Digital control systems for asynchronous electrical drives with vector control principle

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Abstract. Problems of optimizing the operation modes of an asynchronous electric drive according to the criterion of the minimum stator current, as well as the optimal control system of an asynchronous motor with a reference rotor flow vector, which can be used for most serial frequency converters, longitudinal components of the stator current are added to the control channel.

1. Introduction
Currently used energy-saving variable frequency drives based on asynchronous motors with a phase rotor is the main type of variable speed drive. The application of the laws of vector torque control provides the required quality of regulation and significantly increases the efficiency of electronic components. Under conditions of the maximum increment of the starting torque, accompanied by a long stop, overloading occurs with the starting current in the stator circuit of the frequency converter. For the complete elimination of emergency operation modes of the electric drive, it is necessary to limit the time it takes for this process to be maximally, or it is recommended to select a power unit calculated with a certain reserve for high currents. At the same time, due to the increase in the overall dimensions of the units, certain difficulties arise when using these inverters in a traction drive, where it is also necessary to create a condition for providing regenerative braking to a complete stop and ensuring maximum efficiency in normal operating conditions.

2. Method
With the development of modern technologies and the introduction of new circuitry solutions based on the active development of power electronics, microelectronics and microprocessor control systems, automated electric drives can achieve the necessary adjustment characteristics of the machines and mechanisms used, and also can significantly reduce energy consumption [1].

Modern industry development puts high demands on technical solutions for performing technological operations and requires regulation of the position, speed or acceleration of movement, limiting the efforts of the actuator[2].

Design methods for digital control systems differ significantly from the classical methods used in the analysis and synthesis of continuous-type systems. This is due to the following features:
- the basis of the mathematical apparatus for designing digital control systems are difference equations, which replace the differential equations describing continuous systems.
- analysis and synthesis of the system is carried out at the discretization period T, which allows
both the decomposition of the control according to the rate of the processes and the simplification of the equations due to the quasi-constancy of the variables in this period.

- the control system has a memory in which all the dynamic increments of state vectors, and control at previous points in time that can be used to solve the control problem.
- synthesized digital algorithms are implemented on microcontrollers, which have their own limitations on the duration of the calculation cycle and computational capabilities.

The basic value in organizing the calculation in the microprocessor controller is the duration of the calculation cycle (clock cycle), which is closely related to the measurement times and the computational capabilities of the microprocessor[3].

In the analysis of linear discrete systems, difference equations, a discrete Laplace transform, and Z-transform are used.

Using the discrete Laplace transform, we will analyze the linear discrete system of the given structural diagram in figure 1.

Using the structure we can write:

\[ \varepsilon_i(t) = \sum_{k=0}^{\infty} \varepsilon(kT)S(t - kT) \]  (1)

Since an ideal impulse element(IIE) generates a sequence of instantaneous unit pulses (\( \delta \)-functions), the signal at the output of an IIE can be represented as:

\[ \varepsilon^*(t) = \sum_{k=0}^{\infty} \delta(e - kT)\varepsilon(kT) \]  (2)

\[ E(p) \]

\[ G(t) \]

\[ \varepsilon^*(p) \]

\[ W_{\phi}(p) \]

\[ \varepsilon_I(p) \]

\[ W_{N\Phi}(p) \]

\[ X \]

**Figure 1.** Block diagram of a linear discrete system.

By virtue of the properties of IIE, the equivalent circuit has a forming element (FE) with the weight function \( w = S(t) \), which corresponds to the transfer function:

\[ W_{\phi}(p) = L[S(t)] = S(P) \]  (3)

For a sequence of rectangular pulses with a duty cycle of \( \gamma = T_I/T \) (figure 2), the weight function is determined by the expression

\[ S(t) = K_I I(t) - I(t - \gamma T) \]  (4)

Transforming both sides of relation (4) according to Laplace, we obtain the transfer function FE

\[ S(p) = \frac{K_I(1-e^{-\gamma Tp})}{p} \]  (5)

Taking into account (5), for \( K_I = 1 \) and \( \gamma = 1 \) we obtain the transfer function of the Federal Function, which is called an extrapolator of zero order

\[ S(p) = \frac{(1-e^{-\gamma Tp})}{p} \]  (6)
For discrete values of the output quantity $x^*(t)$, we can write

$$x^*(t) = \sum_{k=0}^{\infty} x(kR) \delta(t - kT). \quad (7)$$

The set of harmonic functions into which $\delta(t - kT)$ can be decomposed is equal to $e^{-j\omega_k T}$, therefore the spectrum

$$x^*(j\omega) = \sum_{k=0}^{\infty} x(kT)e^{-j\omega_k T} \quad (8)$$

Replacing $j\omega = p$ in (8), we obtain the formula defining the direct discrete Laplace transform for the lattice function

$$x^*(p) = \sum_{k=0}^{\infty} x(kR)e^{-pT}. \quad (9)$$

Since the quantization frequency $\omega T = 2\pi / T$, we obtain

$$e^{-j(\omega + k\omega T)kT} = e^{-j\omega_k T}e^{-k2\pi / T} = e^{-j\omega_k T}$$

those the entire $p$ plane for a discrete variable is divided into bands along the imaginary axis, the same in size $\omega_T$ (figure 3)[4].

Let us synthesize a digital control system for torque drive. In the synthesis of digital control algorithms, the following principles were used:

- the principle of decomposition, which allows the synthesis to be carried out autonomously for each control task. The possibility of decomposition is determined by a significant separation of the control rates in separate loops (current and torque control processes, processes for estimating the magnitude and direction of a magnetic field, position and speed control processes can be considered independently)[5].
- vector control of an induction motor with orientation along the vector of the magnetic field (flux linkage) of the motor.
- independent control of the electromagnetic moment and magnitude of the field with a constant magnitude of the magnetic field.
- construction of a regulator of electromagnetic moment (active current) in a rotating coordinate system.
- the use in the synthesis of the control algorithm of difference (exact) equations of the processes in the engine, which corresponds (adequately) to the principle of digital processor control.
- the use of autonomous observers (approximators) of the values of the controlled variables and regulation according to the predicted values of the variables, eliminating the delay in control calculations carried out in the processor sequentially in time[6].
- the use of autonomous optimal filters (Kalman filters) that provide filtering of the measured values of state variables without dynamic error.
- the use of finite-step control algorithms (discrete sliding modes) that provide maximum speed
controllers.
- the use of optimal vector algorithms for pulse-width regulation of the output voltage of an autonomous inverter supplying an induction motor.

The structure and components of the torque drive controller are shown in figure 4, which consists of:
- from the current regulator of the current shaper.
- from the vector rotation converter, which consists.
- voltage task generator.
- rotor flux linkage model.
- stand-alone filter.
- systems for receiving torque reference signals.

**Figure 4. Torque drive current control loop.**

The current regulator generates the set values of the voltage vector to the PWM system so that the current vector in the motor is equal to the set voltage. The input of the current regulator receives the values of the set currents in phases and their measured values, and the output of the current regulator is the set phase voltages \([7]\).

The equations in the stator windings are of the form:

\[
\frac{di}{dt} = R_{eq}i + k_1 n \Phi + K_2 U + f, \tag{10}
\]

where \(i, U, \Phi\) are current vectors, stator voltage and rotor flux linkage, \(n\) is rotor rotation speed, \(R_{eq}\), \(k_1\) are coefficients, \(f\) are uncontrolled disturbances.

The rate of change of the magnetic field, rotor speed, and disturbances caused by time delays in transmitting power switch control commands, current pauses, and errors in calculating voltage estimates are rather slow compared to current regulation. With that said, the equation of the error of the current
The equation of the magnetic field of the rotor in the coordinate system oriented in the direction of
the field vector has the form:
\[
d\psi/dt = -(R_f/L_f)(\psi - L_m i_d)
\]
where \(\psi\) is the field value; \(i_d\) - magnetization current.

The direction of the field vector - the angle of rotation of the coordinate system is given by the equation
\[
d\theta/dt = n + \frac{R_i L_m i_q}{L_r \psi}
\]
where \(i_q\) is the active current; \(n\) is the rotor speed. The difference equations of the magnetic field of
the rotor
\[
\theta_{\psi k+1} = \theta_{k+1} + \theta_{sk+1}
\]
\[
\theta_{sk+1} = \theta_{sk} + T \frac{R_i L_m i_q}{L_r \psi}
\]

3. Result and discussion
The formation of a given voltage is carried out in "slow" time according to the static relations between
the voltages in the stator circuit of an induction motor. As is known, the region of the physically
realizable phase voltage of the IM, fed from the RI, is a regular hexagon oriented with a diameter along
the directional unit vectors of the phases (figure 4). To exclude moment pulsations, we use the “smooth” constraint, i.e. limiting the magnitude of the voltage module.

The block of vector pulse-width modulation provides the formation of the law of modulation and the law of switching power switches of an autonomous voltage inverter, which ensure the formation in phase windings of an asynchronous voltage motor in accordance with voltage tasks generated in the voltage limiting block. The law of switching power switches minimizes switching losses in an autonomous voltage inverter. Analytical expressions and PWM algorithms are considered in detail in [4].

4. Conclusion
Thus, the analysis of features, the construction of digital control systems for an asynchronous electric drive with the vector principle of torque control allows us to justify the mathematical apparatus for the development of digital drive algorithms. Taking into account the features of the functioning of digital systems, the general principles for the development of digital algorithms are formulated, on the basis of which analytical dependencies and a procedure for the synthesis of digital control algorithms for asynchronous torque drives are developed.

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