DEVELOPMENT OF MATHEMATICAL MODEL OF A BRUSHLESS DC MOTOR TAKING INTO ACCOUNT THE FAULTS

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Annotation. A model of a brushless direct current (BLDC) motor in the form of differential equations has been developed, taking into account the influence of external factors and defects. The measurement of the output parameters of the BLDC motor takes place in the process of acceleration at constant acceleration. For practical tasks it is proposed to use a correcting link, which allows minimising the change in the output parameters of the BLDC motor, such as angular velocity of rotation and torque. In the presence of defects, the developed system allows to detect them and report their presence if the degradation of parameters reaches a certain threshold value. The obtained research results can be used to build diagnostic systems for electric drives, neutralise the influence of the external environment, change the settings of the parameters of the BLDC motor in the control system.

KEYWORDS

BLDC motor, model, defects, corrective unit

1 INTRODUCTION

A brushless direct current (BLDC) motors are widely used in technical systems due to their high efficiency, reliability and power with lower maintenance costs due to the absence of collector and brushes. BLDC motors have high torque to weight ratio, long life and low noise level. However, external factors and the presence of defects in the BLDC motors can significantly affect their performance. Therefore, it is required to develop a mathematical model of the BLDC motor in the form of differential equations that accounts for external factors and defects.

The paper [Alekseevskiy 2024] presents a comparison of a BLDC motor and a permanent magnet synchronous motor. A virtual model in Simulink is built and transients of different variants of control systems are analysed. Simulation results confirming mathematical calculations are given.

In the article [Velchenko 2024] a mathematical model is developed, in the course of which the voltage equations of three-phase winding of a BLDC motor with permanent magnets, electromagnetic torque of a BLDC motor, electromagnetic power, EMF induction of each winding, differential equation of servo system torque is obtained. On the basis of the constructed mathematical model of a BLDC motor for a specific motor with given parameters, simulation modelling was carried out and dependences of electromechanical quantities: rotor angular velocity, electromagnetic torque, stator phase current and rotor rotation angle on time were obtained. The results of modelling confirmed the theoretical substantiation of the mathematical model. The obtained mathematical description of a BLDC motor can be used to build the architecture of a control unit based on a neural network controller.

In paper [Trefilov 2020a] a nonlinear discrete model of a BLDC motor in a rotating coordinate system with vector control is developed. The novelty of the model is that the torque is specified at each modelling step. The synthesis of optimal control in state space using Riccati equation is performed. The maximum values of voltages and currents are found for practical control problems of the BLDC motor while preserving the identifiability of the model. An investigation of the influence of the moment of the BLDC motor resistance on the identifiability of the control model has been carried out. The study of the change of determinants of the BLDC motor state matrices at increasing the resistance torque has been carried out.

The paper [Rastrepin 2021] presents a review of the spectral composition of BLDC motor stator currents obtained by modelling the motor in MATLAB Simulink software package. The spectrum was obtained using fast Fourier transform (FFT). The modelling results can become a source of statistical data for creating diagnostic systems for such motors and a subsequent basis for control modules that determine the residual life of the motor during operation.

The paper [Alekseevskiy 2022] presents a modified technique for identifying the parameters of a BLDC motor using acceleration curves. The advantage of the proposed technique is the possibility of its use in automatic mode in non-productive control units without the need to install additional sensors and fixtures. On the basis of the mathematical model of the second order the results of comparison of accuracy of identification of parameters of time constants by means of the proposed modified method and by nomograms according to Pasek's method are shown. The influence of the viscous friction coefficient on the accuracy of parameter identification is considered. The possibility of application of the technique has also been verified by means of the developed experimental setup on an electromechanical assembly containing a low-power BLDC motor. Deviations from the passport values caused by changes in a number of parameters have been determined. The acceleration curves obtained experimentally and as a result of computer modelling of the dynamics of a five-dimensional model describing a BLDC motor with parameters determined by identification according to the proposed methodology are shown. It is noted that the modified technique can be used to identify the parameters of BLDC motor with independent excitation.

The paper [Zaitsev 2023] presents mathematical modelling of vector control of a BLDC motor in Scilab software. These results make it possible to facilitate the development of devices for monitoring and control of various electrical power equipment including BLDC motors.

The paper [Kalachev 2020] discusses the technology of electric drive design using modelling and code generation in SimInTech software. In paper [Lychagina 2024] a computer model of a digital twin of the drive based on a BLDC motor is developed.

The paper [Abuzyarov 2020] considers models of BLDC motors with permanent magnets, based on assumptions about the symmetry of the motor stator parameters and/or the ideal form of phase EMF, which reduce the accuracy of assessment of the effectiveness of the proposed solutions, or are unsuitable for modelling the operation of an electric motor with a non-standard semiconductor converter. It is necessary to develop a mathematical model of electric drive on the basis of BLDC motors with permanent magnets, taking into account these design features of the electric motor and allowing variability of the semiconductor converter configuration. The graphical environment MATLAB/Simulink is used. Verification is performed by comparing the modelling results with the results of a known study taken as control. The model is recommended for verification of non-typical design solutions, and in case of programme change of set parameters of the electric drive and restrictions on operating conditions and target functions - for working out algorithms of the control system, automation of search for optimal parameters of the motor and semiconductor converter.

In paper [Trefilov 2020b] a nonlinear discrete model of a brushless dc motor (BLDC) in a rotating coordinate system with vector control is developed. The synthesis of optimal control in the state space is performed using the Riccati equation. The maximum values of voltages and currents are found for practical BLDC motor control problems while preserving the identifiability of the BLDC motor model. The range of acceptable values of the voltage vector in the state space for the obtained nonlinear discrete BLDC-motor model is investigated.

The universal model presented in [Shaburov 2023] allows to investigate the characteristics of a BLDC motor with discrete commutation. The description of the mathematical model in the form of analytical expressions takes into account the discrete commutation of the phases of the BLDC motor. From the analytical expressions, a generalised equation which is valid for all discrete commutation cycles is obtained. A universal mathematical model is constructed on its basis. The obtained modelling results coincide with theoretical representations and confirm the adequacy of the system of current equations proposed in the paper. The results presented in the paper clarify and develop the provisions given in other works and can be used for more accurate modelling and analysis of BLDC motor operation. The obtained mathematical model has been developed to investigate various modes of operation of BLDC motors with discrete commutation.

In paper [Nikitin 2020] a control model of a BLDC motor in a rotating coordinate system in state space with vector control was developed. The identification problem of this model is solved for different values of load torque. It is proposed to use identification from the point of view of compliance of the mathematical model with the results of the object operation. At each stage, the determinant of the extended matrix is calculated and compared with a constant that numerically divides the state matrix space. In this way, the operation of the engines themselves can determine its identification. As the optimality criterion of the identification algorithm, the decision optimality criterion is chosen in combination with the identification criterion of the optimal control algorithm by the minimum quadratic form criterion. A vector-matrix model of the BLDC motor in the state space is presented, taking into account the relative accuracy of the state measurement of the information-measuring subsystem of the BLDC motor. For practical problems it is proposed to determine the identifiability criterion by modelling the state matrix for cases when the state matrix parameters are out of the realizable parameter space of serviceable actuators. The obtained research results can be used to build diagnostic systems for robot drives.

The paper [Jimenez-Gonzalez 2021] presents the parameter identification of a BLDC motor. The presented approach is based on direct identification considering the electromagnetic torque of the three-phase line voltage as a function of electric currents and rotor speed. The evaluation is divided into two steps. First, the electrical parameters are estimated using known no-load and DC tests. Then the mechanical parameters are estimated using a recursive least squares algorithm. The proposed approach is validated by comparing the model responses with real-time motor responses. Furthermore, the design, numerical simulation and real-time implementation of a PI rotor speed controller based on the estimated model validate the identification proposal presented here.

In paper [Nikitin 2019] a diagnostic model of mobile robot drive in state space in vector-matrix form was developed. The classical discrete model of the drive in the state space was extended taking into account the influence of disturbances and defects. Drive diagnostics is performed by observing the deviation (incoherence) between the measured drive state parameters and their ideal values obtained using the reference model. If the signal exceeds the threshold value, a decision about the presence of defects is made. The core of the diagnostic observer is the Luenberger observer.

The paper [Filaretov 2025] considers the problem of obtaining a mathematical model of BLDC motors with an electronic speed controller in the form of a system of differential equations for use in the synthesis of modern high-quality adaptive and self-tuning control systems for the drives of various mobile robots and multistage manipulators. A model of a BLDC motor has been developed, which is described in a convenient form by means of averaging the variable parameters depending on the rapidly changing electrical angle of rotation of the rotor and taking into account the influence on the motor operation of an electronic speed controller containing a three-phase inverter and a controller controlling it, by means of a system of three differential equations of the first order. It is shown that it is possible to use a large modelling step, significantly reducing the requirements to the computing power of onboard computers, without deteriorating the quality of the results obtained. The effectiveness of the developed model has been confirmed in the course of field experiment using an electromechanical stand with a BLDC motor.

The paper [Vorobyeva 2024] presents a mathematical model of a permanent magnet motor with a trapezoidal form of counter-EMF built in MATLAB Simulink software environment. The motor is controlled by a given rotor speed, the feedback is realised by means of three Hall sensors and a speed sensor. The commutation is realised using a three-phase bridge inverter. Speed control is realised by a sawtooth pulse width modulated signal. A single-circuit speed control system is developed, which is realised through a proportional-integral controller and a sawtooth voltage generator. To solve the equations of rotor dynamics and stator electrical equilibrium, the ready-made BLDC motor block from Simscape library is used. The proposed mathematical model allows us to carry out theoretical studies of the operation of electric drives based on a permanent magnet synchronous motor.

The paper [Zafar 2021] considers a fractional-order model of a BLDC motor. To develop a mathematical model, the authors use the concept of the Liouville–Caputo noninteger derivative with the Mittag-Lefler kernel. It was found that the fractional-order BLDC motor system exhibits the character of chaos. For the proposed system, authors show the largest exponent to be 0.711625. Authors calculate the equilibrium points of the model and discuss their local stability. The authors apply an iterative scheme by using the Laplace transform to find a special solution in this case. By taking into account the rule of trapezoidal product integration we develop two iterative methods to find an approximate solution of the system. Authors take into account the numerical solutions for Caputo Liouville product integration and Atangana–Baleanu Caputo product integration. This scheme has an implicit structure. The numerical simulations indicate that the obtained approximate solutions are in excellent agreement with the expected theoretical results.

The paper [Ritika 2020] proposes the Simulation and Analysis of a 3-Phase Induction Motor and a BLDC motor using the MATLAB/Simulink environment. In this paper a three-phase squirrel cage induction motor is simulated under different load conditions and the characteristic graphs of this motor are obtained. Induction motors are the most widely used motor drive and thus the results obtained are important in understanding and designing the motor for precise command and control. In a BLDC motor, the torque characteristic plays an important role in the design and analysis of BLDC motor drive systems which is used in industries for automated vehicles and collaborative robots. Therefore, it is necessary to predict the precise value of torque, which is determined by the characteristics obtained as a result of simulating back EMF vs time for the BLDC motor addressed in this paper. Both these motors are most widely used and find their application in various industries such as Automotive industry, Automobile sector, Aerospace, Pulp and Paper industry, Medical, consumer, Induction Automation Equipment and Instrumentation

In this paper [Zheng 2020], considering the diverse effect on the electric steering gear servo system of unmanned surface vehicles (USV) caused by the external disturbances and parameter perturbations, a novel discrete adaptive global sliding model control scheme (AGSMC) is proposed in this paper. By introducing a nonlinear switch function, the system trajectory stays on the designed sliding manifold at the initial time. On the basis of discrete nonlinear adaptive reaching law, linear extrapolations are adopted to estimate the system uncertainty dynamics to ensure the robustness of the control system. Simulation results show that, in contrast with other discrete sliding mode control methods which are based on the exponential approach law, the proposed AGSMC schemes achieve enhanced tracking precisions with reduced control consumptions where chattering is significantly suppressed.

In paper [Kareem 2024] BLDC motors and derives have gained popularity because of numerous advantages. This motor application is achievable since permanent magnet (PM) technology has advanced. It has higher efficiency, reliability, and power with less maintenance due to the absence of brushes. A higher torque-to-mass ratio and long life are two of the most attractive characteristics making it appropriate for high-performance applications. This study describes the hybrid methodology for analyzing a three-phase, four-pole, 1500 W, BLDC motor with an inner rotor. PI controllers and PWM in Matlab /Simulink, and the chopped current control in Maxwell 2d ae used. BLDC motor modeled by rotation machine export (RMxprt) analytical software and analyzed with a finite element method (FEM) Maxwell 2D software to calculate motor performance, such as torque, speed, and efficiency. The FEM results were verified by comparing them with the results taken from the Matlab/Simulink program and with the aid of the RMxprt software to supply some missing data. The motor torque and efficiency results from Maxwell 2D and Matlab show good agreement. A hybrid FEM-analytical approach is successfully applied to study a BLDC motor using three software packages RMxprt, Maxwell 2D, and Matlab/Simulink despite the lack of motor test data. The RMxprt program offers missing data like stator resistance, stator inductance, and torque constant. It is provided in the design sheet to help us with motor modeling. The successful adoption of the proposed hybrid FEM-analytical methodology will provide a good starting point for future BLDC motor research work.

The article [Manda 2021] presents a solution to this problem by integrating digital twin technology with radio frequency identification (RFID) in order to improve the monitoring and optimization of assembly processes. The objective of this research is to develop a methodology that ensures synchronized data exchange between physical components and their digital counterparts using RFID for improved visibility and accuracy. The methodology entails the configuration of radio frequency identification systems to track the positions of products on conveyor belts, thereby facilitating real-time monitoring and the prompt detection of any deviations. This integration enhances remote monitoring capabilities and markedly optimizes assembly processes in comparison to traditional methods. The research findings suggest that this approach offers real-time data and monitoring capabilities, which can contribute to improved operational efficiency. This study presents an introduction to digital twins and RFID technology, a review of related research, a detailed methodology, an implementation plan, results and analysis, a discussion of the findings, and conclusions with future recommendations. This article presents a comprehensive discussion of the configuration of an RFID-based digital twin for an assembly line, highlighting the benefits and challenges of integrating these technologies into industrial processes.

An open-loop BLDCM output with hardware support and a three-segment method on closed-loop BLDCM were both examined in the study [Demcak 2024]. The research provides a brushless DC motor model that considers the motor's commutation behavior. To make sure that the drive system for BLDC motors works properly, it is important to know the exact torque value, which is based on the back-EMF. The BLDC motor is simulated in MATLAB/Simulink after a basic mathematical model is developed. In open-loop circuits, the intensity may be adjusted by varying the pulse width (or duty), and the motor speed can be increased or decreased by altering the input voltage [Krenicky 2022, Bozek 2023]. Pulse widths and speeds are measured and compared to real-world hardware in this study. This paper presents a comparison of the outcomes of the BLDC motors based on the examination of time responses.

In our paper we have built a mathematical model of the electric drive based on the BLDC motor taking into account the influence of external factors and possible defects. The model is presented in the form of differential equations, transfer functions, which allows us to analyse the dynamic characteristics of the system and develop corrective links to implement effective control under external influences and motor degradation.

2 DEVELOPMENT OF THE MATHEMATICAL MODEL OF THE BLDC MOTOR

The mathematical basis of drive control is differential equations that describe the drive equally correctly both in dynamics and statics. Differential equations can be used to describe the dynamics of an electric drive with an BLDC motor, which take into account both electrical and mechanical processes.

The electrical part of the BLDC motor model is described by a system of differential equations associated with the rotor. The equations of equilibrium of stator windings of BLDC motor when it is included in "star" in fixed phase coordinates ABC are as follows:

$$U_A = L_A \frac{dI_A}{dt} + I_A R_A + e_A, \tag{1}$$

$$U_B = L_B \frac{dI_B}{dt} + I_B R_B + e_B, \tag{2}$$

$$U_C = L_C \frac{dI_C}{dt} + I_C R_C + e_C, \tag{3}$$

where U_A, U_B, U_C are phase voltages, L_A, L_B, L_C are inductances of phase windings, I_A, I_B, I_C are phase electric currents, R_A, R_B, R_C are phase winding active resistance, e_A, e_B, e_C are phase winding counter-EMF.

The equation linking the electrical and mechanical parameters of the BLDC motor is written as follows

$$I = I_A + I_B + I_C, \tag{4}$$

$M_E = k_M I,$ (5)

where M_E is the electromagnetic torque of the BLDC motor.

The mechanical part of the BLDC motor has the same essence as that of any electric motor. The angular acceleration depends on the electromagnetic torque, viscous and dry friction torque, and reduced moment of inertia.

$$J\frac{d\omega}{dt} = M_E - k_{fr}\omega - M_L, \quad (6)$$

$$\omega = \frac{\theta}{t}, \quad (7)$$

$$e = k_E\omega, \quad (8)$$

$$T = \frac{L}{R}, \quad (9)$$

where *I*, *e* are the electric current and counter-EMF of the BLDC motor, *L*, *R*, *T* are inductance, resistance, and electromagnetic time constant of the BLDC motor, *ω*, M_E, M_L, *Ɵ* are angular velocity, electromagnetic torque of the BLDC motor, load torque, and angle of rotation of the BLDC motor shaft, *J* is moment of inertia of the BLDC motor rotor and load, k_E, k_M are coefficients that are design constants of the motor, k_{fr} is coefficient of viscous friction of the BLDC motor.

A mathematical model of BLDC motor is presented in the form of a transfer function:

$$W(S) = \frac{\sum_{m=0}^{m} b_m s^m}{\sum_{n=0}^{n} a_n s^n}. \quad (10)$$

The acceleration of an electric motor occurs at constant acceleration. In this case, the graph of the set speed changes according to a quasi-linear law. Due to the discrete nature of the microprocessor control device operation, the electric motor is affected at discrete moments of time as shown in Fig. 1.

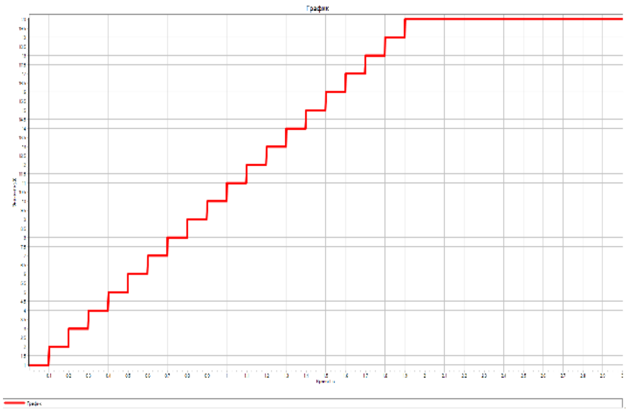

Figure 1. Graph of the voltage applied to the winding of BLDC motor

In real conditions, the parameters of an electric motor are not stable. They vary depending on the environmental conditions, such as temperature, and on emerging defects or material degradation. Also, these parameters are affected by material degradation. Moreover, the load resistance torque has a random nature. Therefore, to control the speed of an electric motor, there are controllers, such as PID or PI controllers, in which a correction is introduced into the control feedback by a special way selected by a mismatch error amplifier. From the correction data it is possible to judge the degradation or parameters of the electric motor model.

The model of the electric motor control system in the form of transfer functions is shown in Figure 2.

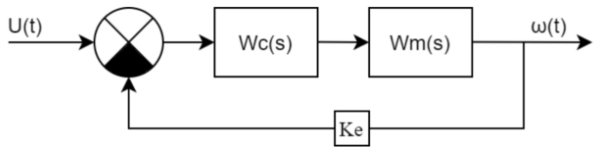

Figure 2. Model of electric motor control system in the form of transfer functions

In Figure 2, Wm(s) is the transfer function of the flywheel electric motor, Wc(s) is the transfer function of the correction link.

At each step i, the angular velocity ωi is measured, and consequently the value of the transfer function of the correction link Wic(s) is calculated, as shown in Figure 3.

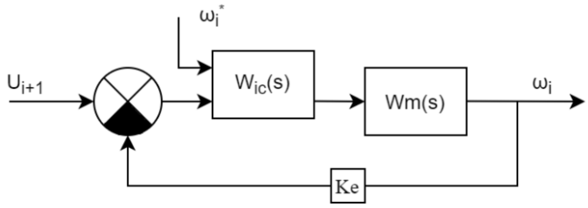

Figure 3. Model of electric motor control system with correction

In Figure 3 ωi* is the measured value of the angular velocity of rotation of the electric motor.

Possible variants of control adaptivity for the corrective unit Wic(s)=ki are presented in Figure 4.

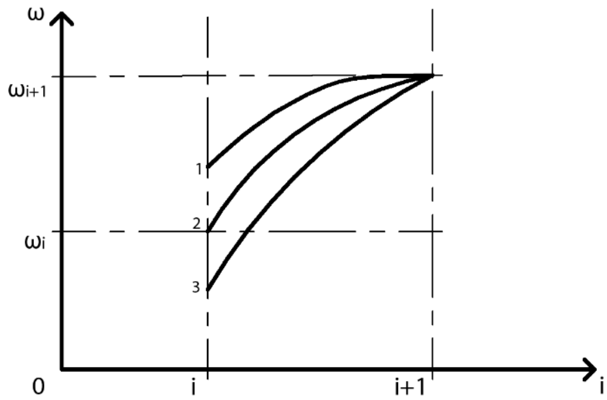

Figure 4. Adaptivity graph of the angular velocity of the electric motor at one step i

Figure 4 shows three trajectories of acceleration of the electric motor (1 - advance from the set speed, 2 - real speed equal to the set speed, 3 - lag from the set speed). Let us assume that Wm(s) provides acceleration along trajectory 2. Then, taking into account linearity, we can find ki.

$$k_i = 1 + \frac{\omega_i - \omega_i^*}{\omega_{i+1} - \omega_i}, \quad (8)$$

where ωi is the set speed of the electric motor, ωi* is the real speed.

Taking into account the correction it is possible to express the control energy:

$$E_c = \sum_{i=0}^{N}(\Delta U - k_i * \Delta U)^2 = \sum_{i=0}^{N} \Delta U^2 * (1 - k_i)^2, \quad (9)$$

where E_c is the control energy, *U* is the supply voltage.

If the acceleration is ideal, the control correction energy is zero, because in the ideal case k_i=1.

Thus, the value of Ec can be considered as a pointer to the degree of influence of external influences on the electric motor, or the degree of deviation of parameters of the electric motor model from the original ones. In the first variant, the impact is random, the second is associated with the degradation of the electric motor or wear of some components, which led to changes in the characteristics of the electric motor (resistance and inductance of windings, coefficients k_e, k_m and k_{fr}).

The simulation results show how the change in the characteristics of the electric motor affects the control accuracy. The influence of external parameters is simulated by varying the motor winding resistance or random values of the load resistance torque. As an example of parameter degradation, a change in the winding resistance of the electric motor is considered.

The transfer function of an electric motor in terms of angular velocity ω of the shaft is determined. The motor is controlled by changing its supply voltage. The transfer function of the electric motor is shown in formula 13.

$$W_M = \frac{\frac{1}{R}}{\frac{L}{R}*s+1} * k_m - \frac{M_E}{J*s}, \tag{13}$$

where R is winding resistance, L is inductance, J is inertia, k_m is moment coefficient, M` is load torque.

The feedback transfer functions are given in formula 14.

$$W_f = k_e, \tag{14}$$

where ke is the self-induction EMF.

The general transfer function of an electric motor with feedback is shown in formula 15:

$$W = \frac{W_{BLDCM}}{1+W_{BLDCM}*W_f}, \tag{15}$$

The BLDC motor parameters are set:
R=0.58;
L=0.0255;
J=0.47;
ke=0.34;
kм=0.34.

The voltage increases linearly from 0 to 20 V in 2 seconds as shown in Fig. 1. A random torque error has been added for the electric motor.

The schematic of the model is done in SimInTech and is shown in Figure 5.

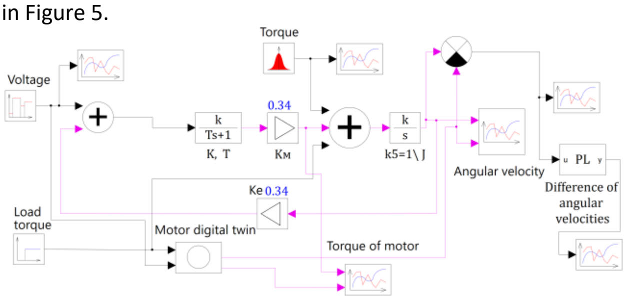

Figure 5. The schematic of the BLDC motor model and digital twin

Listing of the programme block "Mean square deviation of the real motor speed from the set speed":

```
input u;
i=i+1;
summa_kv = summa_kv + u*u;
y = sqrt(summa_kv/i);
output y;
```

The schematic of the model is done in SimInTech and is shown in Figure 5.

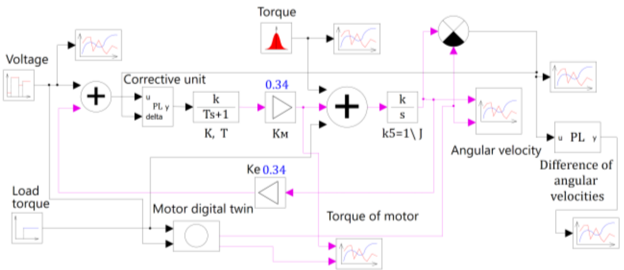

Figure 6. The schematic of the BLDC motor model and digital twin with Corrective unit

The schematic of the Corrective unit software block is shown in Figure 7.

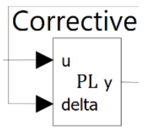

Figure 7. Corrective unit Program block of BLDC motor model

Program listing of the "Corrective unit" block:

```
input u;
input delta;
y = u-delta;
output y;
```

Four mean square deviations were calculated for each motor version, using the following formula:

$$\sigma = \frac{\sqrt{\sum_{i=0}^{N}(\omega_i-\omega_i^*)^2}}{i}, \tag{16}$$

where σ is mean square deviation, ωi and ωi* are angular velocities (ideal and real), N is number of measurements under acceleration.

Program listing of the "Difference of angular velocities" block:

```
input u;
i=i+1;
summa_kv = summa_kv + u*u;
y = sqrt(summa_kv/i);
output y;
```

3 BLDC MOTOR MODELLING RESULTS

The graphs are given without the Corrective unit. As the temperature increases, the resistance of the motor winding increases. As an example, let's assume a 20% increase in motor winding resistance.

R=0.58*1.2=0.7.

Figures 8 and 9 show angular velocities and electric current of the serviceable BLDC motor and the digital twin without Corrective unit.

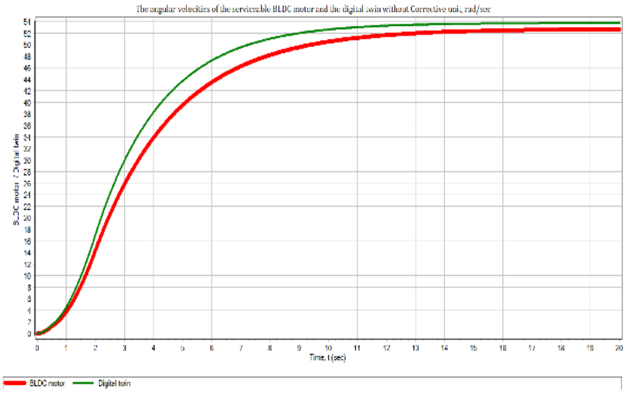

Figure 8. Angular velocities of the serviceable BLDC motor and the digital twin without Corrective unit

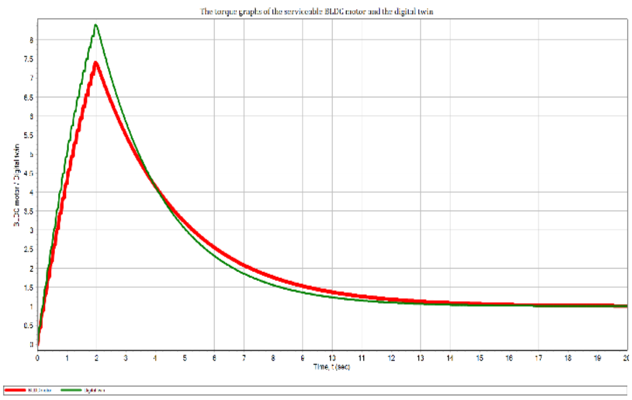

Figure 9. Electric current of the serviceable BLDC motor and the digital twin without Corrective unit

Figure 10 shows mean square deviations of the serviceable BLDC motor and the digital twin without Corrective unit.

The red curve on all graphs corresponds to the BLDS, and the green curve on all graphs corresponds to the digital twin.

With inter-turn phase closure, the motor winding resistance and inductance decrease. As an example, let's take a 20% reduction in the resistance and inductance of the motor winding.

R=0.58/1.2=0.48;
L=0.0255/1.2=0.02125

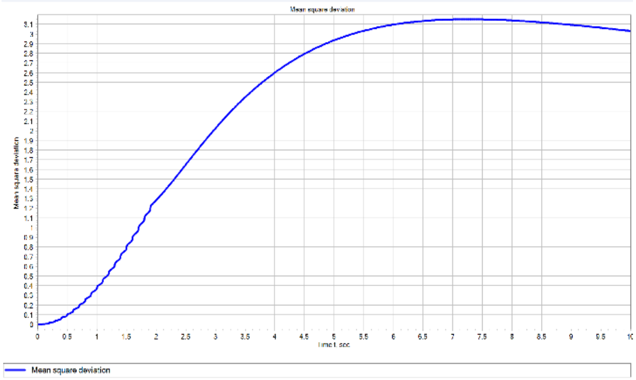

Figure 10. Values of standard deviations of the serviceable BLDC motor and the digital twin without Corrective unit

Figures 11 and 12 show angular velocities and electric current of the BLDC motor with inter-turn phase closure and the digital twin with Corrective unit.

Figure 13 shows mean square deviations of the serviceable BLDC motor with inter-turn phase closure and the digital twin with Corrective unit.

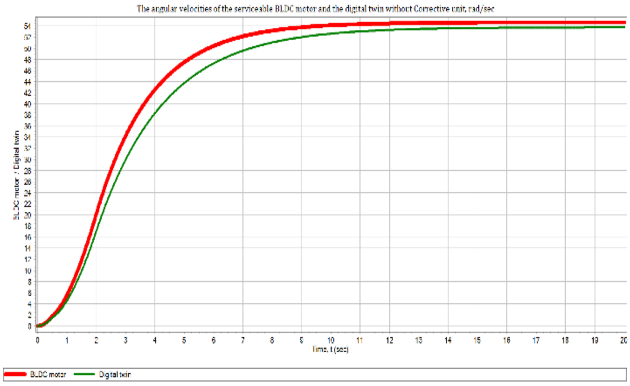

Figure 11. Angular velocities of the BLDC motor with inter-turn phase closure and the digital twin without Corrective unit

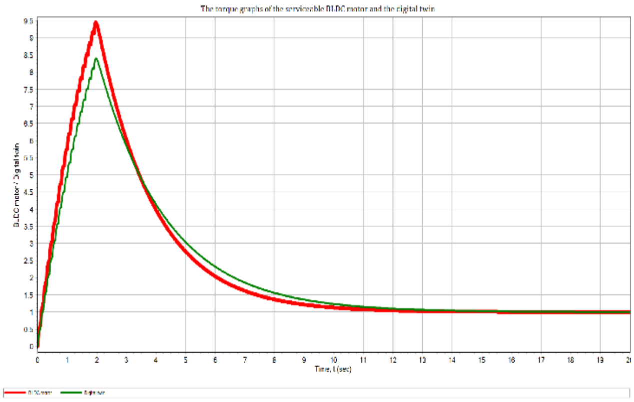

Figure 12. Electric current of the BLDC motor with inter-turn phase closure and the digital twin without Corrective unit

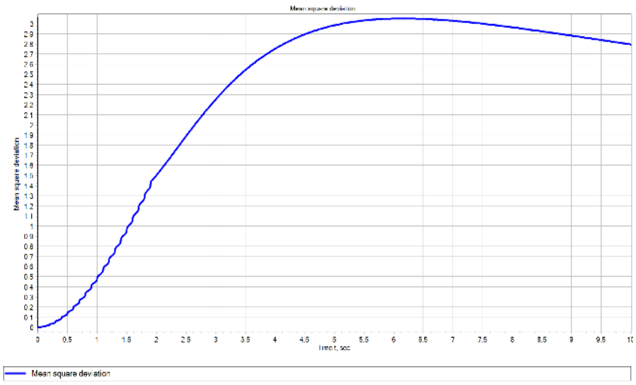

Figure 13. Values of standard deviations of the serviceable BLDC motor and the digital twin without Corrective unit

The next graphs are shown with a Correction union. As the temperature increases, the resistance of the motor winding increases. As an example, let's assume a 20% increase in motor winding resistance.

R=0.58*1.2=0.7.

Figures 14 and 15 show angular velocities and electric current of the serviceable BLDC motor and the digital twin with Corrective unit.

Figure 16 shows mean square deviations of the serviceable BLDC motor and the digital twin with Corrective unit.

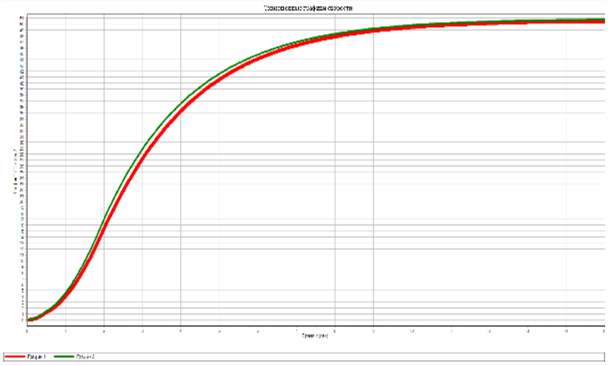

Figure 14. Angular velocities of the serviceable BLDC motor and the digital twin with Corrective unit

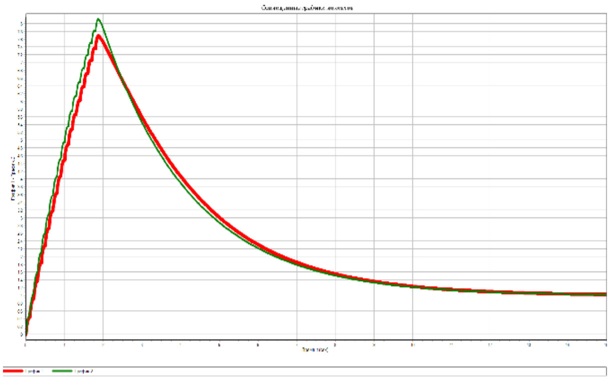

Figure 15. Electric current of the serviceable BLDC motor and the digital twin with Corrective unit

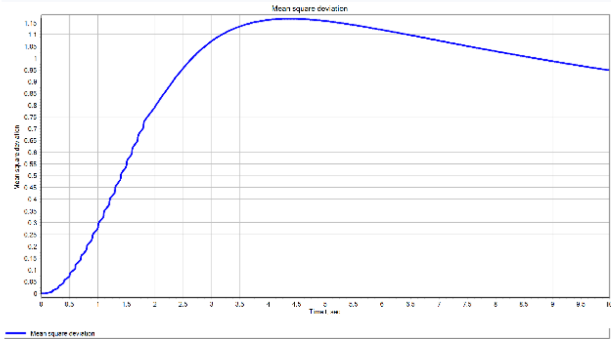

Figure 16. Values of standard deviations of the serviceable BLDC motor and the digital twin with Corrective unit

With inter-turn phase closure, the motor winding resistance and inductance decrease. As an example, let's take a 20% reduction in the resistance and inductance of the motor winding.

R=0.58/1.2=0.48;

L=0.0255/1.2=0.02125

Figures 17 and 18 show angular velocities and electric current of the BLDC motor with inter-turn phase closure and the digital twin with Corrective unit.

Figure 19 shows mean square deviations of the serviceable BLDC motor with inter-turn phase closure and the digital twin with Corrective unit.

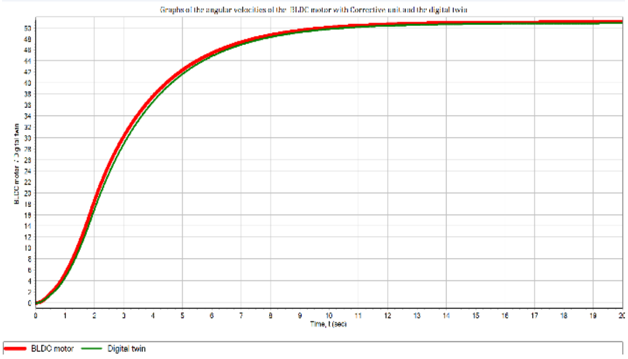

Figure 17. Angular velocities of the serviceable BLDC motor and the digital twin with Corrective unit

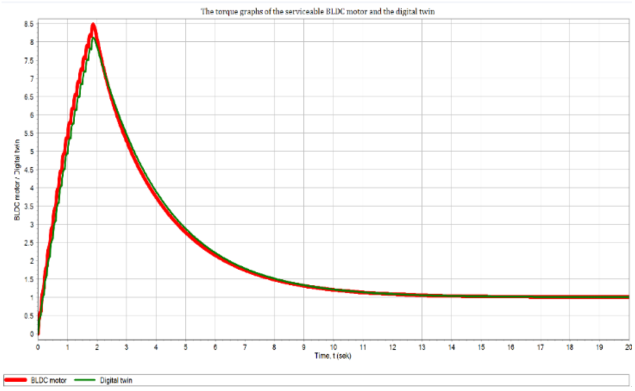

Figure 18. Electric current of the serviceable BLDC motor and the digital twin with Corrective unit

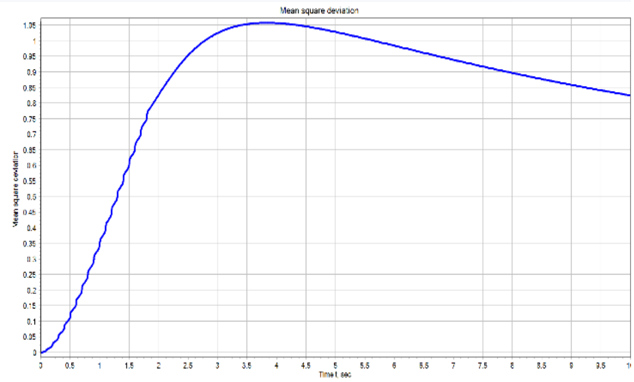

Figure 19. Values of standard deviations of the serviceable BLDC motor and the digital twin without Corrective unit

The motor correction link reduces the influence of external factors such as temperature and phase inter-turn faults.
We obtained the following values shown in Table 1.

Table 1. Values of standard deviations

BLDC motor	without correction	with correction
BLDC motor with winding resistance	3.10	0.95
BLDC motor with 20% intercurrent short-circuit	2.80	0.83

4 CONCLUSIONS

In this paper, an BLDC motor model has been developed to investigate the effect of resistance variation on control accuracy. It was found that an increase in resistance results in sharper acceleration of the BLDC motor. With the help of correction, the control accuracy of a defective motor can be improved before it is repaired or replaced.
The proposed model can be applied in automotive industry, for example [Blatnicky 2020] and specialized trolley [Ciertazsky 2025]. In further research digital image processing can be applied, for example [Kurylo 2019, Karrach 2020, Frankovsky 2022].

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REFERENCES

[Abuzyarov 2020] Abuzyarov, T.H., et al. Development of the systems model development of a high-quality BLDC motor drive. Bulletin of Ivanovo State Power Engineering University, 2020, No. 1, p. 5. DOI: 10.17588/2072-2672.2020.1.031-045.

[Alekseevskiy 2022] Alekseevskiy, S.V., Bushuyev, D.A. Modified Method for a Brushless DC Motor Parameters IdentifiCation from Step Response Curves. Devices and systems. Control, monitoring, diagnostics, 2022, No. 12, pp. 36-45. DOI: 10.25791/pribor.12.2022.1378. (in Russian)

[Alekseevskiy 2024] Alekseevskiy, S.V., et al. Analysis of the model of a BLDC motor. Information systems and technologies, 2024, No. 3, pp. 64-71. (in Russian)

[Blatnicky 2020] Blatnicky, M., Gerlici, J., Saga, M., Lack, T., Kuba, E. Design of a robotic manipulator for handling products of automotive industry. International Journal of Advanced Robotic Systems, 2020, Vol. 17, Issue 1. DOI: 10.1177/1729881420906290.

[Bozek 2023] Bozek, P., Krenicky, T., Prajova, V. Digital Induction Motor Model Based on the Finite Element Method. Applied Sciences, 2023, Vol. 13, No. 8, 5124. https://doi.org/10.3390/app13085124.

[Ciertazsky 2025] Ciertazsky, R., Vargovska, M., Pivarciova, E. Experimental Innovative Prototype Solution for a Specialized Handling Trolley for Sampling Devices. Machines, 2025, Vol. 13, Issue 9. DOI: 10.3390/machines13090775.

[Demcak 2024] Demcak, J., Zidek, K., Krenicky, T. Digital Twin for Monitoring the Experimental Assembly Process Using RFID Technology. Processes, 2024, Vol. 12, 1512. DOI: 10.3390/pr12071512.

[Filaretov 2025] Filaretov, V.F., et al. Development of a mathematical model of a BLDC Motor for synthesis of the self-tuning control systems for manipulation and mobile robots. Izvestiya vysokikh uchebovaniya, Electromechanics, 2025, Vol. 68, No. 2, pp. 39-46. DOI: 10.17213/0136-3360-2025-2-39-46.

[Frankovsky 2022] Frankovsky, P., et al. Modal Analysis Using Digital Image Correlation Technique. Materials, 2022, Vol. 15, Issue 16. DOI: 10.3390/ma15165658.

[Jimenez-Gonzalez 2021] Jimenez-Gonzalez, et al. Parameter Identification of BLDC Motor Using Electromechanical Tests and Recursive Least-Squares Algorithm: Experimental Validation. Actuators, 2021, No. 10, 143. DOI: 10.3390/act10070143.

[Kalachev 2020] Kalachev Yu.N., et al. Electric drive with a BLDC motor the practice of application of modelling and code generation in "Aeroelectromash". Automation and IT in Power Engineering, 2020, Vol. 2, pp. 34-39. (in Russian)

[Kareem 2024] Kareem, A. Abbass, E., Alim A.A.M. Hybrid Analysis of Brushless DC Motor. J. of Engineering and

Sustainable Development, 2024. Vol. 28, No. 4, pp. 499-506. DOI: 10.31272/jeasd.28.4.9.
[Karrach 2020] Karrach, L., Pivarciova, E., Bozek, P. Identification of QR Code Perspective Distortion Based on Edge Directions and Edge Projections Analysis. Journal of Imaging, 2020, Vol. 6, Issue 7. DOI: 10.3390/jimaging6070067.
[Krenicky 2022] Krenicky, T., Nikitin, Y., Bozek, P. Model-Based Design of Induction Motor Control System in MATLAB. Appl. Sci., 2022, Vol. 12, 11957.
[Kurylo 2019] Kurylo, P., Pivarciova, E., Cyganiuk, J., Frankovsky, P. Machine Vision System Measuring the Trajectory of Upper Limb Motion Applying the Matlab Software. Measurement Science Review, 2019, Vol. 19, Issue 1, DOI: 10.2478/msr-2019-0001.
[Lychagina 2024] Lychagina, I.M. Development of the computer model of the digital double drive based on the BLDC motor. Gagarin Readings 2024: Collection of abstracts of the 50th International Youth Scientific Conference, Moscow, 09-12 April 2024. Moscow, OOO Izdatelstvo Pero, 2024, pp. 322-323.
[Manda 2021] Manda, P., Veeramalla, S.K. Brushless DC motor modeling and simulation in the MATLAB/SIMULINK software environment. Advances in Modelling and Analysis B, 2021, Vol. 64, No. 1-4, pp. 27-33. DOI: 10.18280/ama_b.641-404.
[Nikitin 2019] Nikitin, Yu.R., Bozek, P., Pivarciova, E. Development of the diagnostic model of the drive in the state space. In: Proceedings of the 8th Int. Conf. Technical universities: Integration with European and World Education Systems; Izhevsk, 23-24 April 2019; Vol. 1. ISTU, 2019, pp. 287-292. ISBN 978-5-7526-0832-2; ISBN 978-5-7526-0831-5.
[Nikitin 2020] Nikitin, Y. BLDC motor identification based on optimal control model in the state space. IOP Conference Series: Materials Science and Engineering, 2020, Vol. 971. DOI: 10.1088/1757-899X/971/4/042063.
[Rastrepin 2021] Rastrepin, D.E. Investigation of the harmonic composition of the currents of a BLDC motor with permanent magnets. In: Prospects of development of fundamental sciences; Collection of scientific papers of the 18th Int. Conf. of Students, Postgraduates and Young Scientists, Tomsk, 27-30 April 2021; Vol. 7. Tomsk: National Research Tomsk Polytechnic University, 2021, pp. 89-91. (in Russian)
[Ritika 2020] Ritika, Luthra, S., Modi, S. Simulation and Analysis of a 3-Phase Induction Motor and a Brushless DC Motor Using Simulink. Journal of Science and Technology, 2020, Vol. 5, pp. 17-27. DOI: 10.46243/jst.2020.v5.i4.
[Shaburov 2023] Shaburov, P.O. and Kuleva, N.Y. Universal Model for Studying Characteristics of a Brushless DC Motor with Discrete Switching. In: 2023 Int. Ural Conf. on Electrical Power Engineering (UralCon), Magnitogorsk, Russian Federation, 2023, pp. 278-282. DOI: 10.1109/UralCon59258.2023.10291096.
[Trefilov 2020a] Trefilov, S.A., et al. Model of a BLDC motor in the state space at vector control. Automation and Measurements in Machine and Instrument Engineering, 2020, No. 3, pp. 28-38. (in Russian)
[Trefilov 2020b] Trefilov, S. Non-linear discrete model of BLDC motor for studying the range of permissible values of the voltage vector in the state space. In: Int. Conf. on Modern Trends in Manufacturing Technologies and Equipment: Mechanical Engineering and Materials Science (ICMTMTE 2020). MATEC Web Conf., 2020, Vol. 329. DOI: 10.1051/matecconf/202032903070.
[Velchenko 2024] Velchenko, A.A., et al. Mathematical model of the BLDC motor on the basis of the three-phase winding voltage equation. System analysis and applied informatics, 2024, No. 1, pp. 19-25. DOI: 10.21122/2309-4923-2024-1-19-25. (in Russian)
[Vorobyeva 2024] Vorobyeva, A.P., Antropova, I.A. Creating a mathematical model of a BLDC Motor using Matlab Simulink. Polytechnic Youth Journal, 2024, No. 6.
[Zafar 2021] Zafar, Z.U.A., et al. Mathematical modeling and analysis of fractional-order brushless DC motor. Advances in Difference Equations, 2021, No. 1. DOI: 10.1186/s13662-021-03587-3.
[Zaitsev 2023] Zaitsev, I.A. Mathematical modelling of the vector control of a BLDC motor. Science Alley, 2023, Vol. 1, No. 3, pp. 137-145. (in Russian)
[Zheng 2020] Zheng, Z., et al. Adaptive Discrete-Time Sliding Mode Control of Brushless DC Motor Servo System for Unmanned Surface Vehicles. Advances in Intelligent Systems and Computing, 2020, Vol. 928, pp. 496-504. DOI: 10.1007/978-3-030-15235-2_72.

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