Simulation of Electric Drive With Direct Torque Control of Induction Motor

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Contribution to the state of the art

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Abstract: The main requirements for traction electric drives are listed and discussed. The direct torque control of an induction motor electric drive is established by a survey of operation modes of traction electric drives to thoroughly satisfy the requirements for traction electric drive. The topologies and operation principles of two-and three-level voltage source inverters are presented. The advantages and shortcomings of three-level voltage source inverters to be applied on locomotive traction drives are highlighted in relation to the two-level ones. The recommendations of choice between different voltage source inverter topologies are given. The topology and principles of operation of direct torque control of induction motors with two- and three-level voltage source inverters are described. The simulation peculiarities of electric drives with direct torque control and two- and three-level inverters in Matlab are considered. The simulation results are presented. The techniques to reduce the torque oscillations are shown and implemented in Matlab Simulink.

Keywords: induction motor, direct torque control, voltage source inverter, equivalent circuit, control system, Matlab.

Introduction

The choice of the type of electric energy converter, electric motor and its control systems, which have to implement a desired traction forces and torques, is a key clue in a process of designing of up-to-date locomotives. Nowadays, electric drive with induction motors is employed as traction one in locomotives manufactured in Russian Federation [7]. An induction motor with the squirrel-cage rotor has a number of known advantages in front of DC-motor that allows to increase reliability and efficiency and decrease weight and dimensions of the electric drive [5]. A correctly chosen electric drive has to satisfy the next main requirements:

- It has to provide high value of the torque at low values of the speed and high value of the power at high values of the speed.
- It has to have a wide range of the speed including regions with the constant torque and the constant power.
- It has to deliver a fast torque response on the reference change.
- It has to be robust on variation of operation modes,parameters, faults and malfunctions of electrical and mechanical units.
- It has to have high value of the reliability and efficiency in the whole range of modes including braking and reversing.

The survey of electric drives lets us to conclude that the best option for it is a voltage-fed inverter induction motor that satisfies the above listed requirements almost thoroughly [3,4]. There are a numerous structures and techniques to solve the task of speed and/or torque control, the control systems can be divided into three main groups. Historically, the scalar control system is the first technique implicating the frequency converter to control the motor speed [5,6]. It utilizes the simultaneous variation of both magnitude and frequency of the stator voltage regardless to any phase value. The scalar control is easily provided by current sensors, sometimes the speed sensor is added to it for more accuracy delivering. The main applications employing such a type of speed control are a water and oil pumps, fans, conveyers and a range of traction drives of locomotives used in Russian railways. The second group is shaped of vector control systems which adjust continuously not only magnitude and frequency of the stator voltage but also phase between vectors of some currents and/or flux linkages [1]. Vector control needs a high precision current, voltage, flux and speed sensors. Some of sensors are substituted for identifiers and observers in state-of-art electric drives on a base of fast digital signal processors. The third group of control systems uses the discrete way of adjusting provided by using of relay controllers and predetermined states of induction motor and voltage source inverter. This technique of control is named direct torque control [9]. The second and third groups of control systems are implemented for applications requiring high accuracy and fast response. As a payback for its intrinsic structure and complicated network of sensors, these systems deliver higher values of efficiency than the scalar ones.

So, the system of direct torque control is an up-to-date and prospective control system of electric drive. This investigation aims to simulate electric drive with direct torque control and three-level inverter and compare its results to similar drive with the two-level inverter.

Backgrounds of Two- and Three-Level Voltage Source Inverters

The historically traditional type of inverter for traction motor is the two-level voltage source inverter (Fig. 1) [11]. This inverter produces 8 voltage vectors, 2 of which have zero magnitude (Fig. 2). The main requirements for the correct switching of transistors are the following: the capacitor C has not to be short-circuited; the next states of transistor legs have to differ only by state of a single transistor.
The first requirement is satisfied by applying the next switching functions:

$$S_i = 1, \Rightarrow (S_{i1}, S_{i2}) = (1,0) \quad (1)$$
$$S_i = 0, \Rightarrow (S_{i1}, S_{i2}) = (0,1) \quad (2)$$

where i denotes phase of a, b, c.

These switching functions deliver vector of the stator voltage as follow:

$$v_s = (2/3)^{1/2} \left(v_{aN} + v_{bN} e^{-j2\pi/3} + v_{cN} e^{j2\pi/3}\right) \quad (3)$$

where v_a, v_b, v_c denote the voltages of the respective phases.

The second requirement is satisfied by arrangement of switching functions as it shown in Fig. 2.

Since recently, the multi-level voltage source inverters have been employed in electric drive. A number of various inverter topologies has been developed. The main target of it is to enhance the harmonic spectrum of the stator voltage and current, to increase switching frequency of inverter transistors, to reduce the speed of output voltage changing that leads, in its turn, to fewer weight and dimensions of output filters and reactances.

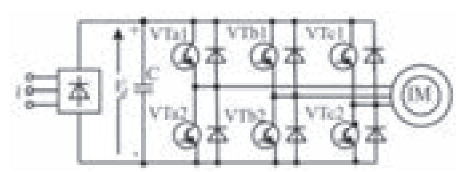


Fig. 1. *Topology of the two-level inverter*

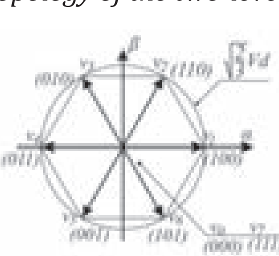


Fig. 2. *Vectors of the output voltage of the inverter (Fig. 1)*

The topology of one of three-level inverters is shown in Fig. 3. This inverter is fed by voltage source with neutral point. The inverter consists of 12 transistors $VT_{a1}...VT_{c4}$ (4 series connected transistors $VT_{i1}...VT_{i4}$ in each leg). All transistors have the anti-parallel diode providing the back direction of current flowing. The scheme is augmented by 6 clamped diodes (2 diodes on each leg) allowing to connect each of phase of the stator winding to the neutral point. All transistor legs have three states. The main requirements for the correct switching of transistors are the same as for the two-level inverter. The switching functions providing the requirement are written as follows:

$S_i = -1 = n, \Rightarrow (S_{i1}, S_{i2}, S_{i3}, S_{i4}) = (0,0,1,1)$ (4)

$S_i = 0 = o, \Rightarrow (S_{i1}, S_{i2}, S_{i3}, S_{i4}) = (0,1,1,0)$ (5)

$S_i = 1 = p, \Rightarrow (S_{i1}, S_{i2}, S_{i3}, S_{i4}) = (1,1,0,0)$ (6)

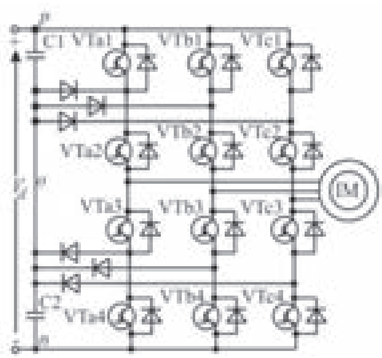


Fig. 3. *Topology of the three-level inverter with clamped diodes*

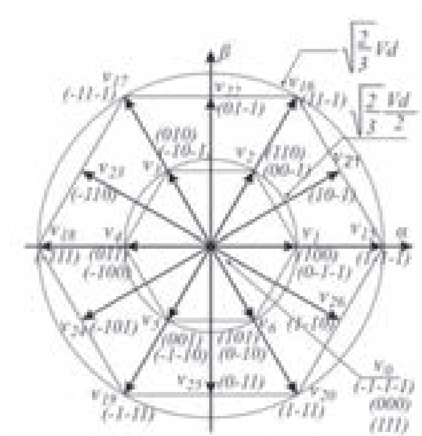


Fig. 4. *Vectors of the output voltage of the inverter (Fig. 3)*

The three-level inverter has 27 vectors of the output voltages. If the values of capacitances *C1* and *C2* are equal then the voltages dropped on each capacitance are also equal. It leads to coincidences of some vectors and only 19 vectors of the voltage are left. All the vectors and its arrangement providing the correct operation of inverter are shown in Fig. 4. The voltage vectors can be divided into 4 groups in regard to its magnitude. The large vectors are created by connection all three phases of the stator winding to the positive *p* or negative *n* points of voltage source, except the state when the three legs connected to the same point. The mean voltage vectors are the vectors formed by connection of one phase of the stator winding to the neutral point *o* while the two others are connected to the positive *p* and negative *n* points of voltage source, respectively. The simultaneous connection of two legs to the same point while the third one connected to the point next to it creates the group of small vectors. The zero vector is produced by simultaneous connection of all three legs to the same point. The feature of the inverter with clamped diodes is that the groups of the small vectors could be formed by two different combinations of the switching functions (4) – (6).

The more complicated three-level inverters have the advantages before the two-level ones as it was stressed earlier. But, such a redundancy of a semiconductor devices could also mean a higher value of likelihood of any device fault or malfunction. The relevance of three-level inverters using in industrial and traction applications is mainly determined from the thermal behavior of power switches and the power losses. As some investigations show, the implementation of the three-level inverters is proved from the thermal conditions of semiconductor devices in the range of medium and high switching frequency since frequency of some kHz.

Background sof direct torque control

The system of direct torque control of an induction motor (Fig. 5) wasfor the first time introducedin the middle of 1980's [10,11,12].The basic principle of its operation lays upon the keeping of permanent values of torque *T*and stator flux linkage ψ_s(regarding to the hysteresis band)which is implemented by choice of some output voltage vectors of voltage source inverter.The references on the output voltage vectors are the values of torque and flux linkage voltage references $\Delta_T$and$\Delta_\psi$taking discrete levels depending on sign and value of torque and flux linkage errors $T_{ref} - T$and$\psi_{ref} - \psi_s$, respectively, and sector of flux linkage. The main difficulty of such control is an accurate evaluation of the torque and flux linkage.The one of possible scheme of direct torque control is shown in Fig. 5. The transformation from three- to two-coordinated reference frame(A, B, C → α, β) is done on the basis of sensors data of the current $I_s$and voltage $V_s$of two phases of the stator. After that, the respective stator flux linkages coordinates are evaluated:

$$\psi_{s\alpha} = \int (V_{s\alpha} - I_{s\alpha} R_s \psi_{s\alpha} = \int (V_{s\alpha} - I_{s\alpha} R_s)\mathrm{dt} \quad (7)$$

$$\psi_{s\beta} = \int (V_{s\beta} - I_{s\beta} R_s \psi_{s\beta} = \int (V_{s\beta} - I_{s\beta} R_s)\mathrm{dt} \quad (8)$$

where R_s denotes the stator resistance.

It is obvious that direct torque control is very sensitive to the correctness of the used value of stator resistance due to the stator flux linkage calculation depends on the procedure of integration. As it shown in [8], the stator resistance calculation error of 1% causes significant drop in the quality indicators. The higher values of this error cause the lost of stability, so it could be recommended to employ the stator winding temperature correction [7].

The electromagnetic torque is evaluated as follow:

$$T = \frac{3}{2} \mathrm{p}_n (I_{s\beta}\psi_{s\alpha} - I_{s\alpha}\psi_{s\beta}) \quad (9)$$

Where p_n denotes the number of pole pairs.

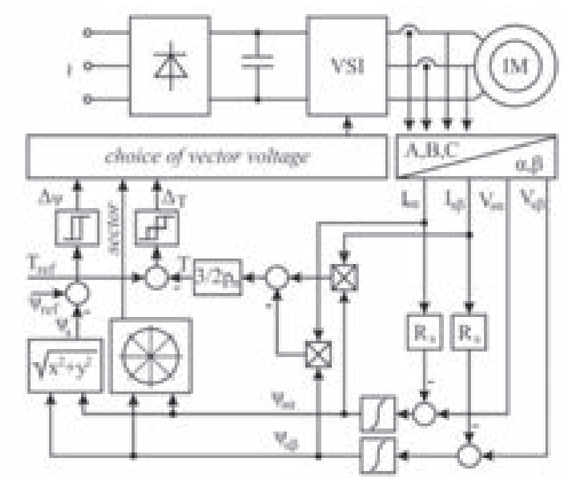


Fig. 5. *Direct torque control topology*

Based on the scientific researches and proceedings survey[3,4,7,8,10], the main advantages of direct torque control relating to the classic version ofrotor field-oriented vector control systemare summarized asfollows:

- small response time of the torque and flux linkage loops;
- absence of the coordinate transformer (Fortran's formation from/to the frame synchronously rotated with the rotor shaft);
- absence of the speed sensor.

Alongside the advantages, there are some drawbacks:

- severe distortion of the stator current, the difficulties of stator current control;
- significant oscillation of torque;
- alternating switching frequency.

It should be noted that the magnitude of the torque oscillations and shape of the stator current depend directly on the type voltage source inverter applied to feed an induction motor.

With the two-level inverter applied in the scheme, the three and two position relay controllers are employed as a torque and flux linkage controllers, respectively.The choice of proper vector voltage of the inverter is corresponded to the data of the Table 1 [9].

Table 1. *The state of inverter (Fig. 1)*

Δ_ψ	Δ_T	sector					
		1	2	3	4	5	6
+1	+1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	+1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

Table 2. *The state of inverter (Fig. 3)*

Δ_ψ	Δ_T	$\omega < \omega_{\rho\alpha\tau}/2$						$\omega > \omega_{\rho\alpha\tau}/2$					
		sector						sector					
		1	2	3	4	5	6	1	2	3	4	5	6
+1	+2	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}	V_{15}
	+1	V_2	V_3	V_4	V_5	V_6	V_1	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}
	0	zero vector						zero vector					
	-1	V_6	V_1	V_2	V_3	V_4	V_5	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}
	-2	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{20}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}
0	+2	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{21}
	+1	V_3	V_4	V_5	V_6	V_1	V_2	V_{17}	V_{18}	V_{19}	V_{20}	V_{15}	V_{16}
	0	zero vector						zero vector					
	-1	V_5	V_6	V_1	V_2	V_3	V_4	V_{19}	V_{20}	V_{15}	V_{16}	V_{17}	V_{18}
	-2	V_{25}	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}
-1	+2	V_{23}	V_{24}	V_{25}	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{21}	V_{22}
	+1	V_3	V_4	V_5	V_6	V_1	V_2	V_{17}	V_{18}	V_{19}	V_{20}	V_{15}	V_{16}
	0	zero vector						zero vector					
	-1	V_5	V_6	V_1	V_2	V_3	V_4	V_{19}	V_{20}	V_{15}	V_{16}	V_{17}	V_{18}
	-2	V_{24}	V_{25}	V_{26}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{21}	V_{22}	V_{23}

With the three-level inverter applied in the scheme, the five and three position relay controllers are employed as a torque and flux linkage controller, respectively. The choice of proper vector voltage in this case is corresponded to the data of the Table 2 [12]. In the Table 2 and after, ω denotes the rotor speed, the index *rat* denotes the rated value.

Description of Simulation Technique

The equivalent circuit of an induction motor in the reference frame used for simulation is shown in Fig. 6. Here, $L_{\sigma s}$, $L_{\sigma r}$ denote the stator and rotor leakage inductances; L_μ denotes the magnetizing inductance; ω_k denotes the speed of the reference frame; i_s, i_r denote the currents flowing through the stator and rotor windings; i_μ denotes the current flowing through the inductance of L_μ; ψ_s, ψ_r, ψ_μ denote the stator, rotor and magnetizing flux linkages, respectively. The equivalent circuit does not account for the stator and rotor iron losses.

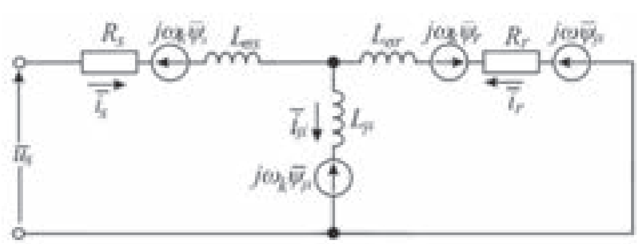


Fig. 6. *Equivalent circuit of induction motor*

To simulate an induction motor, the following equations describing the equivalent circuit (Fig. 6) are used:

$$v_{s\alpha} = R_s i_{s\alpha} + \frac{d\psi_{s\alpha}}{dt} - \omega_k \psi_{s\beta}, v_{s\beta} = R_s i_{s\beta} + \frac{d\psi_{s\beta}}{dt} + \omega_k \psi_{s\alpha}, \quad (10)$$

$$0 = R_r i_{r\alpha} + \frac{d\psi_{r\alpha}}{dt} - (\omega_k - \omega)\psi_{r\beta}, 0 = R_r i_{r\beta} + \frac{d\psi_{r\beta}}{dt} + (\omega_k - \omega)\psi_{r\alpha}, \quad (11)$$

$$\psi_{s\alpha} = L_s i_{s\alpha} + L_\mu i_{r\alpha}, \psi_{s\alpha} = L_s i_{s\beta} + L_\mu i_{r\beta}, \quad (12)$$

$$\psi_{r\alpha} = L_r i_{r\alpha} + L_\mu i_{s\alpha}, \psi_{r\alpha} = L_r i_{r\beta} + L_\mu i_{s\beta}, \quad (13)$$

where α,β denote the coordinate axes.

The mechanical moving is described as follow:

$$T - T_L = J\frac{d\omega}{dt}, \quad (14)$$

where T_L denotes the load torque, J denotes the moment of inertia.

For reaching the correct results of simulation of electromechanical and energy processes it is necessary to take into account the effect of current replacement that influences on operation under low frequency condition. The active and inductive resistance are given by:

$$R_r = K_r R_{r,sl} + R_{r,end}, \quad (15)$$

$$X_r = K_x X_{r,sl} + X_{r,end}, \quad (16)$$

where $R_{r,sl}$ and $X_{r,sl}$ are resistances of slot winding, $R_{r,end}$ and $X_{r,end}$ are resistances of pieces of end rings between neighbor rotor bars, K_r and K_x are coefficients taking resistance change under the effect of

$$K_r = \xi\frac{sh2\xi + sin2\xi}{ch2\xi - cos2\xi}, \quad (17)$$

$$K_x = \xi\frac{sh2\xi - sin2\xi}{ch2\xi - cos2\xi}, \quad (18)$$

where ξ denotes the specified bar height:

$$\xi = 2\pi 10^{-3} h\sqrt{\frac{sf_s b}{10\rho b_{sl}}}, \quad (19)$$

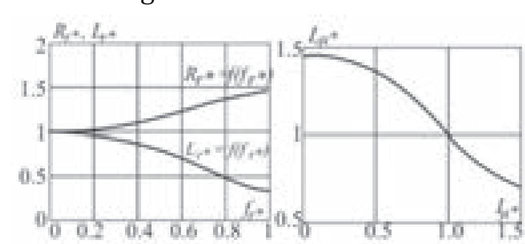
h is the bar height, ρ is specific resistance of the bar material, b is the bar width, b_n is the slot width.

The dependance of the L_μ from the magnitude of magnetising current I_m is as follows

$$L_{\mu*} = -0{,}002I_{\mu*}^6 + 0{,}037I_{\mu*}^5 - 0{,}261I_{\mu*}^4 + 0{,}87I_{\mu*}^3 - 1{,}278I_{\mu*}^2 + 0{,}214I_{\mu*} + 1{,}413. \quad (20)$$

where $L_{m*} = L_m / L_{m,rat}$ and $I_{m*} = I_m / I_{m,rat}$, index *rat* denotes the rated value of some parameter.

The nonlinearity described by (15), (16)and (20) are shown in Fig. 7.



a) b)

Fig. 7. *The rotor resistance and inductance depend on frequency of the rotor current (a), andthe magnetizing inductance depends on the magnetizing current (c)*

The blocks *Real Image to Complex* and *Complex to Magnitude Angle* from library of *Simulink* are implicated to evaluate of magnitude and phase of flux linkage. Generally, if the flux linkage phase was determined, the sector of flux linkage could be found by implying the next expressions (phase θ of the flux linkage is written in grades; simultaneously, it is taken into account that the phase θ varies -180° to 180°):

if -30°<θ≤ 30°, then $\vec{\Psi}_S$ belongs to sector *1*;

if 30° <θ≤ 90°, then $\vec{\Psi}_S$ belongs to sector *2*;

if 90°<θ≤ 150°, then $\vec{\Psi}_S$ belongs to sector *3*;

if θ> 150° or θ≤ -150° then, то $\vec{\Psi}_S$ belongs to sector *4*;

if -150°<θ≤ - 90°, then $\vec{\Psi}_S$ belongs to sector *5*;

if -9 0̊ <θ≤ -30°, then $\vec{\Psi}_S$ belongs to sector *6*.

To calculate the phase sector number, the block *Flux sector seeker* included in the subsystem of *DTC Induction motor drive* (*Sym Power Systems* → *Application Libraries* → *Electric Drives library* → *AC drives*) is used.

The relay controllers of flux linkage and torque implicated for simulation have the static characteristics shown in Fig.8. The implementation of relay controllers by means of Matlab is shown in Fig. 9 (the main units are *Relay*, *Logical operator*, *Gain*, *Data type conversion*, *Sum*).

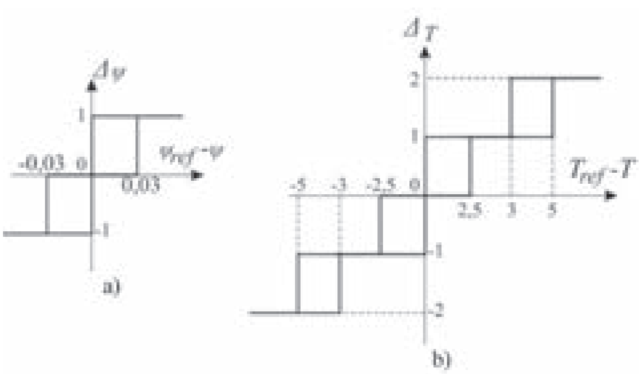


Fig. 8. *Relay controllers of flux linkage (a) and torque (b)*

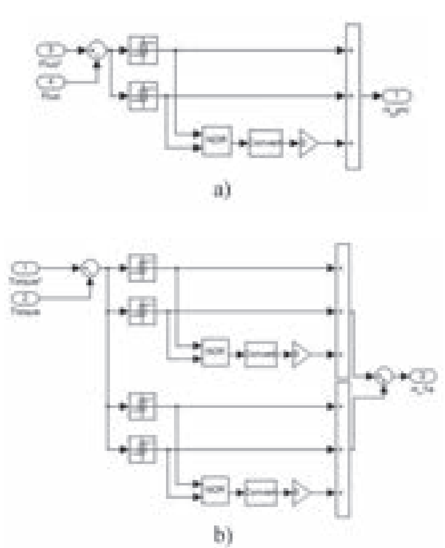


Fig. 9. *Implementation of relay controllers of flux linkage (a) and torque (b)by Matlab Simulink*

The table of voltage source inverter switching is developed in Matlab by blocks *Relay*, *Logical operator*, *Gain*, *Look-Up Table*, *Data type conversion*, *Sum* (some part of the scheme is shown in Fig. 10).

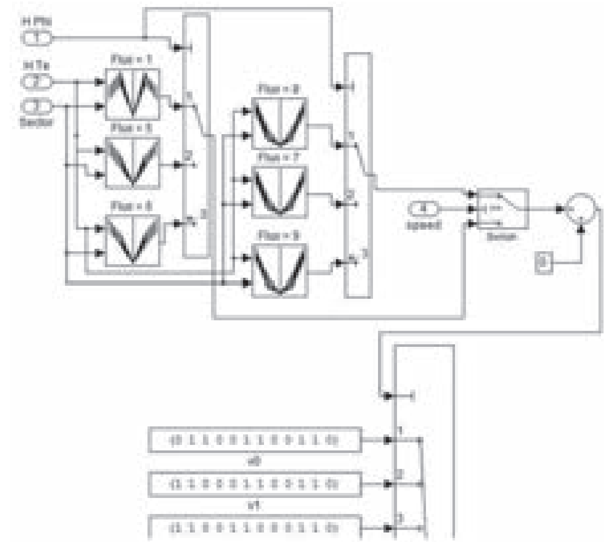
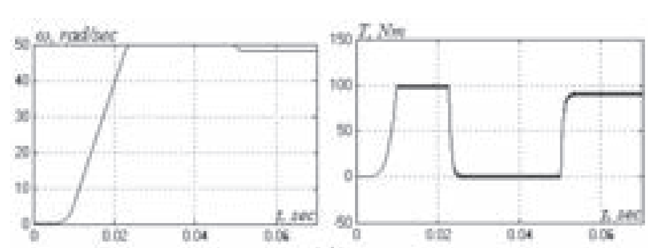


Fig. 10. *Implementation of switching table (Table 2) by means of Matlab Simulink (fragment)*

Results of Simulation

The simulation was carried out in Matlab. The three-level inverter (Fig. 3) was used, the switching functions (4) – (6) were applied to control inverter states.The induction motor was presented in accordance to (9) – (14), the nonlinearity were implemented by (15) – (20) and Fig. 7. Table 2 was employed as the table of inverter optimal switching (Fig. 10). The topology of simulated scheme coincided to the scheme (Fig. 5).

The simulation results of electric drive with the direct torque control of an induction motor are shown in Fig. 11. The parameters of induction motor to be simulated are follows: $V_{s,rat} = 380$ *V*; $I_{s,rat} = 27$ *A*; $P_{rat} = 11$ *kW*; $2p = 4$; $n_{rat} = 1460$ *rev/min*; $f_{s,rat} = 50$ *Hz*; $X_{ls} = 0{,}73\ \Omega$; $R_s = 0{,}34\ \Omega$; $X_{m,rat} = 31\ \Omega$; $X_{lr,start} = 0{,}73\ \Omega$; $X_{lr,rat} = 1{,}68\ \Omega$; $R_{r,start} = 0{,}41\ \Omega$, $R_{r,rat} = 0{,}29\ \Omega$, where P_{rat} denotes the rated mechanical power.



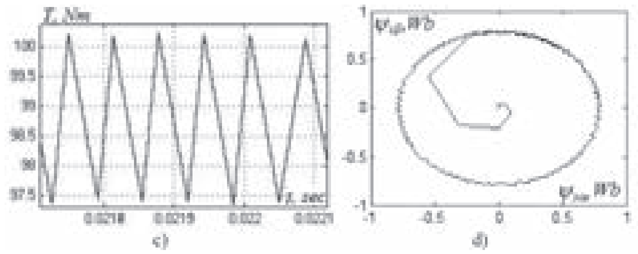


Fig. 11. *Resultsofsimulation:a)–rotorspeedvstime, b) –torquevstime, c) – torque graph (zoom in), d) – plot of stator flux linkage*

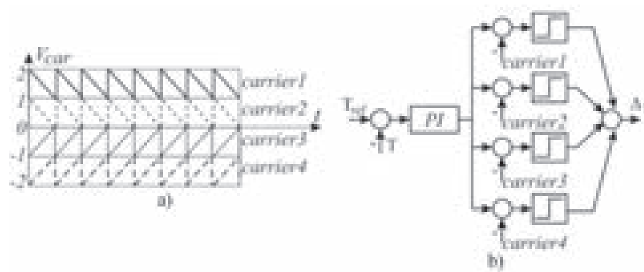


Fig. 12. *Carrier voltages graph (a) and topology of torque controller fixing the switching frequency (b)*

Analyses of the results let us conclude that the electric drive has the small response time and high accuracy of torque and flux linkages loops at the change of reference on the rotor speed and step-like change of the load torque. Relatively to the classic direct torque control with the two-level inverter (results of this system simulation is given in [8]), the investigated scheme of control system allows to reduce the torque oscillation on 25 – 40 % at the same switching frequency.

Fixing the Switching Frequency

As it was stressed earlier in the section 4, one of the main drawbacks of classic direct torque control is a variable switching frequency that imposes some extra requirements for inverter and induction motor control systems. The simple and effective way to mitigate such a drawback is to employ PI-controller of torque and pulse-width modulation [6] instead of relay controllers.To achieve this aim, the four carrier references are needed to be employed (Fig. 12). As it follows from the Fig. 12a, the limits of carrier voltages are justified by the following expressions:

$$1 \leq carrier1 \leq 2,\ 0 \leq carrier2 \leq 1,\ -1 \leq carrier3 \leq 0,\ -2 \leq carrier4 \leq -1.$$

It should be noted that the phases of two positive and two negative carriers shift on period of switching frequency.

The principle of producing the reference voltage Δ_T follows the next rules:

If $T_{ref} - T > carrier1$, then $\Delta_T = 2$;
If $carrier2 \leq T_{ref} - T < carrier1$, then $\Delta_T = 1$;
If $carrier3 \leq T_{ref} - T < carrier2$, then $\Delta_T = 0$;
If $carrier4 \leq T_{ref} - T < carrier3$, then $\Delta_T = -1$;
If $T_{ref} - T > carrier4$, then $\Delta_T = -2$.

The implementation of these rules in Matlab Simulink is shown in Fig. 13. The used blocks are *Gain*, *Integral*, *Saturation*, *Repeating Table*, *Relay* and *Sum*. The parameters *Switch on point* and *Switch off point* of block *Relay* are set out in the value *eps*.

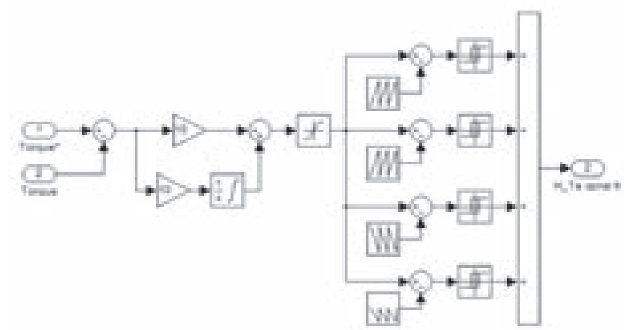


Fig. 13. *Implementation of torque controller (Fig. 12b) by Matlab Simulink*

The results of simulation of direct torque control with the application of torque controller (Fig 12b) instead of torque relay controller in the scheme (Fig. 5) show that this substitution allows to fix swirching frequency accordingly tothe period choosen (Fig. 12a). The magnnitude of torque ripple becomes a variable and non-controlling by control system. It strictly depends on the switching frequency and could be reduced by frequency increasing.

Conclusion

The simulation carried out in the present investigation by means of tools and algorithms of Matlab Simulink shows that the implementation of the three-level voltage source inverter with the three-positioned flux linkage relay controller and five-positioned torque relay controller enhances the quality of direct torque control operation. Relatively to the classic direct torque control with the two-level inverter, the investigated scheme of control system allows to reduce the torque oscillation on 25 – 40 % at the same switching frequency. Also, it leads to reducing the total harmonic distortion of the stator current. The employment of PI-controller and algorithms of pulse-width modulation instead of torque relay controller leads to the fixing of switching frequency.

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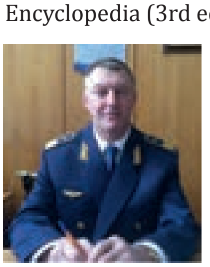

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