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ASSESSMENT OF THE OPERATING CHARACTERISTICS OF BRUSHLESS DC MOTORS

OCENA DELOVNIH ZNAČILNOSTI BREZKRTAČNIH DC MOTORJEV

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Keywords: brushless DC motor, FEM model, transient characteristics

Abstract

This paper presents the operating characteristics of brushless DC motors (BLDC) obtained via analytical, numerical, and simulation software, enabling steady-state and transient characteristics of a motor to be computed. Based on the catalogue data from the producer, Moog, a motor is simulated in a closed-loop control system fed by a voltage inverter. The accuracy of the derived models is verified by comparison with data from the producer. The developed analytical and simulation models enable the studying of various motor operating modes, such as no-load, rated load, and locked rotor, including motor starting characteristics. They are universal and can be easily applied to any brushless DC motor by simple replacement of the motor parameters. A numerical model in FEM software verifies the accuracy of previously derived models by obtaining the motor operating characteristics and the magnetic flux density distribution in a cross-section of the motor. The results obtained from all models have verified the proper design of the motor and laid out the path for further improvement with respect to the various motor parameters or operating characteristics.

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Povzetek

V tem prispevku so predstavljene delovne značilnosti brezkrtačnih DC motorjev (BLDC), pridobljene z analitično, numerično in simulacijsko programsko opremo, ki omogoča izračunavanje enakomernih in prehodnih značilnosti motorja. Na podlagi kataloških podatkov proizvajalca Moog je simuliran motor v krmilnem sistemu zaprtega kroga, ki ga napaja napetostni pretvornik. Natančnost izpeljanih modelov smo preverili s primerjavo s podatki proizvajalca. Razviti analitični in simulacijski modeli omogočajo preučevanje različnih načinov delovanja motorja, kot so brez obremenitve, nazivna obremenitev in zaklenjen rotor, vključno z značilnostmi zagona motorja. So univerzalni in jih je mogoče enostavno uporabiti na katerem koli brezkrtačnem DC motorju s preprosto zamenjavo parametrov motorja. Števílčni model v programski opremi FEM preverja natančnost predhodno izpeljanih modelov z pridobivanjem delovnih lastnosti motorja in porazdelitvijo gostote magnetnega toka v prerezu motorja. Rezultati, dobljeni pri vseh modelih, so omogočili preverbo pravilne zasnove motorja, hkrati so podali pot za nadaljnje izboljšave glede na različne parametre motorja ali delovne lastnosti.

1 INTRODUCTION

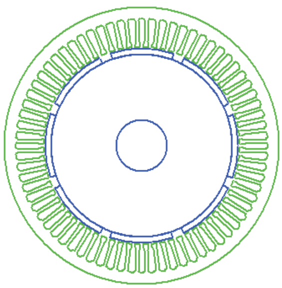
In recent years, BLDC motors have gained popularity due to their wide application in robotics, automotive industrial equipment, and instrumentation. BLDC motors are similar in construction and operation to synchronous motors. Both BLDC and synchronous AC motors have permanent magnets (typically four or more) mounted on the rotor. The rotor magnets can be ferrite, which is less expensive but have a relatively low flux density, or rare-earth alloys, which have a higher flux density but often are more expensive. In BLDC motors, the stator coils are wound trapezoidally and the back-EMF produced has a trapezoidal waveform. Because of their trapezoidal waveform, direct current is required to obtain the best performance of BLDC motors. In contrast, synchronous AC motors are wound sinusoidally and produce a sinusoidal back EMF, so they require sinusoidal drive current to achieve their best performance. The development of power electronics has certainly contributed to the wide application of BLDC motors, as these types of motors are usually electronically commuted by the voltage inverter in closed-loop control systems, utilizing Hall effect sensors for sensing the motor position,*[1]-[2]*. However, sensorless techniques are also available for the detection of the motor position, and they are also widely used,*[3]-[4]*.Some of these sensorless schemes include a smoothing filter algorithm to improve the results obtained through an Extended Kalman Filter (EKF) algorithm in tracking the rotor position for sensorless control of brushless DC motors,*[5]*. Each motor modelling is highly dependent on the accurate identification of motor parameters. Often various optimization techniques are used for that purpose. In recent years, various controlling techniques have been investigated along with the simulation models that allow the accurate control and prediction of motor dynamic regimes,*[6]-[9]*, along with speed regulation techniques based on improved PI controllers utilizing particle swarm optimization algorithms, *[10]*. Torque ripple and the correlation with various commutation techniques are also investigated, *[11]*. Some authors focus on finding the most accurate analytical methodology for BLDC motor design, supported by various software,*[12]-[13]*. The procedure for the determination of optimal speed controller parameters of a PM brushless DC motor drive based on control quality indices is developed, and the impact of controller parameters on transient motor characteristics is presented in *[14]*. Other authors address the implementation of numerical techniques in modeling the various types of BLDC motors and present the properties and features of various magnetic parameters, *[15]-[17]*.

This paper covers various aspects of the BLDC motor design and operation, including motor analytical design and steady-state operating characteristics, motor dynamic analysis, when it is fed by the inverter, and finally motor numerical analysis in FEM software for obtaining various magnetic parameters and operating characteristics, giving an overall insight into complete motor design and operation. Firstly, a motor analytical model (AM) has been calculated in Ansys Maxwell software in order to identify motor parameters and operating characteristics. The accuracy of the developed analytical model was verified by comparing the obtained results from this model with available data from the motor producer, Moog,*[18]*. Once the analytical model was proved to be sufficiently accurate, the obtained motor parameters were used in the simulation model of a BLDC motor fed by an inverter, in a closed-loop system with Hall sensors, modelled in PSIM software. From this model, the transient characteristics of speed, torque, and motor current for rated load operating mode are obtained (PSIM model). Finite Element Analysis (FEA) is regularly used in the motor design as a necessary tool for estimating motor electromagnetic properties in terms of magnetic core saturation, losses, or even calculating various motor operating characteristics, *[19]*. The proper design of the motor should be based on good mechanical design regarding motor geometry accompanied by the adequate electrical design with respect to the winding parameters and properties of the electrical and the magnetic materials. In this paper, an analytical model of the motor including all design parameters, such as motor geometry, dimensions of the stator and rotor core, the geometry of the stator slots, and magnet poles, was derived on the basis of the very few parameters from the motor producer. Therefore, it was necessary that the obtained model of the motor be verified using FEA. From the FEA model, the magnetic flux density in the motor's cross-section was obtained, enabling estimation of the motor design in terms of the magnetic core saturation. From the last model, the motor torque and current were also calculated. The obtained results from AM, FEA, and the PSIM model were compared. They are useful in the assessment of the motor features in the various operating modes, allowing easy prediction of the motor operation during start up, at rated load, or no-load operation.

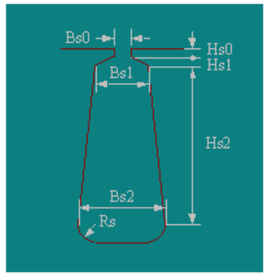
2 VARIOUS MODELS OF BLDC

2.1 Analytical model

The first step in defining the motor analytical model is to design the motor geometry properly. The design of the stator core, including the number and geometry of the slots, is done following the design procedure for asynchronous motors, *[20]*. Consequently, following the mentioned design procedure, presented in detail in *[20]*, the stator core and the rotor dimensions are calculated. As this design procedure for calculating the analytical model of the motor is too long to be presented here, the motor cross-section calculated on the basis of this analytical procedure is presented in Fig. 1. Table 1 presents the key dimensions of the motor, calculated from the design procedure, which are used in the motor analytical model for calculating motor parameters and steady-state characteristics. Therefore, in the present paper, the analytical model of the motor is presented with the output results from this model, which are motor parameters, such as resistances and inductive reactances, presented in Table 2, as well as motor characteristics (torque, current, efficiency, speed, etc.) also presented in Table 2 for various operating regimes. The model is called the "analytical model" as it uses analytical formulas, presented in *[20]*, for calculating motor cross-sections and the parameters of stator winding. Finally, as an output from this model, the motor steady-state characteristics of current, torque, efficiency and output power are calculated (Fig. 2, 3, 4, and 5). The outer motor dimensions like the outer diameter of the stator and the rotor as well as the number of the magnet poles are taken from the motor type BN42-53IP-03TFC of company Moog. Once all the dimensions of the motor are defined, including the properties of all materials, they are input into the Maxwell software, on which basis the input model of the motor (obtained from analytical calculations) gives as an output the results presented in Table 2 and steady-state characteristics of the motor, presented in Fig. 2,3,4, and 5. Thus, the accuracy of this analytical model will be evaluated on the basis of its results presented in Table 2 and in Fig. 2,3,4, and 5, as these results cannot be obtained without an adequate model of the motor, obtained on the base of accurate analytical calculations of the motor dimensions and the winding parameters.



(a)
Motor cross-section



(b)
Stator slot

Figure 1: Motor layout

Table 1: *Key dimensions of the motor*

Stator	
Stator length (mm)	134.6
Outer diameter (mm)	155.14
Inner diameter (mm)	111.7
Nr. of slots	72
Stacking factor	0.95
Stator winding	
Winding layers	2
Parallel branches	1
Conductors per slot	8
Stator slot-dimensions (Fig. 1a)	
Hs0 (mm)	1
Hs1 (mm)	1.5
Hs2 (mm)	11.84
Bs0 (mm)	2
Bs1 (mm)	3.06
Bs2 (mm)	4.33
Rs (mm)	1
Rotor	
Outer diameter (mm)	109.1
Inner diameter (mm)	30
Length (mm)	134.6
Magnet thickness (mm)	3.2

As an output result, the analytical model, defined and solved in the Maxwell software, gives the motor parameters at rated load, no load, and locked rotor (Table 2).

Table 2: *Parameters and operating characteristics of the analytical model*

Steady-state parameters	
D-axis inductance (H)	0.00021
Q axis inductance (H)	0.00021
Zero-sequence inductance L_0 (H)	0.000084
Armature phase resistance at 20°C (Ω)	0.51
Rated load operation	
Armature current (A)	9.09
Input power (W)	1308
Output power (W)	879
Efficiency (%)	67.2
Rated speed (rpm)	2837
Rated torque (Nm)	2.96
Cogging torque (Nm)	0.956
Locked rotor operation	
Locked rotor torque (Nm)	17.14
Locked rotor current (A)	64.19

The analytical model was confirmed to be satisfactorily accurate by comparing the parameters and characteristics of the motor with the available data from the motor catalogue, *[18]*, (Table 3).

Table 3: *Comparison between analytical model and producer*

Parameter/characteristic	Analytical model	Motor producer
Peak torque (Nm)	17	17.14
Rated speed (rpm)	2820	2837
Rated torque (Nm)	2.959	2.958
Rated current (A)	9.1	10.20
Rated power (W)	879	874
Nr. of poles (/)	8	8
Armature phase resistance at 20°C (Ω)	0.51	0.408

According to Table 3, the analytical model is sufficiently accurate, and this model can be used further for deriving the steady-state operating characteristics, the simulation model for obtaining transient characteristics, and finally the numerical model for studying the magnetic flux density in the motor cross-section. The accuracy of the simulation model in PSIM software as well as the numerical model, based on FEM, are highly dependent on the accurate calculation of motor parameters (resistances and inductive reactances), the motor characteristics (current, power, etc.) and motor dimensions, all of which are obtained from the analytical model. From Fig. 2, 3, 4, and 5, for the rated speed of 2820 rpm, the rated current, torque, efficiency and output power of the motor can be read, and they are presented in Table 2. The presented steady-state characteristics of the analytical model allow determining of the motor operation for various operating regimes. i.e., speeds.

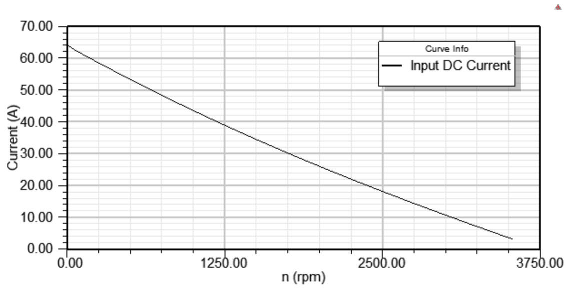


Figure 2: *Steady-state characteristic of the current*

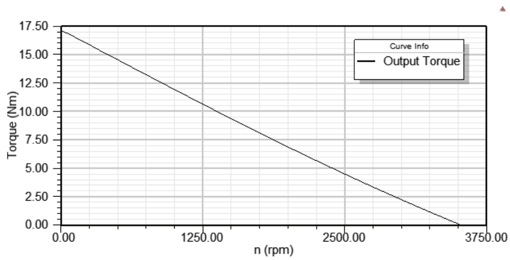


Figure 3: *Steady-state characteristic of the torque*

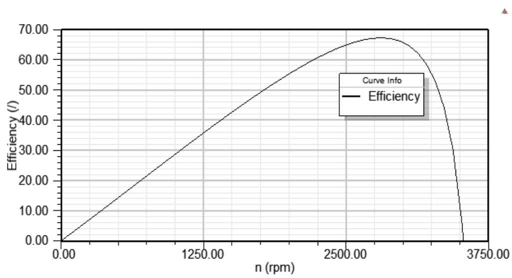


Figure 4: *Steady-state characteristic of the efficiency*

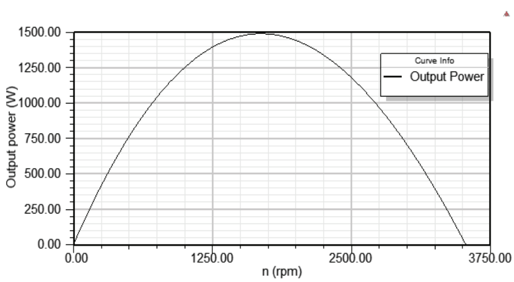


Figure 5: *Steady-state characteristic of the output power*

During the continuous operations, the motor can be loaded up to the rated torque. The motor can run up to the maximum speed, which can be 1.5 times that of the rated speed, but the torque starts to drop. Fig. 6 presents one typical torque-speed characteristic of the BLDC motor, *[21].* It contributes to the easier understanding of Fig. 3.

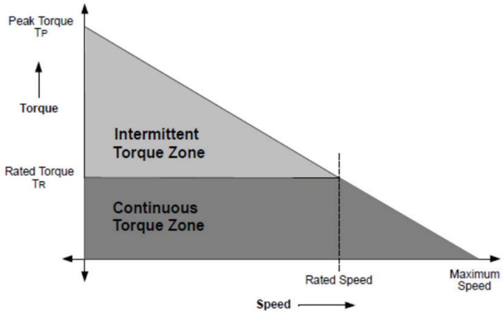


Figure 6: Typical torque/speed characteristic of BLDC motor, *[21]*

Applications that have frequent starts and stops and frequent reversals of rotation with the load on the motor require more than the rated torque. The motor can deliver a higher torque, maximum up to the peak torque, as long as it follows the speed torque curve. Output torque in brushless motors is proportional to stator current over the motor speed range. As for the efficiency factor, the expected maximum is around the rated speed. In practice, the efficiency factor is often lower due to the motor overheating, especially in high-speed applications.

2.2 PSIM model for modelling transient characteristics

Brushless DC motors use electronic switches for current commutation, allowing continuous rotation of the motor. These electronic switches can be connected in the H-bridge structure for single-phase motors or a three-phase structure for three-phase motors. Usually, the switches are controlled using pulse-width modulation (PWM), which converts the DC voltage into a modulated voltage, which easily and efficiently limits the startup current, control speed, and torque. The increase of the switching frequency increases the PWM losses while lowering the switching frequency limits the system bandwidth and can raise the ripple current pulses to the point that they become destructive or shut down the BLDC drive motor, *[22]*. The switching sequence is controlled so that it is synchronized with the position of the rotor. As a result, the stator produces a rotating magnetic field. The stator switches act like a commutator in classic DC motor. In brushless permanent magnet DC motors, the armature currents are commutated exactly according to the rotor position. The signal of the rotor position may be obtained from a position sensor, or from induced voltages for sensor-less control systems, *[23]*. Apart from the steady-state characteristics, motor-transient characteristics are an important part of motor analysis in terms of determining the motor acceleration time. As a six-pulse voltage inverter electronically commutates this type of motor, a closed-loop control scheme is simulated in Power PSIM software. This model will be referred to as a simulation model or PSIM model. BLDC commutation relies on feedback on the rotor position to decide when to energize the corresponding switches to generate the largest torque. The easiest way to accurately detect the position is to use a position sensor. In the simulation circuit, Hall sensors are used for sensing the motor position and the reference speed is set to the nominal speed of 2820 rpm. Fig. 7 presents the simulation circuit, while the output results of speed, torque, and current at rated load operation are presented in Figs 8, 9, and 10, respectively.

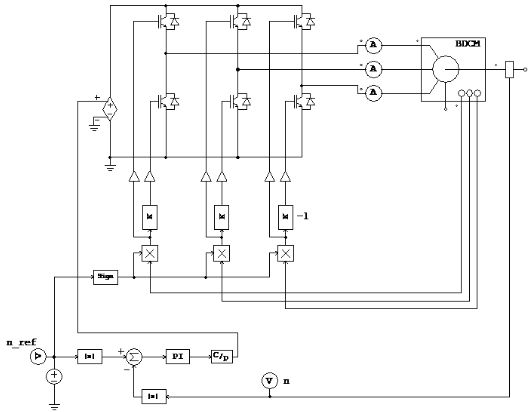


Figure 7: Simulation circuit in PSIM

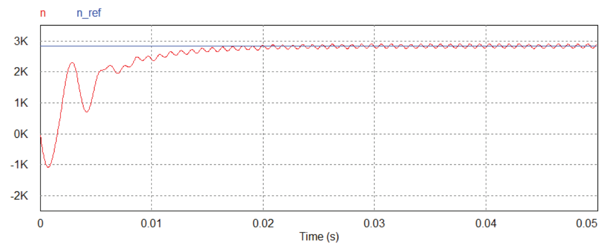


Figure 8: Transient characteristic of speed

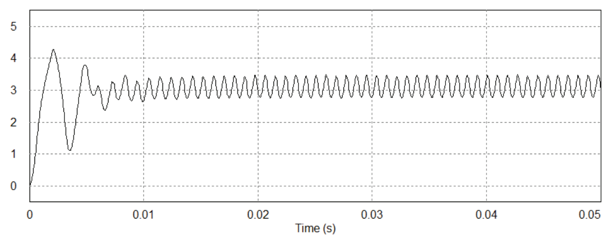


Figure 9: Transient characteristic of torque

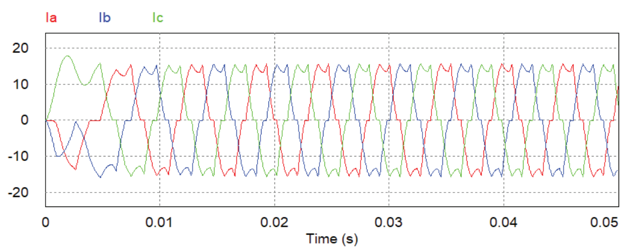
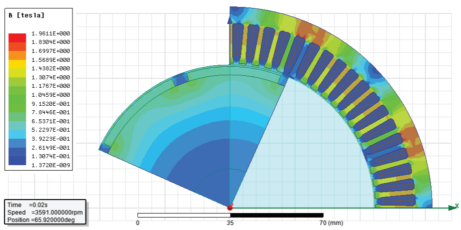


Figure 10: Transient characteristic of current

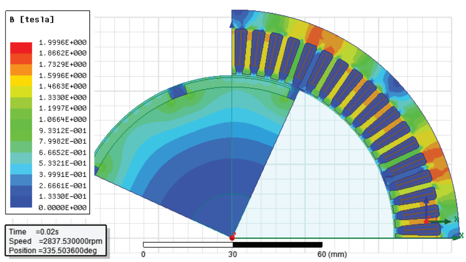
Motor accelerates up to the set speed for 0.02 s. After reaching the nominal speed, the motor current has an approximate rms value of 10 A, which is in good agreement with the results from the analytical model and motor producer data. A similar conclusion can be derived for the motor torque that reaches the average value of 3.3 Nm, which agrees very well with the producer data and the result from the analytical model.

2.3 Numerical FEM model

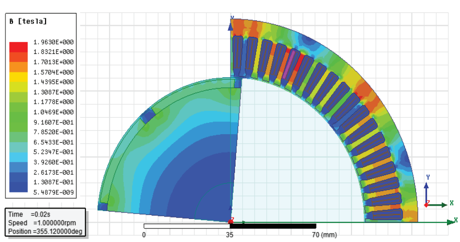
Recently, numerical modelling of electrical machines has gained popularity as a reliable and accurate tool in their design. This is due to the development of information technology that provides fast and accurate software capable of solving the complex differential equations that describe the machine's features. This is also the case with Maxwell's equations, which are solved by the aid of the finite element method in a relatively small region of the machine's cross-section, i.e., in each of the elements of the mesh, distributed all over the machine cross-section. Using Maxwell software, the motor is modelled in FEM, allowing the magnetic flux density distribution in the motor's cross-section to be computed. Fig. 11 presents the magnetic flux density distribution in a motor's cross-section at no-load, rated load, and locked rotor operation.



(a) no-load operation



(b) rated load operation



(c) locked rotor operation

Figure 11: Flux density distribution

3 DISCUSSION OF RESULTS

The main objective of this research is to establish a satisfactorily accurate analytical model of the BLDC that will serve as a basis for the further modifications and the improvements of the motor design. The results from the analytical model that include motor parameters and operating characteristics are presented in Table 2 and Figs. 2, 3, 4, and 5. A comprehensive analysis has been carried out, which includes the simulation model for obtaining the transient characteristics of the motor, the numerical model of the motor for verification of the motor design, and the available data from the producer of the motor. A comparison of the results from all the models of the motor verifies the accuracy of the models and establishes the starting model of the motor, subject to further modifications and optimization. By comparing the results from the simulation and the numerical model, it can be concluded that computed current in the motor's numerical model (Fig. 12) follows the shape of the characteristics and the rms value of the current, computed using the simulation model in PSIM (Fig. 10). A similar conclusion can be derived for the torque characteristics as torque reaches the average value of around 3.1 Nm in the numerical model, which is very close to the data from the motor producer, simulation, and analytical model of the motor (Fig. 9). Starting torque from the analytical model is adequate with data from the producer and starting torque calculated from the numerical model. Table 4 presents the comparison of the obtained results from all models of the motor with the data of the motor producer.

Table 4: *Comparison between analytical model and producer*

Parameter/characteristic	AM	PSIM model	NM	Motor producer
Peak torque (Nm)	17	/	18.2	17.14
Rated speed (rpm)	2820	2837	2837	2837
Rated torque (Nm)	2.959	3.3	3.15	2.958
Rated current (A)	9.1	10.6	10.1	10.20
Rated power (W)	879	/	/	874
Resistance (Ω)	0.51	0.51	0.51	0.408

By comparing the obtained results of motor torque, current, and output power from the analytical model of the motor (Table 3 and Figs. 2, 3, 4, and 5) at the rated speed, with the obtained results from motor simulation model (Figs 8, 9 and 10) and the obtained results of motor current and torque from the numerical model (Fig. 12 and 13), it can be concluded that the results from all three models of the motor are close one to another, which verifies the accuracy of the analytical model of the motor as a good starting point for further modifications and optimizations of the analysed motor.

4 CONCLUSION

The main objective of this paper is to derive various computer models of a brushless DC motor, capable of computing motor parameters and operating characteristics, useful for the assessment of motor operation in various operating regimes. Starting from very sparse catalogue data, the analytical model, set for computer modelling, was derived. The analysis was extended with the simulation model for determining motor-transient characteristics. The third motor model is the numerical model that allows the computing of magnetic flux density in the motor cross-section, as well as motor torque and currents during starting and rated load operation. The obtained results from all motor models are compared, showing very good alignment with data from the motor producer. The derived models are useful for the inexpensive and reliable replacement of motor testing in laboratories in order to determine the motor features and behaviour in various operating modes. Furthermore, the derived models are universal. They can be easily applied to any brushless DC motor by simple replacement of motor parameters. Establishing the accurate model of the BLDC motor is a good basis for the further modification of the motor design aiming towards the optimization of parameters that impact motor efficiency and its overall operation.

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