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EXAMINING ENERGY-EFFICIENT RECUPERATIVE BRAKING MODES OF TRACTION ASYNCHRONOUS FREQUENCY-CONTROLLED ELECTRIC DRIVES

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Наведено результати досліджень питання енергооптимізації режимів рекуперативного гальмування асинхронних частотно-регульованих електроприводів транспортних засобів. Доведено, що можливість реалізації режиму рекуперативного гальмування залежить від величини кутової швидкості. Визначено механізм впливу параметрів схеми заміщення двигуна на ефективність реалізації таких режимів. Запропоновано методику вибору гальмівних моментів з точки зору максимізації обсягу повернутої електроенергії

Ключові слова: асинхронний двигун, рекуперативне гальмування, електромагнітний момент, потокозчеплення, енергоефективність, векторне керування, струм статора, кутова швидкість, гальмівний момент

Представлено результаты исследований проблемы энергооптимизации режимов рекуперативного торможения асинхронных частотно-регулируемых электроприводов транспортных средств. Доказано, что возможность реализации режима рекуперативного торможения зависит от величины угловой скорости. Определен механизм влияния параметров схемы замещения двигателя на эффективность реализации таких режимов. Предложена методика выбора тормозных моментов с точки зрения максимизации объема возвращенной электроэнергии

Ключевые слова: асинхронный двигатель, рекуперативное торможение, электромагнитный момент, потокосцепление, энергоэффективность, векторное управление, ток статора, угловая скорость, тормозной момент

1. Introduction

A problem of efficiency of the braking process of electric drives has always been and still is a relevant direction, which should be explored both as a whole and in particular implementations [1]. Sufficiently effective kind of electric drives braking, especially when designed as a traction variant, is the recuperative braking [2]. These issues gain more importance in the analysis of electric types of transport vehicles with autonomous power supply because entering these modes makes it possible to significantly increase the distance [3] that can be covered per one battery charge, due to return to it of part of the energy, accumulated in the mechanical part of the drive, when slowing down. Over recent time, synchronous motors with permanent magnets have been very popular as traction engines, which is explained by their high power density, large performance efficiency, and the lack of need in the electric contact with moving parts of machinery [4]. The most significant shortcoming of this type of motors is the high price, due to low availability of rare earth materials. In such cases, as an alternative to synchronous motors with permanent magnets, it is possible to consider asynchronous motors (IM), which, although not attaining very large values of performance efficiency [5] because the rotor EMF is provided through an air gap, are much cheaper in the mass production. IM vector control systems are a standard of sorts when controlling IM and are divided into the systems with direct and indirect field orientation [6]. Meanwhile, there are still problems without solution of which the effectiveness of this type of motors is not satisfactory.

2. Literature review and problem statement

Research into parametric constituents and control systems of asynchronous frequency-controlled electric drives has been the subject of a large number of publications. In this case, those authors who examine the issue of constructing sensorless systems, including using adaptive algorithms, control systems of multilevel converters and the principles of designing vector control systems, do not pay sufficient attention to exploring the modes of recuperative braking. This, in turn, prevents full realization of positive effects from the implementation of systems proposed in the studies into electric drives of transport vehicles.

Article [7] examined the issue of systems with two energy accumulators. For the alignment of voltage magnitudes in the storage battery at a certain state of its charge, DC-DC converters are used in the direct current link that allows smoothing the current consumed from the battery. In paper [8], two storage batteries are used to power a hybrid electric transport vehicle when the state of charge in the main battery is close to the minimum permissible value. In the cited work, an integration of traditional hybrid electric transport vehicle is performed. Article [9] presented a more economically expedient variant for a structure of control system. It contains a supercapacitor and a DC-DC converter while switching the windings is done using a simple sensorless algorithm with the scalar formation of voltage magnitude at a change in frequency that makes it possible to realize a smooth transition from the propulsion to the generator mode. In paper [10], an asynchronous motor control system was designed from the standpoint of maximizing the power losses in the stator and rotor windings in the transition to braking mode. This solution allows eliminating the need for using additional circuit solutions in the semiconducting transducer structure. However, it should be noted that in this case the given electric-mechanical system is not capable of recovering the charge of storage batteries during operation under recuperative braking mode. Article [11] presented a modification of the inverter to power a three-phase alternating current machine that makes it possible to build it on two arms, reducing the number of force elements that participate in the formation of output voltage. A significant shortcoming of this solution is a high value of voltage in the direct current link, as well as large input current distortions. The issue of excess voltage in a direct current link is examined in [12]. Authors also made an attempt at maximizing the torque throughout the entire range of change in angular velocity. In this case, a change in the stator current projection along the longitudinal axis serves to control voltage in the direct current link. In [13], voltage stabilization in the direct current link at recuperative braking is achieved through the source inductance.

3. The aim and tasks of the study

The aim of present work is to examine a question about the formation of signal that assigns electromagnetic torque of IM vector control system in order to maximize the amount of electricity returned at recuperative braking.

To achieve the set aim, the following tasks were to be solved:

– to obtain analytical dependences that link braking torque generated by motor under recuperative braking mode with the limitations in current and voltage magnitudes, as well as motor equivalent circuit parameters;

– to analyze operation of motor under recuperative braking mode when working with angular velocity that is less than the basic one, as well as with the field weakening;

– to define boundary conditions for the existence of recuperative braking mode, to find an analytical dependence for the minimum magnitude of angular velocity, working at which it is possible to return energy from the motor to the power source.

4. Materials and methods for examining the recuperative braking modes of asynchronous frequency-controlled electric drives

4. 1. Analysis of equations of asynchronous motor state

Let us consider a mathematical description of asynchronous motor with a short circuit rotor in the coordinate system d-q, which rotates synchronously with a stator power voltage vector. The advantage of this choice of coordinate system is that under steady mode the basic magnitudes will acquire a character of permanent components, which considerably simplifies analysis of the system compared to the similar one, in which sinusoidal components act:

$$\frac{\psi_{sd}}{dt} = u_{sd} - R_s i_{sd} + \omega_e \psi_{sq}; \quad (1)$$

$$\frac{\psi_{sq}}{dt} = u_{sq} - R_s i_{sq} - \omega_e \psi_{sd}; \quad (2)$$

$$\frac{\psi_{rd}}{dt} = -R_r i_{rd} - (p\omega - \omega_e)\psi_{rq}; \quad (3)$$

$$\frac{\psi_{rq}}{dt} = -R_r i_{rq} + (p\omega - \omega_e)\psi_{rd}, \quad (4)$$

where R_s and R_r are the active supports of windings in the motor's stator and rotor, u_{sd}, u_{sq} are the components of voltage vector, applied to the stator of motor, i_{sd}, i_{sq} are the components of stator current, ψ_{sd}, ψ_{sq}, ψ_{rd}, ψ_{rq} are the components of stator and rotor flux linkage vectors, ω is the angular speed of rotor rotation, ω_e is the angular speed of machine field rotation that corresponds to the speed of rotation of coordinate system d-q, p is the number of pole pairs.

In this case, flux linkage can be calculated by the following dependences:

$$\psi_{sd} = L_s i_{sd} + L_m i_{rd}; \quad (5)$$

$$\psi_{sq} = L_s i_{sq} + L_m i_{rq}; \quad (6)$$

$$\psi_{rd} = L_r i_{rd} + L_m i_{sd}; \quad (7)$$

$$\psi_{rq} = L_r i_{rq} + L_m i_{sq}, \quad (8)$$

where L_s, L_r are the stator and rotor windings inductance, L_m is the mutual inductance of stator and rotor.

In this case, torque can be calculated as follows:

$$M_e = L_m p(i_{sq} i_{rd} - i_{sd} i_{rq}). \quad (9)$$

Upon combining these equations and by expressing voltage vector components through them, we obtain:

$$u_{sd} = \frac{\psi_{sd}}{dt} + R_s i_{sd} - \omega_e L_s i_{sq} - \omega_e L_m i_{rq}; \quad (10)$$

$$u_{sq} = \frac{\psi_{sq}}{dt} + R_s i_{sq} + \omega_e L_s i_{sd} + \omega_e L_m i_{rd}; \quad (11)$$

$$0 = \frac{\psi_{rd}}{dt} + R_r i_{rd} + (p\omega - \omega_e) L_r i_{rq} + (p\omega - \omega_e) L_m i_{sq}; \quad (12)$$

$$0=\frac{\psi_{rq}}{dt}+R_r i_{rq}-(p\omega-\omega_e)L_r i_{rd}-(p\omega-\omega_e)L_m i_{sd}. \qquad (13)$$

When working under steady mode, the basic magnitudes take the form of permanent components, which allows us to simplify equation of mathematical description of the system. We shall represent obtained dependences in the matrix form:

$$\begin{pmatrix} u_{sd} \\ u_{sq} \\ 0 \\ 0 \end{pmatrix}=\begin{pmatrix} R_s & -\omega_e L_s & 0 & -\omega_e L_m \\ \omega_e L_s & R_s & \omega_e L_m & 0 \\ 0 & (p\omega-\omega_e)L_m & R_r & (p\omega-\omega_e)L_r \\ -(p\omega-\omega_e)L_m & 0 & -(p\omega-\omega_e)L_r & R_r \end{pmatrix}\begin{pmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{pmatrix}. \qquad (14)$$

In order to study the border between recuperative and non-recuperative braking of asynchronous motor, let us consider a dependence for the power consumed by asynchronous motor:

$$p=M_e\omega+i_{sd}^2R_s+i_{sq}^2R_s+i_{rd}^2R_r+i_{rq}^2R_r+p_{cl}, \qquad (15)$$

where p_{cl} are the losses in machine's steel.

By considering only the steady operation mode, that is, neglecting the existence of flux linkage derivatives in the axes of coordinate system that rotates synchronously with the machine field, we receive the following dependences for components of the rotor current vector:

$$i_{rd}=-\frac{(p\omega-\omega_e)^2L_mL_r}{(p\omega-\omega_e)^2L_r^2+R_r^2}i_{sd}-\frac{R_r(p\omega-\omega_e)L_m}{(p\omega-\omega_e)^2L_r^2+R_r^2}i_{sq}; \qquad (16)$$

$$i_{rq}=\frac{(p\omega-\omega_e)L_mR_r}{(p\omega-\omega_e)^2L_r^2+R_r^2}i_{sd}-\frac{(p\omega-\omega_e)^2L_mL_r}{(p\omega-\omega_e)^2L_r^2+R_r^2}i_{sq}. \qquad (17)$$

This allows us to subsequently get rid of using the given variables of state in the equations, because in the synthesis of control system they are not available for measurement. Then the equations of electrical equilibrium of stator circle will take the form:

$$u_{sd}=\left(R_s-\frac{\omega_eL_m^2R_r(p\omega-\omega_e)}{(p\omega-\omega_e)^2L_r^2+R_r^2}\right)i_{sd}+$$
$$+\left(\frac{L_m^2L_r(p\omega-\omega_e)^2}{(p\omega-\omega_e)^2L_r^2+R_r^2}-L_s\right)\omega_e i_{sq}; \qquad (18)$$

$$u_{sq}=\left(R_s-\frac{\omega_eL_m^2R_r(p\omega-\omega_e)}{(p\omega-\omega_e)^2L_r^2+R_r^2}\right)i_{sq}+$$
$$+\left(L_s-\frac{L_m^2L_r(p\omega-\omega_e)^2}{(p\omega-\omega_e)^2L_r^2+R_r^2}\right)\omega_e i_{sd}. \qquad (19)$$

To assess the magnitude of stator voltage, we shall perform squaring and adding of the given equations. We receive:

$$u_{sd}^2+u_{sq}^2=\left(\left(R_s-\frac{\omega_eL_m^2R_r(p\omega-\omega_e)}{(p\omega-\omega_e)^2L_r^2+R_r^2}\right)^2+\left(L_s-\frac{L_m^2(p\omega-\omega_e)^2}{(p\omega-\omega_e)^2L_r^2+R_r^2}\right)^2\omega_e^2\right)i_{sd}^2+$$
$$+\left(\left(\frac{L_m^2(p\omega-\omega_e)^2L_r}{(p\omega-\omega_e)^2L_r^2+R_r^2}-L_s\right)^2\omega_e^2+\left(R_s-\frac{\omega_eL_m^2R_r(p\omega-\omega_e)}{(p\omega-\omega_e)^2L_r^2+R_r^2}\right)^2\right)i_{sq}^2. \qquad (20)$$

Let us introduce a magnitude of motor sliding into the given expression and, following a series of transforms, we have:

$$u_{sd}^2+u_{sq}^2=$$
$$=\left(\left(R_s-\frac{\omega_e^2sL_m^2R_r}{s^2\omega_e^2L_r^2+R_r^2}\right)^2+\left(L_s-\frac{L_m^2s^2\omega_e^2L_r}{s^2\omega_e^2L_r^2+R_r^2}\right)^2\omega_e^2\right)\left(i_{sd}^2+i_{sq}^2\right). \qquad (21)$$

The magnitude of torque can be expressed as:

$$M_e=L_mp\frac{s\omega_eL_mR_r}{s^2\omega_e^2L_r^2+R_r^2}\left(i_{sq}^2+i_{sd}^2\right). \qquad (22)$$

Based on the received dependence, it may be concluded that the torque can change sign for negative at a change in sign by the magnitude of sliding frequency $\omega_s=s\omega_e$:

$$M_e=\frac{p\omega_sL_m^2R_r}{\omega_s^2L_r^2+R_r^2}\left(i_{sq}^2+i_{sd}^2\right). \qquad (23)$$

4. 2. Optimization of the magnitude of signal that assigns braking torque when operating at angular velocity lower than the base one

When considering an issue of maximizing the torque at recuperative braking, it is expedient initially to analyze the processes in machine when working in the lower part of control range, for which it is acceptable to consider only current magnitude limit

$$i_{max}=\sqrt{i_{sq}^2+i_{sd}^2}$$

at a free change in voltage magnitude within the range to nominal. Then the torque can be calculated as follows:

$$M_e=\frac{p\omega_sL_m^2R_r}{\omega_s^2L_r^2+R_r^2}i_{max}^2. \qquad (24)$$

We shall find an extremum in the given dependence to determine the magnitude of maximum torque:

$$\frac{dM_e}{d\omega_s}=0; \qquad (25)$$

$$\frac{dM_e}{d\omega_s}=pL_m^2R_r\frac{R_r^2-\omega_s^2L_r^2}{\left(\omega_s^2L_r^2+R_r^2\right)^2}i_{max}^2; \qquad (26)$$

$$\omega_s=\frac{R_r}{L_r}. \qquad (27)$$

Then maximal magnitude of braking torque for the work at low angular velocity can be written down as:

$$M_{max}=\frac{pL_m^2R_r^2}{2R_r^2L_r}i_{max}^2. \qquad (28)$$

Therefore, when the signal that assigns braking torque approaches the value calculated by formula (28), the amount of electrical energy that will be returned to the autonomous power source will approach maximum.

4. 3. Optimization of the magnitude of signal that assigns braking torque when working at the angular velocity larger than the base one

Let us consider basic dependences that describing processes in asynchronous motor at the angular velocity larger than the base one. Base angular velocity is the maximum speed at which it is possible to obtain the maximum magnitude of torque. When analyzing motor operation in this range, it is also necessary to consider limitations by the voltage supplied to the motor's stator and which should not exceed the nominal one:

$$u_{max}=\sqrt{u_{sq}^2+u_{sd}^2}. \tag{29}$$

We shall express maximum current through maximum voltage:

$$i_{sd}^2+i_{sq}^2= \\ =\frac{u_{sd}^2+u_{sq}^2}{\left(R_s+\frac{\omega_e^2L_m^2sR_r}{s^2\omega_e^2L_r^2+R_r^2}\right)^2+\left(L_s-\frac{L_m^2s^2\omega_e^2L_r}{s^2\omega_e^2L_r^2+R_r^2}\right)^2\omega_e^2}. \tag{30}$$

Torque under this mode can be estimated as:

$$M_e=\frac{p\omega_sL_m^2R_r}{\omega_s^2L_r^2+R_r^2}\times \\ \times\frac{u_{max}^2}{\left(R_s+\frac{\omega_e^2L_m^2sR_r}{\omega_s^2L_r^2+R_r^2}\right)^2+\left(L_s-\frac{L_m^2s^2\omega_e^2L_r}{\omega_s^2L_r^2+R_r^2}\right)^2\omega_e^2}. \tag{31}$$

Substituting the magnitude of torque in equation of motor electromagnetic power, we receive:

$$p=\frac{i_{max}^2\left(R_sL_r^2+R_rL_m^2\right)\omega_s^2}{2R_r^2}+ \\ +\frac{i_{max}^2p\omega\omega_sR_rL_m^2}{2R_r^2}+\frac{i_{max}^2R_sR_r^2}{2R_r^2}+p_{cl}. \tag{32}$$

An attribute of braking mode is the availability of different signs in the magnitudes of angular velocity and torque, that is:

$$\omega M_e<0. \tag{33}$$

However, the recuperative braking is observed when condition is satisfied:

$$p<0. \tag{34}$$

Let us find the limit of existence of recuperative braking mode, neglecting losses in machine's steel p_{cl}=0:

$$p=0; \tag{35}$$

$$\frac{i_{max}^2\left(R_sL_r^2+R_rL_m^2\right)\omega_s^2}{2R_r^2}+\frac{i_{max}^2p\omega\omega_sR_rL_m^2}{2R_r^2}+\frac{i_{max}^2R_sR_r^2}{2R_r^2}=0; \tag{36}$$

$$\left(R_sL_r^2+R_rL_m^2\right)\omega_s^2+p\omega R_rL_m^2\omega_s+R_sR_r^2=0. \tag{37}$$

Solutions for the given square equation exist under condition of nonnegative character of its discriminant:

$$p^2\omega^2R_r^2L_m^4-4\left(R_sL_r^2+R_rL_m^2\right)R_sR_r^2\geq 0; \tag{38}$$

$$\omega^2\geq\frac{4\left(R_sL_r^2+R_rL_m^2\right)R_s}{p^2L_m^4}; \tag{39}$$

$$|\omega|\geq\frac{2\sqrt{R_s\left(R_sL_r^2+R_rL_m^2\right)}}{pL_m^2}. \tag{40}$$

Thus, recuperative braking of asynchronous motor is impossible when this condition is not satisfied.

In order to maximize the amount of energy that can be returned to the source, we found an extremum in dependence that describes motor electromagnetic power:

$$M_{ref}=-\frac{pL_m^2i_{max}^2\sqrt{R_s\left(R_sL_r^2+R_rL_m^2\right)}}{2R_sL_r^2+R_rL_m^2}. \tag{41}$$

As a result, we obtained the magnitude of assigning torque that provides for the maximum amount of recuperated electric energy.

5. Results of examining the recuperative braking modes of asynchronous frequency-controlled electric drives

In order to further examine obtained analytical dependences, we synthesized a mathematical model of electromechanical system with frequency-controlled asynchronous motor in the programming environment Matlab/Simulink (made by The MathWork, USA) (Fig. 1). Using this model, we studied the behavior of traction asynchronous motor with capacity 37 kW with 2 pole pairs during acceleration and subsequent braking to a full halt by changing parameters of the control system, which assigns the magnitudes of flux linkage and electromagnetic torque, as well as the intensity of braking. From the received graphs (Fig. 2), through integrating, we estimated the amount of electric energy that can be recuperated to power source.

Studying the results of simulation of the given electromechanical system demonstrates a relation between the amount of electrical energy that can be returned to autonomous power source and the torque carried by the shaft. If the shaft has nominal load and the magnitude of braking torque is reduced to the level of 50 % of the nominal one, there is a reduction in the amount of returned energy by 30 %, and increasing the torque to 150 % of the nominal one – growth by 22.8 %. This is explained by the fact that, under such conditions, reduction in braking torque results in the increased braking time, and, during this time, the energy is removed by load, which leads to the reduction in its volume that can be recuperated.

Under condition of absence of load, the maximum amount of electric energy returns to the source at braking torque that, according to the obtained dependences for this type of motor, is 47.08 % of the nominal value. At nominal load on shaft, the amount of recuperated electric energy is reduced by 2 % and at braking with maximum braking torque under condition of existing current limitation – by 13.4 %, which are significant losses when an electric transport vehicle moves in urban cycle.

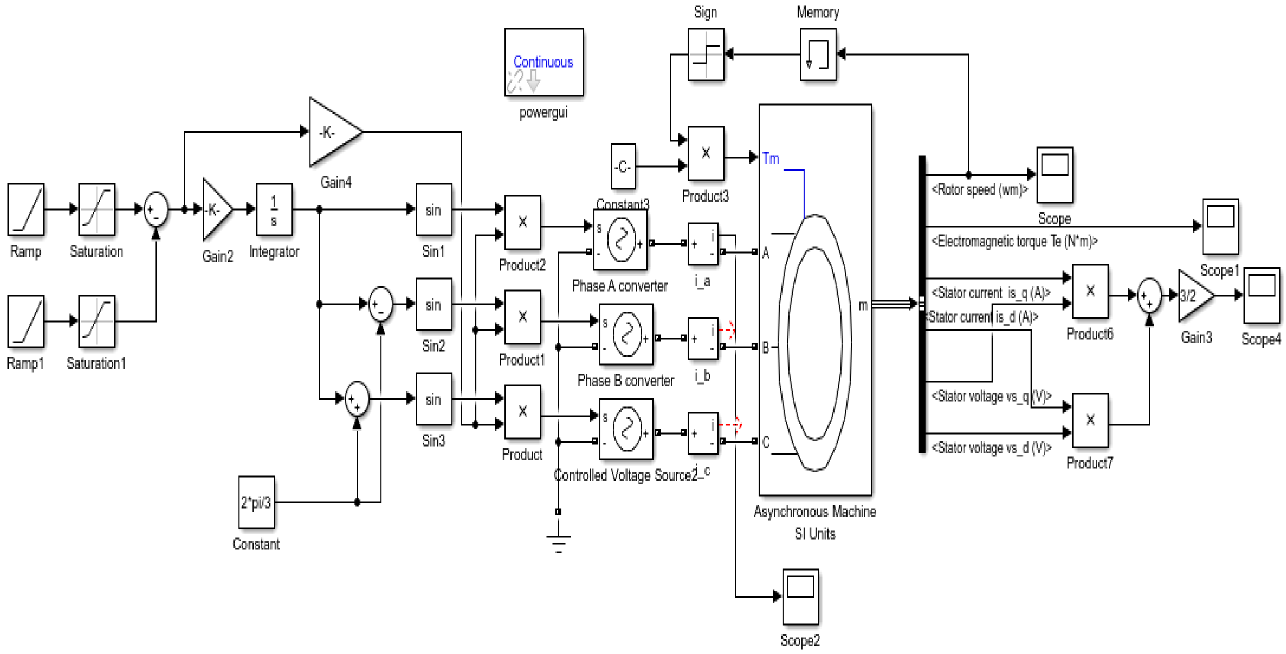

Fig. 1. Structure of mathematical model for electromechanical system with asynchronous frequency-controlled motor

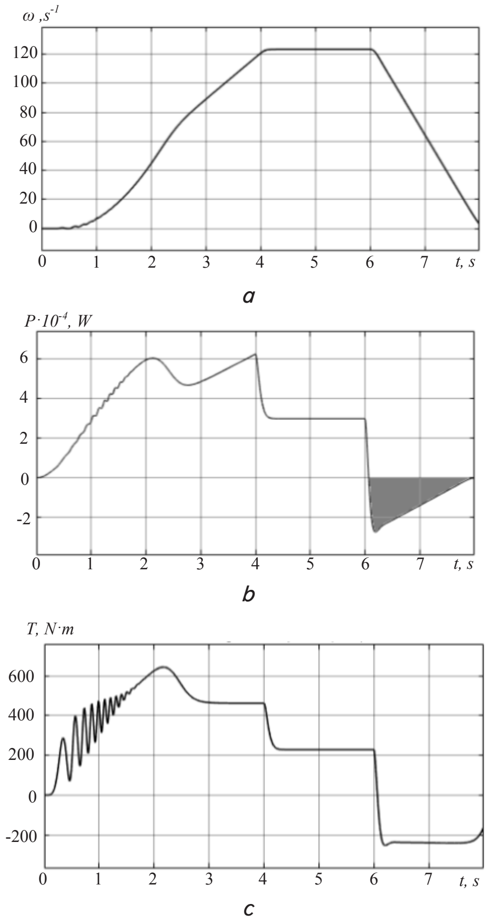

Fig. 2. Graphs of processes in traction electromechanical system at start and braking: *a* – dependence of angular velocity (ω) on time; *b* – torque (T) on time; *c* – consumed energy (P) at start and subsequent braking with energy recuperation (grey color denotes the amount of electric energy that is returned to the source)

6. Discussion of results of examining the recuperative braking modes of asynchronous frequency-controlled electric drives

The studies we conducted on the recuperative braking modes demonstrate that by influencing the variables of asynchronous motor state, it is possible to change energy efficiency of transmission process of freed mechanical energy from the shaft of the traction motor of electric transport vehicle to autonomous power source. Therefore, the search for ways to optimize this process is possible, and in the given paper we presented analytical solution for this problem, as a result of which we received dependences (28) and (41) that allow us to determine the recommended magnitude of signal that assigns braking torque to maximize the amount of returned energy.

The benefit of this study is in the following: due to the fact that at work with angular velocities that are larger or lower than the base one, there are limitations, different in their nature, of variables in the state of control object, these ranges of velocities are analyzed separately. A practical value of obtained results is in the possibility of using presented dependences to devise control algorithms for electric and hybrid transport vehicles.

Performed studies might also be useful when considering the appropriateness of using synchronous motors with permanent magnets, or asynchronous motor, in specific traction electric drives, because by using the given results, in future, fundamental differences may be demonstrated in the realization of the given operation modes, which a priori can be explained by differences in the formation of rotor flux linkage magnitude: in asynchronous motors, due to the excitation of stator windings, and in synchronous motors – through permanent magnets.

6. Conclusions

In present work we examined energy efficient modes of recuperative braking for transport vehicles with traction asynchronous frequency-controlled motors. Results of the studies conducted:

1. By examining the equations of state of asynchronous motor in synchronous reference system, we obtained analytical dependences that link the magnitude of braking torque generated by motor at work under the mode of recuperative braking, with limitations in the variables of state that contribute to its failure-free operation.
2. Based on the conducted analysis of motor operation under the mode of recuperative braking when working at angular velocity that is lower than the base one, as well as at field weakening, we determined the magnitude of braking torque, the application of which in the control system as an assigning signal provides for the maximum amount of electric energy returned to power source in the course of recuperative braking. Since this magnitude is lower than the value of nominal torque (≈47 %), then such an operation mode does not lead to the occurrence of currents that would exceed those permissible, which is also important for the functioning of the given systems.
3. We calculated boundary conditions for the existence of recuperative braking mode, which make it possible to find the minimum angular velocity for such a regime.

Thus, a number of recommendations are devised that might be used by designers of traction electromechanical systems.

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