DEVELOPMENT AND PERFORMANCE INVESTIGATION OF THE DIRECT BRUSHLESS TORQUE MOTOR

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Resume

The paper deals with the brushless torque motor, that was designed for precise positioning device to substitute servo drive for high torque and low speed application. It describes the design, basic parameters as well as the analysis of torque characteristic. The paper also presents the results of realized measurements. Finally, the parameters of the brushless torque motor and servo drive applicated in precise positioning device are compared. A series of measurements like measurement of torque characteristics, loading characteristics and also measurements of drive performances are presented in this paper.

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1 Introduction

Brushless torque motors have gained immense popularity in recent years due to their high torque-to-weight ratio, high efficiency, and precise motion control capabilities. Difference from conventional motors that rely on brushes and commutators to transfer power, brushless torque motors use a system of magnets and windings to generate torque. This design eliminates the need for brushes and commutators, resulting in reduced maintenance requirements and improved reliability [1- 3].

The high torque density of brushless torque motors makes them ideal for a wide range of applications, including robotics, aerospace, and medical devices. They can provide precise control over rotational motion, making them suitable for tasks such as positioning, indexing, and driving linear motion [4-7]. Moreover, their ability to operate at high speeds and torques while maintaining high efficiency makes them an attractive option for power-hard applications.

Classical permanent magnet synchronous motors (PMSM), with a nominal mechanical torque ranging from 1 to 5Nm, are commonly used in servo drives. A linked gearbox is utilized with this one when a larger torque is required from the same PMSM motor [8-10]. These gears often have ratios between 70 and 150. As alternatives to the traditional PMSM with connected gearbox, Direct Drive motors and Slotless brushless ring motors with high torque output and low speed are possible. Industrial applications, such as high precision industrial servo drives, are increasingly using direct drives with brushless motors [11-13].

The EVPU Company designed a number of segments slotless PMSMs to replace PMSM with gearbox solutions. These designed PMSMs were submitted to a number of measurements [1-3]. Results from these measurements should validate the designed permanent magnet linear synchronous motor's electrical properties since it has an ironless moving part at rotation construction and is first referred to as a segment slotless PMSM. Results from these tests should also support the quality of the segment slotless PMSM drive that was designed (such as accuracy, repeatability, stabilization test, and operating instability - in this kind of measurement, the servo drive was in speed mode). Field-oriented control (cascade vector control with feed forward position loop) was put into place on this drive for these measurements (experimental verification). The next stage of development was the design of a DC brushless motor with high torque and low speed application. Target requirements for direct drive DC brushless torque motor for precise positioning device were: max. speed 5 to 40 rad/s, rated torque 150 Nm, supply voltage 300 V DC with alternative 24 V DC. Expected properties: very high accuracy, lower weight of the direct drive torque motor than servo drive, Brushless direct current (BLDC) motor provides the ability of movement without power, sustainability, soft start in freezing.

2 Design of direct brushless torque motor

Electromagnetic and thermal design of BLDC motor was based on volume of servo drive in the precise positioning device, characterized with the space for large

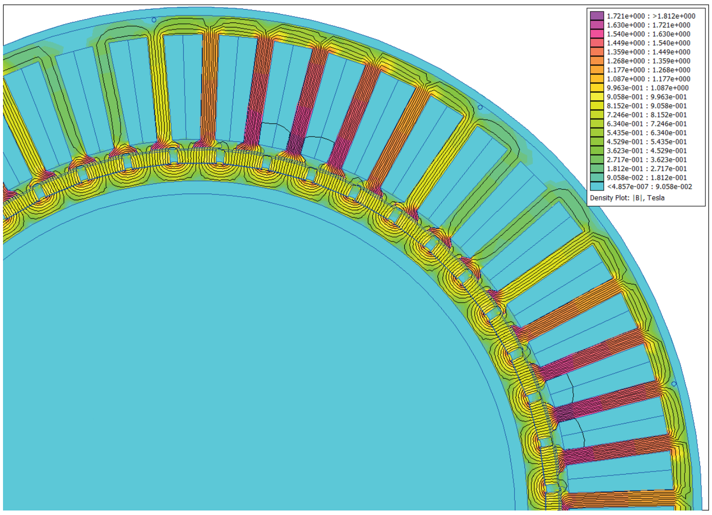

***Figure 1** 2D magnetic flux distribution in cross section of BLDC motor at rated current*

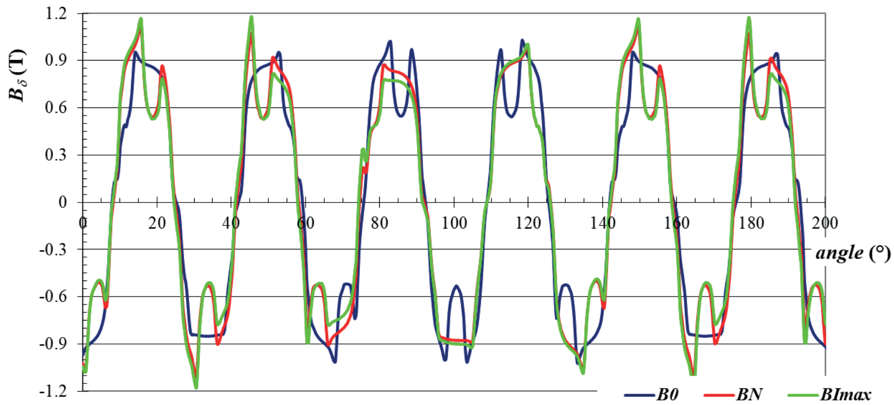

***Figure 2** Air gap magnetic flux density waveform*

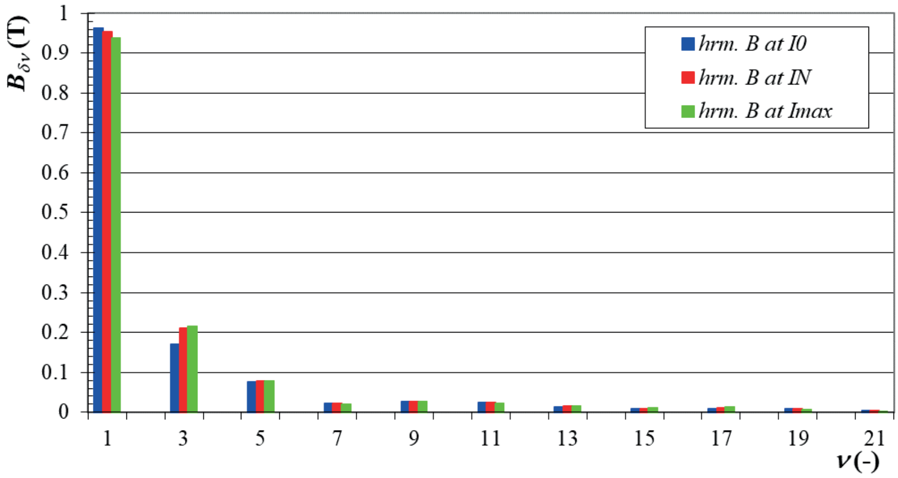

***Figure 3** Harmonic analysis of BLDC motor magnetic flux density at no-load state, at nominal and maximum current*

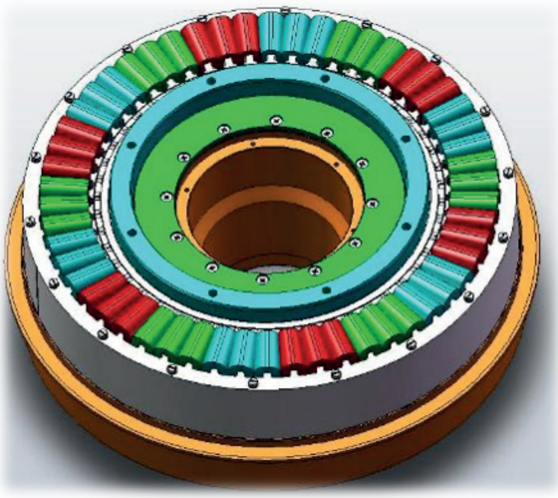

Figure 4 *3D model of designed 3phase BLDC motor with frame*

Q=54
m=3
$2p$=48
Q=0.375
Connection □
Winding diagram (repetition of the scheme from slots Q1÷Q9; 6x):

Slot:	1	2	3	4	5	6	7	8	9
Phase:	+A	-A	+A	+B	-B	+B	+C	-C	+C
Phase:	C-	A-	A+	A-	B-	B+	B-	C-	C+

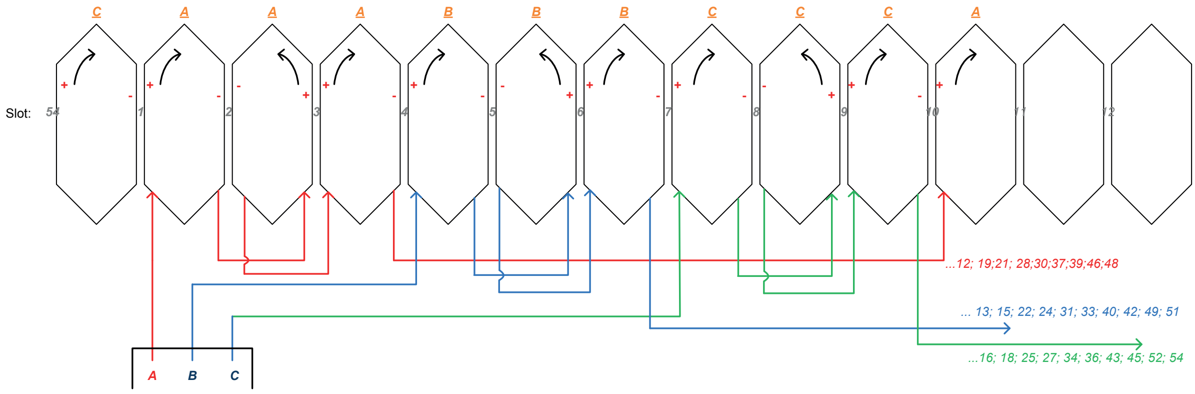

Figure 5 *Winding diagram: connection: triangle, 2p=24, q=0.375, Q=27*

diameter and small length that is, a thin ring motor design. The content of the research and development work in design BLDC motor was:

- selection of the appropriate winding configuration and arrangement of the permanent magnets;
- calculation of the BLDC motor magnetic circuit; determining the volume of PM, the calculation of the magnetic field distribution in the air gap, the calculation of moments, torque ripple et al.

Figure 1 to Figure 3 shows the finite element analysis (FEA) result of the designed BLDC motor. It is well known that by using FEA is possible to optimize the electro-thermal and electro – magnetic properties of the electric machines and electric devices [14-16]. Considering proposed work, the same procedure was used as well.

Using the previously described design approach, then is possible to develop a 3D model of the proposed component. Figure 4 shows 3D interpretation of the construction of investigated BLDC motor, while Figure 5 represents the detailed winding diagram.

Both the dependency of motor torque on rotor position (Figure 6) and the dependence of torque on current (Figure 7) have been studied using FEM analysis. Because the predicted torque's magnitude depends on the mutual rotation of the stator and rotor, the torque ripple was also examined for each point of the vector magnetic field (Figure 8). The electromagnetic torque's dependency on the position of the magnetic field vector, as well as the rotation of the stator and rotor, was detected by combining the estimated changes.

Based on the compiled switching plan for the three-phase winding current vector, the dependence of the torque on the rotor angle for each switching state and position was also recalculated and thus the ripple torque

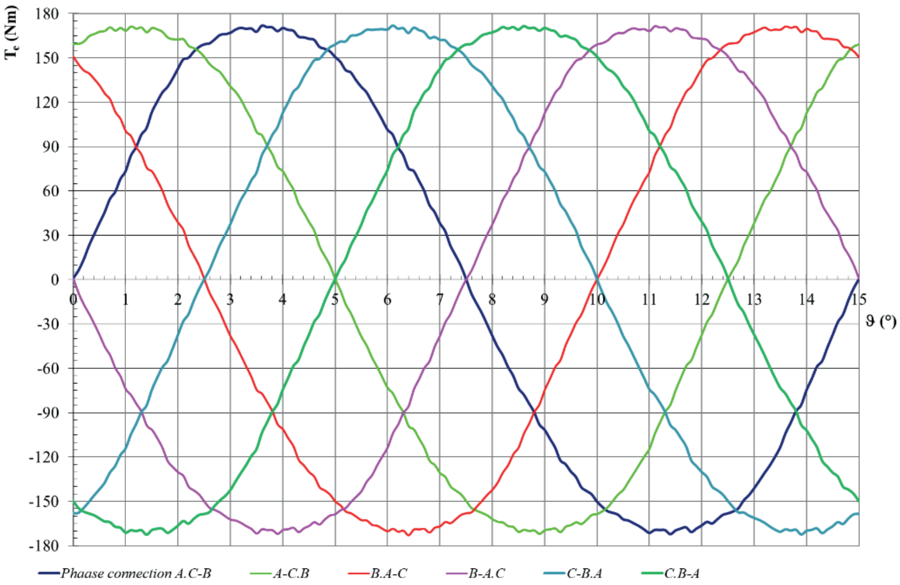

Figure 6 *Torque versus rotor angle*

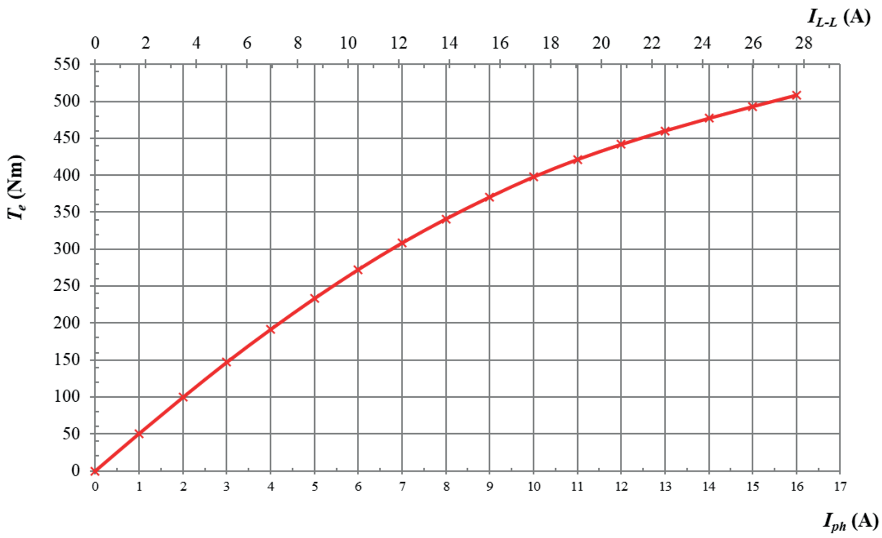

Figure 7 *Torque characteristics on the motor current calculated by FEM*

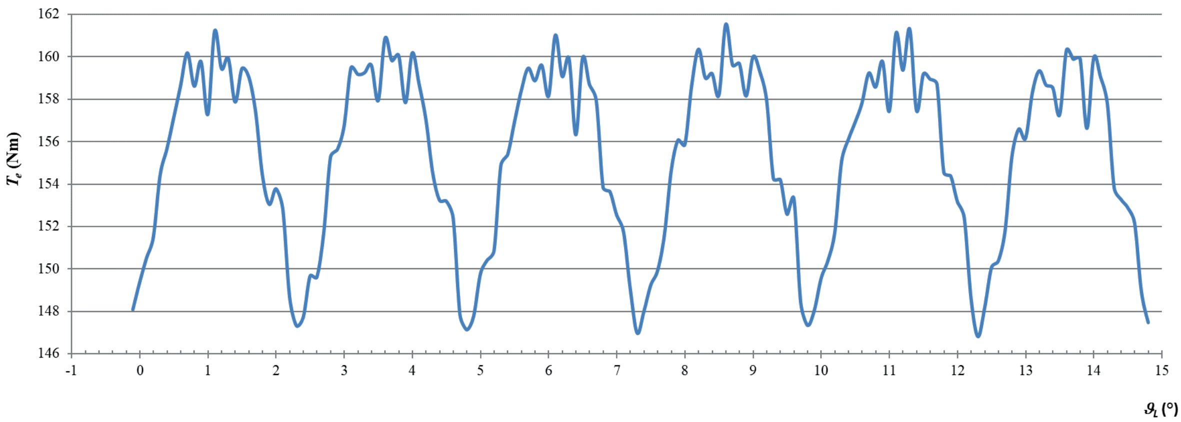

Figure 8 *Torque ripple characteristics calculated by FEM*

Table 1 *Results of the torque ripple determination*

Torques and values		
T_{avg}	155.3881 Nm	
T_{max}	161.5306 Nm	$\text{ripple} = \frac{T_{max} - T_{minx}}{T_{avg}} \ (-; \text{Nm}, \text{Nm})$
T_{min}	146.8124 nm	
ripple	0.094719	

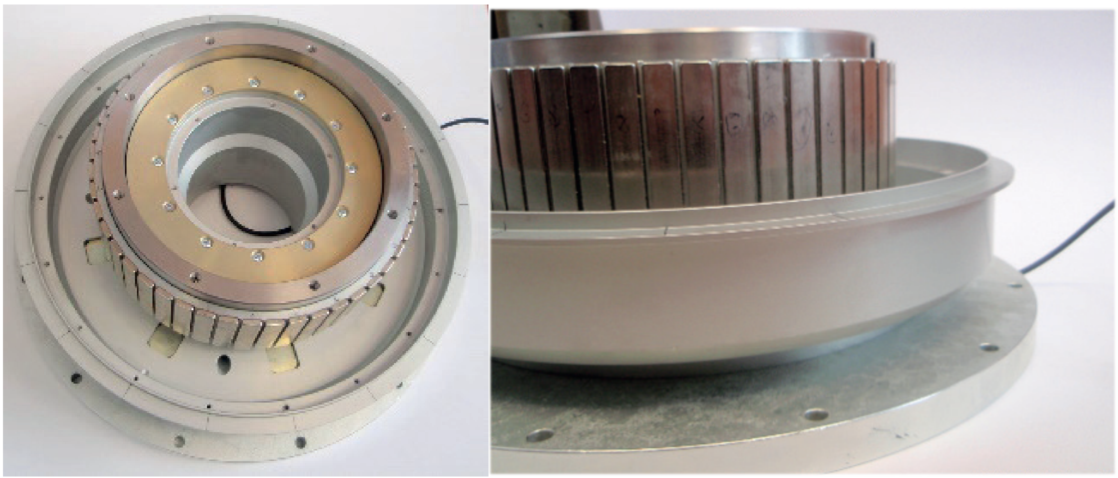

Figure 9 *Photography of the rotor of the BLDC motor with frame*

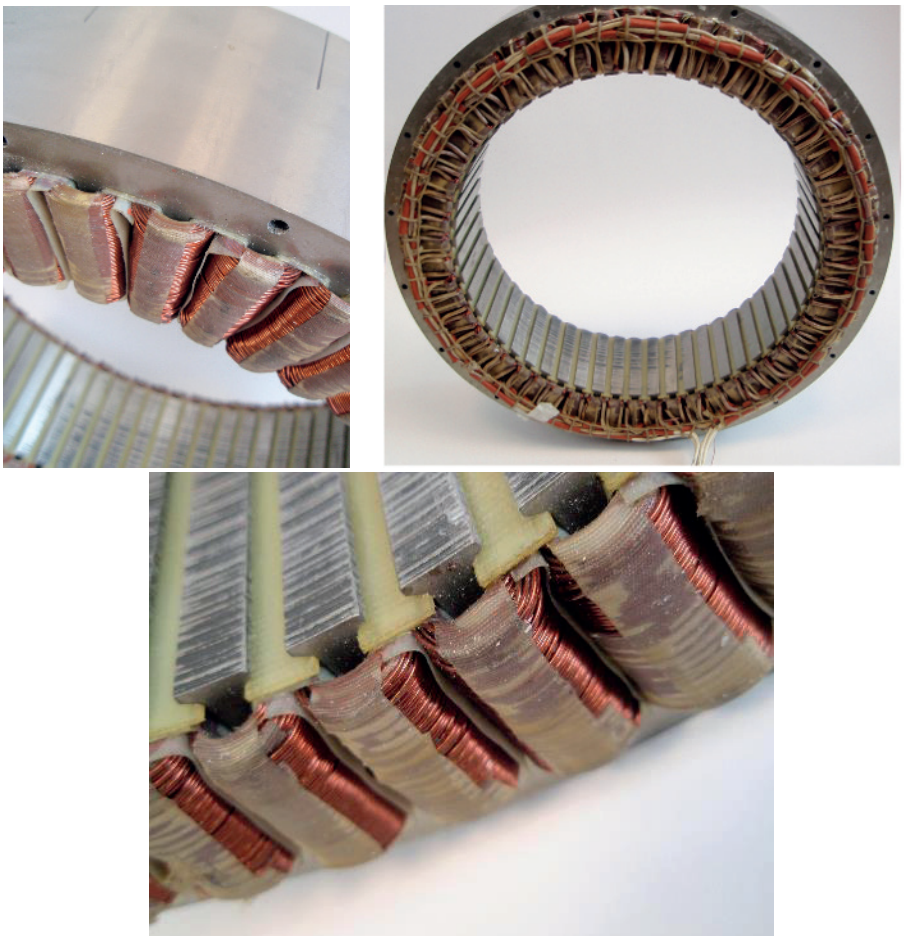

Figure 10 *Photography of the stator of the BLDC motor*

characteristic for the selected operating point was compiled. This calculated dependency is listed in Table 1. together with measured characteristics

3 The basic parameters and characteristics of the BLDC motor

In the Figure 9 and Figure 10 the construction details of the designed motor can be seen, while Table 2. is listing its basic parameters.

As was early mentioned, Figure 7 represents the dependency of the machine torque on the load angle calculated by using FEA. On the other side Figure 11 shows the same characteristic obtained by experimental measurement. For the comparison purposes, the characteristic achieved from the simulation result by using FEM (Figure 6) analysis is shown as well. The measurement was performed at a temperature below the operating temperature of 150°C, and the calculated dependence is for reference temperature.

Table 2 lists the electrical characteristics of the BLDC motor's equivalent circuit as well as other crucial drive characteristics for use with positioning systems. By using the measurement method of the self- and mutual-inductance curve, motor inductance was examined.

The proposed engine was measured on a test bench to investigate the basic parameters, verify the loading characteristics, measure torque ripples, the required starting torque at the lowest ambient temperature. The measurements were verified using a YOKOGAWA precision power analyzer type WT3000. The electrical torque was calculated from the difference between the motor input power and motor losses divided by the mechanical angular velocity. Mechanical losses have been evaluated as well during no-load test. Motor losses are caused only by armature winding copper losses, and are depended on winding temperature. Measured load characteristics of motor are shown in Figure 12 and Figure 13, torque characteristics are shown in Figure 14.

The measurements confirmed the suitability of the design methodology, its correctness and use in manipulators or wheel motor for electric vehicles. The investigated performances are in accordance with the analytical design.

4 Control structure

Field oriented control algorithm in cascade control structure was used. Field oriented structure allows an independent control of magnetic flux and torque of the stator current. In a cascade control arrangement, there are two (or more) controllers of which one controller's output drives the set point of another controller (Figure 15). Also, space vector modulation was used to supply motor phase voltages. Space vector modulation generates a minimum harmonic distortion of the currents in the winding of 3-phase AC motors. Space vector modulation also provides a more efficient use of the supply voltage in comparison with sinusoidal modulation methods.

Experimental verification was carried out with a drive using a 1.05 kVA inverter (type SN100 – 1.05) developed by EVPU with a TI TMS320F2818 digital

Table 2 *Basic parameters of the prototype of the designed motor*

Motor type: MPM BkDC-360-150		
Rated voltage U_{DC} (V)	300	24
Poles - 2p	48	
Stator teeth- N_{z1}	54	
Connection	3 phase, D	
	Serial connection of coils	Parallel connection of coils
Rated current I_s (A)	5.9	46
Overload current I_p (A)	27	156
Rated torque M_{mech} (Nm)	170	145
Frequency f_n (Hz)	0÷47	0÷9
RPM (min^{-1})	0÷166.7	0÷40
Isulation class	F	
Cooling	AN	
Efficiency η (%)	87.5 at 10 rad.s^{-1}	
Outer diameter of stator/iron lenght (mm)	Ø 360 / 75	
Winding resistance at terminals, 20°C (Ω)	4.33	0.119
Winding inductance $L_{\sigma0}$ (mH)	76.7	1.1
L_d (mH)	110	1.7
L_q (mH)	64	0.75

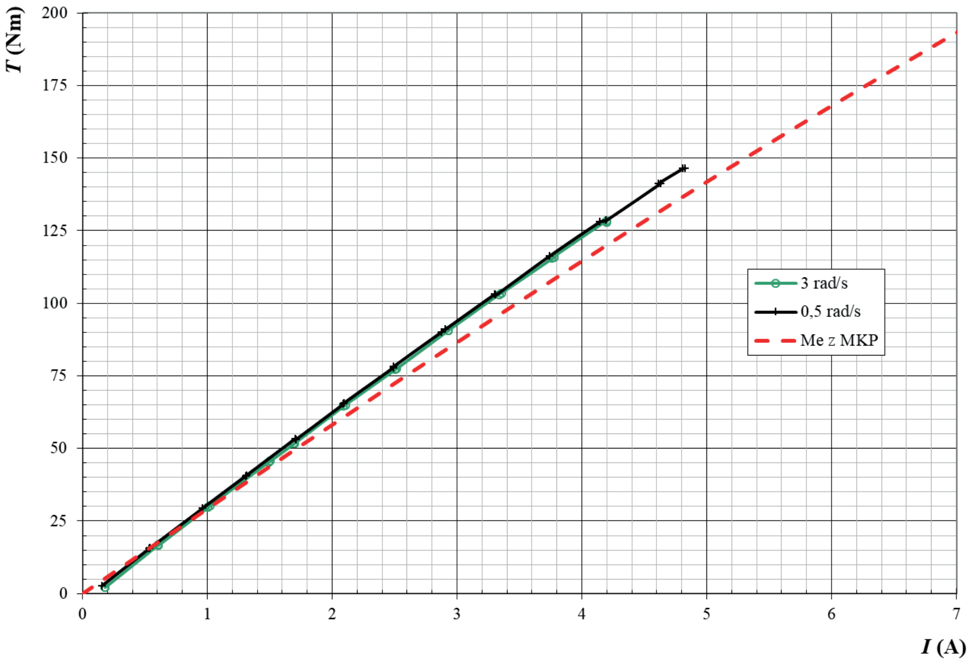

Figure 11 *Calculated and measured load characteristic of BLDC motor*

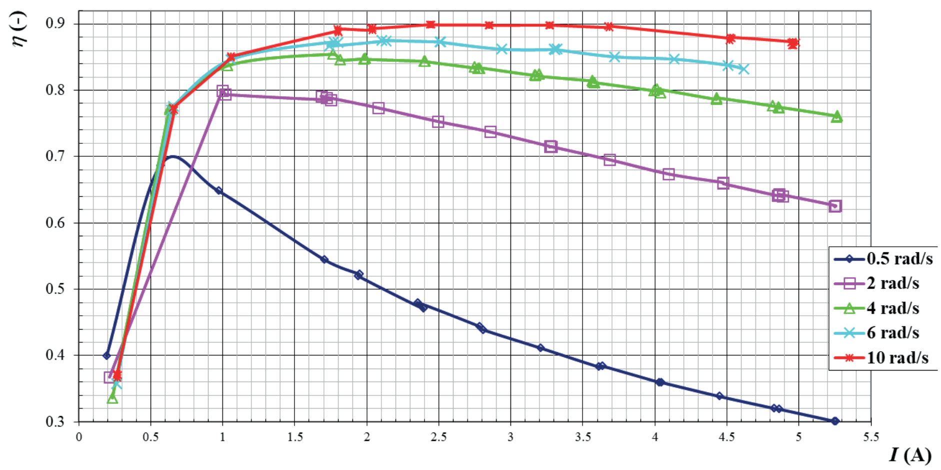

Figure 12 *Load characteristics: efficiency at different angular velocity*

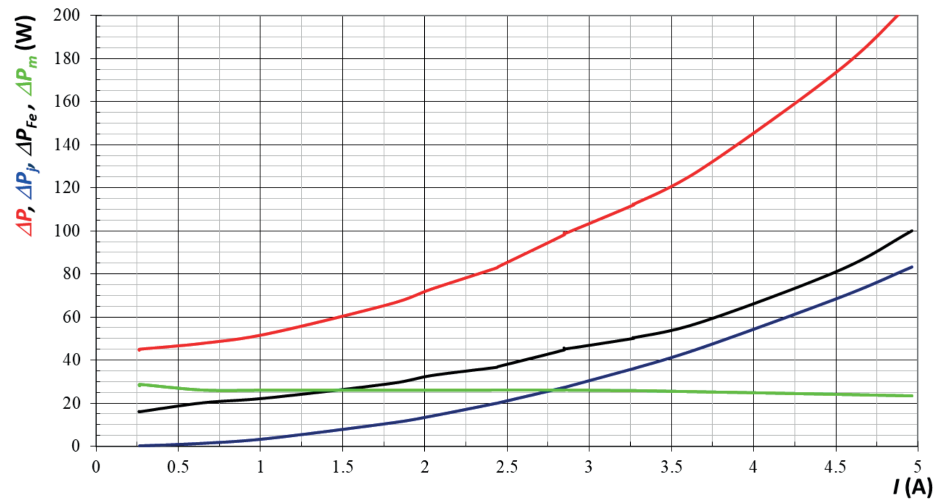

Figure 13 *Load characteristics: power and components of losses (winding, mechanical, iron) at angular velocity 10 rad.s^{-1}*

signal processor. An angular RESM sensor, an optical sensor of the SR read head and a SIGNUM system from RENISHAW with a resolution of 0.1 μm were used as a position sensor. The block diagram of position control loop is shown on Figure 16. The sampling frequency of the current loop was set to 15 kHz. The velocity measurement was performed in a 3 kHz loop to achieve suitable accuracy (pulse counting method was used).

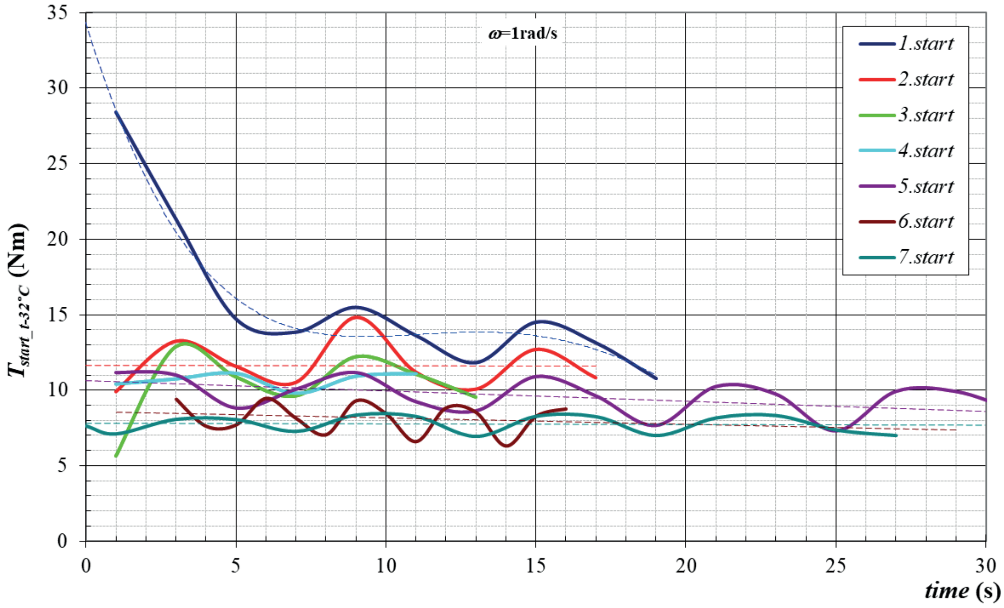

Figure 14 *Torque characteristic in dependency on time and nr. of motor starting (temperature of -32°C, influence of bearing lubricant)*

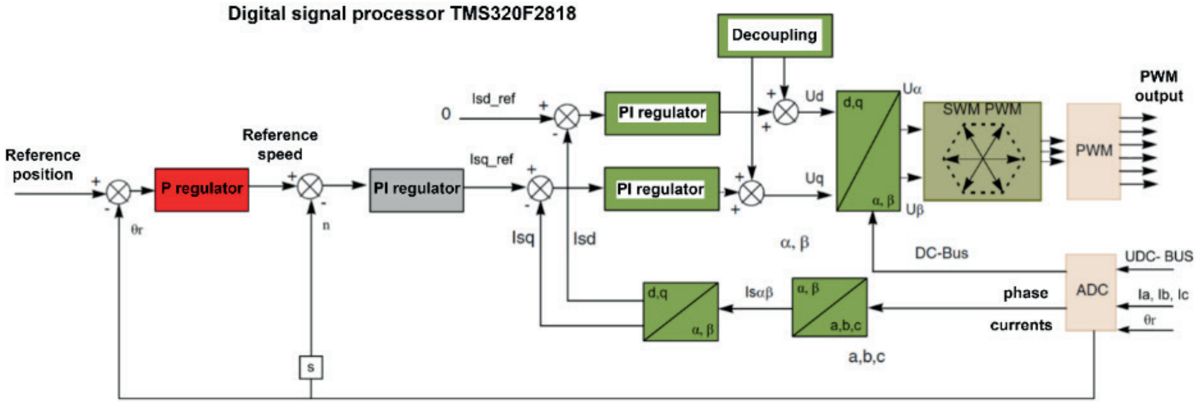

Figure 15 *Basic cascaded control structure was extended and modify with feedforward loops, for our reason, we use a speed feedforward to eliminate a speed latency*

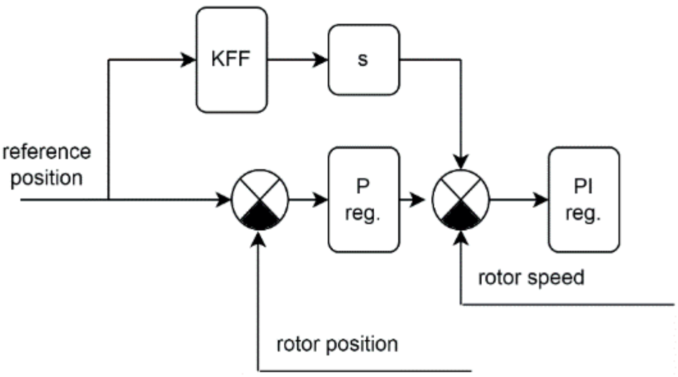

Figure 16 *Block scheme of the position control with feedforward loop of speed*

5 Conclusion

Direct drive with brushless DC motors have their advantages and disadvantages depending on the specific application in they are being used for. Direct drive motors offer high efficiency, high torque, and low noise levels due to the absence of gears and the direct coupling of the motor to the load. However, they are limited in their speed range and can be more expensive and complex to design and manufacture.

On the other hand, brushless DC motors offer a wider range of speeds, are generally more compact and affordable, and require less maintenance due to the absence of brushes, lubricants. They are also capable of high-power density and offer good control and efficiency. However, they can produce more electromagnetic interference (EMI) and have a limited torque density compared to direct drive motors.

Ultimately, the choice between direct drive and brushless DC motors will depend on the specific requirements of the application, including factors such as speed range, torque, efficiency, cost, and size constraints. Understanding the advantages and disadvantages of each type of motor can help designers to make decisions when selecting the best motor for their application.

The proposed motor has been compared with a conventional drive, as servomotor with gearbox, in a particular application such as a precision positioning manipulator. The disadvantages of this comparison were: slightly higher cost of a direct torque motor, 10% higher weight, and due to the larger current draw in sensitive applications, the requirements for a very low level of radiated electromagnetic field need to be addressed. The advantage is better configurability, positioning accuracy and maintenance-free operation.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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