

Analysis and Simulation of Switching Angle Effects on Dynamic Behaviour of Axial Flux Two-Phase Brushless DC Motor

Abstract. The objectives of this paper were to determine by computer simulation and laboratory test the electromechanical characteristics of a double-sided axial flux permanent magnet brushless DC (AFPM BLDC) motor with two-phase winding and analysis the influences of switching angle on motor performance. To study the motor operation, a mathematical dynamic model has been proposed for motor, which became the basis for simulations that were performed using MATLAB/SIMULINK software package. The results of simulations were presented in form of the waveforms of selected quantities and the electromechanical characteristics performed by the motor. The calculation results show that the two-phase motor version develops smooth torque and reaches high efficiency. An experimental device is developed to compare experimental and simulated results. The results obtained from the test practically do not differ from those obtained from simulation. The two-phase motor can be applied where more smooth torque is required. Finally a study on the influences of switching angle on motor performance shows that when advance switching technique is used, the motor operates with the highest efficiency.

Streszczenie: Celem projektu opisanego w artykule było wykonanie symulacji i testów laboratoryjnych charakterystyki elektromechanicznej bezszczotkowej maszyny DC z magnesami trwałymi o strumieniu osiowym (AFPM-BLDC) z uzwojeniem dwufazowym. Model sumacyjny opracowano w programie Matlab/Simulink. Wyniki obliczeń wykazały, że maszyna dwufazowa posiada gładką charakterystykę momentu oraz wysoką sprawność, a zastosowana metoda sterowania i modulacji ma duży wpływ na sprawność maszyny. (Analiza i symulacje wpływu kąta załączeń na dynamikę pracy maszyny AFPM-BLDC).

Keywords: brushless DC motor, switching angle, inverter, dynamic.

Słowa kluczowe: bezszczotkowa maszyna DC, kąt załączeń, falownik, dynamika

Introduction

In the next years many attention has been devoted by the scientific literature regarding the main components of electric and hybrid electric vehicles (energy storage systems, dc-dc and dc-ac converters, electric motors and so on) and about the energy management of the whole vehicle [1]-[8]. Concerning the electric motor many solutions have been proposed but they have not had commercial success. At present all the major motor manufacturing industries make brushless DC motors. DC brushless motors have had a substantial impact in some industry market areas, primarily plastics and fibers, wire drawers, winders, cranes, and conveyors. Most recently a mining company has put several of these drives at 300 HP ratings operating coal conveyors in underground mines. The increasing popularity of brushless permanent magnet motors in recent years is due to the drop in prices of the high energy magnets and electronic devices. The brushless permanent magnet motors perform better and have higher efficiency than the machines with electromagnetic excitation [9]. The research carried out for several decades to increase the torque density and motor efficiency has led to invention of several newer structures of BLDCs. The brushless DC motors are permanent magnet motors where the functions of commutator and brushes were implemented by solid state switches [10]. The brushless DC motors are distinguished not only by the high efficiency but also by their no maintenance [11]. The permanent magnet motors used in this case are single phase or poly phase motors. When operating with single phase or poly phase motors, the inverter plays the role of the commutator [12]-[13]. In this paper two-phase inverters considered. The stator coils of the motor can be connected in single-phase or poly-phase systems. These connections imply the single-phase or poly-phase inverters which supply the winding. The type of winding influences the performance of the motor. The Particular motor that is analysed was described in [14]. So far only single-phase and three-phase motors were considered and no study for two-phase has been done [15].

The main idea in the early stage of the PMSMs was to increase the efficiency of the traditional electric motors by permanent magnet excitation. However, the efficiency increase was not enough for the customers and the

Attempts to enter the market failed [16]-[17]. Despite of this setback, several manufacturers introduced permanent magnet machines successfully during the latest decade. Regardless of the success of radial-flux permanent-magnet machines, axial-flux permanent magnet machines, where the magnetic flux is directed axially in the air-gap and in the stator winding zone and it turns its direction in the stator and rotor core, have also been under research interest particularly due to special application limited geometrical considerations [18]-[19]. A possibility to obtain a very neat axial length for the machine makes axial-flux machines very attractive into applications in which the axial length of the machine is a limiting design parameter. Such applications are, for example electrical vehicles wheel motors and elevator motors. Axial flux machines have usually been used in integrated high-torque applications [20]-[21]-[22]. AFPM motors can be designed as double sided or single sided machines, with or without armature slots, with internal or external rotors and with surface mounted or interior type permanent magnets (PMs) [23]-[24]- [25]- [26]. Comparative study on the performances of slotted and slot-less versions of permanent magnet motors was done in [27]. There, it was observed that for the same amount of torque to be produced, slot-less motors need higher mmf compared to slotted motors. Owing to the supply of such high currents, these motors get heated up very fast and need special heat sinks for dissipating the heat. This is the main advantage of using slotted motors instead of slot-less motors. In this paper the calculations were done for the particular motor which was designed as a water pump with the wet rotor.

Axial Flux Permanent Magnet Motor Structure

Applying Several axial-flux machine configurations can be found regarding the stator(s) position with respect to the rotor(s) positions and the winding arrangements giving freedoms to select the most suitable machine structure into the considered application. The object of study in this paper is double-sided AFPM brushless machine with internal salient-pole stator and two external rotors shown in Figure. 1. It is more compact than the motor with internal rotor. The double-sided rotor with PMs is located at the two sides of the stator. The stator consists of the electromagnetic elements made of ferromagnetic cores and coils wound on

them. These elements are placed axially and uniformly distributed on the stator circumference and glued together by means of synthetic resin. The stator coils can be connected in single-phase and multi-phase systems. The motor of particular winding connection exhibits its unique performance that differs it from the motors of the other connection systems.



Fig.1. Double-sided AFPM motor with two external rotors

In this paper motor with two-phase is studied and are analyzed. On both sides of the stator are the rotors made of steel discs with the permanent magnets glued to the disc surfaces. The distribution of the magnets on the rotor discs has to be adequate to the stator poles polarity. The stator winding in this case is connected as shown in Figure.2. Here the coils of phases A and B are alternatively connected.

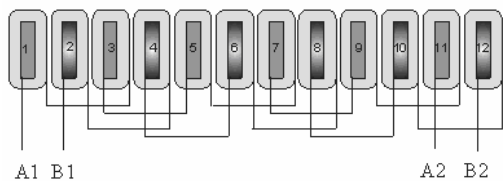


Fig. 2. Windings of the stator is connected in two - phase

Mathematical Model of the Supply-Inverter Motor System

The supply-inverter-motor circuit model is shown in Figure.3.

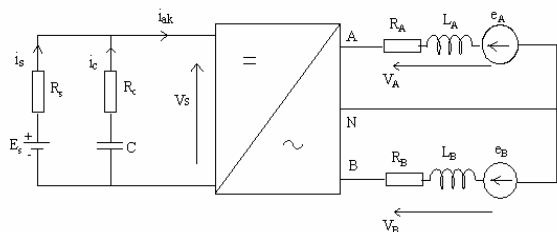


Fig. 3. Circuit diagram of supply-inverter-motor system

The circuit parameters are set up under the following assumptions:

- All elements of the motor are linear and no core losses are considered,
- Electromotive force e_a and cogging torque vary sinusoidally with the rotational electric angle θ_e .
- Due to the surface mounted permanent magnets winding inductance is constant (does not change with the θ_e angle).
- Voltage drops across diodes and transistors and connecting wire inductance are ignored.

The equations that describe the model are as follows:

Voltage equation at the source side

- (1) $E_b - i_s \cdot R_b - i_c \cdot R_c = 0$
- (2) $V_s = V_c + i_c \cdot R_c$
- (3) $i_s = i_{sk} + i_c$
- (4) $V_c = \frac{Q_c}{C}$
- (5) $i_c = \frac{dQ_c}{dt}$

Voltage equations at the motor side (Figure 4) are:

- (6) $V_A = V_{SA}$
- (7) $V_B = V_{SB}$

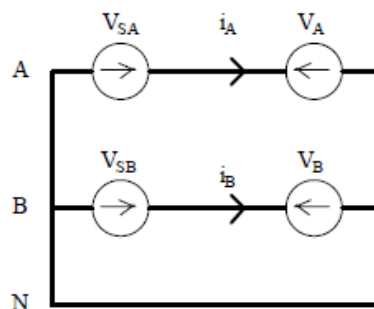


Fig.4. Scheme to the equations 6,7

The equation of the voltages across the motor winding

$$(8) \begin{bmatrix} V_A \\ V_B \end{bmatrix} = \begin{bmatrix} R_A & 0 \\ 0 & R_b \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_A & L_{AB} \\ L_{BA} & L_B \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \end{bmatrix}$$

or in shortened version:

$$(9) V_a = R_a \cdot I_a + \frac{d}{dt} l_a \cdot I_a + E_a$$

Since the resistances R_a of all phases are the same:

$$(10) R_a = \begin{bmatrix} R_a & 0 \\ 0 & R_a \end{bmatrix}$$

Here there is no mutual inductance between the phases A and B, they are displaced by 90° . So, $L_{AB}, L_{BA} = 0$. Due to the symmetrical winding the inductances $L_A = L_B = L$ The inductance matrix takes the form:

$$(11) L_a = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}$$

$$(12) i_a + i_b = 0$$

Thus the voltage equation takes the form:

$$(13) \begin{bmatrix} V_A \\ V_B \end{bmatrix} = \begin{bmatrix} R_A & 0 \\ 0 & R_B \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \end{bmatrix}$$

The electromotive force induced in the phase A winding:

$$(14) e_a = K_E \omega_m \sin(\theta_e)$$

The electromotive force induced in the phase B winding is given by:

$$(15) e_b = K_E \omega_m \sin(\theta_e - 90^\circ)$$

$$(16) \omega_m = \frac{1}{P} \frac{d\theta_e}{dt}$$

The electromotive forces written in a form of matrix E_a :

$$(17) \quad E_a = \frac{K_E}{P} \begin{bmatrix} \sin\theta_e \\ \sin(\theta_e - \frac{\pi}{2}) \end{bmatrix} \frac{d\theta_e}{dt}$$

Equation that links the supply and motor sides:

$$(18) \quad i_{SK} = \frac{I}{V_S} (i_A V_{SA} + i_B V_{SB})$$

results from the equality of the powers at input and output of the inverter. Supply voltages for the phases (v_{SA} , v_{SB}) results from the operation of converter. The mechanical system with all torques is shown schematically in Figure. 5. This system is defined by the following equation 19.

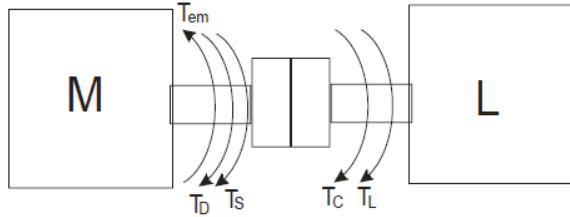


Fig. 5. Mechanical system with torques

$$(19) \quad T_{em} = TJ + TD + Ts + Tc + TL$$

The torque components of equation 19 are expressed by the following equations. Inertia torque:

$$(20) \quad T_J = J \frac{d\omega_m}{dt}$$

Viscous friction torque:

$$(21) \quad T_D = D \cdot \omega_r$$

Coulomb friction torque:

$$(22) \quad T_S = \text{sign}(\omega_r) T_d$$

Cogging torque:

$$(23) \quad T_C = T_{mc} \sin(\varphi_c + \beta)$$

Load torque: T_L

The electromagnetic torque is given by following equation 24 and 25

$$(24) \quad T_{em} = \frac{e_{AiA}}{\omega_\gamma} + \frac{e_{BiB}}{\omega_\gamma}$$

$$(25) \quad T_{em} = \frac{e_{AiA}}{\omega_R} + \frac{e_{BiB}}{\omega_R} = K_e (f_a(\theta_e) \cdot i_A + f_b(\theta_e) \cdot i_B)$$

where:

$$(26) \quad f_a(\theta_e) = \sin(\theta_e)$$

$$(27) \quad f_b(\theta_e) = \sin(\theta_e - \frac{\pi}{2})$$

Combining all the above equations, the system in steady-space form is:

$$(28) \quad \dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$$

$$(29) \quad \mathbf{x} = \begin{bmatrix} i_A \\ i_B \\ \omega_\gamma \\ \theta_e \end{bmatrix}$$

$$(30) \quad \mathbf{A} = \begin{bmatrix} \frac{-R_s}{L} & 0 & -\frac{K_e(f_a(\theta_e))}{L} & 0 \\ 0 & \frac{-R}{L} & -\frac{K_e(f_b(\theta_e))}{L} & 0 \\ \frac{K_e(f_a(\theta_e))}{J} & \frac{K_e(f_b(\theta_e))}{J} & -\frac{D}{J} & 0 \\ 0 & 0 & \frac{P}{2} & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & \frac{-1}{J} \\ 0 & 0 & 0 \end{bmatrix} \quad \mathbf{u} = [V_A \quad V_B \quad T_L]^T$$

Equation of the motor efficiency is

$$(31) \quad \text{Eff}\% = \frac{P_{out}}{P_{in}} \cdot 100\%$$

The average input power:

$$(32) \quad P_{in} = \frac{1}{T} \int_0^T (V_s \cdot i_{ak}) dt$$

The average output power:

$$(33) \quad P_{out} = \frac{1}{T} \int_0^T (T_L \cdot \omega) dt$$

Dynamic Simulation of the Motor

The simulation of the motor operation in dynamic conditions was done using software package MATLAB/SIMULINK®. To simulate this operation, it was assumed that: the drive system is supplied with constant voltage of 300 V, the system is loaded with the rated torque of 6.1 N.m.. The simulation results of starting of the motor are shown in Figs 6, 7, 8, 9 and 10. In particular the Figure.6 shows the rotary speed waveform. The ripple in the speed waveform is due to the oscillation of motor torque. It consists of two components: electromagnetic torque T_{em} and cogging torque T_c . These two components are shown in Figure 10, which were drawn when the motor reached steady state. The electromagnetic torque waveform obtained during the starting process is shown in Figure 9. The results presented in Figure.10 show that the torque developed by the motor is always positive despite the relatively big cogging components. This positive resultant torque is obtained due to displacement of PMs on one of the rotor discs.

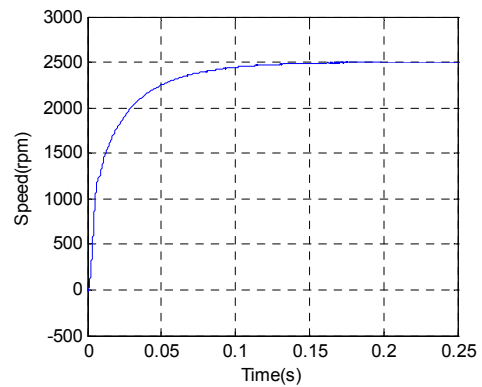


Fig. 6. Waveform of rotary speed

Table1. specifications adopted for the simulated motor

Components	Quantity	Rating values
E_b	emf of the battery	300 V
R_s	source Resistance	1.5 Ω
R_c	resistance in series with capacitor	2 Ω
C	capacitance	10 μ F
R_a	phase resistance of the brushless DC motor	8 Ω
J	moment of inertia	0.001 Kg /m ²

L_c	phase inductance of the brushless DC motor	0.021H
D	friction coefficient	0.001 N/(rad/s)
T_{load}	load torque	2.2 N.m
T_{mc}	maximum cogging torque	0.3 N.m
T_s	coulomb friction torque	0.1 N.m

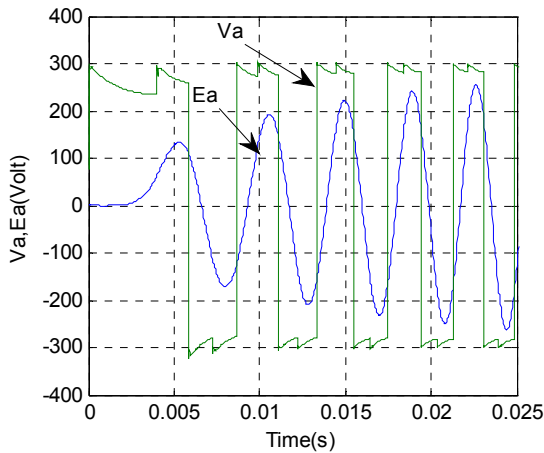


Fig .7. Waveform of EMF (E_a) and armature voltage (V_a)

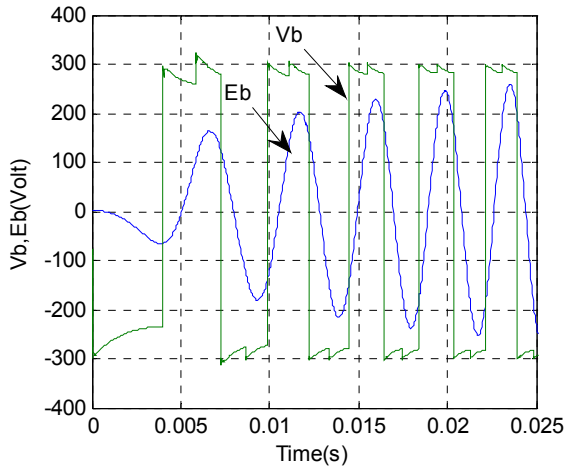


Figure .8. Waveform of EMF (E_b) and armature voltage (V_b)

The waveform of EMF (E_a) and armature voltage (V_a) of phase A and the waveform of EMF (E_b) and the armature voltage (V_b) of phase B are shown in Figs 7. and 8. The induced EMF's and voltage applied to the motor are in phase because the winding was switched ON without any delay with respect to the position of magnets and winding.

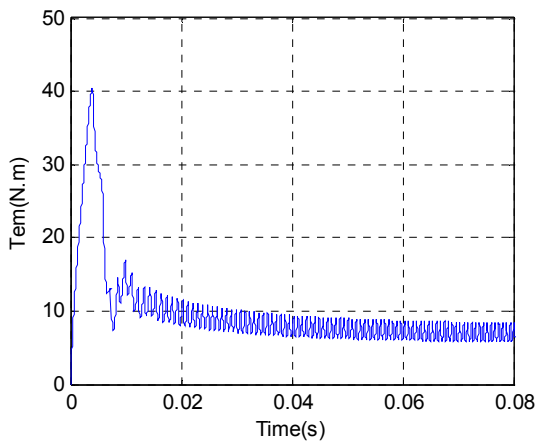


Fig .9. Waveform of electromagnetic torque (T_{em})

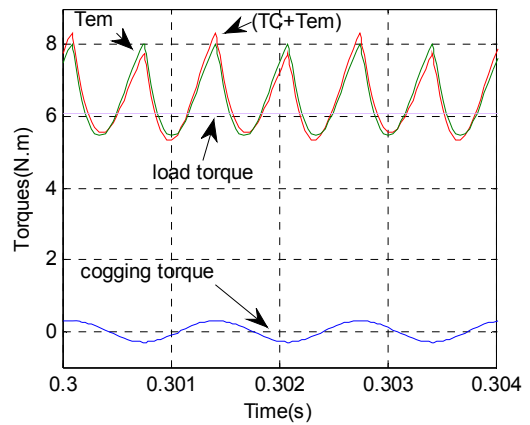


Figure .10. Waveforms of electromagnetic torque, cogging torque and resultant torque

Influence of Switching Angle on Motor

Due to the high-speed operation, the winding inductance causes a significant phase delay in the current waveform. The results in the current and the emf waveforms being out of phase, and a negative torque component is generated, with a consequent reduction of the overall torque. In order to get motor better performance Phase commutation advanced is often employed. In DC brush motor the commutation angle is determined by the position of brushes and is kept constant. In BLDC motors the switching angle may vary accordingly to the controller of the inverter that is used. The inverter considered for the brushless motor with two-phase winding is shown in (Fig.11). The position sensors are placed between the coils in the intervals of 90 degree .These sensors sense the position of the rotor and they trigger the transistors so that they switch on the respective stator winding.

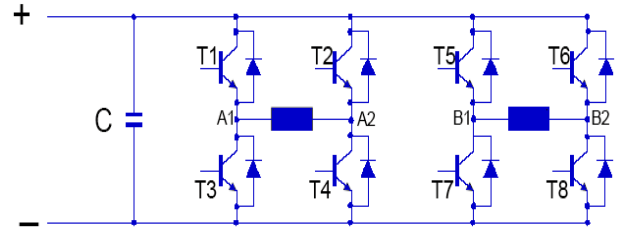


Fig. 11. Inverter considered for BLDC with Two-Phase Winding

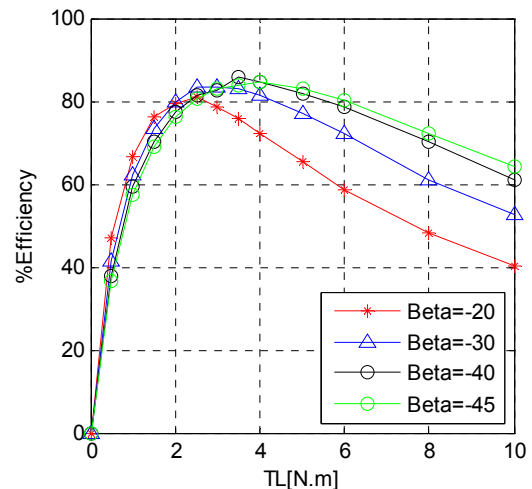


Fig. 12. Efficiency (Eff) vs. load torque(TL)

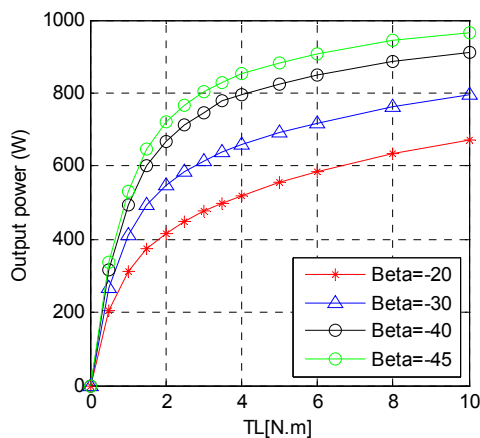


Fig. 13. Mechanical power output (Pem) vs. load torque (TL)

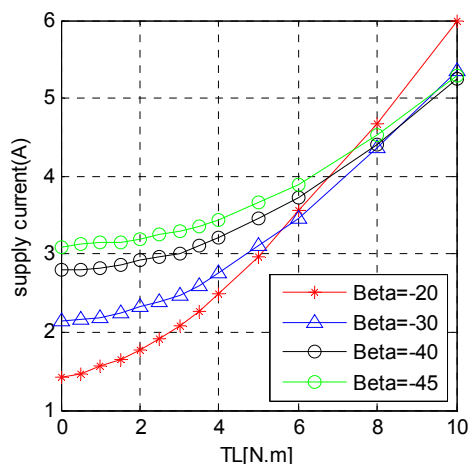


Fig. 14. Input current (Is) vs. load torque(TL)

As the switching angle is advanced, the difference between back-emf and the supply voltage increases, and the torque thereby increases. However, there exists an optimal advanced angle, beyond which the drive performance deteriorates. The simulation was done for the following switching angles $\beta = -20^\circ, -30^\circ, -40^\circ, -45^\circ$. The results of simulation were plotted in the form of characteristics of average values of the efficiency, input current and mechanical power output shown in Figs 12, 13 and 14. The characteristics were drawn in the MATLAB from the results obtained in simulation using dynamic model of the motor. The efficiency was calculated as same as section. III. The motor efficiency is maximum when the switching angle $\beta = -40^\circ$, which means transistors are switched much earlier and the motor efficiency is minimum when $\beta = -20^\circ$.

Comparison of Simulation Results with the experimental Results

To verify the mathematical dynamic model of the brushless DC motor drive the measurements were carried out on the set up shown in Fig. 15. During the test, the waveforms of currents and EMFs were observed. The current waveform of phase A measured by means of oscilloscope is shown in Fig. 16. The currents waveforms obtained from the simulation of the motor model and the experimental results are similar.

To measure the EMF induced in the winding the motor was driven with speed by a DC motor. The measured waveform of EMF is shown in Fig.17. It can be observed that the EMF has a sinusoidal shape. Such a sinusoidal shape has been used in the simulation of the motor.



Fig. 15. brushless DC motor in wheel rim on the test

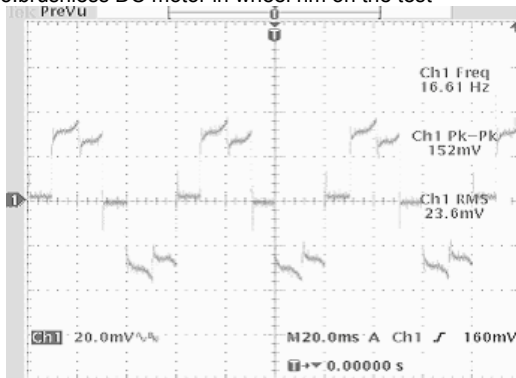


Fig. 16. Waveform of armature current obtained from experimental results

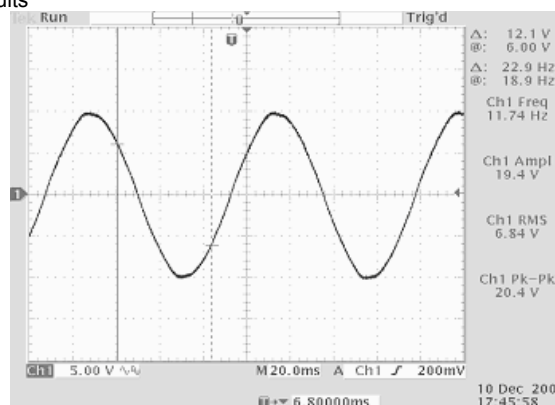


Fig. 17. Waveform of induced EMF (Ea) obtained from experimental results

Conclusion

The performance of the AFPM BLDC motor with two-phase winding was analyzed in this paper. To study the motor operation, a mathematical dynamic model has been proposed. This model became the basis for block diagram and simulations, which was performed using MATLAB/SIMULINK software package. The results obtained from dynamic model and test enabled to deduct the following conclusions:

- The waveforms of obtained from computer simulation and test does not differ much what proves that the mathematical model sufficiently accurate describe the motor in dynamic conditions.
- The two-phase motor develops the torque with low ripple
- The results of simulation at rated torque show the AFPM motor with two-phase winding has high efficiency
- In two-phase motor two sensors and 8 transistors are necessary which makes the circuit complex.

A study done on the influence of switching angle on motor

performance shows that motors operate better when the windings are switched ON earlier with respect to the emfs induced in them. It means the inverters should operate at the advanced switching angle if voltage inverters are applied.

Acknowledgements

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