ISSN 1691-5402
Environment. Technology. Resources
Proceedings of the 9th International Scientific and Practical Conference. Volume 1I

Simulation of Traction Electric Drive with Vector Systems of Direct Torque Control

Ilya Fedotov, Vyacheslav Tikhonov
Pskov State Univeristy, Faculty of Electrical Engineering, Department of drive and automation systems. Address: Russian Federation, 180760, Pskov, Lenin Square, 2

Abstract. **The article deals with investigation of electromechanical and energetic characteristics of traction electric drive with vector systems of direct torque control.**

As a controlled object the traction asynchronous motor ДТА-1У1, which is used to drive the trolley-bus is considered. At the present time the usage of traction asynchronous electric drives for town transport is relevant. Due to development of power electronic devices and microprocessor-based control systems it became possible to replace DC electric drives with electric drives with asynchronous motors.

The article contains brief description of two different types of control systems: field-oriented control (FOC) and direct torque control (DTC). Principles of work for both systems are considered and the main advantages and disadvantages associated with the use of these systems are pointed out. The models of both systems for traction asynchronous electric drive, built in modeling environment MATLAB/Simulink, are given in this article for further comparative analysis. As the main quality factor of control total harmonic distortion (THD) is used.

Keywords **– DTC, FOC, simulation models, THD, traction electric drive.**

I INTRODUCTION

The mass usage of traction asynchronous motors for town transport is very promising direction. The implementation of electric drives with traction asynchronous motors has some executive and technical difficulties, described at [1]. Among them is the requirement to use complicated systems of electrical transformations based at the usage of power and information electronic devices. The efficient solution that can be used at this situation is the usage for power IGBTs combined with microprocessor-based control systems.

Department of Drive and automation systems of Pskov State University in tandem with The Pskov Factory of Electric Machines do mutual research works for development of traction electric drive, based on the usage of traction asynchronous motor, and for the simulation of its operating modes.

II VECTOR SYSTEMS OF DIRECT TORQUE CONTROL

The most preferable control systems used for traction electric drives are vector systems of direct torque control. These ones are: FOC, which is used pulse-width modulation (PWM) of base vectors to control the torque while maintaining the rotor flux linkage, and DTC wherein torque control is performed by stator flux linkage adjustment without using PWM.

FOC Principles

At 1971 F. Blaschke [2] formulated the control method, which was patented by Siemens and called «transvector control». Mathematically it is based at the equations of electromagnetic processes at an asynchronous motor written at the vector form in the reference frame oriented by the direction of magnetic field [3].

For the implementation of systems with vector control of asynchronous motor the every couple of vectors, which can be used at the equation for electromagnetic torque of unified electric machine, can be taken, but the level of system complication depends on this selection.

The equations of electromagnetic processes at an asynchronous motor have the simplest form when it written in the rotor flux linkage terms. If the vectors of rotor flux linkage and stator current are chosen combined with synchronous $(d-q)$ reference frame, and the d-axis aligned with the vector of rotor flux linkage, then the equation of electromagnetic torque of can be written as:

$$M = \frac{3 \cdot p \cdot L_m}{2 \cdot L_2} \psi_{2d} i_{1q} \qquad (1)$$

where L_μ - magnetizing inductance, L_2 - rotor inductance.

The form is similar for the one that used for DC motors, so the main problem will be the identification of ψ_{2d} and i_{1q}.

Hence, the main principle of vector control can be formulated as: in the rotor flux reference frame, the decoupled control of torque and rotor flux magnitude of asynchronous motor can be achieved acting on the q and d axis stator current components, respectively [4].

DTC Principles

The disadvantages of the vector control method are the high complexity of computational algorithm and that the control performance directly depends on the accuracy of measuring and computational operations. The algorithm based on discontinuous control and sliding modes is free of these lacks. It provides the invariability to the external disturbances and therefore, is preferred for the electric drives with severe operating conditions. For the first time the control system for variable frequency electric drives based on the discontinuous control was introduced at 1985. Later this type of control methods was called «direct torque control (DTC)».

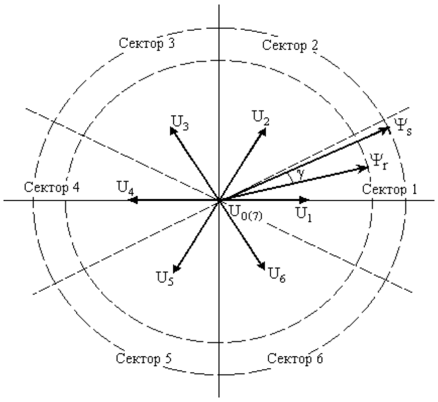


Fig. 1. Positioning the flux and voltage vectors at the $(\alpha-\beta)$ plane

The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits [4].

The main features of the system with DTC are [5]:

- hysteresis-band controllers of the stator flux linkage and electromagnetic torque;
- the presence of model of the motor for the estimation of non-observable parameters (stator flux linkage, electromagnetic torque of the motor and the rotor speed for the sensorless systems) at the control system;
- switching table for the optimal inverter voltage vector selection;
- the identificator of phase sector which the stator flux linkage vector lies in at the current moment;
- the absence of linear coordinate transformations;
- current controllers are expressly absent;
- the absence of PWM signals generator.

The electromagnetic torque of traction asynchronous motor in a DTC scheme is calculated by the expression (2):

$$m=\frac{3}{2}p\frac{k_1k_2}{\sigma L_m}\left|\Psi_s\times\Psi_r\right|= =\frac{3}{2}p\frac{k_1k_2}{\sigma L_m}\Psi_{sm}\cdot\Psi_{rm}\cdot\sin\gamma, \quad (2)$$

where p is the pole pair number; k_1, k_2 - the coefficients, which are calculated as, $k_1=L_m/L_1$, $k_2=L_m/L_2$; L_1 - stator inductance; $\sigma=1-k_1k_2$ - leakage factor of the motor; γ - space angle between stator and rotor flux vectors.

The main principle of DTC is: the electromagnetic torque of the motor can be regulated by regulation of γ angle while maintaining the rotor and stator flux magnitudes constant $\left|\Psi_s\right|=\Psi_{sm}$ and $\left|\Psi_r\right|=\Psi_{rm}$ (Fig. 1).

III Simulation models

To analyze the performance of traction electric drive with using vector systems of direct torque control in the various operating modes the simulation models for both systems were built in modeling environment MATLAB/Simulink.

FOC Model

At the model of system with vector control, shown at Fig. 2, the motor is fed by 3-phase inverter (block «DC/AC Convertor»), which works as the voltage source. For measuring phase stator currents and voltages «Three-Phase V-I Measurement» block is used. The output values of this block go to the «Currents measurement» and «Voltages measurement» blocks, respectively, which are used for transition from 3-phase reference frame to stationary $(\alpha-\beta)$ reference frame and described by the equations (3), shown below:

$$\begin{cases} i_\alpha=i_a \\ i_\beta=\dfrac{i_a+2i_b}{\sqrt{3}}=-\dfrac{i_a+2i_c}{\sqrt{3}} \end{cases}, \qquad \begin{cases} u_\alpha=u_a \\ u_\beta=\dfrac{u_a+2u_b}{\sqrt{3}}=-\dfrac{u_a+2u_c}{\sqrt{3}} \end{cases} \quad (3)$$

The calculated stator currents $i_1^{(\alpha,\beta)}$ and voltages $u_1^{(\alpha,\beta)}$ are used as input signals at the «Flux identification system» block, which is used for rotor flux calculation at stationary $(\alpha-\beta)$ reference frame, basing on the stator equations and equation for the rotor flux at stationary $(\alpha-\beta)$ reference frame:

$$\frac{d\psi_1}{dt}=u_1-i_1r_1;\quad \psi_2=\left(\psi_1-i_1\sigma L_m/k_1\right)/k_2 .(4)$$

where r_1 is stator resistance.

The «Vector-filter» block is used for the calculation of rotor flux magnitude and trigonometric functions defining current space positionace of synchronous reference frame - $\cos\vartheta_1=\psi_{2\alpha}/\left|\psi_2\right|;\sin\vartheta_1=\psi_{2\beta}/\left|\psi_2\right|$. «Rotator1» and «Rotator» blocks are used for direct and inverse Park transformation, respectively. Therefore, above-described blocks provide the transition from 3-phase reference frame to synchronous $(d-q)$ one and vice versa.

Control system has two independent feedback loops: rotor speed and rotor flux ones, and two stator current components subordinate loops, which form the stator current feedback. The information about rotor speed is received from the speed sensor. This signal is subtracted from the reference speed («Speed reference» block), and the calculated error signal is transferred to the speed controller, which forms the torque reference signal.

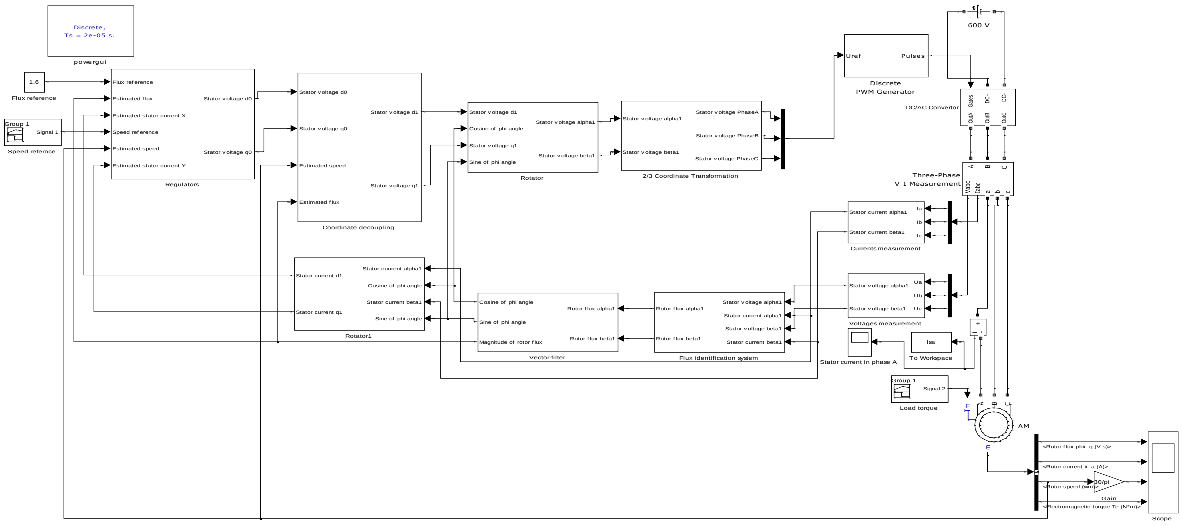


Fig. 2. Simulation model of FOC system with PWM

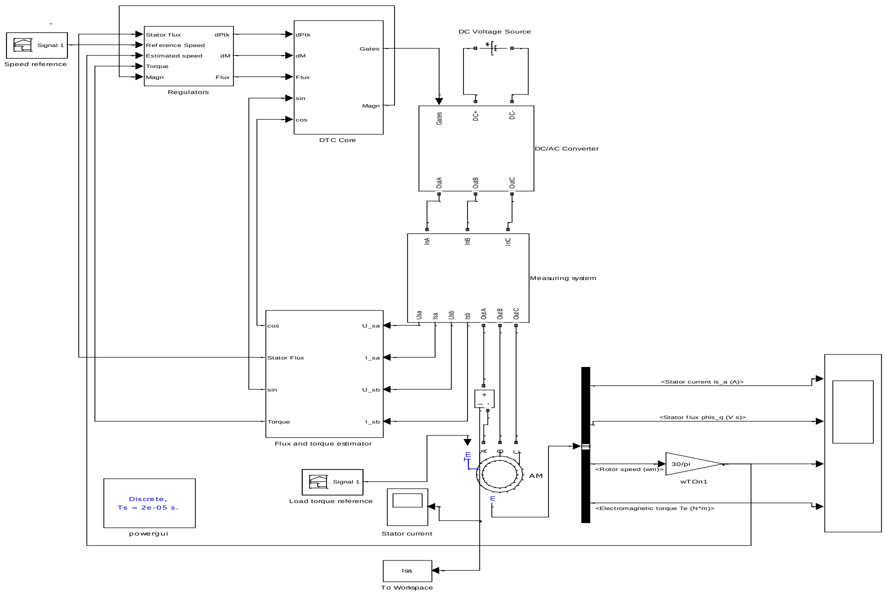


Fig. 3. Simulation model of DTC system

The q-axis stator current reference signal i^*_{1q} is formed by the division of torque reference signal by $|\psi_2|$. Stabilization of rotor flux is provided by rotor flux controller, which forms the d-axis stator current reference signal i^*_{1d}.

«Coordinate decoupling» block is used for the compensation of cross coupling between control loops and described by the expressions (5):

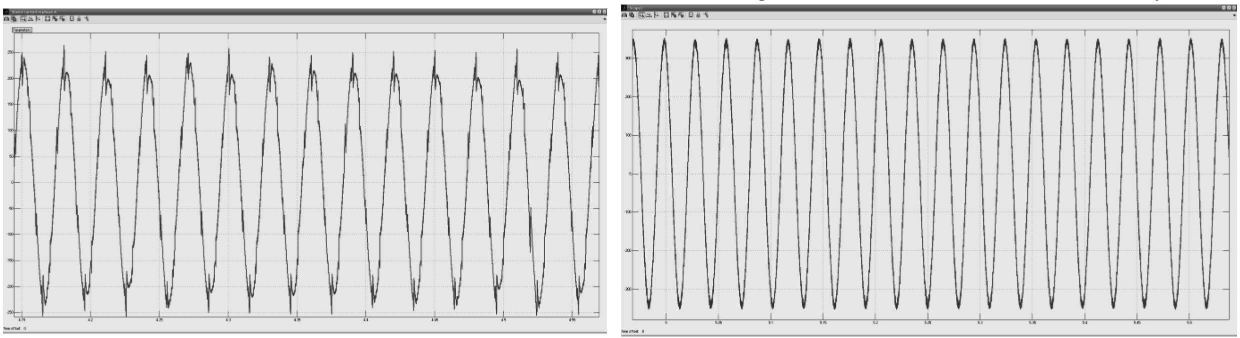
$$\begin{cases} u_{1d} = u^*_{d0} r_1 \left(1 + T_1' p\right) - u^*_{q0} \omega L_1' \\ u_{1q} = u^*_{q0} r_1 \left(1 + T_1' p\right) + u^*_{d0} \omega L_1' + \omega |\psi_2| k_2 \end{cases} ,(5)$$

where L_1' - transient stator inductance, which is calculated as $L_1' = L_1(1 - k_1 k_2)$; T_1' is calculated as $T_1' = L_1'/r_1$.

The output vector of signals $u_1^{(dq)}$ of this block is transformed by «Rotator» block to stationary $(\alpha-\beta)$ reference frame, and then to the 3-phase reference frame by the «2/3 Coordinate Transformation» block. The output signals $u_1^{(abc)}$ go to the «Discrete PWM Generator» block. The inverter is controlled by signals received from the «Discrete PWM Generator» block.

DTC Model

«DTC Core» subsystem consists of «Row Number», «Column number» and «Switching table» subsystems. The input signals of «Row Number» subsystem are the commutation functions of stator flux and electromagnetic torque hysteresis-band controllers *dPtk* and *dM* , respectively. Based on these signals the row number of switching table is calculated. To calculate the targeted column number of switching table, the «Column number» subsystem



(a) – FOC system (b) – DTC system

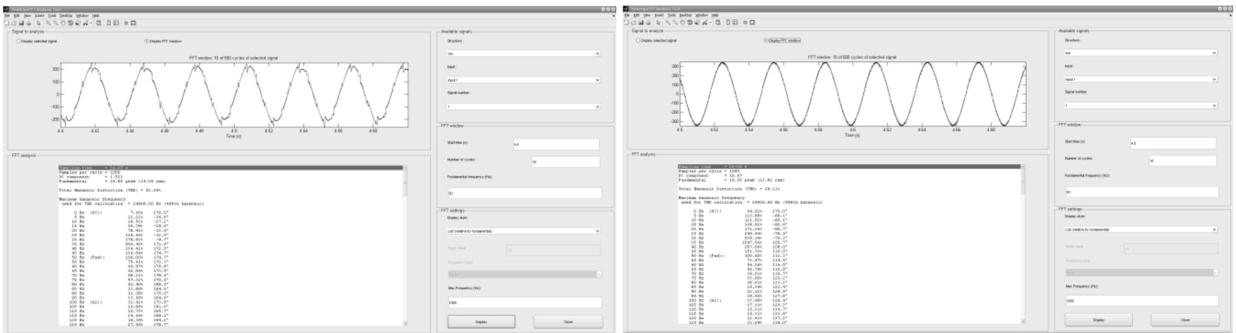
Fig. 4. Stator current waveforms for simulated systems.

Model of system with DTC, shown at Fig. 3, consists of:

- «Speed reference» block, which allows to provide the desirable form of reference signal to the system input;
- «Regulators» subsystem, which have «Reference speed», «Estimated speed», «Torque», «Stator flux» signals as input ones and the commutation functions of stator flux and electromagnetic torque hysteresis-band controllers *dPtk* and *dM* , respectively, as output signals;
- «DTC Core» subsystem;

is used. This subsystem has trigonometric functions *sin* and *cos*, defining position of stator flux vector at base vectors plane, as input signals. The output signal of switching table *Gates*, constituting an eight possible states of inverter output voltage vector U_0-U_7, wherein U_0 and U_7 are zero vectors, is calculated based on the signals entering from the outputs of «Row Number» and «Column number» subsystems.

Measuring system consists of stator current and voltage sensors and coordinate transformers, which are used for transition from 3-phase reference frame to the stationary one based on the equations (6):



(a) – FOC system (b) – DTC system

Fig. 5. Spectral composition of stator current for simulated systems calculated at «FFT Analysis» window

- DC voltage source, simulating the voltage of trolley-bus overhead contact system;
- DC/AC Converter, which transforms DC voltage of trolley-bus overhead contact system into AC voltage to feed the traction asynchronous motor;
- measuring system;
- flux and torque estimator.

$$i_{s\alpha}=\frac{2}{3}\left(i_a-\frac{i_b-i_c}{2}\right);\ i_{s\beta}=\frac{i_b-i_c}{\sqrt{3}};$$
$$u_{s\alpha}=\frac{2}{3}\left(u_a-\frac{u_b-u_c}{2}\right);\ u_{s\beta}=\frac{u_b-u_c}{\sqrt{3}} \qquad (6)$$

Vectors $i_s^{(\alpha\beta)}$ and $u_s^{(\alpha\beta)}$ serve as the basis of stator flux and torque calculation in «Flux and Torque

Estimator» block by the means of expressions (7) shown below:

$$\Psi_s^{(\alpha\beta)} = \int \left(u_s^{(\alpha\beta)} - i_s^{(\alpha\beta)} R_s \right) dt, \qquad (7)$$
$$M = \frac{3}{2} p \left(\Psi_{s\alpha} i_{s\beta} - \Psi_{s\beta} i_{s\alpha} \right).$$

It is useful to calculate trigonometric functions of turning angle of stator flux vector with the reference to the α-axis at this block, because they are required for further calculations. The functions can be found by the means of equations (8):

$$\cos \Psi_s = \frac{\Psi_{s\alpha}}{\Psi_{sm}}; \sin \Psi_s = \frac{\Psi_{s\beta}}{\Psi_{sm}}, \qquad (8)$$

where $\Psi_{sm} = \sqrt{\Psi_{s\alpha}^2 + \Psi_{s\beta}^2}$ is the stator flux magnitude.

IV Results of simulation

The following operating modes of the traction electric drive were investigated during the simulation:

- acceleration from the zero to the rated speed;
- rated speed motion;
- deceleration from the rated speed to the zero.

The characteristics shown the stator current waveforms in the different operating modes were obtained by the simulation of both control systems. The parts of these waveforms corresponding to the rated speed motion with the constant load torque M=1000 N*m are shown at Fig. 4 (a), (b) .

Total harmonic distortion (THD) was chosen as one of the features to investigate. THD is calculated as ratio between mean-square sum of spectral components of output signal, which are absent at the spectrum of input signal, and mean-square sum of spectral components of input signal.

For measuring THD in both systems «FFT Analysis» built-in Simulink tool was used, which calculate the spectral composition and meanings of harmonics at the numerical form or as histogram for the specified signal. The results of using this tool on the investigated models are shown at Fig. 5 (a), (b).

As it is possible to see from the plots above, the meanings of THD for the modeled systems are: THD=52,54% for the system with FOC, THD=28,11% for the system with DTC.

V Conclusion

Based on the obtained results it can be noted that DTC algorithm might be preferred for traction electric drives from the energetical standpoint. During the following investigations is in contemplation to receive the meanings of other energetical features to compare: power factor, efficiency, energy efficiency factor, which is calculated as $\eta_{ef} = \eta \cdot \cos\varphi$.

VI Appendix

The test machine is a three phases and 50 Hz induction machine having the following parameters as shown in Table I.

TABLE I

Parameters of the tested induction machine

Parameter	Parameter value
Power rating, P_{rated}	180 kW
Rated voltage, V_{rated}	450 V
Rated current, I_{rated}	276 A
Pole pair, p	2
Torque rating, M_{rated}	1150 N·m
Stator resistance, R_s	0,02 Ω
Leakage stator inductive reactance, x_s	0,00967 Ω
Rotor resistance, R_r	0,00859 Ω
Leakage rotor inductive reactance, x_r	0,0962 Ω
Magnetizing inductive reactance, x_m	2,6 Ω
Inertia, J	3,2 kg·m^2

VII References

[1] Иньков Ю.М., Федяева Г.А., Феоктистов В.П., «Системы управления для электроприводов с асинхронными тяговыми двигателями», Электротехника, №4, с. 8 – 12, 2009.

[2] F. Blaschke, «A new method for the structural decoupling of A.C. induction machines», in *Conf. Rec. IFAC,* Dusseldorf, Germany, Oct. 1971, pp. 1 – 15.

[3] Усольцев А.А. Частотное управление асинхронными двигателями/ Учебное пособие. СПб: СПбГУ ИТМО, 2006. – 94 с.

[4] D. Casadei, F. Profumo, G. Serra, A. Tani, «FOC and DTC: Two Viable Schemes for Induction Motors Torque Control», IEEE Transactions on Power Electronics, vol. 17, no. 5, pp. 779 – 787, Sep. 2002.

[5] Козярук А.Е., Рудаков В.В. Прямое управление моментом в электроприводе переменного тока машин и механизмов горного производства: Учебное пособие/ Санкт-Петербургский государственный горный институт (технический университет). СПб, 2008. – 99 с.