



$$T = \frac{(L'_{2\sigma} + L_m) \cdot s_\alpha}{R'_2}, \quad (3)$$

where  $L'_{2\sigma}$  – leakage inductance of rotor's windings referred to the stator side;  $L_m$  – magnetizing inductance;  $R'_2$  – resistance of rotor's windings referred to the stator side;  $s_\alpha$  – slip.

$$s_\alpha = \frac{\Delta\omega}{\omega_1}, \quad (4)$$

where  $\omega_1$  – speed of stator magnetic field;  $\Delta\omega$  – difference between rotor mechanical speed and speed of stator magnetic field.

The angle between vectors of stator current and rotor flux is

$$\varphi_0 = \arctg(T\omega_1). \quad (5)$$

Now if we recall the equation for engine torque (1), we get

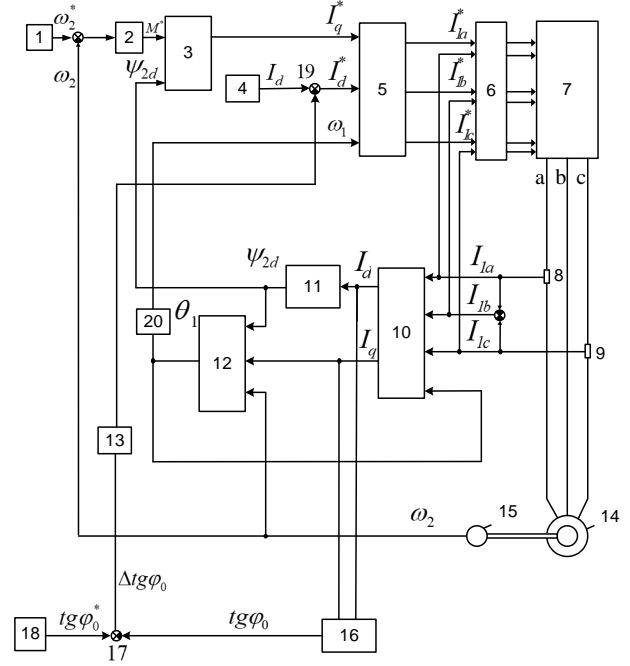
$$M_{EM} = \frac{3}{2} \cdot p \cdot \frac{L_m}{L'_2} L_m |P_1| |\varphi_z| \cdot \sin(\varphi_0) = \frac{3}{2} \cdot p \cdot \frac{L_m^2}{L'_2} \cdot |P_1|^2 \cdot \frac{T \cdot \Delta\omega}{T^2 \cdot \Delta\omega^2 + 1}. \quad (6)$$

Assume  $|P_1| = const$ . From (6) it follows that the engine torque reaches its maximum when  $T \cdot \omega_1 = 1$ ;  $tg\varphi_0 = 1$ . Then the optimal value of the angle between vectors of stator current and rotor flux is

$$\varphi_{0opt} = \frac{\pi}{4}. \quad (7)$$

The block diagram of an optimal frequency-regulated electric drive with the adjustment of current component on the axis  $d$  is shown in Fig. 3. This adjustment aimed to ensure the equation (7).

The AC drive contains a three-phase inverter 7, the outputs of the inverter are connected to the stator windings of the induction motor 14, two current sensors 8, 9. The speed sensor 15 mounted on the shaft of the motor 14. The control inputs of the inverter 7 are connected to the outputs of the pulse width modulation (PWM) block 6. The outputs of the sensors 8, 9 go to the inputs of current adder and the PWM block 6. The output of the speed sensor 15 is connected to negative input of the speed comparison block. The speed reference block 1 connected to positive input of the speed comparison block. Output of the speed comparison block goes to the PI speed controller 2. Output of the speed controller connected to the first input of the current  $I_q^*$  forming block. The reference signal  $I_d$  is forming in the block 4.



**Figure 3.** Block diagram of an optimal frequency-regulated electric drive with the adjustment of the current component  $I_d$  on the axis  $d$ .

The first output of the block 10 connected to the computational block of the rotor magnetic flux 11. The output of the block 11 connected to the first input of the block 12 where the actual value of the angle  $\theta_1$  of coordinate system  $dq$  calculated as follows:

$$\omega_1 = \frac{d\theta_1}{dt} = \Delta\omega + \omega_2,$$

$$\theta_1 = \frac{\omega_1}{p};$$

$$\Delta\omega = I_{1q} \frac{L_m}{T_2 \psi_{2d}},$$

where  $\Delta\omega$  – angular speed of rotor currents,  $\omega_2$  – angular speed of motor shaft rotation.

The second input of block 12 is connected to the second output of the block 10. The third input of the block 12 is connected to the speed sensor 15. The output of block 12 is connected to the fourth input of the block 10 that converts the stator currents from ABC to dq coordinate system.

The adjustment of the current component  $I_d$  on the axis  $d$  for ensuring the optimal value of the angle  $\varphi$  contains the blocks 16, 17, 18, 13. The block 16 calculates

$$tg\varphi_0 = I_{1q} / I_{1d},$$

this signal goes to comparison the block 17 that outputs the difference between reference  $tg\varphi_0^*$  and actual  $tg\varphi_0$  coming from the block 18. The signal from the block 13 goes to the adder 19, and then it corrects the current component  $I_d$ . Outputs from the blocks 3, 19, 20 connected to the block 5 transforming  $(d,q)$  to  $(A,B,C)$ . Three outputs of the block 6 connected to three inputs of the PWM block 6. Six outputs of the block 6 connected to six control inputs of the three-phase inverter 7. The inverter forms the stator current of the induction motor 14 using transistors.

## 2. EXPERIMENTAL RESULTS

The control system discussed in this paper was simulated in Matlab Simulink [6,7]. Parameters of motor used for simulation are: 28 kW, 380 V, 50 Hz. The simulation results of systems with and without proposed adjustment are performed in Table 1. A comparison study was conducting using the values of stator currents in steady state.

**Table 1.** Stator currents

Percent of full load torque, %	Stator current in typical control system, (A)	Stator current in control system with adjustment, (A)
100	80	70
75	65	60
50	52	48
25	39	35

The simulation results demonstrate the reduction of stator current by 12.5% in the system with adjustment in steady state and with the nominal static torque on the motor shaft.

## 3. CONCLUSION

The vector control system of an induction motor with adjustment of mutual position of torque-forming vectors provides an increase in energy savings and reduces the ratio “stator current / torque” in average by 10%.

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