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Modelling of BLDC motor with different fashions of winding connection

***Abstract**. In the paper a BLDC motor unit, including stator winding and electronic commutation circuit, is studied. Two types of three-phase stator winding, i.e. connected in star fashion and delta fashion, are considered in the studies. Mathematical models of the respective structures are formulated and the results of computer simulation are presented and discussed.*

***Streszczenie.** W pracy przedstawiono analizę zespołu silnika BLDC, zawierający uzwojenie stojana i komutator elektroniczny. Rozważono dwa typy trójfazowego uzwojenia stojana, to jest uzwojenie połączone w gwiazdę i w trójkąt. Sformułowano modele matematyczne właściwych struktur oraz zaprezentowano wyniki symulacji komputerowej wraz z dyskusją. (**Modelowanie silnika BLDC o różnych sposobach połączenia uzwojeń**).*

Keywords: BLDC motor, converter and inverter, mathematical modelling, control strategies.
Słowa kluczowe: silnik BLDC, przekształtnik, modelowanie matematyczne, strategie sterowania.

Introduction

Most brushless direct current (BLDC) motors include three-phase stator winding connected in star fashion. Each phase winding is constructed with numerous interconnected coils placed in the slots of stator. There are two types of motors: trapezoidal and sinusoidal [1,3,4]. The difference comes from both the interconnection of coils in stator phase windings and the option of magnets magnetization or the shape of rotor magnet pole shoes giving the different types of back electromotive force (EMF), in trapezoidal or sinusoidal fashion, respectively. The back EMFs and phase currents of sinusoidal motor are sinusoidal, thus the output torque is smooth in contrast to the deformed back EMF and phase currents as well as the rippled torque of trapezoidal motor, causing the additional vibrations and noise.

The stator phase windings should be energized in a proper sequence in order to rotate the BLDC motor. The rotor position angle is required to determine two phase windings, which have to be energized according to the abovementioned sequence. Three Hall effect sensors (HES), embedded into the stator on the non-driving end of the motor, are widely used to determine the rotor position angle of BLDC motor (HES control) [1-6]. In addition to the HES control, the pulse width modulation (PWM) is widely used in order to limit the starting current as well as to control speed and torque of BLDC motor.

In the paper a BLDC motor unit, including stator winding and electronic commutation circuit, is studied. Two types of three-phase stator winding, i.e. connected in star fashion and delta fashion, are considered in the studies. Mathematical models of the respective structures are formulated and the results of computer simulation are presented and discussed.

Mathematical models of BLDC motor unit, including stator winding and electronic commutation circuit

The power electronic switches, consisting of transistors and diodes, are used in order to commutate the current in phase windings of BLDC motor. These switches are usually connected in a three-phase bridge for a three-phase BLDC motor shown in Fig. 1.

The equivalent circuits of BLDC motor unit, including stator winding connected in star fashion and electronic commutation circuit, were proposed in [1,2]. In the case of stator winding connected in delta fashion the following equivalent circuit may be taken into account (Fig. 2). As before, the power electronic switches, included in the real commutation circuit, are replaced by the electric switches shunted with the resistance R_{off} of turn-off transistor.

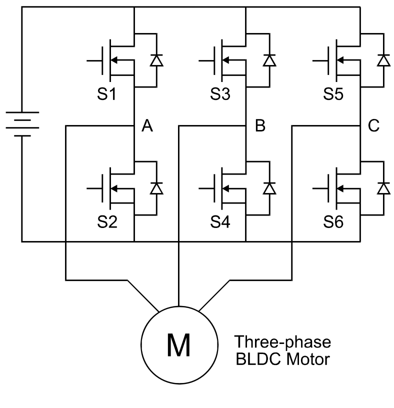


Fig. 1. Three-phase BLDC motor energized by three-phase inverter bridge

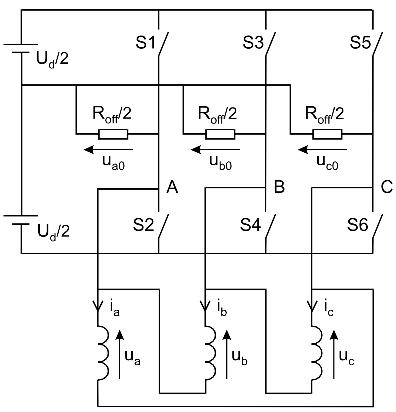


Fig. 2. Equivalent circuit of BLDC motor unit including three-phase stator winding connected in delta fashion and electronic commutation circuit

The PWM-based control strategy [1,2] for the stator winding connected in delta fashion in the first sequence period: (a) S1 = S4 = on, S2 = S3 = S5 = S6 = off (HES code: 100) may be described by the following dependencies:

$$\begin{gathered}\text{if}(K=1)\, u_d = U_d;\ \text{else}\ u_d = 0;\\ \text{if}(0° < \theta_e \le 60°)\{u_{c0} = \tfrac{1}{2} R_{off}(i_c - i_a);\\ \text{if}(u_{c0} > \tfrac{1}{2}u_d)\, u_{c0} = \tfrac{1}{2}u_d;\ \text{if}(u_{c0} < -\tfrac{1}{2}u_d)\, u_{c0} = -\tfrac{1}{2}u_d;\\ u_a = \tfrac{1}{2}u_d + u_{c0};\ u_b = -u_d;\ u_c = \tfrac{1}{2}u_d - u_{c0};\}\end{gathered} \tag{1}$$

where $\theta_e = N_p\theta_m$, $\theta_e \in [0°; 360°)$, N_p is number of pole pairs, θ_m is angle of rotor rotation, K is PWM output [1].
For the next sequence periods:
(b) S1 = S6 = on, S2 = S3 = S4 = S5 = off (HES code: 110)
(c) S3 = S6 = on, S1 = S2 = S4 = S5 = off; (HES code: 010)
(d) S3 = S2 = on, S1 = S4 = S5 = S6 = off; (HES code: 011)
(e) S5 = S2 = on, S1 = S3 = S4 = S6 = off; (HES code: 001)
(f) S5 = S4 = on, S1 = S2 = S3 = S6 = off; (HES code: 101)
the dependencies are analogical.

In the case of control strategy based on PWM and low-pass filter LC [1,2] one modification is taken into account:

(2) $$u_d = u_{ref} U_d / U_n$$

Mathematical model of BLDC motor was presented in [1]. Equations of armature winding voltages:

(3) $$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

(4) $$i_k = (L-M)^{-1}\left(\psi_k - M(L+2M)^{-1}\sum_j \psi_j\right), \quad k, j = a,b,c$$

$L = L_\sigma + L_\mu$, $M = -L_\mu/3$, L_μ is inductance of main magnetic circuit (magnetization inductance), L_σ is leakage inductance. The phase voltages of BLDC motor with stator winding connected in delta fashion are trapezoidal with narrow trapezoid base (60 electrical degrees). Thus, for proper operation of the motor the back EMF should also be trapezoidal with narrow trapezoid base or sinusoidal:

(5) $$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = N_p \Psi_P \omega_m \begin{bmatrix} \sin(\theta_e) \\ \sin(\theta_e - 120°) \\ \sin(\theta_e - 240°) \end{bmatrix}$$

where Ψ_P is flux linkage excited by permanent magnets, ω_m is angular velocity of rotor. Output (electromagnetic) torque:

(6) $$\tau_e = \omega_m^{-1}(e_a i_a + e_b i_b + e_c i_c)$$

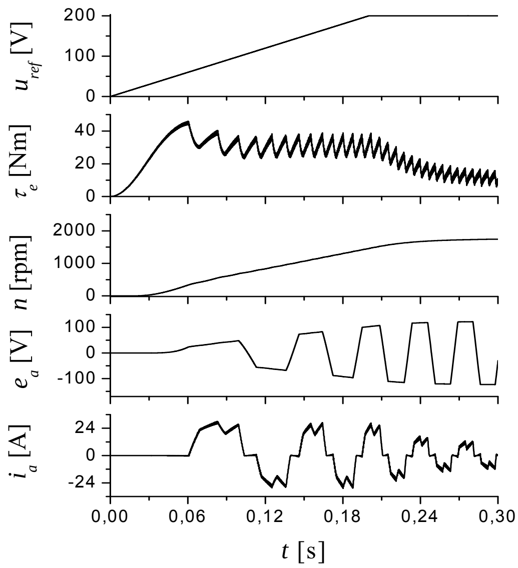
Taking into account Eq. 5:

(7) $$\tau_e = N_p \Psi_P (i_a \sin(\theta_e) + i_b \sin(\theta_e - 120°) + i_c \sin(\theta_e - 240°))$$

Results of computer simulation

In the model-simulation investigations the following rated parameters of BLDC motor were taken into account: 4 kW, 230 V, 3000 rpm, 20 A, 0.025 kgm^2, R_s = 0.5 Ohm, L_μ = 7.4 mH, L_σ = 1.6 mH, $N_p\omega_m\Psi_P$ = 212 V. The carrier frequency of 2 kHz for PWM was adopted.

The selected results of computer simulation are shown in the paper:
1. Results of computer simulation of BLDC motor energized by PWM-controlled converter system are shown in Figs. 3 and 4.
2. Results of computer simulation of BLDC motor energized by PWM-controlled converter system with low-pass filter LC are shown in Figs. 5 and 6.



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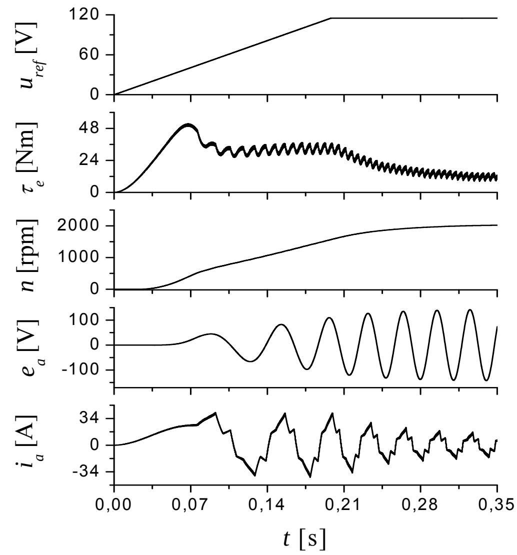
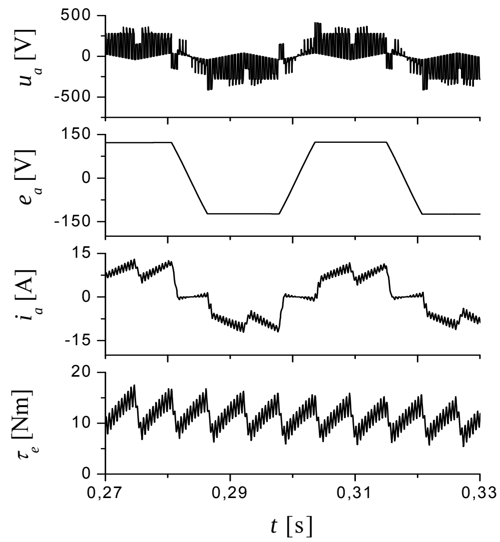


b)

Fig. 3. Reference voltage, output torque, rotational speed, back EMF and phase current during starting the motor: a) stator winding connected in star fashion, b) stator winding connected in delta fashion



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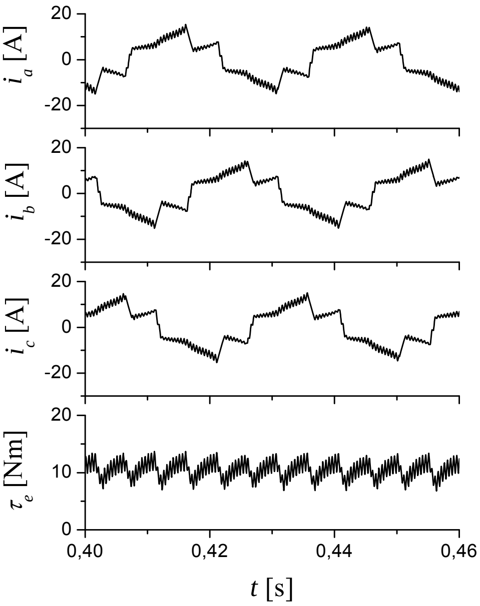

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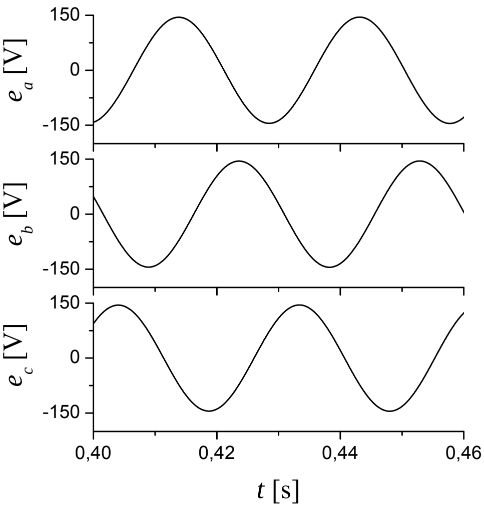
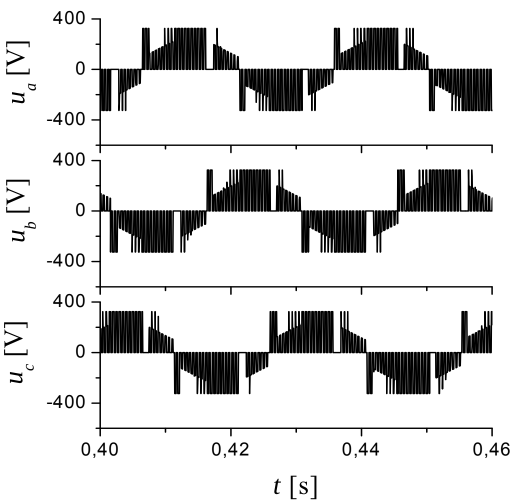
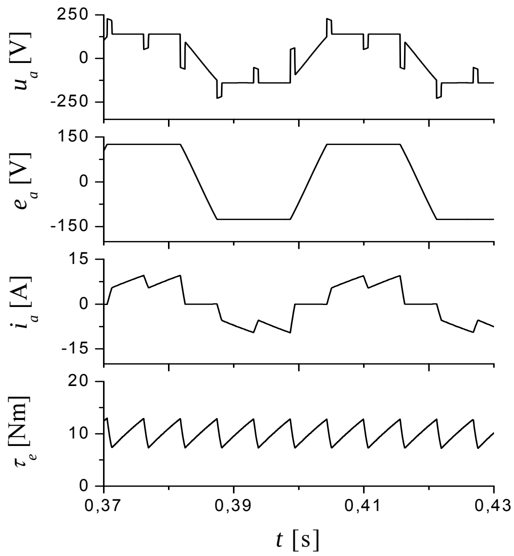


c)



d)

Fig. 4. Phase voltage, back EMF, phase current and output torque of BLDC motor under load condition: a) stator winding connected in star fashion, b), c), d) stator winding connected in delta fashion



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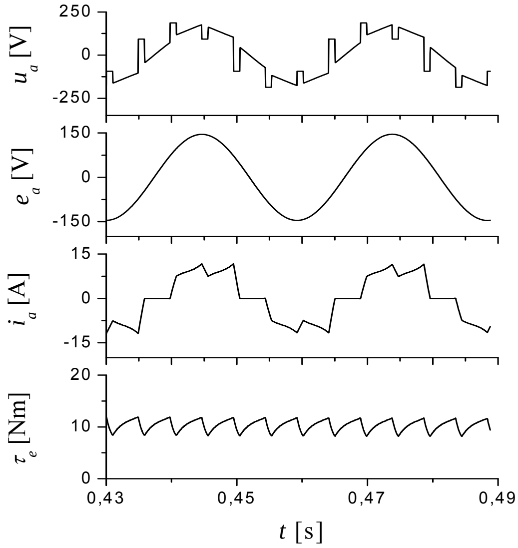

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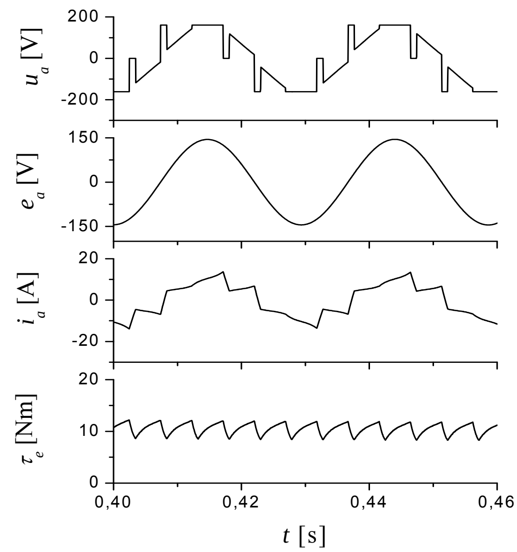


c)

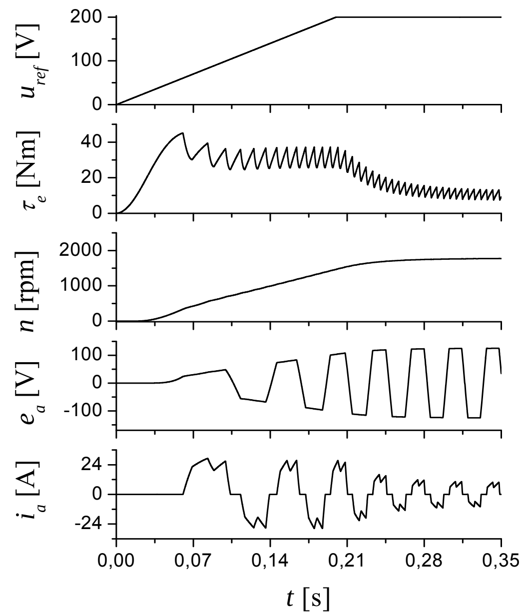
Fig. 5. Phase voltage, back EMF, phase current and output torque of BLDC motor under load condition: a), b) stator winding connected in star fashion, c) stator winding connected in delta fashion

Discussion of the results

Static and dynamic properties of BLDC motor with stator winding connected in star fashion are better than those of BLDC motor with stator winding connected in delta fashion (compare Figs. 5b and 5c as well as Figs. 6b and 6c).

The application of BLDC motor with sinusoidal EMF results in reduction of torque ripple (compare Figs. 3a and 3b as well as Figs. 5a and 5b or 5c), but increases the magnitude of phase currents (compare Figs. 4a and 4b as well as 5a and 5b or 5c). Moreover, it means an additional costs for production of sinusoidal BLDC motor.

Rising the stator winding resistance increases a margin of stability (these results are not shown in the paper). The stator winding resistance can be increased in natural way as a consequence of use of connection cables and internal resistance of applied converter system.



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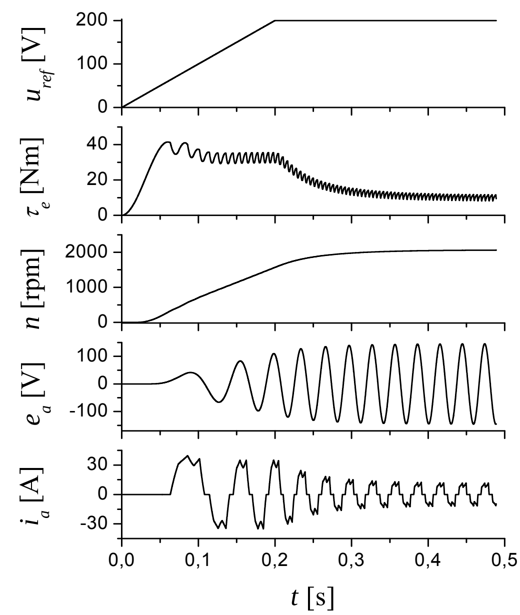

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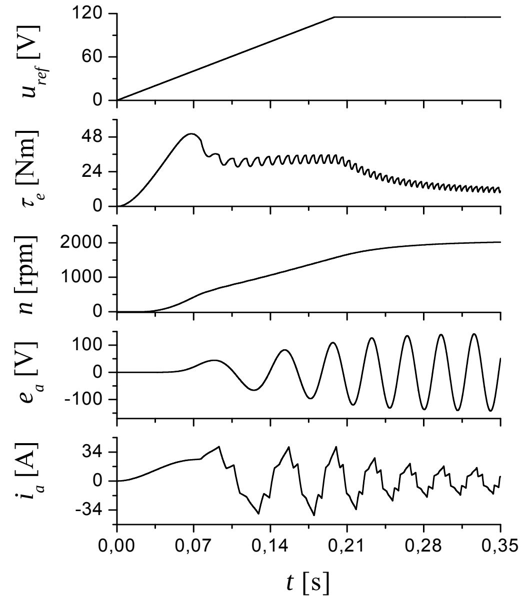

c)

Fig. 6. Reference voltage, output torque, rotational speed, back EMF and phase current during starting the motor: a), b) stator winding connected in star fashion, c) stator winding connected in delta fashion

Conclusions

The presented mathematical models and results of computer simulation of BLDC motor with different fashions of stator winding connection give a good base for design activity dealing with BLDC motor control systems. These models and results may be used to verify various control strategies. Computer simulation based on the presented mathematical models of BLDC motor unit, including stator winding and electronic commutation circuit, can effectively shorten analysis and development cycle of control systems based on BLDC motor as well as evaluate rationality of control algorithm.

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