Features of torque production of synchronous electric drive with direct torque control of mining machines

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Abstract. In article, the direct torque control method of the synchronous electric drive is considered. This control method is characterized by high performance, robustness and small frequency of switching of keys of the converter. The algorithms and structure of direct torque control of the synchronous electric drive allow creating its operation modes by impact on the form of a triangle with sides: flux linkage of the stator, a rotor, and resultant flux linkage.

1. Introduction

The main differences of direct torque control from classical field oriented control are discretization of regulation of vectors of a magnetic flux of the stator and the electromagnetic torque of the motor. In other words, the system does not contain the coordinate converter, and in each timepoint fixed not the instantaneous position of a vector of flux linkage of the stator, and only the sector number in which it is at present [1]. Such approach allows reducing the number of the operations executed by the microcontroller per unit of time and, considering the modern opportunities of an computing technique, provides the best system performance.

Advantages of such control method are:

– one measured motor parameter – the resistance of the stator;

– small load of the microprocessor device of control signals;

– absence of the rotor position sensor of the motor.

Now development of a direct torque control is dictated by the significant progress in the field of information and power electronics [2].

It is necessary to consider a two control method of the induction motor for the decisions required from control system high performance and accuracy: field oriented control (*FOC*) and direct torque control (*DTC*). The first method was offered more than 40 years ago. Approximately, 15 years later, the second method for control of the induction motor [3] was offered. In the late nineties, the ideas of direct torque control extended as well to the synchronous electric drive with permanent magnets on a rotor.

2. Methods and materials

Control motion along the stator bore of a wave of a magnetic flux is the basic principle of operation of the synchronous motor with *DTC*. The half wave of this flux can be regulated by the amplitude and speed (i.e. by frequency). The authors will provide this half wave as vector ψ (see Fig. 1), having regulated amplitude ψ and an angle of rotation α [4]. Value of amplitude ψ impacts value of phase currents of the synchronous motor, and an angle α – the frequency of the same currents forming the symmetric three-phase system. If the vector ψ in case of rotation in the same side, as a rotor of the synchronous motor, "runs forward", then the motor develops the positive torque "forward", in case of lag – "backward" [5].

In the publications devoted to *DTC* control of the synchronous motor with permanent magnets on a rotor, it is offered to regulate a value and an angle of rotation of a vector of flux linkage of the stator ψ_S [6]. There are publications on *DTC* of the reluctance electric drives where it also offered to regulate a vector of flux linkage of the stator. At the same time, not enough attention is paid to features of formation of the electromagnetic torque in the synchronous machines and in this control method [7].

The concept of field-oriented control of the a.c. synchronous motors is tightly connect to a concept of a torque triangle. The sides of this triangle are vectors of flux linkage of the stator, a rotor and resultant

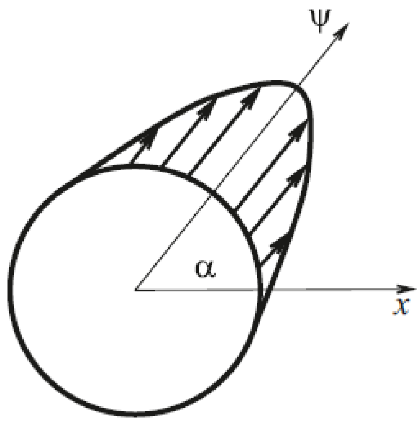

Figure 1. The representation of the half-wave of the magnetic flux of the synchronous machine of the space vector ψ

flux linkage. Influencing the form of a triangle by means of the control system, it is possible to realize different operation modes of the electric drive [8].

In case of implementation of *DTC* control laws, it is also necessary to consider influence of different laws of modulation of a voltage vector [9].

For *DTC* of the synchronous motor with the active rotor (with the field winding or with permanent magnets on a rotor) (Fig. 2, a), it is possible to construct a torque triangle on two sides (resultant flux linkage and flux linkage of a rotor) and an angle in between [10]. Such option of creation is explained by the reference for the considered system of values of the electromagnetic torque, resulting flux linkage and values of excitation of a rotor.

For *DTC* of the synchronous motor with a reluctance rotor (with a passive rotor) [11, 12] (Fig. 2, b) a

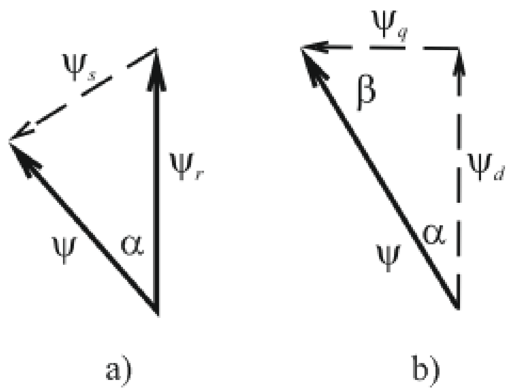

Figure 2. Production of the torque triangle in a synchronous electric drive with *DTC*: A) - active rotor; B) - reluctance rotor

torque triangle can be constructed on the side (resultant flux linkage) and two adjacent angles (an angle between flux linkage of the stator and a rotor always of the right angle, the angle between flux linkage of a rotor and a resultant flow is set by the value of the torque, and the resultant angle equals the sum of angles in a triangle 180 °) [13].

For detection of features of *DTC* of the synchronous motor, the authors addressed the similar principle of control of the induction motor which is described in many sources, for example, in [14]. If vector of resultant flux linkage rotates in one side, then the torque will increase, in case of rotation in other side – to decrease.

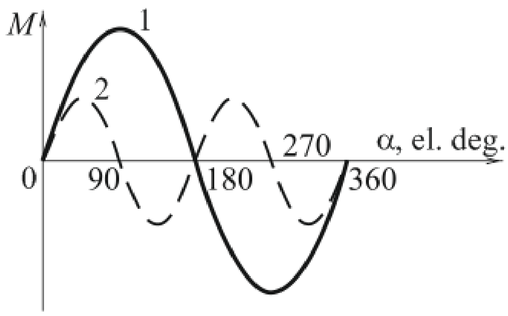

Figure 3. The power-angle curve of the synchronous machine: 1 – active rotor; 2 – reluctance rotor

Feature of the considered control method to the synchronous motor is the accounting of sign-variable character of the electromagnetic torque in case of rotation of a vector of resultant flux linkage concerning a rotor. In case of the active rotor, the torque has one period on one electrical revolution of rotor (Fig. 3, a curve 1) [15]. Here it is possible to select a section of increase of the torque and a section of reduction of the torque.

For a reluctance rotor – two periods are on one electrical revolution and on two sections of reduction and increase in the torque (Fig. 3, curve 2). Thus, it is necessary in addition to the position of a rotor to calculate an angle of rotation of a resultant vector of flux linkage of rather magnetic axis of a rotor for direction finding of rotation of this vector that would cause the required change of the electromagnetic torque [16].

3. Calculations and experiments

In Fig. 4 the block diagram of *DTC* control of the synchronous motor is shown. The control object is provided by the synchronous machine (*SM*) which receives a supply from the three-phase frequency converter (*UZ*) executed by the two-unit principle [17]. The rectifier is realized on uncontrollable keys, the inverter represents six transistors, which are switched on a three-phase bridge circuit. The switching table, controllers of speed, the torque and a flux, and the model of the synchronous machine provide the control system [18].

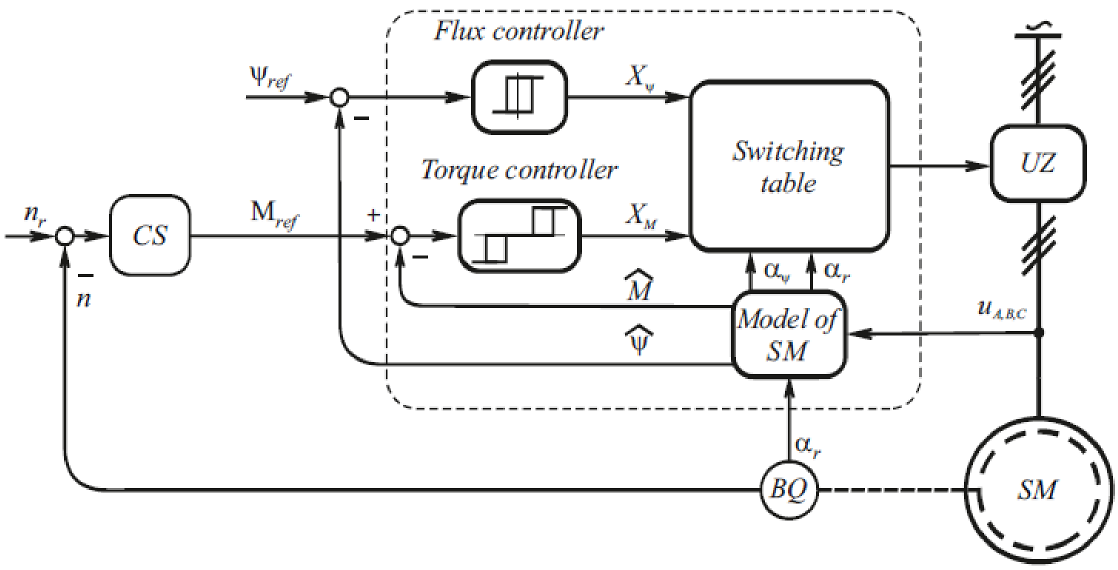

Figure 4. Block diagram of the *DTC* of synchronous electric drive

The relay characteristic of torque controller and of a flux controller, first, promotes a forcing of processes in the subsequent links of direct circuit, increasing performance of system of the electric drive, and secondly, sharply simplifies logic of operation of the subsequent links of the control system, restricting the change of their status to a limited set of the fixed values [19]. The model of the synchronous machine (*SM*) is implemented based on a system of equations in *d-q* coordinates:

$$\begin{cases} U_d = i_d R + L_d \dfrac{di_d}{dt} + \omega_r p L_q i_q \\ U_q = i_q R + L_q \dfrac{di_q}{dt} - \omega_r p (L_q i_q + \psi_r) \end{cases},$$

where U_d, U_q and i_d, i_q – voltages and currents in coordinates of d and q; R – ohmic resistance of windings; L_d, L_q – inductance of windings in coordinates of d and q, ω_r – angular speed of a rotor, p – number of pairs of poles, ψ_r – flux linkage of a rotor.

The system works as follows: input signals of the speed reference ω_{ref} and resultant flux linkage ψ_{ref} comes to inputs of summator of a speed loop and a control loop of a magnetic flux. From outputs of summator, error signals of speed and of flux come to inputs of controllers of a flux and speed [20]. Output signal of the torque reference comes to input of the summator of a control loop of the torque from a speed controller, and the signal from an output of the relay controller of a flux comes to the table of switching.

The error signal of the torque comes to input of the appropriate controller, and from the output of this controller comes to the table of switching. Control signals comes to the converter from the unit "table of switching" where the resultant vector of voltage formed from values of signals at outputs of controllers (X_Ψ and X_M) and the actual coordinates of the electric drive is created: rotation angle of vector of resultant flux linkage α_Ψ and rotation angle of a magnetic axis of a rotor α_r. The called coordinates of the electric drive comes from an output of the model of the synchronous machine [21, 22].

It is known that in the symmetric three-phase systems with the harmonic character of change of phase voltage, this vector can be calculated as:

$$\overline{U} = \frac{2}{3}\left(U_a + U_b \cdot e^{j\frac{2\pi}{3}} + U_c \cdot e^{j\frac{4\pi}{3}} \right).$$

Theoretical and the experimental researches allowed evaluating dynamic indexes of the electric drive with the synchronous machine in the block with *DTC*. The main criterion of a research was performance of the electric drive with the reluctance motor in case of change of parameters of a ratio L_d/L_q. The program based on the data obtained by means of the generalized mathematical model gave the chance to evaluate electric drive parameters with the synchronous machine [23, 24].

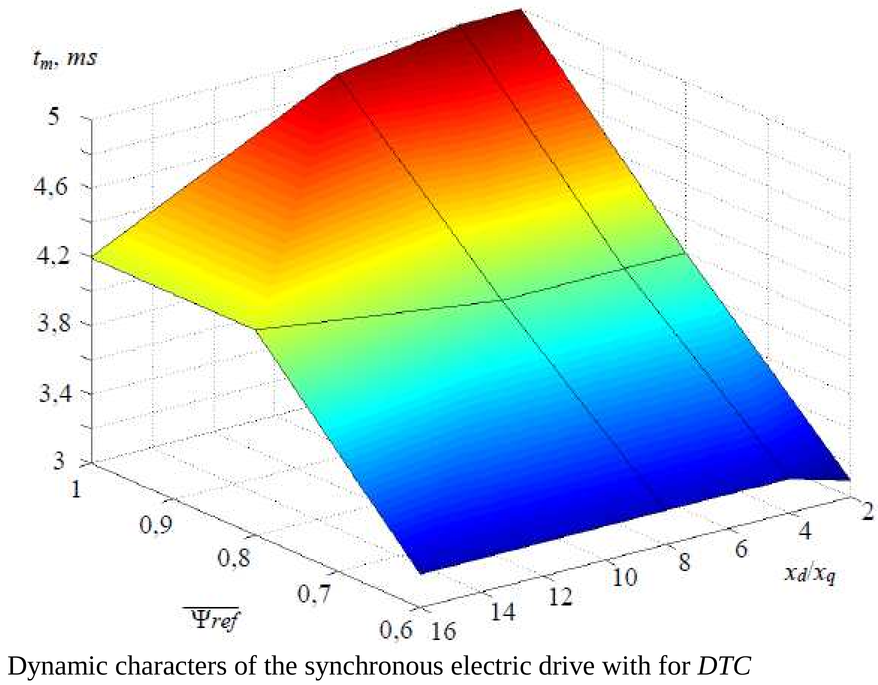

Figure 5. Dynamic characters of the synchronous electric drive with for *DTC*

The research was performed on purpose to reveal dependence of response time (control loop of the electromagnetic torque) in case of change parameters X_d/X_q, at the same time amplitude of the vector of the flux linkage of the stator Ψ, value which moved on a system input controls, was different. Results of the research are shown on Fig. 5 in the form of a surface. Response time in a control loop of the torque practically does not change as in case of complete flux, and in case of a setting of a flux, equal to a half of a complete flux [25, 26].

4. Conclusion

Change of parameters of the reluctance motor slightly impact dynamic indexes in case of *DTC*. On a laboratory prototype, the synchronous machine (for one value of a ratio X_d/X_q) similar researches were perform. Obtained results of theoretical and the experimental researches are almost identical [27].

In case of the discrete system, this function is separated into sections, and within one zone voltage remains to constants. The choice of sector is carried out by the algorithm described in based on an output of the two-level controller of a flux and the three-level controller of the torque where the third level is a zero state [28].

The distinctive feature of this system is mandatory existence of the rotor position sensor for restriction of the displacement angle between a resultant vector of a magnetic flux and a magnetic axis of a rotor. As a result of mathematical simulation it is shown that performance in a control loop of the torque is same, as well as in the induction motor, and does not exceed (2–3) ms, that is, urgent for technological mechanisms with increased requirements on performance and accuracy, for example, for the electric drive of feed of cold pilgering mill [29, 30].

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