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Diagnostics brushless DC motors

Ivan Abramov[1, a], Pavol Božek[2,b] Andrej Abramov [1,c], Ella Sosnovich[1,d] and Yuri Nikitin[1,e]

[1]The "Mechatronic Systems" Department, Kalashnikov Izhevsk State Technical University, Izhevsk, Russian Federation

[2]Full Slovak University of Technology, Faculty of Materials Science and Technology, Institute of Production Technologies, J. Bottu 25, 917 24 Trnava, Slovakia

[a]ms@istu.ru, [b]pavol.bozek@stuba.sk, [d]ms@istu.ru,

[c]ellasosnovich@istu.ru, [e]nikitin@istu.ru

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Abstract. This paper presents the BLDC motors - one of the types of electric motors, which rapidly gaining popularity due to its good performance and the development of microprocessor-based control. New PWM switching strategy to minimize the torque ripples in BLDC motor which is based on sensored rotor position control is discussed in the paper. Analyzed defects and diagnostic parameters of BLDC motors. A mathematical model for diagnosing BLDC motors and its implementation in MatLab software product based on fuzzy logic are presented. Simulation results of BLDC motors are presented.

Introduction

BLDC motors - one of the types of electric motors, which rapidly gaining popularity due to its good performance and the development of microprocessor-based control. New PWM switching strategy to minimize the torque ripples in BLDC motor which is based on sensored rotor position control is discussed in the paper [1]. Tuning methodology for the parameters of adaptive current and speed controllers in a permanent-magnet BLDC motor drive system is presented in paper [2]. Two Fault Detection and Diagnosis strategies for detecting Brushless DC Motor faults were considered involving wavelets and state estimation [3]. Bearing faults and stator winding faults, which are responsible for the majority of motor failures, are considered [3]. A novel method using windowed Fourier ridges is proposed in paper [4] for the detection of rotor faults in BLDC motors operating under continuous non-stationarity. The use of quadratic TFRs is presented as a solution for the diagnostics of rotor faults in brushless DC (BLDC) motors operating under constantly changing load and speed conditions [5]. Four time-frequency representations are considered short-time Fourier transform (STFT), Wigner-Ville distribution (WVD), Choi-Williams distribution (CWD), and the Zhao-Atlas marks distribution (ZAM) [5]. Three new algorithms for the detection BLDC motors faults are proposed that can track and detect rotor faults in non-stationary or transient current signals [6]. Park's vector method was used to extract the features and to isolate the BLDC motors faults from the current measured by sensors [7]. Proposed a model of a fault diagnosis expert system with high reliability to compare identical well-functioning BLDC motors [8].

The authors propose the integration of control and diagnostic systems. The economic efficiency of diagnostic systems due to an increase in reliability and quality, reduction of accidents, reduced rejects, decrease downtime of expensive equipment, reducing costs for maintenance and repair, increase service life. Currently, artificial intelligence technologies are widely used for control and diagnostics of electric motors and drivers [9-13].

Theoretical part

Simulation model of Brushless DC motors

To investigate the **BLDC motor** control proposed a simulation model in a natural (phase) coordinate system in the software **complex "Modeling In Technical Devices"** (MITD) developed in Bauman Moscow State Technical University [10], shown in Fig. 1. MITD is an alternative software products such as SIMULINK, VisSim, MATRIXx etc

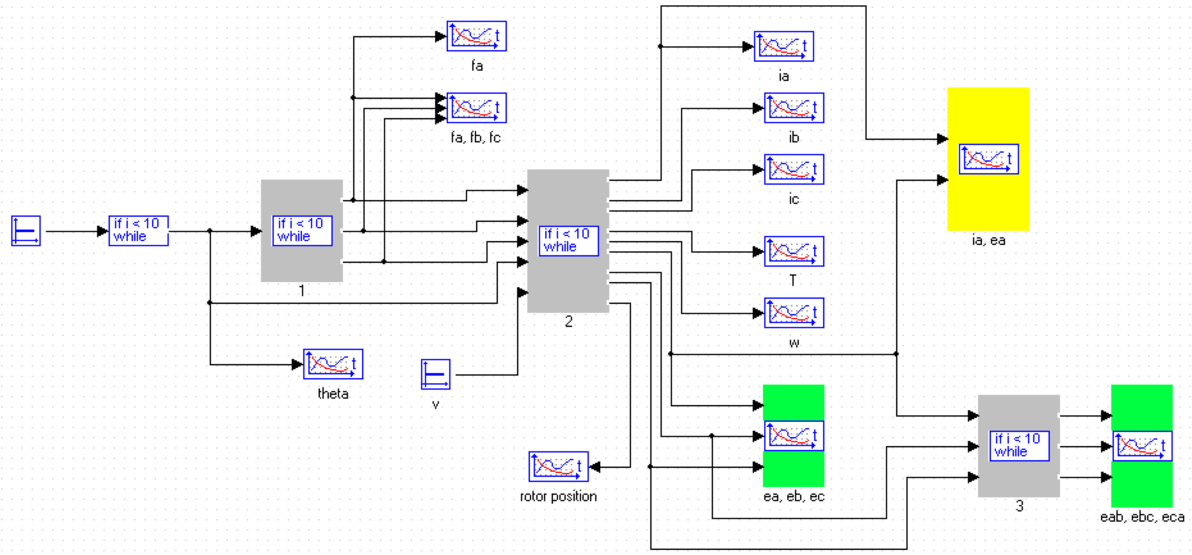

Fig. 1. Simulation model of BDSM

Input data of the simulation model BLDC motor are angle and rotor speed. Relation electrical and mechanical parameters of the angle are obtained. The resulting functions are shown in Fig. 2.

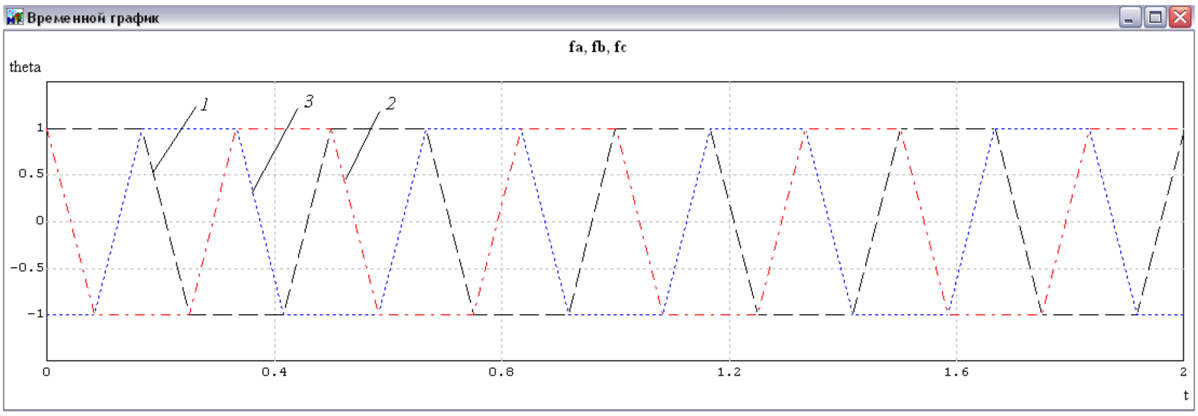

Fig. 2. Dependence functions $f_a(\theta)$, $f_b(\theta)$, $f_c(\theta)$ of the angle of rotor rotation, where 1 - function $f_a(\theta)$, 2 - function $f_b(\theta)$, 3 – function $f_c(\theta)$

Dependence the phase a current ia (on the graph function 1) and electromotive force ea (on the graph function 2) of the rotor rotation angle is shown in Fig. 3.

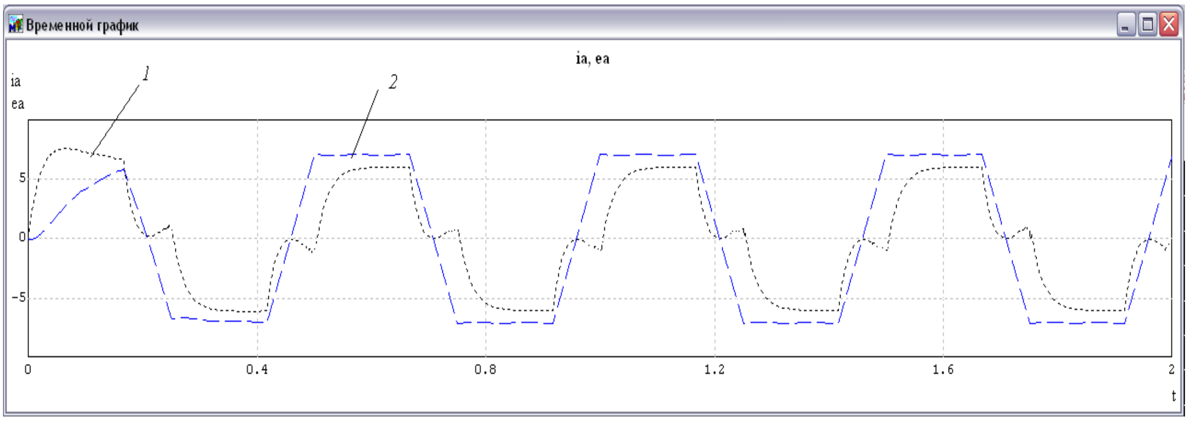

Fig. 3. Dependence the phase *a* current i_a (on the graph function 1) and electromotive force e_a (on the graph function 2) of the rotor rotation angle

Organization of the Text Simulation model allows you to control BLDC motor dependence of the phase currents and electromotive force for the perfect BLDC motor that allows you to use these results as a diagnostic parameter [11,12,13]. To improve the reliability of diagnosis is necessary to analyze defects and other diagnostic parameters of BLDC motor.

BLDC motor defects and diagnostic parameters

BLDC motor defects are divided into two classes: electrical and mechanical. BLDC motor defects are shown in Tab. 1.

Tab.1. BLDC motor defects

Electrical defects:	Mechanical defects:
open conductors in the winding; insulation between windings; unacceptable reduction of insulation resistance due to its aging or excessive moisture; disorders contacts and connections.	degradation processes in the bearings - the destruction of the separator, balls or rollers; deterioration in heat transfer due to fouling and dusty coils; deformation of the rotor shaft.

Selected diagnostic parameters: current, vibration, temperature, which are shown in Tab. 2.

Tab. 2. BLDC motor diagnostic parameters

Diagnostic parameters	Reason for change diagnostic parameter
Current	overload; open or shorted winding; changing the mains voltage.
Vibration	shaft misalignment; bearing defects.
Temperature	overload; winding circuit; ambient temperature changes.

The measurement results of the diagnostic parameters should be processed for a decision on the BLDC motor technical condition. Most appropriate mathematical tools to construct diagnostic model is fuzzy logic [14,15,16].

Logical-linguistic diagnostic model of BLDC motor

Logical-linguistic diagnostic model of BLDC motor based on fuzzy logic is represented by a system of equations:

$$\begin{cases} x(t) = F(x1(t), x2(t), x3(t)), \\ D(t) = G(x(t), t), \\ Z(t) = H(x(t), D(t), t), \end{cases} \tag{1}$$

where $x(t) = F(x1(t), x2(t), x3(t))$ – the equation of diagnostic parameters;

$x(t)$ – vector diagnostic parameters;

$x1(t), x2(t), x3(t)$ – a set of measurements of diagnostic parameters;

$D(t) = G(x(t), t)$ – calculation of trend vector equation diagnostic parameters;

t – worn-out time;

$Z(t) = H(x(t), D(t), t)$ – evaluate the technical condition equation.

Logical-linguistic diagnostic model of BLDC motor is implemented by a software MatLab in Fuzzy Logic Toolbox. Fuzzy inference system technical condition assessment is implemented on a fuzzy knowledge base of Mamdani type with three input variables x, D, t. Scheme fuzzy inference system is shown in Fig. 4.

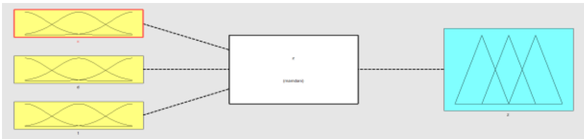

Fig. 4. Scheme fuzzy inference system technical condition assessment with three input variables x, D, t

As the term of membership functions of the linguistic variable M is selected Gaussian function, as it is quite simple, differentiable, given only 2 parameters, which reduces the computational complexity of the algorithm. As the membership functions of terms L, H linguistic variable chosen z, s functions.

Selected Mamdani fuzzy inference, as t-norm selected maximum deffuzification conducted by the method of the center of gravity, as it provides good accuracy and speed settings fuzzy knowledge base [17, 18, 19]. As adjustable parameters used weights rules coordinates highs membership functions M linguistic variable term. Example of terms L, M, H membership functions of input and output variables are shown in Fig. 5.

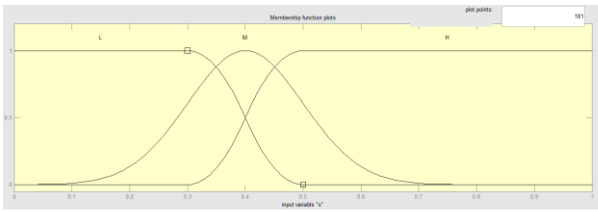

Fig. 5. Example of terms L, M, H membership functions of input and output variable

When using three linguistic variables with three terms by combining logical operations AND, OR, received 7 rules reflecting the dependence of the technical condition of the values of diagnostic parameters, the trend of diagnostic parameters and to develop the resource as shown below:

If (x is L) and (d is L) and (t is L) then (z is L)
If (x is M) and (d is L) and (t is L) then (z is M)
If (x is L) and (d isM) and (t is L) then (z is M)
If (x is L) and (d is L) and (t is M) then (z is M)
If (x is H) then (z is H)
If (d is H) then (z is H)
If (t is H) then (z is H)

Response surface fuzzy inference system evaluate the technical condition shown in Fig. 6. This drawing shows how the BLDC motor technical condition (output variable z) depending on the input variables x, D.

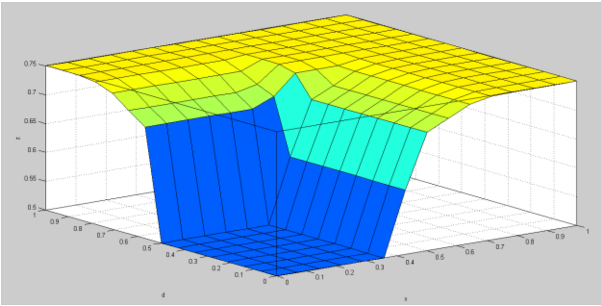

Fig. 6. Response surface fuzzy inference system technical condition assessment

Fig. 6 shows that for small values of integral diagnostic parameter x and low values of the diagnostic parameter trend the BLDC motor condition is serviceable. Examples of visualization of the rule base of fuzzy inference system for assessing the technical condition of the engine shown in Fig. 7, 8.

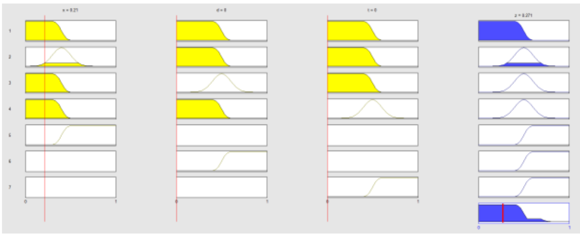

Fig. 7. Example visualization of the rule base of fuzzy inference system technical condition assessment BLDC motor (x = 0.21, D = 0, t = 0, Z = 0.271 - good technical condition of BLDC motor)

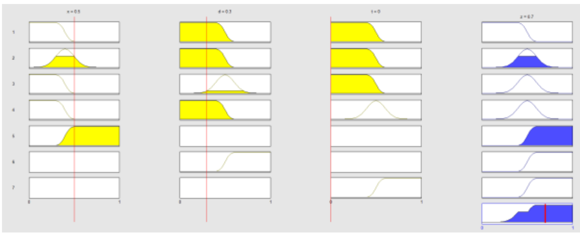

Fig. 8. Example visualization of the rule base of fuzzy inference system for assessing the technical condition of the engine (x = 0.5, D = 0.3, t = 0, Z = 0.7 - BLDC motor with defects)

Simulation model of BLDC motor diagnostics system

Model diagnostic system based on the mathematical apparatus of fuzzy logic, allows to determine the BLDC motor condition based diagnostic parameters (current, vibration, temperature). A simulation model of a BLDC motor diagnostics system designed by MITD. Fig. 9 shows the simulation model of diagnosis, determining BLDC motor condition.

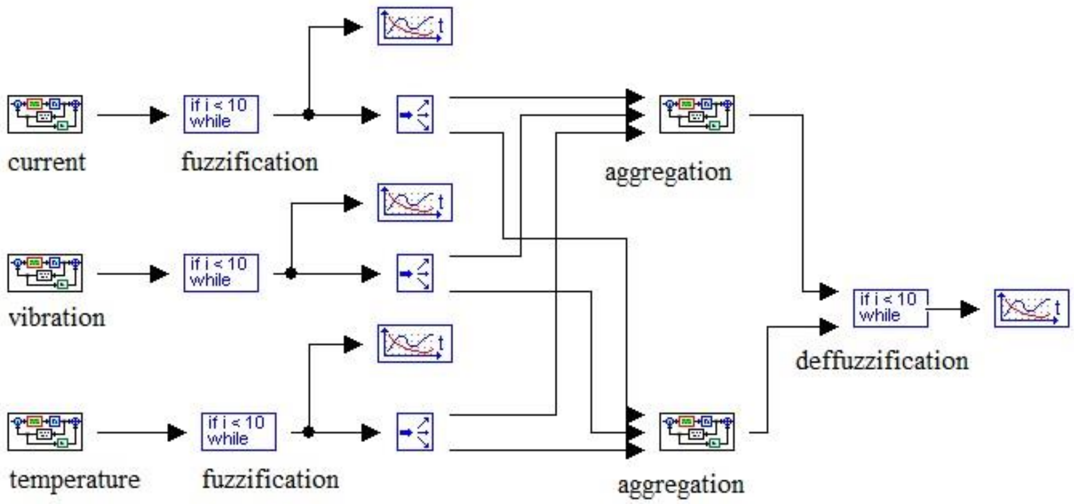

Fig. 9. Simulation model of BLDC motor diagnostic systems

Experimental part

As an example, the simulation results show changes depending on the input signals (current, vibration, temperature) from time to time in relative units with the appearance of BLDC motor defects in Fig. 10. Fig. 11 shows an example of change in the output variable characterizing the degree of development of BLDC motor defects.

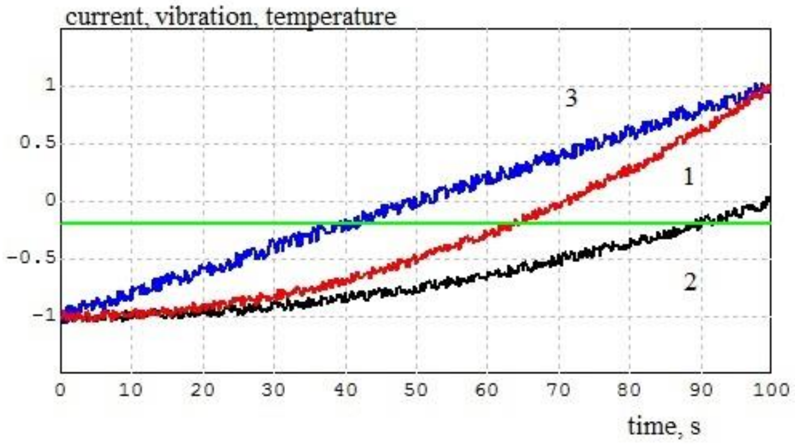

Fig. 10. Simulation results change depending on input signals (current, vibration, temperature) from time to time in relative units with the appearance of defects

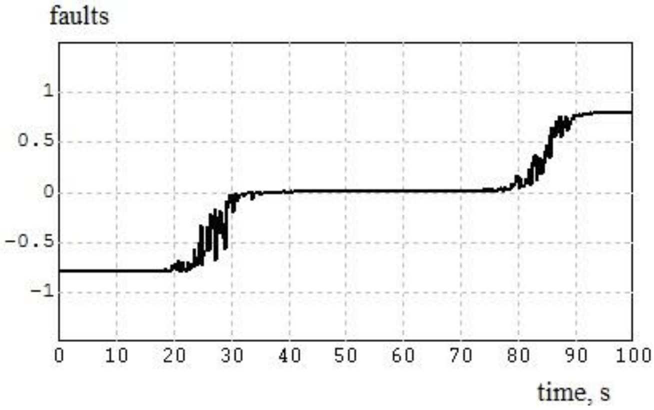

Figure 11 - Condition of the diagnosis depending on the diagnostic parameters in the process of BLDC motor degradation

Discussion

Upon receipt of the schedule can be concluded that the BLDC motor condition for range 0 ... 20 s. can be described as a workable development BLDC motor degradation processes occur in the interval 30 ... 80 s., BLDC motor alarm condition occurs in the interval 90 ... 100 s. By the nature of the graph can be judged on the dynamics of degradation processes - change of state of emergency comes to working-not once, but with the rise of increasing diagnostic parameters.

Thus, analyzing the diagnostic parameters, the trend and the operating time can foresee the emergence, to minimize the risk of accidents, timely schedule a maintenance. Experiments in which the diagnostic parameters were within the normal parameters and the output of the tolerance range. Experiments were carried out at the same supply voltage and load torque. A simulation model of the system control and diagnostics BLDC motor allows to investigate the influence of the diagnostic parameters on the performance.

Conclusions

In this paper we show that for the diagnosis BLDC motor can be effectively applied to the simulation model of the system diagnostic software developed by MITD, is based on the mathematical apparatus of fuzzy logic, which determines the BLDC motor condition based diagnostic parameters - current, vibration and temperature.

The BLDC motor simulation obtained depending phase currents, which can serve as the basis for selection of diagnostic parameters that are associated with BLDC motor physical models.

Analysis of diagnostic parameters was performed using the original software package that implements a fuzzy inference system MatLab. Feature of the system is the use of fuzzy inference integral parameter diagnostics combining information about diagnostic parameters and their derivatives.

Adapting this BLDC motor model accomplished by injecting a BLDC motor specific technical parameters.

Trend of change of the integral parameter allows to foresee the time to reach the limit of technical condition and through organizational and technical measures to minimize the risk of premature failure, plan maintenance and repair. With the development of BLDC motor degradation processes in the operation mechatronic system may change the control action on BLDC motor by reducing the current and move to more lenient modes of operation.

Computational experiments conducted confirmed the effectiveness of the proposed model of diagnosis and the prospect of its application in the diagnosis of mechatronic systems with real BLDC motor.

Acknowledgements

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