The development of an energy efficient electric drive for agricultural machines

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Abstract. Agriculture is a socially significant sector of the economy. The growth of agricultural production contributes to the stable development of society. It is necessary to use new mechanisms driven by induction motors to increase agricultural productivity. Three-phase induction motors are mainly used in the electric drive of agricultural machines. At the same time, it is advisable to use a single-phase network to supply power to remote farms. In this regard, the development of a single-phase electric drive using three-phase motors becomes relevant. In this work, a study of an original semiconductor device for starting a three-phase induction motor from a single-phase network is made. The simulation model of the device created in the Matlab Simulink environment made it possible to study the electromechanical characteristics of the induction motor when operating from a single-phase network. A comparison of the characteristics of the motor during operation from a three-phase and a single-phase network is carried out. The most significant results of the work are the data obtained that the developed device can be used to start and operate a squirrel cage induction motor from a single-phase network. At the same time, the engine energy parameters change slightly.

1. Introduction
At present, agriculture in Russia has great potential for development. If in large agrarian enterprises, modern technological complexes and electrified mechanisms are already used to increase labor productivity and increase the output of finished products, then in small farms, as a rule, outdated production methods are still used.

A great economic effect is achieved when new mobile electrified machines are introduced into agricultural production: feed grinders, mechanical conveyors, electric pumps, milking machines, etc. The use of the above devices leads to an increase in labor productivity, reduces maintenance and repair costs, and improves working conditions.

Induction motors are used to drive machines, mechanisms and units. In most cases, a three-phase asynchronous electric drive is used in agricultural devices. Induction motors have the advantages: lower capital costs, higher efficiency, low maintenance costs. The disadvantage of a three-phase electric drive is the rise in the cost of the power supply system due to the need to use three-core cables. For this reason, it is often more economically justified to use a cheaper single-phase power supply system for remote farms.

Thus, an economical electric drive should combine the advantages of a three-phase and a single-phase power supply system and be devoid of their disadvantages. Therefore, the problem of choosing an effective method for starting a three-phase induction motor from a single-phase network arises.

2. Development of a simulation model of a three-phase induction motor
The «Semiconductor device for starting a three-phase induction motor from a single-phase network» was developed at the Polzunov Altai State Technical University by the staff and students of the department «Electrical Engineering and Automated Electric Drive» [1]. The schematic diagram of the device is shown in Figure 1.

There are similar devices that also allow starting three-phase induction motors from a single-phase network, made on the basis of inductance and a large paper capacitor [2]. They have a number of disadvantages: low reliability, unpredictability rotation direction of the engine, low energy performance. All these disadvantages are eliminated in the semiconductor starting device due to the original engine control system, made on the basis of two power semiconductor switches. IGBT, MOSFET transistors and others can be used as semiconductor switches.

![Figure 1. Schematic diagram of a semiconductor device for starting squirrel cage induction motor from a single-phase network.](image)

To test the performance of such devices, it is necessary to create prototypes. At the initial stages of development, this is economically unprofitable, and in conditions of limited funding, it is often not possible. Therefore, scientists and researchers are increasingly resorting to computer simulation tools [3-13]. Their features include the relative cheapness of research, the ability to simulate the behavior of the system in time. One of these tools is the interactive graphical environment for simulation Matlab Simulink. This environment allows us to simulate electrical machines, and also has a graphical presentation of the simulation results [14-17].

To carry out a computer experiment, a mathematical model of the motor is required. Simulink standard blocks cannot be used for the correct experiment, since the stator windings are fed asymmetrically with vector-algorithmic motor control. In this regard, an original mathematical model of an induction motor was developed. This model allows calculating static and dynamic modes with an asymmetric power supply [18]. On the basis of a mathematical model, a simulation model was built in the Matlab Simulink environment. According to mathematical model the electromechanical characteristics of a three-phase induction motor with a semiconductor starting device were calculated. The simulation model was made on the basis of the parameters of a real motor (AIS56V4U3). This squirrel-cage induction motor has the following nominal characteristics: power, $P_r = 90 \, \text{W}$; voltage, $U_r = 380 \, \text{V}$; current, $I_r = 0.42 \, \text{A}$; the moment developed by the motor, $T_r = 0.64 \, \text{Nm}$; rotation frequency, $n = 1350 \, \text{rpm}$; efficiency value, $\eta_r = 55\%$; the value of the power factor, $\cos \varphi = 0.6$, as well as the multiplicity of the starting torque, $k_s = T_s/T_r = 2.1$; multiplicity of the maximum torque, $\lambda = T_{max}/T_r = 2.2$; multiplicity of the minimum torque, $k_{min} = T_{min}/T_r = 1.8$. The stator windings of the induction motor are star-connected.

3. Operation investigation of an electric drive powered from a three-phase network

At the first step, the electromechanical characteristics of the motor powered from a three-phase network were calculated. The obtained results were compared with the semiconductor starting device
characteristics. Figure 2 shows a simulation model of the direct start of an induction motor, created in the Simulink environment. The electric drive in the simulation model is powered from ideal AC voltage sources that simulate a three-phase network from the standard Electrical Sources library. The characteristics of the induction motor were recorded using measuring units «Scope».

![Figure 2. Model of squirrel cage induction motor with direct start in the Simulink environment.](image)

The results are presented in Figures 3 - 8.

![Figure 3. Oscillogram of angular velocity change in start-up mode, anti-inclusion braking and reverse.](image)

![Figure 4. Oscillogram of angular velocity change in start-up and operation under load.](image)

Figure 3 shows that the steady state of the angular speed of the motor shaft at start-up comes in 0.2 sec. Opposition braking starts at 0.3 sec and ends at 0.48 sec (duration 0.18 sec). In the steady state, the angular velocity of the motor shaft during reverse occurs at the simulation time of 0.68 sec, respectively, the time until the steady state at start and reverse is the same (equal to 0.2 sec).

Figure 4 shows how the change in the angular speed of the induction motor shaft occurs at start-up at the time from the start of the simulation (0 sec) to the instantaneous change in the nominal load torque (0.64 Nm) after 0.4 sec on the shaft. It should be noted that after connecting the load to the steady-state value, the angular velocity comes in 0.1 sec.

Figure 5 shows how the torque on the motor shaft changes during the simulation time. In the period from the start of the simulation to the start of the anti-rotation braking, the torque fluctuates from 1.8 Nm to -0.5 Nm and tends to a steady-state value of 0 Nm. The torque during opposing braking, at a time from 0.3 sec to 0.48 sec, ranges from -3.3 Nm to 1.8 Nm and tends to a steady-state value of -1 Nm. The torque during reverse, at a time from 0.48 sec until the end of the simulation time, ranges from -1.5 Nm to 0.5 Nm and tends to a steady-state value of 0 Nm.
Figure 6 shows that at start-up, the torque on the motor shaft, at times from the start of the simulation (0 sec) and up to 0.4 sec, fluctuates from 1.8 Nm to -0.5 Nm and tends to a steady-state value of 0 Nm. With an instantaneous change in the nominal load torque (0.64 Nm) after 0.4 sec, the torque fluctuates from 0 Nm to 1 Nm and tends to a steady-state value of 0.64 Nm.

Figure 5. The oscillogram of the change in torque on the shaft in start-up mode, anti-inclusion braking and reverse.

Figure 7 shows that the efficiency of the electric motor at rated load is $\eta \approx 55\%$, the power factor is $cos\phi \approx 0.6$. These values are close to the motor manufacturer's ratings.

Figure 8 shows the value of the starting torque of the induction motor, which is $T_s = 1.3$ Nm, while the value of the critical torque is $T_{cr} = 1.35$ Nm.

Based on the obtained data, it can be concluded that the obtained characteristics of the induction motor are close to the nominal ones.

Figure 6. The oscillogram of the change in torque on the shaft in the mode of start-up and operation under load.

Figure 7. Three-phase mains motor performance.

Figure 8. Mechanical characteristics of the motor with three-phase power.

4. Investigation of the operation of an electric drive with a vector-algorithmic type converter using the developed simulation model

Figure 9 shows a model of an electric drive with the motor and a semiconductor starting device, created in the Simulink simulation environment.
In this model, as in the previous one, the transistor control system is simulated using pulse generators. They are easy to configure for issuing control signals with the desired frequency and amplitude. To simulate the operation of the device according to the clockwise field rotation algorithm, the «B / H» switches for all transistors are moved to the position to the upper signal generator «B», to simulate the operation of the device counterclockwise, the switches are moved to the position to the signal generator «H».

Models of «n-p-n» bipolar transistors are taken from the standard library «Power Electronics», which is included in the library for modeling electrical devices and energy systems «SimPowerSystems». Transistor models are accepted as ideal semiconductor switches that do not alter the operation of the drive system.

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Figure 9. Model of an electric drive with a semiconductor starting device in a Simulink environment.

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torque (0.64 Nm) after 0.4 sec on the shaft. It should be noted that after connecting the load, the angular velocity reaches a steady-state value (123 rad/sec) in 0.12 sec.

Figure 12 shows how the torque on the motor shaft changes during the simulation time. In the period from the start of the simulation to the start of the anti-rotation braking, the torque fluctuates from 1.3 Nm to -1.4 Nm. The torque during opposing braking, in the time interval from 0.3 sec to 0.78 sec, ranges from -1.6 Nm to 1.6 Nm and tends to an average steady-state value of -0.3 Nm. The torque during reverse, in the period from 0.78 sec to the end of the simulation time, ranges from 1.4 Nm to -1.3 Nm.

Figure 13 shows that at start-up, the torque on the motor shaft at times from the start of simulation (0 sec) and up to 0.4 sec, ranges from 1.3 Nm to -1.4 Nm. With an instant change in the rated load torque (0.64 Nm) after 0.4 sec, the torque fluctuates from 1.7 Nm to -0.4 Nm.

Figure 14 shows that the power of the electric motor when working with a semiconductor starting device is slightly less than the value of the rated power. This is due to the fact that the stator windings are not supplied simultaneously. In this case, the efficiency reaches the value $\eta \approx 40\%$, the power factor $\cos \varphi \approx 0.42$.

Figure 15 shows that the starting torque of the induction motor is $T_s \approx 0.8$ Nm, the critical moment is $T_{cr} \approx 0.85$ Nm.
Figure 16 shows that the values of the power factor and the efficiency of the induction motor in both cases practically coincide at power values up to 50 W.

Figure 17 shows that the value of the starting torque of an induction motor with a semiconductor starting device, which is equal to $T_s \approx 0.8$ Nm, which is 54% of the starting torque when powered from a three-phase network. The value of the critical torque of the induction motor is equal to $T_{cr} \approx 0.85$ Nm, which is 56% of the critical torque when powered from a three-phase network.

5. Conclusion

Thus, as a result of the study the characteristics of the three-phase induction motor with a semiconductor starting device operating from a single-phase network, in the Matlab Simulink simulation environment were modelled. It was found that the starting torque of the engine is $T_s \approx 0.8$ Nm, the critical torque is $T_{cr} \approx 0.85$ Nm, the efficiency reaches the value $\eta \approx 40\%$, the power factor is equal to $cos\varphi \approx 0.42$. At the rated torque, the speed of the induction motor when operating on an artificial characteristic is 12% less than the speed of the induction motor on a natural characteristic, which slightly reduces the performance of the electric drive.

Based on the foregoing, it can be concluded that the use of the developed electric drive with a semiconductor starting device in the absence of a three-phase power supply is fully justified.

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References
[1] Stalnaya M I, Eremochkin S Y, Dorokhov D V 2019 Semiconductor device for starting a three-phase asynchronous electric motor from a single-phase network Patent RF no. 192777
[2] Glazenko T A and Khrisanov V I 1983 Semiconductor systems of low-power impulse asynchronous electric drive (Leningrad: Energoatomizdat) p 176
[3] Huan-Liang Tsai and Phuong Truong Le 2016 Self-sufficient energy recycling of light emitter diode/thermoelectric generator module for its active-cooling application Energy Conversion and Management 118 170-8
[4] Ouansli N El, Motahhir S, Derouich A, Ghzizal A El, Chebahbi A, Taoussi M 2019 Improved DTC strategy of doubly fed induction motor using fuzzy logic controller Energy Reports 5 271-9
[5] Abdin Z, Webb CJ, Mac E and Gray A 2018 One-dimensional metal-hydride tank model and simulation in Matlab–Simulink International Journal of Hydrogen Energy 43(10) 5048-67
[6] Sung-ho Hur 2018 Modelling and control of a wind turbine and farm Energy 156 360-70
[7] El-Kharashi E, Massoud J G, Al-Ahmari M A 2019 The impact of the unbalance in both the voltage and the frequency on the performance of single and cascaded induction motors Energy 181 561-75
[8] Zhifu W, Jun F, Zhijian S and Qiang S 2017 Study on Speed Sensor-less Vector Control of Induction Motors Based on AMESim-Matlab/Simulink Simulation Energy Procedia 105 2378-83
[9] Abdin Z, Webb C J, Mac E and Gray A 2016 PEM fuel cell model and simulation in Matlab–Simulink based on physical parameters Energy 116(1) 1131-44
[10] Musio F, Tacchi F, Omati L, Stampino PG, Dotelli G, Limonta S, Brivio D and Grassini P 2011 PEMFC system simulation in MATLAB-Simulink environment International Journal of Hydrogen Energy 36(13) 8045-52
[11] Ilimbetov R Yu, Popov V V and Vozmilov A G 2015 Comparative Analysis of “NGTU – Electro” Electric Car Movement Processes Modeling in MATLAB Simulink and AVL Cruise Software Procedia Engineering 129 879-85
[12] Asbjörnsson G, Hulthén E and Evertsson M 2013 Modelling and simulation of dynamic crushing plant behavior with MATLAB/Simulink Minerals Engineering 43 112-120
[13] Bhola M, Kumar N and Ghoshal S K 2018 Reducing fuel consumption of Front End Loader using regenerative hydro-static drive configuration-an experimental study Energy 162 158-170
[14] Xiaolin Tang, Dejui Zhang, Teng Liu, Amir Khajepour, HaishengYu and Hong Wang 2019 Research on the energy control of a dual-motor hybrid vehicle during engine start-stop process Energy 166 1181-93
[15] Guoheng Wu, Junhong Yang, Jianzhong Shang and Delei Fang 2020 A rotary fluid power converter for improving energy efficiency of hydraulic system with variable load Energy 195 116-957
[16] Eyhab El-Kharashi and Maher El-Dessouki 2014 Coupling induction motors to improve the energy conversion process during balanced and unbalanced operation Energy 65 511-16
[17] Ahmed Abrar, Yelamali Palaksh and Udayakumar R 2020 Modelling and simulation of hybrid
technology in vehicles *Energy Reports* **6** 589-94

[18] Stal'naya M I, Eremochkin S Y 2015 Simulation of the electromechanical characteristics of a three-phase electric motor with a vector-algorithmic type converter in MATLAB SIMULINK. *Elektroprivody peremennogo toka: Trudy shestnadcatoy Mezhdunarodnoy nauchno-tekhnicheskoy konferencii. Ekaterinburg* 145-8