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RESEARCH ARTICLE

Effect of winding and power supply parameters on the starting characteristics of an upgraded brushless DC motor

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Abstract
Objectives. This work is aimed at determining the optimum number of turns in each winding and the effect of winding and power supply parameters on the starting characteristics of an upgraded brushless direct current motor (BLDC motor).
Methods. A full-scale experiment on a test bench consisting of an upgraded BLDC motor, a power supply source, and a speed controller was conducted. Methods of mathematical simulation, linear programming, and approximation were also applied.
Results. During the experiments, the dependencies of inrush current and starting speed on the number of turns in each winding of the upgraded BLDC motor were obtained. It was experimentally established that the number of turns in the windings has a limiting value, which is confirmed by either the intersection of the curves of inrush current and starting speed, or the disappearance of the functional dependence between the inrush current and motor speed. A mathematical model for the upgraded BLDC motor was developed, which showed good agreement with the experimental results. Using this mathematical model, the optimum number of turns in each of the motor windings and the efficiency of a BLDC motor can be determined. A parametric model for determining the motor starting speed by the values of inrush current and battery voltage at the number of turns in the winding from 8 to 14 was proposed. The developed models make it possible to determine the motor characteristics at the design stage.
Conclusions. There exists an interval of the number of turns in each of the windings of a BLDC motor, where the motor demonstrates its optimum efficiency. Inrush current and supply voltage were found to be the parameters that are easily measurable in practice and sufficient for determining the basic starting characteristics of a BLDC motor.

Keywords: brushless direct current motor, BLDC motor, motor starting characteristics, motor windings, number of motor winding turns, mathematical simulation

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НАУЧНАЯ СТАТЬЯ

Влияние параметров обмоток и источника питания на пусковые характеристики модернизированного бесщеточного двигателя постоянного тока

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Резюме
Цели. Цель работы – определение оптимального количества витков в каждой из обмоток и влияния параметров обмоток и источника питания на пусковые характеристики модернизированного бесщеточного двигателя постоянного тока (brushless direct current electric motor, BLDC-двигателя).
Методы. Использованы методы натурного эксперимента на испытательном стенде, состоящем из модернизированного BLDC-двигателя, источника питания и регулятора скорости. Также использовались методы математического моделирования, решения задачи линейного программирования и аппроксимации.
Результаты. В ходе экспериментов получены зависимости пускового тока и числа оборотов на старте от числа витков в каждой из обмоток для модернизированного BLDC-двигателя. Экспериментально установлено, что количество витков в обмотках имеет предельное значение, признаками чего является пересечение кривых пускового тока и стартовых оборотов или исчезновение функциональной зависимости между пусковым током и оборотами двигателя. Разработана математическая модель модернизированного BLDC-двигателя, которая хорошо согласуется с экспериментальными результатами. Используя математическую модель, можно определить оптимальное количество витков в каждой из обмоток двигателя, а также уровень коэффициента полезного действия BLDC-двигателя. Предложена параметрическая модель, которая позволяет определить значение стартовых оборотов двигателя по значению пускового тока и напряжению батареи для диапазона витков в обмотке от 8 до 14. Данные модели позволяют определять характеристики двигателя на стадии его проектирования.
Выводы. Выявлено, что существует интервал для количества витков в каждой из обмоток BLDC-двигателя, в котором будет наблюдаться оптимум коэффициента полезного действия двигателя. Также выявлено, что для определения базовых пусковых характеристик BLDC-двигателя достаточно двух параметров, которые легко измерить на практике: пусковой ток и уровень напряжения источника питания.

Ключевые слова: BLDC-двигатель, пусковые характеристики двигателя, обмотки двигателя, количество витков в обмотках двигателя, математическая модель

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INTRODUCTION

Brushless direct current (BLDC) motors find application in various industries and domains [1, 2]. At present, this type of motor can achieve efficiencies around 94%, provided that losses in the speed controller are minimized [3, 4] and battery operation is optimized [5]. The minimum set of equipment required to operate a BLDC motor involves an electronic speed controller (ESC) and a power battery to supply the speed controller, the converted voltage from which is fed to each of the three phases of the motor.

Structurally, a BLDC motor consists of a stator with windings and permanent magnets, and a rotor that rotates within the stator. 12N14P is one of the most common BLDC motor designs with 12 stator windings and 14 rotor magnetic poles. However, this is a three-phase motor comprising in reality only three, rather than 12, windings. One wire is wound around four magnets. Three-phase speed controllers are used to control such a motor. These devices are sensitive to voltage ripple, which in turn leads to sudden changes in torque and reduces efficiency [6].

The torque fluctuations can be reduced by improving the control of each individual winding [7], which enhances the stability of the system and reduces the power consumption. In this connection, one path for upgrading BLDC motors consists in increasing the number of individual windings. Thus, the researchers in [8] increased the number of windings in a five-phase motor. Such a change in the number of phases resulted in an increased stability and reliability of the motor.

Similar examples [9] demonstrate the feasibility of upgrading BLDC motor by both introducing a modified speed controller and improving the entire motor design. Instead of the conventional scheme based on three windings, 12 separate windings can be used. This allows the current in each winding to be controlled individually, providing for a more precise control of the magnetic field and torque. Such an upgrading approach improves the dynamic characteristics of the motor, reduces pulsation, ensures a more flexible adaptation to different operating modes, and increases reliability [10, 11]. This is particularly important when the motor is operated under severe conditions.

The first stage of the above work consists in upgrading a conventional BLDC motor. This requires modification of all motor windings and creating of separate leads for each of them. Consequently, the effect of the number of windings on the operating parameters of the BLDC motor, particularly on its starting characteristics, should be assessed.

The optimum number of turns in a winding is conventionally determined based on the following parameters [12]: required torque, operating frequency, resistance, and winding inductance. When shifting to 12 separate windings, it is important to consider the increase in resistance due to the increase in the number of turns, as well as the effect of their mutual inductance.

In this work, we aim to determine the optimum number of turns in each winding and the effect of winding parameters and power supply on the starting characteristics of a modernized BLDC motor.

MATERIALS AND METHODS

The BrotherHobby Avenger 2806.5 1300kV motor (BrotherHobby, China) was selected as the research object due to its similarity with the conventional 12N14P BLDC configuration. In this motor, N52H arc magnets are mounted on the rotor, the stator is made of Kawasaki 0.2 mm silicon steel, the housing material is Al 7075 aluminum alloy, and the shaft is hollow and made of titanium alloy. The motor uses a 0.75 mm copper winding.

The two motors were disassembled and rewound with copper wire of the same cross section to create 12 separate windings, each with its own separate lead. Each of the 12 windings was placed into a separate slot according to the stator layout. The original BLDC motor (left) and the upgraded motor (right) are shown in Fig. 1, where three wires coming from the original motor and 12 wires coming from the modernized motor can be seen.

In order to ensure the reproducibility of the values obtained, measurements were carried out for two engines. No differences in the performance of the first and second upgraded engines were noted.

Fig. 1. BLDC motor 2806 + 1350kV before rewinding (left) and after rewinding with the rotor removed (right)

The GW INSTEK GPD-73303S constant current source (GOOD WILL INSTRUMENT, China with a voltage error of ±(0.03% + 10 LSD) and a current error of ±(0.3% + 10 LSD)) was used as a battery power source to control the applied voltage level and to limit the maximum current at the ESC controller. A standard three-phase ESC controller was also used. The speed controller was connected to the upgraded motor by applying voltage to each of the windings, with each phase of the ESC controller applying voltage to four motor windings.

The ESC controller was characterized by an input voltage of DC 5-36 V (specific voltage equal to the nominal motor voltage), an output current of within 15 A, and a protection current of 15 A.

Measurements were conducted under different numbers of turns (from 8 to 16) in each of the motor windings with a step of 1 turn. The supply voltage was varied in the range of 5–7 V with a step of 1 V. The current limit of the power supply was set to 1 A. The selected relatively narrow voltage range is explained by the possibility of large overvoltages during the startup process and the random character of the measured inrush current values at supply voltages higher than 7 V.

The current from the source was supplied to the ESC controller, which supplies the BLDC motor via a special decoupler. The inrush current was measured at the motor input using a Tektronix DMM4020 digital universal meter (Tektronix Corporation, China) with the instrumental error of 0.015%.

A screw with a reflective strip attached to the motor shaft was used to measure the rotational speed. A DT2234A laser type digital tachometer (Shenzhen Sanpo Instrument, China) with a resolution of 1 revolution per minute (rpm) over the entire measuring range and an accuracy of ±0.05% was used.

EXPERIMENTAL RESULTS

In order to determine the optimum number of turns, the relationships between the number of turns in each of the 12 motor windings, the inrush current, and the initial rotational speed at a fixed battery voltage supplied to the motor via the speed controller were obtained (Figs. 2–4).

The inrush current is the minimum value of the current on each phase of the motor (as well as at the ESC controller output) at which the motor starts. The motor starting speed is the number of motor revolutions per minute at a current equal to the inrush value.

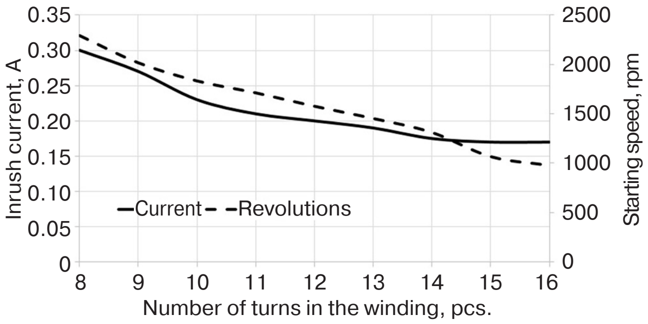

Fig. 2. Inrush current and starting speed as a function of the number of turns in each winding at 5 V battery voltage

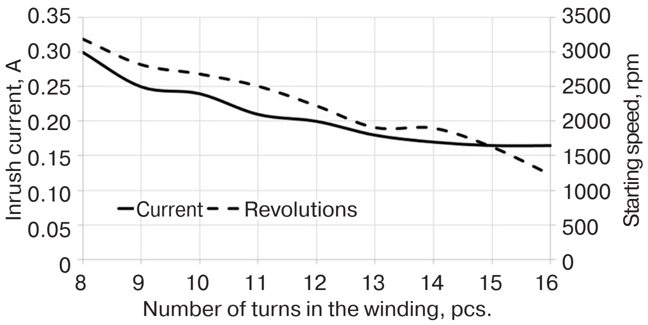

Fig. 3. Inrush current and starting speed as a function of the number of turns in each winding at 6 V battery voltage

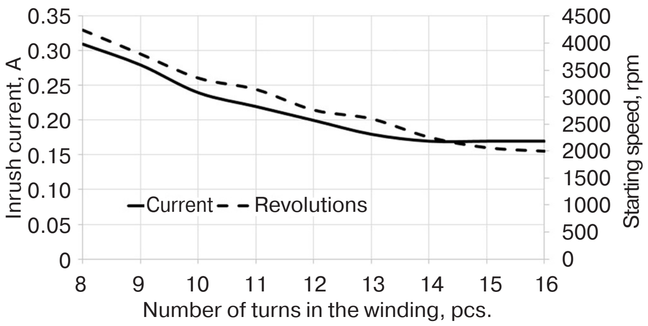

Fig. 4. Inrush current and starting speed as a function of the number of turns in each winding at 7 V battery voltage

It can be seen from Figs. 2–4 that, following 14 turns, the inrush current stabilizes and the speed decreases. This number of revolutions is the maximum permissible value. At this value, the functional dependence between inrush current and motor speed disappears. The characteristic relationship between these values is shown in Fig. 5. Under an increase in the number of turns, the inrush current ceases to change and the starting speed continues to decrease.

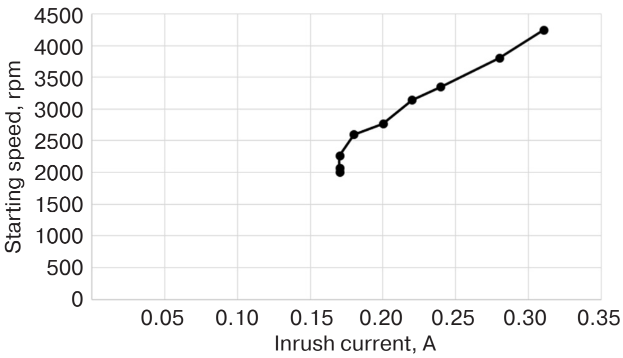

Fig. 5. Relationship between inrush current and motor starting speed at 7 V battery voltage

Figure 5 shows the presence of three points with the same value of inrush current under a decrease in the motor speed. Similar dependencies were obtained at other levels of the battery voltage studied. This fact indicates that the number of turns in each of the windings, whose number exceeds 14, is inappropriate as only increasing the losses and not improving the speed characteristics of the motor (its starting speed in particular).

Thus, it was experimentally established that the number of turns in the windings has a limiting value, the sign of which is the disappearance of a functional dependence between inrush current and motor speed (see Fig. 5). Exceeding a certain limit number of turns in each winding (14 turns in the case studied) leads to a deterioration in the performance of the BLDC motor.

SIMULATION AND DISCUSSION

In order to elucidate the dependencies obtained in the previous section, a BLDC motor model was built in the *MATLAB*[1] environment with respect to the deviations introduced by the motor elements and the ESC controller [13, 14].

In order to describe the relationships between inrush current, motor starting speed, and the number of turns, taking into account the deviations introduced by the motor elements and the ESC controller, a mathematical model that takes into account the characteristics of the system elements and the interrelationship of these parameters was developed. The model is based on the characteristics of the BLDC motor, taking the parameters of electromagnetic resistance and inductance into account.

The electrical parameters are as follows:

1. The winding resistance per phase R_{phase} and its inductance L_{phase}, which depend on the number of turns N.
2. The internal resistance R_{ESC} and inductance L_{ESC} of the controller.
3. Battery parameters: voltage V_{bat} and internal resistance R_{bat}.

The starting parameters are as follows:

1. Inrush current I_{start}.
2. Starting angular velocity ω_{start}.

The dependence of the following parameters on the number of turns was plotted:

1. Winding inductance:

$$L_{phase}(N) = k_L N^2, \quad (1)$$

where k_L is the inductance coefficient per turn, depending on the material and geometry of the winding.

2. Winding resistance:

$$R_{phase}(N) = k_R N, \quad (2)$$

where k_R is the resistance coefficient per turn.

3. Total resistance R_{total} and inductance L_{total} of the circuit:

$$R_{total} = R_{phase} + R_{ESC} + R_{bat}, \quad (3)$$

$$L_{total} = L_{phase} + L_{ESC}. \quad (4)$$

When the motor starts, the inrush current is determined by the total resistance and inductance, as well as the battery voltage. At the moment of starting, no counter electromotive force (EMF) due to zero angular velocity is observed:

$$I_{start} = \frac{V_{bat}}{R_{total}}. \quad (5)$$

Modeling the inrush current as a function of the number of turns.

Since R_{total} and L_{total} depend on the number of turns N, I_{start} can be expressed as follows:

$$I_{start}(N) = \frac{V_{bat}}{k_R N + R_{ESC} + R_{bat}}. \quad (6)$$

Modeling the starting angular velocity as a function of inrush current.

The starting angular velocity ω_{start} depends on the starting torque T_{start} generated by the inrush current. In this case, the torque is defined as follows:

$$T_{start} = K_t I_{start}, \quad (7)$$

where K_t is the motor torque constant.

Accordingly, the starting angular velocity ω_{start} is determined by the equation of motion, where the resisting forces at the starting moment do not affect its value:

$$\omega_{start} = \frac{K_t I_{start}}{J}. \quad (8)$$

[1] https://www.mathworks.com/products/matlab.html. Accessed May 19, 2025.

An increase in inertia J leads to a decrease in the starting angular velocity ω_{start}; therefore, the motor requires more time to accelerate to the initial revolutions.

It is now possible to express the dependence of I_{start} and ω_{start} by the number of turns:

$$I_{start}(N) = \frac{V_{bat}}{k_R N + R_{ESC} + R_{bat}}. \quad (9)$$

$$\omega_{start}(N) = \frac{K_t V_{bat}}{J(k_R N + R_{ESC} + R_{bat})}. \quad (10)$$

To account for variations in the system, random disturbances may be added to the resistance and inductance values:

- winding resistance $R_{phase} = (1 + \delta_R)k_R N$, where δ_R is the random variation of the winding resistance;
- winding inductance $L_{phase} = (1 + \delta_L)k_L N^2$, where δ_L is the random variation of the winding inductance.

Subsequently, taking possible variations into account:

- inrush current

$$I_{start}(N) = \frac{V_{bat}}{(1+\delta_R)k_R N + R_{ESC} + R_{bat}}, \quad (11)$$

- starting angular velocity

$$\omega_{start}(N) = \frac{K_t V_{bat}}{J((1+\delta_R)k_R N + R_{ESC} + R_{bat})}. \quad (12)$$

Angular velocity is converted to revolutions per minute (rpm) as follows:

$$RPM_{start} = \omega_{start}\frac{60}{2\pi}. \quad (13)$$

The starting speed, taking variations into account, has the following form:

$$RPM_{start}(N) = \omega_{start}(N)\frac{60}{2\pi} = \frac{K_t V_{bat} 60}{2\pi J((1+\delta_R)k_R N + R_{ESC} + R_{bat})}. \quad (14)$$

This model expresses the dependence of the motor starting speed RPM_{start} on various factors such as number of turns N, supply voltage V_{bat}, resistance R, winding inductance, and moments of inertia of the system. The motor torque T is proportional to the current flowing through the windings, taking into account the coefficient K_t which reflects the design of the motor. On starting, the motor encounters a resistive torque that is determined by the resistance of the windings and external circuits (controller R_{ESC} and battery R_{bat}), as well as by the internal friction.

The equation takes into account variations in winding resistance δ_R that may occur due to heating or other external factors. The resistance of the entire system is expressed as the sum of $(1 + \delta_R)k_R N + R_{ESC} + R_{bat}$.

Winding inductance affects the response time of the motor; however, the presented model takes the inductance into account indirectly by changing the electrical parameters (resistance and voltage drop). An increase in the number of turns N results in a decrease in the starting speed due to an increase in the total resistance of the system. An increase in the supply voltage V_{bat} increases the starting speed. Variations in the winding resistance δ_R and other system elements can significantly reduce the starting efficiency of the motor.

Therefore, the presented model shows the dependence of the starting speed on the electrical and mechanical parameters of the system. It takes the actual state of the components into account, thereby allowing the motor design to be optimized and the desired performance to be achieved.

The simulation results of the inrush current corresponding to Figs. 2–4 are shown in Fig. 6. Here, the experimental and calculated dependence of the inrush current on the number of turns at 6 V battery voltage is shown. At other battery voltages, a similar good agreement of the calculated and experimental values was observed. Thus, the constructed model is capable of describing the actual dependencies of the inrush current.

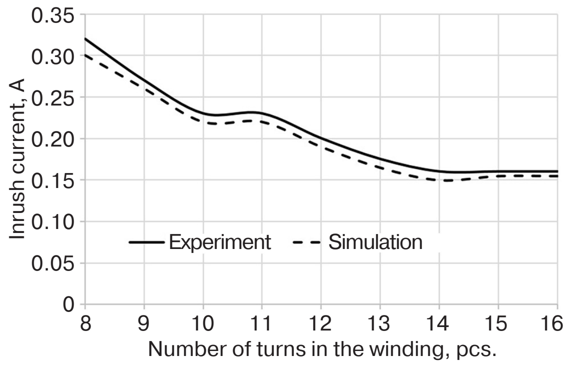

Fig. 6. Experimental and calculated dependence of the inrush current of the upgraded motor on the number of turns in each winding at 6 V battery voltage

Of particular interest are the results obtained when simulating the motor efficiency shown in Fig. 7. It can be seen that, at the number of turns less than 8 and more than 14, the efficiency values are minimal, particularly compared to the range of turns from 12 to 14. In other words, when the number of turns in the winding is low, the efficiency of the motor is also low due to the insufficient intensity of the magnetic field. When the number of turns exceeds 14, low torque is observed due to high power losses at the winding resistance.

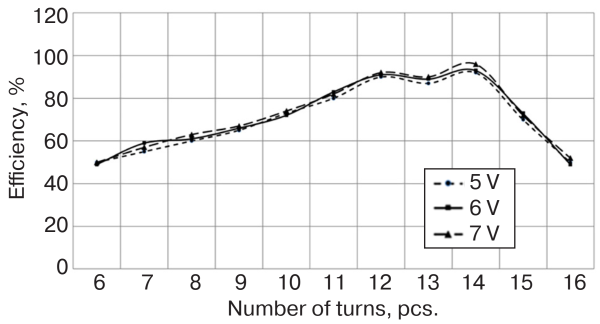

Fig. 7. Motor efficiency as a function of the number of turns in each winding at battery voltages of 5–7 V

The above results allow us to conclude that the values corresponding to 15 and 16 turns should be removed from the data series for inrush current and starting speed of the motor. At the same time, it is also unreasonable to add the values for 6 and 7 turns, since the corresponding efficiencies are too low. In this case, the full functional dependencies between starting speed and inrush current can be obtained. The dependencies of the number of turns on the inrush current and their approximations at three levels of battery voltage are shown in Fig. 8.

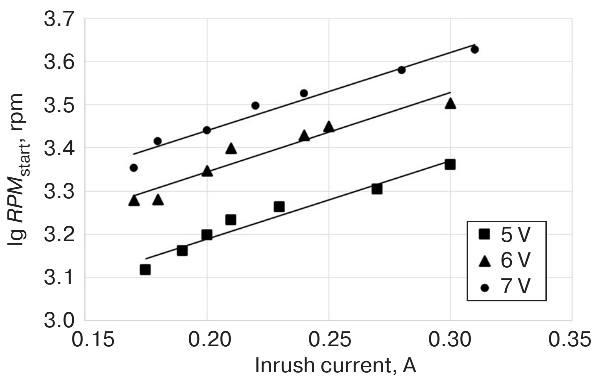

Fig. 8. Number of turns as a function of inrush current at different battery voltage levels

It can be seen that all three curves can be approximated by linear relationships [15], with the angle of inclination of these lines being the same.

In addition to the mathematical model proposed above, a parametric model allowing sufficiently simple and fast engineering calculations was developed. This model predicts the value of the starting speed RPM_{start} from the value of the inrush current I_{start} and the battery voltage V_{bat} for the range of turns in the winding from 8 to 14. As a result, the following analytical relationship was obtained:

$$\lg RPM_{start} = 1.817 I_{start} + \frac{1}{8} V_{bat} + 2.2. \qquad (15)$$

Thus, it becomes possible to calculate the starting speed from the easily measured characteristics of the inrush current and battery voltage for different numbers of turns. This facilitates the process of motor design with predetermined characteristics.

The table shows the motor revolutions calculated using formula (15) compared with the values measured experimentally for a 5 V battery.

The table shows that the relative deviation between the calculated and experimental values did not exceed 6%. For other battery voltages, the relative deviation did not exceed 9%.

Therefore, it can be concluded that the equation proposed in this work can be used to determine the motor starting speed at the design stage with sufficient accuracy for engineering calculations.

CONCLUSIONS

In this work, we propose a mathematical model for an upgraded BLDC motor, which showed good agreement with the actual prototype. This model can be used to determine the optimal number of turns in each winding by calculating the motor efficiency.

Table. Comparison of the values of the motor starting speed obtained experimentally and based on calculations according to Eq. (15) at a battery voltage of 5 V

Number of turns in each motor winding, pcs.	Inrush current, A	Motor starting speed, experiment	Motor starting speed, calculation	Relative deviation
8	0.30	2293	2345	2%
9	0.27	2017	2068	3%
10	0.23	1833	1749	5%
11	0.21	1712	1609	6%
12	0.20	1576	1543	2%
13	0.19	1452	1480	2%
14	0.175	1310	1390	6%

A parametric model to calculate the starting speed of a BLDC motor based on the values of inrush current and battery voltage was developed. The relationship between the starting speed of the upgraded motor and the basic characteristics of power supply and ESC controller, which can be easily measured, is presented. The equation obtained allows engineering calculations to be carried out at the motor design stage.

In order to obtain similar dependencies for motors of other configurations, further research and construction of appropriate mathematical models is required. In addition, the presence of the constant summand “2.2” in formula (15) assumes that not all fundamental dependencies have been discovered and that the engine revolutions might be determined by three, rather than two, physical quantities. Further research should verify this hypothesis.

Authors’ contributions

A.S. Krivoguzova—literature review, deriving the calculation formulas, writing the computer programs, conducting the model calculations, plotting, and discussing the results.

S.N. Tkachenko—formulating the problem, verifying the mathematical correctness of the calculation formulas, proofreading the text of the article, and discussing the results.

A.A. Shpilevoy—formulating the problem, the idea of deriving the calculation formulas, and discussing the results.

REFERENCES

1. Moosavi S.S., Djerdir A., Amirat Y.A., Khaburi D.A. Demagnetization fault diagnosis in permanent magnet synchronous motors: A review of the state-of-the-art. *J. Magn. Magn. Mater*. 2015;391:203–212. https://doi.org/10.1016/j.jmmm.2015.04.062
2. Mohanraj D., Aruldavid R., Verma R., Sathyasekar K., Barnawi A., Chokkalingam B., Mihet-Popa L. A Review of BLDC Motor: State of Art, Advanced Control Techniques, and Applications. *IEEE Access*. 2022;10:54833–54869. https://doi.org/10.1109/ACCESS.2022.3175011
3. Nguyen Q., Tran V., Pham Q.D., Giap V.N., Trinh M. Design brushless DC motor control by using proportional-integral strategy for a smart storage cabinet system. *Int. J. Power Electron. Drive Syst*. 2023;14:708–718. https://doi.org/10.11591/ijpeds.v14.i2.pp708-718
4. Carev V., Roháč J., Tkachenko S., Alloyarov K. The Electronic Switch of Windings of a Standard BLDC Motor. *Appl. Sci*. 2022;12(21):11096. https://doi.org/10.3390/app122111096
5. Conradt R., Heidinger F., Birke K. Methodology for Determining Time-Dependent Lead Battery Failure Rates from Field Data. *Batteries*. 2021;7(2):39. https://doi.org/10.3390/batteries7020039
6. Zhu Z., Leong J. Analysis and mitigation of torsional vibration of PM brushless AC/DC drives with direct torque controller. *IEEE Trans. Ind. Appl*. 2012;48(4):1296–1306. https://doi.org/10.1109/TIA.2012.2199452
7. Premkumar K., Manikandan B.V. Adaptive Neuro-Fuzzy Inference System based speed controller for brushless DC motor. *Neurocomputing*. 2014;138:260–270. https://doi.org/10.1016/j.neucom.2014.01.038
8. Assoun I., Idkhajine L., Nahid-Mobarakeh B., Meibody-Tabar F., Monmasson E., Pacault N. Wide-Speed Range Sensorless Control of Five-Phase PMSM Drive under Healthy and Open Phase Fault Conditions for Aerospace Applications. *Energies*. 2023;16(1):279. https://doi.org/10.3390/en16010279
9. Tapre M., Karampuri R. Design and Comparison of Five-Phase Induction Motors with Different Dimensions for Heavy Duty Electric Vehicles. In: *IEEE 3rd International Conference on Sustainable Energy and Future Electric Transportation* (*SEFET*). IEEE; 2023. P. 1–6. https://doi.org/10.1109/SeFeT57834.2023.10245615
10. Xia K., Li Z., Lu J., Dong B., Bi C. Acoustic noise of brushless DC motors induced by electromagnetic torque ripple. *J. Power Electron*. 2018;17(4):963–971. https://doi.org/10.6113/JPE.2017.17.4.963
11. Viswanathan V., Seenithangom J. Commutation torque ripple reduction in the BLDC motor using modified SEPIC and three-level NPC inverter. *IEEE Trans. Power Electron*. 2018;33(1):535–546. https://doi.org/10.1109/TPEL.2017.2671400
12. Varshney A., Gupta D., Dwivedi B. Speed response of brushless DC motor using fuzzy PID controller under varying load condition. *J. Electr. Syst. Inf. Technol*. 2017;4(2):310–321. https://doi.org/10.1016/j.jesit.2016.12.014
13. Manda P., Veeramalla S.K. Brushless DC motor modeling and simulation in the MATLAB/SIMULINK software environment. *Adv. Modelling Anal. B*. 2021;64(1–4):27–33. https://doi.org/10.18280/ama_b.641-404
14. Sial M., Sahoo N. Torque ripple minimization and speed control of switched reluctance motor drives using extremum-seeking PI controller. *Electr. Eng*. 2024;106(6):7301–7322. https://doi.org/10.1007/s00202-024-02427-3
15. Harris F.E. *Mathematics for Physical Science and Engineering*. Academic Press; 2014. 944 p.

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