1. Mohamed QAWAQZEH[1], 2. Huthaifa A. AL_ISSA[1], 3. Kostiantyn SOROKA[2], 4. Viktor KHARCHENKO[2], 5. Mykola LYSYCHENKO[3], 6. Oleksandr MIROSHNYK[3], 7. Stepan KOVALYSHYN[4], 8. Taras SHCHUR[4], 9. Paweł KIEŁBASA[5]

Al Balqa Applied University (1),
O.M. Beketov National University of Urban Economy in Kharkiv (2),
State Biotechnological University (3),
Lviv National Agrarian University (4),
University of Agriculture in Krakow (5).
ORCID: 1. 0000-0001-7027-5577, 2. 0000-0002-0768-8325, 3. 0000-0002-0143-2409 4. 0000-0001-9091-6861, 5. 000-0003-1209-609X, 6. 0000-0002-4424-0159, 7. 0000-0002-6144-7573, 8. 0000-0003-0205-032X, 9. 0000-0003-0249-8626

doi:10.15199/48.2023.03.17

Modeling and research of methods for speed and torque control of DC motors

Abstract. *The analysis ways of speed control and torque of the collectorless electric motor is executed. A mathematical model by SAC with an operational amplifier in the SCILAB / XCOS package has been developed. Modeling and research of quality of work of the electric motor with various types of regulators is carried out. On the basis of the conducted studies, the optimal parameters of the PID controller were selected. Recommendations for the use of engines with various types of regulators have been developed.*

Streszczenie. *Przeprowadzono analizę sposobów regulacji prędkości i momentu obrotowego bezkolektorowego silnika elektrycznego. Opracowano model matematyczny przez SAC ze wzmacniaczem operacyjnym w pakiecie SCILAB / XCOS. Przeprowadzono modelowanie i badanie jakości pracy silnika elektrycznego z różnymi typami regulatorów. Na podstawie przeprowadzonych badań wybrano optymalne parametry regulatora PID. Opracowano zalecenia dotyczące eksploatacji silników z różnymi typami regulatorów.* ***(Modelowanie i badanie metod sterowania prędkością oraz momentem obrotowym silników prądu stałego)****.*

Keywords: DC motors, speed and torque control, operational amplifier, modes of operation
Słowakluczowe: silniki prądu stałego, regulacja prędkości i momentu obrotowego, wzmacniacz operacyjny, tryby eksploatacji

Introduction

The operation of brushless direct current (BLDC) motors involves controlled switching of the stator windings. This requires proper control devices and switches. Modern advances in information technology, power microelectronics and microprocessor technology have created the conditions for the development and widespread use of actuators based on valve motors. Despite the higher price, the valve motors, in comparison with the collector ones, prove to be competitive in such areas as: robotics, electric transport, flexible production systems, instrument making, computer engineering, etc. At the forefront are their functional and operational characteristics. BLDCs allow to create gearless drives of technical devices [1-8], a motor-wheel of vehicles and significantly simplify the design of mechanisms. They provide a huge starting torque and the ability to change speeds over a wide range, work in dynamic and transient modes, high quality of transients. The power range of the valve motors is quite wide: from 1W, and up to 1000 kW in traction drive of railway transport.

In modern electric vehicles from using DC motors with rheostat control going to asynchronous AC motors and the most perspective DC motors. Complex electrical processes in such motors require the development of control methods that would ensure their operation in a wide range of changes in the moment of loading on the shaft and the quality of work, which is determined by the nature and duration of the transition process. With this in view, it is important to create mathematical models and their using in the development of electric vehicles.

In [9-14] the methods of control of speed of rotation of BLDC are considered: continuous, pulse, relay and discrete-phase. The continuous method involves a smooth change in the voltage supplied to the stator windings. Pulse control is usually performed by pulses of different polarity, corresponding to positive or negative, in the mode against switching on, the torque of the motor. The relay method is to use a relay that compares the value of the control voltage with the motor speed sensor readings and switches the motor on or off. The discrete-phase method of optimal control is performed by comparing the motor frequency with the reference frequency of the reference generator.

In addition to indicated methods, the paper [2, 15-17] considered methods of sensorless control, which takes into account the rate of change of current, the value of the third harmonic and determines the inductance of the stator winding at a certain point in time. The third harmonic value is used for control. Faking into account a number of factors affecting the operation of the motor and the nonlinear relationship between current, magnetic flux, and rotation torque, a control system based on fuzzy logic, i.e. artificial intelligence methods, is used.

In [18-21], the speed and torque control of an optical telescope drive with a BLDC using relay method is considered. A mathematical computer model has been developed and a comparison of the BLDC operation with a similar collector motor is made. The results of the mathematical model study and the test of the models of electric drives on the stand showed the coincidence of dynamic characteristics of the collector and valve motors.

In [22] a method of controlling the operation of a valve electric drive of a vehicle based on mechanical and electromechanical characteristics is considered. The pulse control of the motor by means of the relay is carried out: after the output to the natural electromechanical characteristic, the movement on it and the transition to the artificial characteristic is carried out, similarly, as in the case of the execution of the collector motor.

The above analysis shows that the relay control method is one of the effective for solving the problems of regulation and stabilization of speed and torque of BLDC. The disadvantage of the relay regulators are necessity to reduce the discreteness intervals, to ensure the accuracy of regulation, and limited opportunities to implement known principles of regulation. This in practice leads to using numerical controllers. An alternative to such regulators are analog regulators implemented on operational amplifiers.

Construction of mathematical model

An analysis of the methods of controlling the speed of BLDC showed that one of the most effective is the relay method of controlling the speed and torque of the motor. The results of studies [18-22] show that the mechanical characteristics of the valve and collector motors are the same. In view of this, a method of controlling the speed of BLDC is proposed according to the circuit presented in Figure 1.

According to the circuit, the current from the power source E through the transistors VT flows directly to the stator windings. The operation of the transistors is controlled by the switch on control commands coming from the microprocessor. The microprocessor processes the signals of the rotor position sensor RPS and issues commands to the switch. This control is carried out from start-up and acceleration of the motor and to steady or dynamic operation mode. This ensures the operation of the BLDC at any speed. The operation of the rotor position sensor is based on the photoelectric or inductive principle, or the use of a Hall sensor [11, 28].

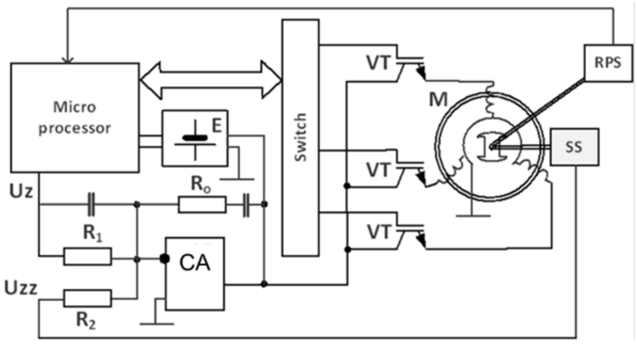

Fig.1. Schematic diagram of a brushless motor with an operational amplifier

In the method proposed in this work, the control of the speed and torque of the BLDC is carried out by feedback from the regulator, and the CA operational amplifier CA is used as which [23-27]. The gain of the regulator is set by the resistors R0 and R1. Regulators of different types can be built on the basis of the operational amplifier by changing the connection circuit of resistors and capacitors. The automatic control system (ACS) [29-31] feedback is provided by the speed sensor SS. Control is carried out by changing the value of the current in the windings of the BLDC stator. The speed sensor can be a tachogenerator, a photoelectric sensor or other type of sensor [11, 28]. Changing the motor speed can be performed, for example, by changing the voltage Uz at the input of the operational amplifier, by commands transmitted over the CAN network [32].

According to the proposed circuit, the speed control of the BLDC is carried out by changing the amount of current supplied through the transistors VT to the windings of the stator of the motor M. That is, relay control, during which only the power source was switched on or off, replaced by the ACS, which regulates the value of current in the stator windings. The frequency of the motor is set by the voltage UZ supplied to the input of the operational amplifier CE. Control is carried out by the rotor speed measured by the speed sensor SS. The sensor voltage corresponding to the rotor speed in the feedback circle is fed to the input of the operational amplifier CA. The control method involves the use of different types of regulators. The type of regulator can be changed by permuting the elements of the circuit of the operational amplifier CA by introducing additional capacitors or resistors. In the following, this brushless DC motor (BLDC) with an operational amplifier will be abbreviated (BLDC-OA).

An indicator that determines the functional suitability of the electrical drive is the accuracy of adherence to a given speed and providing the desired value of torque. The operation of the engine in the composition, such as the electric drive of a quadcopter or other vehicle, was investigated using a mathematical model by applying to its inputs different values of voltage and torque. The study of the electric drive was performed on the basis of its mathematical model. The study was performed in static and dynamic modes. Regarding the magnitude of the loads, and its operation is subject to accuracy requirements [31, 33].

A motor with 12 stator poles and 8 rotor poles (12/8) is considered. Rotation speed within from 3200 rpm to 15000 rpm. Engine torque is determined by the amount of energy consumed. Voltage on the BLDC-OA U = 12 V, current I = 0.52 A, where the power is P = 6.24 W. The efficiency of BLDC is about 75-80%. Part of the energy is dissipated, and the rest is spent to overcome the forces of resistance. Torque on the motor shaft of the order ΔP = 5 Н · м.

To construct a mathematical model, the motor is represented as a second-order aperiodic link with two time constants: T_E – of the electrical part of the motor and T_M – of the mechanical part (Fig. 2). Quite often the engine is presented as an aperiodic link of the electrical part and integrating for mechanical parts. Electric drive with BLDC-OA often has a high speed, so a significant role in its operation is played by viscosity. Therefore, in this model, the mechanical part is represented as an aperiodic link with a time constant Tm. The feedback is provided by a speed sensor SS with the transmission factor K_V. The speed sensor signal U_{ZZ} is fed to the differential input of the voltage regulator. The motor speed is regulated by the voltage U_Z. Motor speed control is carried out depending on the difference between the U_{ZZ} feedback voltage and the set voltage U_Z.

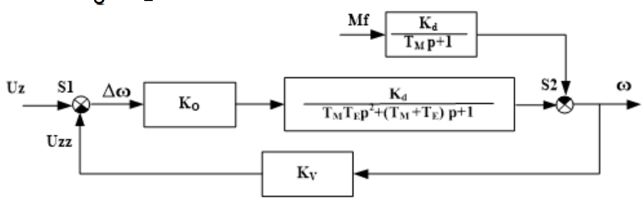

Fig.2. Schematic diagram of the automatic engine speed control system BLDC-OA

The numerical values of the motor parameters are as follows: stator winding resistance R_{st} = 2.7 Ω; inductance L_{st} = 1.8 μH; moment of inertia of the rotor $J = 1.25 \cdot 10^{-4}$ kg·m^2; constant of the motor $K_k = 4.3 \cdot 10^{-3}$.

Mathematical simulation in SCILAB/XCOS software environment was performed to study the operation of BLDC with different types of regulators implemented on an operational amplifier. SCILAB is open source software and does not require licensing [34]. This package successfully replaces the Matlab/Simulink license package [34-39]. Other solutions for simulations and calculationa sin [40-42] can be also used.

Investigation of the modes of operation of BLDC-OA

Studying the accuracy of the motor operation should distinguish between static and dynamic control errors. Static error is the error in the static operation mode. Dynamic error occurs in dynamic mode when the value of the resistance forces changes. Control error has two components: on the input, the control value and on the value of the load on the shaft. The values of these errors were determined by experimental study of the model. Theoretically, the values of the relative control errors are calculated according to the formulas [31]:

- error on the control signal:

(1) $$\delta_x = \frac{1}{1+K} = S \;;$$

- on the disturbing action:

(2) $$\delta_f = \frac{K_f}{1+K} \,.$$

where K_o, K_d, K_f are the gains of the operational amplifier, the motor, and the link, respectively ($K = K_o{\cdot}K_d$).

BLDC motor operation when directly connected to a power supply without an operational amplifier

Engine model, when connected directly to the power supply without the use of ACS with operational amplifiers, is shown in Figure 3. The values of the model parameters are as follows: supply voltage U_Z = 12 V, the value for the moment of resistance force M_f = 5 N·m, the time of moving the magnetic head from the parking position on the working surface of the disk t_f = 5 s. The results of the simulation in the form of a graph of motor speed change are shown in Fig. 4, the numerical values of speed and error of control are given in Table 1 (section – direct motor start).

Model coefficients are calculated according to the formulas:

(3) $$\begin{cases} K_o = R_o/R_1; \\ K_d = 1/K_K; \\ T_E = L_{st}/R_{st}; \\ T_m = R_{st} \cdot j/K_K{}^2. \end{cases}$$

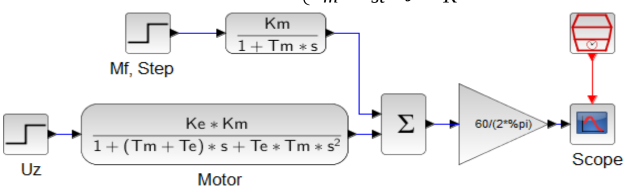

Fig.3. Model of the BLDC-OA electric drive at direct start of the motor

According to the simulation results on a computer model (Fig. 4), the motor speed during acceleration changes within 5 s and reaches V = 9311 rpm. Further, the rocker moves the magnetic head from the parking position to the surface of the disk and the motor speed drops to V_f = 6153 rpm.

The results of the experiment show that the operation of the electric drive with such BLDC is extremely unsatisfactory. Acceleration exceeds 5 s. When the magnetic head moves to the surface of the disks, a transient of the same duration occurs, and the motor speed decreases by δ_f = 34%. The motor without ACS is not suitable for use: the first, the acceleration time is quite large; the second is the speed of the motor drops sharply as the load changes, and the third is speed stabilization is not provided. To ensure the quality of operation of the electric drive with this motor it is necessary to use the ACS.

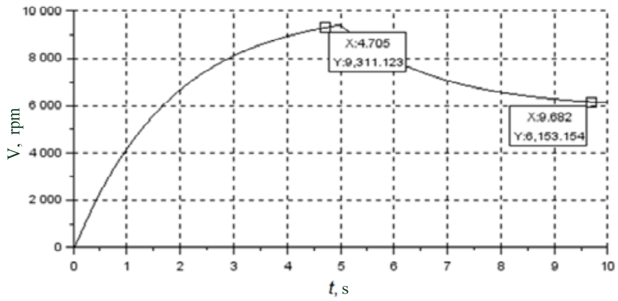

Fig. 4. Motor speed change graph directly plugged into the power supply

Use of the ACS with a proportional (P) regulator and study of the operation of the electric drive

The simplest ACS includes feedback and a proportional regulator. The mathematical model corresponding to such ACS is presented in Figure 5. The model is reduced to a single feedback and the speed output is calculated in revolutions per minute. The CE operational amplifier is used as a regulator. The model has two inputs: the first – by the signal U_Z, the second – by the resistance force M_f which occurs when moving the rocker with a magnetic head.

The study of the motor was performed under the following conditions: simulation time is 10 s, the time of application of the perturbation force is 5 s, the interval of discreteness of integration is 0.1 ms, the voltage of the power supply U_Z = 12 V, the perturbation signal is stepped, the moment of the perturbation force M_f = 5 N·m, the setpoint speed of the motor spindle is 7200 rpm. The integration of the equations of motion is performed according to the method of Runge-Kutta of the 4th order.

Table 1. Results of the study of the accuracy of the operation of the electric drive the BLDC-OA

K	S	Acceleration of the motor			Read/Write			Transient	
		V, rpm	ΔV, rpm	δV, %	V_f, rpm	ΔV_f, rpm	δ_f, %	Type	Duration t_{PP}, s
Direct motor connection (without ACS)									
–	–	9311			6153	–	34	M	5
Static control system (P-regulator)									
16.5	0.315	5725	411	5.69	62295	977	13.6	M	1.6
29.8	0.033	6972	234	3.25	66490	557	7.74	A	0.35
87.5	0.011	7125	81	1.12	7013	193	2.68	O	0.3
Astatic integrating (I-regulator)									
0.33	0.75	7206	0	0	7206	0.04	0	M	35
1.65	0.48	7207	0.03	0	7207	0.02	0	O	20
Proportional-integrating (PI-regulator)									
3.31	–	7206	0		7207	0	0	M	2.5
46	–	7206	0		7203	4.4	0	O	0.5
Proportional-integro-differential (PID-regulator)									
Static, 5 N·m		7208	1.5	0	7206	1.7	0	A	0.03
Dynamic, 5 N·m/s		7205	1.5	0	7194	11.0	0.15	A	0.03

Transient: M – monotonous, A – aperiodic; O – oscillatory

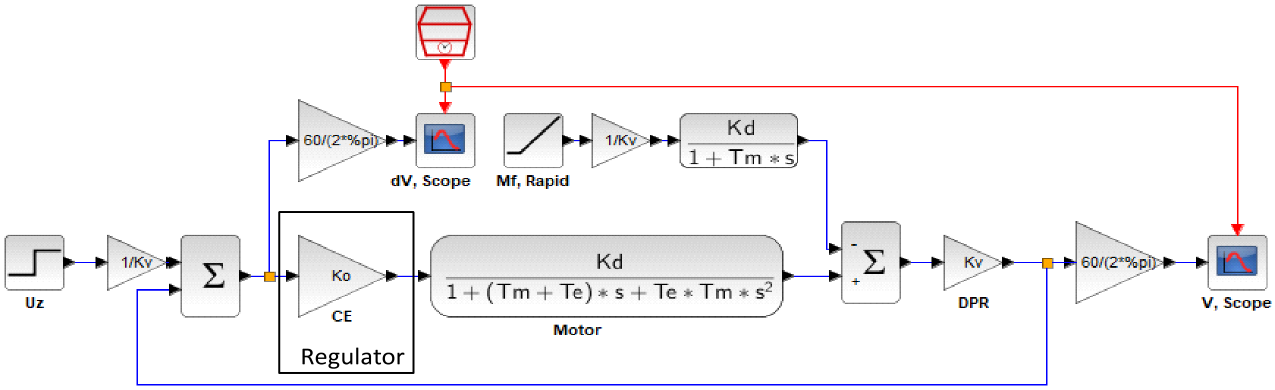

Fig.5. Model of the ACS of the electric drive with the P-regulator reduced to a single feedback

The results of the experiment are shown in Figure 6. After switching on the motor accelerates (Fig. 6, *a*) to a speed corresponding to the set value with a certain error. When the value of the gain K_o = 15.5 transient is monotonic, with increasing K_o up to 29.8 transient becomes aperiodic, and at K_o = 87.5 in oscillatory (Table 1, section P-regulator). The acceleration time is within t_{PP} = 1.6 s at monotonous and t_{PP} = 0.3 s in the case of oscillatory transient.

The dependence of the error of control ΔV is presented in Fig. 6,*b*. Control error after motor acceleration is δV = 1.12%. At the time of change of the disturbing action corresponding to "take-off" and positioning of the magnetic head, the speed of the motor decreases from V = 7125 rpm to V_f = 7013 rpm, and the control error is δV = 2.28%.

In the case of aperiodic transient, the value of the overregulation is 10%, and the duration of the transient is t_{PP} = 0.35 s. The performed analysis shows that the motor operates significantly better than when directly connected.

For dynamic operation studies, the stepped signal is replaced with a dynamic signal. To do this, we introduce into the model a block of constantly increasing signal "M_f, Rapid" (Fig. 5). The signal growth rate is selected as 5 N·m/s. The results of the study are presented in Figure 7. In the case of increasing resistance force by the linear law, the speed of the motor is constantly decreasing. In 5 s the speed decreased from V_f = 7125 rpm to V_f = 6083 rpm.

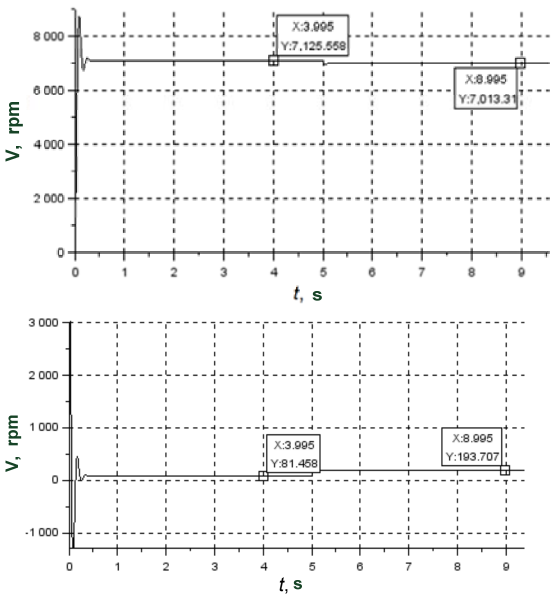

Fig.6. Graphs at oscillatory transient:
a) speed of rotation of disks, *b*) error of control

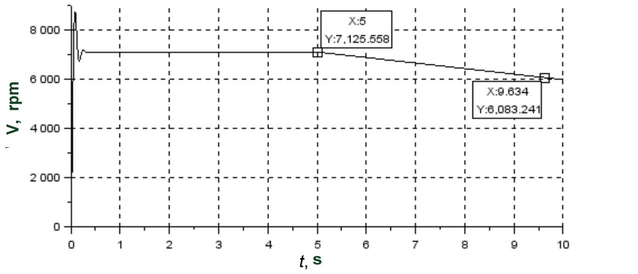

Fig.7. Change in the speed of rotation of the disks in case of change shaft torque at constant speed

Therefore, the considered static ACS does not provide a constant motor speed in dynamic operation mode. The control system requires correction and conversion from static to astatic. For this purpose, an integrating link is introduced into the system [29-31].

The use of an astatic integrating I-regulator

The results of the study of the operation of the electric drive after the introduction to the regulator of the integrating link are shown in Table 1 (section I-regulator). From the above data it is seen that in the case of the gain equal to K_o = 0.33 the regulator operates in monotonous, and at the value of K_o = 1.65 in the oscillatory transient. The motor speed, at the end of the transient, is set to the setpoint V = 7200 (7206 due to the model setting). The control errors on the control signal δV as well as on the perturbation signal δ_f are zero. This is the positive side of the regulator. However, the duration of transient is unacceptably long: t_{PP} = 35 s and t_{PP} = 20 s. Therefore, such a regulator cannot be used.

Proportional-integrating PI-regulator

By introducing the amplifier link in parallel to the integrating one (Fig. 5 and Fig. 8), an astatic control system with proportional-integrating regulator (PI-regulator) was obtained. During the study of the operation of the electric drive with this regulator, the gain of the parallel link and the operational amplifier are selected experimentally. The operation in monotonous and oscillatory transients is considered (Table 1, section PI-regulator). The analysis shows that the control error on static input and disturbing signals is zero. The duration of the monotonous transient t_{PP} = 2.5 s, and in the case of oscillatory transient t_{PP} = 0.5 s. That is, BLDC-OA provides acceleration of disks to a predetermined speed and zero control error after the transition period. The disadvantage is the rather long duration of the transient.

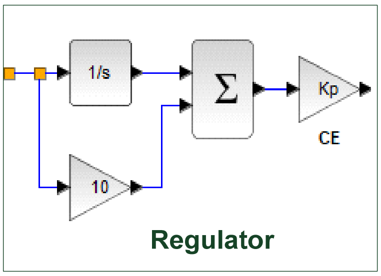

Fig.8. Correcting link of the PI-regulator

ACS correction using proportional-integro-differential PID-regulator

Improvement of the electric drive operation is made by using a PID-regulator [43-46]. The regulator includes a chain of differential, integrating and proportional links (Fig. 9). The parameters of the links were selected experimentally.

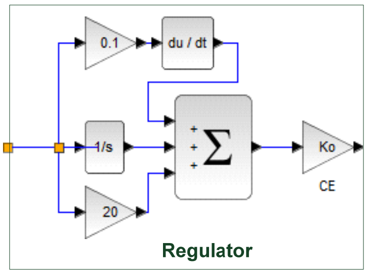

Fig.9. Correcting link of the PID-regulator

Graph of operation in dynamic mode is shown in Figure 10, the numerical values of speed and error of control – in Table 1 (section PID-regulator). Also considered is the dynamic operation of the motor when increasing the shaft torque at speed of M_f /c=5 N·m/s. The stable speed value changes from V = 7205 rpm to V_f = 7194 rpm, i.e. just for δ_f = 0.15%. Figure 11 shows the transient separately. The overregulation value is 12%, and the duration of transient of the disks acceleration t_{PP} = 0.03 s.

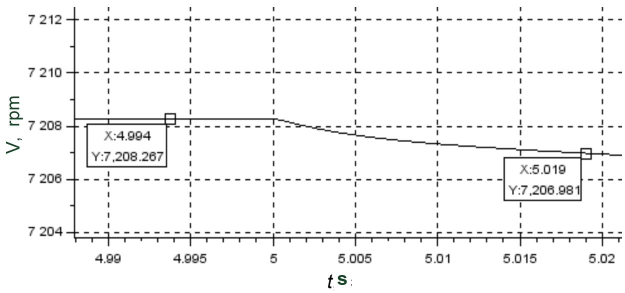

Fig.10. Graphs of the BLDC-OA electric drive operation with PID-regulator in dynamic mode

The obtained results show that the considered BLDC with the PID-regulator operates qualitatively with significant changes of the torque on the shaft. In the case of a sudden movement of the magnetic head from the position of parking and changing the torque on the shaft, the value of the change in speed is within ΔV_f = 10.68 rpm, i.e. the error of regulation is not more than δ_f = 0.15 %.

The results of the study show that in the case of implementation using an operational amplifier ACS with PID controller, the parameters of which can be determined using the proposed mathematical model, allow to provide high characteristics of the electric drive. Valve motors with this control system are suitable for use in systems for different purposes.

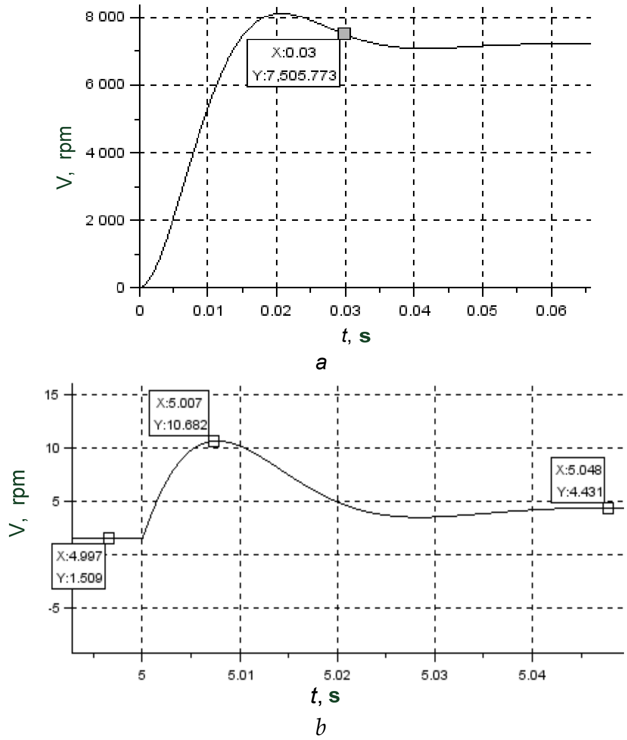

Fig.11. Transition process of BLDC-OA with PID-regulator: *a*) acceleration of the disks, *b*) error during pulse change of the load

Conclusions

One effective way to control the speed and torque of a valve motor is to use a relay method that uses an automatic control system instead of a relay allows to expand functionality of the regulator and to transfer from step to smooth regulation.

A computer model of the valve motor control system has been developed using an operational amplifier, which allows to implement various control principles.

It is shown that the PID-regulator based on an operational amplifier allows to create an electric drive that meets the requirements of accuracy and quality. A mathematical model was created, with the help of which the parameters of the PID-regulator were selected, which ensure the observance of a given speed with an accuracy of 0.15% in dynamic modes of operation and the duration of transients of 30 ms.

The obtained data show that the functionality of the valve motor is quite wide, and in the case of selecting the appropriate control method and type of regulator, provide a constant speed of the electric drive when changing the torque on the shaft from zero to the operating value Mf and at dynamic change with the rate of change M_f / *c*.

Valve motors with PID-regulators should be used to design actuators for mechanisms that require high precision, high quality transients and operate in harsh operating conditions, with a wide range of speed and torque changes.

Acknowledgement

Funded by a subsidy of the Ministry of Education and Science for the Agricultural University of Hugo Kołłątaj in Krakow for 2023.

Author*: Assistant Professor Mohamed Zaidan Qawaqzeh, Al-Balqa Applied University, Department of Electrical and Electronics Engineering, Al Salt 19117, Jordan, E-mail:* qawaqzeh@bau.edu.jo; *prof. dr hab. inż. Huthaifa A. Al_Issa, Al-Balqa Applied University, Department of Electrical and Electronics Engineering, Al Salt*

19117, Jordan, E-mail: h.alissa@bau.edu.jo; *Assistant Professor Kostiantyn Soroka, O.M. Beketov National University of Urban Economy in Kharkiv, Department of Electric transport, str. Marshala Bazhanova, 17, Kharkiv, 61002, Ukraine, E-mail:* kasoroka@ukr.net; *prof. dr hab. inż. Viktor Kharchenko, O.M. Beketov National University of Urban Economy in Kharkiv, Department of Electric transport, str. Marshala Bazhanova, 17, Kharkiv, 61002, Ukraine, E-mail:* kharchenko1054@gmail.com; *prof. dr hab. inż. Mykola Lysychenko, State Biotechnological University, Department of Electromechanics and Robotics, str. Rizdviana, 19, 61052 Kharkiv, Ukraine, E-mail:* 1prlysychenko@ukr.net*; prof. dr hab. inż. Oleksandr Miroshnyk, State Biotechnological University, Department of Power Supply and Energy Management, str. Rizdviana, 19, 61052 Kharkiv, Ukraine, E-mail:* omiroshnyk@ukr.net; *Assistant Professor Taras Shchur, Lviv National Agrarian University, Department of Cars and Tractors, str. Volodymyr Great,1, 80381 Dubliany, Ukraine, E-mail:* shchurtg@gmail.com*; Paweł Kiełbasa Associate Professor, University of Agriculture in Krakow, Faculty of Production and Power Engineering, Balicka Av. 116B, 30-149 Krakow, E-mail:pawel.kielbasa@urk.edu.pl.*

REFERENCES

[1] Łukasik Z, Czaban A, Szafraniec A. Mathematical model of asynchronous pump drive with distributed mechanical parameters. *Przegląd Elektrotechniczny*, 2018, 6, 155-159. doi:10.15199/48.2018.06.32
[2] Manca, R.; Circosta, S.; Khan, I.; Feraco, S.; Luciani, S.; Amati, N.; Bonfitto, A.; Galluzzi, R. Performance Assessment of an Electric Power Steering System for Driverless Formula Student Vehicles. *Actuators* 2021, 10, 165. https://doi.org/10.3390/act10070165
[3] Carev, V.; Roháč, J.; Šipoš, M.; Schmirler, M. A. Multilayer Brushless DC Motor for Heavy Lift Drones. *Energies* 2021, 14, 2504. https://doi.org/10.3390/en14092504
[4] Yan, L.; Xuejun, S.; Di, L. Comparative Study on Performance of Aeronautical ISG Based on Brushless Synchronous Generator and PMSG. *Journal of Physics: Conference Series* 2021, 1871, 1. DOI :10.1088/1742-6596/1871/1/012037
[5] Praveen, R.P. A novel slot less Halbach-array permanent-magnet brushless DC motor for spacecraft applications. *IEEE Trans. Ind. Electron*. 2012, 59, 9, 3553–3560.
[6] Wu, J.; Sun, F.; Deng, X.; Zhang, Z.; Yu, D.; Wang, Z.; Li, Z. Design and calculation of sine wave permanent magnet brushless motor for electric vehicle. *E3S Web of Conferences*. 2021, 261, 01056. DOI :10.1051/e3sconf/202126101056
[7] Tshambe, P.N.; Wei, J. Sensorless Starting Control of Brushless Synchronous Machine (BSM) for Aircraft. *Journal of Physics: Conference Series* 2021, 1914, 1. DOI :10.1088/1742-6596/1914/1/012030
[8] Ebus, T.; Dietz, M.; Hupfer, A. Experimental and numerical studies on small contra-rotating electrical ducted fan engines. *CEAS Aeronautical Journal* 2021, 12, 3, 559-571. DOI:10.1007/s13272-021-00517-
[9] Khasawneh, A.; Qawaqzeh, M.; Kuchanskyy, V.; Rubanenko, O.; Miroshnyk, O.; Shchur, T.; Drechny, M. Optimal Determination Method of the Transposition Steps of An Extra High Voltage Power Transmission Line. *Energies* 2021, 14, 6791. https://doi.org/10.3390/en14206791.
[10] Łukasik Z., Czaban A., Szafraniec A., Żuk V., - The mathematical model of the drive system with asynchronous motor and vertical pump Przegląd Elektrotechniczny, R. 94 NR 1/2018, 133-138
[11] Kolano, K.; Drzymała, B.; Gęca, J. Sinusoidal control of a brushless dc motor with misalignment of hall sensors. *Energies* 2021, 14, 13. DOI :10.3390/en14133845
[12] Abdelfattah, H.; Mosaad, M.I.; Ibrahim, N.F. Adaptive neuro-fuzzy technique for speed control of six-step brushless DC motor. *Indonesian Journal of Electrical Engineering and Informatics* 2021, 9, 2, 302-312. DOI:10.52549/ijeei.v9i2.2614
[13] Grechushkin, Yu.V.; Epifanov, O.K. On Control of Brushless Torque Motors with High Phase Inductance in Direct Drives of Gyro Devices. *Journal of Physics: Conference Series* 2021, 1864, 1. DOI :10.1088/1742-6596/1864/1/012018
[14] Szafraniec A. Modelowanie matematyczne procesów oscylacyjnych w napędzie elektrohydraulicznym o podatnej transmisji ruchu, *Przegląd Elektrotechniczny*, R. 93 NR 12/2017, 167-170
[15] Song X.; Han B.; Wang K. Sensorless Drive of High-Speed BLDC Motors Based on Virtual Third-Harmonic Back EMF and High-Precision Compensation. *IEEE Transactions on Power Electronics* 2019, 34, 9, 8787-8796. doi:10.1109/TPEL.2018.2885031.
[16] Sikora, A.; Woźniak, M. Impact of current pulsation on BLDC motor parameters. *Sensors* 2021, 21, 2, 1-18. DOI:10.3390/s21020587
[17] Wang, Z.; Zhang, Y.; Yu, P.; Cao, N.; Dintera, H. Speed control of motor based on improved glowworm swarm optimization. *Computers, Materials and Continua* 2021, 69, 1, 503-519. DOI:10.32604/cmc.2021.017624
[18] Peicheng S.; Suo W.; Rongyun Z.; Ping X. Study on the fuzzy proportional–integral–derivative direct torque control strategy without flux linkage observation for brushless direct current motors. *International Journal of Advanced Robotic Systems* 2019, 16, 3, 172988141985314. doi:10.1177/1729881419853141.
[19] Rusek A., Czaban A., Lis M., Klatow K., Model matematyczny układu elektromechanicznego z długim sprężystym wałem napędowym, Przegląd Elektrotechniczny, 91 (2015), nr 12, 69-72.
[20] Patel, H.; Chandwani, H. Simulation and experimental verification of modified sinusoidal pulse width modulation technique for torque ripple attenuation in Brushless DC motor drive. *Engineering Science and Technology, International Journal* 2021, 24, 3, 671-681. DOI:10.1016/j.jestch.2020.11.003
[21] Majdoubi, R.; Masmoudi, L.; Bakhti, M.; Jabri, B. Torque control oriented modeling of a brushless direct current motor (BLDCM) based on the extended park's transformation. *Journal Europeen des Systemes Automatises* 2021, 54, 1, 165-174. DOI:10.18280/jesa.540119
[22] Czaban A., Lis M., Klatow K., Nowak M., Patro M., Model matematyczny napędu synchronicznego o podatnej transmisji ruchu w fizycznych współ, rzędnych prądów (A-model), *Przegląd Elektrotechniczny*, 92 (2016), nr 12, 29-32.
[23] Franklin G.F.; Powell J.D.; Emami-Naeini A. Feedback Control of Dynamic Systems. 6th Edition, *Prentice Hall*, 2009, 840.
[24] Beloso-Legarra, J.; de la Cruz-Blas, C.A.; Lopez-Martin, A.J.; Ramirez-Angulo, J. Gain-boosted super class AB OTAs based on nested local feedback. *2021 IEEE Transactions on Circuits and Systems I: Regular Papers* 2021, 68, 9, 9467261, 3562-3573. DOI: DOI:10.1109/TCSI.2021.3090154
[25] Gifta, G.; Rani, G.N.; Rajaram, S. Design of Low Noise, Low Power, Bulk-Driven CMOS Based Operational Transconductance Amplifier for Biosensor Applications. *Journal of Electrical Engineering and Technology* 2021, 16, 5, 2793-2807. DOI: 10.1007/s42835-021-00770-0
[26] Kolano, K. Determining the Position of the Brushless DC Motor Rotor. *Energies* 2020, 13, 1607. https://doi.org/10.3390/en13071607
[27] Mousavi-aghdam, S.R. Design and analysis of a novel topology for slotless brushless DC (BLDC) motors with enhanced torque and efficiency. *IET Electric Power Applications* 2020, 284-298. https://doi.org/10.1049/elp2.12020
[28] Zhang, X.; Zhao, Y.; Lin, H.; Riaz, S.; Elahi, H. Real-Time Fault Diagnosis and Fault-Tolerant Control Strategy for Hall Sensors in Permanent Magnet Brushless DC Motor Drives. *Electronics* 2021, 10, 1268. https://doi.org/10.3390/electronics10111268
[29] Al_Issa, H.A.; Qawaqzeh, M.; Khasawneh, A.; Buinyi, R.; Bezruchko, V.; Miroshnyk, O. Correct Cross-Section of Cable Screen in a Medium Voltage Collector Network with Isolated Neutral of a Wind Power Plant. *Energies* 2021, 14, 3026. https://doi.org/10.3390/en14113026.
[30] Bezruchko, V.; Buinyi, R.; Strogii, A. Application of GSM technology for identification of phase-to-ground faults in electric networks with isolated neutral and pin-type isolation. *Tekhnichna elektrodynamika* 2018, 5, 96-99. https://doi.org/10.15407/techned2018.05.096
[31] Olena Rubanenko, Vitalii Yanovych, Oleksandr Miroshnyk, Dmytro Danylchenko. Hydroelectric Power Generation for Compensation Instability of Non-guaranteed Power Plants. 2020 *IEEE 4th International Conference on Intelligent Energy and Power Systems (IEPS)* 52-56, 20199422. DOI: 10.1109/IEPS51250.2020.9263151
[32] Pazyi V., Miroshnyk O., Moroz O., Trunova I., Savchenko O, Halko S. Analysis of technical condition diagnostics problems

and monitoring of distribution electrical network modes from smart grid platform position. *2020 IEEE KhPI Week on Advanced Technology (KhPIWeek)*, 57-60, 20168725 DOI: 10.1109/KhPIWeek51551.2020.9250080.

[33] Qawaqzeh M., Zaitsev R., Miroshnyk O., Kirichenko M., Danylchenko D., Zaitseva L. High-voltage DC converter for solar power station. *International journal of power electronics and drive system*. – 2020. – Vol. 11, No. 4. – P. 2135-2144. DOI:10.11591/ijpeds.v11.i4.pp2135-2144

[34] Iegorov, O.; Iegorova, O.; Miroshnyk, O.; Savchenko, O. Improving the accuracy of determining the parameters of induction motors in transient starting modes. *Energetika* 2020, 66, 1, 15-23. DOI:10.6001/energetika.v66i1.4295

[35] Qawaqzeh, M.Z.; Miroshnyk, O.; Shchur, T.; Kasner, R.; Idzikowski, A.; Kruszelnicka, W.; Tomporowski, A.; Bałdowska-Witos, P.; Flizikowski, J.; Zawada, M.; Doerffer, K. Research of Emergency Modes of Wind Power Plants Using Computer Simulation. *Energies* 2021, 14, 4780. https://doi.org/10.3390/en14164780

[36] Miroshnyk, O., Kovalyshyn, S., Tomporowski, A., Kruszelnicka, W., Bałdowska-Witos, P. Research of probability characteristics of current and voltage unbalance based on using graphs of load for the duration at the substation. *Journal of Physics: Conference Series*, Volume 1426, Issue 1, 012036, 2020. DOI: 10.1088/1742-6596/1426/1/012036

[37] Miroshnyk, O., Szafraniec, A. Investigation of power saving modes in 10/0.4 kV distribution networks. *Przeglad Elektrotechniczny*. R. 96, №4, 2020, 174-177 pp. doi:10.15199/48.2020.04.36.

[38] Qawaqzeh M., Szafraniec A., Halko S., Miroshnyk O., Zharkov A. Modelling of a household electricity supply system based on a wind power plant. *Przegląd Elektrotechniczny*, № 96, p. 36-40, 2020 doi:10.15199/48.2020.11.08.

[39] Benômar, Y.; Croonen, J.; Verrelst, B.; Van Mierlo, J.; Hegazy, O. On analytical modeling of the air gap field modulation in the brushless doubly fed reluctance machine. *Energies* 2021, 14, 9. DOI :10.3390/en14092388

[40] Sikora R., Markiewicz P. The influence of modern luminaires on the supply network, Przegląd Elektrotechniczny 2010, 86 (6), 61-64

[41] Sikora, R.; Markiewicz, P.; Pabjańczyk, W. The Active Power Losses in the Road Lighting Installation with Dimmable LED Luminaires. Sustainability 2018, 10, 4742. https://doi.org/10.3390/su10124742

[42] Korzeniewska, E.; Sekulska-Nalewajko, J.; Gocławski, J.; Rosik, R.; Szczęsny, A.; Starowicz, Z. Surface Morphology Analysis of Metallic Structures Formed on Flexible Textile Composite Substrates. Sensors 2020, 20, 2128. https://doi.org/10.3390/s20072128

[43] Singh, S. K.; Boolchandani, D.; Modni, S. G.; Katal, N. Multi-Objective Optimization of PID Controller for Temperature Control in Centrifugal Machines Using Genetic Algorithm. *Research Journal of Applied Sciences, Engineering and Technology* 2014, 7, 9, 1794-1802.

[44] Komada, P.; Trunova, I.; Miroshnyk, O.; Savchenko, O.; Shchur, T. The incentive scheme for maintaining or improving power supply quality. *Przegląd Elektrotechniczny* 2019, 5, 79-82. doi:10.15199/48.2019.05.20.

[45] Iegorov, O.; Iegorova, O.; Miroshnyk, O.; Cherniuk, A. A calculated determination and experimental refinement of the optimal value of the single-phase induction motor transformation ratio. *Energetika* 2021, 67, 1, 13-19. DOI: 10.6001/energetika.v67i1.4483

[46] Chen, Y.; Ma, Y.; Yun, W. Application of Improved Genetic Algorithm in PID Controller Parameters Optimization. *TELKOMNIKA Indonesian Journal of Electrical Engineering* 2013, 11, 3, 1524–1530. doi:10.11591/telkomnika.v11i3.2301.