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METHODOLOGICAL AND INSTRUMENTAL SUPPORT TO DEVELOPMENT OF ELECTRIC TRACTION SYSTEMS WITH ASYNCHRONOUS MOTOR

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Abstract. The present work aims to analyze from a methodological and instrumental point of view the development of asynchronous motor propulsion systems. For this purpose, PWM and SVM modulation methods, FOC and DTC vector control techniques, as well as their advantages and disadvantages are described. The theoretical bases and functional schemes of FOC and DTC control are given, including the asynchronous motor mathematical model, similar to the direct current motor model. Special attention is paid to creating of a common meaning for describing the components operation equations of the traction system, equations that can be used for system modeling and simulation. The paper also refers to a series of modern voltage converters with vector control, which are produced by several companies in different countries and are intended for the control of three-phase asynchronous motors. The results of the study create a basis for research and development of traction systems with multiphase asynchronous motors for urban electric passenger vehicles.

Keywords*: DTC control technique, FOC control technique, PWM modulation, SVM modulation, vector control.*

Rezumat. Această lucrare își propune să evidențieze sprijinul metodologic și instrumental pentru dezvoltarea sistemelor de propulsie cu motoare asincrone. În acest scop, sunt descrise metode de modulare PWM și SVM, tehnici de control vectorial FOC și DTC, precum și avantajele și dezavantajele acestora. Sunt prezentate bazele teoretice și schemele funcționale ale controlului FOC și DTC, inclusiv modelul matematic al motorului asincron, similar modelului motorului cu curent continuu. O atenție deosebită este acordată creării unui sens comun pentru descrierea ecuațiilor de funcționare a componentelor sistemului de tracțiune, ecuații care pot fi utilizate pentru modelarea și simularea sistemului. Lucrarea se referă și la o serie de convertoare moderne de tensiune cu control vectorial, care sunt produse de mai multe companii din diferite țări și sunt destinate controlului motoarelor asincrone trifazate. Rezultatele studiului stau la baza cercetării și dezvoltării sistemelor de tracțiune cu motoare asincrone polifazate pentru vehiculele de pasageri electrice urbane.

Cuvinte cheie: *tehnica de control DTC, tehnica de control FOC, modulație PWM, modulație SVM, control vectorial.*

1. Introduction

Passenger transport has been and remains a challenge for the administration of large and medium-sized cities. An adequate response to this challenge involves the creation of a balanced and efficient urban transport system, using different types of transport, including subway, tram, trolleybus, bus, minibus, etc. At the same time, taking into account international and European regulations on the reduction of energy consumption and emissions, at present, the development of urban transport systems focuses on the predominant use of electric transport, including trolleybuses, which are more efficient and environmentally friendly [1]. For example, the efficiency of electric transport is 95-98%, and that of the internal combustion engine 20-30% [2].

In the evolution of electric traction systems, traction systems with three-phase asynchronous motors show a number of advantages compared to DC motors systems, including reduced size, weight and cost at equal powers, higher power and speed at the same size, high reliability, better operating characteristics, etc. For example, the efficiency of asynchronous traction motors is 3-5% higher that of the DC motor [3].

This paper aims to highlight and systematize the methods and instruments for electric traction systems realization and to create a basis for research and development of the traction systems with multiphase (more than three) motors for urban passenger electric vehicles. The expected objectives include: identification of the study object; description of the control principle and operating equations of PWM modulator; presentation of theoretical bases and block diagrams of vector control; description of FOC control algorithm of the asynchronous motor; presentation of DTC technique and of SVM modulation principle.

2. Traction system of urban electric passenger vehicles

It is known that the traditional traction system of urban electric passenger vehicles based on three-phase asynchronous motors consists of a three-phase converter, an asynchronous traction motor, a feedback loop and a data bus (figure 1).

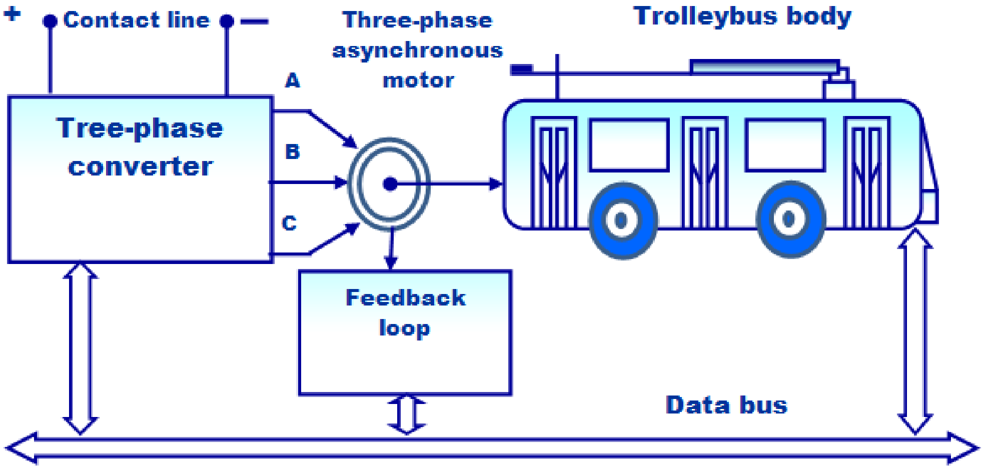

Figure 1. Electric traction system.

The three-phase converter converts DC energy from the contact line into a three-phase system with variable voltage and frequency that ensures the regulation of the asynchronous motor speed. It can be a current inverter or a voltage inverter. The current inverter has a simpler control system, but only changes the frequency of the output voltage and a voltage converter is required to regulate the inverter current. Meanwhile, the voltage inverter with modulated signals changes both the frequency and the voltage of the three-phase output system. It does not require a voltage converter; instead, it has a sophisticated control system.

Due to widespread use of the results of technical-scientific progress and modern achievements in the field of electro mechanics, power electronics and information technologies, the traction system converter becomes multifunctional with communication capabilities, protection and diagnosis of equipment, automatic adjustment of traction and braking regimes, intelligent optimization, traffic monitoring, etc. [1, 3, 4].

In general, the voltage inverter consists of two distinctive components, namely, the control circuit and the power circuit (figure 2). The power circuit (figure 3) transforms the direct current energy into three-phase alternating current, using the control principle with width-modulated pulses. It can be made as a bridge inverter or a bridge arm inverter. The bridge arm inverter has several advantages (simpler design and operating principle, twice the number of power transistors, reduced overall dimensions, etc.) compared to the bridge inverter and is used more frequently in practice. The control circuit generates the control signals for the power circuit and ensures the complete control of the traction system.

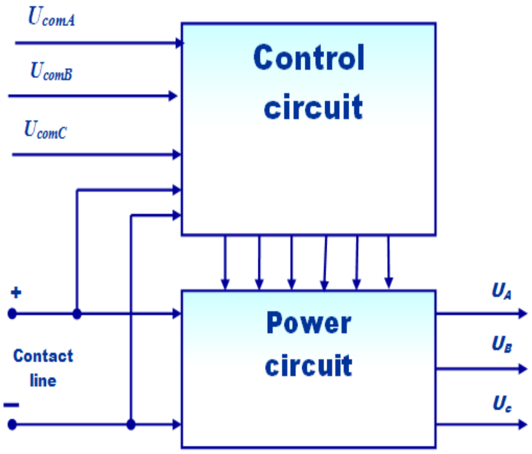

Figure 2. Voltage invertor.

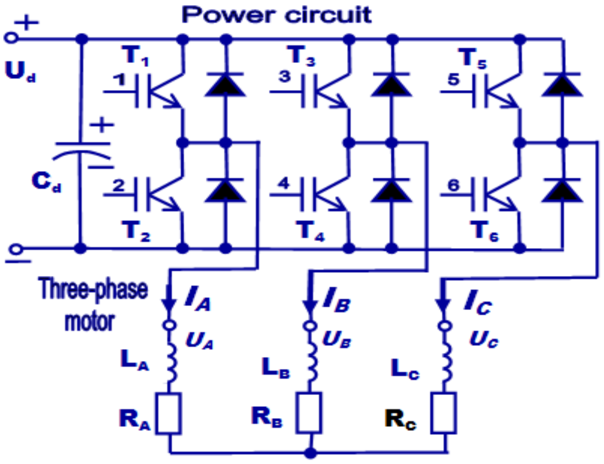

Figure 3. Power circuit.

For the transformation of direct current energy into three-phase alternating current, it is necessary that:

- the pairs of transistors T_1T_2, T_3T_4, T_5T_6 of the three bridge arms, work in series, with the blocking /conduction time, determined by the pairs of the respective control signals;
- to ensure a pause (a “dead time”) when switching the bridge arm transistors from the driving mode to the blocking mode, in order to avoid short-circuit cases;
- to ensure a 120° electrical phase shift between the control signal pairs of the force circuit arms.

As the load of the inverter is inductive, transistors T_1-T_6 must be supplemented with discharge diodes [5].

The switching elements of the power circuit are built with Insulated Gate Bipolar Transistors (IGBT), with IGBT intellectual power modules or with Metal – Oxide – Semiconductor Field Effect Transistors (MOSFET), completed with discharge/recovery diodes.

As mentioned, the inverter control circuit ensures the switching regime of the power circuit transistors, according to the selected modulation principle. There are several operating principles of the control circuit, but, at the moment, the practical traction systems of urban passenger electric vehicles mainly use PWM modulation.

3. Width-modulated pulse control principle

PWM voltage inverter is widely described in the literature, here there will be specified some general aspects, necessary to describe its operating equations. The principle of PWM modulation is given in figure.4.

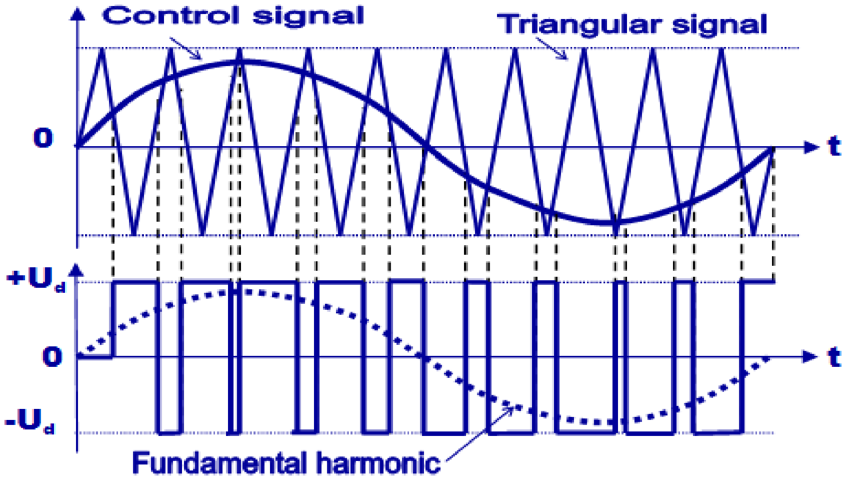

Figure 4. Principle of PWM modulation.

The PWM modulation technique consists in comparing a sinusoidal modulator control signal U_{com}(t) with an alternating periodic triangular signal U_{tr}, as a carrier signal.

$$U_{com}(t) = U_{com}\sin\omega t = U_{com}\sin 2\pi f t \tag{1}$$

The intersection points of the two signals determine the switching frequency of the bridge arm transistors. By means of frequency *f* and the amplitude U_{com} of the control signal, the frequency and amplitude of the bridge arm output signal are varied. The output voltage (fundamental harmonic) of the PWM inverter is an approximation of a series of width-modulated pulses with variable filling factor, so that the average value on each switching period of the bridge arm transistors corresponds to an inverter output voltage sinusoid.

The following operating equations can be used to model and simulate the three-phase voltage inverter [5]. The inverter control signals U_{comA}, U_{comB}, U_{comC} are described by the equations system:

$$\begin{cases} U_{comA}(t) = U_{com}\sin\omega t \\ U_{comB}(t) = U_{com}\sin(\omega t - 2\pi/3) \\ U_{comC}(t) = U_{com}\sin\omega t + 2\pi/3) \end{cases} \tag{2}$$

In these formulas, $\omega = 2\pi f$, and *f* is the frequency of the fundamental harmonics of the voltages U_A, U_B, U_C at the inverter output.

Line voltages U_{AB}, U_{BC}, U_{CA} and phase voltages U_A, U_B, U_C (figure 3) are described by the output voltages of the inverter arms U_{AN}, U_{BN}, U_{CN} with respect to the negative bar of the contact line.

$$\begin{cases} U_{AN}(t) = \frac{U_d}{2} + \frac{U_d}{2} m_a \sin\omega t \\ U_{BN}(t) = \frac{U_d}{2} + \frac{U_d}{2} m_a \sin(\omega t - 2\pi/3) \\ U_{CN}(t) = \frac{U_d}{2} + \frac{U_d}{2} m_a \sin(\omega t + 2\pi/3), \end{cases} \tag{3}$$

$$\begin{cases} U_{AB}(t) = U_{AN}(t) - U_{BN}(t) \\ U_{BC}(t) = U_{BN}(t) - U_{CN}(t) \\ U_{CA}(t) = U_{CN}(t) - U_{AN}(t) \end{cases} \tag{4}$$

Phase voltages U_A, U_B, U_C and the currents I_A, I_B, I_C at the output of the inverter arms (figure 3) are determined with the systems of equations:

$$\begin{cases} U_A = \frac{2}{3}\, U_{AN} - \frac{1}{3}\, (U_{BN} + U_{CN}) \\ U_B = \frac{2}{3}\, U_{BN} - \frac{1}{3}\, (U_{AN} + U_{CN}) \\ U_C = \frac{2}{3}\, U_{CN} - \frac{1}{3}\, (U_{AN} + U_{BN}); \end{cases} \tag{5}$$

$$\begin{cases} U_A(t) = R_A I_A(t) + L_A \frac{dI_A(t)}{dt} + E_A(t) \\ U_B(t) = R_B I_B(t) + L_B \frac{dI_B(t)}{dt} + E_B(t) \\ U_C(t) = R_C I_C(t) + L_C \frac{dI_C(t)}{dt} + E_C(t). \end{cases} \tag{6}$$

But PWM modulation is not the only function of the control circuit; it also performs a series of asynchronous motor control techniques, including vector control, automatic motor speed adjustment, the traction system status monitoring and information etc. For this purpose, the electric traction system (figure 1) contains a feedback loop with sensors and transducers (current, voltage, speed), as well as an interface bus of the system components.

4. Theoretical bases of vector control

Vector control is an efficient technique for aligning the dynamic characteristics of the asynchronous motor with those of the DC motor. This refers, first of all, to the regulation in a wide range and with a high precision of the three-phase asynchronous motor rotation speed which depends on the load torque. Being of major importance for the performance of the traction system, this control technique is extensively described in current profile publications [6-10] and is based on the integration of asynchronous motor mathematical model with the voltage inverter model. The vector control, initially developed by Blaschke, provides the synthesis of a complex current of two components, one of them generates the flux, and the other - the electromagnetic torque of the motor.

According to [7], vector control is based on two fundamental principles:

1) Transformation of three-phase system (axes A, B, C) into an orthogonal system (figure 5), attached to the stator, with a direct current (X axis) and a square current (Y axis), which generates, respectively, the flow and electromagnetic torque of the motor (Clarke transformation).

2) The transition from a stationary reference system to a dynamic system (figure 6) that rotates synchronously with the electromagnetic torque of the rotor, by transforming a sinusoidal quantity of the stationary reference system into a constant quantity of the dynamic system that rotates with the frequency of the sinusoidal quantity (Park transformation).

The Clarke transformation is performed with the following equations [8, 9].

$$\begin{bmatrix} I_{Xs}(t) \\ Ii_{Ys}(t) \end{bmatrix} = \begin{bmatrix} 1 & \cos(\varphi) & \cos(2\varphi) \\ 0 & \sin(\varphi) & \sin(2\varphi) \end{bmatrix} \cdot \begin{bmatrix} I_{As}(t) \\ I_{Bs}(t) \\ I_{Cs}(t) \end{bmatrix}, \tag{7}$$

where: $I_{As}(t), I_{Bs}(t), I_{Cs}(t)$ are the three-phase system stator currents; $I_{Xs}(t), I_{Ys}(t)$ - stator current $I_s(t)$ components in the *X-Y* system; $\varphi = 2\pi/3$.

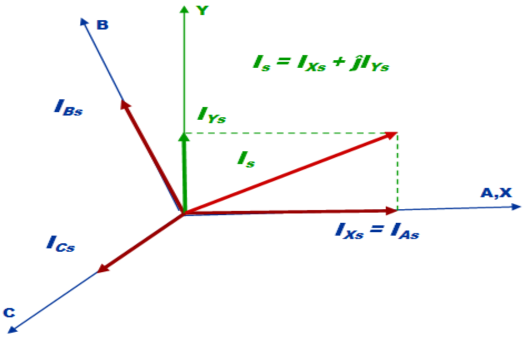

Figure 5. Clarke transformation.

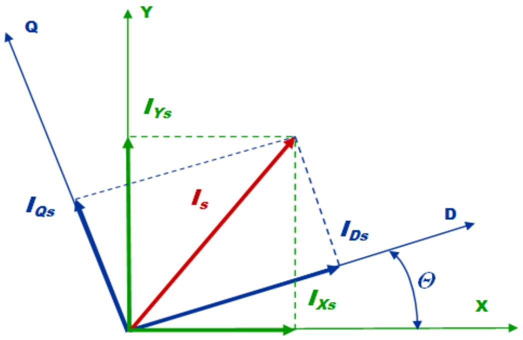

Figure 6. Park transformation.

Transition from a stationary reference system to a dynamic system and the relations between the two systems quantities are described a:

$$\begin{bmatrix} I_{Ds}(t) \\ I_{Qs}(t) \end{bmatrix} = \begin{bmatrix} \cos(\Theta) & -\sin(\Theta) \\ \sin(\Theta) & \cos(\Theta) \end{bmatrix} \cdot \begin{bmatrix} I_{Xs}\ (t) \\ I_{Ys}\ (t) \end{bmatrix}, \tag{8}$$

where: $\Theta = \omega t$ is the vector I_s angle of rotation, and ω - the motor rotation speed or its mechanical angular velocity.

The mathematical model of the asynchronous motor (Figure 3) in the stationary X-Y system, attached to the stator, is described by the following equations [6]:

- Stator voltage differential equations:

$$\begin{cases} U_{Xs} = R_s I_{Xs} + \frac{d}{dt}\psi_{Xs}; \\ U_{Ys} = R_s I_{Ys} + \dfrac{d}{dt}\psi_{Ys}, \end{cases} \tag{9}$$

where: R_s is the stator phase resistance, and ψ_{Xs}, ψ_{Ys}, - the stator flux components.

- Differential equations of rotor voltage:

$$\begin{cases} U_{Xr} = 0 = R_r I_{Xr} + \frac{d}{dt}\psi_{Xr} + \omega\psi_{Yr}; \\ U_{Yr} = 0 = R_r I_{Yr} + \dfrac{d}{dt}\psi_{Yr} - \omega\psi_{Xr}, \end{cases} \tag{10}$$

where: R_r is the rotor phase resistance.

- The stator and rotor flux equations, expressed by the spatial vectors of their currents:

$$\begin{cases} \psi_{Xs} = L_s I_{Xs} + L_m I_{Xr}\ ,\ \psi_{Ys} = L_s I_{Ys} + L_m I_{Yr}; \\ \psi_{Xr} = L_r I_{Xr} + L_m I_{Xs}\ ,\ \psi_{Yr} = L_r I_{Yr} + L_m I_{Ys}, \end{cases} \tag{11}$$

where: L_s and L_r are, respectively, the stator and the rotor phase inductance.

L_m - the mutual stator-rotor inductance.

- Torque equation, expressed by the spatial vectors of flux and currents:

$$m_e = \frac{3}{2} P_p(\psi_{Xs} I_{Ys} + \psi_{Ys} I_{Xs}), \tag{12}$$

where: P_p is the number of poles per phase.

When switching from the stationary *X-Y* reference system to the *D-Q* system, the mathematical model of the motor is described by the following equations [6]:

$$\begin{cases} U_{Ds} = R_s I_{Ds} + \frac{d}{dt}\psi_{Ds} - \omega_s \psi_{Qs}; \\ U_{Qs} = R_s I_{Qs} + \frac{d}{dt}\psi_{Qs} + \omega_s \psi_{Ds}; \\ U_{Dr} = 0 = R_r I_{Dr} + \frac{d}{dt}\psi_{Dr} - (\omega_s - \omega)\psi_{Dr}; \\ U_{Qr} = 0 = R_r I_{Qr} + \frac{d}{dt}\psi_{Qr} - (\omega_s - \omega)\psi_{Qr}; \\ \psi_{Ds} = L_s I_{Ds} + L_m I_{Dr}\,, \; \psi_{Qs} = L_s I_{Qs} + L_m I_{Qr}; \\ \psi_{Dr} = L_r I_{Dr} + L_m I_{Ds}\,, \; \psi_{Qr} = L_r I_{Qr} + L_m I_{Qs}; \\ m_e = \frac{3}{2} P_p (\psi_{Ds} I_{Qs} + \psi_{Qs} I_{Ds}), \end{cases} \qquad (13)$$

where: ω_s is the synchronous angular speed of the motor.

The operating equations “Eq. (1) - Eq. (13)” are the modeling and simulation basis of vector control systems with asynchronous motor. To implement vector control, the FOC and DTC techniques are frequently used.

5. Field-oriented control of the asynchronous motor

The field-oriented control, as one of the vector control approaches, provides the decomposition of the stator current into the components generating flux and torque with their separate control. The vector control diagram of the asynchronous motor with PVM modulation is given in figure 7.

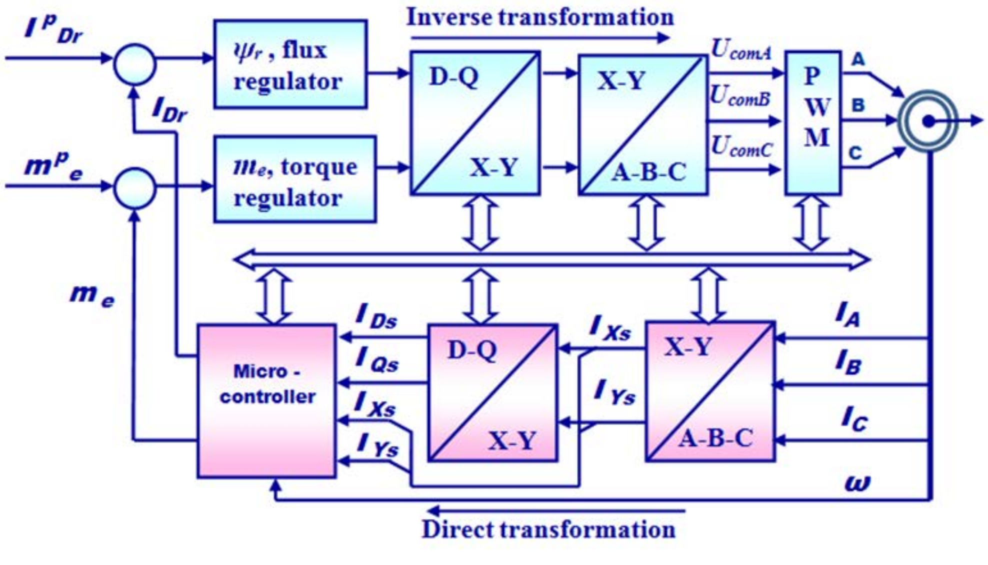

Figure 7. Field-oriented control scheme.

The microcontroller: assists the direct/inverse transformations of the reference systems and of the respective signals; ensures the feedback loop (signals I_{Dr}, m_e) of the flux and torque regulators; leads the PVM modulation process; ensures the analog/digital and digital/analog transformations etc. Flux and torque regulators can be PID-type standard regulators or can be replaced with microcontroller special software applications, if the response time of the system allows it. I^p_{Dr}, m^p_e signals determine the prescribed or reference values of the motor flux and torque, while I_{Dr} and m_e are the calculated values that characterize the motor current state.

According to [6], inverse transformation of the reference system *D-Q* into *A-B-C* (Fig. 7) and generation of control signals for the power circuit transistors (Fig. 3) can also be achieved by the Space Vector Modulation (SVM) technique. This combination is known as SVM-PWM control technique.

6. Direct torque control technique

As mentioned, FOC technique controls the asynchronous motor speed and torque indirect, by decomposing the stator current into the flux and torque generating currents with their separate control. That requires multiple calculations and transformations and, together with PVM modulation, increases the reaction time of the traction system, which diminishes the control process quality indices and limits the FOC application.

To improve the performance of the control system, a Direct Torque Control (DTC) technique is used (fig. 8). DTC is similar to FOC technique, except that it is based on the flux and torque decomposition with their independent control [8].

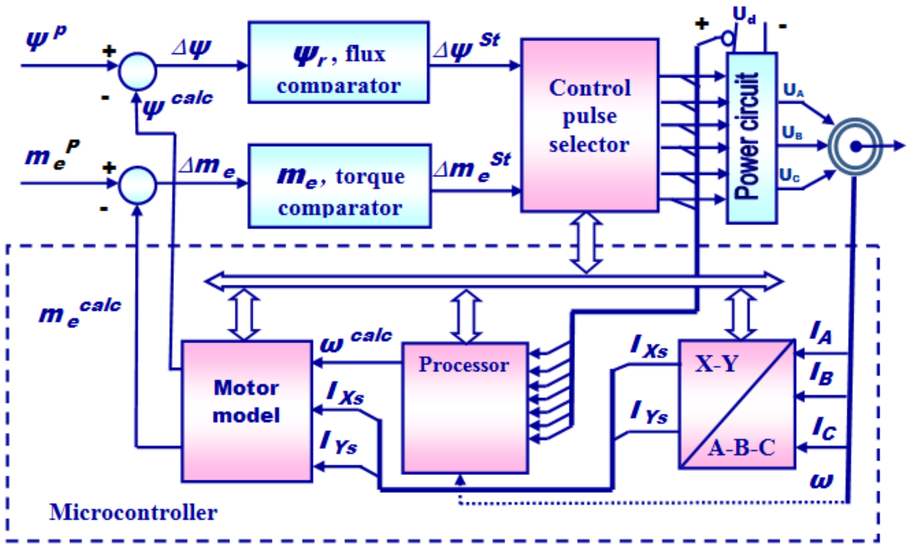

Figure 8. Direct torque control scheme.

In principle, the DTC technique ensures direct flux and torque calculation without the use of speed sensors or rotor shaft positioning. This technique is based on performant signal processing technologies and the creation of advanced mathematical models of the asynchronous motor, which allow the high-precision simulation of its operating characteristics. As the created model exactly reflects the characteristics of the physical motor, the calculation of the flux and the current torque is performed in real time, with high precision and speed, which contributes to improving the performance of the control system [8].

The flux and torque comparators determine the current state of the $\Delta\psi$ flow and Δme torque error, compared to their prescribed values ψ^P, m_e^P and a hysteresis band. The flux comparator is bi-positional and determines the state of increase $\Delta\psi^i$ or decrease $\Delta\psi^d$ of the error, and the torque comparator is three-positional and determines the states of increase Δm_e^i, decrease Δm_e^d and equality Δm_e= of the torque error. The outputs of the comparators are connected to the control pulse selector which performs the SVM modulation technique. For this purpose, eight state variants (table 1) of the power circuit (fig. 3) are identified and, respectively, eight stator voltage vectors, depending on the switching combinations of transistors T_1-T_6 [12, 13].

The inverter output voltage vector or stator voltage vector is determined by the equation

$$U_s = \frac{2}{3} U_d \left(U_A + e^{\frac{j2\pi}{2}} U_B + e^{\frac{j4\pi}{2}} U_C \right) \tag{14}$$

Vectors V_0 and V_7 are zero and when applied the motor flux and torque become zero [12].

It is important that selection of the stator voltage vector depends not only on the outputs of the flux and torque comparators, but also on the current positioning of the stator flux vector.

Table 1

Power circuit states

Inverter state	Voltage vector	State code	Inverter arm		
			U_A	U_B	U_C
State 0	V_0	000	T_2	T_4	T_6
State 1	V_1	100	T_1	T_4	T_6
State 2	V_2	110	T_1	T_3	T_6
State 3	V_3	010	T_2	T_3	T_6
State 4	V_4	011	T_2	T_3	T_5
State 5	V_5	001	T_2	T_4	T_5
State 6	V_6	101	T_1	T_4	T_5
State 7	V_7	111	T_1	T_3	T_5

This is why the trajectory of the stator circular flux vector is divided into six symmetrical sectors (figure 9), and the microprocessor determines the current stator voltage vector based on the data in table 2 [10-12]. Fig.9 shows the selection variants of the voltage vector, when the stator flux vector is in sector 1.

Table 2

Voltage vector selection

Error		**Sector**					
Flux	**Torque**	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**
$\Delta\psi^i$	Δm_e^i	V_2	V_3	V_4	V_5	V_6	V_1
	$\Delta m_e^=$	V_0	V_7	V_0	V_7	V_0	V_7
	Δm_e^d	V_6	V_1	V_2	V_3	V_4	V_5
$\Delta\psi^d$	Δm_e^i	V_3	V_4	V_5	V_6	V_1	V_2
	$\Delta m_e^=$	V_7	V_0	V_7	V_0	V_7	V_0
	Δm_e^d	V_5	V_6	V_1	V_2	V_3	V_4

Based on the above, the FOC and DTC control techniques, as well as the PWM and SVM modulation methods have both advantages and disadvantages, and the selection of an optimal option depends on the pursued objectives. This must be done in the research and development process.

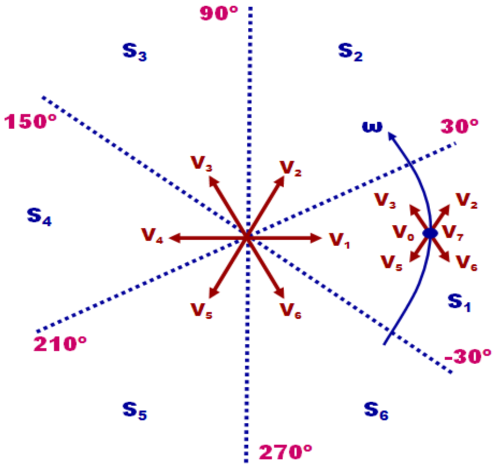

Figure 9. Stator flux sectors.

It should be mentioned that according to [14-18], the theoretical approaches and techniques described in this paper, with some modifications and completions, can be successfully used in the research and development of control systems with poly-phase asynchronous motors, including six-phase motors.

7. Conclusions

The current development trend of traction systems for urban electric passenger transport is manifested by the replacement of direct current motors with asynchronous motors. This involves the use of the voltage inverter and asynchronous motor control techniques, similar and as efficient as those of the DC motor. More frequently, the voltage inverter is made on the PVM and SVM principles, using the controlled power transistors. At the moment, vector control is the optimal control solution for the asynchronous motor. For this purpose, FOC and PWM control techniques are used. In this paper, continuity and a common sense is ensured in the description of operating equations of the components of traction systems with asynchronous motors, which can be used for research and development of control systems with poly-phase motors, including six-phase motors.

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Conflicts of Interest: The authors declare no conflict of interest.

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