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Maximum Torque per Ampere Control of Novel Transverse Flux Permanent Magnet Motor with Brushless DC Drive

***Abstract**. A novel transverse-flux permanent magnet motor (TFPMM) with relatively simpler structure and BLDC drive is well suited for direct-drive electric vehicle. The commutation process in 120°-elec.-conduction is analyzed. To obtain maximum torque per ampere in open-loop application, a cost-effective approach based on phase advance commutation is proposed. Under varying load torque conditions, the required phase advance angle is automatically determined by both DC bus current and rotor speed. Both simulations and experiments are presented to verify its validity.*

***Streszczenie.** Zaprezentowano nową odmianę silnika bezszczotkowego DC z poprzecznym strumieniem wytwarzanym przez magnesy trwałe w zastosowaniu do pojazdów elektrycznych. Do otrzymania maksymalnego momentu opracowano optymalny system komutacji. Przy zmieniającym się obciążeniu wymagana faza wyprzedzenia kątowego jest określana automatycznie na podstawie prądu szyny i prędkości wirowania. (**Projektowanie silnika bezszczotkowego DC z poprzecznym strumieniem dla uzyskania maksymalnego momentu napędowego**)*

Keywords: Transverse flux permanent magnet motor, brushless DC drive, maximum torque per ampere, phase advance commutation.
Słowa kluczowe: silnik bezszczotkowy, pojazdy elektryczne.

Introduction

In recent years, electric vehicle has been the focus of our concern, in consideration of both energy crisis and environmental protection. With relatively high torque density and good performance at low speeds, transverse flux permanent magnet motor (TFPMM) has been expected to be a preferred embodiment for electric vehicle applications [1-3]. The well known double-sided topologies, where the rotor is sandwiched between an inner stator and an outer one, are given an increasing attention in electric and hybrid propulsion systems of ships and heavy-duty vehicle such as buses and trucks [1, 4]. The single-sided topologies, with just one air gap and an inverted structure with the rotor in the outside, are suitable for direct wheel drive applications [2, 3]. And a claw pole TFPMM is presented to highlight the simplicity of the single-sided topologies and the high performances of the double-sided ones [5]. Nevertheless, complicated structure and strict manufacturing technology still hamper the miniaturization of TFPMM. By contrast, a novel TFPMM presented in [6] has relatively simpler structure, which makes it more possible to apply TFPMM to direct-drive electric vehicles with small or medium-sized power, such as cars and golf carts. In doing so, less costs, less weight and the free layout of the drive components can be obtained without both gears and axle.

On the other hand, most topologies are designed to operate as permanent magnet synchronous motor (PMSM), and low power factor, in the range of 0.35-0.55, is the common problem [7]. Although brushless DC (BLDC) drive has been adopted in some topologies of TFPMM [8, 9], the advantages of using standard converters are not utilized. For novel TFPMM, of particular interest is the three-phase design, and BLDC drive with 120° elec. conduction is employed to cut down the cost of control system. However, the essential difference causes the control of novel TFPMM different with conventional brushless DC motor (BLDCM).

In this paper, phase advance commutation is employed in novel TFPMM to achieve maximum torque per ampere (MTPA). And a cost-effective approach for obtaining MTPA under varying load torque conditions, where the required phase advance angle is automatically determined by both DC bus current and rotor speed. Its effectiveness is validated by both simulations and experiments.

The structure of novel TFPMM

The three-phase prototype has 8 pole-pairs. Axially-magnetized permanent magnets are evenly distributed along the circumference and alignedly fixed to the rotor by aluminum-made annular holder, between the stator U-shaped stator cores. The air gaps are also in axial direction, and 3-phase stator yokes are shifted by 15° mechanical angle (corresponding to 120° elec.) from each other. As shown in Fig.1, novel TFPMM has some highlighted characteristics such as shorter axial dimension, relatively simpler and more robust structure. In addition, outer rotator with flat appearance is adopted to match wheel hub, as shown in Fig.2. As can be seen, novel TFPMM is designed for direct-drive electric vehicles.

Since the permeability of permanent magnets is close to that of the air, d- axes and q-axes have almost the same magnetic path. And Novel TFPMM can be analysed as non-salient machine.

In fact, there are two drive modes for the novel TFPMM, that is to say, PMSM drive and BLDC drive. In order to cut down the cost of control system, only open-loop BLDC drive with 120° elec. conduction is discussed in this paper.

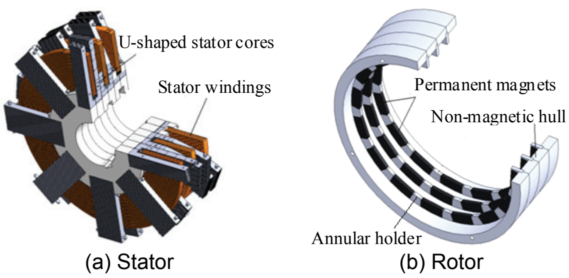


Fig.1. Structure of novel three-phase TFPMM

Fig.2. Photo of the prototype

MTPA control based on BLDC Drive

For conventional BLDCM, conventional commutation is generally adopted to achieve MTPA. Namely the commutation point is corresponding to 30° elec. behind no-load back EMF zero crossing, for small armature reaction can usually be ignored.

As a result of the existence of inductance, the current of the turn-off phase windings cannot decline to zero immediately. Supposing that the resistance voltage drop is ignored and the duty cycle of pulse width modulation (PWM) is kept unit. And back electromotive-force (EMF) is assumed to be constant during the commutation process, although this is clearly not the case. The commutation angle can be expressed as:

$$\theta_{\mathrm{f}} = \frac{3(L_{\mathrm{s}} - M)I_{\mathrm{m}}}{U_{\mathrm{dc}} + 2E_0} \tag{1}$$

where: L_s – phase self-inductance, M – mutual inductance, U_{dc} – DC link voltage, E_0 – no-load back-EMF, I_m – peak value of phase current.

Compared with conventional BLDCM, the influencing factors on commutation process of novel TFPMM are highlighted in the following.

The phase self-inductance of TFPMM can be given as:

$$L_{\mathrm{s}} = \psi_{\mathrm{a}} / I_{\mathrm{a}} = N^2 \Lambda_{\mathrm{m}} = \frac{\mu_0 N^2 p A_{\mathrm{m}}}{l_\delta} \tag{2}$$

where: ψ_a – phase flux linkage, I_a – phase current, N – number of turns of windings, Λ_m – phase permeance, μ_0 – the air permeability, p – the number of pole pairs, A_m – the effective area of air gap per pole, and l_δ – the effective length of air gap including the length of permanent magnet.

It is indicated that the phase self-inductance is in proportion to the number of pole pairs, leading to relatively larger inductance. Furthermore, there is no mutual inductance (namely M=0) for the magnetically decoupled phases.

Further, both low voltage and large current are determined by the limited space for batteries in electric vehicles with small or medium-sized power. TFPMM achieves the decoupling of the space requirement of the magnetic path and the space occupied by the armature windings. Thus, larger embedding space for armature windings makes it easy to meet the application requirements.

In particular, armature reaction of novel TFPMM is much stronger than that of conventional BLDCM for its relatively bigger phase flux linkage. Similar to dc brush motor, the forward distortion of back EMF waveform occurs in heavy load, which causes phase lag of the commutation point relative to load back EMF, as illustrated in Fig.3. It should be noted that this situation counts against phase-current commutation.

For aforementioned reasons, referring to equation (1), the commutation process gets much longer, which is disadvantageous to the performance of the motor [10]. The phase current lags behind back EMF with load torque increasing. The larger the current is, the bigger the lag angle will be, and then, the worse the performance will be. More specifically, soft torque-speed characteristic, poor efficiency and low torque per ampere will appear if the same commutation point as conventional BLDCM is employed in novel TFPMM.

Phase advance commutation [11] is a more practical solution to aforementioned problems in novel TFPMM. It can reduce current rise time as well as current fall time by making use of the edge of back EMF. But even more important, it is conducive to the axis of phase current in coincidence with that of back EMF. Only on this condition, the product of phase current and back EMF becomes biggest, that is to say, MTPA in 120° elec. conduction will be obtained and the corresponding phase advance angle is deemed to be optimal.

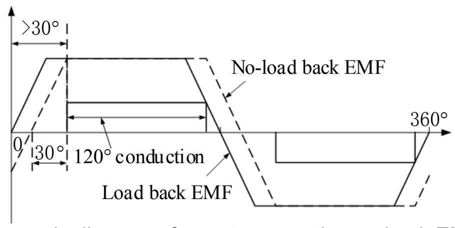


Fig.3. Schematic diagram of armature reaction on back EMF

However, the optimal phase advance angle relies on the accuracy of electrical parameters. And relatively strong armature reaction makes it much more difficult to calculate optimal phase advance angle by an analytic expression. For engineering application consideration, phase advance angle with minimum dc bus current is identified as the optimal one under the same load torque and rotate speed. Since only variable voltage control is analyzed in this paper, the relatively weak influence of rotate speed is ignored. The measured relation curve between optimal phase advance angle (namely α in this paper) and load torque (namely T_L in this paper) is shown in Fig.4, which provides data to software compensation in the implementation of phase advance commutation.

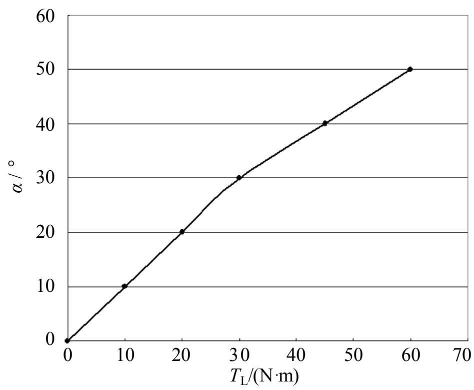


Fig.4. Measured relation curve between optimal phase advance angle and load torque

Generally, phase advance commutation is implemented by delay time control. And in this case, position signal is taken as a benchmark. In novel TFPMM, Hall position sensors are in coincidence with the axis of no-load back EMF. The common delay scheme of 30°-α will get invalid when phase advance angle is greater than 30° elec.. Therefore, the delay scheme of 90°-α is employed to solve this problem, which is illustrated in Fig.5.

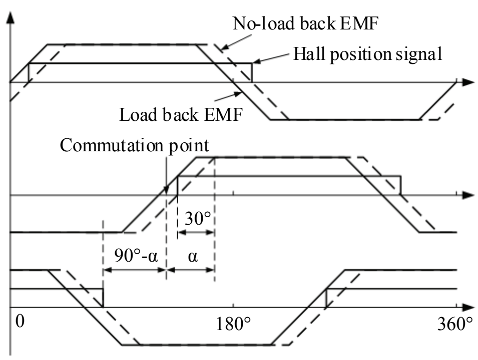


Fig.5. Schematic of the delay scheme of 90°-α

As an indirectly measured variable, torque estimation is complicated process [12]. However, it can be transformed into DC bus current by the conversion formula expressed as:

$$T_L = 9.55 U_{dc} \eta \times \frac{I_{dc}}{n} \quad (3)$$

where: η – efficiency, n –rotor speed.

Obviously, the relation between load torque and DC bus current is nonlinearity, which is influenced by rotate speed and efficiency. However, one or several fitted curves can be utilized in stead of load torque, in order to meet the engineering application requirements. As given in Fig.6, the fitted curves between load torque and the ratio of I_{dc}/n are measured at the corresponding optimal point, which provide date support to select phase advance angle through both DC bus current and rotate speed. And the method just needs one current transducer.

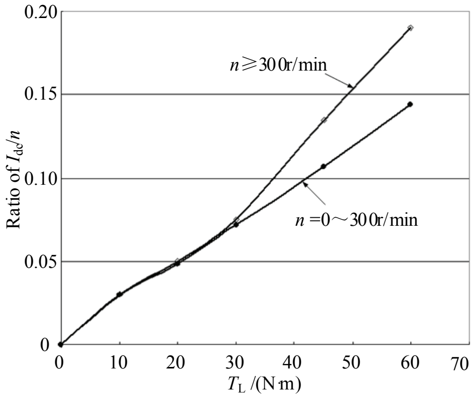


Fig.6. Measured curves between between load torque and ratio of I_{dc}/n.

Therefore, the open-loop BLDC drive system of novel TFPMM is presented in Fig.7, in which MTPA control can be obtained to meet the engineering application requirements. With the same hardware design as conventional BLDCM controller, the proposed system is simple, practicable and cost-effective.

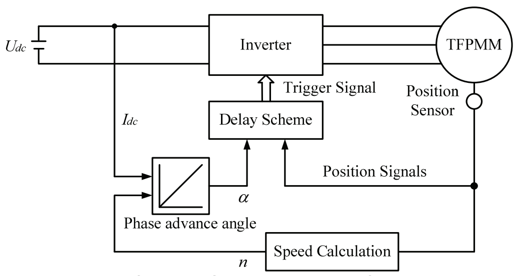


Fig.7. Block diagram for BLDC drive system of TFPMM

Simulations and experiments

The proposed approach for obtaining MTPA in open-loop BLDC drive system, as shown in Fig.7, has been validated by simulation in Matlab/Simulink and experiment on the prototype of novel TFPMM. The parameters of the prototype are listed in Table 1.

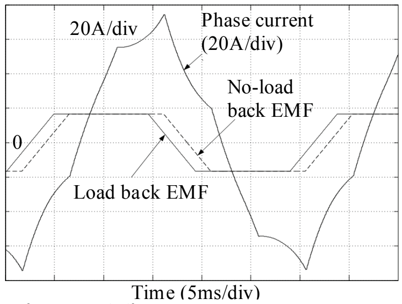
To predict the drive performance, the simulated model use trapezoidal back EMF and load back EMF is assumed to be still trapezoidal with a certain phase advancing no-load back EMF, as shown in Fig.3. Besides, the internal loss torque of the motor is also ignored.

The experimental facility is composed of a common open-loop BLDC controller with 120° elec. conduction and dSPACE-Release6.2 (DS1103 control board). The control algorithms for phase advance commutation are implemented in the dSPACE. The three Hall position signals and DC bus current are sampled by ADC ports, and then three output signals from DAC ports, namely processed position signals, are input into BLDC controller.

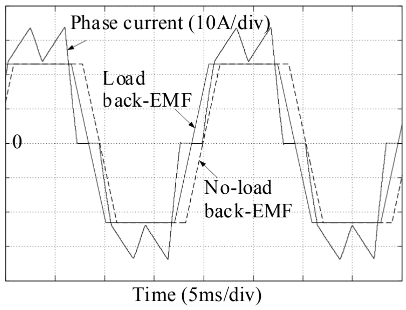
Fig.8 and 9 show the simulated and measured waveforms of phase current with the same load torque, respectively. As will be seen, compared with conventional commutation (α=0), the proposed method improves the phase-current waveform and gains much lower phase current.

Table 1. The parameters of the prototype

Number of poles, p	8
DC link voltage [V]	60
Rated Torque [N·m]	45
PM excitation flux linkage, ψ_f [Wb]	0.0764
Phase resistance [Ω]	0.04
Phase inductance [mH]	1.3
Outer diameter [mm]	314
Axial length [mm]	130

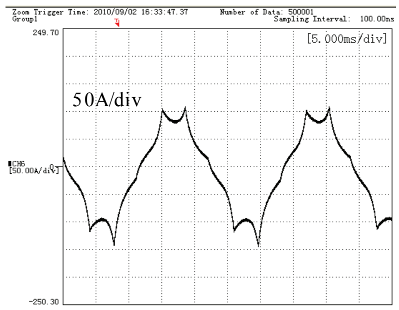


a) Conventional commutation

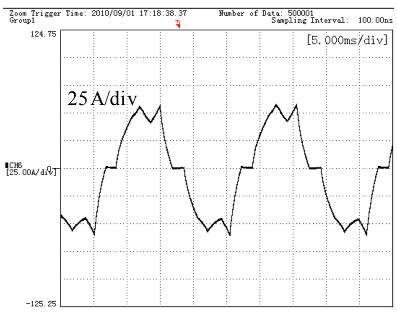


b) Proposed method

Fig.8. Simulated waveforms of phase current with T_L=35N·m

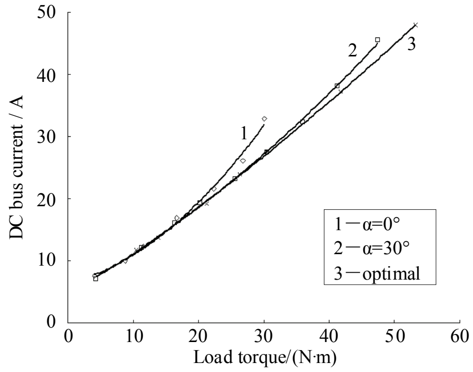


a) Conventional commutation

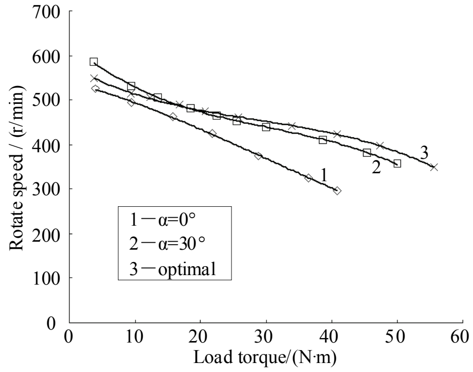


b) Proposed method

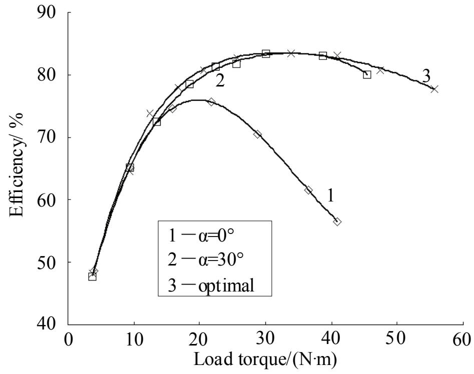
Fig.9. Measured waveforms of phase current with T_L=35N·m



a) DC bus current under the same speed (n=375r/min)



b) Torque-speed characteristic



c) Efficiency

Fig.10. Comparative results with different phase advance angles

Fig.10 compares conventional commutation (α=0), fixed phase advance angle (α=30°) and the proposed method, under varying load torque conditions. As will be seen, the performance of the prototype is effectively improved with optimal phase advance angle which is obtained by the proposed method, such as much larger torque per ampere, harder torque-speed characteristic and higher efficiency. In addition, it should be noted that the efficiency is corrected to the input ports of the motor.

Conclusions

The commutation process of novel TFPMM in 120°-elec.-conduction BLDC drive has been analyzed, and a cost-effective approach, which automatically selects optimal phase advance angles through both DC bus current and rotor speed, has been proposed to obtain MTPA in open-loop application. Effectively improved performance of the motor, including much larger torque per ampere, has been demonstrated by both simulations and experiments.

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