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Design of High Torque Density Slim Motor Application to Electric Bikes

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Abstract

The high torque density slim motor was designed to be utilized in an electric bike (e-bike). Regarding the software analysis, the design of the motor mechanism and the motor performance simulation is discussed, that enhance the reliability and stability within the propulsion system of the e-bike. In the hardware implementations, the control kernel of the motor drive is TMS320F2808 and there by generating PWM control signals for motor drives. By introducing the design process embedded in proposed 250W motor schemes, not only the high torque density can be achieved, but also the thickness of 1 inch is also guaranteed. In addition, the e-bike can be ridden on the road smoothly and successfully by the designated slim motor is installed.

Keywords: *High Torque Density, Slim motor, Electric Bike*

1. Introduction

Electric (or power assistance) bike is the most environmentally friendly and efficient transportation. Due to its no pollution, quiet, and saving lots of space, the environmental pollution and traffic congestion problems can be substantially improved. On the basis of time-efficient and effort-saving requirements, electric bike can meet the satisfaction in general public easily for go shopping or commuting a shot distance travel demand…etc. However, the purpose of electric bike is covered in different domain, some areas are considered as leisure products and some are commuting of transportations.

Generally, the commercial electric bike (e-bike) motors are heavy, low torque, prone to overheating, and restricted its climbing ability. Regarding to the features of the slim motor with high torque density and thin shape, it can develop a modular power wheel in e-bike which can improve the drawbacks of the heat dissipation problem.

The Permanent Magnet Synchronism Motor (PMSM) is classified into inner-rotor and outer-rotor two types based on the structure of the rotor. The slim motor is an inner rotor PMSM, can be mounted on the side of the tire without disassembling spoke. An ITRI-conceived e-bike is installed the proposed 250W slim motor, not only can the cost be reduced but also the assembling process can be simplified. By utilizing the control strategies and controller design, the maximum value of the torque of the 250W slim motor is 12N-m and its thickness is only 1 inch.

This paper organizes as follow. In Section Ⅱ, we describe the slim motor design processes that include geometric design, magnetic analysis, and Noise Vibration Harshness (NVH) measurement. In Section Ⅲ, we illustrate and discuss some experiment results . Finally, we draw the slime motor conclusion.

2. Design of the high torque slim motor of the ITRI-conceived foldable e-bike

The ITRI-conceived foldable e-bike with the designated 250W slim motor is shown in Fig. 1, Fig.2 and Fig. 3. In order to ride e-bike smoothly and powerfully, high torque and low torque ripple are two major targets in the motor design. Besides, the slim motor noise vibration harshness analysis is also considered. The following descriptions show that the design process and the motor control scheme analysis.

2.1. The Slim Motor Design

An ITRI-conceived e-bike is installed the proposed inner rotor slim motor, which is applied axial flux permanent magnet technology [4]. With the benefit of light, thin and high torque, the slim motor can be placed on any kinds of bikes. The purpose of slim motor is designed to achieve higher torque density, what can make the propulsion system more powerful. With axial flux permanent magnet technology, its magnet flux is larger than traditional motors. As a result, the slim motor can produce higher torque. The innovation of e-bike driving device is designed to mount the slim motor on the side of e-bike hub's disc brake. User can assemble e-bike quickly to simplify the assembling process and reduce the cost.

Considering the motor parameters such as magnet shape, slot opening width, tooth structure and yoke size, the 3-phase, 18-slot and 12-pole slim motor are chosen firstly. For the motor windings design, the concentrated winding is proposed since it is suitable for the characteristic of low speed and high torque motor. All coils are used in the double layer windings, which allow more freedom in obtaining the desired spatial distributions of the air gap quantities. Based on the electric analysis of the motor, the winding factor in the first order harmonic is 1 and much higher than any other order ones.

It is known that the high performance slim motor can be controlled and implemented by the above describes. According to the e-bike direct-drive motor information, the thickness of traditional motor and slim motor are 3.3 inch and 1 inch. The traditional motor is twice as heavy as slim one demonstrated in Fig. 4. Although the slim motor is only 1 inch, its maximum torque can achieve 12 N-m which the desired value of the e-bike is satisfied.

Fig. 1. The ITRI-conceived e-bike.

Fig. 2. The foldable e-bike

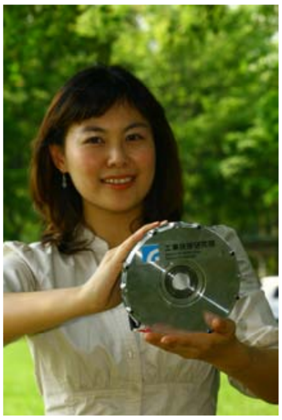

Fig. 3. The e-bike motor

The results of slim motor computer analysis are simulated by the software Ansoft and the specification is shown in Table 1. One can see that the slim motor is applied to the foldable bike easily, which can be carried on the mass transport system. With the advantages of lighter and thinner, users flank mounted motor and assemble e-bike fast in 15 minutes. It is a practical sightseeing for family traveling and commute tool. For the purpose of the slim motor operation, the control schemes and driving circuit are represented below.

Fig. 4. The traditional motor and the slim motor

Table 1: Slim motor specification

Motor Type	Axial Flux Permanent Magnet Motor
Max. Torque	12 Nm
Motor Weight	2.1 kg
Motor Dimension	Φ18 cm X 2.5 cm
Operation Voltage	24V
Max. Power	250W

2.2. The control scheme analysis

The control block of the motor controlled system in e-bike is shown in Fig. 5, there are calibration tool, programming cable, CPU, power unit, power supply and hub motor. In this paper, the controlled system is designed by two parts. One is hardware including the motor driving circuit of power unit, illustrated in Fig. 6, and the other is operation system of software programs which were burned into CPU to operate the motor via calibration tool and programming cable. We designed six transistors in the motor driving circuits and the control kernel of software, a TMS320F2808 Digital Signal Processor (DSP) of Texas Instrument Company, can generate PWM control signals to drive motor.

The relationship between the hall sensor signals (H_a, H_b, H_c) and back-emf (e_{ab}, e_{bc}, e_{ca}) are depicted in Fig. 7. The 3-phase motor is composed of A-phase, B-phase and C-phase. They are separated 120° each. We install three hall sensors to detect the variations of the magnetic poles in the hub motor. The electric cycle is 360°. It indicates that the electric angle for each state is 60°, since there are six in a cycle. By utilizing the relationship between hall sensors and back-emf, Six Step Trapezoidal Control is applied in a control strategy. Besides, the Proportional-Integral (PI) controller is a well-known technology in a motor control; one can adjust control parameters Kp and Ki to maintain the motor operation smoothly, also proposed in this research.

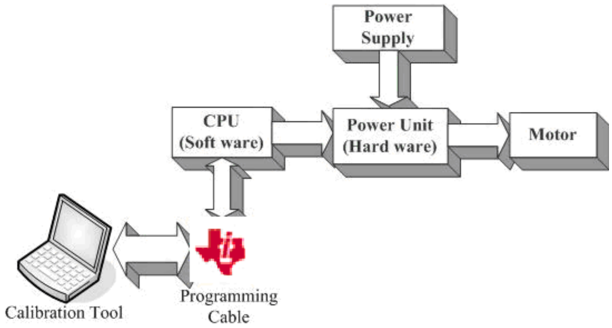

Fig. 5. The control block of the e-bike controlled system.

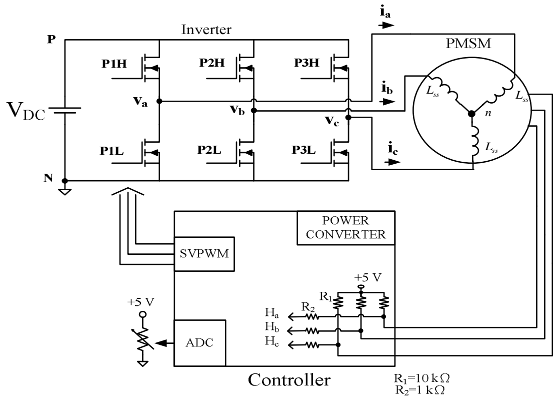

Fig. 6. The motor driving circuit.

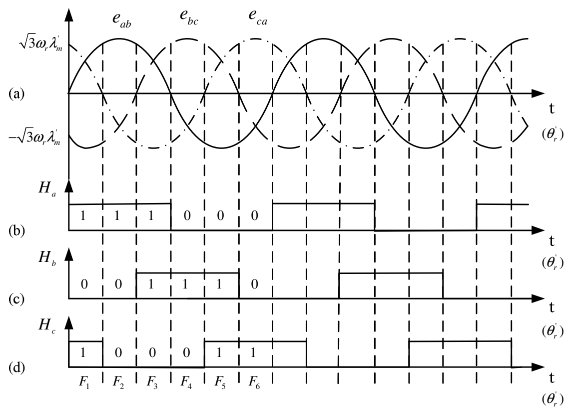

Fig. 7. The hall sensor v.s. back-emf.

2.3. Noise Vibration Harshness

After introducing the motor control schemes and design descriptions, the motor noise vibration harshness analysis is also an essential topic in the propulsion system. The detection devices are developed by noise monitor apparatus, as shown in Fig. 8. There are four measurable points A~D to detect the noise values, such as horizontal distance from the motor 10cm, horizontal distance from the motor 1m, horizontal distance 1m and vertical distance 1.2m from the seat, and vertical distance from the seat 70cm. By utilizing set measurable points, one can expect the influence of motor noise vibration for rider hearing.

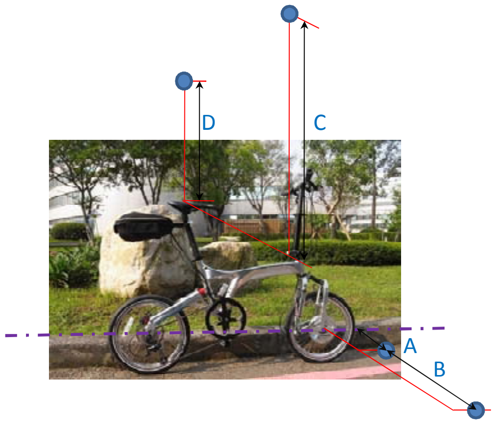

Fig. 8. The noise vibration analysis of the slim motor

3. Experiment Results

The motor performance test platform is developed by the Mechanical and System Research Lab of the ITRI, displayed in Fig. 9, which includes dynamometer, torque meter and slim motor. For the application of the torque measure, a practical slim motor is installed in the platform. The size of the motor controller is about 9 cm×6 cm×2.6 cm, which can drive the motor by the DSP program as illustrated in Fig. 10. Therefore, motor controller and battery can be put in the e-bike packet, so that rider will take it off after riding. It is convenient to take away when the battery needs to be charged.

The experiment results are obtained by the test procedure. It is observed that the peak torque and rated torque are 12 N-m and 7 N-m when the dc current are 30A and 10A, which is exhibited in Fig. 11. The weight of the designated slim motor is 2.1kg, then one can find out the torque density is 5.71 N-m/kg; hence, the high torque density slim motor can be achieved. Noted that the maximum speed is probably 550rpm; besides, the speed of the ITRI-conceived e-bike is also allowed.

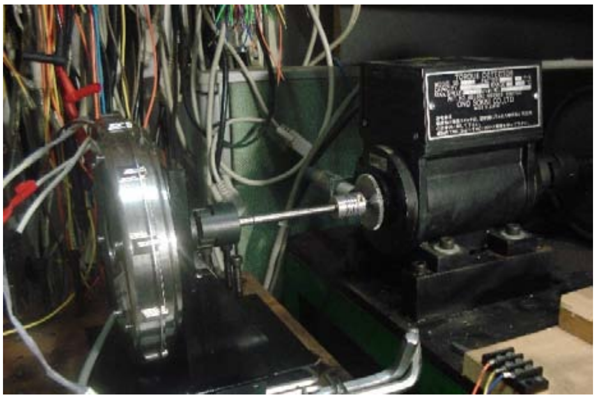

Fig. 9. The performance test bench

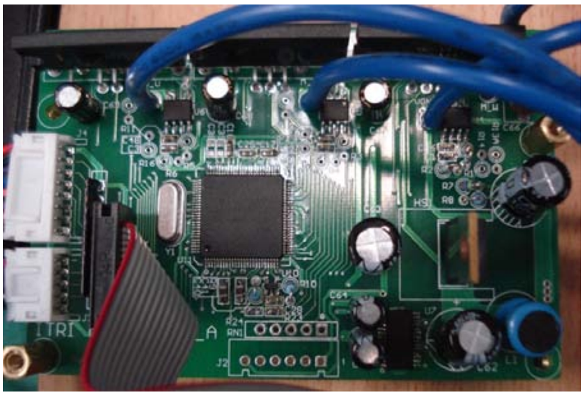

Fig. 10. The motor controller.

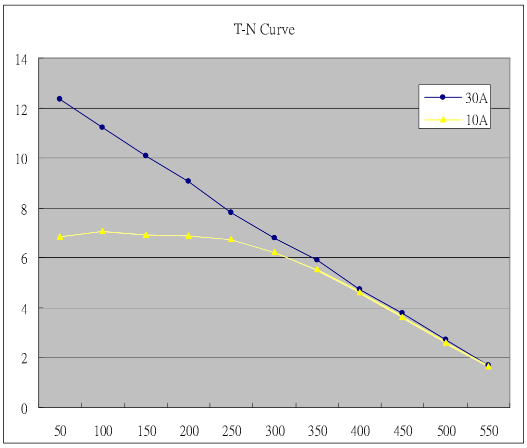

Fig. 11. The slim motor performance(experiment).

After introducing the motor's performance, its NVH analysis is also an essential topic in the e-bike motor. We choose 4 measurable points A~D to check if the noise will influence on rider or not presented in Fig. 8. The experiment result shown in Tab. 2 is observed that the maximum decibel in motor full load condition at point C is 60 dB and the rider can ride the e-bike with ease.

Table 2: The NVH experiment results

Noise, Vibration, and Harshness test (unit: dB)	No load	Part load	Full load
Horizontal distance from the motor 10cm (A)	77.9	78.7	78.6
Horizontal distance from the motor1m (B)	64.0	64.4	63.8
Horizontal distance 1m and Vertical distance 1.2m from the seat(C)	60.5	60.7	60.4
Vertical distance from the seat 70cm (D)	56.6	56.5	57.8

Fig. 17. The vehicle test platform in laboratory.

4. Conclusions

In this paper, in order to solve the low climbing problems, the design of the high torque density 250W slim motor is successfully proposed for the ITRI-conceived e-bike. The results clearly clarified that the proposed noise vibration harshness analysis and control scheme are capable of overcoming the motor noise vibration problem and achieving e-bike operation smoothly.

5. References

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