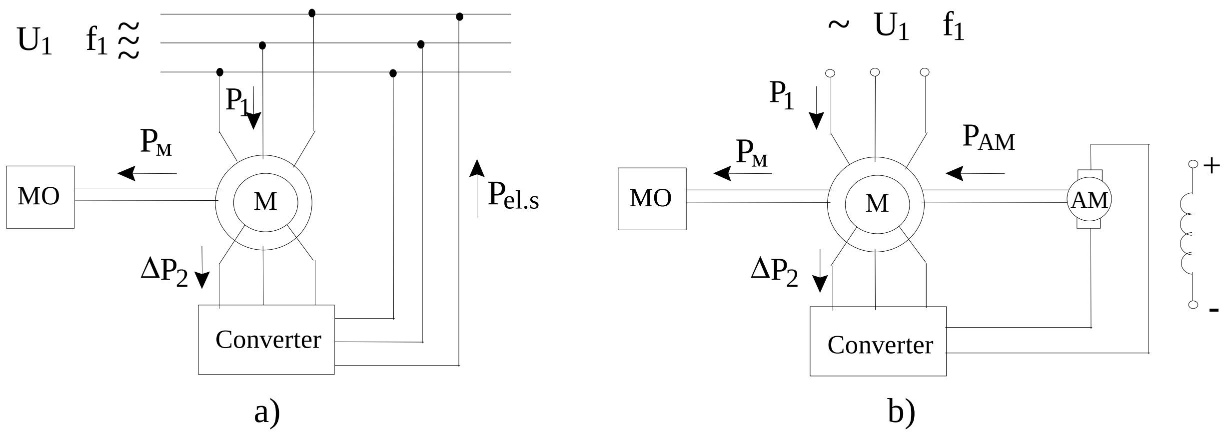


Fig. 3.42

In the electromechanical cascade the slip power minus losses in the rotor converter and auxiliary mashine AM enters the shaft in the form of mechanical power P_{AM}:

$$P_{AM} = \Delta P_2 - \Delta P_n - \Delta P_{2el} - \Delta P_{AM}.$$

If it neglects the losses in the cascade scheme, that the power comes on the shaft from the IM $P_M = P_2 = M \cdot \omega$ and the power of AM $P_{AM} = \Delta P_2 = M\omega_0 S$. The total power of the shaft:

$$P_\Sigma = P_M + P_{AM} = M\omega + M\omega_0 S = M\omega_0 = P_{EM},$$

therefore, these cascades are called cascades of constant power.

Cascades are: a) the machine, and b) a machine-valve, c) valve.

Machine- valve cascades, in turn, may be electromechanical (Figure 3.43) and electrical (Figure 3.44).

Speed control of a machine-valve stages is due to changes in the regulation E_{BM} of excitation current I_f.

By increasing the I_f will increase E_{AM} and decrease the rectified current I_d:

$$I_d = \frac{E_{rec} - E_{AM}}{R_\Sigma}.$$

Reducing the rectified current I_d and current I_2 will decrease the torque, as a result of the speed of IM begins to fall, $E_2^{`} = E_{2k} \cdot S$ and S start to grow. This will increase the current I_2 and the torque of IM. Motor will operate at a low speed with required torque.

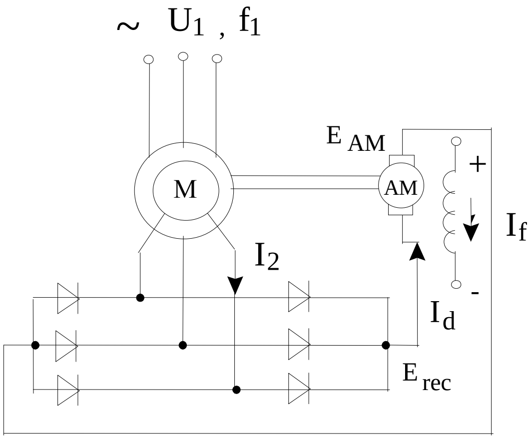


Fig. 3.43

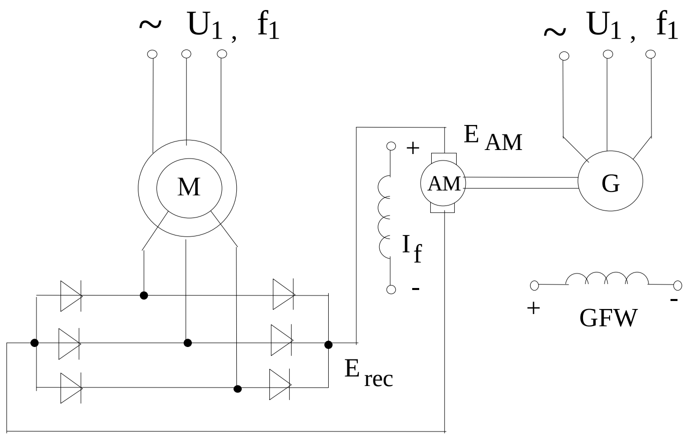
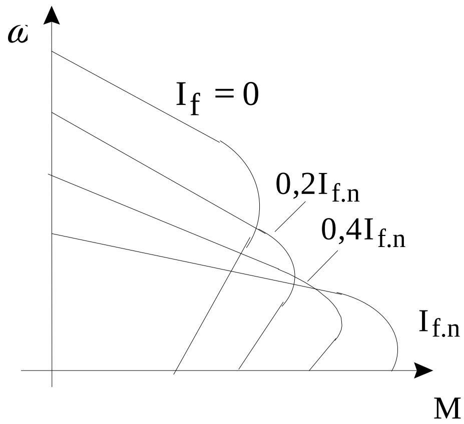


Fig. 3.44

The mechanical and electrical characteristics of the mechanical and electromechanical cascades are shown in Fig. 3.45, 4.46.

Machine-valve electric cascade can be replaced by a static FC with a rectifier R and inverter I. This is called asynchronous-valve cascade (Fig. 3.47).

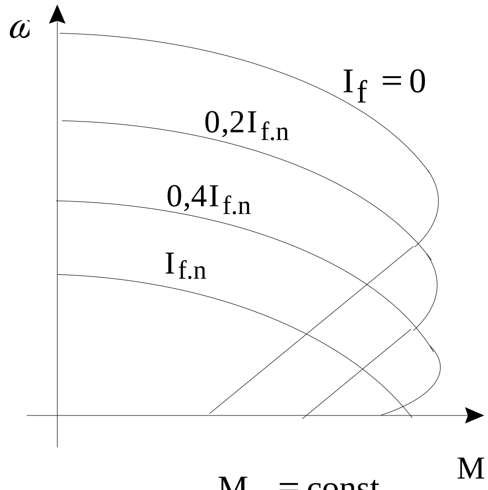
Mechanical characteristics are similar to those of the cascade of constant torque (Fig. 3.45). Such cascading schemes are the most economical, allow to adjust the speed of both downwards and upwards from synchronious and are called with dual-zone control.



$P_M = M_{cr} \cdot \omega = const$

Cascade of constant power

Fig. 3.45



$M_{cr} = const$

Cascade of constant torque

Fig. 3.46

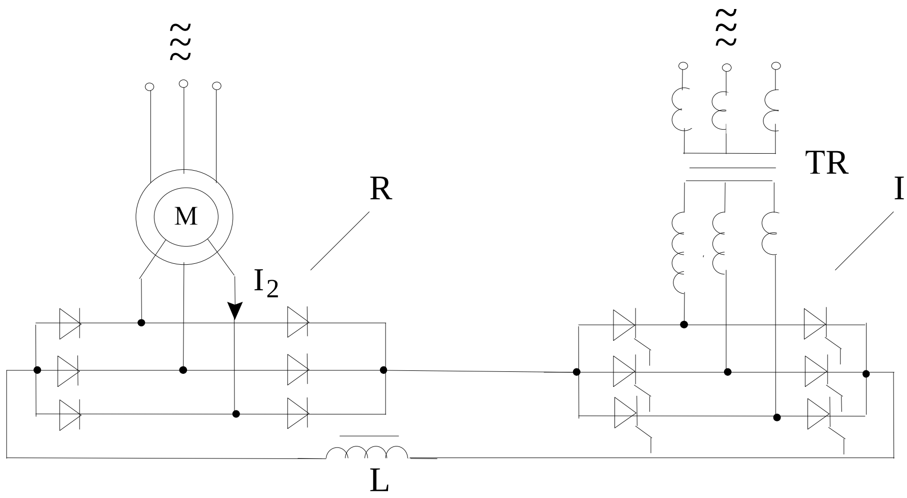


Fig. 3.47

3.10 Pulse method of IM coordinates control

The essence of this method of regulation is pulsed (periodic) changes in the parameters of the main circuit, in particular supply voltages U_1, additional resistance in the circuit of the rotor R_{2add} or stator R_{1add}.

The principle of pulse speed control of IM consider on the diagram in Fig. 3.48, where the additional resistor R_{2add} is short-circuited by the switch K in each phase of the rotor.

Fig. 3.49 presents IM mechanical characteristics (1, 2), and industrial machinery (3), and chart speed change ω under different operating modes of switchs, shunting R_{2add}. When the switchs are closed the resistance R_{2add} = 0, which corresponds to the natural mechanical characteristics of IM (curve 1), open-loop K corresponds to an artificial mechanical characteristic (curve 2).

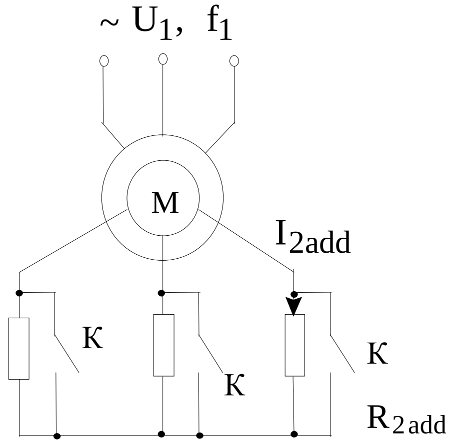


Fig. 3.48

If it takes t_0 - time of open (open-loop) state of the switch, t_3 - the closed (closed-loop) state of the switch, and the cycle period $T = t_3 + t_0$, then the duty cycle $\gamma = \frac{t_3}{T}$ will determine the amount of resistance R_{2add} and the nature of the mechanical characteristics of IM.

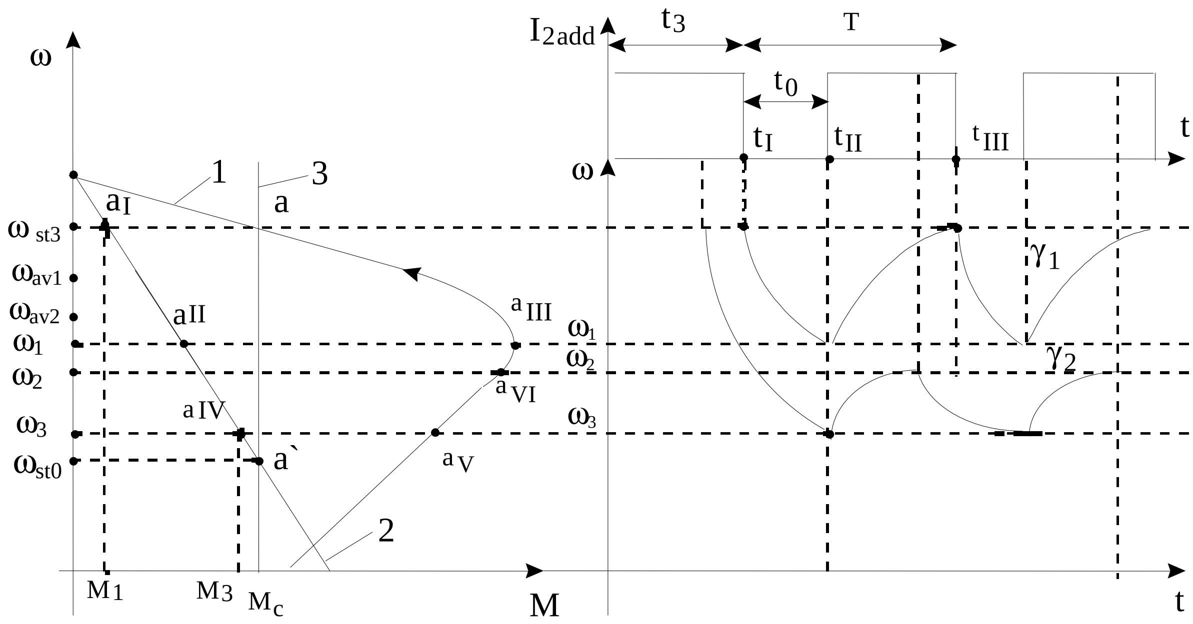


Fig. 3.49

At $t_3 = T$, $\gamma = 1$, $R_{2add} = 0$, corresponding to ω_{st3} (point a on the characteristic 1). At $t_3 < T$, $\gamma_1 < 1$ at time t_I introduced resistance R_{2add} and made the transition to caracteristic 2 in point a_I. At this point, $M < M_C$ and speed falls from ω_{st3} to ω_1 (point a_{II}) exponentially as shown in the diagram. At time t_{II} with switch K the resistance $R_{2add} = 0$ the transition proceeds to the point characteristic 1 in the point a_{III}. The speed increases exponentially, as $M > M_C$. If it turns off switchs at time t_{III} process is repeated. Consequently, at the duty cycle γ_1 the speed changes from ω_{st3} to ω_1, and the average speed is ω_{av1}.

If the duty cycle is $\gamma_2 < \gamma_1$ (dotted lines in the timing diagram), when open-loop speed switchs the speed will fall from ω_{st3} to ω_3 by the characteristic 2 in the point 2 and a_{IV}, and for the closure of switchs the process enters the characteristic 1 in the point a_V, whereupon the speed will increase to ω_2 (point a_{VI}). Therefore, when $\gamma_2 < \gamma_1$ the speed control is provided in a large range (from ω_{st3} to ω_{av2}). Thus, by adjusting the duty cycle, you can adjust the speed of IM with a wound rotor. Similarly, it can adjust the speed not by varying the duty cycl, yet by the frequency of switch closure.

As commutating switch are used thyristor switchs (Fig. 3.50). In this scheme, the thyristor VS commutes resistance R_{2add} with a given duty-cycle and frequency of from PPCC for speed adjustment. The only one resistor R_{2add}, is used, which activated alternately in different phases. The losses (heat) are reduced because instead of three resistances include one.

The main disadvantage of using open loop control - speed depends on the load on the shaft. For rigid characteristics is used closed-loop control system with feedback, which provide a speed range up to 20.

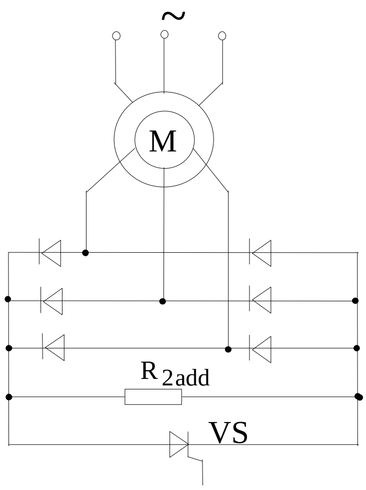


Fig. 3.50

3.11 Braking of induction motors

Methods of braking:

1) plugging;

2) regenerative braking;
3) dynamic braking.

1) Plugging brake can be done in two ways:

a) the change of voltage phase sequence. Mechanical characteristics of the direct phase sequence (1), reverse (2) shown in Fig. 3.51, ab - section of plugging;

b) the load-lowering, providing braking of IM. R_{2add} is introduced into the rotor circuit, providing an artificial characteristic 3. Since $M_C > M_{start}$ cargo will be lowered with the steady speed - ω_{st}.

2) Regenerative braking is carried out when the speed exceeds the synchronous with the return energy to the mains. This mode occurs when the two-speed switching IM with high speed transfers at low speed. Fig. 3.52 presents the mechanical characteristics of the two-speed IM (curves 1, 2), and the mechanism (curve 3). If IM worked with the speed ω_{st1} when switching the number of pole pairs will work in characteristic 2. The section b c - regenerate braking energy to the mains.

The same braking mode is when the system drive is FC - IM. If there is a decrease the frequency f_{reg}, then synchronous speed $\omega_0 = 2\pi f_{reg} / P$ will decrease, but the current speed due to mechanical inertia will decrease more slowly ω_0 than ω would exceed the speed of the magnetic field. Consequently, there is a braking mode (generator) to return power to the mains.

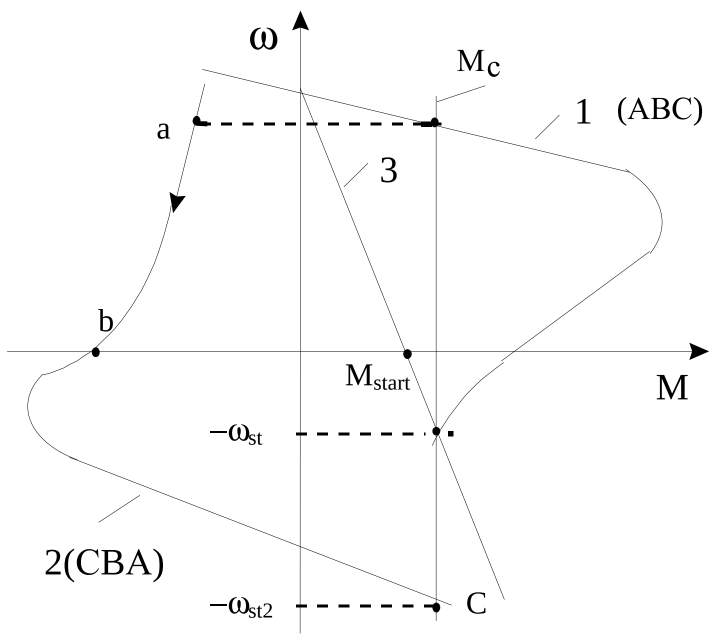


Fig. 3.51

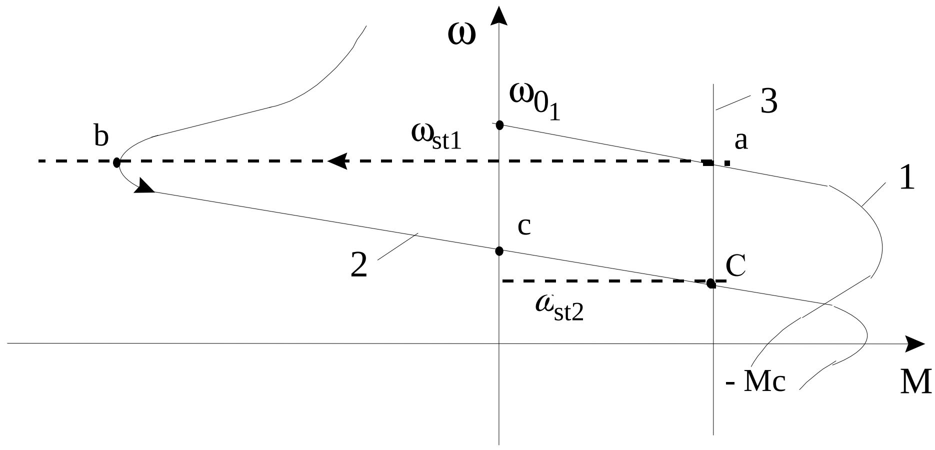


Fig. 3.52

In lifting devices when it occurs load-lowering switches the IM transfer to the characteristic 2 and after acceleration to the other side the IM will operate at the speed ω_{st2} (point C) - the load-lowering is happened with the return energy to the mains (regenerative operation). Regenerative braking - the most economical mode of adjustment of IM.

3) Dynamic braking

Fig. 3.53 shows a diagram of the IM dynamic braking.

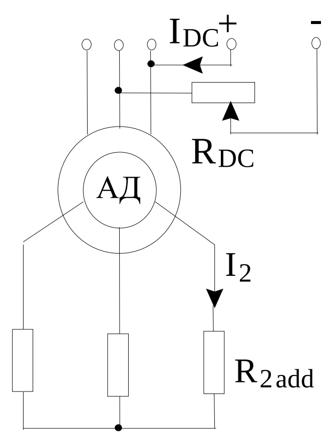


Fig. 3.53

The two phases of IM are connected to a constant voltage across R_{DC}, one phase is disconnected from the mains. Current I_{DC}, flowing through the two phases of the stator windings creates a stationary magnetic field in the space. When the rotor rotates in this field it is induced E_2 and current I_2, which creates a magnetic flux Φ_2. The interaction of the rotor current with the resulting magnetic flux creates a braking torque. The motor operates as a generator, converting mechanical energy into electrical energy that is dissipated as heat in the rotor circuit.

For the analysis of the IM in the dynamic braking mode, assume that the stator is supplied with alternating three-phase current I_{equiv}, creating the same magnetomotive force MMF as the current I_{DC}.

$$F_{DC} = \sqrt{3} I_{DC} W_1 = A = \frac{3\sqrt{2}}{2} I_{equiv} W_1,$$

where: $I_{equiv} = \sqrt{\frac{2}{3}} \cdot I_{DC}$.

The equivalent circuit for this case is shown in Fig. 3.54.

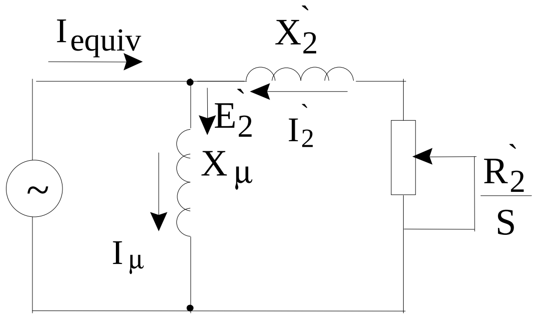


Fig. 3.54

Whence, after transformations obtain:

$$I_2' = \frac{I_{equiv} \cdot X_\mu}{\sqrt{\left(\frac{R_2'}{S}\right)^2 + \left(X_\mu + X_2'\right)^2}}.$$

Then the mechanical characteristics of IM in dynamic braking mode is determined:

$$M = \frac{3 I_2'^2 R_2'}{\omega_0 S} = \frac{2 I_{equiv}^2 X_\mu^2 \cdot R_2'}{\omega_0 S \left[\left(\frac{R_2'}{S}\right)^2 + \left(X_\mu + X_2'\right)^2\right]}.$$

Consequently, I_2' and M depends not only on S, but also on the magnetic state of the motor (X_μ). If it assumes IM unsaturated (X_μ = const), then the current and torque will be the only functions of the slip S.

Then:
$$S_к = \frac{R_2^`}{X_\mu + X_2^`},$$
$$M_{cr} = \frac{3I_{equiv}^2 X_\mu^2}{2\omega_0 (X_\mu + X_2^')}.$$

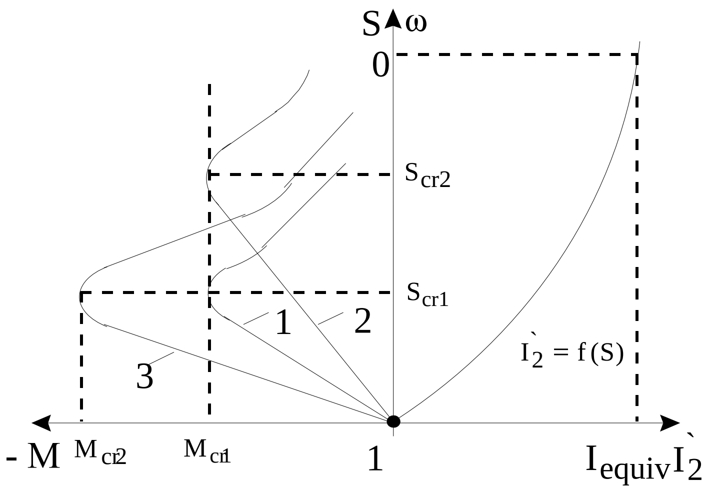


Fig. 3.55

Fig. 3.55 shows the electromechanical characteristics of IM (the first quadrant), and built the mechanical characteristics of IM for two values of I_{DC} ($I_{DC1} < I_{DC2}$ curves 1 and 3) and $R_{2Д}$ ($R_{2Д_1} < R_{2Д_2}$ - curves 1 and 2) for the dynamic braking mode in the second quadrant.

Analysis of the mechanical properties shows that when the current I_{DC} increases sharply critical torque of IM increases, besause M_{cr} depends on the square of the current I_{DC}. Change of additional resistance R_{2add} leads to a change of the critical slip at constant critical torque. Thus, by adjusting the current I_{DC} and R_{2add} it can be obtained the desired mechanical characteristics of IM in dynamic braking mode.

4 ELECTRIC DRIVES WITH SYNCHRONOUS MOTORS

4.1 Electromechanical properties of synchronous motors

There is a field winding on the rotor of Synchronous Motor (SM), which is powered by a DC voltage, and a three-phase stator winding is connected to the network (Fig. 4.1).

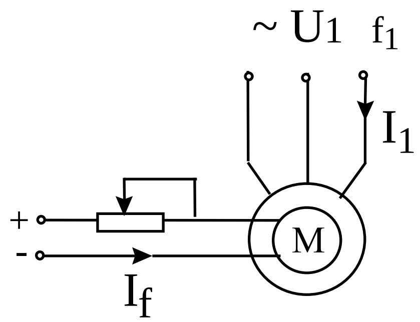


Fig. 4.1

The rotor of SM may be a salient-pole and implicit-pole. SM has an asynchronous start-up, for which the rotor is performed starting squirrel winding in the form of a squirrel cage.

The SM is presented in the form of generalized electrical machine (Fig. 4.2).

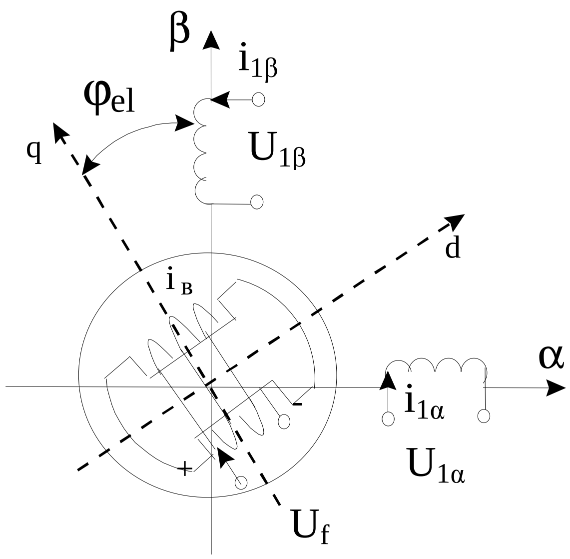


Fig. 4.2

Then the equations of the electromechanical characteristics of SD are of the form:

$$\begin{cases} U_{1\alpha} = R_1 i_{1\alpha} + d\Psi_{1\alpha} / dt, \\ U_{1\beta} = R_1 i_{1\beta} + d\Psi_{1\beta} / dt, \\ U_f = R_f i_f + d\Psi_f / dt. \end{cases} \tag{4.1}$$

Asynchronous start of SM is carried out on the mechanical characteristics (Fig. 4.3) to the sub-synchronous speed, $0.95\omega_0$. Then, under the synchronizing torque M_{syn} motor retracts in synchronism and rotates with the synchronous speed. Fig. 4.4. shows the mechanical characteristics of SM, according to which ω_0 remains constant:

$$\omega_0 = \frac{2\pi f_1}{P_n} = \text{const}$$

When the load increases to $M = M_{MAX}$, then after an overload the SM falls out of synchronism and stops on an asynchronous mechanical characteristics.

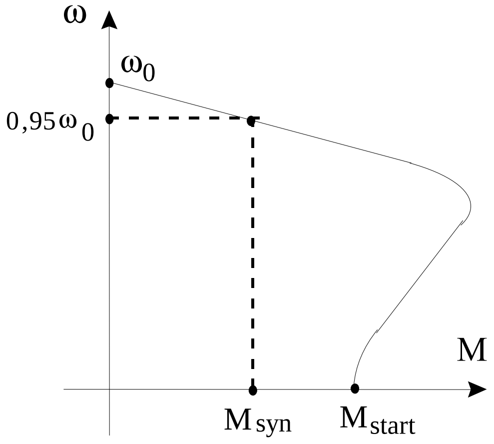


Fig. 4.3

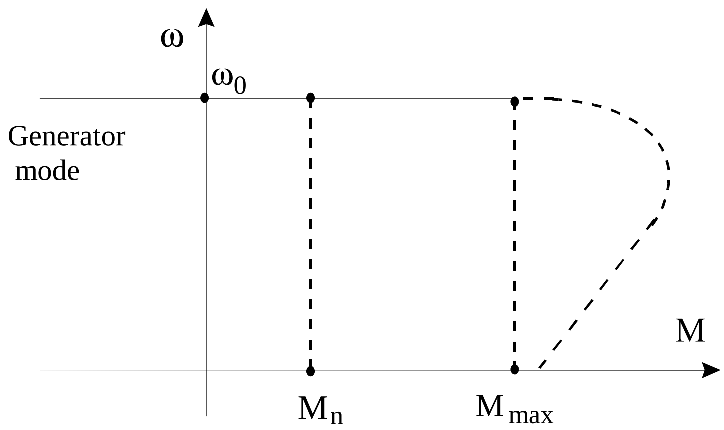


Fig. 4.4

When operating in motor mode, the rotor lags behind the stator field at an angle θ (internal angle SM) $\theta = \varphi_0 - \varphi_{el}$. Equations 4.1 in the axes d and q are of the form:

$$\begin{cases} U_{1m} Sin\theta = R_1 i_{1\alpha} + d\Psi_{1d} / dt - \omega\Psi_{1q} \ ; \\ -UCos\theta = R_1 i_{1q} + d\Psi_{1q} / dt - \omega\Psi_{1d} \ ; \\ U_f = R_f i_f + d\Psi_f / dt \ ; \\ M = P_n(\Psi_{1d} i_{1q} - \Psi_{1q} i_{1d}) \ . \end{cases} \tag{4.2}$$

After the transformation, neglecting $R_1 = 0$ and $i_f = I_f = \text{const}$ the equations (4.2) take the form:

$$\begin{cases} U_{1m}Sin\theta = -\omega_0 L_{1q} I_{1q} = -X_{1q} I_{1q} \; ; \\ -U_{1m}Cos\theta = \omega_0 L_{1d} I_{1d} - \omega_0 L_{1,2d} I_f = X_{1d} I_{1d} - E_m ; \\ M = P_n \left[-L_{12d} I_f I_{1f} + \left(L_{1d} - L_{1q} \right) I_{1d} I_{1q} \right] . \end{cases} \quad (4.3)$$

Lets evaluate stator currents I_{1q} и I_{1d}:

$$I_{1q} = -\frac{U_{1m} Sinq}{X_{1q}}, \quad (4.4)$$

$$I_{1d} = -\frac{E_m - U_{1m} Cos\theta}{X_{1d}}, \quad (4.5)$$

and substitute into the equation the torque, after transformations obtain the equation of mechanical characteristics:

$$M = \frac{2U_1 E \cdot SinQ}{\omega_0 X_{1d}} + \frac{3U_1^2}{2\omega_0} \left(\frac{1}{X_{1q}} - \frac{1}{X_{1d}} \right) Sin2\theta . \quad (4.6)$$

Consequently, the electromagnetic torque SM consists of two components: the first is due to the interaction of the rotating stator field with the field of the rotor, and the second is the reaction torque due to the execution of salient rotor.

Dependence of the torque of SM from the interior angle θ called load angle characteristic.

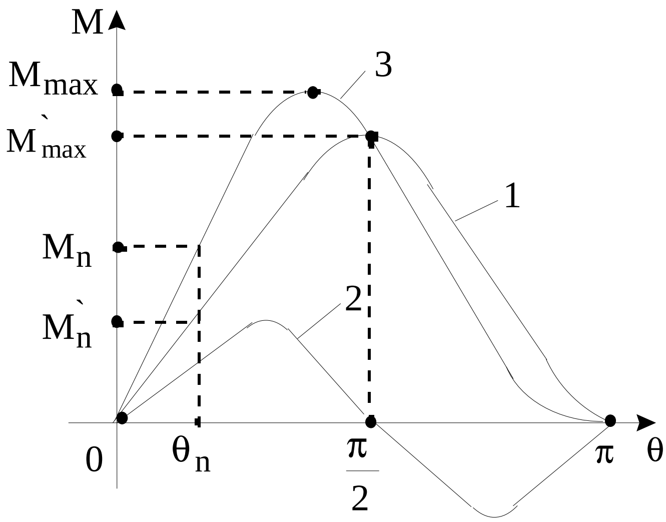


Fig. 4.5

Fig. 4.5. shows the load angle characteristic implicit-pole SM (curve 1), salient pole SM (curve 3) and the dependence of the reaction torque of SM from the interior angle (curve 2).

Maximum torque implicit-pole of SM occurs when $\theta = \frac{\pi}{2}$ and is

$$M_{max} = \frac{3U_{ph}E}{\omega_0 X_1}. \qquad (4.7)$$

Rated operating mode of SM corresponds to θ = 25-30^0. If the angle θ reaches $\frac{\pi}{2}$ SM falls out of synchronism. The ratio $\lambda = \frac{M_{max}}{M_n}$ determines the overload capacity of the SM, which can reach λ = 2 - 3,5.

Synchronous motors can operate in different modes, motor and the generator (simultaneously, sequentially and independently from the mains), and a synchronous compensator.

Generator mode consistent with the mains (plugging) is rarely used because it is accompanied by high inrush current.

For braking SM is often used in regenerative operation irrespective of the mains (dynamic braking, as shown in Fig. 4.6).

Mechanical characteristics of SM similar with characteristics of induction motor during dynamic braking (Figure 4.7).

Motor control system with SM should provide start-up, synchronization with a mains, resynchronization, speed control, braking, adjusting the excitation current.

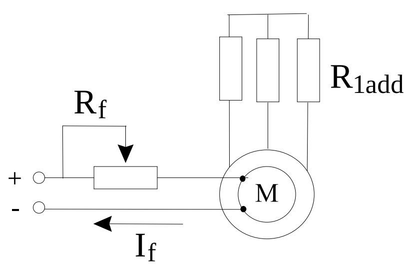


Fig. 4.6

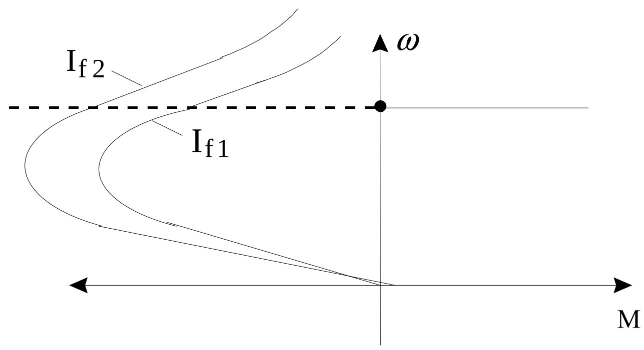


Fig. 4.7

Electric drives with SM are divided into 3 classes:

a) ED with the same or slowly varying load (ED pumps, fans, compressors, etc.). CD should have P_n from 10 kW to 5 MW;

$$\frac{M_{start}}{M_n} = 0,4 \div 0,6; \qquad \frac{M_{INPUT}}{M} = 0,8 \div 1,2; \qquad \frac{M_{max}}{M_n} = 1,5 \div 2.$$

b) ED with pulsating loads (ED of rocking pumps oil, piston compressors P_n from 100 kW to 10 MW) should ensure

$$\frac{M_{start}}{M_n} = 0,4 \div 1; \quad \frac{M_{INPUT}}{M} = 0,4 \div 0,6 \; ; \quad \frac{M_{max}}{M_n} = 1,5 \div 2,5 .$$

c) ED with sharp variable load (ED crushers, mills mining industries, saws and shears for metal, winches blast furnaces) P_n from 1 MW to 200 MW. ED should provide:

$$\frac{M_{start}}{M_n} = 1,2 \div 2 ; \quad \frac{M_{INPUT}}{M} = 1 \div 1,5 \; ; \quad \frac{M_{max}}{M_n} = 2,5 \div 3,5 .$$

4.2 The electric drives with stepper motors

ED with stepper motors belong to a class of discrete drive, make dosage move latching position at the end of the movement. Well with the digital control machines and software devices. Widely used in machines with programmed numerical control for robots and manipulators.

Stepper motor – synchronous motor , however , the magnetic field rotates in air gap discrete (steps) by pulsed excitation winding via an electronic switch. The rotor is typically a permanent magnet (double-pole) on the shaft is called active. Fig. 4.8 is a diagram of a stepping motor rotor with active rotor.

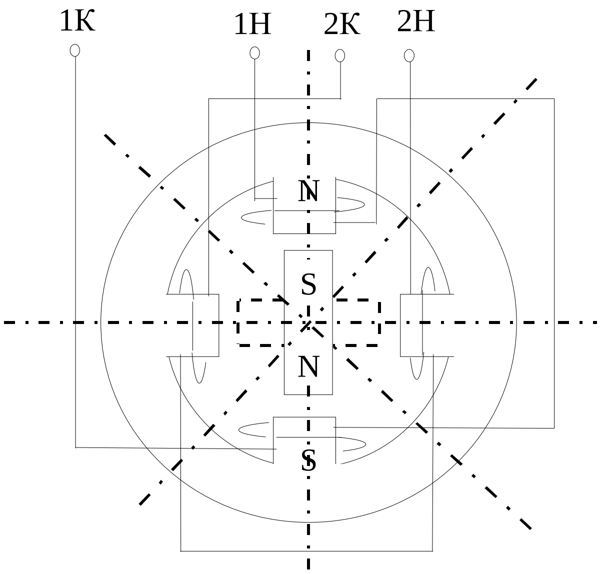


Fig. 4.8

When a voltage pulse comes to the coil 1H - 1K rotor is vertical, with coil power 2H - 2K - horizontal position, providing a step equal to 90^0. The position will be steady, since the deviation from it on the rotor operates synchronizing torque, $M = M_{max} Sin\theta$, where θ - angle between the magnetic fields of the stator and the rotor. If the pulse voltage supplies to both coils simultaneously, the axis of the stator magnetic field will be located at 45^0.

The rotor turns thus by 45^0 to its maximum field crossed. If the voltage is removed from the coil 1H - 1 K, the rotor will be horizontally (next step), and then by changing the polarity of the voltage axis of the magnetic field is moved by another 45^0, etc. (This is known as asymmetric).

The angular displacement of the stepper motor is determined by:

$$\alpha = \frac{2\pi}{\mathrm{Pn}}, \tag{4.8}$$

где Pn - число пар полюсов ротора;
n – number of operations (measures) in a cycle equal to the number of phases stepper motor with symmetrical switching and twice the number of phases in asymmetric switching.

Stepping movement of the rotor is performed by applying pulses to the switching windings (one commutation cycle - one step of the rotor). The total angle of rotation is proportional to the number of pulses stepper motor, and its speed - a pulse frequency, amplitude, and pulse shape may be different. To reverse the stepper motor to turn in the opposite polarity of the winding, which is currently disabled, and then the rotor will move in another direction.

The main mode stepper motor – the dynamic. stepper motor is a synchronization of dormancy and braked himself. Therefore, the stepper motor provides start-up, braking, reversing and the transition from one frequency to another of control pulses. Start stepper motor is abrupt or gradual increase in the frequency of the input signal to the operating, braking - reduce it to zero, reverse - changing the switching winding stepper motor.

According to the construction stepper motor can be single phase, two-phase, multi-phase, with active or passive rotor. Active rotor is constructed in the form of permanent magnets or an excitation winding as a synchronous motor (magnetoelectric steppers). These are a major step stepper motor rotor from 90 to 15^0. To reduce the number of steps to increase the phase and clock switching, and also use two stators or twin-rotor design.

Maximum response frequency at which the possible start stepper motor from standstill without loss of sync (skip steps) is the frequency of acceleration. The higher the electromagnetic and mechanical inertia of the stepper motor and the load torque is greater, the lower the frequency of acceleration.

Maximum speed of stepper motor with the active rotor is 208 - 314 rad/s, the frequency of the pickup is from 70 to 500 Hz, nominal torque from $10 \cdot 10^{-6}$ to $10 \cdot 10^{-3}$ Nm. For high frequencies of the pickup stepper motors with passive rotor is used, which are divided into reactive and inductor. The rotor is made of ferromagnetic material has not windings (passive). Armature projections

Z_C (salient poles) with the windings are on the stator, armature projections Z_P without windings are on the rotor.

If $Z_P > Z_C$ every switching the stator winding reduces rotor rotates (steps), equal to:

$$\alpha = \tau_c - \tau_p = \frac{360^0}{Z_c} - \frac{360^0}{Z_p} = \frac{360(Z_p - Z_c)}{Z_p \cdot Z_c}. \qquad (4.9)$$

Reducing the difference between the Z_P - Z_C, you can reduce the step of the rotor. Stepper motor with passive rotor have a resolution of 1.5 to 9^0, the torque of $2{,}5 \cdot 10^{-6} - 10 \cdot 10^{-3}$ Nm, rate of pickups frequency from 250 to 1200 Hz.

Control circuit of discrete electrical drive

Specific sequence of voltage pulses feeds on the stator winding. Average speed of stepper motor depends on the switching frequency coils f_K:

$$\omega = \alpha \cdot f_k, \qquad (4.10)$$

which provides by electronic switch and varies widely. The switch is a converter frequency (CF) and the digital drive – system with frequency-controlled stepper motor.

Fig. 4.9 shows the block diagram of a stepper motor drive,
where ECS - the electronics crushing step;
BSSB - block of smooth start and braking;
PS - power supply unit;
PFVR - pulse frequency voltage regulator;
PG - pulse generator;
PD - pulse distributor;
IA - intermediate amplifier;
FC – frequency converter;
FBA – feedback amplifier;
SP – sensor position and speed;
DR – digital regulator.

The control signal f_C in the form voltage pulses applied to the input of PG, which generates pulses of duration and amplitude, PD – converts the pulses generated in the system in four unipolar voltage pulses corresponding to the number of phases of the motor. Amplified by IA pulses are applied to the switch to power the stepper motor windings. Normally the switch is powered by a DC source. Fig. 4.10 is a diagram of a thyristor converter.

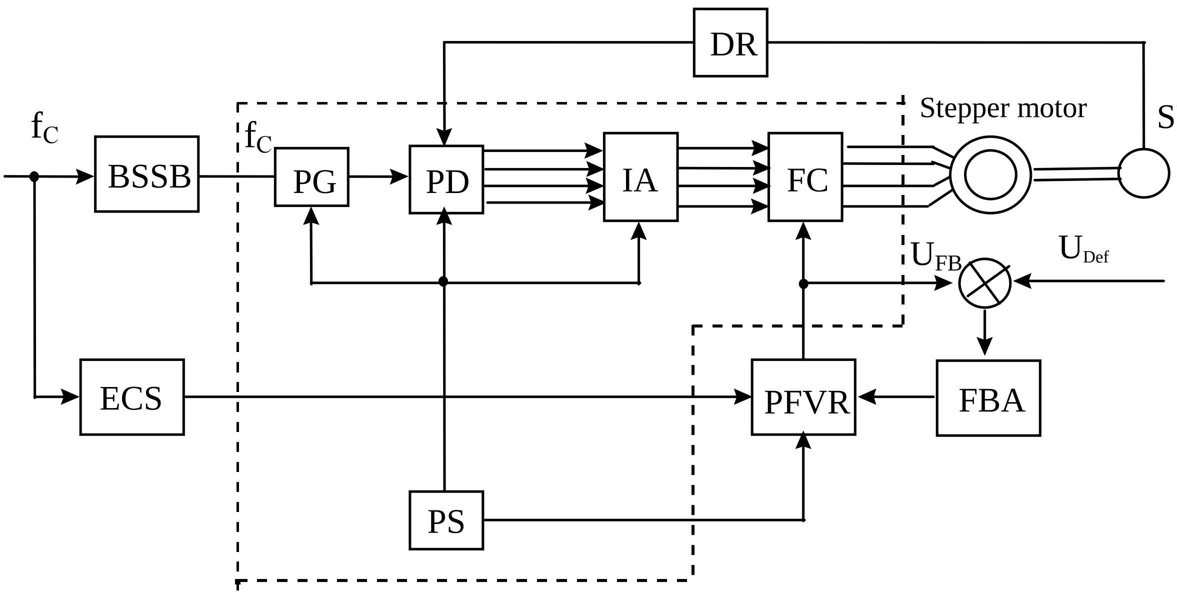


Fig. 4.9

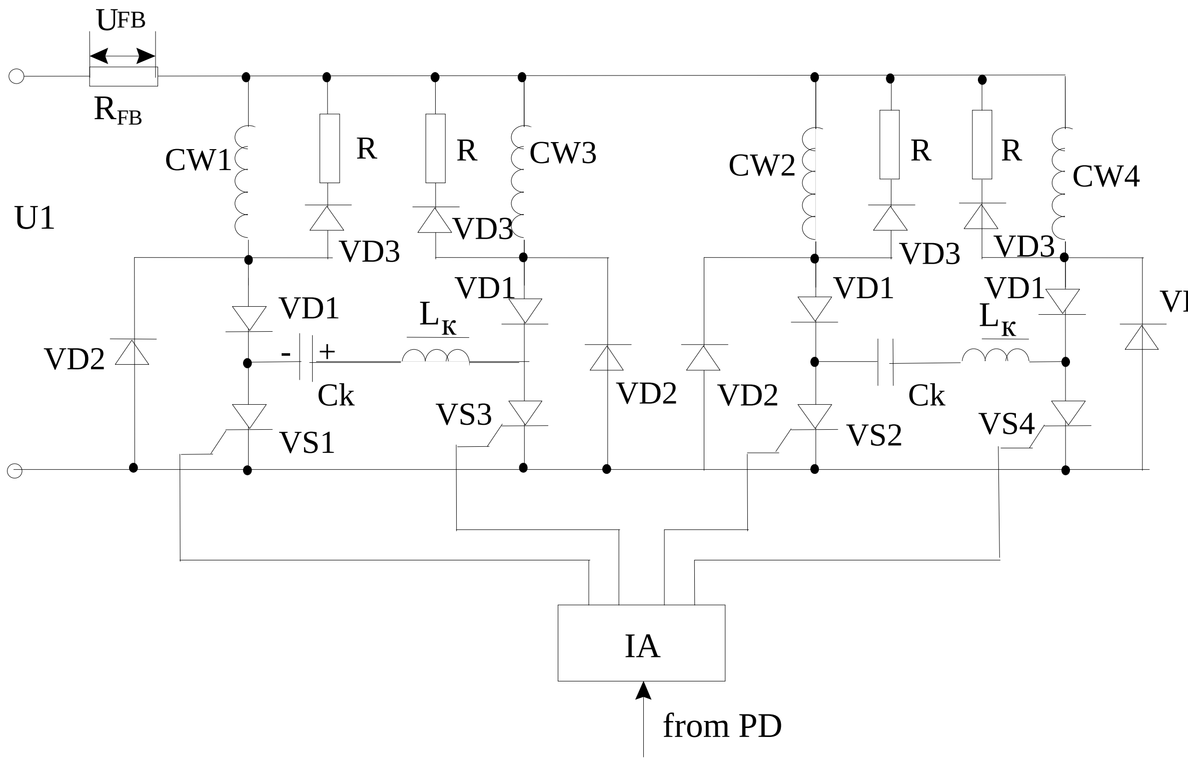


Fig. 4.10

Thyristors VS1 - VS4 provide coils pair switching of stepper motor, in every moment the two windings of the 4 (four phase) are used; VS1 and VS3; VS2 and VS4 form a circuit of two triggers in which the thyristor switch are realized by oscillating circuit L_K - C_K.

For example, in the initial position thyristor VS1 is open and current flows Control Cinding 1 (CW1), and the thyristor VS3 closed. By applying a control pulse on VS3, then it opens up, the winding CW3 will pass current. At the same time recharging of the capacitor C_K begins and thyristor VS1 will be closed, as the cathode potential becomes more positive than the potential of the anode. Thyristors VS1 and VS3 are working in alternate trigger circuit.

Trigger made by thyristors VS2 and VS4 works similarly. To remove the surge circuits are used, R - VD3.

Closed circuit (Fig. 4.9) with a negative current feedback provides automatic stabilization current in the windings, the signal U_{FB} is taken from the resistor R_{FB}. The signal difference U_{FB} and U_{Def} defines the control signal, which is input to the feedback amplifier FBA.

4.3 Electric drives with valve motors

DC motors have good adjustment properties, but the presence of the collector-brush assembly increases the operating costs, the size and cost of the DCM. With the development of semiconductor technology the opportunity to replace the mechanical rectifier-collector by electronic brushless commutator switch is appeared, which represents a frequency converter, controlled in dependence on the position of the motor rotor (armature). These motors were called Valve Motors (VM). They have ample opportunity to regulate the speed and torque by changing the voltage, excitation current and control angle of valve inverter.

By construction, the VM is a synchronous motor. At the three-phase stator winding is AC, fed from the valve switch. The rotor may be formed with permanent magnets or with an excitation winding, supplied via the slip rings DC. In VM uses 2 types of frequency converters: with an intermediate DC (two-tier), and directly connected to the mains, discussed earlier.

Switching current in the inverter can be natural or artificial. Natural switching valves used in those cases when the inverter load (three-phase winding SM) comprises a source of electromotive force at the same frequency as the inverter output voltage.

Scheme of VM with natural commutated of inverter gates is shown in Fig. 4.11. Controlled rectifier circuit comprises a controlled rectifier CR, a smoothing reactor L, controlled inverter CI, thyristor exciter TE of motor and rectifier control system RCS and inverter control system ICS. The angular position of the rotor is controlled indirectly by the phase voltage U(φ) on the outputs of the stator winding.

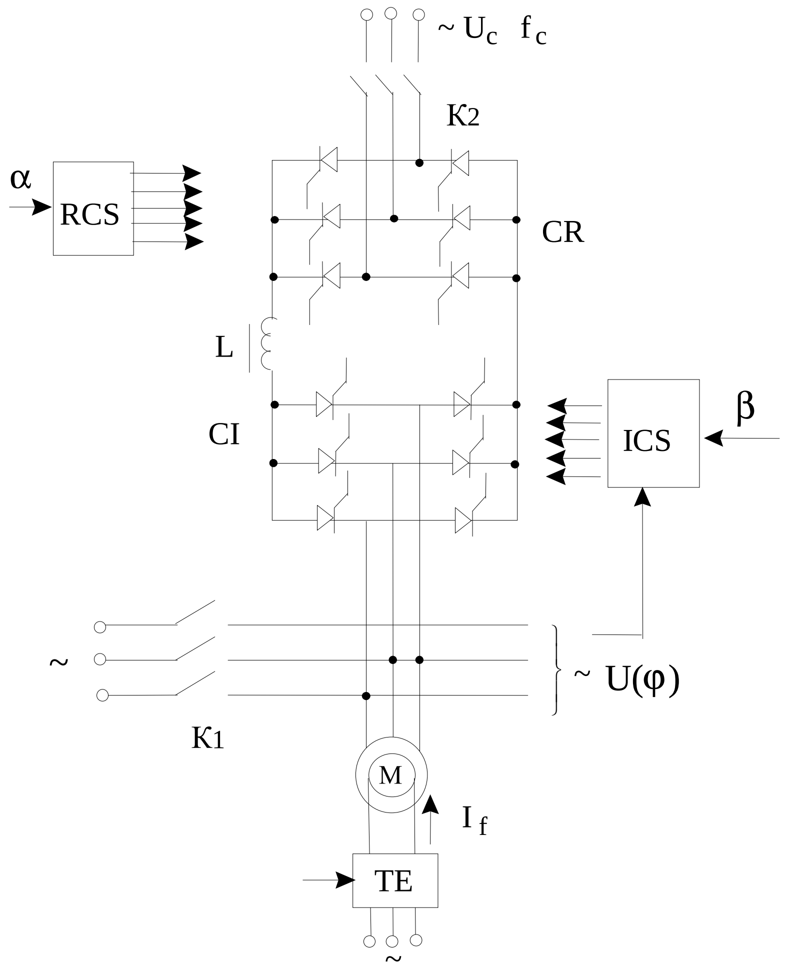


Fig. 4.11

Speed control is produced by changing the rectified voltage at the output of the CR or current excitation via TE.

Natural switching valves can be carried out only at the big EMF of motor, which occurs at speed of not less than 10% of nominal. Therefore, when initially starting the asynchronous start is produced by contactor K1 directly from the mains and then K1 is disconnected and K2 is switched on in the valve or inverter mode.

The inverter with artificial valves switching - DC-DC or DC to AC with forced commutation valves eliminates the difficulty in starting. VM scheme with artificial valves switched inverter is shown in Fig. 4.12.

The inverter is made on thyristors VS1 - VS6, controlled rectifier - on thyristors VS9 - VS14. Rectifier control system (RCS) delivers pulses to the control electrodes of the thyristors CR, and inverter control system (ICS) to the control electrodes of the thyristors CI. The circuit comprises switching thyristors VS7 - VS8, the reverse bridge, performed diodes VD1 - VD6, discharge resistors and diodes R1, R2, VD7, VD8, power filter L_1, C_1 and the tank circuit switching L2 - L5, C_2, C_3.

Artificial switching is done by the expense of the energy stored in the capacitors C2, C3 from an additional source of recharge.

The control of inverter is made in function of the position of the rotor position sensor RPS, which affects the ICS. Adjustment of speed control occurs by changing the rectified voltage of RCS and CR (adjusting the angle of the control), the excitation current and the control angle β thyristors of inverter through the ICS. For high-quality management scheme with feedback on the principle of a slave control is used (closed circuit electric drive).

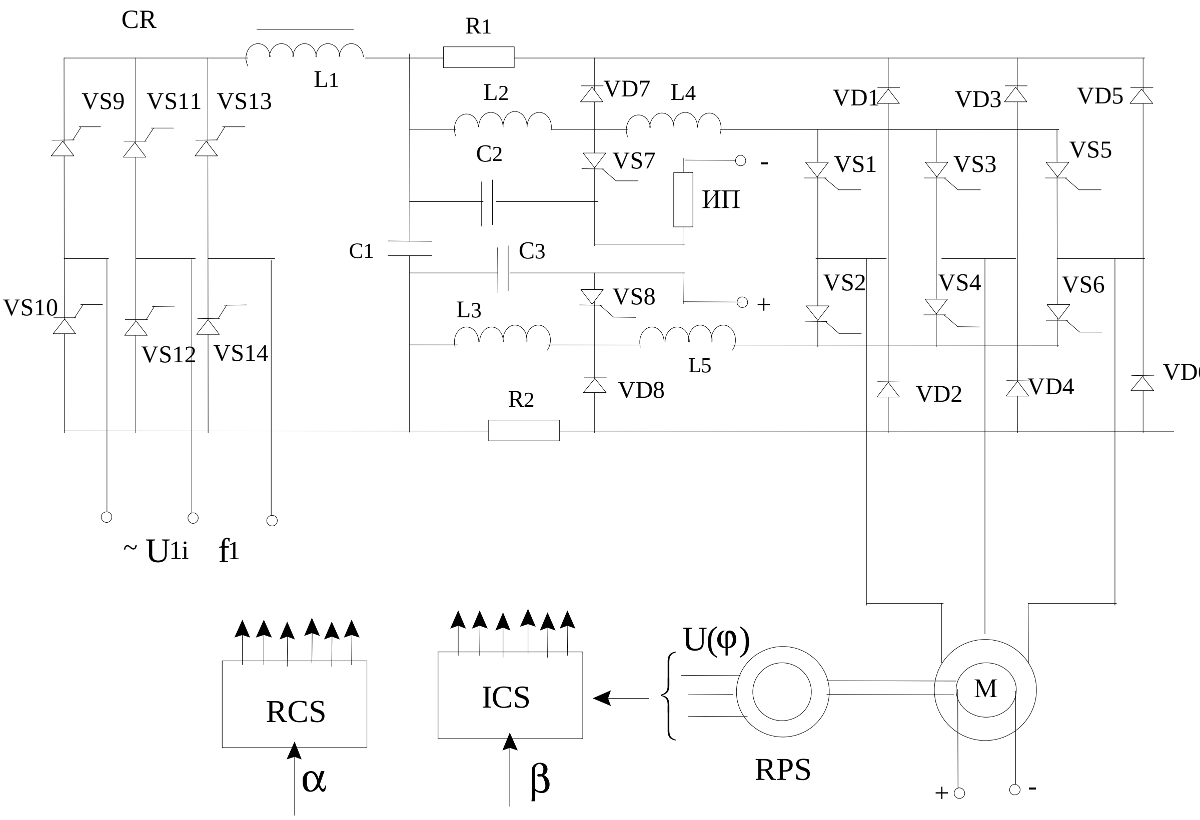


Fig. 4.12

CONCLUSION

The course "Electric drive" refers to the direction of general professional disciplines 140400 - "Electric Power and Electrical Engineering" and the main purpose of this lecture notes - form students' basic knowledge of electric drive for further in-depth study of special subjects .

This manual consists of four chapters. One is devoted to the mechanics of the drive: motor and mechanisms characteristics, stability of work, calculation multimass mechanical systems.

The next three chapters are devoted to a detailed description of the actuators on the basis of the most common types of motors: a DC motor with separate excitation, DC motor series excitation, the induction motor and synchronous motor. Each type of the drive comprises circuitry, differential equations, static characteristics, methods for controlling the electric drive coordinates, as well as ready-made solutions for automated control systems of electric drives.

The study course "Electric Drive" should be accompanied by practical tasks and laboratory works . This guide will help students to preview the theoretical material and prepare thoroughly for all types of student work that ultimately will improve the quality of education.

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