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MTPA STRATEGY FOR THE ELECTRIC VEHICLE DRIVE

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Abstract. *The purpose of the work is to develop a torque control system of an induction motor using the MTPA strategy, which provides the maximum value of the electromagnetic torque at the nominal value of the current in the stator winding. A comparative analysis of the traction induction electric drive properties when applying the MTPA strategy and field-oriented vector control of the stator current of the induction motor was carried out. As a result, a formula was obtained that allows for the same value of current in the stator winding of an induction motor to determine the multiplicity of the increase in the electromagnetic torque when applying the MTPA strategy in comparison with field-oriented vector control of the stator current of an induction motor. A study of the requirements that the MTPA strategy presents to the technical parameters of the traction induction motor and the limitations that the real parameters of the induction motor impose on the MTPA strategy was carried out.*

Keywords: *induction motor, vehicle, electromagnetic torque, energy, strategy MTPA.*

Introduction

Traction induction motors (IM) are widely used in modern electric vehicles (EV). They are the simplest in design, the most reliable and the cheapest.

In vehicles with an autonomous energy source it is very important to minimize energy losses in the electric drive, as this allows to increase the path of movement of the vehicle without additional recharging of the autonomous energy source. A significant share of energy losses in traction electric drives are losses of electrical energy in the windings of traction motors, which depend on the value of current flowing in the windings. Therefore, in order to minimize energy losses in the windings of traction motors, it is necessary to develop a system of vector control of the stator current of an induction motor, in which the nominal value of the stator current of the induction motor will develop the maximum electromagnetic torque. Limiting the stator current to the nominal value will prevent overheating of the traction motor in long-term operation.

Today, the problem of obtaining the maximum electromagnetic torque per unit of stator current is solved by the MTPA strategy. A significant number of publications are devoted to MTPA control systems built on the basis of IM. In [1, 2], an IM control system is proposed, which maximizes the value of the motor torque, taking into account the saturation of the IM magnetic system. Article [3] is devoted to the study of energy losses when applying the MTPA strategy in indirect control of the rotor flux coupling based on IM. In [4-6], the application of the MTPA strategy to sensorless induction electric drives is considered. Unified direct vector control of IM in the MTPA system is considered in [7]. In [8] the application of the MTPA strategy to induction electric drives is considered. In [9] an adaptive strategy for controlling the maximum torque per ampere is considered. In [10, 11] an improved MTPA strategy for IM is considered. In [12] a system for controlling the maximum torque per ampere for induction electric drives is proposed, taking into account iron losses and using feedback linearization. In the article [13] the application of the MTPA strategy for synchronous motors with excitation from permanent magnets is considered. In [14] the issue of minimizing energy losses in an induction electric drive is considered.

In the article [15] field-oriented vector control of an asynchronous motor for electric vehicles is considered. In [16-20], an analysis of IM control systems is carried out, which work with minimal energy losses during vector control of the IM stator current and direct control of the driving torque of the IM. In [21] an analysis of the influence of the main and higher harmonics of voltage and current on energy losses in steel for motors of different power was carried out. In [22] an analysis of energy losses in various elements of the electric drive system with a frequency converter and an induction motor was carried out. In the article the requirements for the IM parameters of the traction electric drives of electric vehicles are considered.

A large number of publications on the strategy of MTPA confirms the relevance of this topic. But in literary sources, not enough attention is paid to clari-

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fying the requirements that the MTPA strategy imposes on the technical parameters of IM and the limitations that the real parameters of IM impose on the MTPA strategy.

1. Research objectives

The purpose of the work is to develop a torque control system using the MTPA strategy, which ensures the maximum value of the electromagnetic torque per unit current in the stator winding, to conduct a comparative analysis of the traction properties of an induction electric drive when using the MTPA strategy and when applying the field-oriented vector controlling the stator current of an induction motor, as well as clarifying the requirements that the MTPA strategy imposes on the technical parameters of the IM and clarifying the limitations that the real parameters of the IM impose on the MTPA strategy. Research was conducted on the example of traction induction electric drive intended for modification of the "Bohdan" A-092 bus.

It is known that according to building codes, the largest slope of the highway in cities should not exceed 5-6%, and the slope of roads outside the city should not exceed 8%. Taking into account these requirements, the calculation of the load torque, which is created on the shaft of the traction motor by the forces of resistance to the movement of a full bus on a horizontal road and up a road with a slope of 8%, was carried out. When calculating the force of resistance, the force of friction of the bus wheels on the asphalt road, the force of resistance from the slope of the road, as well as the force of air resistance were taken into account. The transmission of an electric bus ensures the movement of a full bus on a horizontal road at a speed of 95 km / h at a nominal frequency of rotation of the traction IM shaft of 1500 rpm. The load torque on the shaft of the traction motor when moving a full bus on a horizontal road is 639.2 Nm and when moving a full bus up the road with a slope of 8% is 1915.0 Nm.

The 4A280S4 induction motor was selected on the con-dition that the nominal value of the traction motor torque should be greater than the loading torque on its shaft, which corresponds to the movement of a full bus on a horizontal road at a speed of 95 km / h.

To develop a mathematical model of IM with a short-circuited rotor winding in the "x-y" coordinate system, which rotates relative to the stator with a circular frequency Ω_{0EL}, consider the system of equations written for spatial vectors

$$\tilde{U}_1 = R_1\tilde{I}_1 + \frac{d\tilde{\Psi}_1}{dt} + j\Omega_{0EL}\tilde{\Psi}_1; \quad (1)$$

$$0 = R_2\tilde{I}_2 + \frac{d\tilde{\Psi}_2}{dt} + j\Omega_R\tilde{\Psi}_2 \quad (2)$$

$$\tilde{\Psi}_1 = L_1\tilde{I}_1 + L_m\tilde{I}_2 \quad (3)$$

$$\tilde{\Psi}_2 = L_m\tilde{I}_1 + L_2\tilde{I}_2 \quad (4)$$

where $\tilde{U}_1$ – voltage vector on the stator winding;$\tilde{\Psi}_1$, $\tilde{\Psi}_2$ – stator and rotor flux coupling vectors; $\tilde{I}_1$, $\tilde{I}_2$– stator and rotor current vectors; R_1, R_2 – active phase resistance of stator and rotor windings; L_1, L_2 – full phase inductance of the stator and rotor windings; L_m – mutual inductance of stator and rotor windings; Ω_{0EL}, Ω_R – the circular frequency of the voltage on the stator winding and the circular frequency of the EMF, which the magnetic field induces in the rotor winding.

From equation (4) we determine the rotor current vector through vectors $\tilde{\Psi}_2$ and $\tilde{I}_1$

$$\tilde{I}_2 = \frac{1}{L_2}\left(\tilde{\Psi}_2 - L_m\tilde{I}_1\right) \quad (5)$$

Substitute the right-hand side of equation (5) into equation (3). After transformations we will receive the equation which allows to define a vector of flux coupling of a stator through vectors $\tilde{\Psi}_2$ and $\tilde{I}_1$

$$\tilde{\Psi}_1 = \sigma L_1\tilde{I}_1 + k_2\tilde{\Psi}_2 \quad (6)$$

where σ – a factor that takes into account the scattering flux of the stator and rotor windings of the IM

$$\sigma = \left(1 - \frac{L_m L_m}{L_1 L_2}\right)$$

k_2 – a factor that takes into account the scattering flux of the IM rotor winding

$$k_2 = \frac{L_m}{L_2}.$$

Performing the Laplace transform from equations (1), (2), (5), (6) we obtain

$$\tilde{U}_1 = R_1\left[1 + p\sigma T_1 + j\Omega_{0EL}\sigma T_1\right]\tilde{I}_1 + \left(p + j\Omega_{0EL}\right)k_2\tilde{\Psi}_2 \quad (7)$$

$$0 = -L_m\tilde{I}_1 + \left[\left(1 + T_2 p\right) + j\Omega_R T_2\right]\tilde{\Psi}_2 \quad (8)$$

where $T_1 = L_1/R_1$, $T_2 = L_2/R_2$ – electromagnetic time constants of the stator and rotor windings.

When orienting the "x" axis of the "x-y" coordinate system on the vector $\tilde{\Psi}_2$, we obtain that the projection of the vector $\tilde{\Psi}_2$ on the "y" axis will be zero ($\psi_{2Y} = 0$), and the projection of the vector $\tilde{\Psi}_2$ on the "x" axis will be equal to the modulus of the rotor coupling vector

$$\psi_{2Y} = 0 \tag{9}$$

$$\psi_{2X} = \left|\tilde{\Psi}_2\right| = \Psi_2 \tag{10}$$

When representing spatial vectors through their projections on the axis of the coordinate system "x-y" equations (7) and (8) take the form

$$\begin{aligned} &u_{1X} + ju_{1Y} = \\ &= R_1\left[1 + p\sigma T_1 + j\Omega_{0EL}\sigma T_1\right]\left(i_{1X} + ji_{1Y}\right) + \left(p + j\Omega_{0EL}\right)k_2\Psi_2 \end{aligned} \tag{11}$$

$$0 = -L_m\left(i_{1X} + ji_{1Y}\right) + \left[\left(1 + T_2 p\right) + j\Omega_R T_2\right]\Psi_2 \tag{12}$$

After the transformations we will get

$$u_{1X} = R_1 i_{1X} + p\sigma T_1 R_1 i_{1X} - \Omega_{0EL}\sigma T_1 R_1 i_{1Y} + pk_2\Psi_2 \tag{13}$$

$$u_{1Y} = R_1 i_{1Y} + p\sigma T_1 R_1 i_{1Y} + \Omega_{0EL}\sigma T_1 R_1 i_{1X} + \Omega_{0EL}k_2\Psi_2 \tag{14}$$

Equations (13) and (14) can be used to determine the projections of the voltage vector on the "x" and "y" axes, as well as to determine the desired value of the modulus of the space vector of the voltage that must be applied to the stator winding.

From equation (12) after transformations we obtain

$$0 = -L_m i_{1X} + \left(1 + T_2 p\right)\Psi_2 \tag{15}$$

$$0 = -L_m i_{1Y} + \Omega_R T_2 \Psi_2 \tag{16}$$

Based on equation (15) we obtain the equation of the connection of the projection of the stator current on the axis "x" (i_{1X}) and the modulus of the flux coupling vector of the rotor

$$\Psi_2 = \frac{L_m i_{1X}}{T_2 p + 1} \tag{17}$$

Based on equation (16) we obtain the formula for the relationship between the EMF frequency (Ω_R), which is induced in the rotor winding, the amplitude of the flux coupling of the rotor (Ψ_2) and the projection of the stator current on the axis "y"(i_{1Y})

$$\Omega_R = \frac{k_2 R_2 i_{1Y}}{\Psi_2} \tag{18}$$

The value of the electromagnetic torque of the IM due to the projection of the spatial vectors of the flux coupling of the rotor and the stator current on the axis of the coordinate system "x-y"

$$M_{EM} = \frac{3}{2} p_n k_2 \left(\psi_{2X} i_{1Y} - \psi_{2Y} i_{1X}\right) \tag{19}$$

Substitute the right-hand sides of equations (9) and (10) into formula (19) and we get

$$M_{EM} = \frac{3}{2} p_n k_2 \Psi_2 i_{1Y} \tag{20}$$

Equation of motion of the mechanical part of the electric drive

$$\omega = \frac{1}{p}\left[\frac{1}{J}\left(M_D - M_C\right)\right] \tag{21}$$

where M_C – the loading torque on the IM shaft; J – moment of inertia of the mechanical part of the electric drive.

Circular frequency of the voltage on the stator winding

$$\Omega_{0EL} = p_n\omega + \Omega_R \tag{22}$$

From equations (11) and (12) it follows that in this mathematical model of IM there is a mutual influence of stator current projections i_{1X} and i_{1Y}, as well as the dependence of their values on the value of Ψ_2 and the value of the circular frequency Ω_{0EL}. This interaction can be mitigated by using stator current projection control circuits. When using a relay current regulator in the stator current control circuit, we obtain the equation of connection between the signals of setting the stator current projections u_{Z1X}, u_{Z1Y} and stator current projections i_{1X} and i_{1Y} on the axis of the coordinate system «x-y»

$$i_{1X} = \frac{u_{Z1X}}{k_{OT}} \qquad i_{1Y} = \frac{u_{Z1Y}}{k_{OT}} \tag{23}$$

where k_{OT} – stator current feedback ratio.

Fig. 1 shows a block diagram of the speed control system of IM (in the absence of the BC unit) in the orientation of the axis "x" coordinate system "x-y" on the rotor flow coupling vector $\tilde{\Psi}_2$, which was obtained on the basis of independent control of stator current projections on the axis of the coordinate system "x-y" (23). Equations (17), (18), (20), (21) and (22) were also used.

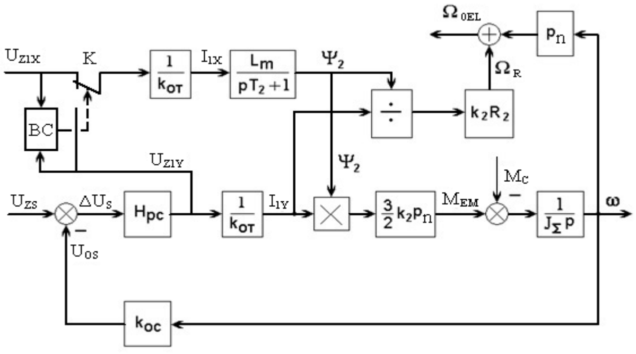

Fig. 1. Block diagram of the system for speed control of the IM when the orientation of the axis "x" of the coordinate system "x-y" on the flow vector of the rotor $\tilde{\Psi}_2$

2. Application of the MTPA strategy to the system of vector control of the stator current of an induction motor

From the formula (17) for the steady-state operation of the IM we obtain the equation of the relationship between the modulus of the flux coupling vector of the rotor and the projection of the spatial vector of the stator current on the «x» axis

$$\Psi_2 = L_m i_{1X} \tag{24}$$

Substitute the right-hand side of equation (24) into equation (20):

$$M_{EM} = \frac{3}{2} p_n k_2 L_m i_{1X} i_{1Y} \tag{25}$$

Determine the projections of the spatial vector of the stator current on the axis of the coordinate system «x-y» through the modulus of the spatial vector of the stator current and the value of the angle of rotation of the space vector of the stator current relative to the "x" axis of the «x-y» coordinate system, which is directed along the rotor flux coupling vector $\tilde{\Psi}_2$:

$$i_{1X} = \left|\tilde{I}_1\right| \cos\theta\,; \tag{26}$$

$$i_{1Y} = \left|\tilde{I}_1\right| \sin\theta \tag{27}$$

After substituting the right-hand sides of equations (26) and (27) into equation (25) we obtain

$$M_{EM} = \frac{3}{2} p_n k_2 L_m \left|\tilde{I}_1\right|^2 \cos\theta \cdot \sin\theta .$$

After the transformations we get

$$M_{EM} = \frac{3}{4} p_n k_2 L_m \left|\tilde{I}_1\right|^2 \sin 2\theta \tag{28}$$

Determine the value of the angle θ at which the IM will develop the greatest torque at the same value of the modulus of the spatial vector of the stator current, the projection of which on the "x" axis determines the flux coupling of the rotor. To do this, take the derivative

$$\frac{dM_{EM}}{d\theta} = \frac{3}{2} p_n k_2 L_m \left|\tilde{I}_1\right|^2 \cos 2\theta$$

$$\frac{dM_{EM}}{d\theta} = 0$$

From here we get

$$\theta = \frac{\pi}{4} \tag{29}$$

After substituting (29) in equations (26) and (27) we obtain that the AD will develop the greatest moment provided that the projections of the spatial vector of the stator current on the axis of the coordinate system «x-y» will be the same

$$i_{1X} = i_{1Y} = \frac{\left|\tilde{I}_1\right|}{\sqrt{2}} \tag{30}$$

After substituting (29) in equation (28) we obtain the value of the largest torque that the IM can develop at a given value of the stator current

$$M_{EM.OPT.} = \frac{3}{4} p_n k_2 L_m \left|\tilde{I}_1\right|^2 \tag{31}$$

Divide (31) by (28)

$$\frac{M_{EM.OPT.}}{M_{EM}} = \frac{1}{\sin 2\theta}$$

$$M_{EM} = M_{EM.OPT.} \sin 2\theta . \tag{32}$$

If in the stator current vector control system, the angle between the stator current vector and the rotor current coupling vector differs from 45 electrical degrees, then at the same value of current in the stator winding IM will develop less electromagnetic moment according to formula (32). The value of the electromagnetic moment that IM develops will be zero at θ = 0 electric degrees or at θ = 90 electric degrees.

Based on the parameters of the 4A280S4 motor according to formula (31), the value of the maximum torque that IM can develop at the nominal value of the stator current when applying the MTPA strategy is calculated

$$M_{EM.OPT.} = 1997.0\ Nm$$

This is 2.56 times the nominal value of the electromagnetic torque of the motor 4A280S4 (779.4 Nm).

According to formula (30), the largest value of the magnetizing current, which corresponds to the nominal value of the stator current when applying the MTPA strategy is calculated

$$i_{1X} = i_{1Y} = \frac{\left|\tilde{I}_{1F.H}\right|}{\sqrt{2}}$$

$$i_{1X} = i_{1Y} = \frac{283.1}{\sqrt{2}} = 200.2\ A$$

According to formula (24), the highest value of the modulus of the rotor coupling vector, which corresponds to the nominal value of the stator current of the motor 4A280S4

$$\Psi_{2MAX.} = L_m i_{1X}$$

$$\Psi_{2MAX.} = 0.01715 \cdot 200.2 = 3.4334\ Wb .$$

This is 3.55 times higher than the nominal value of the flux coupling of the motor rotor (0.9668 Wb).

The increased value of the flux coupling of the rotor leads to an increase in the value of the EMF induced in the stator winding, and accordingly requires an increase in the value of the voltage to be applied to the stator winding of the motor. The calculation according to formulas (13) and (14) showed that when applying the MTPA strategy the required value of the modulus of the spatial voltage vector at the nominal value of the voltage frequency on the stator winding should be $|\tilde{U}_{1H}| = 1112$ V. Phase voltage on the stator winding is 786 V. This is 3.57 times higher than the nominal value of the phase voltage on the stator winding of the motor 4A280S4.

The structural diagram of the IM speed control system with the application of the MTPA strategy to the vector control system of the stator current of an induction motor is shown in Fig. 1. In reality, the driver performs the function of the outer circle of IM rotor speed control in relation to the circle of control of the projections of the stator current vector on the "x" and "y" axis. The driver ensures the limitation of the value of acceleration during acceleration and during braking of IM and reduces overshooting in the speed of the rotor.

When modeling the speed control system, the driver's functions were assigned to the speed controller with the H_{PC} transfer function, at the input of which the values of the speed reference signal U_{ZS} and the speed feedback signal U_{OS} are compared.

The IM torque control system includes the BC block, which compares the reference signals of the stator current projections (i_{1X} and u_{Z1Y}) on the axis of the «x-y» coordinate system (i_{1X} and i_{1Y}). At a small value of the torque developed by IM, ($u_{Z1Y} \leq u_{Z1X}$), the angle θ between the stator current vector and the rotor flux coupling vector will be less than 45 electrical degrees. In this case, the BC block does not change the position of the contact K, and the flux coupling of the rotor will be determined by the signal u_{Z1X}. IM will work at the nominal value of the projection of the stator current onto the «x» axis ($I_{S.X.H}$ = 56.4 A) and, accordingly, at the nominal value of the rotor flux coupling (Ψ_{2H} = 0.9668 Wb).

If IM develops a large moment ($u_{Z1Y} \geq u_{Z1X}$), then in the vector control system of the stator current, the flux-coupling of the rotor will also be determined by the signal (u_{Z1X}). IM will continue to work at the nominal value of the projection of the stator current on the «x» axis of the «x-y» coordinate system ($i_{1X} = I_{S.X.H}$ = 56.4 A). In this case, the rotor flux linkage will be equal to the nominal value (Ψ_{2H} = 0.9668 Wb), and the angle θ between the stator current vector and the rotor flux linkage vector will be greater than 45 electrical degrees.

When applying the stator current vector control system with a large value of the torque to be developed by IM, the value of the stator current projection reference signal on the «y» axis will exceed the value of the stator current projection reference signal on the «x» axis ($u_{Z1Y} \geq u_{Z1X}$). When applying the MTPA strategy in this case, the BC block switches contact K so that the rotor flux-coupling will also be determined by the u_{Z1Y} reference signal. As a result, IM will work at a rotor flux coupling value greater than the nominal value (Ψ_{2H} = 0.9668 Wb), since the projection of the stator current on the "x" axis will be equal to the projection of the stator current on the "y" axis ($i_{1X} = i_{1Y}$) and will exceed the nominal value of the magnetizing current ($I_{S.X.H}$ = 56.373 A). Therefore, with a large torque, which will be developed by IM, the angle θ between the stator current vector and the rotor flux coupling vector will be equal to 45 electrical degrees.

The value of the u_{Z1Y} signal must be limited to a level that corresponds to the nominal value of the stator current, which will prevent overheating of the traction motor in long-term operation.

3. Transient processes in a traction electric drive with a system of vector control of the stator current of an induction motor

The model of the IM stator current vector control system is made in the Matlab Simulink package. The mathematical model was used to study the acceleration processes of a full electric bus on a horizontal road to a given speed. After the full electric bus on a horizontal road accelerated to a given speed, the movement of the electric bus up the road with an 8% slope was simulated. Fig. 2 shows graphs of transient processes during acceleration of a full electric bus on a horizontal road to a given speed of 95 km/h, which corresponds to the angular speed of the traction IM shaft of 157 rad/s.

In the time interval from 0 s up to 5 s the input of the traction speed control system receives a signal to set the speed U_{ZS} = 0 (graph 1). Therefore, the shaft of the IM does not rotate (graph 2), but a current flows in the stator winding, which is equal to the nominal value of the magnetizing current $I_S = I_{S.X.H.}$ = 56.4 A (graph 5). Therefore, the flux coupling of the rotor is equal to the nominal value Ψ_{2H} = 0.9668 Wb (the transient process of increasing the flux coupling of the rotor in graph 6 is not shown).

At the time of 5 s, the maximum reference signal of the U_{ZSMAX} is received, which corresponds to the maximum value of the set angular speed of the IM 157 rad / s (graph 1). At the same time in the stator winding the stator current increases from the nominal value of the magnetizing current $I_S = I_{S.X.H.}$ = 56.4 A to the nominal value of the stator current I_S = 283 A (graph 5). The flux coupling of the rotor remains unchanged and is equal to the nominal value Ψ_{2H} = 0.9668 Wb. The electromagnetic torque of the IM increases from zero to the nominal value of 779.4 Nm (graph 3). At a time interval of 5 s up to 134 s IM speed increases from 0 rad / s to 157 rad / s (graph 2). This corresponds to a maximum speed of of the electric bus of 95 km / h. Thus, the acceleration time of a full electric bus with a non-optimized vector control system for the stator current of an IM to a maximum speed of 95 km / h on a horizontal road is 129 s.

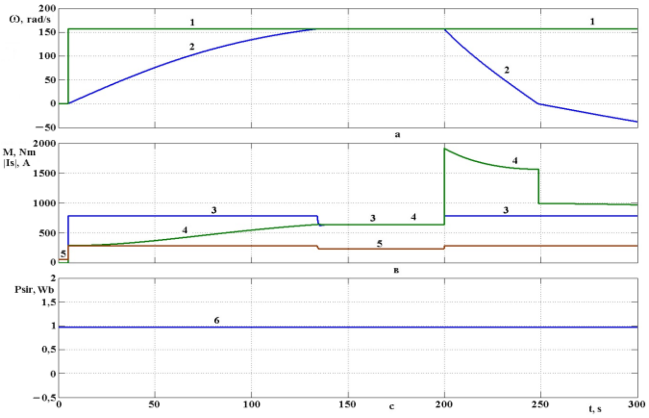

Fig. 2. Graphs of transient processes in the system of vector control of the stator current of an IM during acceleration and when the electric bus is moving at a speed of 95 km/h

During the acceleration of the electric bus, the load torque on the IM shaft increases from 287 Nm to 639 Nm (graph 4), which is due to the increase in air resistance. When the electric bus is moving at a constant speed of 95 km / h, the IM electromagnetic torque decreases from 779 Nm to 639 Nm (graph 3). The current in the stator winding decreases from the nominal value of 283 A to 234 A (graph 5). The flux coupling of the rotor remains unchanged and is equal to the nominal value Ψ_{2H} = 0.9668 Wb (graph 6).

At the time of 200 s the electric bus starts moving up the road with a slope of 8%. The loading torque, reduced to the electromagnetic moment of IM, immediately increases from 639 Nm to 1915 Nm (graph 3). The current in the stator winding increases from 234 A to a nominal value of 283 A (graph 5). The flux coupling of the rotor remains unchanged and is equal to the nominal value Ψ_{2H} = 0.9668 Wb (graph 6). The IM electromagnetic torque increases from 639 Nm to a nominal value of 779 Nm (graph 3). Since the electromagnetic torque (779 Nm) is much less than the loading torque (1915 Nm), the speed of IM, and with it the speed of the electric bus begins to decrease (graph 2).

At the moment of time 248 s the speed of the electric bus decreases to zero, the electric bus stops and begins to roll down the road, which has a slope of 8%. When the electric bus moves down the road, the reactive component of the load torque on the IM shaft, which is equal to the torque of rolling resistance and the torque of air resistance, changes its direction. As a result, the load torque on the IM shaft, reduced to the IM electromagnetic torque, is equal to 988 Nm.

4. Transient processes in the traction electric drive when applying the MTPA strategy

Fig. 3 shows graphs of transient processes during acceleration of a full electric bus on a horizontal road to a set speed of 95 km / h. when applying the MTPA strategy to the vector control system of the stator current of an IM.

In the time interval from 0 s up to 5 s at the input of the speed control system of the traction motor receives a signal to set the speed U_{ZS} = 0 (graph 1). The motor does not rotate (graph 2), in the stator winding there is a nominal magnetizing current $I_S = I_{S.X.H.}$= 56.4 A (graph 5). The flux coupling of the rotor increases from zero to the nominal value Ψ_{2H} = 0.9668 Wb (graph 6).

At the time of 5 s the signal of the speed reference sygnal U_{ZSMAX} is fed to the input of the system, which corresponds to the maximum value of the angular velocity of the shaft of the traction induction motor 157 rad / s. (graph 1). The stator current increases from the nominal value of the magnetizing current $I_S = I_{S.X.H.}$ = 56.4 A to its nominal value I_S = 283 A (graph 5). In the time interval from 5 s to 10 s the flux coupling of the rotor increases from the nominal to the maximum value (from 0.9668 Wb to 3.4335 Wb) (graph 6). At the same time interval, the electromagnetic torque of the motor increases from zero to 1997 Nm (graph 3). In the time interval from 5 s to 33 s IM accelerates to 157 rad / s, which corresponds to a maximum speed of the electric bus of 95 km / h. (graph 2).

Thus, on a horizontal road, the acceleration time of the electric bus with the maximum number of passengers to a maximum speed of 95 km / h is equal to 28 s. During the acceleration of the electric bus, the load moment on the IM shaft increases from 287 Nm to 639 Nm (graph 4), which is due to the increase in air resistance with increasing speed.

When moving the electric bus on a horizontal road at a constant speed of 95 km / h the electromagnetic torque of the motor decreases from 1997 Nm to 639 Nm (graph 3). The current in the stator winding decreases from 283 A to 160 A (graph 5), which is significantly lower compared to the which is significantly smaller compared to the vector control system of the stator current of an IM (234A). The flux coupling of the rotor decreases from the maximum value of Ψ_{2MAX} = 3.4335 Wb to 1.9425 Wb (graph 6). The movement of the electric bus with a constant speed of 95 km / h occurs in the time interval from 33 s up to 50 s.

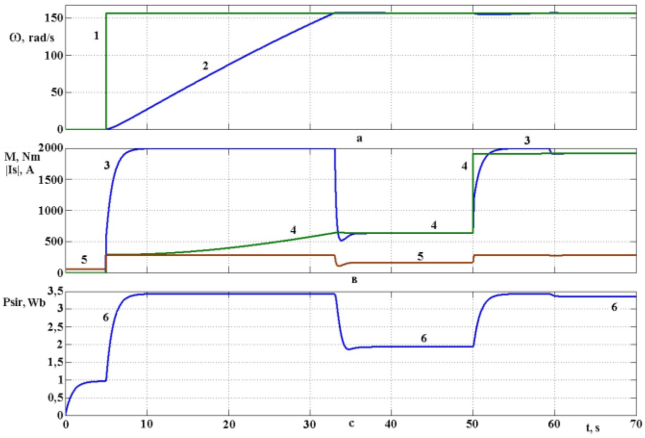

Fig. 3. Graphs of transient processes when applying the MTPA strategy to the vector control system of the stator current of an IM during acceleration and movement of an electric bus at a speed of 95 km/h

At a time of 50 s, the electric bus begins to move up the road with a slope of 8%. The load torque immediately increases from 639 Nm to 1915 Nm (graph 3). The motor speed of the electric bus briefly decreases to 154.9 rad / s (graph 2). The current in the stator winding increases from 160 A to a nominal value of 283 A (graph 5). The flux coupling of the rotor increases from 1,942 Wb to 3,433 Wb in the time interval from 50 s to 59 s (graph 6). At the same time interval, the electromagnetic torque of the motor increases from 639 Nm to 1997 Nm (graph 3).

At time 59 s, the speed of the electric bus increases to a set value of 157 rad / s (graph 2). Then the current in the stator winding decreases from the nominal value of 283 A to 277 A (graph 5). The flux coupling of the rotor decreases from 3,433 Wb to 3,362 Wb (graph 6). The electromagnetic torque of the engine decreases from 1997 Nm to 1915 Nm (graph 3).

5. Conclusion

1. The MTPA strategy is considered, which consists in the fact that with the same value of current in the stator winding of IM will develop the largest electromagnetic torque, if in the system of vector control of the stator current the angle between the vector of the stator current and the vector of the flux coupling of the rotor is equal to 45 electrical degrees.

2. When applying the considered MTPA strategy to the system of vector control of the stator current of an asynchronous motor, at the same value of the stator current, it allows the motor to develop a significantly greater electromagnetic torque compared to the system of vector control of the stator current. When limiting the stator current at the nominal level, the application of the considered MTPA strategy to the vector control system of the stator current theoretically allows obtaining an electromagnetic moment 2.56 times greater. This is due to the fact that the motor must work with a rotor flux coupling almost 3.55 times greater than with vector control of the stator current, which is not realistic for a general industrial IM with a nominal voltage of 380 V.

3. When applying the considered MTPA strategy to the vector control system of the stator current of an asynchronous motor, it is necessary to increase the effective value of the voltage on the stator winding by 3.57 times relative to the nominal value of the voltage, which is also not realistic for a general industrial IM.

4. When using general industrial engines, it is unlikely to be possible to use the considered MTPA strategy to increase the electromagnetic moment, since this strategy requires a multiple increase in the value of the flux coupling of the IM rotor and a multiple increase in the value of the voltage on the stator winding. For the considered example of the application of the considered strategy, the MTPA requires special high-voltage IMs with a nominal current of 200 A and a nominal line voltage of 1362 V.

5. For general industrial motors, the considered MTPA strategy can be used only with values of the stator current significantly lower than the nominal one. In order for the rotor flux coupling not to exceed the nominal value, it is necessary that the amplitude value of the magnetizing current does not exceed the nominal value. The application of the considered MTPA strategy means that the value of the current amplitude in the stator winding of the motor 4A280S4 should not be more than 79.8 A. At the same time, the maximum value of the electromagnetic moment that will be developed by IM will be equal to 158.5 Nm, which is much smaller than the nominal value.

6. The energy losses in IM steel, which make up a significant share of the total energy losses, were not taken into account. The saturation of the IM magnetic system was also not taken into account.

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MTPA STRATEGY FOR THE ELECTRIC VEHICLE DRIVE

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Abstract. When the vehicle is moving, the driving torque that the traction motor should develop can be very large. Therefore, to prevent over loading of the traction motor by current, it is necessary to limit the current in the stator winding to the nominal value. In this regard, it is necessary to develop a system of vector control of the stator current of an induction motor, in which, at the nominal value of the stator current, the induction motor will develop the largest possible electromagnetic moment. Today, the problem of obtaining the maximum electromagnetic moment per unit current stator decides the MTPA strategy. Therefore, the aim of the work is to develop a system for regulating the moment of induction motor using the MTPA strategy, which provides the maximum value of the electromagnetic moment per unit current in the stator winding, as well as conducting a comparative analysis of the traction properties of an asynchronous electric drive when applying the MTPA strategy and in its absence. It is also necessary to clarify the requirements that the MTPA strategy imposes on the technical parameters of the induction motor and the restrictions that the real parameters of the induction motor impose on the MTPA strategy. The study was conducted on the example of a traction asynchronous electric drive of a city bus.

As a result of this work, it was found that with the same current value in the stator winding, the induction motor will develop the greatest electromagnetic moment if the angle between the stator current vector and the rotor flux vector is equal to 45 electric degrees. By limiting the current of the stator induction motor at the nominal level, the application of the MTPA strategy allows obtaining an electromagnetic moment 2.56 times greater than in the absence of an MTPA strategy. This is due to the fact that when applying the MTPA strategy, the rotor flux linkage should exceed 3.55 times the nominal flux coupling of induction motor. To get so big the flux coupling of the rotor must increase the value of the voltage on the stator winding by 3.57 times relative to the nominal voltage value.

When applying the MTPA strategy, the flux linkage of the rotor will not exceed the nominal value only at stator current values 3.54 times less than the nominal value of the stator current. In this case, the maximum value of the electromagnetic moment that will develop induction motor will be 4.92 times less than the nominal value of the moment of induction motor.

In developing the MTPA strategy, the saturation of the magnetic system AD was not taken into account.

Keywords – induction motor, vehicle, electromagnetic moment, energy, MTPA strategy.

СТРАТЕГІЯ МТРА ДЛЯ ЕЛЕКТРОПРИВОДА ТРАНСПОРТНОГО ЗАСОБУ

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Анотація. При русі транспортного засобу значення рушійного моменту, який має розвивати тяговий двигун, може бути дуже великим. Тому для запобігання перенавантаженню тягового двигуна за струмом необхідно обмежити струм в обмотці статора номінальним значенням. В зв’язку з цим треба розробити систему векторного керування струмом статора асинхронного двигуна, в якій при номінальному значенні струму статора асинхронний двигун буде розвивати максимально великий електромагнітний момент. Сьогодні задачу отримання максимального електромагнітного моменту на одиницю струму статора вирішує стратегія МТРА. Тому метою роботи є розробка системи регулювання моменту АД з застосуванням стратегії МТРА, яка забезпечує максимальне значення електромагнітного моменту на одиницю струму в обмотці статора, а також проведення порівняльного аналізу тягових властивостей асинхронного електроприводу при застосуванні стратегії МТРА і при її відсутності. Також необхідно з’ясувати вимоги, які стратегія МТРА пред’являє до технічних параметрів АД і обмежень, які реальні параметри АД накладають на стратегію МТРА. Дослідження проводилось на прикладі тягового асинхронного електропривода міського автобуса.

В результаті проведеної роботи було з’ясовано, що при однаковому значенні струму в обмотці статора АД буде розвивати найбільший електромагнітний момент, якщо кут між вектором струму статора і вектором потокозчеплення ротора буде дорівнювати 45 електричних градусів. При обмеженні струму статора АД на номінальному рівні застосування стратегії МТРА дозволяє отримати електромагнітний момент у 2,56 рази більший ніж при відсутності стратегії МТРА. Це обумовлено тим, що при застосуванні стратегії МТРА потокозчеплення ротора має перевищувати у 3,55 рази номінальне потокозчеплення АД. Для отримання такого великого потокозчеплення ротора необхідно збільшити значення напруги на обмотці статора у 3,57 рази відносно номінального значення напруги.

При застосуванні стратегії МТРА потокозчеплення ротора не буде перевищувати номінального значення лише при значеннях струму статора в 3,54 рази менших за номінальне значення струму статора. При цьому максимальне значення електромагнітного моменту, який буде розвивати АД, буде у 4,92 рази меншим за номінальне значення моменту АД.

При розробці стратегії МТРА не було враховане насичення магнітної системи АД.

Ключові слова – асинхронний двигун, транспортний засіб, електромагнітний момент, енергія, стратегія МТРА.

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