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ELECTRIC DRIVE

Study guide

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The book is a study guide, which contains basic information on the electric drive. The material of the manual can be useful not only to students of the specified field, but also to engineering and technical personnel working in the field of automated electric drive.

Illustrations 103. Bibliography 7 names

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THE CONTENTS

LIST OF ABBREVIATIONS

AM – is an asynchronous motor;

C – is a converter;

DCM IE – is a direct current motor of independent excitation;

DCM SE – is a direct current motor of series excitation;

DCM ME – is a DC motor of mixed excitation;

EMS – is a electromechanical systems;

ED – is electric drive;

SM – is a synchronous motor;

SC – is a speed controller;

TR – is a torque regulator.

FOREWORD

The proposed book is a study guide written for full-time students of the specialization 0922 – «Electromechanics».

The manual is intended for studying the following disciplines: «Fundamentals of electric drive», «Electric drive», «Automated electric drive» and others.

The content of the manual can be useful for independent work, course design, performance of computational and graphic tasks and laboratory work.

This book is not able to replace a number of already published textbooks by professors L. V. Akimov, A. B. Zelenov, V. B. Klepikov, O. Y. Lozynskyj, M.G. Popovich, A. V. Sadovyi. etc. in any way.

It is a minimum of basic knowledge of the electric drive, which will allow a reader to successfully master a number of special issues of the modern theory of the electric drive in the future.

The authors consider it necessary to thank their colleagues – employees of the «Automated electromechanical systems» department of the National Technical University «Kharkiv Polytechnic Institute» for their help in the work and useful tips given during the discussion of the book manuscript.

The comments of the head of the department, professor V. B. Klepikov contributed to the improvement of the content of the textbook.

Quite a lot of work with the manuscript of the book was done by the reviewers – Professor Y. V. Shcherbak. and Professor O. M. Synchuk, to whom the authors express their sincere gratitude.

1 INTRODUCTION

The course of lectures is based on such disciplines:

– The theoretical mechanics;

– Electric machines;

– Electric devices;

– Industrial electronics;

– Theory of automatic control.

The course purpose is to learn the properties and characteristics of electromechanical systems (EMS), and to study the basics of selection and calculations of power electrical equipment of an electric drive (ED).

The course consists of the following sections:

– ED mechanics;

– ED motors characteristics;

– ED transients;

– ED torque and speed control;

– choice and capacity calculation of ED motor.

Electric drive is EMS, intended for driving of mechanisms or machines by electric motor which is a source of mechanical energy [1].

Modern ED, in comparison with other electric drives, has a number of advantages that ensure its wide distribution. These advantages include:

– high efficiency;

– possibility of automation of the different technological processes;

– the ability to implement almost any laws of movement of the working body;

– wide range of ED capacities (from fractions of watts to hundreds of thousands watts).

The advantages of ED are due to such qualities of electricity as its ability to be transmitted over longer distances, constant readiness for use, ease of transformation into other types of energy and, in particular, into mechanical energy.

1.1 Function chart of the electric drive

The functional scheme of the ED is presented in fig. 1.1

Electric drive contains:

– power conversion device (PCD);

– electric motor (EM);

– transfer device (TD);

– control unit (CU);

– direct and reverse connections

The working machine (WM) is not a part of ED.

On this scheme U_{c1} … U_{cn} – are control inputs. Dotted lines show direct and reverse connections which may or may not be absent.

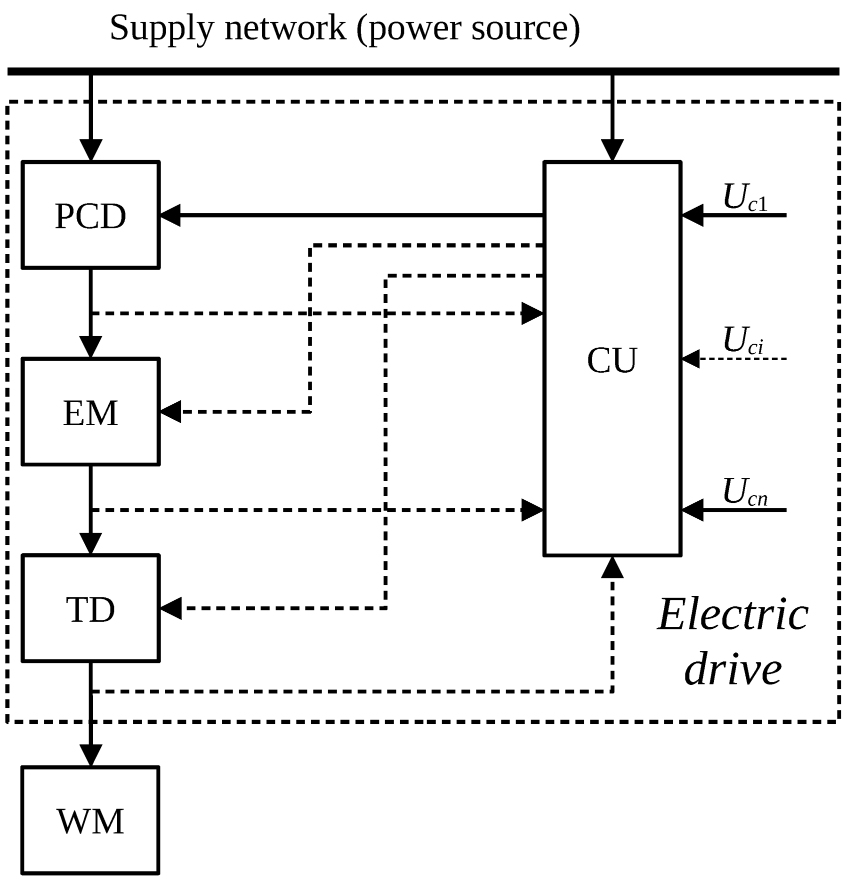

Figure 1.1 – The functional scheme of the electric drive

1.2 Electric drive classification

1. ED may differ in power:

- low power – from 0 to 10 kW;
- average power – from above 10 to 100 kW;
- big power – from above 100 to 1000 kW;
- giant power (super power) – more than 1000 kW.

2. In the type of current:

- DC ED;
- AC ED.

The type is determined by the type of engine

3. By the degree of manageability ED:

- not automated;
- automated;
- automatic.

A non-automated ED is an ED that is a system without external reverse connections.

Automated ED assumes the presence of at least one external reverse connection.

Automatic ED is an automated ED, in which the controlling influence is formed automatically.

1.3 The modern trends in the development of the electric drive

Increasing requirements for the quality of the technological process, productivity, energy consumption and reliability determine the peculiarities of the development of ED at the current stage.

The first feature of the development of the ED is the expansion of the field of application of the regulated ED.

The second feature of the ED development is the increase in the complexity of

ED automatic control systems, as a result of which microprocessor devices are introduced into the control circuits, and in some cases, special control computing machines.

The third feature of the development of ED is the tendency to unify the element base of ED, the creation of complete ED, built according to the block-modular principle.

The main method of ED research is the method of mathematical modeling, which involves the development of a mathematical model.

A mathematical model is a set of equations that identically (adequately) describe the real EMS.

The mathematical model of ED includes:

– equations of mechanics;

– equations of power electric circuits;

– equations of control chains and feedback chains;

– equation of electromechanical energy conversion.

When compiling a mathematical model, it is necessary to do the following.

1. Formulate the task of the research, determine which processes, phenomena or characteristics are being studied.

2. Determine the assumptions under which the task is solved.

Assumptions depend on the properties and constituent parts of the ED, the conditions of its operation and operation.

3. Bring the mathematical model to some convenient form:

– differential equation of the *n*-th order;

– system of differential equations;

– structural scheme;

– matrices;

– directed graphs, etc.

4. Determine the algorithms and software tools for solving the task.

2 MECHANICS OF THE ELECTRIC DRIVE

2.1 Calculation scheme of the mechanical part of the electric drive

The mechanical part includes all the moving masses of the ED, mechanically connected to each other. The design of the mechanical part of the ED is shown in the kinematic diagram.

It makes it possible to draw up a calculation diagram of the mechanical part, which reflects the properties of the connections between the moving masses of the mechanical part of the ED (the presence of elastic connections, viscous friction and gaps in the kinematic chain).

Let's make a calculation diagram of the mechanical part of the ED fan, the kinematic diagram of which is shown in fig. 2.1.

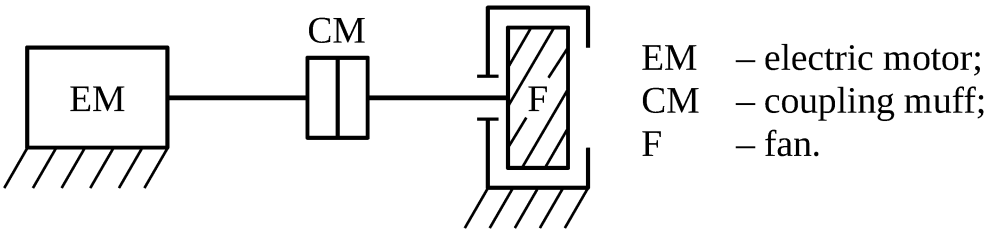

Figure 2.1 – Ventilating fan kinematical scheme

Let's designate the moments of inertia:

J_1 – motor rotor; J_2 – first half-coupling;

J_3 – second half-coupling; J_4 – fan propeller.

And rigidity (stiffness coefficient) of the:

c_{12} – motor shaft; c_{23} – muff coupling; c_{34} – fan shaft.

On the calculation diagram, we’re going to show all moving masses in the form of circles, and we will consider the connections between them as elastic (fig. 2.2).

The initial calculation scheme is described by a fourth-order differential equation. The scheme can be simplified if you use the following principle: when drawing up the calculation scheme, take into account the largest moments of mass inertia and the smallest stiffness coefficients [2,3,4].

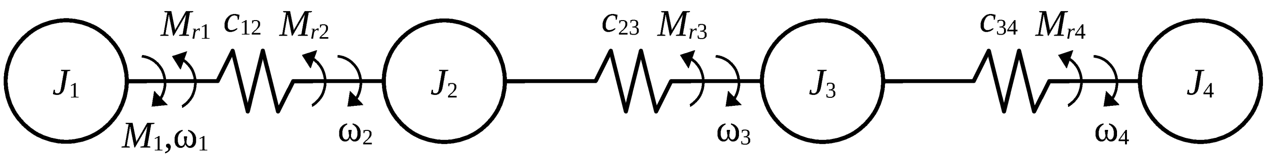

Figure 2.2 – Four-mass calculation scheme of the mechanical part of the ED fan

On this scheme: M_1 – torque, created by the electric motor;

$\omega_1 \div \omega_4$ – rotating speeds from first to fourth masses accordingly;

$M_{r1} \div M_{r4}$ – moments of resistance from first to fourth masses accordingly.

Suppose that the connecting coupling has the smallest stiffness coefficient, which differs from the stiffness coefficients of the shafts by several times. In this case, the initial four-mass calculation scheme can be reduced to the two-mass scheme shown in fig. 2.3.

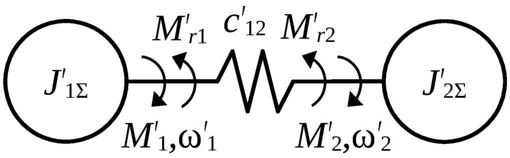

Figure 2.3 – Two-mass ED design scheme of the ventilating fan

On this scheme: $J'_1 = J_1 + J_2$; $J'_2 = J_3 + J_4$; $c'_{12} = c_{23}$.

Such a scheme is presented by a differential equation of second order.

If the muff is absolutely rigid, then the design scheme of the ED mechanical part will be one-mass (fig. 2.4).

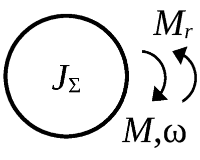

Figure 2.4 – Ventilating fan ED one-mass design scheme

On this scheme: $J_\Sigma = J_1 + J_2 + J_3 + J_4$.

The one-mass design scheme is presented by the equation

$$M - M_r = J_\Sigma \frac{d\omega}{dt},$$

where M – drive moment;

M_r – moment of resistance;

$$M - M_r = M_{dyn};\ M_{dyn} = J\frac{d\omega}{dt},$$

If $M_{dyn} = 0$, ED is motionless, or moves with constant speed.

If $M_{dyn} > 0$ – ED is accelerated. If $M_{dyn} < 0$ – ED is decelerated.

$\omega = f(M)$ is called the ED speed-torque (mechanic) characteristic;

$\omega = f(M_r)$ is called the load speed-torque (mechanic) characteristic.

All moments of static loading M_r are classified on active and reactive (passive). The direction of an active moments of resistance don't depend on ED movement direction, they are called by external energy sources.

Reactive moments of resistance are response on ED movement. They always are directed opposite to movement.

The moments of static loading, depending on the mechanism, can be:

- M_r = const;
- $M_r = f(\omega)$;
- $M_r = f(\varphi)$, where φ is an angle of rotation or path;
- $M_r = f(\varphi, \omega)$;
- M_r – a random function.

2.2 Equations of electric drive movement

A mechanical system that has movement restrictions can be conveniently described by the Lagrange equation [2,7]:

The Lagrange equation looks like:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i,$$

where L – a Lagrangian function. It is equal to the difference of the kinematical and potential system energies:

$$L = W_k - W_p,$$

q_i – generalized coordinate; $\dot{q}_i$ – generalized speed;

Q_i – generalized force – is defined as the sum of elementary work from the action of all external forces and moments of forces on elementary movement;

i – number of a mechanical system freedom degree.

Let's assume that the calculation scheme of the mechanical part is one-mass (fig. 2.4). The number of degrees of freedom i = 1. In this case, the Lagrange function has the form

$$L=\frac{J\omega_2}{2};$$

$$q=\varphi;\ \dot{q}=\omega;$$

$$\frac{\partial L}{\partial\omega}=J\omega;\ \frac{\partial L}{\partial\varphi}=0;\ \frac{d}{dt}\left(\frac{\partial L}{\partial\omega}\right)=J\frac{d\omega}{dt};$$

$$Q=\frac{M\delta\varphi-M_r\delta\varphi}{\delta\varphi}=M-M_r,$$

Thus the system is presented by the equation:

$$J\frac{d\omega}{dt}=M-M_r.$$

This equation is called the basic equation of ED movement.

Let's assume that the calculation scheme of the mechanical part is two-mass. The number of degrees of freedom is i = 2 (fig. 2.3). The Lagrange function has the form

$$L=\frac{J_1\omega_1^2}{2}+\frac{J_2\omega_1^2}{2}-c_{12}\frac{(\varphi_1-\varphi_2)^2}{2}.$$

Regarding the first mass, we can write:

$$\frac{\partial L}{\partial\omega_1}=J_1\omega_1;\ \frac{d}{dt}\left(\frac{\partial L}{\partial\omega_1}\right)=J_1\frac{d\omega_1}{dt};\ \frac{\partial L}{\partial\varphi_1}=-c_{12}(\varphi_1-\varphi_2);$$

$$Q_1=\frac{M_1\delta\varphi_1-M_{r1}\delta\varphi_1}{\delta\varphi_1}=M_1-M_{r1};\ J_1=\frac{d\omega_1}{dt}+c_{12}(\varphi_1-\varphi_2)=M_1-M_{r1}.$$

where $c_{12}(\varphi_1-\varphi_2)=M_e=M_{12}$ – is the elastic moment.

Regarding the second mass we can write:

$$\frac{\partial L}{\partial \omega_2}=J_2\omega_2;\ \frac{d}{dt}\left(\frac{\partial L}{\partial \omega_2}\right)=J_2\frac{d\omega_2}{dt};\ \frac{\partial L}{\partial \varphi_2}=-c_{12}(\varphi_1-\varphi_2);$$

$$Q_2=\frac{-M_{r2}\delta\varphi_2}{\delta\varphi_2}=-M_{r2};\ J_2=\frac{d\omega_2}{dt}+c_{12}(\varphi_1-\varphi_2)=-M_{r2}.$$

Thus, the system of the differential equations by which the two-mass design scheme of a mechanical part is presented looks like:

$$\begin{cases} M_1-M_{r1}-M_{12}=J_1\dfrac{d\omega_1}{dt}; \\ M_{12}-M_{c2}=J_2\dfrac{d\omega_2}{dt}. \end{cases}$$

2.3 Concept of stiffness of mechanical characteristics

The shape of motor and load speed-torque characteristics is defined by rigidity:

$\beta=\dfrac{dM}{d\omega}$ is the rigidity of the mechanical characteristics of the engine;

$\beta_r=\dfrac{dM_r}{d\omega}$ is the rigidity of the mechanical characteristics of the working body.

In fig. 2.5. linear mechanical characteristics are shown, the stiffness of which has different values.

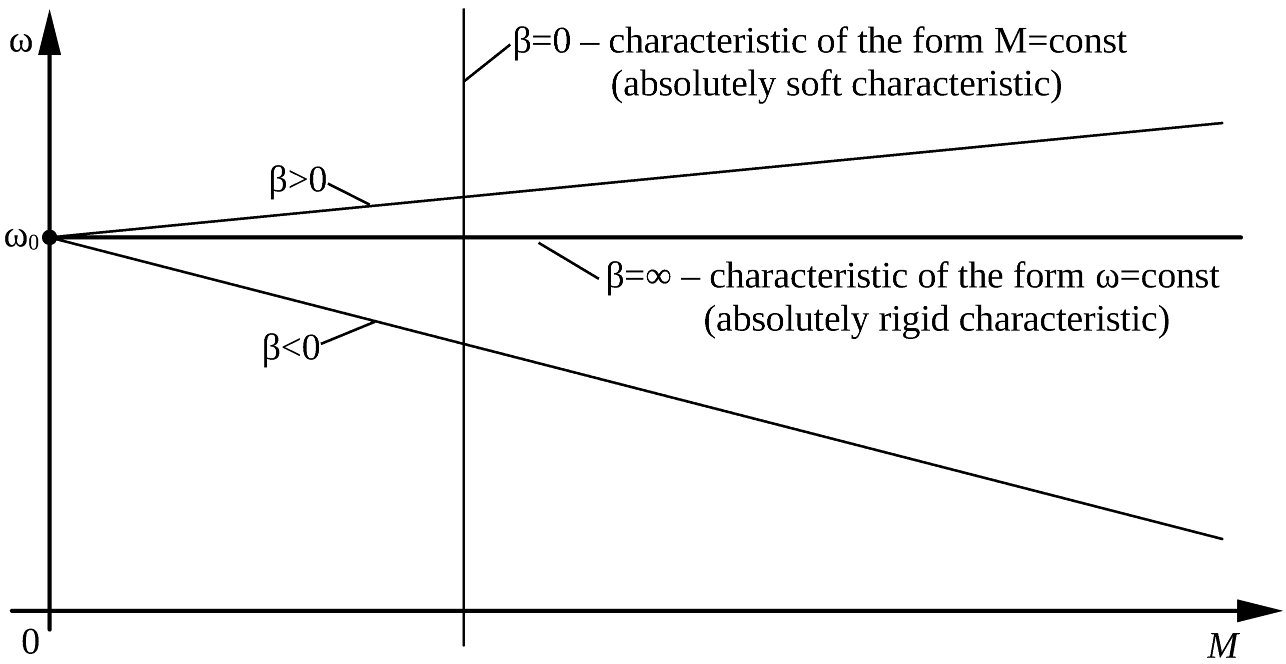

Figure 2.5 – The mechanical characteristics with different stiffness

Physically, stiffness means the slope of a mechanical characteristic. For electric motors, the stiffness value in the working area is negative. This means that a positive increase in moment corresponds to a negative increase in speed.

2.4 The condition of a stable established mode of operation of the electric drive

The established operating mode of the ED takes place when the condition is met

$$M_{dyn} = J\frac{d\omega}{dt} = 0.$$

Graphically, this means that the mechanical characteristic of the engine has a point of intersection with the mechanical characteristic of the working body.

The stability of ED operation is understood as its ability to automatically restore the established mode after its violation due to a change in the driving torque M or the resistance moment M_r without the help of the regulator, but only thanks to the properties of the ED, determined by the mechanical characteristics of the engine and the working body.

Let's obtain a mathematical condition for a stable steady-state operation of the ED. To do this, we will write down the basic equation of motion of the ED in finite increments relative to the point of static equilibrium

$$\Delta M - \Delta M_r = J\frac{d\Delta\omega}{dt}.$$

We consider the mechanical characteristics to be linear, therefore:

$$\beta = \frac{\Delta M}{\Delta\omega};\ \beta_r = \frac{\Delta M_r}{\Delta\omega}.$$

The original equation, taking into account the expressions for stiffness, will be written as

$$\beta\Delta\omega - \beta_r\Delta\omega = J\frac{d\Delta\omega}{dt},\ \text{or}\ \Delta\omega(\beta-\beta_r) = J\frac{d\Delta\omega}{dt} | : (\beta-\beta_r);$$

$$\frac{J}{\beta-\beta_r}\cdot\frac{d\Delta\omega}{dt} - \Delta\omega = 0.$$

The solution of differential equation in a general view:

$$\Delta\omega = Ce^{\frac{\beta-\beta_C}{J}\cdot t},$$

where C is an integration constant.

It is obvious, that at $t \to \infty$, $\Delta\omega \to 0$, if $\beta - \beta_r < 0$.

In this case $\Delta\omega = \frac{C}{e^{\frac{\beta-\beta_C}{J}\cdot t}}$.

This way, the condition of stable steady-state operation of the ED is determined by the inequality.

Thus, the stiffness of the mechanical characteristics of the engine to ensure stability should be less than the stiffness of the mechanical characteristics of the working body [3,4,5].

2.5 Bringing mechanical quantities to the same speed of movement

In the mechanical part of the ED, individual elements can move at different speeds due to the presence of reducers, V-belt gears, variators and other motion converters in the transmission. Therefore, a direct comparison of their moments of inertia, link stiffness's, moments, angular displacements *is inadmissible* in this case, and therefore it is necessary to bring the specified mechanical quantities to the same speed.

The speed to which the drive is carried out is most often the speed of the motor shaft or the speed of the working body, although the drive can be carried out to the speed of any element of the kinematic chain.

During reduction, it is necessary to ensure the preservation of the reserve of kinetic and potential energy of the system, as well as the elementary work of all forces and moments acting in the system on possible movements [2, 3].

When reducing the moment of inertia J_{red} according to the principle formulated above to the speed ω, it is necessary to ensure the preservation of the reserve of kinetic and potential energy of the system.

Suppose some *i*-th mass with a moment of inertia J_i rotates at a speed ω_i. From the induction condition, we can write:

$$\frac{J_{red}\,\omega_2}{2}=\frac{J_i\,\omega_i^2}{2};$$

$$J_{red}=J_i\left(\frac{\omega_i}{\omega}\right)^2=J_i\frac{1}{i_g^2},$$

where i_g – is gear ratio;

ω – is motor angular velocity.

Let's assume, the mass m_k moves translationally with linear speed V_k. From a reduction condition it is possible to record:

$$\frac{J_{red}\,\omega_2}{2}=\frac{m_k V_k^2}{2};$$

$$J_{red}=m_k\left(\frac{V_k}{\omega}\right)^2=m_k\rho^2,$$

where ρ is a reduction radius.

Let the moment M_k act on the *k*-th shaft in the kinematic chain. Bringing the given moment to the speed ω means finding such a moment on the shaft, which during the same time will do the same work as the moment M_k. From the condition of equality of work:

$$M_{red}\,\Delta\varphi=M_k\,\Delta\varphi_k;\ \text{since}$$

$$\omega=\frac{\Delta\varphi}{\Delta t};$$

$$M_{red}\,\omega\,\Delta t=M_k\,\omega_k\,\Delta t;$$

$$M_{red}=M_k\frac{\omega_k}{\omega}=M_k\frac{1}{i_g}.$$

In translational motion, from the condition of equality of work, it is possible to write:

$$M_{red}\,\Delta\varphi=F_k\,\Delta l_k;\ \text{since}\ V_k=\frac{\Delta l_k}{\Delta t};$$

$$M_{red}\,\omega\,\Delta t=V_k\,\Delta t;\ M_{red}\,F_k\frac{V_k}{\omega}=F_k\rho,$$

where Δl_k – is elementary linear movement.

Reduction of rigidity of an elastic element is satisfied from a condition, that the potential energy of *k*-th elastic shaft twisted on angle $\Delta\varphi_k$ should be an equal to potential energy of the motor shaft twisted on angle $\Delta\varphi$:

$$\frac{c_{red}\Delta\varphi^2}{2}=\frac{c_k\Delta\varphi^2}{2}\text{ ; since }\omega=\frac{\Delta\varphi}{\Delta t};$$

$$c_{red}\,\omega^2=c_k\,\omega_k^2;$$

$$c_{red}=c_k\left(\frac{\omega_k}{\omega}\right)^2=c_k\frac{1}{i_g^2}.$$

At a translational motion from a condition of equality of potential energies

$$c_{red}=c_k\left(\frac{V_k}{\omega}\right)^2=c_k\rho^2.$$

2.6 Features of a mechanical system with an elastic connection and a gap

The calculation scheme of the mechanical part of the ED with an elastic connection and a gap has the form (fig. 2.6).

The gap has the characteristic of the «zone of insensitivity» type (fig. 2.7).

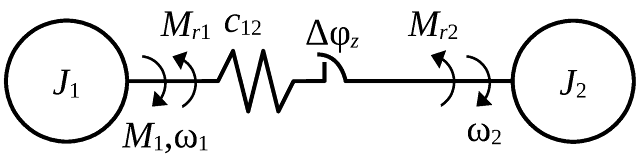

Figure 2.6 – Calculation scheme of the mechanical part of the electric drive with an elastic connection and a gap

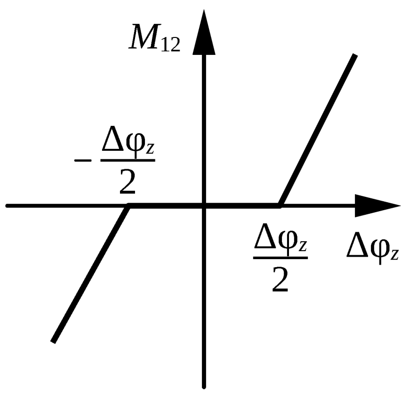

Figure 2.7 – Zone of insensitivity characteristic

$$M_{12}=\begin{cases} 0, & \text{where: } \Delta\varphi \le \dfrac{\pm\Delta\varphi_g}{2}; \\ c_{12}(\varphi_1-\varphi_2), & \text{where: } \Delta\varphi > \dfrac{\pm\Delta\varphi_g}{2}. \end{cases}$$

Let's observe that the system starts with an open gap.

After ED turning on and appearance of moment M_1 the first mass will accelerate $\frac{d\omega_1}{dt}=\frac{M_1}{J_1}$ and explicate some speed to the moment of gap closing. At the same time speed of the second mass ω_2 is equal to null. At the moment of gap closing there is a hit therefore the part of a kinetic energy of the first mass $W_k=\frac{J_1\omega_1^2}{2}$ goes on acceleration of the second mass, and the part passes in a potential energy of twisting $W_p=\frac{c_{12}\Delta\varphi^2}{2}$ that calls increase in elastic moment $M_{12} = c_{12}\,\Delta\varphi$. In some cases this increase can be essential and thus there is an oscillating process. Oscillating process negatively affects precision, reduces process quality indicators, and increases deterioration of the mechanism. Therefore it is rather desirable to avoid the opened gaps at starting [1, 3].

2.7 Restrictions on movement in the electric drive

Restrictions on the movement of the mechanical part of the ED are imposed based on technological or strength considerations. The following types of restrictions are distinguished:

1. Limitation on speed:

$$\omega<\omega_{\text{max.per}}.$$

2. Limitation on acceleration:

$$\frac{d\omega}{dt}<\left(\frac{d\omega}{dt}\right)_{\text{max.add}}.$$

The acceleration limit is nothing more than a current limit because:

$$I_a = \frac{J}{k\Phi}\frac{d\omega}{dt} + I_c.$$

3. Jerk limit (second derivative of speed):

$$\frac{d^2\omega}{dt^2} < \left(\frac{d^2\omega}{dt^2}\right)_{\text{max,per}}.$$

Limitation on jerk represents limitation on $\frac{dI_a}{dt}$.

4. Limitation on hit (third derivative on speed):

$$\frac{d^3\omega}{dt^3} < \left(\frac{d^3\omega}{dt^3}\right)_{\text{max,per}}.$$

Higher velocity derivatives have no physical sense.

2.8 Questions for self-testing

1.Draw and explain the functional diagram of the ED.

2. How does the kinematic scheme differ from the calculation scheme of the mechanical part of the ED?

3. Write down and explain the Lagrange equation.

4. What is the difference between active and reactive moment of resistance?

5. Draw a two-mass calculation diagram of a mechanical part and give the equation that describes it.

6. What is mechanical characteristic stiffness?

7. Formulate the condition for a stable mode of operation of the ED.

8. Under what conditions and for what is the reduction of mechanical quantities to the same speed performed?

9. Explain the physical meaning of the starting process of a two-mass mechanical system with a gap and an elastic connection?

10. Name the restrictions on the movement of ED.

3 CHARACTERISTICS OF ENGINES IN ELECTRIC DRIVES

In this section, the static electromechanical and mechanical characteristics of the DC motor of independent excitation (DCM IE), DC motor of series excitation (DCM SE), DC motor of mixed excitation (DCM ME), asynchronous motor (AM) and synchronous motor (SM) are considered.

3.1 Characteristics of DCM IE

The circuit design of DCM IE shown on fig. 3.1.

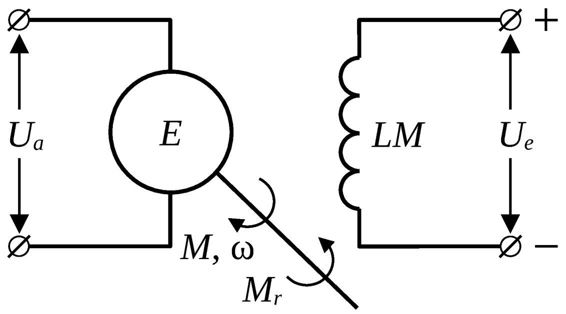

Figure 3.1 – The circuit design of DCM IE

The power anchor circuit of the motor is marked out by the character *E* and powered from a source with voltage U_a. The low-current circuit of a field winding is marked out as *LM* and powered from a source U_e. The motor creates torque *M*. On-coming moment of resistance is marked out M_r, motor speed is marked out ω.

It is necessary to obtain the equation of electromechanical $\omega = f\,(I_a)$ and mechanical characteristics $\omega = f\,(M)$. We will consider, that the magnetic flux created by a field winding $\Phi = \Phi_{nom}$ = const. The anchor reaction phenomenon is not considered. The design scheme of a mechanical part is one-mass.

The specified assumptions allow us to take advantage of an equivalent circuit resulting in fig. 3.2.

In the diagram, the direction of currents and EMF is indicated for the motion mode.

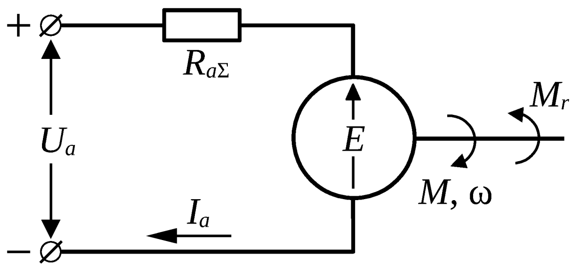

Figure 3.2 – DCM IE equivalent circuit

For the substitution scheme, you can write the equation based on Kirchhoff's 2nd law:

$$U_a = R_{a\Sigma} I_a + E, \tag{3.1}$$

where $R_{a\Sigma}$ – is a total resistance of an motor anchor circuit;

$$R_{a\Sigma} = k_t (R_z + R_{cp} + R_{cw}) + 2R_b,$$

k_t = 1,24 – is the temperature coefficient;

R_a – is the resistance of an anchor winding;

R_{cp} – is the resistance of compoles;

R_{cw} – is the resistance of a compensating winding;

R_b – is the resistance of a brush contact,

$$R_b = \frac{\Delta U_b}{I_{a\,nom}}$$

ΔU_b = (0,5 ÷ 1,5) **V** – is a brushes voltage;

$I_{a\,nom}$ – is a nominal anchor current.

The motor EMF is defined as:

$$E = k \cdot \Phi \cdot \omega, \tag{3.2}$$

where k – is a constructive constant of the motor which is equated $k = \frac{pN}{2\pi a}$;

p – is the number of pairs poles;

N – is the number of active conductors of an anchor winding;

a – is the number of parallel paths of anchor winding.

Having solved the equation (3.1) concerning speed ω taking into account (3.2), we will obtain DCM IE's electromechanical characteristic equation:

$$\omega = \frac{U_a}{k\Phi} - \frac{I_a R_{a\Sigma}}{k\Phi}. \quad (3.3)$$

The equation (3.3) graphically represents a straight line (fig. 3.3)

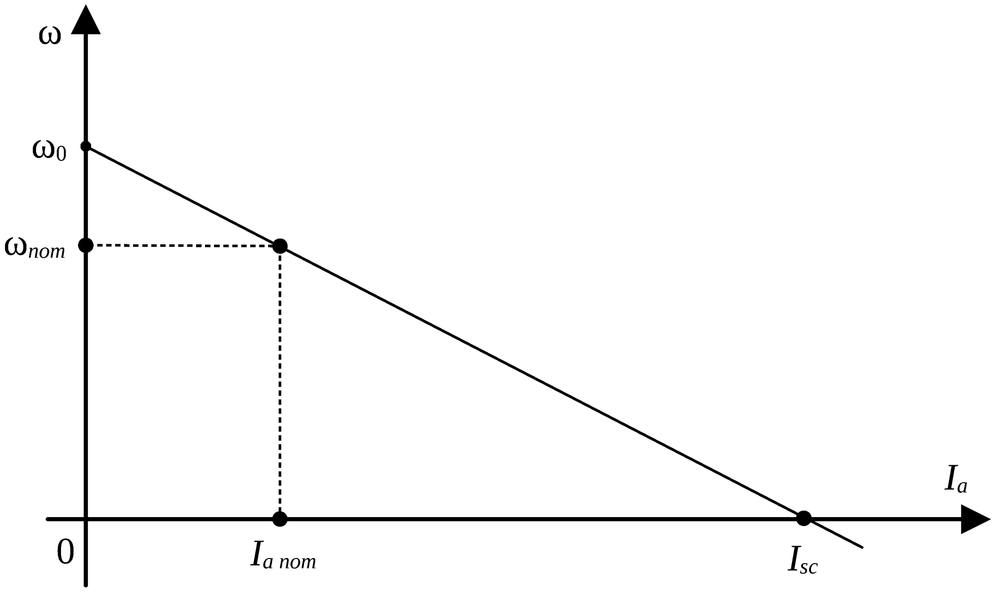

Figure 3.3 – DCM IE electromechanical characteristic

The electromechanical characteristic passes through the point of ideal idling, which is characterized by the speed of ideal idling and the short-circuit point characterized by the short-circuit current – $\omega_0 = \frac{U_a}{k\Phi}$ and $I_{sc} = \frac{U_a}{R_{a\Sigma}}$.

The motor torque will be recorded as:

$$M = k \cdot \Phi \cdot I_a. \quad (3.4)$$

If in (3.3) the armature current is expressed in terms of the moment, we obtain the equation of the mechanical characteristics of the motor:

$$\omega = \frac{U_a}{k\Phi} - \frac{M \cdot R_{a\Sigma}}{(k\Phi)^2}. \quad (3.5)$$

The equation (3.5) graphically represents a straight line (fig. 3.4).

The important index of electromechanical properties of the motor is rigidity of speed-torque characteristic:

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

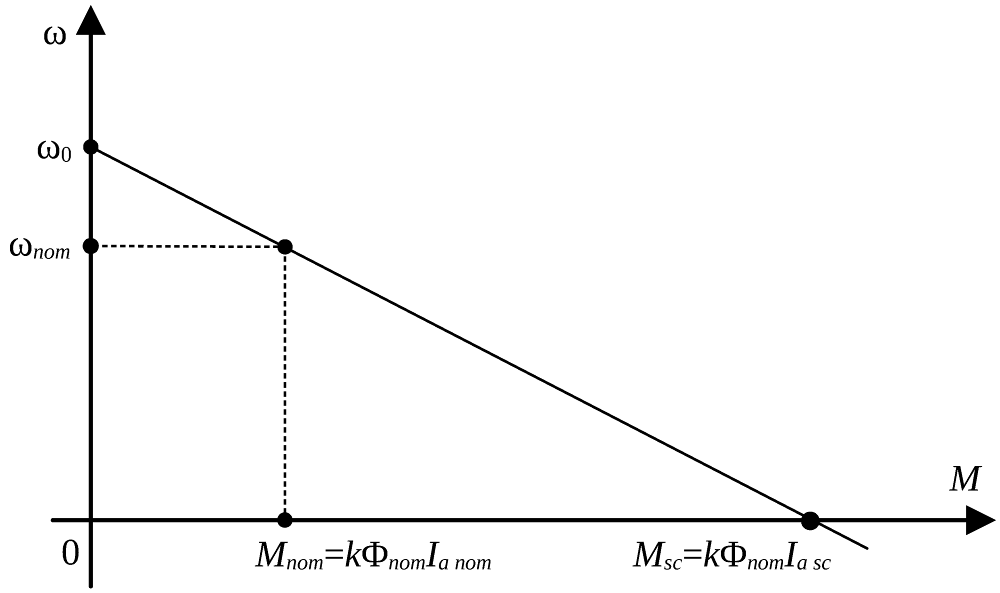

Figure 3.4 – DCM IE speed-torque characteristic

Let's determine the stiffness of the mechanical characteristics of the DCM IE. To do this, we differentiate equation (3.5) with respect to ω, and obtain

$$\beta=-\frac{(k\Phi)^2}{R_{a\Sigma}}. \quad (3.6)$$

The «minus» sign in (3.6) indicates that a positive increase in torque corresponds to a negative increase in speed. Among the catalog data of the motor, which must include rated power, rated voltage, rated armature current, rated speed, winding resistance, its overload capacity is provided.

$$\lambda=\frac{M_{max}}{M_{nom}}.$$

where M_{max} is a maximal admissible moment.

For DCM IE of common industrial application λ = 2÷2,5.

The mechanical characteristics of the engine can be natural or artificial.

The natural mechanical characteristics of the DCM IE are obtained in the absence of additional resistances in the armature circuit, with the nominal magnetic flux and the nominal armature voltage in the normal switching scheme (provided by the manufacturer in the engine passport).

Artificial mechanical characteristics take place if at least one of the listed requirements for obtaining a natural characteristic is not fulfilled.

Let's consider possible cases of obtaining artificial characteristics.

Let's call the additional resistance R_{ad} which can change. When increasing R_{ad}, the idling speed of the engine ω_0 remains unchanged, is diminished the short-circuit moment $M_{sc}=\frac{U_a}{R_{a\Sigma}+R}\cdot k\Phi$, rigidity $\beta=-\frac{(k\Phi)^2}{R_{a\Sigma}+R_{ad}}$ of a motor speed-torque characteristic becomes less.

Natural and artificial characteristics displayed on fig. 3.5.

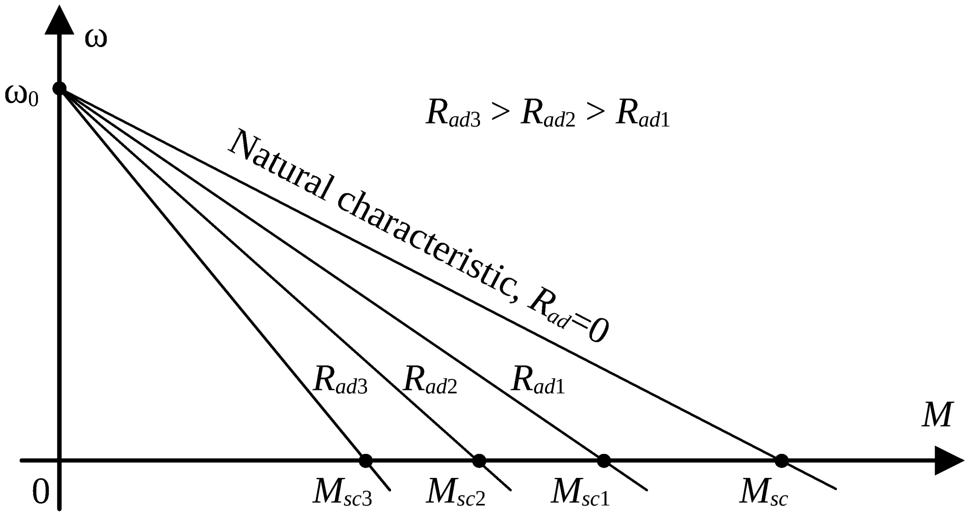

Figure 3.5 – DCM IE natural and artificial characteristics at R_{ad} = var

Now let's assume that the anchor voltage changes decreases. It is obvious that this diminishes $\omega_0=\frac{U_a}{k\Phi}$ and $M_{sc}=\frac{U_a}{R_{a\Sigma}+R}\cdot k\Phi$.

Rigidity of characteristic doesn't change. Taking into account it looks like the way it displayed on fig. 3.6.

It is advisable to change the magnetic flux of the motor to the side of the decrease if the operating point is on the knee of the magnetization curve. In this case, the limiting factors will be the speed, which should not exceed the design speed, and the commutation conditions, which deteriorate when the magnetic flux weakens.

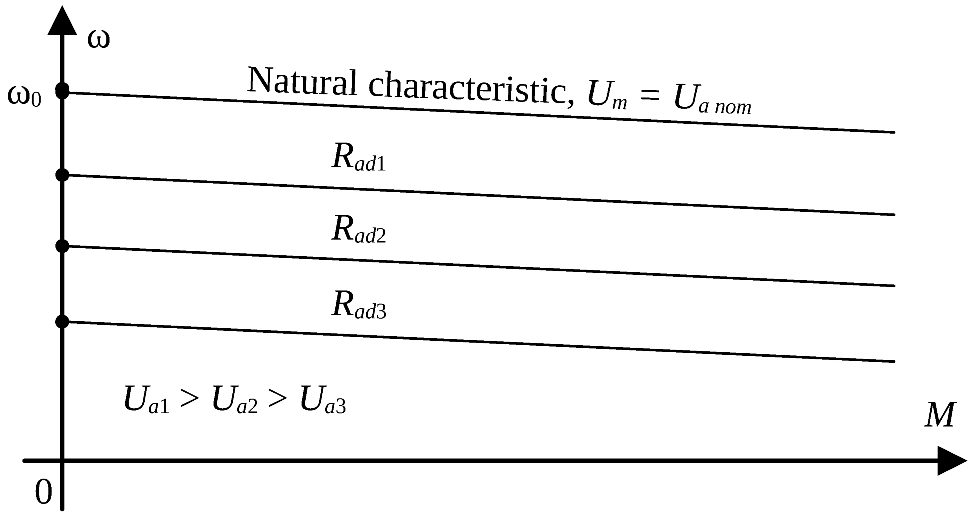

Figure 3.6 – Natural and artificial DCM IE characteristics at change of anchor voltage U_a = var

Speed $\omega_0 = \dfrac{U_a}{k\Phi}$ increases, $M_{sc} = \dfrac{U_a}{R_{a\Sigma} + R} \cdot k\Phi$ and $\beta = -\dfrac{(k\Phi)^2}{R_{a\Sigma} + R_{ad}}$ diminishes at the decrease of a magnetic flux.

Taking this into account, the natural and the family of artificial characteristics have the form shown in fig. 3.7.

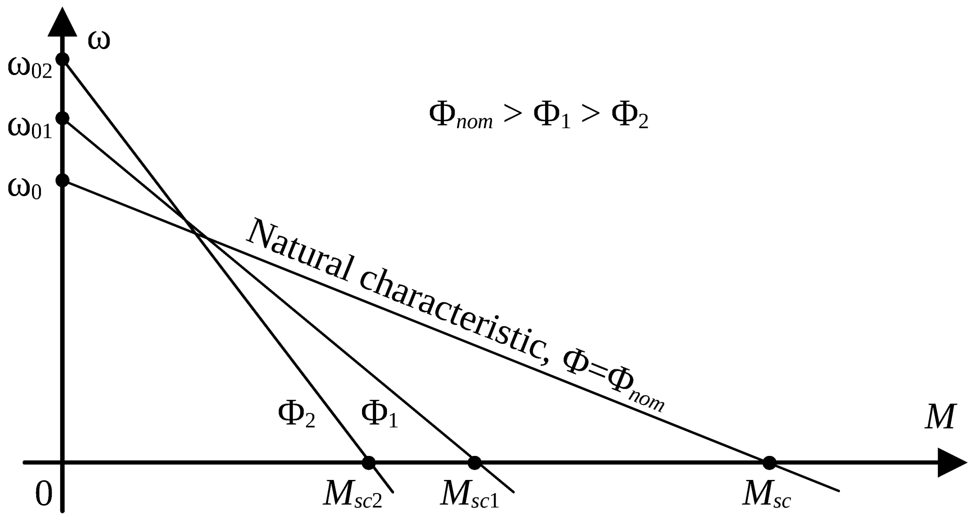

Figure 3.7 – Natural and artificial DCM IE characteristics at Φ = var

DCM IE is a reversible electric machine and can work in generator mode.

Regenerative braking modes include regenerative braking, reverse braking and dynamic braking modes.

In order to put the engine into regenerative braking mode, it is necessary to create conditions under which the moment of resistance *Mr* does not hinder the movement, but promotes it *M'r* (fig. 3.8).

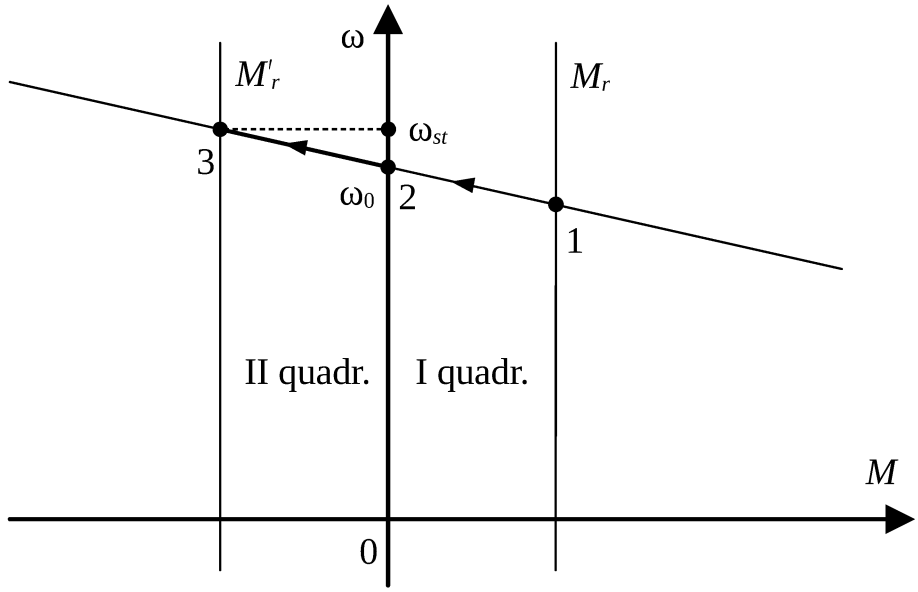

Figure 3.8 – DCM IE speed-torque characteristic at regenerative braking mode

In this case, the operating point moves along the characteristic from the I quadrant (point 1) to the II quadrant (point 3). The motor speed becomes greater than speed ω_0. In this case, $E > U_a$, the anchor current changes sign, and the engine in characteristic section 2-3 operates as a generator.

Mechanical energy is transformed into electrical energy, given to the power source, excluding thermal losses. The stable mode takes place at point 3 and is characterized by a constant value of the velocity ω_c.

In order to transfer the motor to the mode of braking by counter-switching when active M_r = const, it is necessary to introduce additional resistance into the anchor circuit of the motor R_{ad} (fig. 3.9).

Motor speed hasn't varied during initial time due to inertia, however the operating point was displaced on a new characteristic (from point 1 to 2). Motor is braked under influence of the negative dynamic moment, speed decreases, in a point 3 $\omega = 0$ and further the operating point will be displaced from I to IV quadrant.

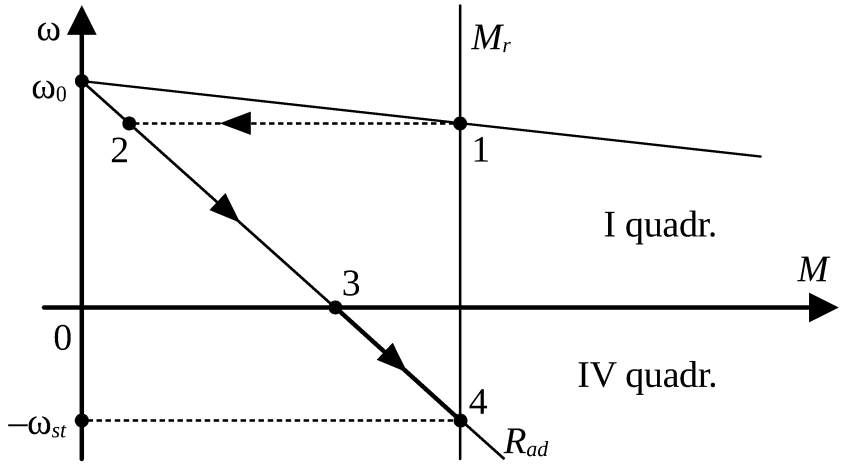

Figure 3.9 – DCM IE speed-torque characteristics at plugging mode

Steady state mode occurs in a point 4 and is characterized by speed $-\omega_s$. Motor operates at a plugging mode on a section of characteristic 3-4.

When a resistance moment is reactive it is necessary for plugging to include additional resistance R_{ad} into an anchor circuit and then to change polarity of anchor voltage (look fig. 3.10).

At the first moment of time, due to inertia, the speed of the engine did not change, but the operating point moved to a new characteristic from the I quadrant to the II quadrant (point 2). Under the action of a negative dynamic moment, the speed decreases, at point 3 $\omega = 0$.

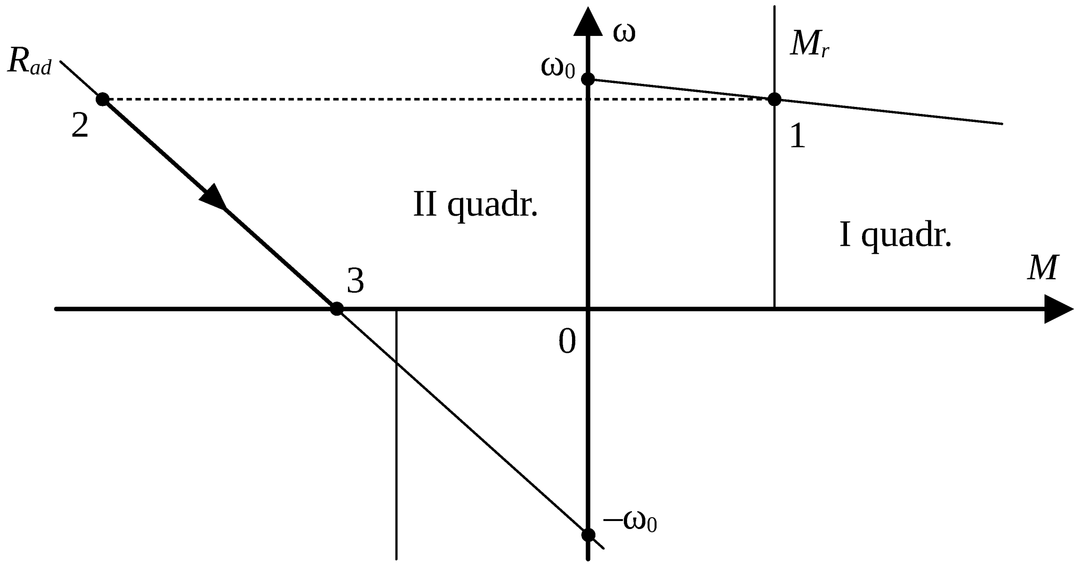

Figure 3.10 – DCM IE speed-torque characteristics at plugging mode when a resistance moment is reactive

Next, it is necessary to disconnect the motor anchor from the power source and turn on the mechanical brake. In the section 2-3, the engine works in the mode of braking by counter-disconnection.

In order to put the engine in dynamic braking mode, it is necessary to disconnect its anchor chain from the power source, and then short it to an additional resistance (look fig. 3.11).

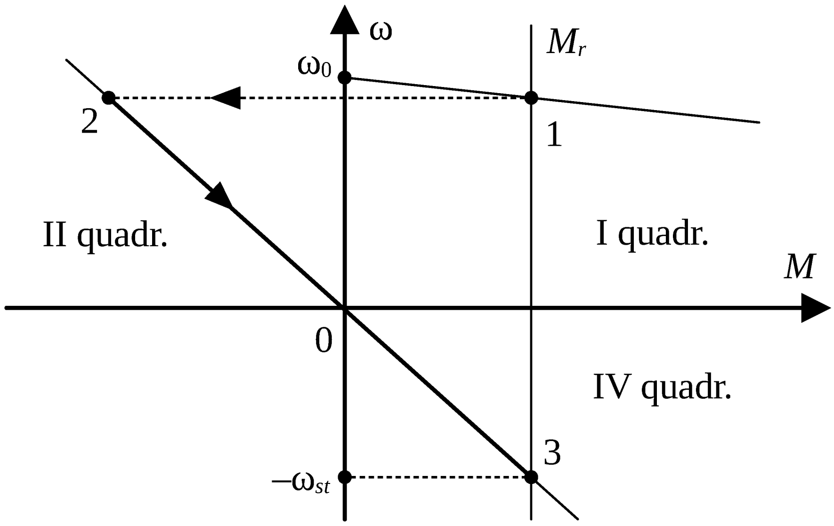

Figure 3.11 – DCM IE speed-torque characteristics at dynamic braking mode

At the first moment of time, due to inertia, the speed of the engine did not change, but the operating point moved to a new characteristic from the I quadrant to the II quadrant (point 2). Under the action of a negative dynamic moment, the operating point of the characteristic passing through the origin of the coordinates will move to the IV quadrant. The stable mode of operation takes place at point 3. At section 2-3, the engine operates in dynamic braking mode. In that case, if M_r is reactive, the braking process ends at $\omega = 0$.

We will use the obtained ideas about the static mechanical characteristics of the DCM IE to analyze its operating modes from the point of view of energy.

As an example, consider the scheme of the lifting mechanism. At the same time, we will assume that $\Phi = \Phi_{nom}$ = const.

To lift a load with a weight of G_{gr} at a speed of V_{gr}, the engine is turned on according to the scheme shown in fig. 3.12.

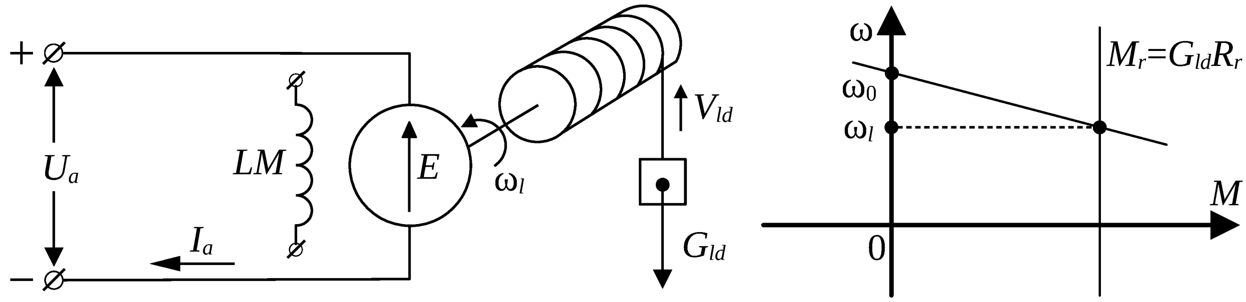

Figure 3.12 – Motor scheme at load lifting mode and its speed-torque characteristics

During the ascent, the steady mode of operation is characterized by the ascent speed ω_{as} and based on Kirchhoff's 2nd law, it can be written

$$U_a = I_a + E, \tag{3.7}$$

where $E = k \cdot \Phi \cdot \omega$.

Multiplying the left and right parts of (3.7) by I_a, we obtain the power balance equation in this mode

$$U_a I_a = I_a^2 R_{a\Sigma} + k\Phi I_я \omega_{as}. \tag{3.8}$$

Consumed electric power $P_c = U_a \cdot I_a$ converts to mechanical power $P_m = k \cdot \Phi \cdot \omega_a \cdot \omega_{as} = M \cdot \omega_{as}$ minus thermal losses in armature circuit $P_{tl} = R_{a\Sigma} \cdot I_a^2$. This is in motor mode.

To lower the load at the same speed, it is necessary to change the polarity of the armature voltage, as shown in fig. 3.13.

On the basis of Kirchhoff's 2nd law for the load lowering mode, it is possible to write

$$k\Phi\omega_d = U_a + R_{a\Sigma} I_a. \tag{3.9}$$

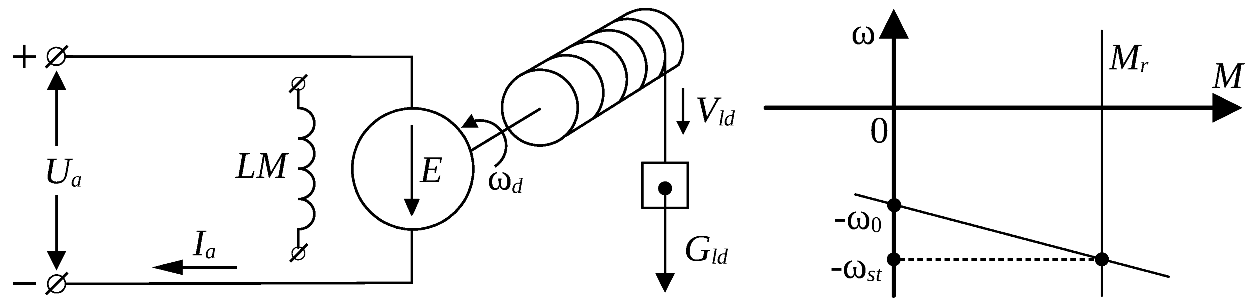

Figure 3.13 – Motor scheme at load descent mode and its speed-torque characteristics

Multiplying the left and right parts of (3.9) by I_a , we obtain the power balance equation

$$P_m = P_c + P_{tl}. \tag{3.10}$$

In equation (3.10), the mechanical power is converted into electrical power and supplied to the power network, except for heat losses in the anchor circuit. This is the regenerative braking mode.

To obtain a reduced speed of cargo descent, an additional resistance R_{ad} is introduced into the engine armature chain, at which M_{sc} is less than the active moment M_c (look fig. 3.14).

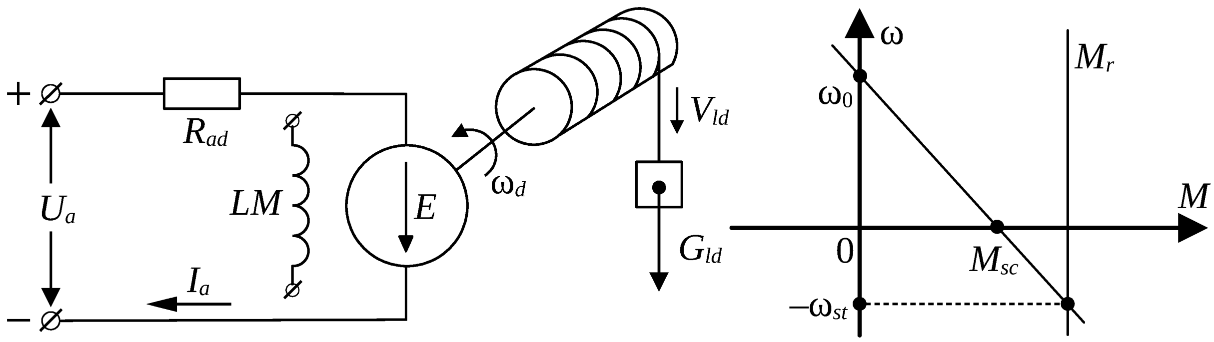

Figure 3.14 – Motor scheme for decrease of load descent speed and its speed-torque characteristics

On the basis of Kirchhoff's 2nd law, we can write

$$U_a + k\Phi\,\omega_d = (R_{a\Sigma} + R_{ad}) \cdot I_a. \tag{3.11}$$

Multiplying the left and right parts of (3.11) by I_a, we obtain the power balance equation

$$P_c + P_m = P_{tl}. \tag{3.12}$$

In equation (3.12), the power consumed from the network and the mechanical power are converted into the power of heat losses in the anchor circuit. This is the mode of braking by counter-disengagement.

Compared to the anti-locking mode, the dynamic braking mode is more economical, which can ensure the lowering of the load at a reduced speed (fig. 3.15).

In the dynamic braking mode, the armature chain is disconnected from the supply network, and then shorted to R_{ad}.

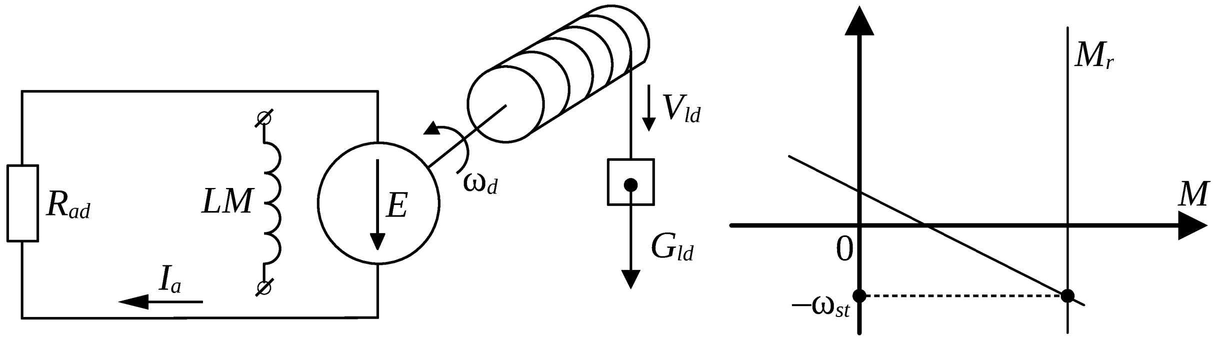

Figure 3.15 – Motor scheme for decrease of load descent speed and its speed-torque characteristics for dynamic braking

For this scheme, you can write

$$k\Phi\,\omega_d=(R_{a\Sigma}+R_{ad})\cdot I_a. \tag{3.13}$$

Multiplying the left and right parts of (3.13) by I_a, we obtain the power balance equation

$$P_m=P_{tl}. \tag{3.14}$$

In (3.14), the mechanical power is transformed into the heat loss power. This is the dynamic braking mode.

Thus, it follows from the power balance equations that the regenerative braking mode is the most economical, followed by the dynamic braking mode and the most uneconomical braking mode – counter-switching.

3.2 DCM SE characteristics in electric drive

DCM SE scheme looks the way it is displayed on fig. 3.16.

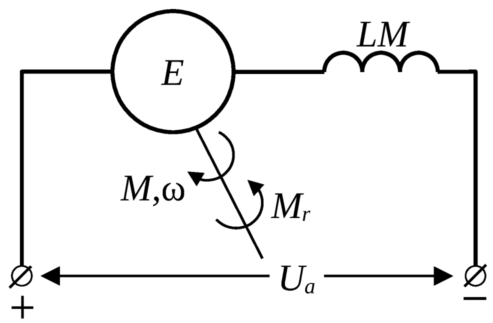

Figure 3.16 – DCM SE scheme

In this scheme, the *LM* excitation winding is connected in series to the armature power circuit. Therefore, a change in the armature current caused by a change in M_r leads to a change in the magnetic flux.

Due to this equation, electromechanical and mechanical characteristics are nonlinear:

$$\omega = \frac{U_a}{k\Phi(I_a)} - \frac{I_a R_{a\Sigma}}{k\Phi(I_a)}; \tag{3.15}$$

$$\omega = \frac{U_a}{k\Phi(I_a)} - \frac{I_a R_{a\Sigma}}{[k\Phi(I_a)]^2}; \tag{3.16}$$

where $\Phi = f(I_a)$ – is the nonlinear function (DCM SE magnetization curve).

To obtain analytical expressions of electromechanical and mechanical characteristics, we approximate the magnetization curve piecewise linearly, as shown in fig. 3.17.

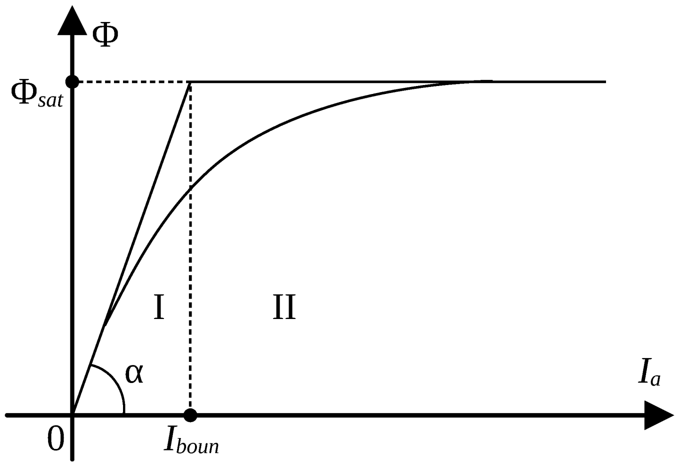

Figure 3.17 – Piecewise linear approximation of magnetization curve

For a section I: $\Phi = k\,\Phi \cdot I_a$ at $I_a < I_{lim}$, where $k\,\Phi = \text{tg}\alpha$.

The equation of electromechanical characteristics will look like:

$$\omega = \frac{U_a}{k \cdot k_\Phi \cdot I_a} - \frac{R_{a\Sigma}}{k \cdot k_\Phi}. \tag{3.17}$$

As $M = k \cdot k\Phi \cdot I_a^2$. the equation of a speed-torque characteristic looks like:

$$\omega = \frac{U_a}{\sqrt{k \cdot k_\Phi \cdot M}} - \frac{R_{a\Sigma}}{k \cdot k_\Phi}. \tag{3.18}$$

For a section II: $\Phi = \Phi_{sat}$, $I_a \geq I_{lim}$.

The equation of electromechanical characteristic will be recorded as:

$$\omega = \frac{U_a}{k\Phi_{sat}} - \frac{R_{a\Sigma} \cdot I_a}{k\Phi_{sat}}, \tag{3.19}$$

and the equation of a speed-torque characteristic will look like:

$$\omega = \frac{U_a}{k\Phi_{sat}} - \frac{M \cdot R_{a\Sigma}}{\left(k\Phi_{sat}\right)^2}. \tag{3.20}$$

From the equations (3.17÷3.20) follows, that at $I_a \to 0$, $\omega_0 \to \infty$, and the speed-torque characteristic is asymptotic to be aimed at an axis of ordinates.

In reality, the speed of ideal idling is a finite value:

$$\omega_0 = \frac{U_a}{k\Phi_{res}}, \tag{3.21}$$

where Φ_{res} = (5÷10) % Φ_{nom} is a residual magnetic flux.

Because of the smallness of Φ_{res}, ω_0 exceeds admissible speed on mechanical strength conditions.

When the armature current exceeds the limit, the magnetic circuit of the motor is saturated and the characteristics become linear.

Taking into account the distinctive features, the mechanical characteristics of the DCM SE have the form shown in fig. 3.18.

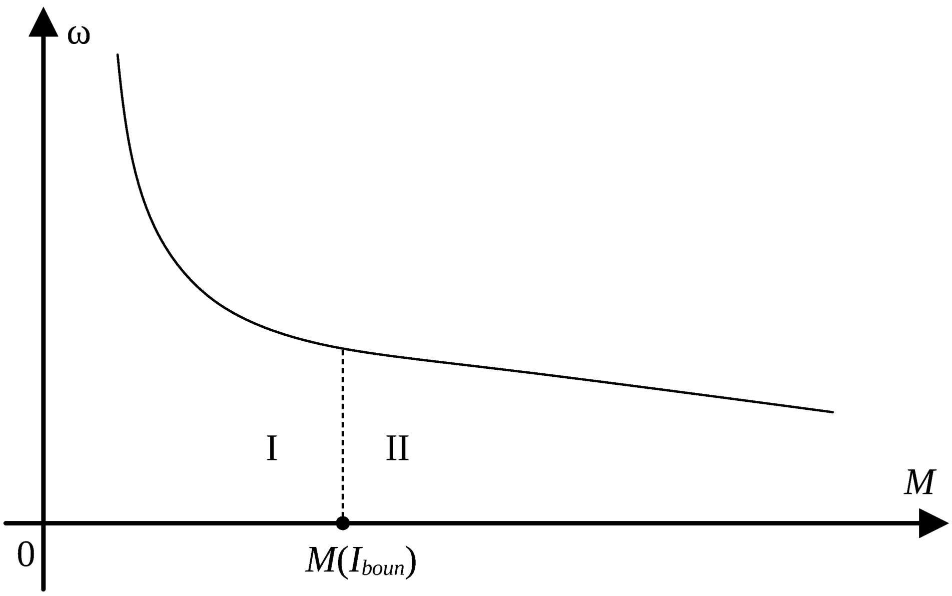

Figure 3.18 – DCM SE Speed-torque characteristic

The strong positive feedback created by the excitation winding practically eliminates the effect of the demagnetizing armature reaction in the area of nominal and higher loads and leads to an increase in the magnetic flux by 10÷20%. Therefore, the load capacity of DCM SE

$$\lambda = \frac{M_{max}}{M_{nom}} = 2{,}5 \div 3.$$

In addition, the engine torque, as distinguished above, is proportional to the square of the current. From the one shown in fig. 3.18 of mechanical characteristics shows that stiffness is a variable value. As the load increases, the stiffness increases and tends to a constant value.

The natural mechanical characteristic of the DCM SE engine is removed in the absence of additional resistance in the armature circuit, the nominal armature voltage in the normal circuit.

Artificial mechanical characteristics occur if at least one of the listed requirements is not met. Let's consider possible cases of obtaining artificial characteristics.

Suppose an additional resistance R_{ad} is introduced into the armature circuit, which can change.

From the equations of the mechanical characteristics, it can be seen that with an increase in R_{ad}, the speed decreases.

Rigidity $\beta = -\frac{k\Phi(I_a)}{R_{a\Sigma}}$ in each point of a speed-torque characteristic will be decreased, as shown in fig. 3.19.

Let's say that the armature voltage changes in the direction of decrease. It is obvious that in this case we obtain a family of equidistant characteristics (fig. 3.20)

DCM SE is a reversible electric machine and can work in generator mode. The generator braking mode includes the anti-switching braking mode and the dynamic braking mode with self-excitation. The regenerative braking mode is not possible in the normal switching scheme, because it is impossible to operate this engine at idle speed.

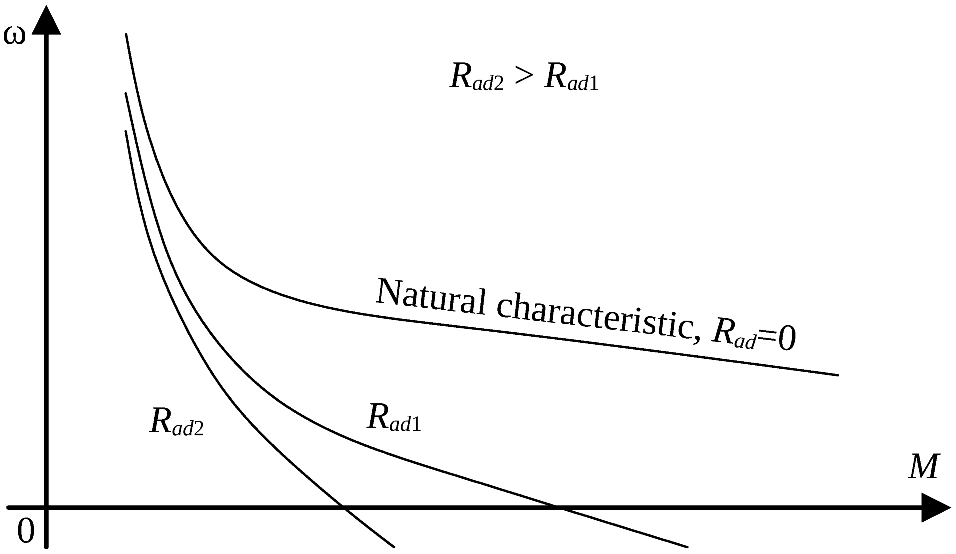

Figure 3.19 – Natural and artificial DCM SE characteristics at R_{ad} = var

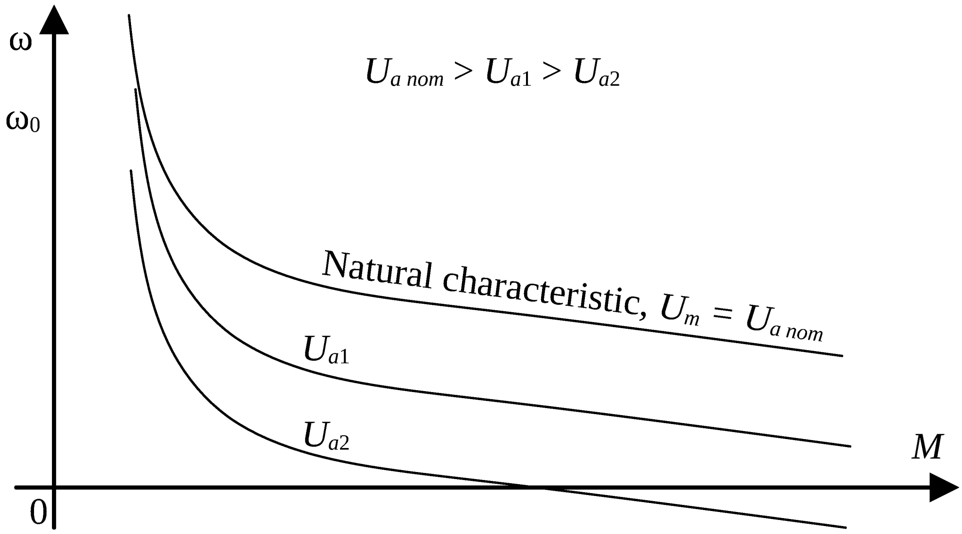

Figure 3.20 – Natural and artificial DCM SE characteristics at U_a = var

In order to transfer the motor to the mode of braking by reverse switching when M_r = const is active, it is necessary to introduce additional resistance R_{ad} into the armature circuit of the motor (fig. 3.21).

At the first moment of time, due to inertia, the speed of the engine does not change, however, the operating point has moved to a new characteristic (from point 1 to point 2). Under the influence of a negative dynamic moment, the engine slows down, the speed drops, at point 3 ω=0 and then the operating point moves from I to II quadrant. The stable mode takes place at point 4 and is characterized by the speed ω_v.

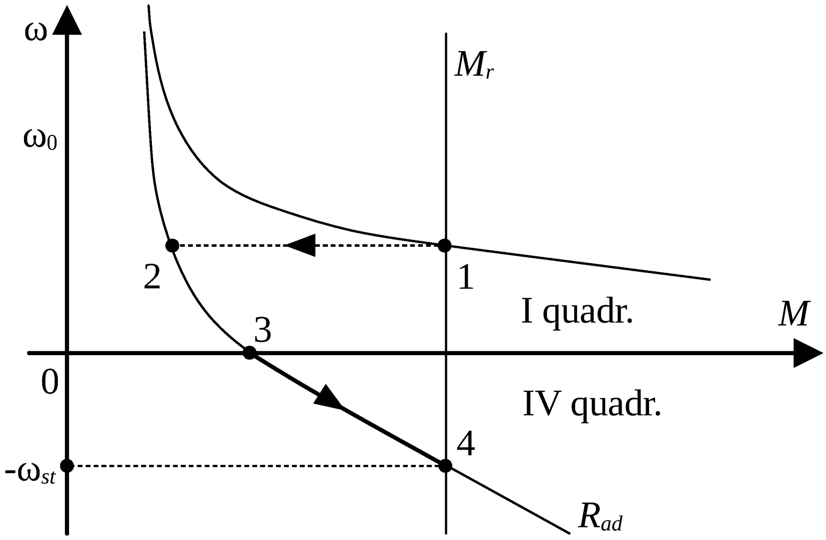

Figure 3.21 – DCM SE speed-torque characteristics at plugging mode

In the area of characteristics 3-4, the engine works in the mode of braking by counter-disconnection.

If the resistance moment of the motor is reactive, then to brake it with a reverse circuit, it is necessary to introduce additional resistance into the armature circuit, and then change the polarity of the armature voltage (fig. 3.22).

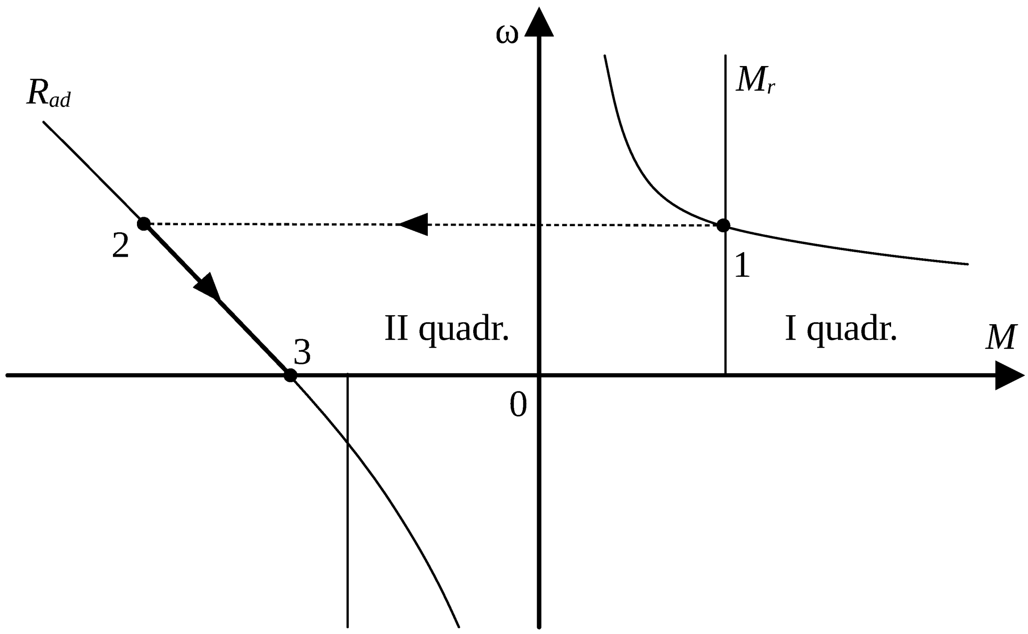

Figure 3.22 – DCM SE speed-torque characteristics at plugging mode when resistance moment is reactive

At the first moment of time, due to inertia, the speed of the engine did not change, but the operating point moved to a new characteristic from quadrant I to quadrant II (point 2). Under the influence of a negative dynamic moment, the speed decreases, at point 3 ω = 0. Next, it is necessary to disconnect the engine armature from the power source and turn on the mechanical brake. In section 2-3, the engine works in the anti-lock braking mode.

In order to transfer the motor to the dynamic braking mode with self-excitation, it is necessary to disconnect its armature chain from the power source, and then short-circuit it with an additional resistance.

The engine creates a braking torque when two conditions are met.

The first condition: the residual magnetic flux, given the direction of rotation, must create an emf that causes a current that increases the magnetic flux. Fulfillment of the first condition is achieved by changing the polarity of the inclusion of either the armature winding or the excitation winding (fig. 3.23). The second condition follows from the current-voltage characteristics (fig. 3.24).

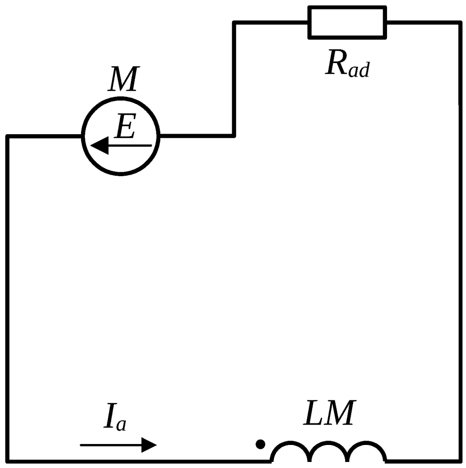

Figure 3.23 – DCM SE scheme at mode of dynamic braking with self excitation

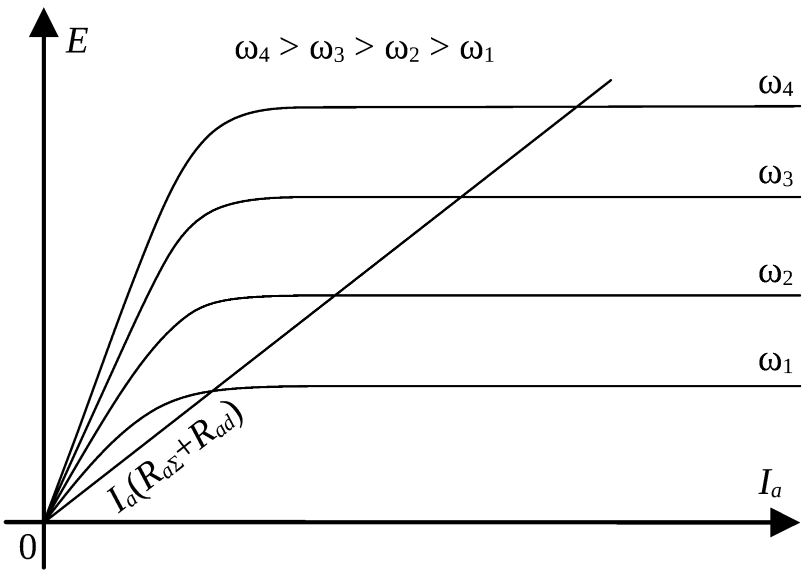

Figure 3.24 DCM SE voltage-current characteristics

At steady mode it is possible to write for the scheme displayed on fig. 3.23:

$$E = I_a \left(R_{a\Sigma} + R_{ad} \right), \tag{3.21}$$

where $E = k\Phi(I_a) \cdot \omega$.

Graphically (3.21) means that the voltage-current characteristic has an intersection point with rheostatic characteristic. Apparently from fig. 3.24 intersection points exist from some value $\omega > \omega_{lim}$. And the bigger $R_{a\Sigma} + R_{ad}$ means bigger ω_{lim}.

Speed-torque characteristic looks the way it is displayed on fig. 3.25.

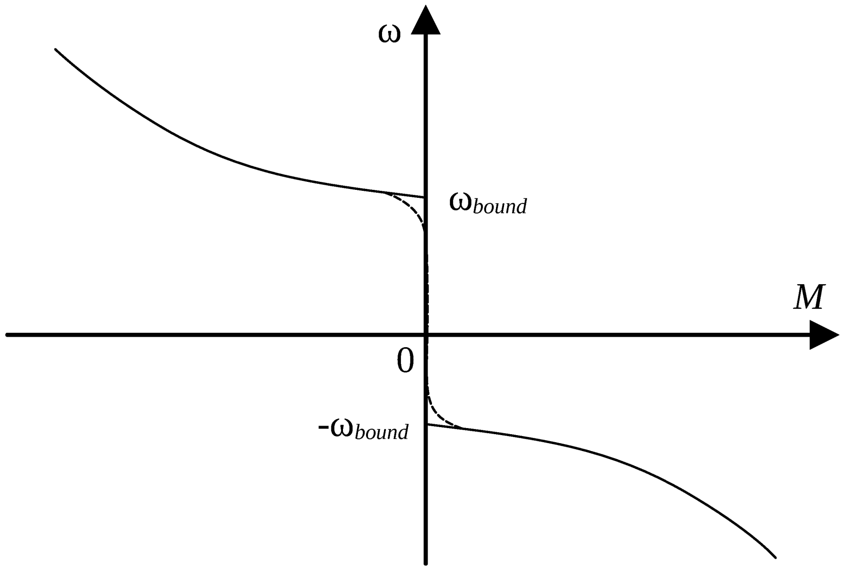

Figure 3.25 – DCM SE speed-torque characteristic at mode of dynamic braking with self excitation

3.3 DCM CE characteristics

DCM CE scheme looks like it is displayed on fig. 3.26.

Motor magnetic flux is created by independent field winding LMI at $\Phi_{ind} = (0,7 \div 0,85)\ \Phi_{nom}$ and series field winding. So electromechanical and mechanical characteristics equations are nonlinear.

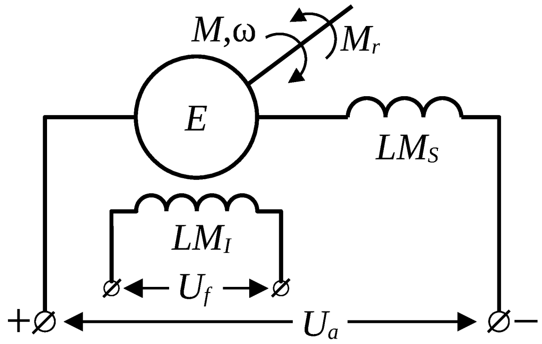

Figure 3.26 – DCM CE scheme

$$\omega = \frac{U_a}{k\Phi(I_a)} - \frac{I_a \cdot R_{a\Sigma}}{k\Phi(I_a)};\ \omega = \frac{U_a}{k\Phi(I_a)} - \frac{M \cdot R_{a\Sigma}}{[k\Phi(I_a)]^2}.$$

Motor idle speed in difference from DCM SE is a constant and defined as

$$\omega_0 = \frac{U_a}{k\Phi_{ind}};$$

$$\omega_0 = (1{,}3 \div 1{,}6)\,\omega_{nom}.$$

When the engine is transferred to the generator mode in the second quadrant, the change in the sign of the magnetomotive power (MMP) of the series excitation winding leads to a rapid decrease in the flux, which is zero at a current of $-I_{nom.m}$ (fig. 3.27).

Asymptote matches to this armature current. Function $\omega = f\ (I_a)$ at $\omega \to \infty$ comes nearer that asymptote. Dependence $\omega = f\ (M)$ has a maximum at generating mode and comes nearer to an axis of ordinates asymptotic at the left at increment of speed as is shown in fig. 3.28.

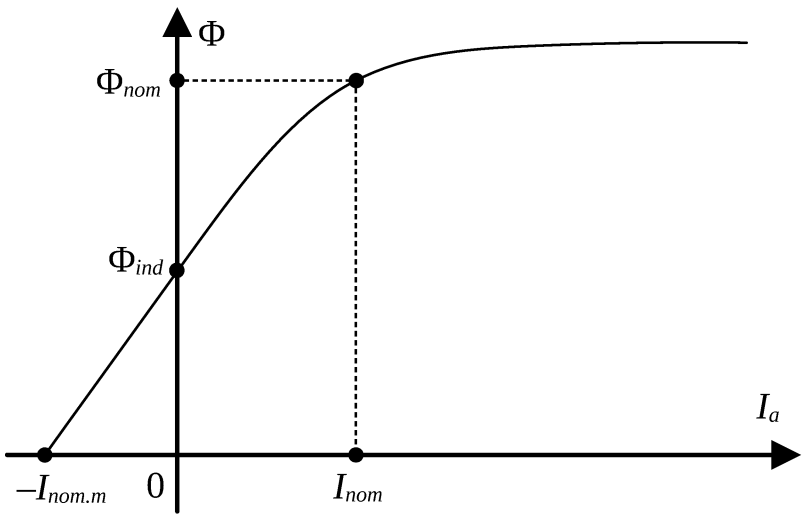

Figure 3.27 – DCM CE magnetization curve

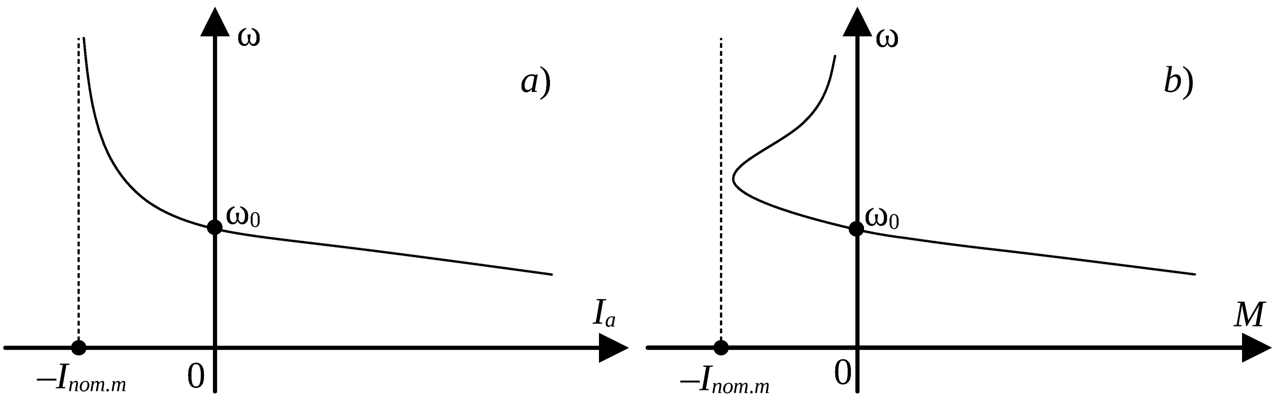

Figure 3.28 – DCM CE electromechanical *a*) and mechanical *b*) characteristics

3.4 Induction motor characteristics

The scheme of induction motor displayed on fig. 3.29.

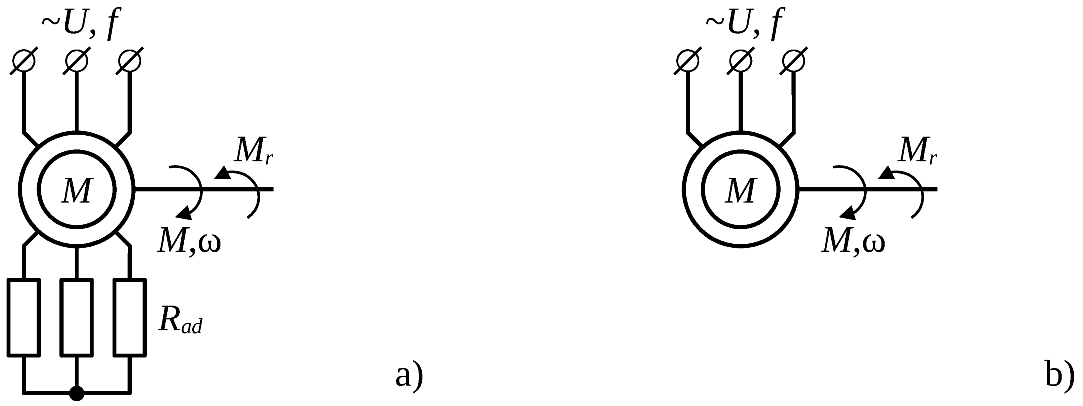

Figure 3.29 – Scheme of induction motor with a phase *a*) and short-circuited rotor *b*)

In this scheme, an alternating current flows through the three-phase stator winding and creates a rotating magnetic field. The speed of rotation of the magnetic field

$$\omega_0 = \frac{2\pi f}{p},$$

where f – is a voltage frequency,

p – is the number of pairs of poles.

Motor rotor rotation speed differs from field rotation speed on slip

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

Because AM is a rotary transformer based on the principle of operation, to obtain the equation of electromechanical characteristics, you can use the T-shaped scheme of replacing the transformer, which is shown in fig. 3.30.

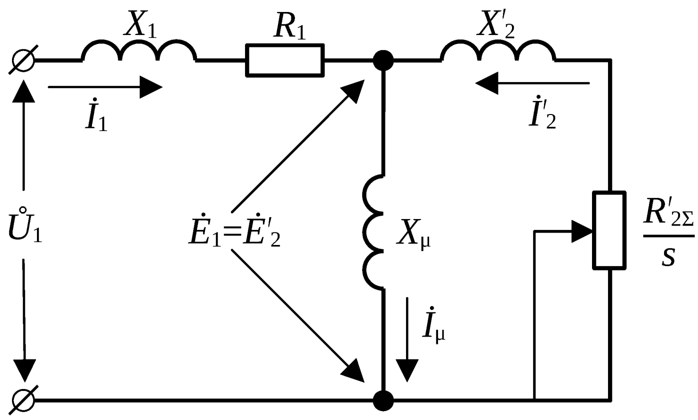

Figure 3.30 – Transformer T-equivalent circuit

On this scheme:

$\mathring{U}_1$ – is stator winding phase voltage;

$\dot{I}_1$ – is stator current;

$\dot{I}_\mu$ – is magnetization current;

$\dot{I}'_2 = \dot{I}_2 \cdot k_e$ – is rotor current reduced to a stator winding;

$k_e = \dfrac{E_1}{E_2}$ – is EMF transformation ratio;

$E_1 = 4{,}44\, w_1 \cdot \Phi \cdot f \cdot k_{w1};$

$E_2 = 4{,}44\, w_2 \cdot \Phi \cdot f \cdot k_{w2},$

where k_{w1}, k_{w2} – is winding coefficient of stator and rotor winding accordingly;

w_1, w_2 – is the number of turns of stator and rotor winding accordingly;

x_1, R_1 – is X-reactance and resistance of stator winding phase accordingly;

$x'_2, R'_{2\Sigma}$ – is reduced X-reactance and total resistance of a rotor winding phase;

x_μ – is the X-reactance of magnetization circuit.

If we do not take into account the effect of the voltage drop on the winding resistances from the magnetizing current, then it is possible to switch from the T-shaped substitution scheme to the U-shaped scheme (fig. 3.31).

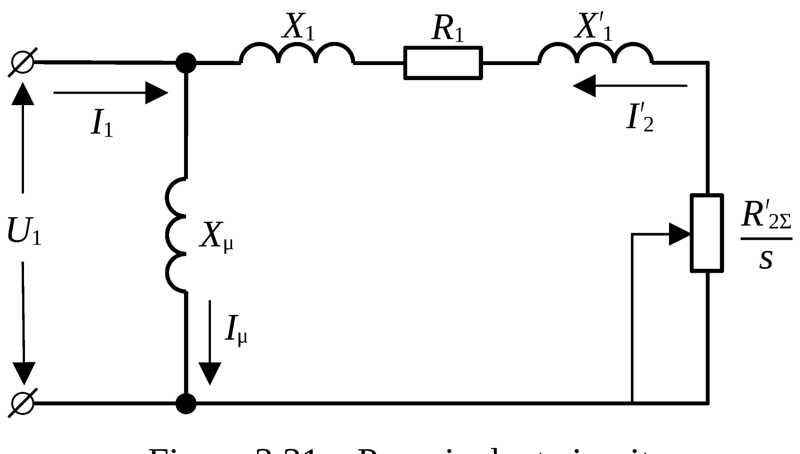

Figure 3.31 – P-equivalent circuit

For the P-equivalent circuit design it is possible to write the equation of electromechanical characteristic:

$$I'_2 = \frac{U_1}{\sqrt{\left(R_1 + \frac{R'_{2\Sigma}}{S}\right)^2 + x_{sc}^2}}, \qquad (3.22)$$

where $x_{sc} = x_1 + x'_2$ – is inductive phase short circuit impedance.

The analysis of (3.22) shows, that at generating mode at $S = -\frac{R'_{2\Sigma}}{R_1}$ maximum is attained $I'_{2max} = \frac{U_1}{x_{sc}}$, and in a motor mode maximum is attained at S $\to$ 0

$$I'_2 \to I'_{2\lim} = \frac{U_1}{\sqrt{R_1^2 + x_{sc}^2}}.$$

Taking into account these features the electromechanical characteristic looks like:

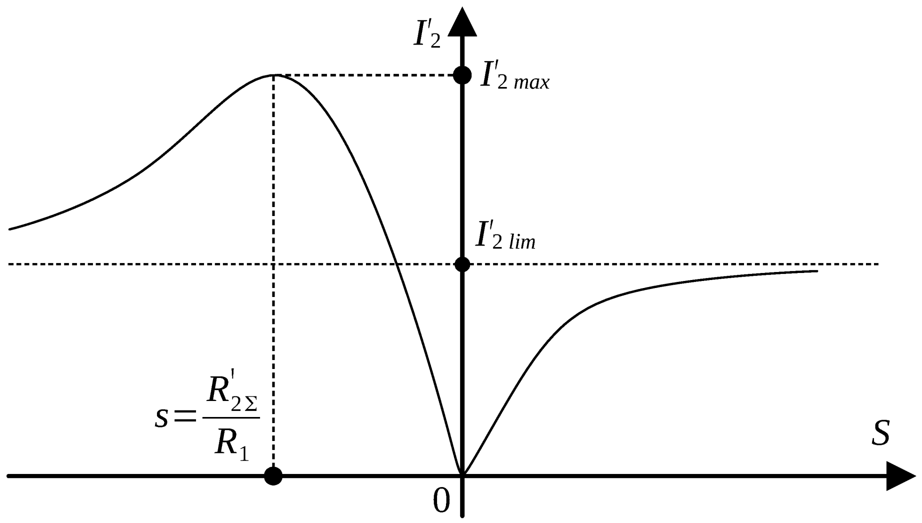

Figure 3.32 – Electromechanical characteristic of induction motor

To obtain the equation of the mechanical characteristics, we write down the condition of transmission of electromechanical power P_{12} through the air gap between the stator and the rotor:

$$P_{12} = 3 I_2'^2 \cdot \frac{R'_{2\Sigma}}{S} = \frac{3 U_1^2 \cdot \frac{R'_{2\Sigma}}{S}}{\left(R_1^2 + \frac{R'_{2\Sigma}}{S}\right)^2 + x_{sc}^2} = M \cdot \omega_0,$$

from here

$$M=\frac{3U_1^2\cdot R_{2\Sigma}^{'}}{S\omega_0\left[\left(R_1+\frac{R_{2\Sigma}^{'}}{S}\right)^2+x_{sc}^2\right]}. \qquad (3.23)$$

The analysis of (3.23) shows that the function has an extreme with coordinates S_{cr} and M_{cr}. We'll define the critical sliding S_{cr} from condition $dM / dS = 0$.

$$S_{cr}=\pm\frac{R_{2\Sigma}^{'}}{\sqrt{R_1^2+x_{sc}}}. \qquad (3.24)$$

We substitute (3.24) in (3.23) and define critical moment M_{cr}.

$$M_{cr}=\frac{3U_1^2}{2\omega_0\left(R_1\pm\sqrt{R_1^2+x_{sc}^2}\right)}. \qquad (3.25)$$

Sign «+» in (3.24), (3.25) corresponds to a motor mode, «–» for a generating mode.

We'll obtain Kloss' formula if (3.23) to express through (3.24) and (3.25)

$$M=\frac{2M_{cr}(1-aS_k)}{\frac{S_{cr}}{S}+\frac{S}{S_{cr}}+2aS_k}, \qquad (3.26)$$

where $a=R_1/R_{2\Sigma}^{'}$.

The Kloss' formula is an equation for the mechanical characteristics of AM. This equation is nonlinear, and the characteristic has the form shown in fig. 3.33.

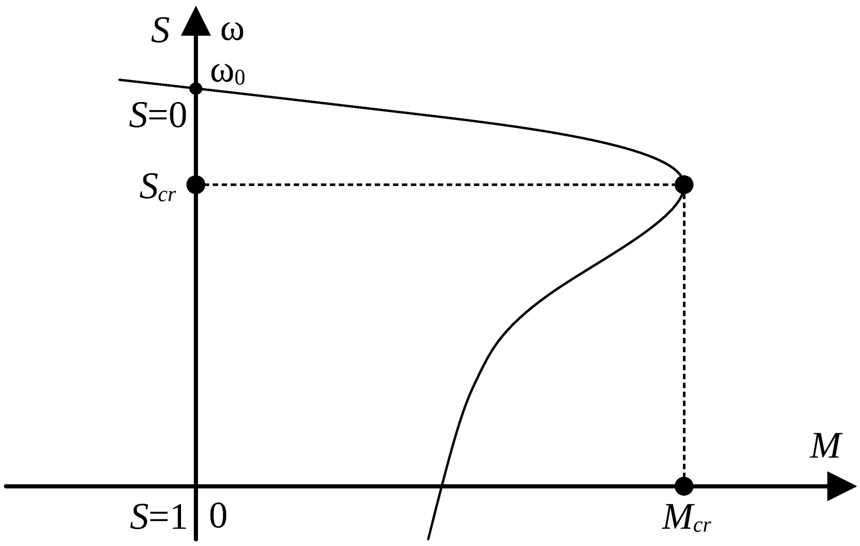

Figure 3.33 – Speed-torque characteristic of induction motor

Let’s say that $R_1 = 0$, $a = R_1 / R_{2\Sigma} = 0$, then we’ll get simplified Kloss’ formula:

$$M = 2M_{cr} / \left(\frac{S_{cr}}{S} + \frac{S}{S_{cr}} \right). \qquad (3.27)$$

The natural mechanical characteristic of AM is removed in the absence of additional resistances in the stator and rotor circuits, at the nominal voltage and frequency, for a normal switching scheme.

Artificial mechanical characteristics occur if at least one of the listed requirements is not met.

Suppose an additional resistance R_{1d} is introduced into the stator circuit, which can change. An increase in R_{1ad} causes a decrease in S_{cr} and M_{cr}, which follows from (3.24) and (3.25), and ω_0 remains constant. At the same time, the family of artificial characteristics has the form shown in fig. 3.34.

Let's admit, additional resistance R_{2ad}, which can vary, is included into a rotor circuit. At increase R_{2ad}, idle speed $\omega_0 = 2\pi f / p$ remains unchanged, S_{cr} and M_{cr} increase, that follows from (3.24) and (3.25). The set of artificial characteristics displayed on fig. 3.35.

Let’s assume that the stator voltage changes in the direction of decrease. This causes a decrease in M_{cr} according to (3.25), while S_{cr} and ω_0 remain unchanged.

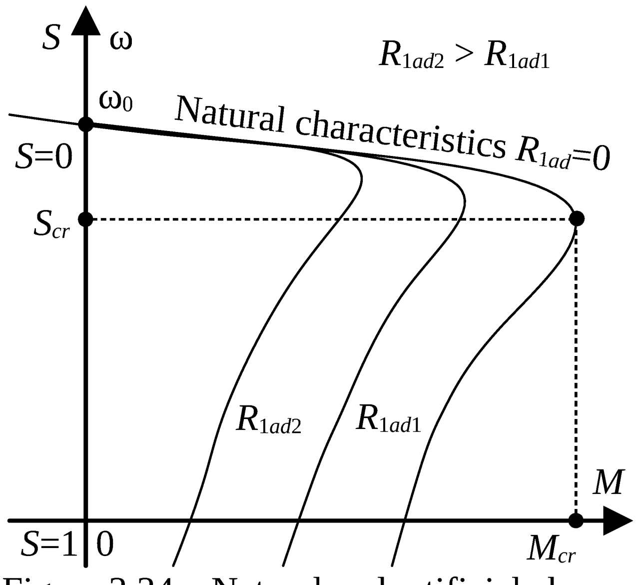

Figure 3.34 – Natural and artificial characteristics of induction motor at R_{1ad} = var

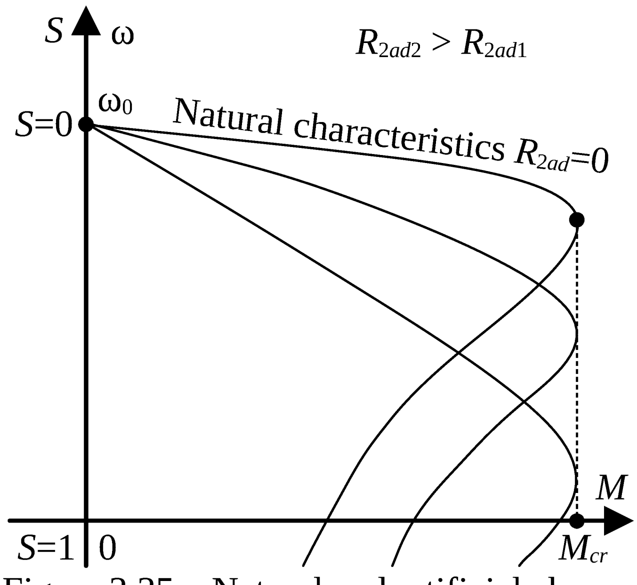

Figure 3.35 – Natural and artificial characteristics of induction motor at R_{2ad} = var

The family of mechanical artificial characteristics is shown in fig. 3.36.

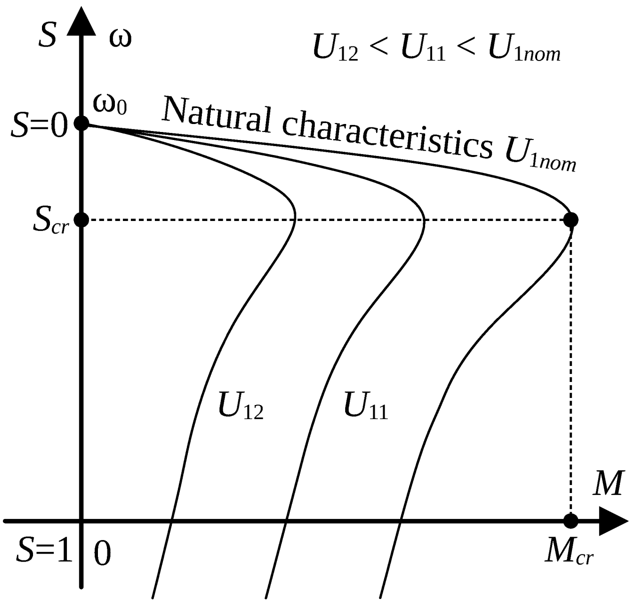

Figure 3.36 – Natural and artificial characteristics of induction motor at U_1 = var

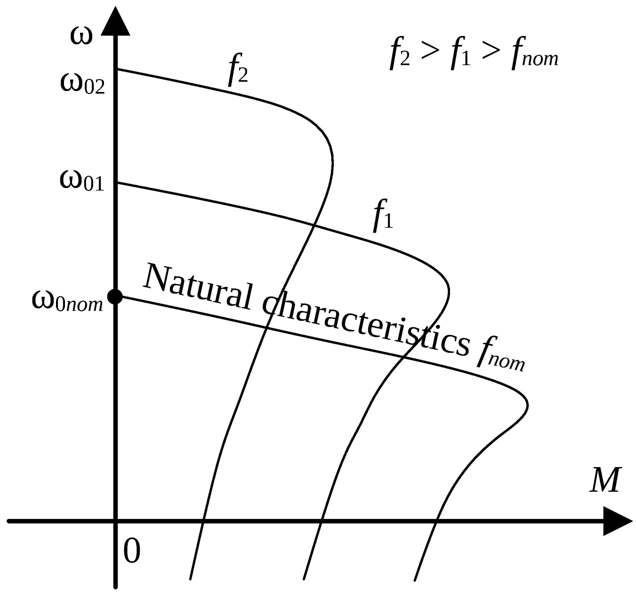

Figure 3.37 – Natural and artificial characteristics at f = var

Let's assume that the frequency of the supply voltage changes while its amplitude does not change. In this case, a change in frequency is possible only to the side of increase. To explain this condition, let's write down the equation of electrical balance of the stator circuit

$$\dot{U}_1 = \dot{I}_1 Z_1 + \dot{E}_1.$$

If $Z_1 \approx 0$ we’ll obtain

$$U_1 \approx E_1 = 4{,}44\, k_{w_1} \cdot \Phi \cdot f \cdot w_1.$$

From here

$$\Phi \approx \frac{U_1}{4{,}44\, k_{w_1} \cdot \Phi \cdot f \cdot w_1} \tag{3.28}$$

From (3.28) follows, that frequency decrease leads to increase of magnetic flux. The operating point is displaced along magnetization curve to saturation area, X-reactances of windings are decrease ($x_L = 2\pi f L$), currents increase, the motor is overheated and that is inadmissible.

Frequency increase leads to decrease of magnetic flux, idle speed ω_0 increases, the critical moment decreases. Set of speed-torque characteristics on fig. 3.37.

We can see that motor overload capacity $\lambda = M_{cr} / M_{nom}$ decreases when frequency increases. For motors of common industrial application $\lambda = 1{,}7 \div 2{,}2$.

Induction motor is an invertible electric machine and can operate in a braking mode. Such modes are regenerative braking, reverse braking (plugging) and dynamic braking.

To turn on a regenerative braking it would be necessary to create conditions when moment of resistance M_r does not hinder with driving, and promotes M'_r. In this case the operating point is displaced on characteristic from I quadrant (point 1) to II quadrant (point 3). Motor speed exceeds ω_0. Motor operates as the asynchronous generator. Mechanical energy will be converted to electricity and given to the electrical power network minus losses.

Motor operates at regenerative braking mode on a section 2, 3 and the steady state mode occurs in a point 3 (fig. 3.38). To turn on a plugging mode at active M_r = const it would be necessary to switch on additional resistance R_{2ad} into the motor rotor circuit (fig. 3.39).

At the same time, the operating point is moved to a new characteristic (point 2). Under the influence of a negative dynamic moment, the engine decelerates, the speed drops and at point 3 $\omega = 0$.

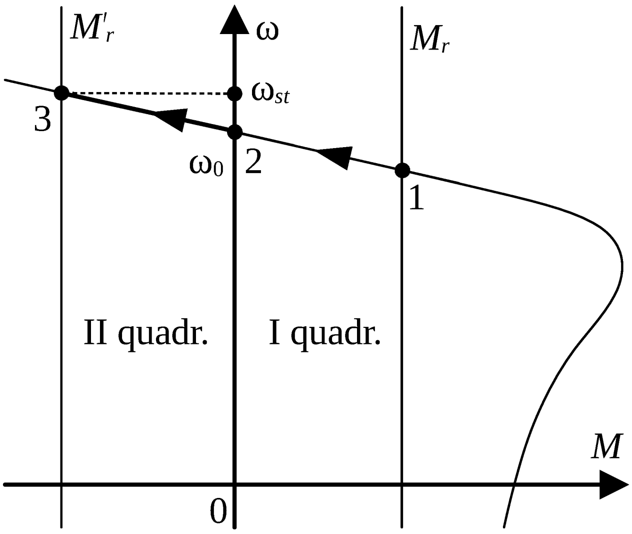

Figure 3.38 – Induction motor speed-torque characteristic at regenerative braking mode

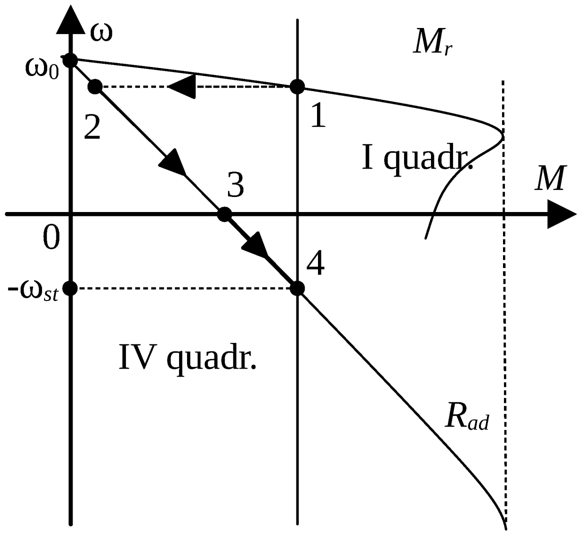

Figure 3.39 – Induction motor speed-torque characteristic at plugging mode at active M_r

The operating point moves to the fourth quadrant. In the area of characteristics 3-4, the engine works in the mode of braking by counter-disconnection. The stable mode takes place at point 4 and is characterized by the speed ω_l. In this mode, mechanical and energy consumed from the network is transformed into the energy of heat losses.

In order to transfer the motor to the anti-switching mode with active M_r, it is necessary to enter R_{2ad} in the rotor circuit to limit the current, and then change the order of alternating phases to ensure reverse (fig. 3.40).

Due to the inertia of the system, at the first instant of time the engine speed did not change, but the operating point moved to a new characteristic (point 2) in the second quadrant. Under the influence of a negative dynamic moment, the speed drops, in the section of characteristics 2-3, the engine works in the mode of braking by counter-disconnection. At point 3 (ω=0), it is necessary to disconnect the motor from the power supply network and turn on the mechanical brake.

In order to transfer AM to dynamic braking mode, it is necessary to disconnect the stator winding from the three-phase alternating current network, and then apply direct current to the stator circuit, as shown in fig. 3.41.

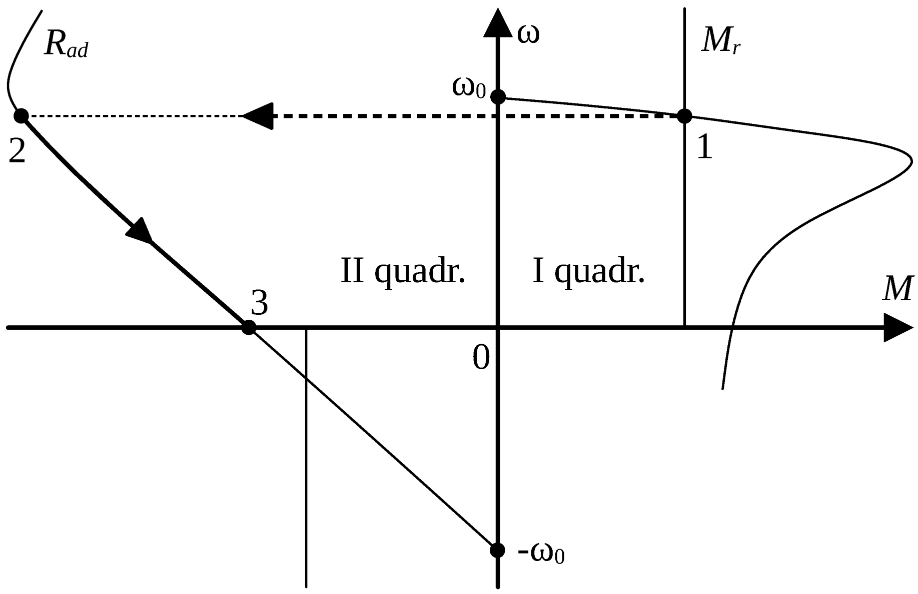

Figure 3.40 – Induction motor speed-torque characteristic at plugging mode at reactive M_r

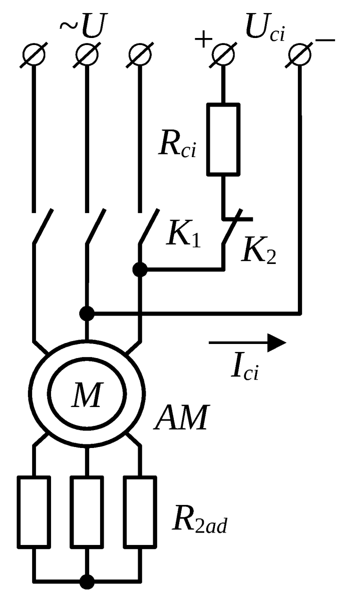

Figure 3.41 – Scheme of inclusion of AM in dynamic braking mode

In such a switching scheme, AM is a synchronous generator with unexpressed poles, operating at a variable frequency [2,3]. The load of the generator is R_{2ad}. The phases of the stator winding can be connected according to one of the schemes shown in fig. 3.42.

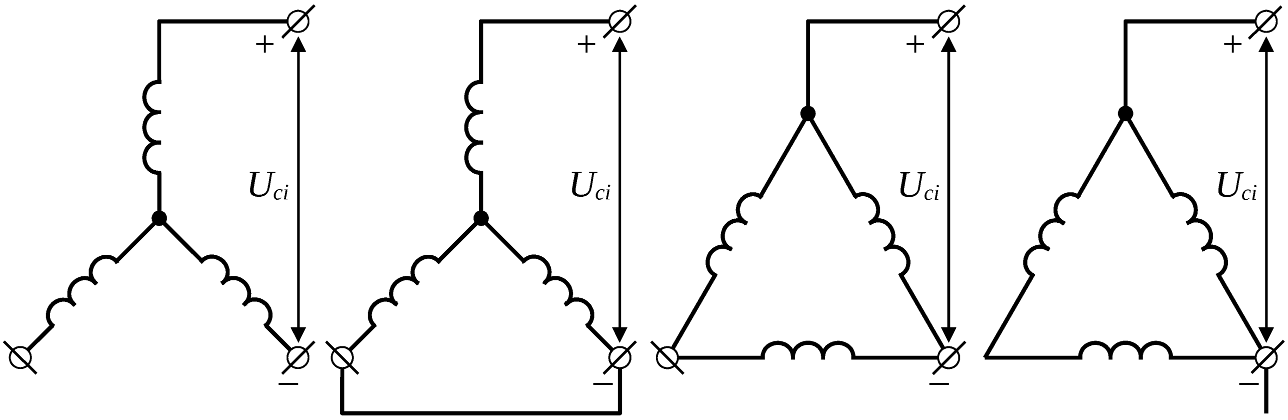

Figure 3.42 – Schematics of connecting the phases of the AM stator winding in the dynamic braking mode

Schemes differ in direct current resistance, different MMP, the number of switching equipment and loss power.

To derive the equation of the mechanical characteristic in the dynamic braking mode, the asymmetric direct current excitation system can be replaced by an equivalent symmetric three-phase current system, from the point of view of the magnetizing force amplitude. With such a replacement, the equality of the MMP must be observed

$$F_{dc} = F_{\sim}.$$

Next, we will use the AM substitution scheme in the dynamic braking mode.

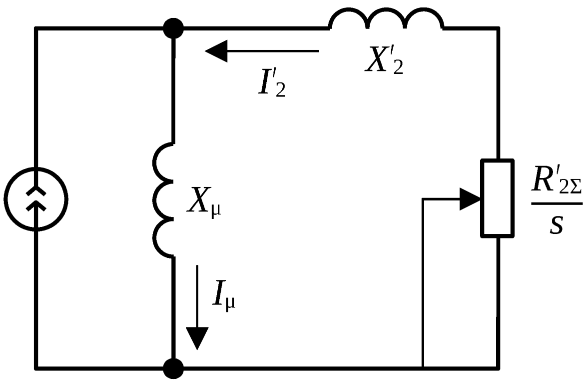

Figure 3.43 – The scheme of AM substitution in dynamic braking mode

This circuit design is correct at $R_{dc} >> R_1$, and in this scheme $I_{eq} = 0{,}816 I_{dc}$ [2, 3, 4].

On the basis of an equivalent circuit it is possible to obtain the speed-torque characteristic at dynamic braking mode [2,3,4]

$$M = \frac{2 M_{dbc}}{\frac{S_{db}}{S_{dbc}} + \frac{S_{dbc}}{S_{db}}}, \qquad (3.29)$$

where $S_{db} = -\frac{\omega}{\omega_{0nom}}$; $\omega_{0nom} = \frac{2\pi f_{nom}}{p}$;

$$S_{dbc} = \frac{-R'_{2\Sigma}}{x'_{2nom} + x'_{\mu nom}};$$

$$M_{dbc} = \frac{3\left(x'_{\mu nom} \cdot I_{eq}\right)^2}{2\omega_{0nom}\left(x'_{2nom} + x_{\mu nom}\right)}.$$

Induction motor speed-torque characteristics at dynamic braking mode (3.29) is displayed at fig. 3.44.

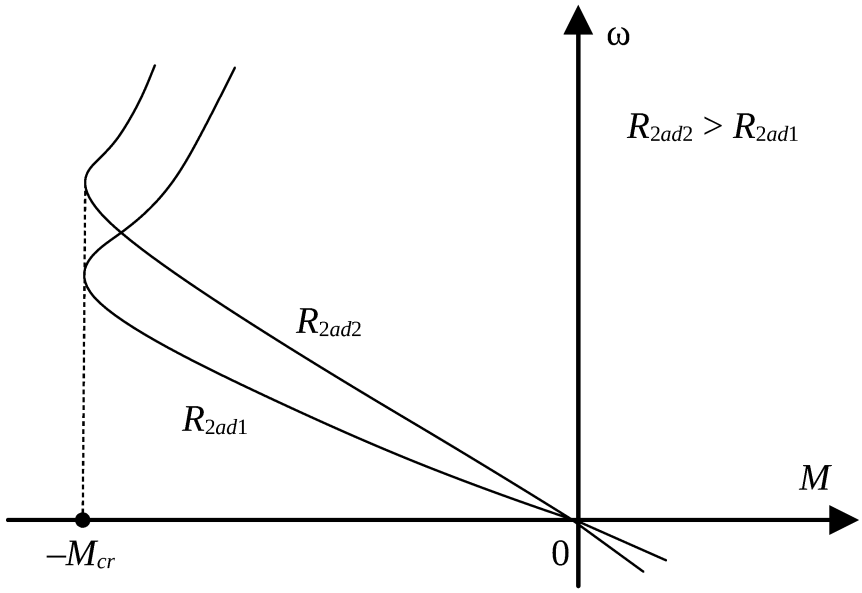

Figure 3.44 – Speed-torque characteristics of induction motor at dynamic braking mode

3.5 Synchronous motor characteristics

Synchronous motor circuit design is displayed on fig. 3.45.

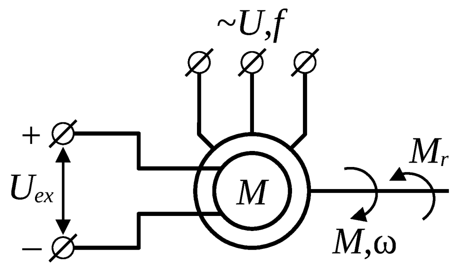

Figure 3.45 – Synchronous motor circuit design

This motor has a conventional AC machine stator. On the rotor there is an excitation winding of the EW, through which a direct current flows. After start-up and the synchronization process, the speed of the SM is determined by the ratio

$$\omega = \omega_0 = \frac{2\pi f}{p}. \tag{3.29}$$

Expression (3.29) is an equation of the mechanical characteristics of the SM. Graphically, it is a line parallel to the moment axis.

During the operation of the engine and the increase in M_r, the instantaneous values of the speed will differ from ω_0 due to the lagging of the rotor from the stator field, which is determined by the excitation flux.

In this connection, the dependence of the engine torque on the internal shift angle between the EMF vectors and the mains voltage (angle of departure Θ) is important. This dependence is called the angular mechanical characteristic of a synchronous motor $M = f(\Theta)$.

Let's obtain the equation of the angular mechanical characteristic of the SM.

To do this, by introducing the assumption $R_1 = 0$, we write down the equation of electrical balance for the stator circuit:

$$\bar{U}_1 \approx \bar{E}_1 + j\,\bar{I}_1 x_1. \tag{3.30}$$

Using (3.30), we build a Blondel vector diagram (fr. André-Eugène Blondel), resulting in fig. 3.46.

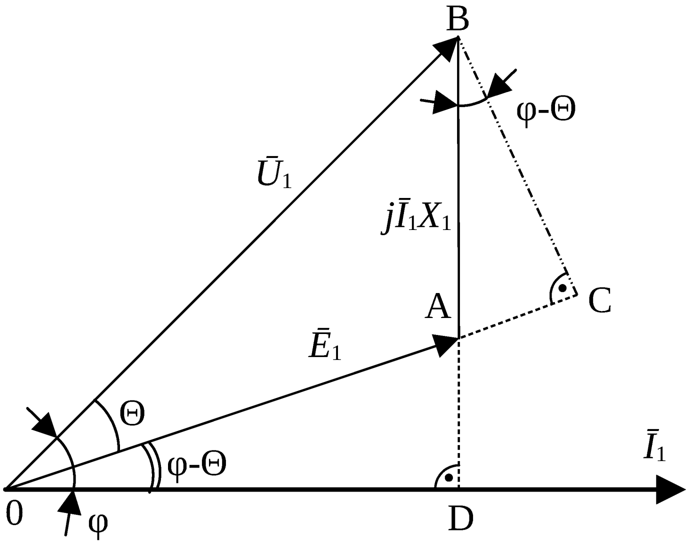

Figure 3.46 – Synchronous motor vector diagram

According to the accepted assumption, all the active power consumed from the network is transferred to the motor rotor.

$$3U_1 I_1 \cos\varphi = M \cdot \omega_0 . \tag{3.31}$$

From here:

$$M = \frac{3U_1 I_1 \cos\varphi}{\omega_0} . \tag{3.32}$$

From a vector diagram:

$$U_1 \cos\varphi = E_1 \cos(\varphi - \theta) .$$

Besides, auxiliary triangle *OAD* is similar to an auxiliary triangle *BAC*, that allows to record:

$$\cos(\varphi - \theta) = \frac{BC}{AB} = \frac{U_1 \sin\theta}{I_1 x_1} .$$

From here:

$$U_1 \cos\varphi = \frac{E_1 U_1 \sin\theta}{I_1 x_1} ;$$

$$M = \frac{3E_1 U_1 \sin\theta}{x_1 \omega_0} = M_{max} \sin\theta , \tag{3.33}$$

where $M_{max} = \frac{3U_1 E_1}{x_1 \omega_0}$.

Expression (3.33) allows building an angular characteristic (fig. 3.47).

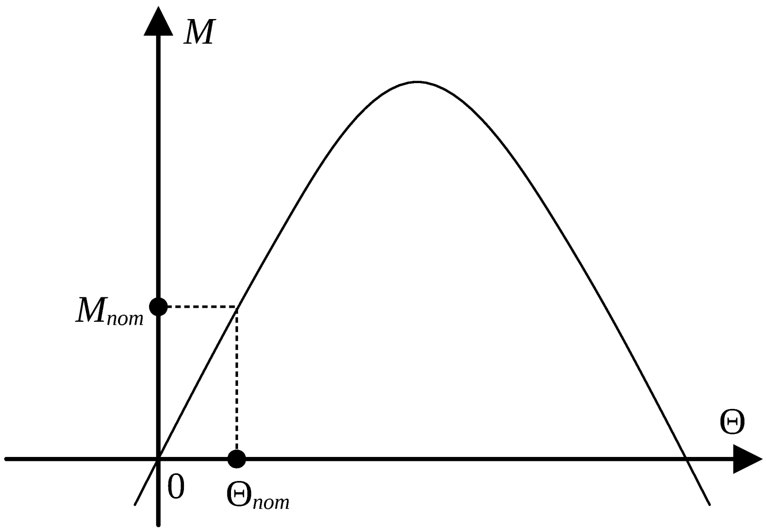

Figure 3.47 – Synchronous motor angular characteristic

On an ascending sector of characteristic at θ_{nom} = (25÷30)° the nominal point is chosen. Such choose of an operating point ensures overload factor $\lambda = M_{max} / M_{nom} =$ $= 2{,}5 \div 3$.

The dropping sector of characteristic θ = (90 ÷ 180)° is non-working since with an increase in loading the motor moment decreases, the negative dynamic moment appears, the motor breaks, torque angle increases, the drive moment decreases even more, and the process occurs as an avalanche. Motor falls out of synchronism, currents increase inadmissible that follows from a vector diagram.

As can be seen from the mechanical characteristics, the SM does not have a starting moment. If it is connected to an alternating current network, when the rotor is stationary, and a direct current flows through the excitation winding, then in one voltage period the electromagnetic moment will change direction twice and its average value will be zero.

In addition, due to inertia, the motor will not start rotating and will not reach synchronous speed during one period of voltage.

The asynchronous start method is used to start the LED. In this method, the motor is provided with a «white cage» type winding.

In the braking modes of the SM, it is possible to implement recovery and dynamic braking modes. Anti-lock braking is practically not used due to difficult transient processes.

Synchronous motor can operate at cosφ = 1 and even to produce a reactive power in the power source.

Total motor magnetic flux is defined as:

$$\Phi_{\Sigma} = \Phi_{st}(I_1) + \Phi_{rot}(I_e),$$

where Φ_{st} – stator magnetic flux created by stator current I_1;

Φ_{rot} – rotor magnetic flux created by exciting current I_e.

At $\Phi_{rot} = 0$, all flux is created by the stator, and the motor consumes only a reactive current.

If to excite the motor, the flux part will be created by field winding located on a rotor and reactive current consumption will be decreased.

U-shaped characteristics which represent dependence $I_1 = f(I_e)$ and $\cos\varphi = f(I_e)$ illustrate operation of synchronous motor as reactive power compensator. *U*-shaped idling characteristics are resulted on fig. 3.48.

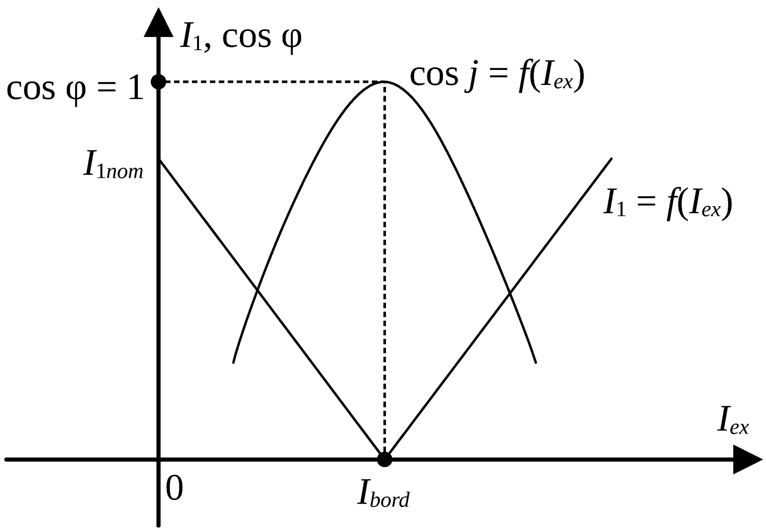

Figure 3.48 – Synchronous motor U-shaped characteristics

From characteristics follows that when exciting current increases from null, the stator current is diminished (because reactive component is decreased.

At some critical exciting current, the stator reactive current is equal to null, and $\cos\varphi = 1$. At the further increase in an exciting current, the reactive current has a leading phase and the synchronous motor produces reactive energy to the power network.

Generation area is displaced towards large excitation currents when motor loading grows.

3.6 Questions for self-verifying

1. Draw and explain DCM IE natural and artificial characteristics.

2. How DCM IE electric braking modes are realized?

3. Draw and explain DCM SE natural and artificial characteristics.

4. How DCM SE electric braking modes are realized?

5. What are the features of DCM CE electromechanical and mechanical characteristics?

6. Draw and explain induction motor natural and artificial characteristics.

7. How induction motor electric braking modes are realized?

8. Draw and explain angular speed-torque characteristic of synchronous motor.

9. Explain U-shaped characteristics of a synchronous motor.

4 ELECTRIC DRIVE TRANSIENTS

Transient processes (dynamic modes) occur during the transition from one stable mode of ED operation to another during start-up, braking, change of direction of movement, change of load on the shaft. Transient processes are caused by the inertia of the masses of the mechanical part moving in rotation and translation, as well as the electromagnetic inertia of the electrical circuits of the EP. Taking transient processes into account allows you to correctly choose the engine and control equipment. In some cases, transitional processes significantly affect such important technical and economic indicators as quality and productivity.

4.1 Transient processes at the start of the DCM IE without taking into account the electromagnetic inertia

In fig. 4.1 shows the start-up scheme of the DCM IE with the current-limiting resistance R_{ad} at U_a = const.

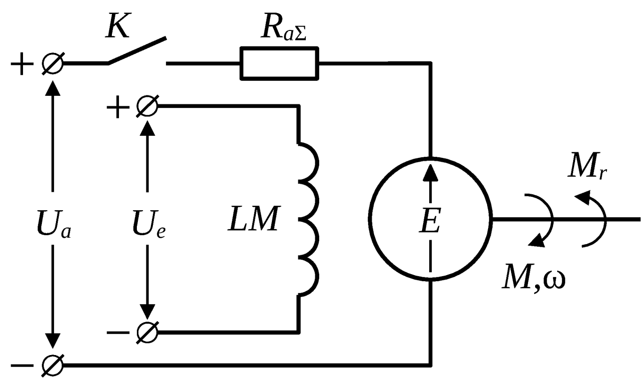

Figure 4.1 – Circuit design of shunt motor starting

Let's assume $\Phi = \Phi_{nom}$ = const, summarized inductance of armature circuit $L_{a\Sigma} = 0$, M_r = const, $R_{a\Sigma} = 1{,}24\ (R_a + R_{ap} + R_{cw}) + 2R_b + R_{ad}$, a switch K – ideal.

Let's obtain the law of change of speed and moment of the engine in time. In this case, the moment and current in the armature are connected by a proportional relationship. However, armature current is much easier to measure using sensors and devices than torque. Therefore, in this case, if we are talking about transient processes in the ED with DCM IE at Φ_{nom} = const, the armature current is considered instead of the moment. Taking into account the assumptions, let's move on to the substitution scheme in fig. 4.2.

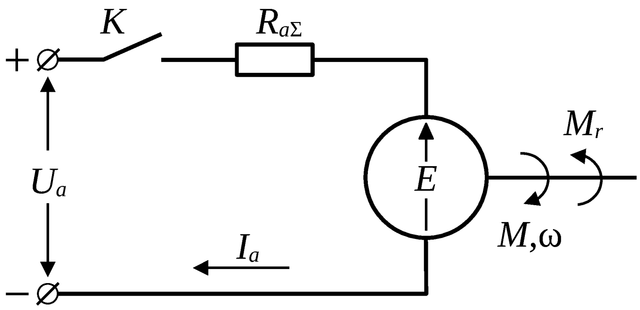

Figure 4.2 – Scheme of replacement of DCM IE without taking into account electromagnetic inertia

For the equivalent circuit we can write

$$U_a = R_{a\Sigma} I_a + E; \tag{4.1}$$

$$M - M_r = J\frac{d\omega}{dt}; \tag{4.2}$$

$$E = k\Phi\omega; \tag{4.3}$$

$$M = k\Phi I_a. \tag{4.4}$$

Let’s express in (4.2) the moment due to the current taking into account (4.4):

$$I_a = \frac{J}{k\Phi}\frac{d\omega}{dt} + I_r. \tag{4.5}$$

Let's write equation (4.1) taking into account (4.5) and (4.3):

$$U_a = R_{a\Sigma}\left(I_r + \frac{J}{k\Phi}\frac{d\omega}{dt}\right) + k\Phi\omega, |: k\Phi;$$

$$\frac{U_a}{k\Phi} = \frac{R_{a\Sigma} I_r}{k\Phi} + \frac{JR_{a\Sigma}}{(k\Phi)^2}\frac{d\omega}{dt} + \omega. \tag{4.6}$$

Let's use following expressions:

$\frac{U_a}{k\Phi} = \omega_0$; $\frac{R_{a\Sigma} I_r}{k\Phi} = \frac{\Delta U_r}{k\Phi} = \Delta\omega_r$; $\frac{JR_{a\Sigma}}{(k\Phi)^2} = T_m$ – electromechanical time constant.

$$T_m = \frac{J \cdot R_{a\Sigma} \cdot U_a}{k\Phi \cdot U_a \cdot k\Phi} = \frac{J\omega_0}{M_{sc}}. \tag{4.7}$$

From (4.7) T_m physical sense follows as a time when ED with moment of inertia J it will be accelerated from a motionless condition to ideal idle speed ω_0 under the influence of short circuit torque M_{sc}.

Taking into account the accepted expressions (4.6) we will record as:

$$T_m \frac{d\omega}{dt} + \omega = \omega_0 - \Delta\omega_s = \omega_s \tag{4.8}$$

where ω_s – motor speed caused by M_r at a steady state.

Let's differentiate on a time (4.1) and then solve relatively $d\omega / dt$.

$$\frac{d\omega}{dt} = -\frac{R_{a\Sigma}}{k\Phi}\frac{dI_a}{dt}. \tag{4.9}$$

Having substituted (4.9) in (4.5) we will gain

$$T_m \frac{dI_a}{dt} + I_a = I_s. \tag{4.10}$$

Expressions (4.8) and (4.10) are ordinary linear differential equations of the first order by which ED starting is presented. The solution (4.8) in a general view we'll record as

$$\omega = \omega_s + C e^{-\frac{t}{T_m}},$$

where C – an integration constant.

Let's define C from initial conditions: at $t = 0$, $\omega = \omega_{in}$, $C = \omega_{in} - \omega_s$. Thus

$$\omega = \omega_s + (\omega_{in} - \omega_s) e^{-\frac{t}{T_m}}. \tag{4.11}$$

Let's analogously define the law of a modification of starting armature current:

$$I_a = I_r + (I_{in} - I_s) e^{-\frac{t}{T_m}}. \tag{4.12}$$

As starting often make from a motionless condition ($\omega_{in} = 0$, $I_{in} = 0$) relationships (4.11) and (4.12) we'll record as

$$\omega = \omega_s \left(1 - e^{-\frac{t}{T_m}}\right); \tag{4.13}$$

$$I_a = I_r \left(1 - e^{-\frac{t}{T_m}}\right). \tag{4.14}$$

Let's build transients at the shunt motor starting without electromagnetic inertia on the gained relationships (4.13) and (4.14) (fig. 4.3).

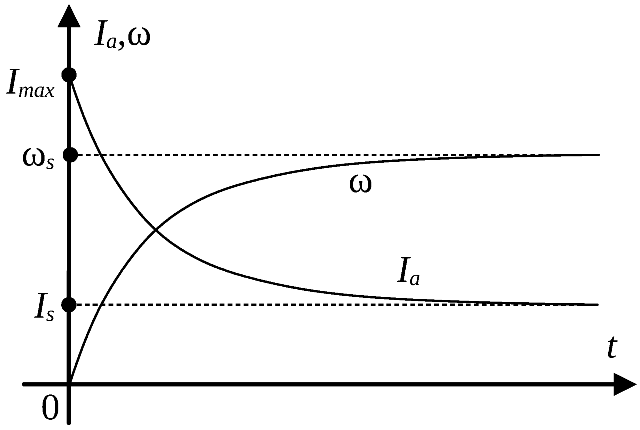

Figure 4.3 – Transients of shunt motor starting without electromagnetic inertia

The maximum value of the armature current is determined by the overload capacity of the motor I_{max} = (2÷2.5)I_a. As the speed of the motor increases, so does its EMF, the armature current decreases and tends to the static current due to the static load moment. Theoretically, the start-up process ends in an infinitely long time. However, the start-up is practically completed at t_{start} = (3÷4)T_m, because at t_{start} = 3T_m, $\omega = 0.95\omega_s$; t_{start} = 4T_m, $\omega = 0.98\omega_s$.

4.2 Transients at shunt motor starting taking into account electromagnetic inertia

In some cases, the total inductance of the armature circuit $L_{a\Sigma}$ must be taken into account when calculating transient processes. This is done when the time of mechanical transient processes is comparable to the time of electromagnetic ones. In fig. 4.4 shows the start-up scheme of the DCM IE, taking into account the electromagnetic inertia ($L_{a\Sigma} \neq 0$) and the current-limiting resistance R_{ad} at U_a = const.

Let's assume $\Phi = \Phi_{nom}$ = const, motor speed-torque characteristics are linear, $R_{a\Sigma}$ = 1,24 ($R_a + R_{ap} + R_{cw}$) + 2R_b + R_{cl}, $L_{a\Sigma} \neq 0$, M_r = const. We will gain the modification law of motor speed and armature current (moment) in a time at starting. Taking into account assumptions we will pass to an equivalent circuit (fig. 4.5).

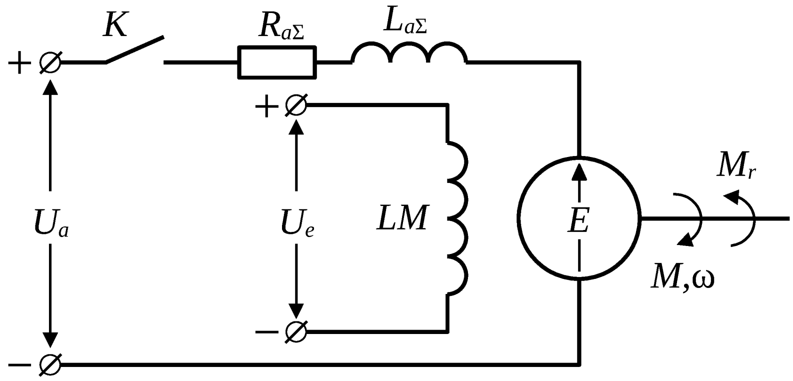

Figure 4.4 – Circuit design of shunt motor starting taking into account electromagnetic inertia

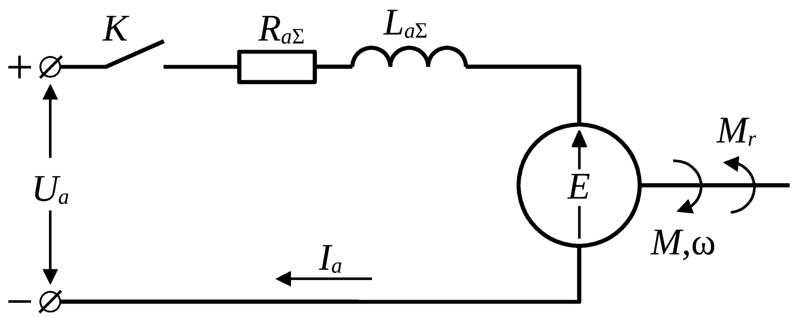

Figure 4.5 – Equivalent circuit of shunt motor taking into account electromagnetic inertia

For the given equivalent circuit it is possible to write:

$$U_a = R_{a\Sigma} I_a + L_{a\Sigma} \frac{dI_a}{dt} + E; \quad (4.15)$$

$$M - M_r = J \frac{d\omega}{dt}; \quad (4.16)$$

$$E = k\Phi\omega; \quad (4.17)$$

$$M = k\Phi I_a. \quad (4.18)$$

Let's express torque in (4.16) through a current taking into account (4.18)

$$I_a = \frac{J}{k\Phi} \frac{d\omega}{dt} + I_s. \quad (4.19)$$

From here:

$$\frac{dI_a}{dt} = \frac{J}{k\Phi} \frac{d^2\omega}{dt^2}. \quad (4.20)$$

Let’s record the equation (4.15) taking into account (4.19) and (4.20):

$$U_a = R_{a\Sigma}\left(I_s + \frac{J}{k\Phi}\frac{d\omega}{dt}\right) + \frac{L_{a\Sigma}}{R_{a\Sigma}}\cdot\frac{JR_{a\Sigma}}{k\Phi}\cdot\frac{d^2\omega}{dt^2} + k\Phi\omega \,|: k\Phi;$$

$$\frac{U_a}{k\Phi} = \frac{R_{a\Sigma} I_s}{k\Phi} + \frac{JR_{a\Sigma}}{(k\Phi)^2}\cdot\frac{d\omega}{dt} + \frac{L_{a\Sigma}}{R_{a\Sigma}}\cdot\frac{JR_{a\Sigma}}{(k\Phi)^2}\cdot\frac{d^2\omega}{dt^2} + \omega. \qquad (4.21)$$

Taking into account the accepted expressions we’ll record (4.21) as:

$$T_m T_e \frac{d^2\omega}{dt^2} + T_m \frac{d\omega}{dt} + \omega = \omega_0 - \Delta\omega_s = \omega_s. \qquad (4.22)$$

where $T_e = L_{a\Sigma} / R_{a\Sigma}$ – is electromagnetic time constant.

$$T_e = \frac{L_{a\Sigma}(I_a^2/2)}{R_{a\Sigma}(I_a^2/2)} = \frac{2W_e}{P_t}. \qquad (4.23)$$

From (4.23) follows the physical meaning of T_e – it is the time required to transform the entire stock of electromagnetic energy W_e in the anchor circuit into heat losses, and half of all heat losses are released every second.

$$\frac{d\omega}{dt} = \frac{k\Phi}{J}(I_a - I_s). \qquad (4.24)$$

Let's differentiate on a time the left and right sides of an equation (4.15):

$$R_{a\Sigma}\frac{dI_a}{dt} + L_{a\Sigma}\frac{d^2 I_a}{dt^2} + k\Phi\frac{d\omega}{dt} = 0. \,|: R_{a\Sigma}. \qquad (4.25)$$

Let's substitute in (4.25) expression (4.24) and taking into account the accepted expressions we’ll gain:

$$T_m T_e \frac{d^2 I_я}{dt^2} + T_m \frac{dI_a}{dt} + I_a = I_s. \qquad (4.26)$$

Relationships (4.22) and (4.26) are second order ordinary linear differential equations by which ED starting taking into account electromagnetic inertia is presented. In a general view it is possible to present the solution of these equations as:

$$\omega = A_1 e^{p_1 t} + A_2 e^{p_2 t} + \omega_s;\ I_a = B_1 e^{p_1 t} + B_2 e^{p_2 t} + I_s.$$

where A_1, A_2, B_1, B_2 – are integration constants;

p_1, p_2 – are roots of characteristic equation.

$$T_m T_e p^2 + T_m p + 1 = 0. \qquad (4.27)$$

The solution of an algebraic characteristic equation (4.27) we will write as:

$$p_{1.2} = -\frac{1}{2T_e} \pm \sqrt{\frac{1}{4T_e^2} - \frac{1}{T_m T_e}} = -\frac{1}{2T_e} \pm \varepsilon. \qquad (4.28)$$

If $T_m \geq 4T_e$, roots are real, the solution of differential equations is written as:

$$\omega = e^{-\frac{t}{2T_e}}\left(A_1 e^{\varepsilon t} + A_2 e^{-\varepsilon t}\right) + \omega_s; \qquad (4.29)$$

$$I_a = e^{-\frac{t}{2T_e}}\left(B_1 e^{\varepsilon t} + B_2 e^{-\varepsilon t}\right) + I_s. \qquad (4.30)$$

Transient has aperiodic character, and the starting plot at a start from a standstill looks the way it’s displayed on fig. 4.6:

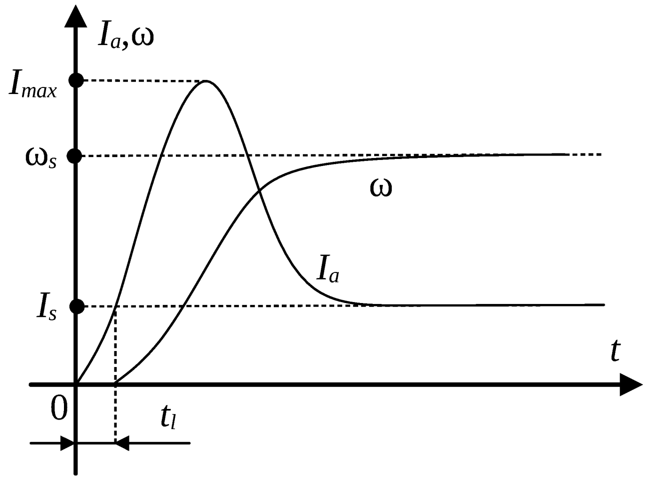

Figure 4.6 – Transient processes during the start-up of the DCM IE, taking into account the electromagnetic inertia under the condition $T_m \geq 4T_e$.

The moment of resistance is reactive.

It can be seen from the diagram that until the armature current I_a reaches the static load current I_s, the motor armature is stationary. When the delay time t_l is reached, the anchor starts to rotate. The angular velocity asymptotically tends to ω_s, and the current, having reached a maximum, decreases and asymptotically tends to the current I_s. The maximum current can be reduced if additional inductance is introduced into the armature circuit. However, in this case it may turn out that $T_m < 4T_e$.

If $T_m < 4T_e$, roots of characteristic equation are complex conjugate:

$$p_{1.2} = -\frac{1}{2T_e} \pm j\Omega . \quad (4.31)$$

The solution of differential equations can be written as:

$$\omega = A e^{-\frac{t}{2T_e}} \sin(\Omega t + \varphi) + \omega_s ; \quad (4.32)$$

$$I_a = B e^{-\frac{t}{2T_e}} \sin(\Omega t + \psi) + I_s . \quad (4.33)$$

where A, B, ϕ, ψ – are defined from initial conditions;

$\Omega = 2\pi f$ – is a frequency of electromechanical oscillations.

The transient process has an oscillatory character and has the form shown in fig. 4.7.

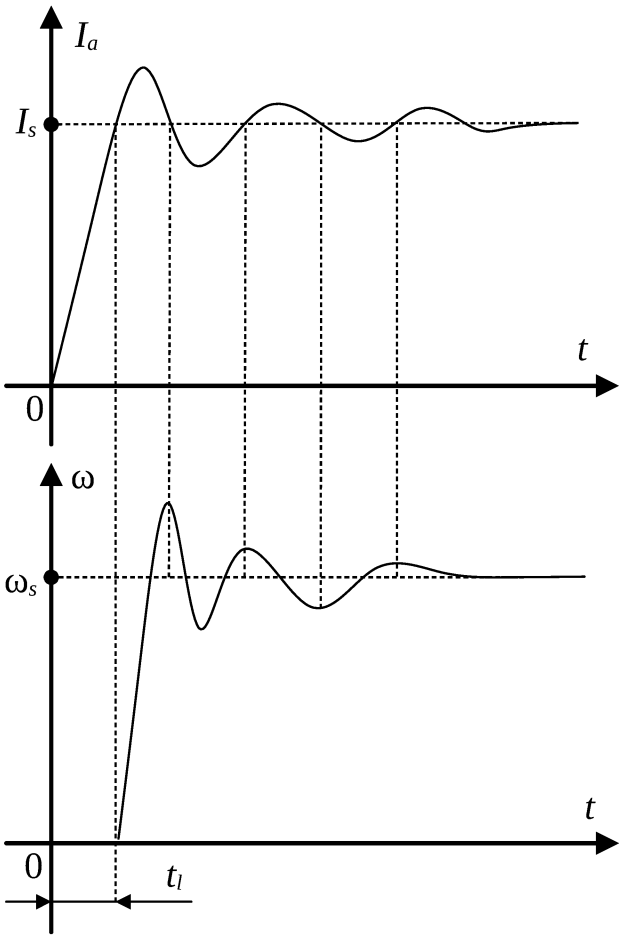

Figure 4.7 – Transient processes during the start-up of the DCM IE, taking into account the electromagnetic inertia under the condition $T_m < 4T_e$.

The load moment is reactive

It follows from relations (4.32) and (4.33) that the change in angular velocity and current has the character of damping oscillations. The fluctuating nature of the process significantly increases the start-up time, in some cases there is a significant overshoot of the speed above a constant value. Therefore, it is advisable to choose the ED parameters in such a way as to exclude the oscillatory nature of the process.

4.3 Transient processes during dynamic braking of DCM IE

Shunt motor dynamic braking is carried out by switching off an armature winding from the power supply, and its shorting on R_{ad}.

Thus we considered $\Phi = \Phi_{nom}$ = const, $L_a\Sigma = 0$, load torque M_r = const.

Input equations will be written as:

$$0=(R_{a\Sigma}+R_{ad})I_a+E; \tag{4.34}$$

$$M-M_r=J\frac{d\omega}{dt}; \tag{4.35}$$

$$E=k\Phi\omega. \tag{4.36}$$

At dynamic braking mode the equation of shunt motor speed-torque characteristic looks like:

$$\omega=-\frac{M_b(R_{a\Sigma}+R_{ad})}{(k\Phi)^2}. \tag{4.37}$$

From here:

$$M_b=-\frac{(k\Phi)^2}{R_{a\Sigma}+R_{ad}}\omega. \tag{4.38}$$

At steady state $M = M_r$, $\omega = \omega_s$, and basic equation of ED motion (4.35) taking into account (4.38):

$$-\frac{(k\Phi)^2}{R_{a\Sigma}+R_{ad}}\omega+\frac{(k\Phi)^2}{R_{a\Sigma}+R_{ad}}\omega_s=J\frac{d\omega}{dt}\,|:\frac{(k\Phi)^2}{R_{a\Sigma}+R_{ad}};$$

$$T_m\frac{d\omega}{dt}+\omega=\omega_s. \tag{4.39}$$

The solution of a differential equation (4.39) in a general view we’ll write as:

$$\omega = \omega_s + C e^{-t/T_m}.$$

Let's define C from initial conditions: at t = 0, ω = ω_{in}, $C = \omega_{in} - \omega_s$. Thus

$$\omega = \omega_s + (\omega_{in} - \omega_s) \cdot e^{-t/T_m}. \quad (4.40)$$

Multiplying (4.40) on $-\frac{(k\Phi)^2}{R_{a\Sigma} + R_{ad}}$ we will obtain:

$$M_a = M_r + (M_{in} - M_r) \cdot e^{-t/T_m}. \quad (4.41)$$

Taking into account $\Phi = \Phi_{nom}$, it is possible to record:

$$I_a = I_s + (I_{in} - I_s) \cdot e^{-t/T_m}. \quad (4.42)$$

Relationships (4.40) and (4.42) allow building shunt motor dynamic braking transients (fig. 4.8).

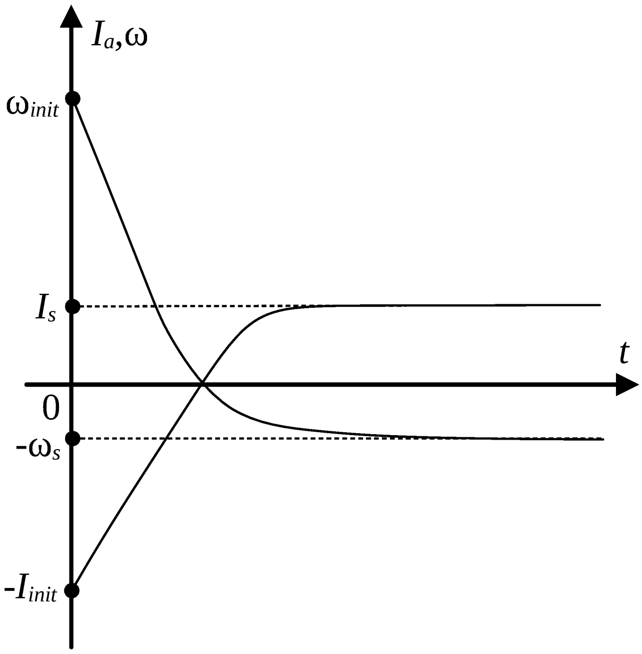

Figure 4.8 – Shunt motor dynamic braking transients. Load torque is active.

If load torque is reactive, the equation (4.35) is nonlinear and also a problem has no analytical solution. In this case all transients are completed at ω = 0.

4.4 Transients in ED with nonlinear speed-torque characteristics

Non-linear mechanical characteristics have DCM IE, DCM ME, AM. The load characteristics can be non-linear, if the moment of resistance is reactive, when

$M_r = f(\omega)$, $M_r = f(\omega)$, etc. In this case, calculations of transient processes are performed by numerical methods using computer technology. Many numerical methods are based on the grapho-analytical method, which will be illustrated by an example of the calculation of the start-up of the AD with a fan load (fig. 4.9).

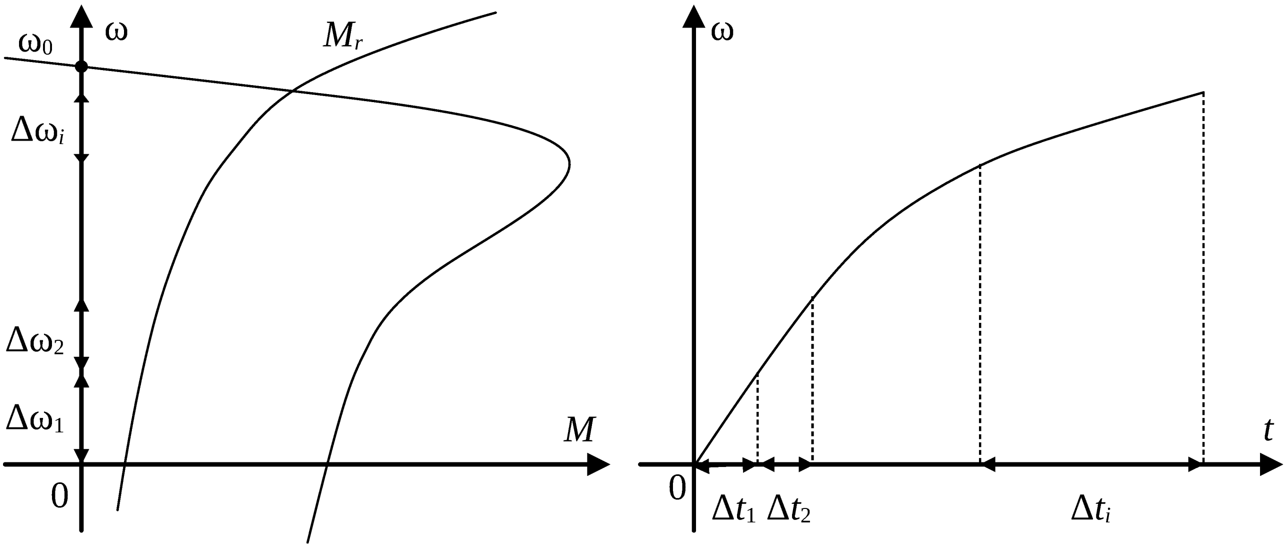

Fig. 4.9 a) Mechanical characteristics of AD and load,

b) Transient process during AD start-up

$$M_i - M_{ri} = J\frac{\Delta\omega_i}{\Delta t_i}, \tag{4.43}$$

where $\Delta\omega_i$ – is speed increment by which we are set for each *i*-th rated interval.

From (4.33) it is possible to define

$$\Delta t_i = \frac{J\,\Delta\omega_i}{M_i - M_{ri}}. \tag{4.44}$$

Value of a motor torque and load torque for each i-th interval it is definable as an average

$$M_i = \frac{M_{i\,max} + M_{i\,min}}{2};$$

$$M_{ri} = \frac{M_{ri\,max} + M_{i\,min}}{2}.$$

Thus, having made sequentially a number of calculations for Δt at set $\Delta\omega$ we construct an IM starting speed-time plot (fig. 4.9b).

4.5 Questions for self-verifying

1. What inertias form ED transients?

2. Write an initial system of equations presenting a shunt motor starting without electromagnetic inertia.

3. Draw and explain the plot of the shunt motor starting transient without electromagnetic inertia.

4. Write an initial system of equations presenting a shunt motor starting taking into account electromagnetic inertia.

5. When the shunt motor starts transient taking into account electromagnetic inertia aperiodic and oscillating.

6. Draw and explain the plot of shunt motor starting transient taking into account electromagnetic inertia, if $T_m > 4T_e$.

7. Draw and explain the plot of shunt motor starting transient taking into account electromagnetic inertia, if $T_m < 4T_e$.

8. Draw and explain the plot of shunt motor dynamic braking transient, if load torque is active.

9. Explain graphic-analytical calculation method of IM starting transient for $M_r = f(\omega)$.

5 SELECTION AND CALCULATION OF THE POWER OF THE DRIVE MOTOR

5.1 General provisions

The choice of electric motors is made taking into account the following factors:

1. Kind of current. The motor must have a type and magnitude of voltage corresponding to direct or alternating current networks.

2. Value of speed. If the gearbox is already available, the selection is made according to the specified speed of the working body.

3. Constructive performance. The design of the selected engine must meet the conditions of its arrangement with the executive body. The engines that are produced have a variety of structural designs in terms of the location of the shafts and the methods of attachment to the working machine.

4. Method of ventilation and environmental protection. According to the method of ventilation, engines with natural ventilation, self-ventilation and forced ventilation are distinguished.

Open, closed and hermetic engines are distinguished by the methods of protection against the environment. For work in special environmental conditions – tropical climate, chemically active environments, high humidity, explosive environment, etc. – special engines are produced.

5. By power. The main requirement when choosing an engine is the compliance of its power with the conditions of the technological process in which the working body is directly involved.

Excessive power leads to an increase in weight, capital costs, moment of inertia, reduces efficiency and power factor.

Insufficient power leads to increased heating, accelerated aging of the insulation, and reduced service life.

When choosing an electric motor, its compliance with starting conditions and possible overloads should also be checked.

Usually, the choice of an electric motor is made in the following sequence:

– power calculation and preliminary selection;

– check of the selected engine according to start-up conditions and overload;

– checking the engine for heating.

Let's consider the stages of choosing an electric motor for the case when a mechanical transmission is selected, its gear ratio or drive radius and efficiency are known.

The starting data for calculations are the loading diagram and the speed diagram (tachogram) of the working body.

The load diagram is the dependence of the static load moment reduced to the speed of the motor shaft on time $M_s(t)$.

The dependence of the engine speed of the working body on time is called a tachogram.

In fig. 5.1 shows a loading diagram of the type M_s = const, and the tachogram contains acceleration, movement at a constant speed, braking and a pause.

The full cycle time is:

$$t_c = t_a + t_s + t_b + t_p,$$

where t_a – is acceleration time;

t_s – is time of driving with the steady speed ω_s;

t_b – is braking time;

t_p – is pause time.

Dynamic torque $M_{dyn} = J\frac{d\omega}{dt}$ in this case at constant moment of inertia on the acceleration interval is defined as:

$$M_{dyn} = J\frac{\omega_s}{t_a}.$$

On the interval with the motor steady speed T_{dyn} = 0;

On the breaking interval $M_{dyn} = -J\frac{\omega_s}{t_b}$.

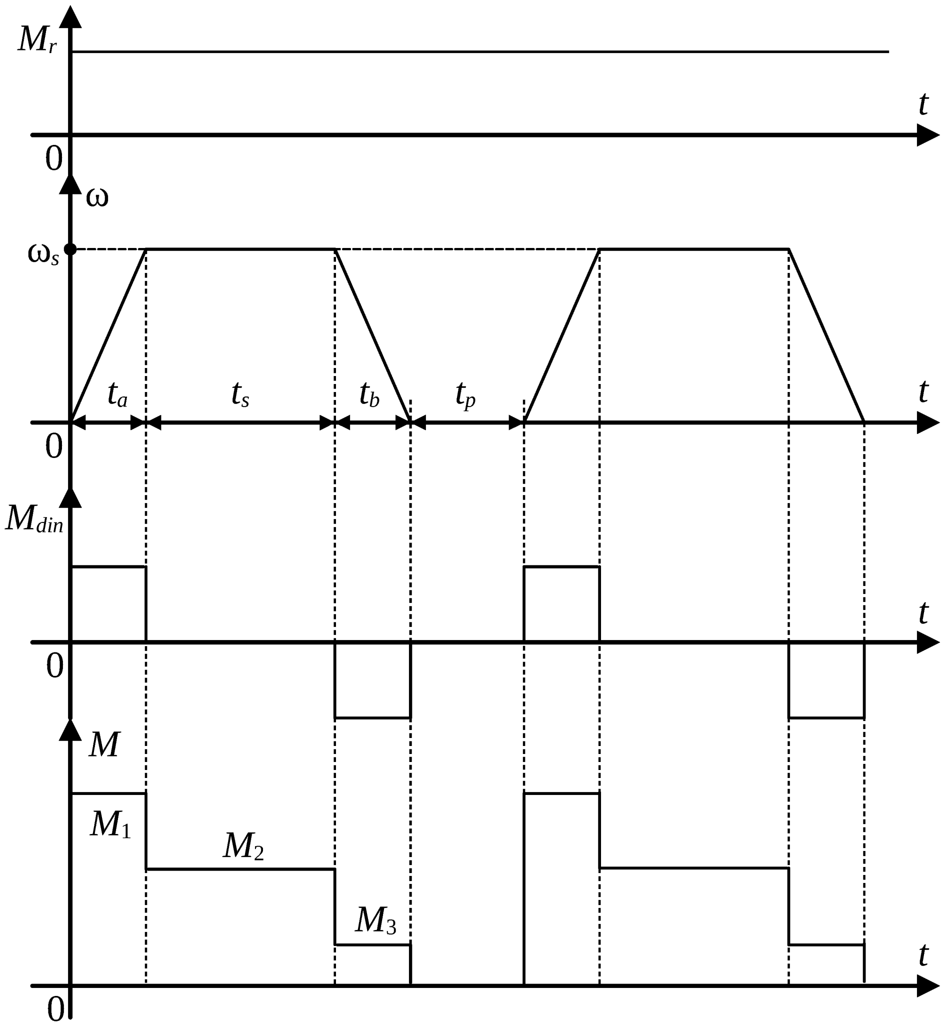

Figure 5.1 – Diagram for calculation of motor

We define motor torque M for each time interval, by using basic ED motion equation

$$M = M_{dyn} + M_s.$$

The rated torque of the engine is calculated using the ratio

$$M_{nom} \geq k_s \cdot M_s, \tag{5.1}$$

where k_s is a safety factor considering dynamic processes, called by speed control.

If M_s varies in a time and the load diagram has some sections, $M_{s\,eq}$ is defined as a root-mean-square value:

$$M_{seq} = \sqrt{\frac{1}{t_c} \cdot \sum_{i=1}^{n} M_{si}^2 t_i}, \tag{5.2}$$

where M_{si}, t_i is the moment and duration of i-th section of the load diagram.

The nominal design power is as:

$$P_{nom}=M_{nom}\cdot\omega_s.$$

where ω_s – is a steady speed value from tachogram.

Next, the engine of the closest higher power and speed, which has the necessary structural performance, is selected from the catalog. To check the selected engine for overload capacity, compare the maximum allowable engine torque M_{max} with the largest torque from the constructed diagram (fig. 5.1).

$$M_{max}=\lambda M_{nom}\geq M_1.$$

When choosing AD, it is necessary to check the starting conditions, for which the starting moment M_{st} is compared with the largest resistance moment:

$$M_{st}>M_{s\,max}.$$

The next stage of calculations is related to checking the pre-selected engine for heating conditions. The permissible engine heating temperature is determined by the class of insulation.

The main classes of insulation used in the manufacture of engines are B, F, H.

The permissible maximum heating temperature for class B is 130 °C, for class F – 155 °C, for class H – 180 °C.

When performing thermal calculations, the ambient temperature is set equal to 40 °C. This temperature corresponds to the nominal power indicated on the motor shield. Calculations are performed under the following assumptions:

– the engine is considered as a homogeneous body with the same temperature at all points;

– heat transfer to the external environment is proportional to the first power of the temperature difference between the engine and the environment;

– the environment has an infinitely large heat capacity and its temperature is a constant value.

The heat balance equation for an elementary period of time, taking into account the assumptions, has the form

$$dQ_1=dQ_2+dQ_3,$$

where dQ_1 – is the amount of heat which is emitted into motor,

dQ_2 – is the amount of heat which is emitted into environment,

dQ_3 – is the amount of heat which is accumulated into motor.

If equation (5.3) is expressed in terms of thermal parameters of the engine, then after identical transformations we obtain [2,4,5]

$$T_h \frac{d\tau}{dt} + \tau = \tau_s, \tag{5.4}$$

where $T_h = C / A$ – is a heating time response;

C – is heating capacity, amount of heat necessary for increase of motor temperature on 1°C;

A – is heat transfer, amount of heat emitted by the motor into environment for 1 second;

$\tau = t°C_m - t°C_{ex}$ – is temperature excess (overheating), a motor and circumambient temperature difference;

τ_s – is a steady value of temperature excess.

Solution of the equation (5.4) will be recorded as:

$$\tau = (\tau_{in} - \tau_s) e^{-\frac{t}{T_h}} + \tau_s. \tag{5.5}$$

Expression (5.5) can be used to study the change in temperature excess, both when it is heated and when it is cooled. It is only necessary to substitute the corresponding τstart, τu and the heating time constant in (5.5).

During the cooling of the engine caused by its stop, the conditions of heat transfer change, therefore the cooling time constant also changes

$$T_c = \frac{T_h}{\beta_c},$$

where β_c – is a heat transfer decline factor when the rotor is motionless.

For the self-ventilated motor β_c = 0,45 ÷ 0,55.

Motor heat curves for various τ_{in} and various motor power losses ΔP are obtained at fig. 5.2.

Larger power losses correspond to larger steady-state values of overtemperature.

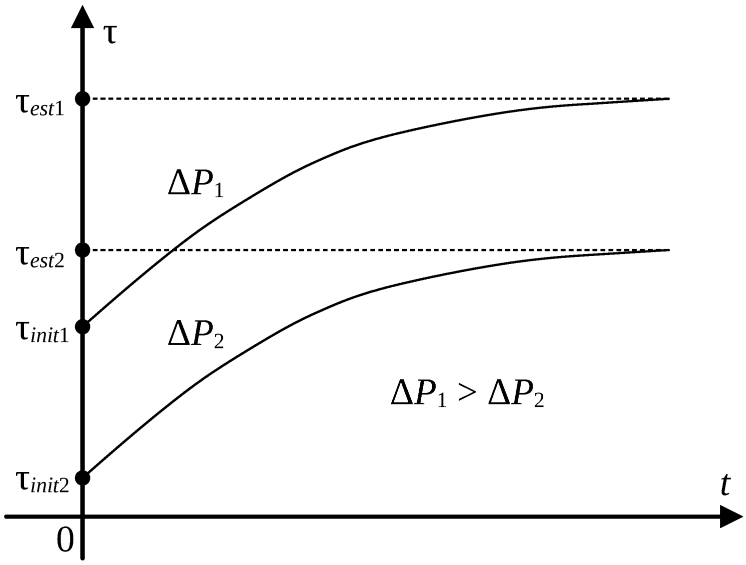

Figure 5.2 – Motor heat curves

Thus, the essence of checking the engine for heating is to compare the temperature permissible for it by excesses with the one it has during operation. Obviously, if the operating temperature of the engine does not exceed the permissible one, then the engine is operating in the permissible thermal mode.

This method of testing by heating requires the calculation of thermal parameters – heat capacity and heat transfer. These parameters are usually not indicated in the catalog data, which significantly complicates the use of the method with the construction of heating curves.

In this regard, in most cases, the heating check is carried out by methods that do not require the construction of a $\tau(t)$ graph.

They include the method of average losses and equivalent values.

The essence of the method of average losses consists in determining the average power losses ΔP_{mid} during the cycle time t_c and comparing them with the nominal ΔP_{nom}.

It is established that if $\Delta P_{mid} \leq \Delta P_{nom}$, then the medium temperature excess is not more than permissible. The maximum temperature exceedance differs from the medium, but when $t_c << T_h$ and $q \cdot t_c > 4T_h$, where q is the number of engine starts, this discrepancy is insignificant [2,3,4,5].

The order of calculations by the method of average losses is as follows.

1. Using the load diagram and tachogram, we determine the average power on the motor shaft:

$$P_{mid}=\frac{\sum_{i=1}^{n} P_i t_i}{\sum_{i=1}^{n} t_i}.$$

For the case of a self-ventilated engine at different angular velocities at intervals, the average power is determined as

$$P_{mid}=\frac{\sum_{i=1}^{n} P_i t_i \cdot \frac{\omega_{nom}}{\omega_i}}{\sum_{i=1}^{n} t_i \beta_i},$$

where $\beta_i=\beta_c+(1-\beta_c)\cdot\frac{\omega_i}{\omega_{nom}}$ – is the motor heat transfer decline factor.

2. Taking into account the dynamic loads associated with the change in angular velocity, we enter into the calculation the reserve factor k_{sf}:

$$P'_{mid}=k_{sf}\cdot P_{mid},$$

where k_{sf} = 1,1÷1,3.

3. We choose motor under the catalogue using condition

$$P_{nom}\geq P'_{mid}.$$

At the same time, the start-up conditions must be met:

$$M_{st}>M_{s\,max},$$

and also motor should have necessary overload capacity:

$$\lambda M_{nom}\geq M_{s\,max}.$$

4. Having the catalog dependence of the engine efficiency as a function of its power (fig. 5.3), we find the power loss for each time interval Δp_i.

$$\Delta P_i=\frac{P_i(1-\eta_i)}{\eta_i}.$$

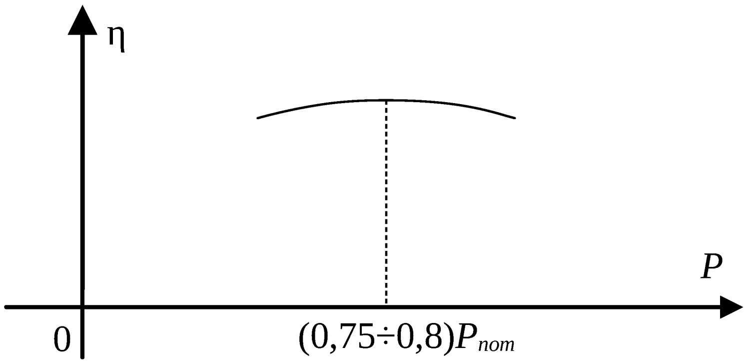

Figure 5.3 – Dependence of motor efficiency from its power

5. We define average power losses for a cycle:

$$P_{mid}=\frac{\sum_{i=1}^{n} P_i t_i \cdot \frac{\omega_{nom}}{\omega_i}}{\sum_{i=1}^{n} t_i \beta_i}.$$

We compare average power losses to the nominal ones.

The average excess of temperature is no more admissible, if

$$\Delta P_{mid} \leq \Delta P_{nom}=\frac{P_{nom}(1-\eta_{nom})}{\eta_{nom}}.$$

5.2 Method of equivalent quantities

In case of difficulties in determining the efficiency depending on the power and if there is a graph of the current consumed by the motor, the equivalent current method can be used.

The equivalent current I_{eq} is a constant value current that causes the same losses in the motor as the actual current flowing in it.

Power losses in the engine consist of constant ΔP_c and variable ΔP_v losses

$$\Delta P=\Delta P_c+\Delta P_v=k+I_{eq}^2 \cdot R.$$

Permanent losses, in turn, consist of mechanical, steel and excitation losses. Let's express the average losses in the engine due to constant and variable losses:

$$P_{mid}=\frac{\sum_{i=1}^{n} P_i t_i}{\sum_{i=1}^{n} t_i}=\frac{\sum_{i=1}^{n}\left(k+I_i^2 R\right) t_i}{\sum_{i=1}^{n} t_i}=\frac{\left(k+I_1^2 R\right) t_1+\left(k+I_2^2 R\right) t_2+\ldots+\left(k+I_n^2 R\right) t_n}{t_1+t_2+\ldots+t_n}=$$

$$=\frac{k\left(t_1+t_2+\ldots t_n\right)}{t_1+t_2+\ldots+t_n}+\frac{R\left(I_1^2 t_1+I_2^2 t_2+\ldots I_n^2 t_n\right)}{t_1+t_2+\ldots+t_n}=k+I_{eq}^2 R.$$

After transformations we'll obtain:

$$I_e=\sqrt{\frac{I_1^2 t_1+I_2^2 t_2+\ldots+I_n^2 t_n}{t_1+t_2+\ldots+t_n}}=\sqrt{\frac{\sum_{i=1}^{n} I_i^2 t_i}{\sum_{i=1}^{n} t_i}}.$$

Motor temperature excess is less than admissible if $I_{eq} \le I_{nom}$, $\tau \le \tau_{acc}$.

We may use a method of an equivalent moment at Φ = const and presence of the moment graph:

$$M_{eq}=\sqrt{\frac{\sum_{i=1}^{n} M_i^2 t_1}{\sum_{i=1}^{n} t_1}}.$$

If $M_{eq} \le M_{nom}$, $\tau \le \tau_{acc}$.

We may use a method of an equivalent power if we have a power diagram:

$$P_{eq}=\sqrt{\frac{\sum_{i=1}^{n} P_i^2 t_1}{\sum_{i=1}^{n} t_1}}.$$

If $P_{eq} \le P_{nom}$, $\tau \le \tau_{acc}$.

The method of equivalent current, moment, power is called the method of equivalent quantities.

Depending on the nature of the change in load on the shaft, the characteristics of heating and cooling, there are eight modes marked S1 ÷ S8. The first three modes S1, S2, S3 are the main and most characteristic. Others are much less common and are varieties of the first. Consider the main modes S1, S2, S3.

Mode S1 is called long nominal. In this mode, the engine operates at a constant nominal load for such a time that the temperature rise of all parts of the electric motor reaches a fixed value. The graph of changes in power on shaft P, power losses ΔP, and temperature rise for this mode is shown in fig. 5.4.

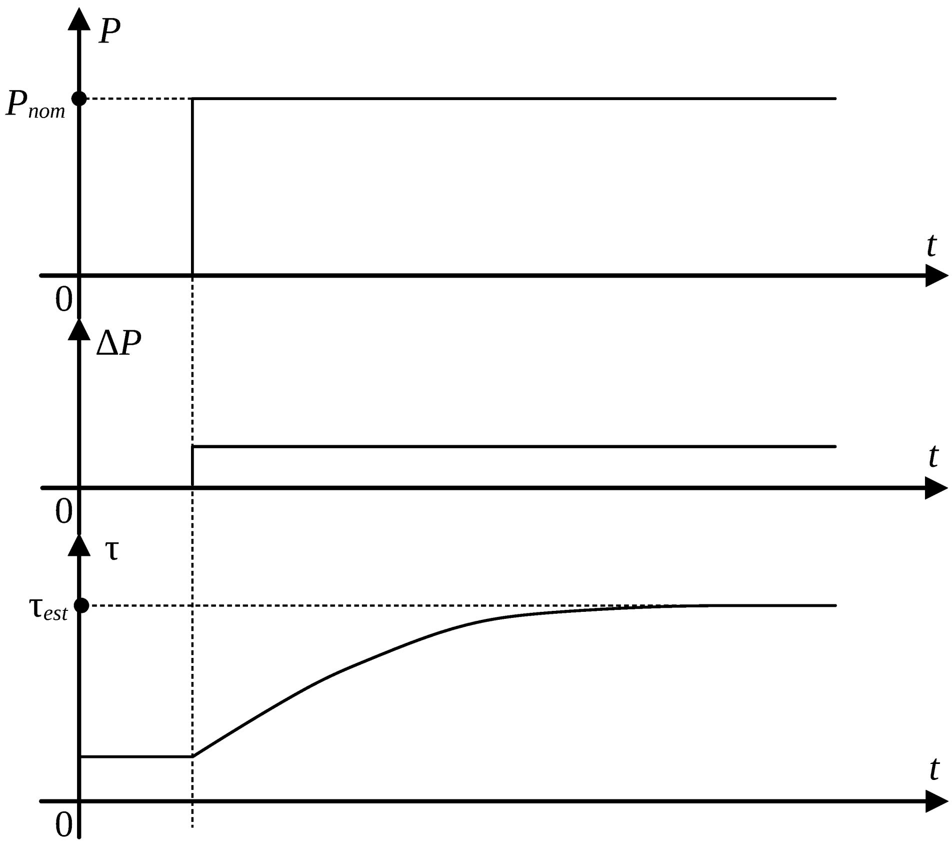

Figure 5.4 – S1 duty graph

Mode S2 is called short-term nominal. In this mode, short-term periods of unchanged nominal load alternate with periods of disconnection. During the time of inclusion, the excess temperature does not reach the established value. During shutdown, the engine cools down to ambient temperature (fig. 5.5).

A standard range of values for the duration of operation in the S2 mode is set, t_{st} = 10, 30, 60, 90 minutes.

Mode S3 is called repeated-short-term nominal. In this mode, short-term periods of unchanged nominal load alternate with periods of disconnection. Moreover, both working periods and shutdown periods are not so long that the temperature rise reaches steady values (fig. 5.6).

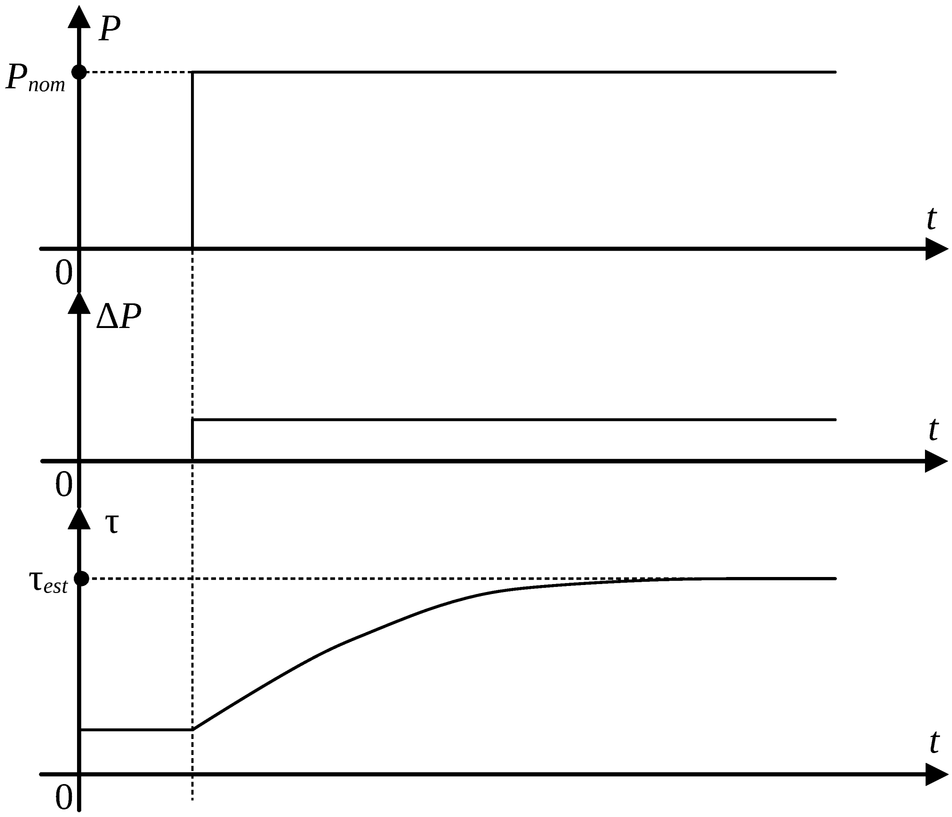

Figure 5.5 – S2 duty graph

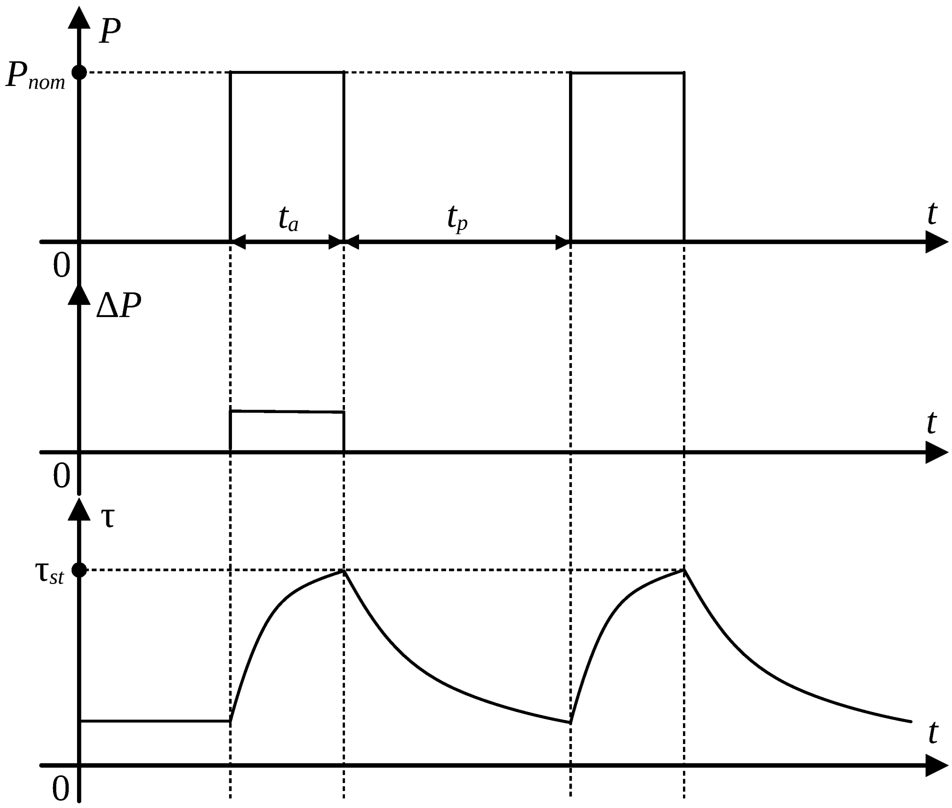

Figure 5.6 – S3 duty graph

The given regime is characterized by duty cycle DtC, %:

$$\text{DtC}\% = \frac{t_a}{t_a + t_p} \cdot 100\%,$$

where $t_c = t_a + t_p$ is a cycle time. It shouldn't exceed 10 minutes.

The recommended values for duty cycle are 15, 25, 40, 60 and 100 %. Motors that are used in different kinds of hoisting mechanisms and those used in trams, trolley buses etc. are subjected to intermittent duty.

Calculation of motor power is made taking into account features of each duty.

Average losses and equivalent quantities methods are used for S1 duty.

5.3 Calculation of motor power for S2 mode

For mode S2, as a rule, an engine designed for operation in mode S1 is used. In this case, in order for the electric machine to be fully used for heating, it is advisable to have the maximum allowable temperature excess at the end of switching on, as shown in fig. 5.7

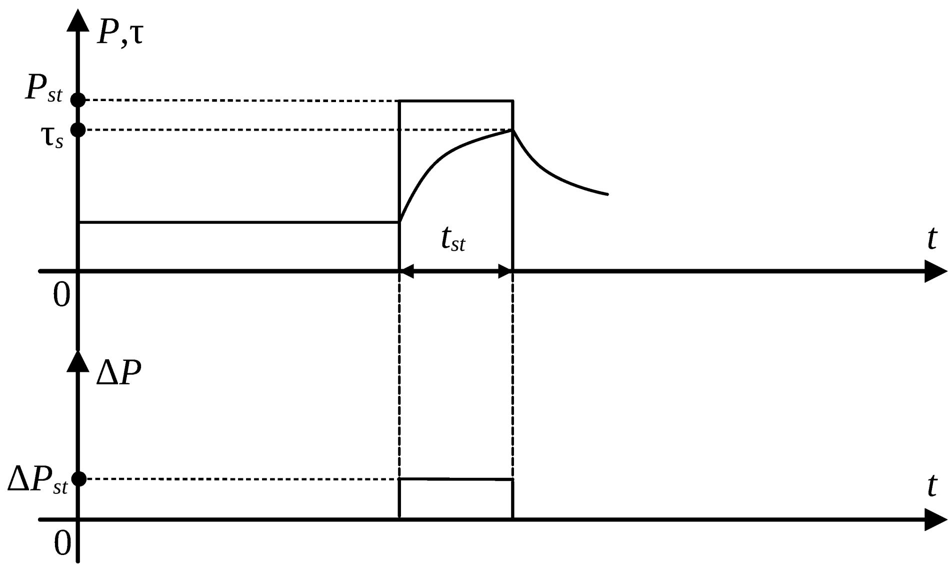

Figure 5.7 – S2 mode graph

Obviously, under such conditions, the engine must work with an overload. The ratio of losses in the engine, which ensure the same temperature increase, is called the thermal overload coefficient p_t:

$$p_t = \frac{\Delta P_{st}}{\Delta P_{lg}},$$

where ΔP_{st} – is the power losses at the motor for S2 duty;

ΔP_{lg} – is the power losses at the motor for S1 duty.

In the long-time mode, the temperature rise asymptotically approaches the permissible value of τ_v:

$$\tau_v = \frac{\Delta P_{lg}}{A}. \quad (5.6)$$

In the short-time mode τ_v is attained at time t_{st} which can be determined from a ratio:

$$\tau_v = \frac{\Delta P_{st}}{A} \cdot \left(1 - e^{-\frac{t_{st}}{T_h}}\right). \quad (5.7)$$

Having equated right members of (5.6) and (5.7) we'll obtain:

$$p_t = \frac{\Delta P_{st}}{\Delta P_{lg}} = \frac{1}{1 - e^{-\frac{t_{st}}{T_h}}}. \quad (5.8)$$

Dependence $p_t = f(t_{st} / T_h)$ is displayed on fig. 5.8.

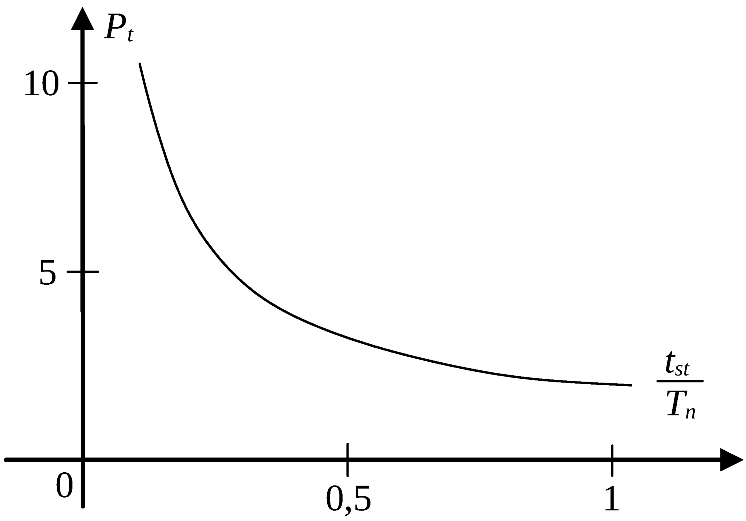

Figure 5.8 – Factor of thermal overloading vs. relative time in use

From the coefficient of thermal overload, it is possible to find the coefficient of mechanical overload p_m, which is equal to the ratio of P_{st} to the nominal power in mode S1, $P_{lg} = P_{nom}$.

To do this, in (5.8) the power losses ΔP_{st} and ΔP_{lg} need to be expressed in terms of constant and variable losses, which after identical transformations allows us to obtain [2,5]:

$$p_t = \frac{a + p_m^2}{a+1}, \qquad (5.9)$$

where $a = \Delta P_c / \Delta P_v$ – is a factor of a ratio of permanent losses to variable losses at rated load;

$p_m = P_{st} / P_{nom}$ – is a factor of mechanical overloading.

From here

$$p_m = \sqrt{(1+a)\, p_t - a}. \qquad (5.10)$$

Neglecting permanent losses (a = 0) we're able to write (5.10) as

$$p_m = \sqrt{p_t} = \sqrt{\frac{1}{1 - e^{-\frac{t_{st}}{T_h}}}}. \qquad (5.11)$$

The equation allows to define factor of a mechanical overloading at given t_{st} and T_h. Then the motor is chosen through the catalogue from a condition:

$$P_{nom} \geq \frac{P_{st}}{p_m}. \qquad (5.12)$$

If p_m calculation it is not possible, we may use the ratio:

$$p_m = \frac{M_{st}}{M_{nom}} \approx \lambda, \qquad (5.13)$$

where λ – motor overload capacity.

5.3 Calculation of motor power for S3 mode

For repeated short-term operation, a series of special machines are produced, in the catalog data of which the nominal power is indicated at standard values of DtC_{st}: 15%, 25%, 40%, 60% and 100%.

Moreover, the duration of the work cycle should not exceed ten minutes.

If the loading diagram, tachogram and duration of inclusion of DtC_1 are specified, and $DtC_1 = DtC_{st}$, then the engine is selected from the catalog under the condition:

$$P_{nom} \geq P_1,$$

where P_1 is defined under the load chart and tachogram.

In this case, if $DtC_1 \neq DtC_{st}$ and $P_1 \neq P_{nom}$ it is possible to confirm on method of average power losses that motor temperature average excess will not exceed admissible temperature if average power losses for a cycle at P_1 and DtC_1 will not exceed ones at P_{nom} and DtC_{st}, i.e. $\Delta P_1 \, DtC_{st} \leq \Delta P_{nom} \, DtCst$ [2-4].

From here a condition

$$\Delta P_{nom} \geq \Delta P_1 \frac{DtC_1}{DtC_{st}}. \tag{5.14}$$

Thus, that at operation with power P_1 and D_tC_1 average excess of temperature of the propeller did not exceed admissible, relationship (5.14) between powers losses should be respected.

Thus, in order for the average temperature rise of the engine not to exceed the permissible one when working with power P_1 and DtC_1, there must be a ratio between the power losses determined by (5.14).

The choice of engine in the considered case comes down to checking the preselected engine with the nearest P_{nom} and $DtCst$

The pre-selected motor can also be checked using the following ratios between currents, torques and powers.

We substitute in (5.14) power losses on permanent and variable, introduce their ratio a = $\Delta P_c / \Delta P_v$, transform and obtain:

$$I_{nom} \geq I_1 \sqrt{\frac{DtC_1}{a(DtC_{st} - DtC_1) + DtC_{st}}}. \tag{5.15}$$

For DCM IE operating with a constant magnetic flux, as well as for AD operating within the linearized part of the mechanical characteristic, it is possible to obtain similar ratios for moment and power:

$$M_{npm} \geq M_1 \sqrt{\frac{DtC_1}{a\left(DtC_{st} - DtC_1\right) + DtC_{st}}}; \quad (5.16)$$

$$P_{npm} \geq P_1 \sqrt{\frac{DtC_1}{a\left(DtC_{st} - DtC_1\right) + DtC_{st}}}. \quad (5.17)$$

If difference between DtC_1 and DtC_{st} is not considerable, then

$$I_{nom} \geq \sqrt{\frac{DtC_1}{DtC_{st}}}; \quad (5.18)$$

$$M_{nom} \geq \sqrt{\frac{DtC_1}{DtC_{st}}}; \quad (5.19)$$

$$P_{nom} \geq \sqrt{\frac{DtC_1}{DtC_{st}}}. \quad (5.20)$$

The last two expressions allow defining motor rated power.

5.5 Questions for self-examination

1. Write down the equation of heat balance and its solution.
2. What is the heat capacity and heat dissipation of the motor?
3. Name the features of the motor modes S1, S2, S3.
4. How to calculate motor power by the method of average losses?
5. What is an equivalent current?
6. How to calculate motor power by the method of equivalent torque?
7. How to calculate motor power by the method of equivalent power?
8. How to calculate the motor power for S2 mode?
9. How to calculate motor power for S3 mode?

6 REGULATION OF TORQUE AND SPEED IN ELECTRIC DRIVE

When controlling the ED, such mechanical quantities as moment and speed must change according to a given law or be maintained at a given level. In this section, only some general principles of construction and properties of electromechanical systems for regulating the specified quantities are considered.

Torque and speed regulation is possible in open (without external feedback) and closed (with external feedback) systems. Regulation can be parametric, carried out by forced influence on the parameters of the engine or the parameters of the power electric circuit in which it is included. Regulation can be amplitude – by forcing the source from which the engine is powered.

6.1 Regulation of the moment in the electric drive

Moment regulation takes place when it is necessary to precisely dose the effort (moment) on the working body, if there is a need to limit the moment in transient processes, when it is necessary to form a mechanical characteristic or its section of the form M = const. In a number of cases, if Φ = const, I_a and M are connected by proportional dependence. Then, instead of adjusting the torque, you can adjust the current. For this case, we will consider the rheostat regulation of the armature current (limiting the armature current) when starting the DCM IE. The three-stage engine start scheme is shown in fig. 6.1.

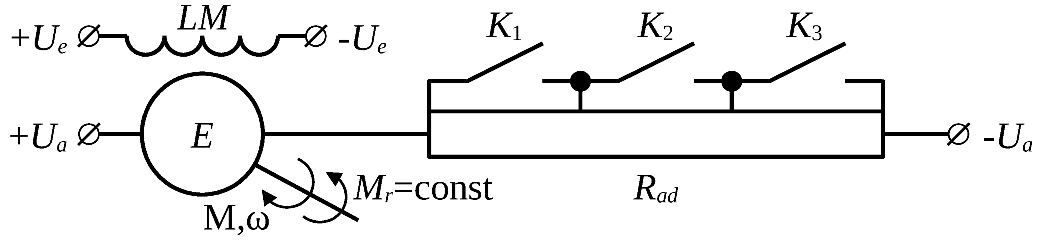

Figure 6.1 – Circuit design of shunt motor rheostatic starting

The R_{ad} value is calculated in such a way that the maximum value of the armature current, taking into account the overload capacity, is within

$$I_{max}=I_1=(2\div 2,5)I_{a\,nom}.$$

Step R_{ad} decreasing during motor acceleration is made at a switching current

$$I_{sw}=I_2=(1,1\div 1,2)I_r,$$

where $I_r=\frac{M_r}{k\Phi}$.

If $\Phi = \Phi_{nom}$ = const it is possible to assume, that in such system limitation (regulating) of a current (torque) is provided at starting at the set level. Electromechanical characteristics for the given circuit design are presented on fig. 6.2.

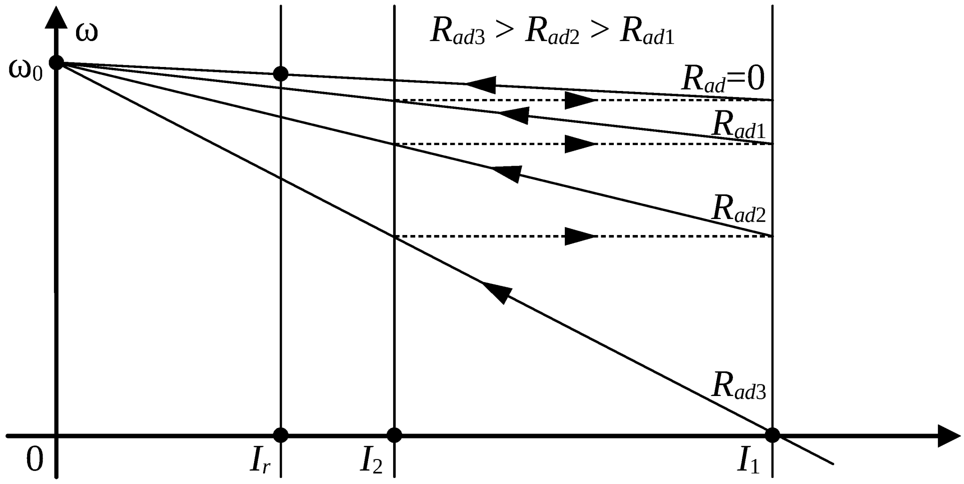

Figure 6.2 – Rheostatic starting electromechanical characteristics

Torque regulation is possible in closed systems using static converters, regulators (proportional, proportional-integral, and others), torque or current sensors.

In fig. 6.3 shows the functional diagram of the closed-loop torque control system in the «converter – motor» system.

In this diagram, *SC* – is a static converter, *TR* – is a torque regulator (proportional), *TS* – is a torque sensor (its output signal is proportional to the motor torque), u_{tt} – is the input voltage of the torque task, u_{fb} – is the feedback voltage, u_{cc} – is the converter control voltage.

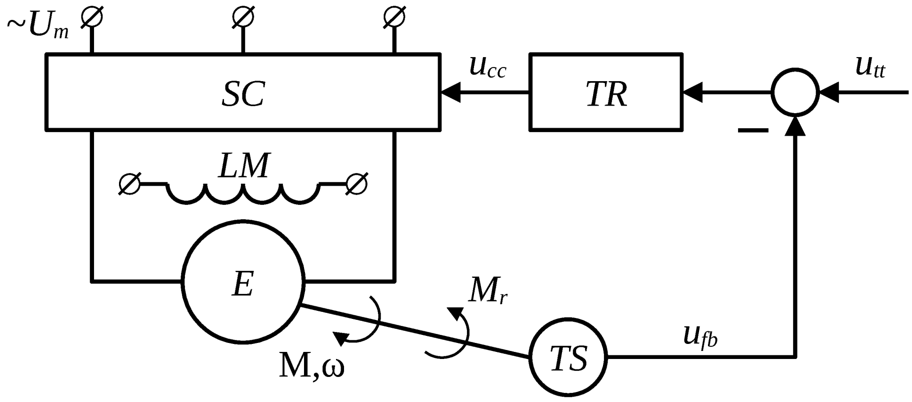

Figure 6.3 – Functional diagram of torque regulation in the system «converter-motor»

We consider Φ = $Φ_{nom}$ = const, the mechanical characteristics of the system are linear, then

$$\omega=\omega_0-M/\beta, \qquad (6.1)$$

where $\beta=(k\Phi)^2/R_{a\Sigma}$ – is the speed-torque characteristic rigidity modulus of an open-circuit system.

From (6.1) we will gain:

$$M=\beta(\omega_0-\omega). \qquad (6.2)$$

Let's mark out: k_{cg} – is converter gain; k_{tr} – is torque regulator transfer ratio; k_{nt} – is transfer ratio for torque negative feedback. Taking into account the accepted labels it is possible to write:

$$u_{cc}=k_{tr}(u_{tt}-u_{fb})=k_{tr}(u_{tt}-k_{nt}M), \qquad (6.3)$$

$$\omega_0=\frac{U_a}{k\Phi}=\frac{k_{cg}U_{ct}}{k\Phi} \qquad (6.4)$$

Let's mark out $k'_{cg}=\frac{k_{cg}}{k\Phi}$ and then we will gain:

$$\omega_0=k'_{cg}k_{tr}(u_{tt}-k_{nt}M). \qquad (6.5)$$

Having substituted (6.5) in (6.2), we will record the equation of a speed-torque characteristic of a looped system on the torque:

$$M=\frac{k'_{cg}k_{tr}\beta}{1+\beta k'_{cg}k_{tr}k_{nt}}u_{tt}-\frac{\beta\omega}{1+\beta k'_{cg}k_{tr}k_{nt}}. \qquad (6.6)$$

If the left and right parts of (6.6) are differentiated by ω, then one can find an analytical expression for the stiffness of the mechanical characteristic of the system with negative moment reverse connection

$$\beta_{nt} = \frac{\beta}{1+\beta k'_{cg} k_{tr} k_{nt}}. \tag{6.7}$$

It is obvious that when $k'_{cg}k_{tr}k_{nt} \to \infty$, $\beta_{nt} \to 0$ it is possible to obtain an «absolutely soft» mechanical characteristic of the form M = const. The family of mechanical characteristics for different values of u_{tt} and the final value of the product $k'_{cg}k_{tr}k_{nt}$, limited from above by the natural characteristic, is shown in fig. 6.4.

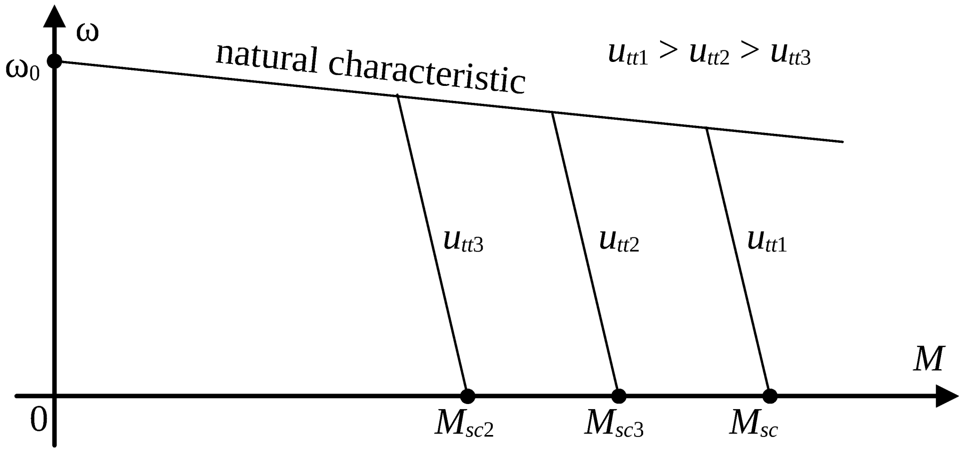

Figure 6.4 – Set of speed-torque characteristics of system with a negative reverse connection on the torque

To increase the accuracy of torque regulation by compensating the internal negative speed feedback, external positive speed feedback is additionally introduced into the system

$$M = \beta\left[k'_{cg} k_{tr}\left(U_{tt} - k_{nt} M + k_{ts}\,\omega\right) - \omega\right], \tag{6.8}$$

where k_{ts} – is a transfer ratio of speed external positive feedback.

If system parameters are chosen so, that $k'_{cg}k_{tr}k_{ts} = 1$ the equation of a speed-torque characteristic of system will be recorded as:

$$M = \frac{k'_{cg} k_{tr} \beta}{1+\beta k'_{cg} k_{tr} k_{nt}} U_{tt}. \tag{6.9}$$

The equation (6.9) represents a characteristic curve M = const for a given value U_{tt}. In such a system smooth torque regulating is provided by U_{tt} modification.

Performances M = const can be gained also in the system «current source-motor». It is necessary to power the armature circuit for this purpose from the current source (CS) (fig. 6.5).

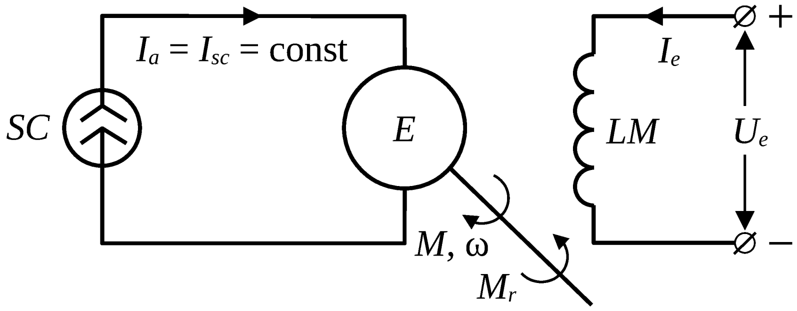

Figure 6.5 – Circuit design of system «current source-shunt motor»

In this scheme, $M = k\Phi I_a$ = const for a fixed value of the magnetic flux. An inductive-capacitive converter is used as a current source, which uses the phenomenon of voltage resonance in an inductive-capacitive circuit (fig. 6.6).

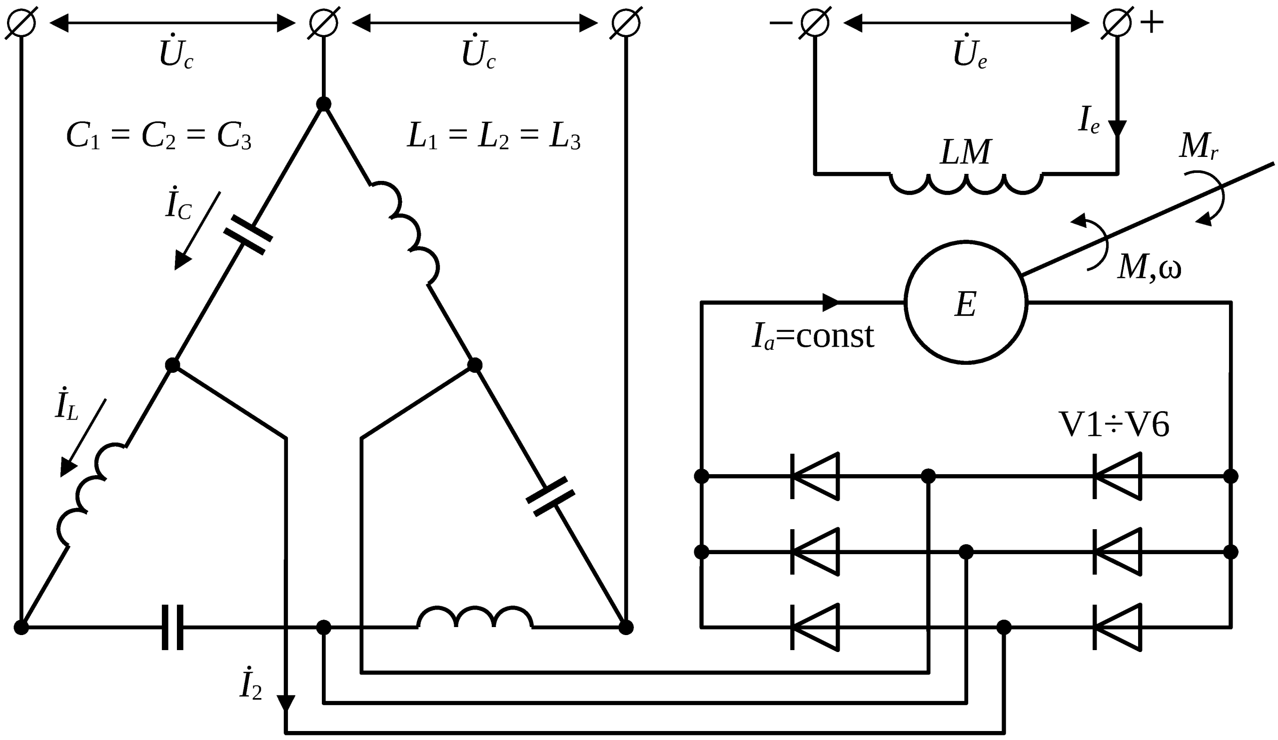

Figure 6.6 – Scheme of the «current source – DCM IE» system with an inductive-capacitive converter

When voltage resonance, the current does not depend on a load resistance since $R << X_L = X_C$ and it is possible to record for these conditions:

$$\dot{I}_2 = \dot{I}_C - \dot{I}_L = -\frac{\dot{U}_C}{jX_C} - \frac{\dot{U}_L}{jX_L} = |X_L = X_C = X| = -\frac{\dot{U}_C}{jX} - \frac{\dot{U}_L}{jX} = -\frac{1}{jX}\left(\dot{U}_C + \dot{U}_L\right) = j\frac{\dot{U}_{cn}}{X}.$$

Because U_L = const, I_2 = const and $I_a = k_{cg}I_2$ = const, the controlling influence is formed along the excitation winding circuit, and these conditions allow obtaining a family of mechanical characteristics of the form M = const for different values of the magnetic flux. In such a system, with ideal reactive elements, the armature current does not depend on the back emf and resistance of the load chain.

For AM, in order to obtain a characteristic of the type M = const, it is necessary to stabilize the effective value of the active component of the rotor current and to ensure the removal or dissipation of the rotor slip energy.

Because the current and EMF of the AM rotor have a variable frequency during regulation

$$f_2 = f_1 s,$$

where f_1 is stator current frequency, f_2 is rotor current frequency, the possibility of stabilizing the rotor current by direct connection to the inductive-capacitive converter is excluded due to violation of the resonance tuning conditions.

Fig. 6.7 shows the current stabilization scheme of AM with an additional rectifier in the rotor circuit.

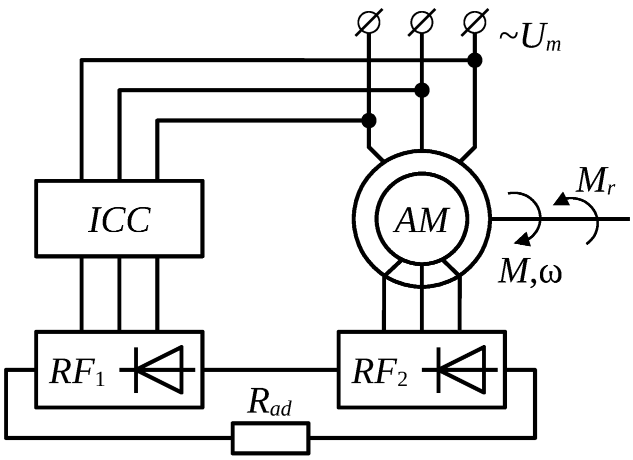

Figure 6.7 – Function chart of system «current source – AM»

In this scheme, the *ICC* is an inductive-capacitive converter, RF_1, RF_2 are the first and second unregulated rectifiers, R_{ad} is an additional resistance that provides dissipation of sliding energy. The scheme makes it possible to obtain the mechanical characteristics shown in fig. 6.8.

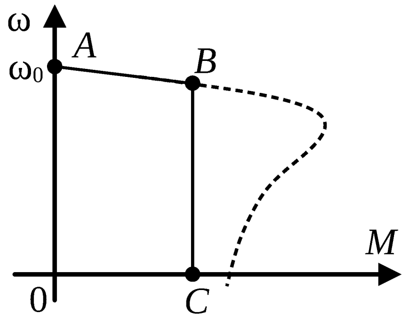

Figure 6.8 – Speed-torque characteristic of «current source – AM» system

In the *AB* section of the characteristic, the rotor current is less than the DC output current. All valves RF_2 are open, which corresponds to a short circuit of the rotor AM. At the same time, the power consumed from the *ICC* network is completely dissipated on R_{ad}. As the moment of load on the shaft increases, the rotor current increases, at point *B* the *ICC* and rotor currents are equal, the switching processes of the valves in the rectifier RF_2 begin. The mechanical characteristic has a segment *BC* of the form M = const. The sliding energy is dissipated on R_{ad}. The energy characteristics of the system can be improved if the sliding energy is returned to the power supply network. For this, an inverter (INV) is introduced instead of R_{ad}.

Since the electromagnetic moment AM $M = k\Phi I_2\cos\varphi$ at I_2 = const can be adjusted by changing the magnetic flux, taking into account that $U_1 \approx E_1 = 4{,}44 k_w f w \Phi$, a stator voltage regulator (VR) is introduced into the system, as shown in fig. 6.9.

Such a system makes it possible to obtain a family of mechanical characteristics shown in fig. 6.10.

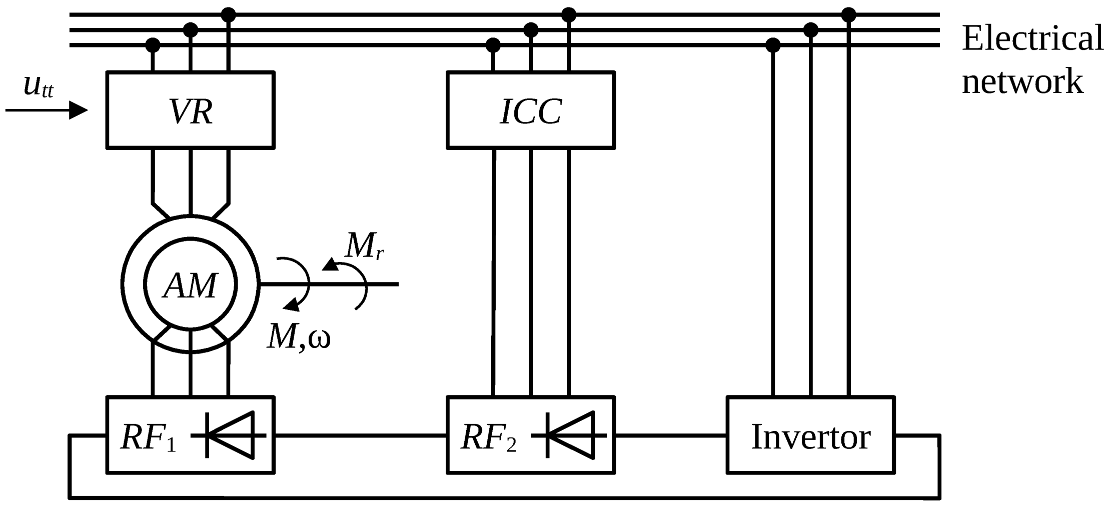

Figure 6.9 – Functional scheme of the «current source – AM» system with a slip energy inverter

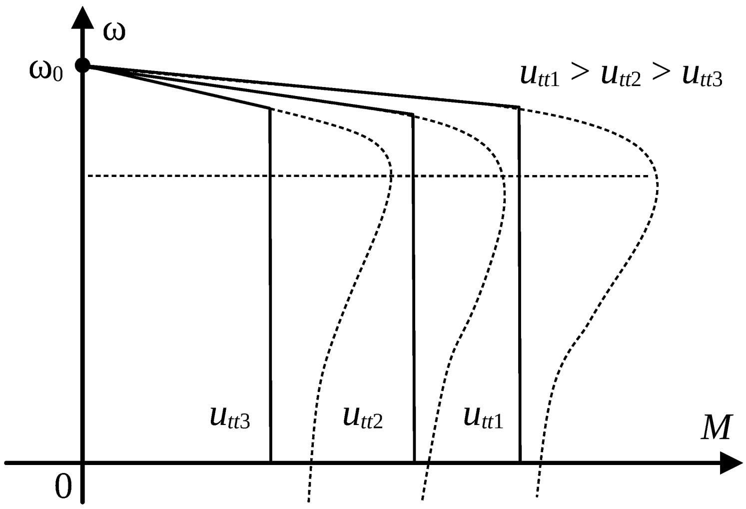

Figure 6.10 – Mechanical characteristics of the AM current source system with a slip energy inverter

6.2 Electric drive speed regulation

Regulation of the speed of the working body in accordance with the requirements of the technological process can be carried out mechanically, by means of a smooth or stepped change of the gear ratio in the mechanical transmission. However, in this case, the mechanical part becomes more complicated and the process of automatic speed regulation becomes significantly more difficult. These disadvantages are absent if the speed of the electric motor is adjusted using the parametric method or the amplitude adjustment method. Regulation of the speed of the electric motor occupies a special place because the speed affects in a number of cases the productivity and quality of the technological process.

It is quite simple to regulate the speed of DC motors by introducing an additional resistance R_{ad} in the armature circuit. For AM with a phase rotor, additional resistance R_{ad} is introduced into the rotor circuit.

If the mechanical characteristics of the electric motor are linear or linearized, you can write

$$\omega = \omega_0 - \frac{M}{\beta}, \tag{6.10}$$

where β – is the speed-torque characteristic rigidity module.

For DC motor $\beta = \frac{(k\Phi)^2}{R_{a\Sigma}}$. It is possible for AM to linearize characteristics on an operating section, as shown on fig. 6.11.

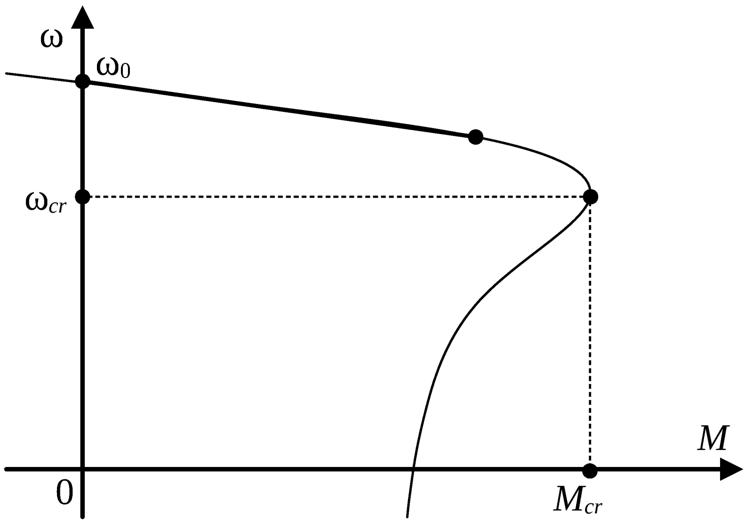

Figure 6.11 – AM speed-torque characteristic linearized on operating section

Rigidity modulus for linearization is definable as

$$\beta = \frac{\Delta M}{\Delta \omega} = \frac{M_{cr}}{\omega_0 - \omega_{cr}} = \frac{M_{cr}}{s_{cr}\,\omega_0},$$

where $s_{xr} = \pm \frac{R'_{2\Sigma}}{\sqrt{R_1^2 + X_{sc}^2}}$.

Taking into account a ratio for the AM rigidity modulus and from (6.10) follows, that motor speed is decreased when R_{ad} is included. Thus rheostatic speed control provides a control range

$$D=\frac{\omega_{max}}{\omega_{min}}\leq 2. \qquad (6.11)$$

Let's define ED power losses ΔP at rheostatic speed control:

$$\Delta P=P_1-P_2,$$

where $P_1 = U_a I_a$ – is an electrical power consumed from a network;

$P_2 = M\omega$ – is a mechanical power.

$$\Delta P=U_a I_a-M\omega=k\Phi\omega_0 I_a-k\Phi I_a\omega=k\Phi I_a\omega_0\left(\frac{\omega_0-\omega}{\omega_0}\right)=P_1\left(\frac{\omega_0-\omega}{\omega_0}\right).$$

When the speed is reduced by two times compared to the idle speed, the losses will be 50%

$$\Delta P=P_1\left(\frac{\omega_0-0{,}5\omega_0}{\omega_0}\right)=0{,}5P_1.$$

In addition to the low energy efficiency of rheostat regulation, it is necessary to note the dependence of the speed regulation range on the moment of resistance. Obviously, the smaller the M_r, the smaller the range of regulation, and there is no speed regulation at idle speed with any changes in R_{ad}. Some expansion of the range is provided by speed regulation by shunting the armature winding with resistance R_{sh} (fig. 6.12).

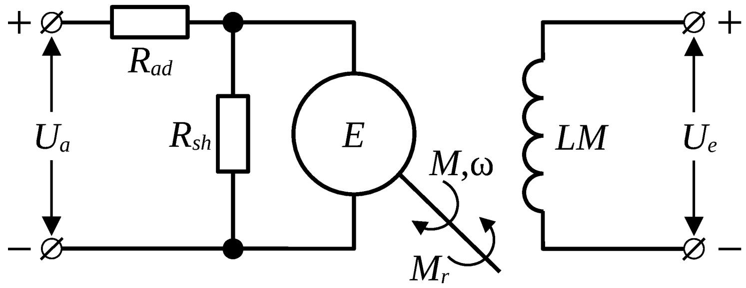

Figure 6.12 – Shunt motor circuit design with armature winding shunting

Let's assume, that $\Phi = \Phi_{nom}$ = const, M_r = const. We're going to move from the turning on circuit design to an equivalent circuit which is displayed on fig. 6.13.

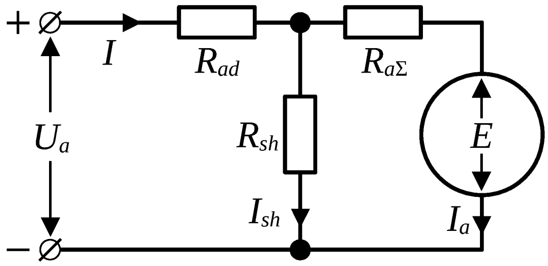

Figure 6.13 – Shunt motor equivalent circuit with armature winding shunting

On the basis of Kirchhoff's laws we can write the equations:

$$U_a = R_{a\Sigma} I_a + E + R_{ad} I;$$
$$R_{sh} I_{sh} = R_{a\Sigma} I_a + E;$$
$$I = I_{sh} + I_a.$$

Having excluded from equations I_{sh}, I, and using substitution $E = k\Phi\omega$ and $M = k\,\Phi\,I_a$, we will gain the speed-torque characteristic equation:

$$\omega = A\omega_0 - \frac{M(R_{a\Sigma} + A\,R_{ad})}{(k\Phi)^2}, \qquad (6.14)$$

where $A = R_{sh} / (R_{sh} + R_{ad}) < 1$.

Differentiating (6.14) on ω we will gain expression for rigidity of a speed-torque characteristic

$$\beta_{sh} = \frac{(k\Phi)^2}{R_{a\Sigma} + A\,R_{sh}}.$$

At $R_{sh} \to 0$ and $A \to 0$, $\beta_{sh} \to -(k\Phi)^2 / R_{a\Sigma}$ to the rigidity of the natural shunt motor speed-torque characteristic. Thus, armature winding shunting decreases idle speed and increases rigidity of artificial rheostatic characteristics (fig. 6.14).

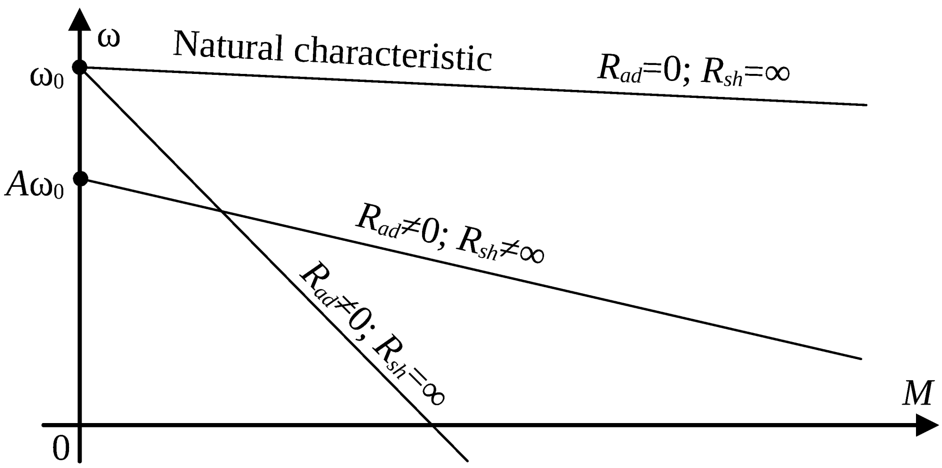

Figure 6.14 – Shunt motor natural and artificial characteristics

Let's observe a case, when R_{ad} = var, R_{sh} = const.

At $R_{ad} = 0$, $A = 1$ the equation of a speed-torque characteristic looks like

$$\omega = \omega_0 - \frac{M R_{a\Sigma}}{(k\Phi)^2}. \tag{6.15}$$

Expression (6.15) represents the equation of natural shunt motor speed-torque characteristic.

At $R_{ad} = \infty$, $A = 0$ the equation of a speed-torque characteristic looks like:

$$\omega = -\frac{M(R_{a\Sigma} + R_{sh})}{(k\Phi)^2}. \tag{6.16}$$

Expression (6.16) represents the equation of shunt motor speed-torque characteristic at a dynamic braking mode. The natural speed-torque characteristic and dynamic braking mode characteristic, and also other characteristics for intermediate R_{ad} values are intersected in a point *a* (fig. 6.15).

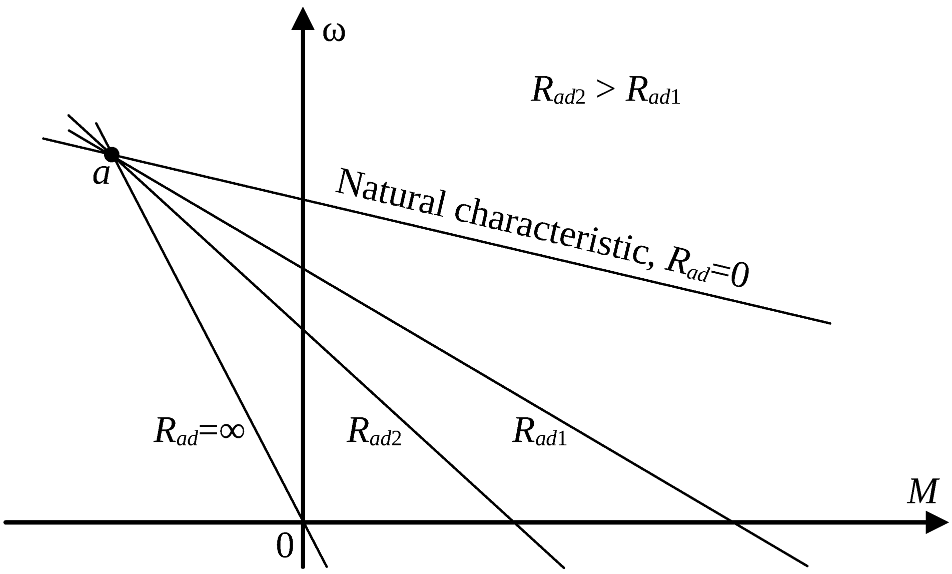

Figure 6.15 – Natural and artificial performances at R_{ad} = var

The point *a* matches to such mode when the current does not flow past through R_{ad}. It is possible when the motor EMF is completely equilibrated by voltage U_a and an interior armature voltage drop

$$E = R_{a\Sigma} I_a + U_a.$$

Let's observe a case, when R_{sh} = var, R_{ad} = const.

At $R_{sh} = 0$, $A = 0$ the equation of a speed-torque characteristic looks like:

$$\omega = -M \frac{R_{a\Sigma}}{(k\Phi)^2}. \tag{6.17}$$

Expression (6.17) represents the equation of shunt motor speed-torque characteristic at dynamic braking mode.

At $R_{sh} = \infty$, $A = 1$, the equation of a speed-torque characteristic looks like:

$$\omega = \omega_0 - \frac{M(R_{a\Sigma} + R_{ad})}{(k\Phi)^2}. \tag{6.18}$$

Expression (6.18) represents the equation of artificial shunt motor speed-torque characteristic at introduction R_{ad} in armature circuit. Artificial speed-torque characteristics for different values R_{sh} and dynamic braking mode characteristics intersect in a point *b* (fig. 6.16).

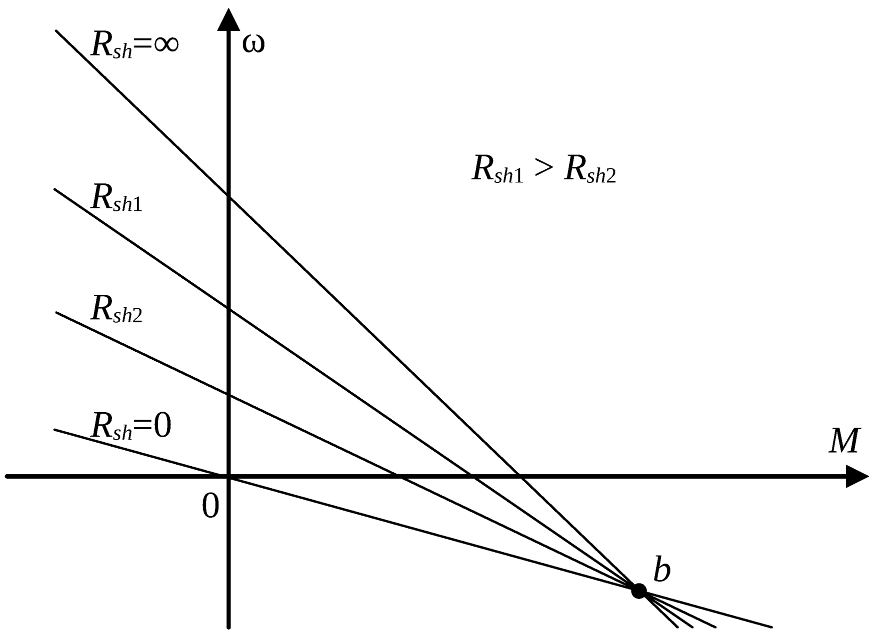

Figure 6.16 – Natural and artificial characteristics at R_{sh} = var

In a point *B* R_{sh} does not work upon an armature current. It is possible at a negative speed when $E = -I_a R_a$. In this case the current does not pass through R_{sh} at any one's value.

Armature winding shunting allows the series motor to gain a finite value of idle speed, since at $I_a = 0$, $I_{ex} = I_{sh}$ (fig. 6.17).

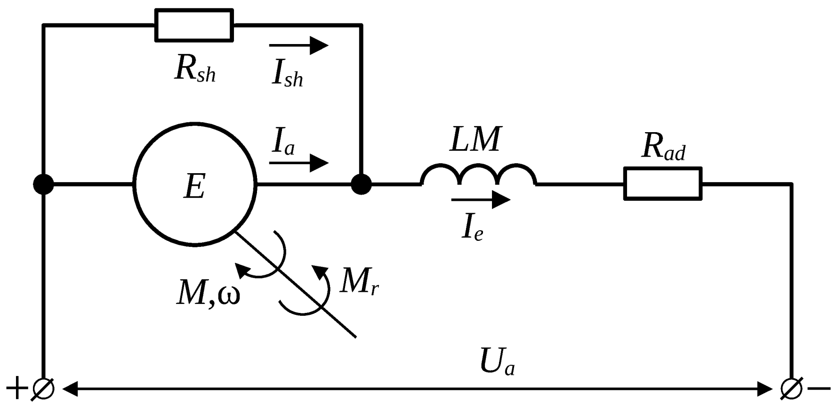

Figure 6.17 – Series motor circuit design with armature winding shunting

If the engine speed is greater than the ideal idling speed during shunting, the machine switches to the regenerative braking mode, when the mechanical energy is converted into electrical energy, which is given to the power source with the exception of heat losses on R_{sh}, R_{ad}, $R_{a\Sigma}$. Shunting of the armature winding refers to the parametric method of speed regulation. This method is used in low-power EDs and provides an adjustment range of 2.5 ÷ 3.

Rheostat speed regulation and regulation by shunting the armature winding allows you to change the speed down from the main one. By the main we mean the nominal value. Changing the magnetic flux of the motor allows you to adjust the speed up from the main one. This method is easy to implement and ensures sufficient smoothness, because the regulation is carried out by the low-current circuit of the excitation winding (fig. 6.18).

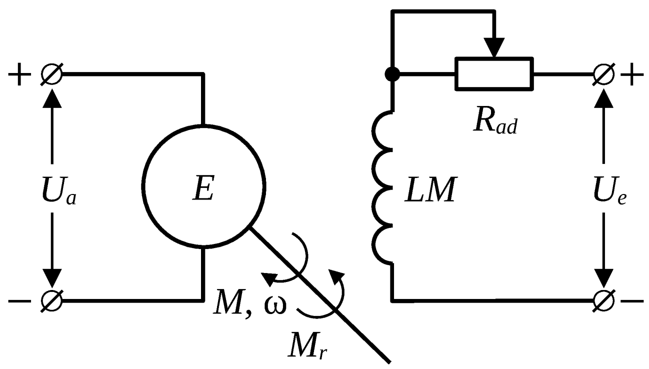

Figure 6.18 – Scheme of inclusion of DCM IE when adjusting the speed by changing the magnetic flux

If the operating point is on the knee of the magnetization curve, then it is advisable to change the magnetic flux in the direction of decrease. The limiting factor in this case will be the design speed (above the design speed, mechanical destruction occurs) and the switching conditions, which deteriorate. For engines of general industrial use, a field weakening of 2 ÷ 6 times is allowed, but this is possible at a nominal speed of 450 rpm and less. The reduction of the magnetic flux is carried out by reducing the current in the excitation winding (fig. 6.18), which leads to an increase in speed in accordance with the mechanical characteristic equation:

$$\omega = \frac{U_a}{k\Phi} - \frac{MR_{a\Sigma}}{(k\Phi)^2}.$$

Besides, magnetic flux decrease reduces admissible torque, however admissible power remains invariable. Let’s explain that feature. For this purpose we will use electromechanical characteristics displayed on fig. 6.19.

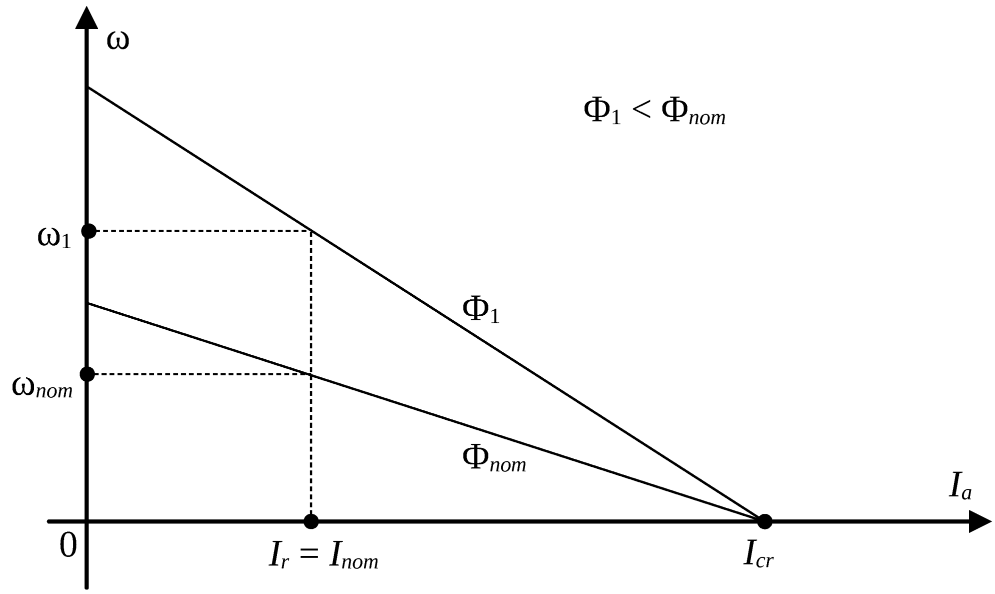

Figure 6.19 – Natural and artificial characteristics at magnetic flux weakening

Let's assume, that $M_r = M_{nom}$ = const. At such loading the motor reaches speed ω_1 at magnetic flux weakening and its EMF

$$E_1 = k\Phi_1\omega_1 = U_{nom} - I_{nom}R_{a\Sigma}. \qquad (6.19)$$

At a nominal magnetic flux its velocity ω_{nom} and and EMF

$$E_{nom} = k\Phi_{nom}\omega_{nom} = U_{nom} - I_{nom}R_{a\Sigma}. \qquad (6.20)$$

As right members (6.19) and (6.20) are equal, having equated the left parts we will gain:

$$\Phi_1 = \Phi_{nom} \frac{\omega_{nom}}{\omega_1}.$$

The admissible moment at magnetic flux weakening is defined as:

$$M_{adm} = k\,\Phi_{nom} \frac{\omega_{nom}}{\omega_1} I_{nom}.$$

The admissible power is equated to the nominal:

$$P_{adm} = M_{adm}\omega_1 = M_{adm}\omega_{nom} = P_{nom}. \qquad (6.21)$$

From (6.21) follows, that at weakening of a magnetic flux the motor can achieve nominal power, ensuring a speed control range 1,5 ÷ 2,5.

The increase of the control range can be achieved in the «converter-motor» system with a negative reverse connection on speed. The system function chart is displayed on fig. 6.20.

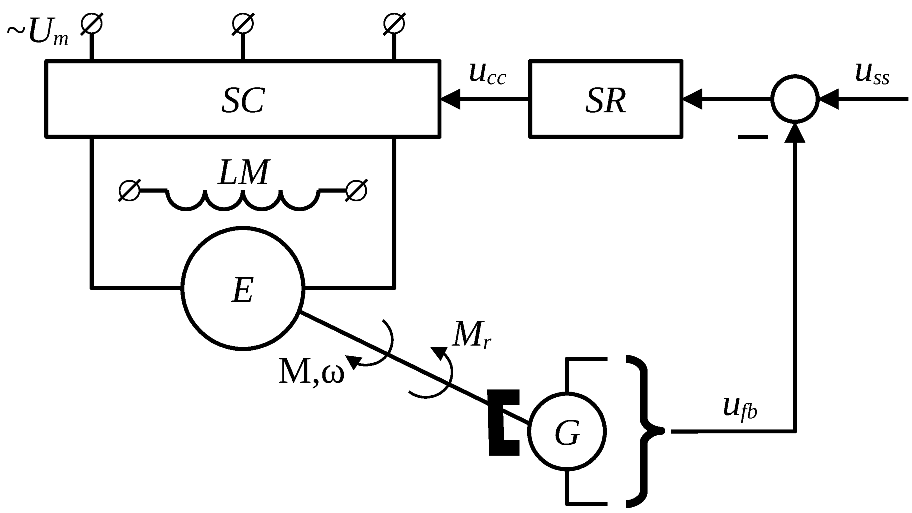

Figure 6.20 – Function chart of speed control in «converter-motor» system

On this circuit design *SC* – is the static converter ensures smooth regulating U_a; *SR* – is the speed regulator (proportional); *G* – is speed sensor producing a signal of negative feedback u_{fb}; u_{ss} – is the speed set-point voltage; u_{cc} – is converter control voltage.

Let's assume $\Phi = \Phi_{nom} = \text{const}$, system speed-torque characteristics are linear and then it is possible to record:

$$M = \beta(\omega_0 - \omega), \quad (6.22)$$

where β – is an open-loop system speed-torque characteristic rigidity module.

Let's mark out through:

k_{cg} – is converter gain;

k_{sr} – is speed regulator transfer ratio;

k_{fb} – is transfer ratio of speed negative feedback.

Taking into account the accepted labels it is possible to write:

$$U_{cc} = k_{sr}(u_{ss} - u_{fb}) = k_{sr}(u_{ss} - k_{fb}\omega); \quad (6.23)$$

$$\omega_0 = \frac{U_a}{k\Phi} = \frac{k_{cg}u_{cc}}{k\Phi}.$$

Having marked out $k'_{cg} = \frac{k_{cg}}{k\Phi}$ we'll gain:

$$\omega_0 = k'_{cg}k_{sr}(u_{ss} - k_{fb}\omega). \quad (6.24)$$

Having substituted (6.24) to (6.22), we will record the equation of a speed-torque characteristic of system with speed negative feedback

$$\omega = \frac{k'_{cg}k_{sr}}{1 + k'_{cg}k_{sr}k_{fb}}U_{ss} - \frac{M}{\beta(1 + k'_{cg}k_{sr}k_{fb})}. \quad (6.25)$$

If (6.25) left and a right member to differentiate on ω it is possible to discover an analytical form for system speed-torque characteristic rigidity with speed negative feedback

$$\beta_{fb} = -\beta(1 + k'_{cg}k_{sr}k_{fb}). \quad (6.26)$$

It is obvious, that at $k'_{cg}k_{sr}k_{fb} \to \infty$, $\beta_{fb} \to \infty$, i.e. it is possible to obtain an absolutely rigid characteristic of the form ω = const.

The set of speed-torque characteristics for various U_{ss} and final product $k'_{cg}k_{sr}k_{fb}$ is displayed on fig. 6.21.

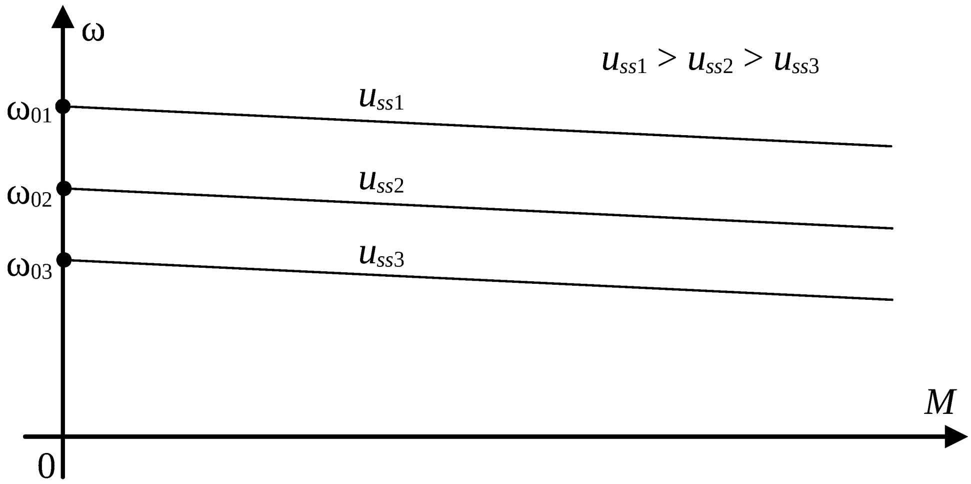

Figure 6.21 – Set of speed-torque characteristics of «converter–motor» system with a speed negative reverse connection

Combined control is used to increase the accuracy of speed control without significantly complicating the system. In this case, the system is supplemented by positive feedback on the moment with the transmission ratio k_{pm}:

$$M=\beta\left[k'_{cg}k_{sr}\left(u_{ss}-k_{fb}\omega+k_{pm}M\right)-\omega\right]. \tag{6.27}$$

If $\beta k'_{cg}k_{sr}k_{pm}=1$ the equation of system speed-torque characteristic of we will record as:

$$\omega=\frac{k'_{cg}k_{sr}}{1+k'_{cg}k_{sr}k_{fb}}u_{ss}. \tag{6.28}$$

The equation (6.28) represents the curve characteristic ω = const for given value U_{ss}. In such a system smooth speed control by modification U_{fbm} is ensured. Thus a velocity control range is 10 times more, than at rheostatic regulating or regulating by magnetic flux weakening.

In the simplest case, speed control of an asynchronous squirrel-cage motor is possible by switching the number of pole pairs

$$\omega=\frac{2\pi f}{p}(1-s),$$

where p – the number of poles which can vary by stator winding sections switching.

At such speed control use special multispeed motors.

One of the most widespread circuit designs of switching is transition from «star» to «double star» (fig. 6.22).

For «star» circuit design it is possible to record

$$\omega_{0Y}=\frac{2\pi f}{2p};\ \omega_{0el\,Y}=\pi f. \tag{6.29}$$

Equivalent reactive phase resistance taking into account (6.29):

$$X_{eq\,Y}=2\,\omega_{0el}L=2\pi fL, \tag{6.30}$$

where L – is stator winding section inductance.

For «double star» circuit design it is possible to record:

$$\omega_{0\,YY}=\frac{2\pi f}{p};\ \omega_{0el\,YY}=2\pi f. \tag{6.31}$$

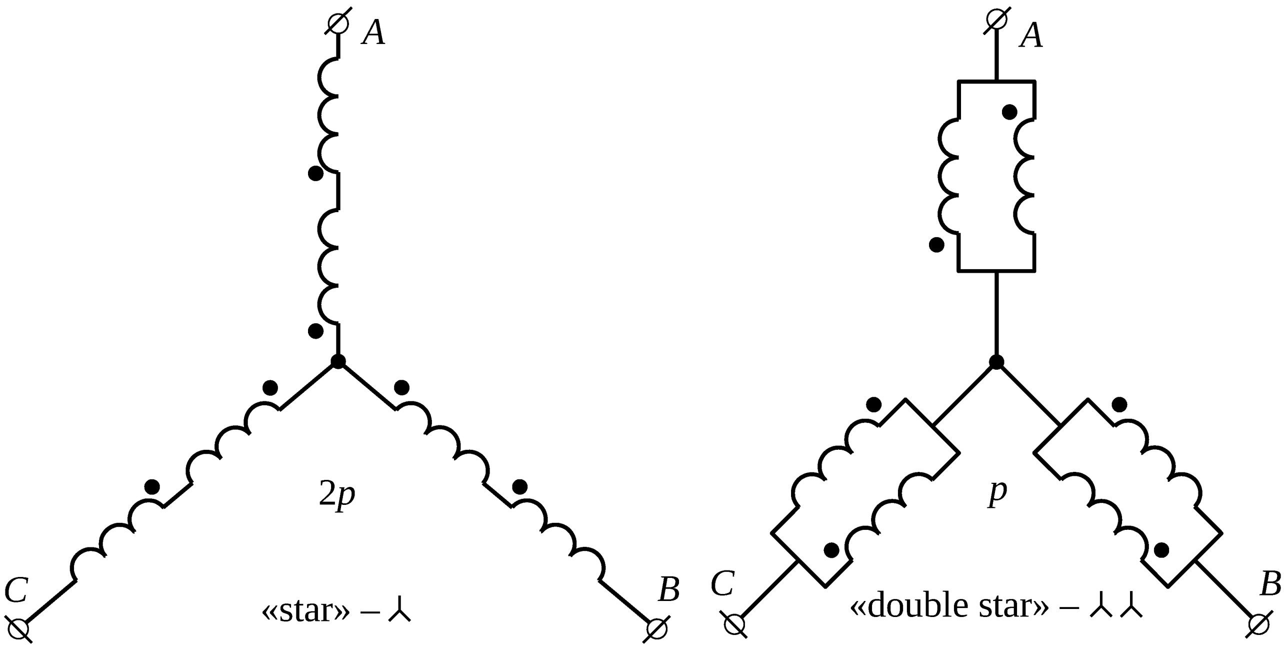

Fig. 6.22 Circuit design of AM stator winding switching from «star» to «double star»

Equivalent reactive phase resistance taking into account (6.31):

$$X_{eq\,YY}=0{,}5\,\omega_{0el}L=\pi fL. \tag{6.32}$$

From (6.30) and (6.32) follows, that such switching allows to double admissible power if to consider $\varphi_Y \approx \varphi_{YY}$.

$$P_Y=3U_{1nom}I_{1nom}\cos\varphi_Y;$$
$$P_{YY}=3U_{1nom}2I_{1nom}\cos\varphi_{YY}.$$

If we assume that the speed will increase twice after switching, thus speed-torque characteristics look like displayed on fig. 6.23.

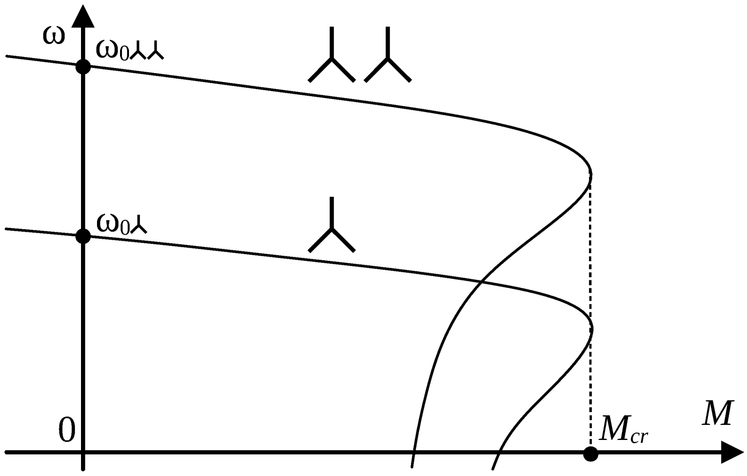

Figure 6.23 – AM speed-torque characteristics at stator winding sections switching from «star» to «double star»

Speed control is carried on at constant torque, as

$$M_{adm\,YY} = \frac{2P_{adm\,Y}}{2\omega_Y} = = M_{adm\,Y}.$$

The circuit design of transition from «triangle» to «double star» has gained no smaller extending (fig. 6.24).

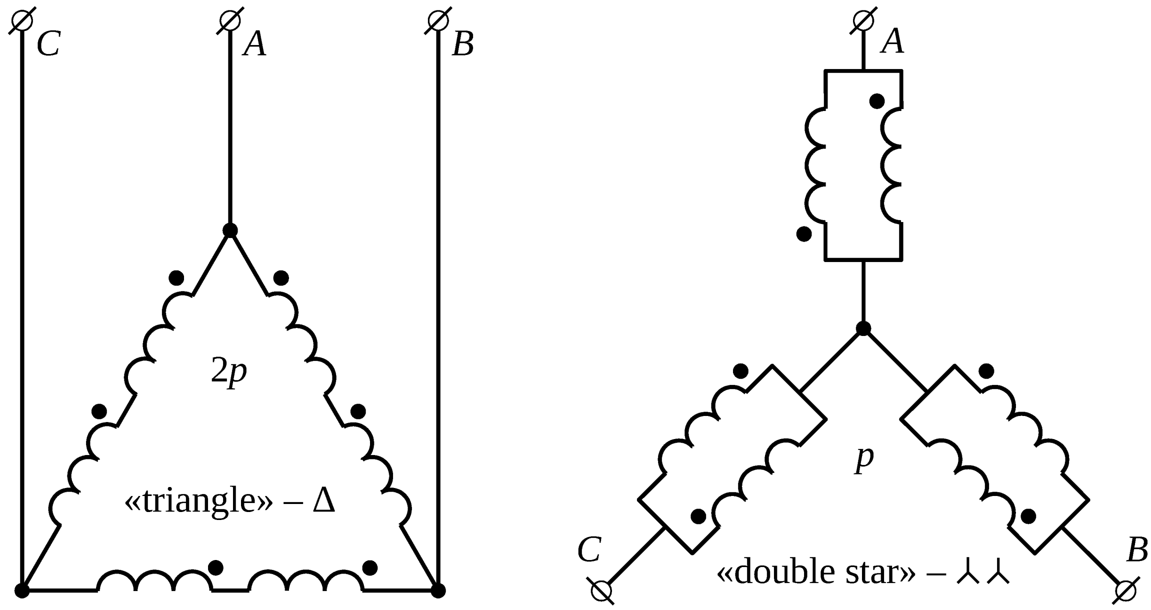

Figure 6.24 – Circuit design of AM stator winding switching from «triangle» to «double star»

At such switching the admissible power is defined as

$$P_{adm\,\Delta} = 3\sqrt{3}\,U_{1\,nom} I_{1\,nom} \cos\varphi_{\Delta};$$

$$P_{adm\,YY} = 3U_{1\,nom} I_{1\,nom} \cos\varphi_{YY};$$

$$\frac{P_{adm\,\Delta}}{P_{adm\,YY}} = \frac{\sqrt{3}}{2}\frac{\cos\varphi_{\Delta}}{\cos\varphi_{YY}}.$$

As $\cos\varphi_{\Delta} > \cos\varphi_{YY}$, and $\sqrt{3} < 2$ it is possible to consider:

$$\frac{P_{adm\,\Delta}}{P_{adm\,YY}} \approx 1.$$

Speed-torque characteristics look like displayed on fig. 6.25.

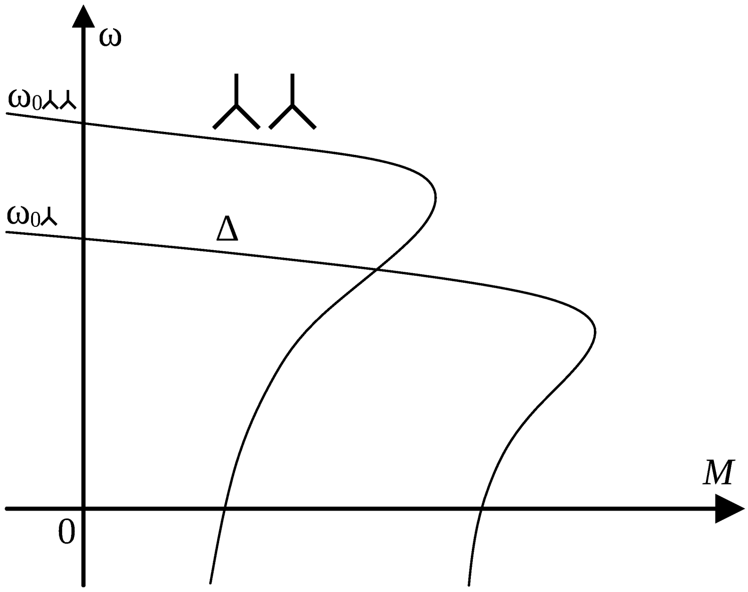

Figure 6.25 – AM speed-torque characteristics at stator winding sections switching from «triangle» to «double star»

The observed circuit designs of poles number switching are simple in implementation, do not demand additional converters and other regulating devices, ensure sufficient energy efficiency, but all have one disadvantage – discrete speed control.

This deficiency is deprived of «stator voltage regulator – asynchronous motor» with a feedback on a velocity which function chart is displayed on fig. 6.26.

On this circuit design *VR* – is the stator voltage regulator; *SR* – is the speed regulator (proportional); *G* – is the speed sensor producing a signal of negative feedback u_{fb}; u_{ss} – speed set-point voltage; u_{cc} – converter control voltage.

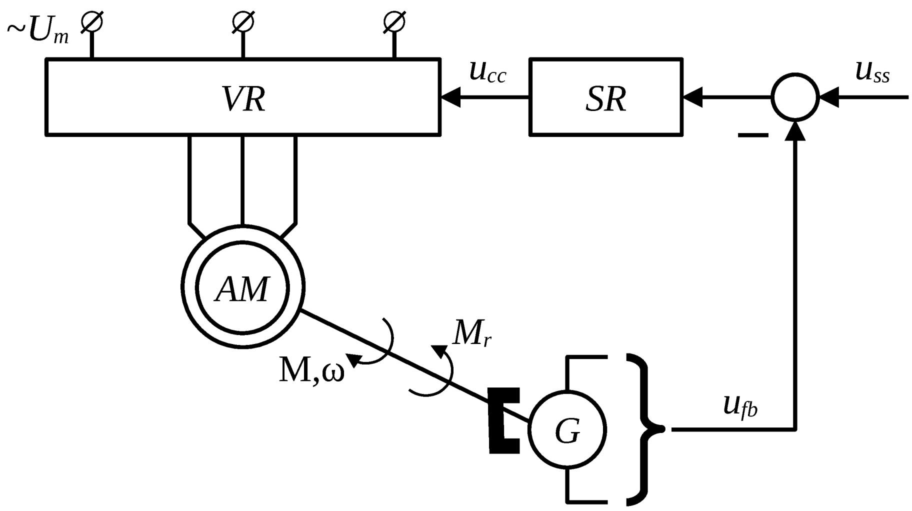

Figure 6.26 – Function chart of speed control in system
«stator voltage regulator – asynchronous motor»

VR exit voltage has no sinusoidal form and depends on thyristors regulating angle α, and also an actively-inductive load angle φ_{ld}. However, AM electromagnetic torque is defined by a first harmonic of voltage U_1 and it is possible to neglect by magnitude of the higher harmonics.

VR regulating characteristics are nonlinear and look like, displayed on fig. 6.27

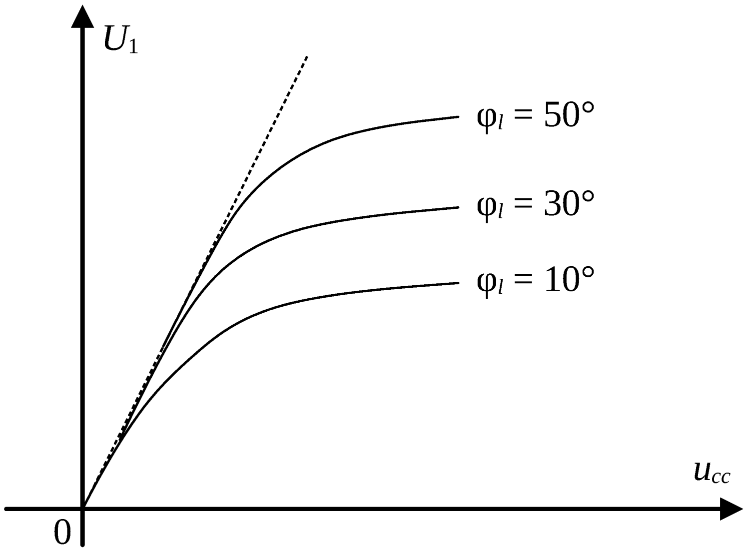

Figure 6.27 – Regulating characteristics of stator voltage regulator

If angle $\varphi_{ld} = X_{ld} / R_{ld}$ is in limits φ_{ld} = 400 ÷ 600, it is possible to linearize regulating characteristics, thus, we're having a fair ratio

$$U_1 = k_{vr} u_{cc}, \tag{6.33}$$

where k_{vr} – is the approximation factor.

AM moment is proportional to a voltage square. This formula is nonlinear, however, it is possible to record for small deviations from static balance point:

$$M = k_m U_1, \tag{6.34}$$

where k_m – is approximation factor.

Having substituted (6.33) to (6.34) we will obtain:

$$M = k_m k_{vr} u_{cc}; \tag{6.35}$$

$$U_{cc} = k_{sr} (u_{fb} - u_{ss}). \tag{6.36}$$

where k_{sr} – is the speed regulator transfer ratio;

$$u_{fb} = k_{fb} \omega;$$

k_{fb} – is the speed negative reverse connection loop transfer ratio.

Taking into account (6.35) and (6.36) the equation of the mechanical characteristics of the «stator voltage regulator – asynchronous motor» system with negative speed feedback

$$\omega = \frac{u_{ss}}{k_{fb}} - \frac{M}{k_m k_{vr} k_{ss} k_{sr}}. \tag{6.37}$$

For various u_{ss} it is possible to build a set of straight speed-torque characteristics which are located between natural and artificial AM characteristics, corresponding to minimum stator voltage (fig. 6.28).

The speed regulating range depends on characteristics rigidity which will be the more than more k_{fb}. Taking into account possible parameters of system $D \approx 10$.

Rotor power losses on sliding at AM speed control are defined as:

$$\Delta P_{adm} = M_{adm} \omega_0 - M_{adm} \omega = M_{adm} \omega_0 s.$$

From here: $M_{adm} = \dfrac{\Delta P_{adm}}{\omega_0 s}$.

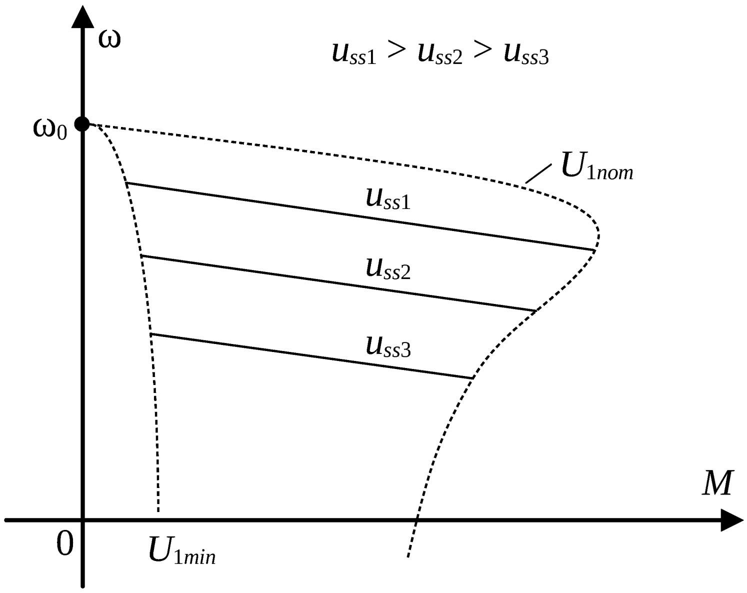

Figure 6.28 – Set of speed-torque characteristics of «stator voltage regulator – asynchronous motor» system with a speed negative feedback

Therefore, in order for the engine not to overheat when the slip increases, the load must be reduced. The increase in slippage in this system is greater, the greater the adjustment range at constant speed ω_0.

AM speed regulation by changing the frequency of the supply voltage occurs without a significant increase in slip, as with rheostat regulation or regulation by changing the stator voltage, discussed above. Therefore, with this method of regulation, slip losses are estimated to be small, and therefore the frequency method is the most economical and provides a greater range of regulation.

Its principle is that, by changing the frequency of the supply voltage with the help of a static frequency converter, it is possible, according to the formula $\omega_0 = 2\pi f_1/p$ to change its synchronous speed, thus obtaining different artificial mechanical characteristics.

For better use of AM and obtaining high energy indicators of its operation – power factor, efficiency, overload capacity – at the same time as changing the frequency, it is necessary to change the value of the supply voltage.

When choosing the ratio between the frequency and the voltage applied to the stator, it is often assumed that its overload capacity is constant, determined by the ratio of the critical moment to the static load moment

$$\lambda = \frac{M_{cr}}{M_{sl}} = const\,. \tag{6.38}$$

Neglecting an active resistance of the stator and considering, that $X_{cr} \sim f_1$ and $\omega_0 \sim f_1$ (6.38) it is possible to write as:

$$\lambda = \frac{3U_1^2}{2\omega_0 X_{cr} M_{sl}} = \frac{AU_1^2}{f_1 M_{sl}} = const \tag{6.39}$$

From (6.39) follows, that for any two meanings of frequency f_{1i} and f_{1k} the relationship should be observed:

$$\frac{U_{1i}^2}{f_{1i}^2 M_{sl\,i}} = \frac{U_{1k}^2}{f_{1k}^2 M_{sl\,k}}$$

From here we have the voltage change fundamental law of AM speed frequency control (academician Kostenko's law):

$$\frac{U_{1i}}{U_{1i}} = \frac{f_{1i}}{f_{1k}} \sqrt{\frac{M_{sl\,i}}{M_{sl\,k}}}\,. \tag{6.40}$$

From (6.40) voltage and frequency change laws can be obtained at various relations of a load torque from speed.

At M_{sl} = const according to (6.40)

$$\frac{U_1}{f_1} = \mathrm{const}\,. \tag{6.41}$$

Speed-torque characteristics are obtained on fig. 6.29 at execution of a condition (6.41).

Frequency control is carried out by means of the static converter of frequency with a direct connection with the power network or the static converter with a direct current link. Last allows controlling frequency both downwards, and up from rating value that ensures more speed control range. On fig. 6.30 the function chart of the AM speed frequency control system with a frequency converter with a direct current link is obtained.

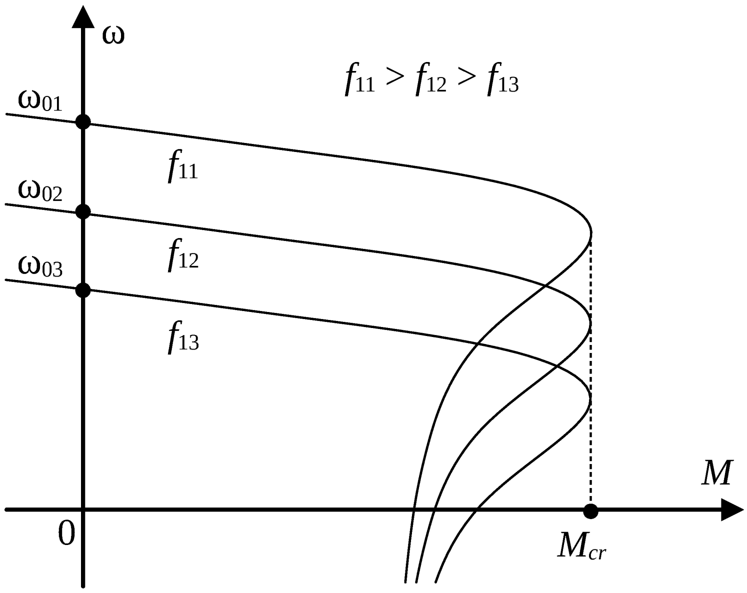

Figure 6.29 – AM speed-torque characteristics at execution of condition U_1 / f_1 = const

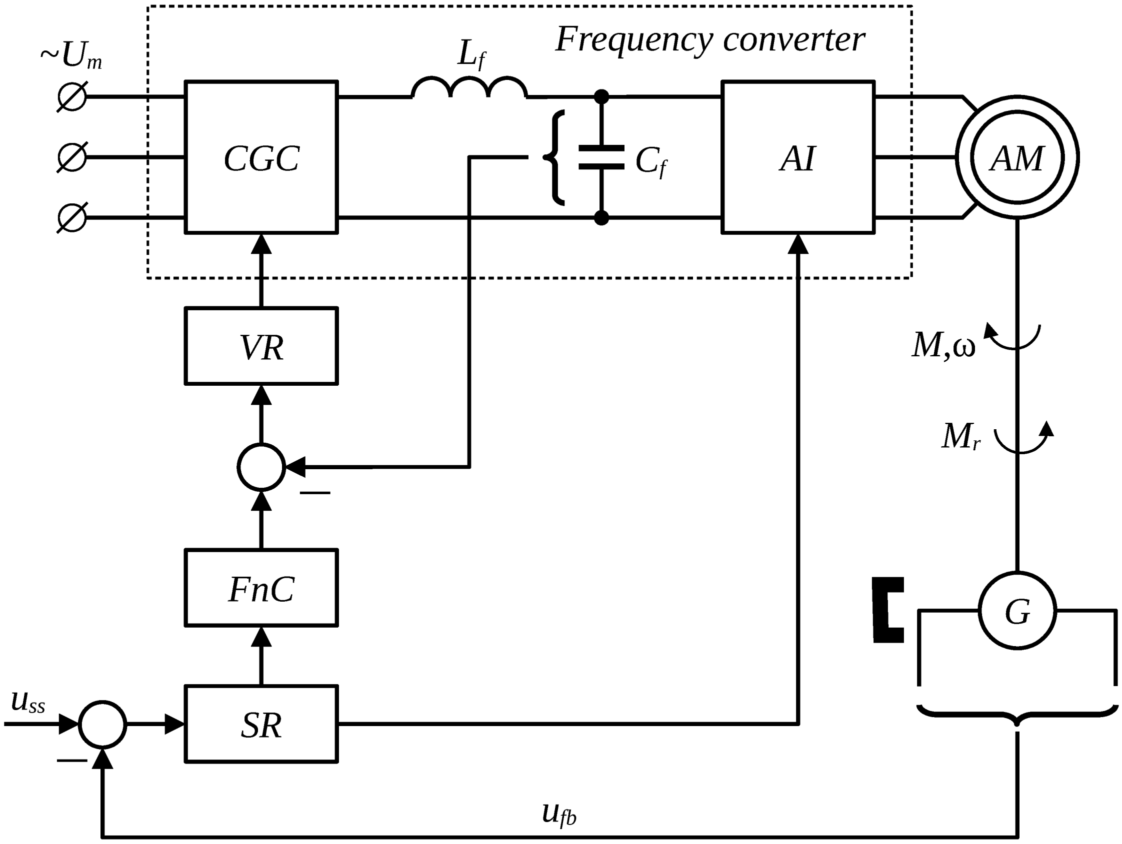

Figure 6.30 – Function chart of AM speed frequency control system

On this circuit design *FC* – is the frequency converter with a link of a direct current which contains controllable gate converter (*CGC*), *AI* – is the autonomous inverter, L_f and C_f – is the filters, *VR* – is the voltage regulator, *SR* – is the speed regulator, *FnC* – is the functional converter ensuring control action U_1 / f_1 = const, u_{fb} – the negative speed feedback implemented by means of tachogenerator *G*, which augments rigidity of speed-torque characteristics that allows to increase a speed control range.

In addition, the system has a circuit for stabilizing the output voltage of the *CGC* for moment stabilization. Sometimes, instead of the voltage control circuit, a magnetic flux control circuit is introduced. The magnetic flux is measured indirectly based on the vector equation of electrical balance for the stator circuit. Stabilization of the magnetic flux together with hard negative speed feedback provide the necessary overload capacity with a speed adjustment range of $D = 20 \div 30$.

6.3 Questions for self-testing

1. Explain the features of rheostat torque regulation.

2. Derive the equations of the mechanical characteristics of the «converter – motor» system with negative torque feedback.

3. Draw and explain the mechanical characteristics of the «current source – motor» system.

4. Draw a functional diagram of the «current source – AM» system.

5. Explain the features of rheostat speed control.

6. Prove that with a weakened magnetic flux, the DCM IE can reach the nominal power.

7. Obtain the equation of the mechanical characteristics of the system «converter – motor» with negative feedback on speed.

8. Explain the features of AM speed control by changing the number of pairs of poles.

9. Obtain the equation of the mechanical characteristics of the «stator voltage regulator – AM» system with negative speed feedback.

10. Derive the law of the voltage change when the frequency changes, based on the unchanged overload capacity of AM.

11. Draw and explain the functional diagram of frequency control of AM speed.

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