Comparative analysis of electric drive control systems for technological facilities in the agricultural sector

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Abstract. The article provides a comparative analysis of the most common electric drive control systems: scalar control, vector control and direct torque control DTC. The analysis is carried out according to the criteria for the performance of the torque loop, the robustness of the systems, the level of torque ripple and overshoot in the torque loop. Comparison is made by subjectively assigning points for each of the criteria based on a qualitative assessment. The simplified mathematical models are used for analysis, that taking into account the pulsating moment pulsations. In conclusion, it is concluded that it is advisable to use one or another control system for electrical equipment in various fields of agricultural use.

1. Introduction
The use of one or another principle of electric drive control is determined by the requirements for it. So, in systems that do not require high accuracy and speed of transients, but at the same time require speed control to ensure efficiency - electric drives of pumps, fans, conveyor belts, etc., systems with scalar control are most widely used. The electric drive with scalar control is cheaper, easier to commission and use. Technological processes that require greater accuracy and speed make it necessary to use more complex control systems. The most widely used are vector control systems and direct torque control systems (relay-vector systems) DTC. The latter are patented and actively used by ABB. Comparing them according to a number of criteria requires analysis.

2. Simplified mathematical model
The simplified model is a mathematical model containing analytical expressions, a system of equations, the calculation of which is carried out by numerical methods. The refined model is a model in which the electromechanical converter with a finite element model [1].

For electric machines with an explicit pole rotor, pronounced tooth pulsations of the moment are characteristic, the amplitude of which can reach up to 30% of the moment created by the machine [2]. It is possible to take into account ripple data when calculating a machine using the finite element method. But if this FE model is integrated into the control system, then the calculation of one second of the simulated time can take up to 18 hours of real time [3].

The way out of this situation can be a preliminary magneto static calculation in the spatial formulation of the problem of the angular characteristics of the machine, namely the flow and torque as a function of current and angle of rotation. Further, when simulating transients in the control system, the obtained data sets in tabular form are used as a model of an electric machine [4]. This approach can significantly reduce the amount of required computing resources, with the exception of preliminary calculation [5].
Figure 1. Dependence of current a) and electromagnetic moment b) obtained by the finite element method.

The indicated dependences are shown in the figure 1 which obtained when calculating the magnets of the fields of the synchronous reluctance machine SRM, based on the 4A280S6U3 induction motor [6]. The stator geometry of the machine is built entirely according to the catalog data. The rotor of the machine is salient pole, the number of poles is six, made without winding. Engine rated power is 75 kW [7].

The wave-like appearance of the graphs is due precisely to the pulsation of the teeth. The choice of this brand of machine is explained solely by the availability of available equipment for the experiment [8].
The control system model of a direct torque control system is presented in the figure 1, in which the magnetic system of an electric machine is presented in tabular form for data obtained as a result of calculation by the finite element method [9].

The oscillograms of currents obtained on a simplified model as described above in the Matlab software product a) and on a refined model calculated by the finite element method in the AnsysSimplorer b) system are presented in the figure 1 [10].

With the exception of the current sign inversion, the characteristics qualitatively coincide and clearly demonstrate the convergence of the results of the simplified and finite element models. The convergence of the results was numerically confirmed by statistical methods based on a sample of 32 transient waveforms. The obtained Student quantile values did not exceed critical values [11]. Experimental curves were used as reference curves [12]. The error of the model with the tabulated parameters of the magnetic system of the electromechanical converter did not exceed 5% when working in the vicinity of the nominal point, and did not exceed 12% when working in the overload mode [13]. Less accurate results in the overload mode are due to the fact that the parameters of the magnetic system were calculated on the linear portion of the magnetization curve and did not take into account saturation. The finite element model implemented in the Simplorer package had a lower level of error in the nominal mode - less than 3% [14].

On the model in which the machine’s magnetic system was considered analytical expressions, an unsatisfactorily high level of error was obtained - more than 27% at low speeds. This is due to the fact that a model with lumped parameters, unlike a model with distributed parameters, does not take into account the pulsating moment pulsations. In this regard, this model was not used in further research [15].

3. The control synthesis
The evaluation of the performance of a system with DTC control, a mathematical model was created in the Matlab system. In the $d$-$q$ coordinate system rigidly connected with the rotor, the drive coordinates will be described by the following system of equations [16]:

$$
\begin{align*}
\frac{d}{dt} i_d &= \frac{1}{L_d} u_d - \frac{R}{L_d} i_d + \frac{L}{L_d} p \omega_r i_q \\
\frac{d}{dt} i_q &= \frac{1}{L_q} u_q - \frac{R}{L_q} i_q + \frac{L}{L_q} p \omega_r i_d \\
M &= 1.5 \, pp (L_d - L_q) i_d i_q,
\end{align*}
$$

where $R$ is the stator winding resistance, $\omega_r$ is the angular velocity of the rotor, $pp$ is the number of pole pairs, $M$ is the electromagnetic moment created by the motor, $M_r$ is the moment of resistance, $\phi$ is the angle of rotation of the shaft [17].

The system has an observer of the state of the current coordinates of the electric drive, not available for measurement using sensors [18]. We are talking about the electromagnetic moment and flux linkage. These coordinates are calculated indirectly [19]. Phase voltages, by contrast, are available for measurement [20]. Their projections on the axis of the fixed coordinate system $\alpha$-$\beta$ associated with the stator are determined by the system of equations [21]:

$$
\begin{align*}
U_a &= U_a - \frac{1}{2} (U_b + U_c) \\
U_\beta &= \sqrt{3} \, \frac{1}{2} (U_b - U_c)
\end{align*}
$$
The angle of rotation of the rotor $\theta$ is calculated by the observer. Knowing it, we find the projections of the stress vector in the $d$-$q$ coordinate system associated with the rotor [22]:

\[
\begin{cases}
U_d = U_a \cdot \sin \theta + U_b \cdot \cos \theta \\
U_q = U_a \cdot \cos \theta + U_b \cdot \sin \theta
\end{cases}
\tag{2}
\]

Further, substituting (1) in (2), we obtain [23]:

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

where $U_d$, $U_q$ and $i_d$, $i_q$ are voltages and currents in the $d$-$q$ coordinate system; $pp$ is the number of pole pairs, $L_d$, $L_q$ are the inductances of the windings in the coordinates $d$, $q$, $\omega_r$ is the angular velocity of the rotor, $R$ is the resistance of the windings; $\psi_r$ - flux linkage of the rotor [24].

Having calculated the projections in a similar way, we obtain the components of the stator current in the axes $d$ and $q$ [25]:

\[
\begin{cases}
i_d = \frac{U_d + i_q \cdot \omega_r \cdot pp \cdot L_q}{L_d \cdot p + R} \\
i_q = \frac{U_q - i_d \cdot \omega_r \cdot pp \cdot L_d}{L_q \cdot p + R}
\end{cases}
\]

The stator flux linkage vector module is determined by the formula [26]:

$$\Psi = \sqrt{\psi_d^2 + \psi_q^2},$$

where $\psi_d = i_d \cdot L_d$, $\psi_q = i_q \cdot L_q$.

Finally, knowing the current values of the projections of currents and flux linkages on the $d$ and $q$ axes, we find the electromagnetic moment [27]:

$$M = \frac{3}{2} pp (\psi_d \cdot i_q - \psi_q \cdot i_d).$$

The torque control circuit in the DTC system was set by two relay controllers: a stator flux linkage regulator and an electromagnetic torque regulator [28]. The difference between the reference signal and the calculated coordinate was input to the regulators [29]. To reduce the ripple of the moment due to switching keys, it was decided to increase the number of levels of the relay flow controller to three.

Inductance is calculated based on the known ratio of flux to current [30]:

$$L = \frac{\Psi}{I}.$$

A similar model was created for the vector control system. With the same description of the coordinates of the drive, regulation is carried out directly, without the use of a table switch [31].

4. **Comparative analysis of systems**

The best performance indicators of the system were achieved in a system with DTC-control. In this system, the magnitude of the moment created on the shaft is controlled by adjusting the angle between the stator and rotor flux link vectors [32]. The maximum speed of this system is limited by the computing capabilities of the controller, which calculates the coordinates of the observer [33].
To compare the systems, a point-rating system of subjective assessment was organized [34]. If the system fully met the specified requirements by the criterion under consideration, it received ten points. If it is not completely satisfied - zero [35].

The performance of the systems was evaluated by the time of the transition process, ceteris paribus, starting conditions [36]. The tabular method for controlling the stator flux linkage vector in the DTC system allows achieving the highest speed in this system. According to the agreed assessment principle, the system of direct control of the moment received 9 points [37]. The vector control system was optimally tuned according to the stability criterion. In this regard, the highest possible speed was not achieved. The final grade is six points [38].

Overshoot in the torque loop was evaluated by comparing the maximum values. It should be noted that for the DTC system, ideal monotonic transients were obtained [39]. On a 10-point scale, this system received 10 points. In the vector control system with optimal settings, the overshoot did not reach more than two amplitude maxima. However, the amplitude of the first maximum was quite high. By this criterion, the system was assigned six points.

![Figure 2. The transition process (a) and overshoot (b) in the CRM depending on the resistance r1.](image)

The level of moment pulsations is caused by the presence of tooth pulsations of the moment of angular characteristic of the electric machine, which cannot be leveled by the control system. So switching current ripple. A direct moment control system is obviously characterized by a sharper change in the direction of the stator flux linkage vector, which leads to a higher amplitude of moment pulsations. In the vector control system, a more acceptable result was obtained, estimated at 8 points.

In this case, the robustness of the system was considered the stability of the system, overshoot, the transition process with a significant change in the parameters of the system, namely, changes in the stator winding resistances due to overheating, a significant change in the ratio of inductive resistances of the longitudinal and transverse components xd / xq in the overload mode.
A significant change in these parameters can lead to incorrect adjustment of the system coordinates and require a new setting. The direct torque control system is more adaptive in structure to changes in these parameters. Figure 2 shows the dependences of the transition process time and overshoot in the torque control loop when the resistance $r_1$ and the ratio of inductive resistances $x_d/x_q$ change. As can be seen from the figures, the system does not lose speed when changing the active resistance in the deviation range of 20% from the nominal value, and changing the ratio of inductive resistances within 30% of the nominal point. Such high indicators allow us to assign 9 points to the DTC system according to the robustness criterion.

For the vector control system, similar indicators of stability and speed were achieved only in the range of 4%. Such a modest indicator did not allow to evaluate the system above four points.

Table 1. Point-rating comparison of control systems.

| Control system                  | DTC | Vector control |
|---------------------------------|-----|----------------|
| System speed                    | 9   | 6             |
| Robustness                      | 9   | 4             |
| The level of moment pulsations  | 4   | 8             |

| Control system                  | DTC | Vector control |
|---------------------------------|-----|----------------|
| Overregulation in the system    | 10  | 6             |
| The final grade                 | 32  | 24            |

The total score, expressed in points, is subjective and takes into account the score only according to the above criteria. Reliability, ease of system configuration, maintenance costs and other important criteria are not considered in this assessment.

5. Conclusion

The choice of an electric drive control system should be carried out individually for each technological object. It is impossible to give universal recommendations. For systems with low requirements for positioning accuracy, speed control of speed and torque, it is recommended to use a scalar control system. This recommendation includes watering and irrigation equipment, sowing equipment.

For facilities whose main requirement is system speed and stability when working in a wide range of loads, whether it be traction electric drives of tractors, combines, seeders for various purposes, cleaning equipment - it is recommended to use a direct torque control system.

Finally, for mechanisms and assemblies requiring high positioning accuracy, such as fertilizer application equipment, individual crop cultivation equipment, planting equipment, automated milking systems, etc., it is recommended to use a vector control system for the electric drive for positioning the working body.

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