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ASSESSMENT OF OPERATING CHARACTERISTICS OF BRUSHLESS DC MOTOR

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Abstract: Paper presents operating characteristics of brushless DC motor (BLDC) obtained by analytical, numerical and simulation software, allowing steady-state and transient characteristics of the motor to be computed. Based on catalog data from producer Moog, motor is simulated in closed-loop control system fed by voltage inverter. Derived analytical and simulation models allow studying of various motor operating modes like no-load, rated load and locked rotor. Therefore, they are a useful tool in analysis of motor characteristics and operation. Finite Elements model of the motor is derived in order to verify the results of the previous models as well as to calculate magnetic flux density in motor cross-section.

Keywords: brushless DC motor, FEM model, transient characteristics

INTRODUCTION

In the 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 are 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 in order to get 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 best performance. The development of the power electronics has certainly contributed to the wide application of BLDC motors, as these types of the motors are usually electronically commuted by the voltage inverter in closed loop control system utilizing Hall effect sensors for sensing the motor position [1]-[2]. However, sensorless techniques are also available for detection of the motor position and they are widely used as well [3]. Each motor modeling is highly dependant of accurate identification of motor parameters. Often various optimization techniques are used for that purpose. During recent years, various controlling techniques have been investigated along with the simulation models that allow accurate control and prediction of motor dynamic regimes [4]-[5]. In this paper motor analytical model (AM) has been calculated in software Ansys Maxwell in order to identify motor parameters and operating characteristics. Accuracy of the developed analytical model was verified by comparing the obtained results from this model with available data from the motor producer, company Moog [6]. Once that the analytical model has been proved to be sufficiently accurate, the obtained motor parameters have been used in the simulation model of BLDC motor fed by inverter , in closed loop system with Hall sensors, modeled in software PSIM. 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 necessary tool for estimating motor electromagnetic properties in terms of magnetic core saturation, losses or even calculating various motor operating characteristics [7]. Proper design of the motor should rely on good mechanical design regarding motor geometry accompanied by adequate electrical design with respect to the winding parameters and properties of electrical and magnet materials. In this paper analytical model of the motor including all design parameters such as motor geometry, dimensions of the stator and rotor core, geometry of the stator slots and magnet poles was derived on the base of the very few parameters from the motor producer. Therefore, it was necessary obtained model of the motor to be checked and verified by FEA. From the FEA model, the magnetic flux density in motor cross section was obtained allowing estimation of the motor design in terms of the magnetic core saturation. From the last model, the motor torque and current was calculated as well. Obtained results from AM, FEAM and PSIM model were compared. They are useful in assessment of motor features in various operating modes allowing easy predication of motor operation during start up, rated load or no load operation.

VARIOUS MODELS OF BLDC

Analytical model

The first step in defining the motor analytical model is to properly design the motor geometry. The design of the stator core including number and geometry of the slots was done following the design procedure for asynchronous motors [8]. The major motor dimensions like the stator and rotor outer diameter as well as the number of the magnet poles rely on the motor type BN42-53IP-03TFC of company Moog. Fig.1 presents the motor cross-section.

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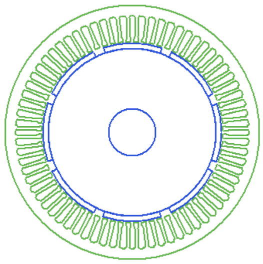


Fig.1 – *Cross- section of the motor.*

The properties of all magnet and electrical material are defined in the software program as well. Output results from the computer model set in Maxwell are the motor parameters at rated load, no load and locked rotor. Table 1 presents them.

Table I

Parameters and operating characteristics of analytical model

Steady state parameters	
D-axis inductance (H)	0.00021
Q axis inductance (H)	0.00021
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

Analytical model was verified by comparing the motor parameters and characteristics with available data from themotor catalog [6]. Table 2 presents this comparison.

Table II

Comparison analytical mode/producer

Parameter/characteristic	Analytical model	Motor producer
Peak torque (Nm)	18.08	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 2, analytical model is sufficiently accurate and the obtained data 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 motor cross-section. Figs. 3, 4 and 5 present the steady-state characteristics of current, torque and efficiency factor for the analyzed motor.

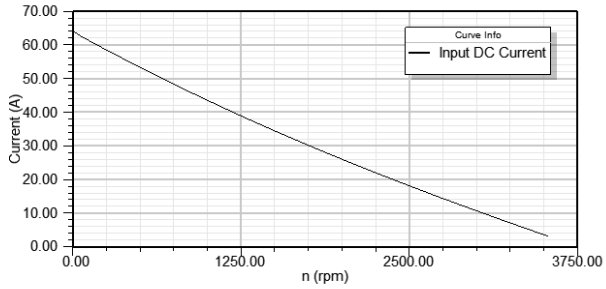


Fig.2 – *Steady-state characteristic of current.*

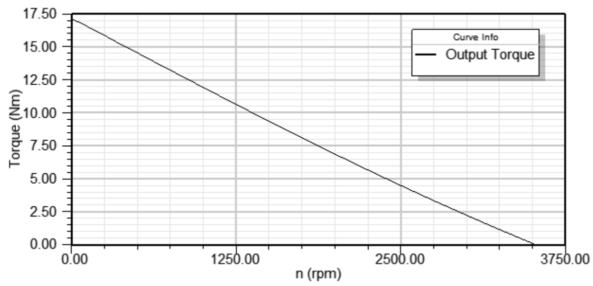


Fig.3 – *Steady-state characteristic of torque.*

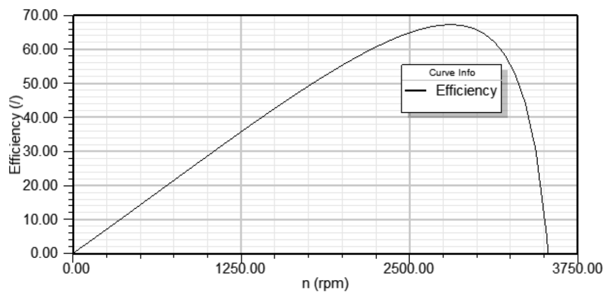


Fig.4 – *Steady-state characteristic of efficiency factor.*

During the continuous operations, the motor can be loaded up to the rated torque. The motor can run up to the maximum speed that can be the 1.5 times of the rated speed, but the torque starts to drop. Fig. 5 presents one typical torque-speed characteristic of the BLDC motor [9]. It contributes to the easier understanding of Fig. 3.

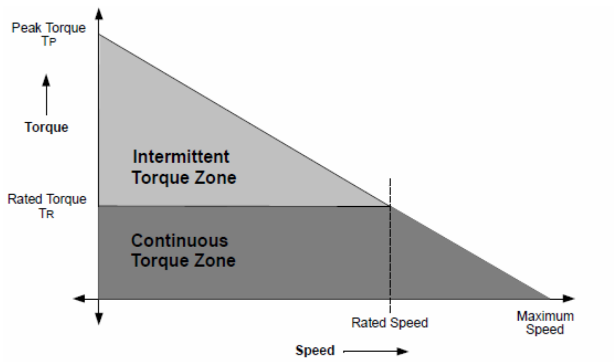


Fig.5 – *Typical torque/speed characteristic of BLDC motor [9].*

Applications that have frequent starts and stops and frequent reversals of rotation with load on the motor, demand 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, expected maximum is around the rated speed. In practice, often efficiency factor is lower due to the motor overheating especially in high-speed applications.

PSIM model for modelling transient characteristics

Apart from the steady-state characteristics, motor transient characteristics are important part of motor analysis in terms of determining the motor acceleration time. As this type of the motor is electronically commutated by 6-pulse voltage inverter, a closed-loop control scheme is simulated in software package Power PSIM. This model will be referred as simulation model or PSIM model. Hall sensors are used for sensing the motor position and the reference speed is set to the nominal speed of 2837 rpm. Fig. 6 presents the simulation circuit, while output results of speed, torque and current are presented in Figs 7, 8 and 9 consequently.

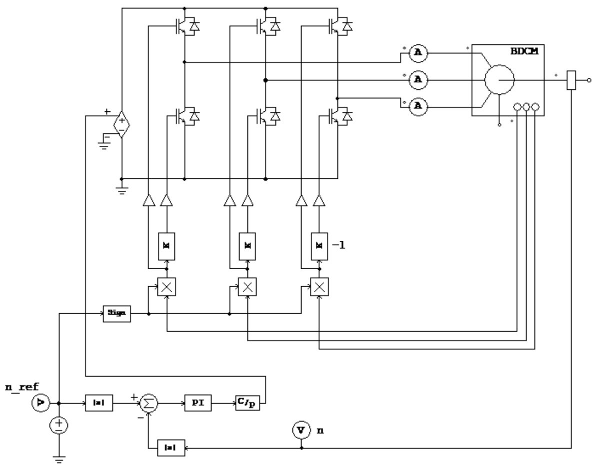


Fig.6 – *Simulation circuit in PSIM.*

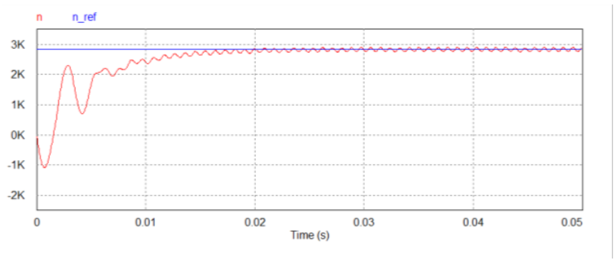


Fig.7 – *Transient characteristic of speed.*

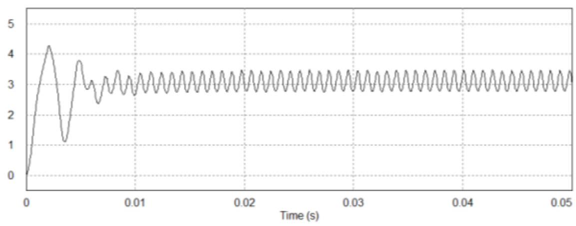


Fig.8 – *Transient characteristic of torque.*

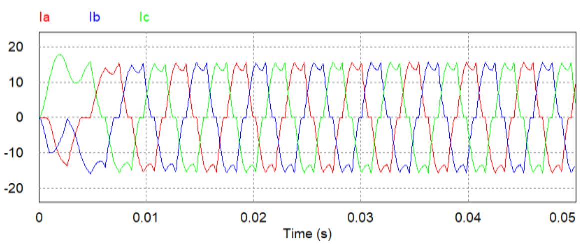
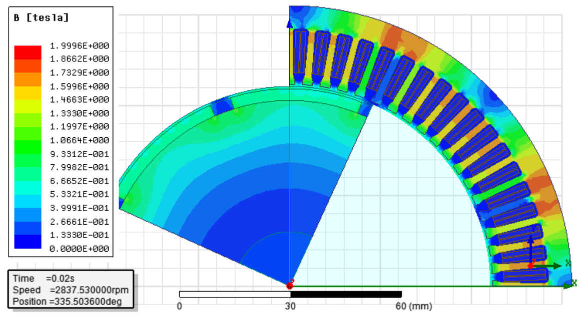


Fig.9 – *Transient characteristic of current.*

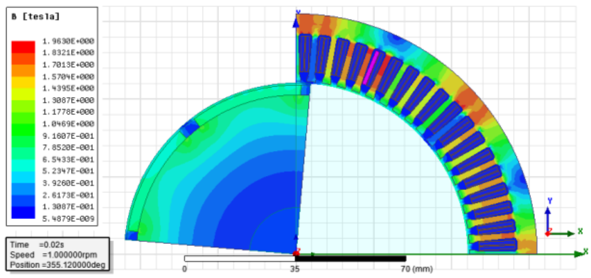
Motor accelerates up to the set speed for 0.02 s. After reaching the set nominal speed, the motor current is approximately rms value of 10 A which is in good agreement with the results from analytical model and motor producer data. Similar conclusion can be derived for motor torque that reaches the average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

FEM model-numerical model

Recently, numerical modeling of electrical machines has gained popularity as reliable and accurate tool in machine design. This is due to the development of information technology, which provides fast and accurate software programs capable of solving the complex differential equations that describe the machine features and characteristics. This is also the case with Maxwell's equations that are solved in relatively small region of the machine cross section i.e. in each of the elements of the mesh, distributed all over the machine cross section. Using Maxwell software, motor is modeled in FEM, allowing magnetic flux density distribution in motor cross section to be computed. Fig. 10 presents magnetic flux density distribution in motor cross section at rated load and locked rotor operation.



(a) rated load operation



(b) locked rotor operation

Fig.10 – *Flux density distribution.*

From the presented results in Fig. 10, it can be concluded that motor is well designed with respect to the magnetic flux density distribution as maximum values of the flux density are near to the point of the core saturation but not exceeding the knee point of the magnetization curve. Therefore, motor is well designed regarding the geometry. Further more, FEM model is derived from the analytical model so it can be concluded that motor design satisfy the electrical, operating and magnetic features requested from this type of the motor. The next step in the motor analysis is to find the torque and the current computed in the numerical model and to compare them with the obtained data from the analytical and the simulation model. Fig. 11 presents the motor currents at rated load operation while Fig. 12 presents the motor torque for operating regimes, rated load-meaning operation with 2837 rpm and locked rotor operation or motor starting. Both torque characteristics are computed for a constant speed using time stepping method and they do not represent motor transient characteristics.

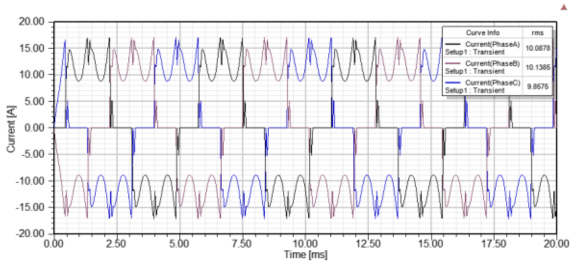
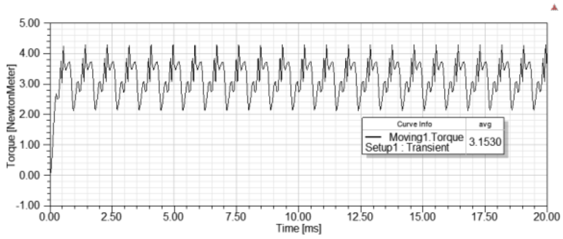
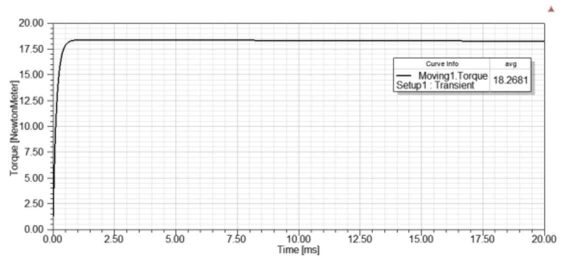


Fig.11 – *Characteristic of current-numerical model*



(a) rated load



(b) locked rotor

Fig.12 – *Torque characteristic- numerical model*

Table III
Comparison of results from all models

Parameter/characteristic	AM	PSIM model	NM	Motor producer
Peak torque (Nm)	18.08	/	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

The computed current in the motor numerical model (Fig. 11) follows the shape of the characterisitcs and the rms value of the current, computed by the simulaiton model in PSIM (Fig.9). Similar conclusion can be derived for the torque characterisitcs as torque reaches the average value of around 3.1Nm in the numerical model which is very close to the data from the motor producer, simulation and analytical model of the motor. Table III presents the comparison of the obtained results from all motor models with the data of the motor producer.

CONCLUSION

The main objective of this paper was to derive various computer models of brushless DC motor, capable of computing motor parameters and operating characteristics, useful for assessment of motor operation in various operating regimes. Starting from a very few catalogue data, the analytical model, set for computer modelling, was derived. Analysis was extended with the simulation model for determining motor transient characteristics. The third motor model is the numerical model that allows computing of magnetic flux density in motor cross section also 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 as inexpensive and reliable replacement of motor testing in laboratories in order to determine the motor features and behaviour in various operating modes. Further more, the derived models are universal. They can be easily applied to any brushless DC motor by simple replacement of motor parameters.

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