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A Design Study of Dual-Stator Permanent Magnet Brushless DC Motor

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Abstrak

Motor DC brushless magnet permanen dengan stator ganda (DSBLDC) memiliki efisiensi dan torsi yang tinggi. Dengan kemampuannya untuk beroperasi pada berbagai keadaan yang ada pada berbagai mode sambungan belitan, menjadikannya sesuai untuk penggerak kendaran listrik. Namun demikian, struktur stator ganda yang dimilikinya menyebabkan motor ini sukar didesain dengan menggunakan metode desain yang telah ada. Paper ini menunjukkan bagaimana sebuah DSBLDC dengan struktur magnetik seri dapat dianggap sebagai dua motor DC brushless yang independen, yang terdiri atas motor DC brushless rotor dalam dan motor DC rotor luar. Jadi, sebuah DSBLDC dapat dibagi menjadi dua motor DC brushless stator tunggal. Berdasarkan paparan ini, metode desain dapat diverifikasi dengan analisis finite elemen (FEA), dan diperoleh langkah-langkah desain dasar. Lebih jauh lagi, melalui hasil percobaan motor yang diperoleh bukti kebenaran metode ini, selain itu juga diperoleh indikasi bahwa motor yang diperoleh memiliki kinerja yang lebih baik untuk digunakan pada kendaraan listrik.

***Kata kunci**: analisis finite elemen, desain rangkaian magnetik, kendaraan listrik, motor DC brushless stator ganda (DSBLDC)*

Abstract

Dual-stator permanent magnet brushless DC Motor (DSBLDC) features high efficiency and torque-density. As DSBLDC could operate in various states according to different winding connection modes, it is fully qualified for electric vehicle (EV) drive. Unfortunately, due to the particular dual-stator structure, this kind of motor is difficult to be designed by available design methods. However, this paper demonstrates that a DSBLDC with series magnetic circuit structure can be regarded as being consisted of two independent BLDCs, an inner-rotor BLDC and an outer-rotor BLDC. Thus, the DSBLDC can be divided into two single-stator BLDCs. Based on this demonstration, the design method is verified by finite element analysis (FEA), and the basic design steps are given. Furthermore, experimental results of the prototype motor have verified the correction of the method, which also indicates that the motor with superior performance is adapted to EV drive.

***Keywords**: dual-stator permanent magnet brushless DC Motor (DSBLDC), electric vehicle drive, finite element analysis, magnetic circuit design*

1. Introduction

Electric vehicles (EV) propose some primary requirements on their motor drive system, such as: 1) large torque production, which meets the EV needs of starting, accelerating, load climbing, etc. in low speed, and, 2) a wide speed range, which meets the EV needs of high-speed traveling, overtaking, etc. According to these requirements, the dual-stator permanent magnet brushless DC Motor (DSBLDC) is quite qualified for EV drive. Compared with conventional single-stator BLDC, the DSBLDC shown in Figure 1 fully uses its internal space, providing a higher torque density [1-3]. Moreover, there are two sets of stator windings separately placed in the inner and outer stators, connected either in series or independently, so the motor can operate in various states according to the different winding connection modes [4]. While the inner and outer stator windings are connected in series and applied the whole voltage, the DSBLDC features a high torque at a low speed. While only one set of windings is applied the whole voltage, the motor features a low torque at a high speed, avoiding the need of field-weakening. In fact, the inner and outer stator windings can be applied different voltages, therefore, multiple torque-speed profiles can be obtained to adjust to various EV traveling

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states. Additionally, if one set of windings breaks down, the other set can work alone to maintain the motor fault-tolerance running.

Though DSBLDC is suitable for EV drive, there is a barrier that this kind of motor is difficult to be designed by available design methods. Figure 2 shows the magnetic field distribution of the DSBLDC at no load, revealing that the series magnetic circuit structure of the motor and the mutual restrained parameters of inner and outer stators are the major sticking points in the design process [5-7]. The finite element analysis (FEA) software can be used to analyze DSBLDC, but the modeling process is complex and some necessary parameters such as slot fill factor, thermal load, etc. can not be directly obtained.

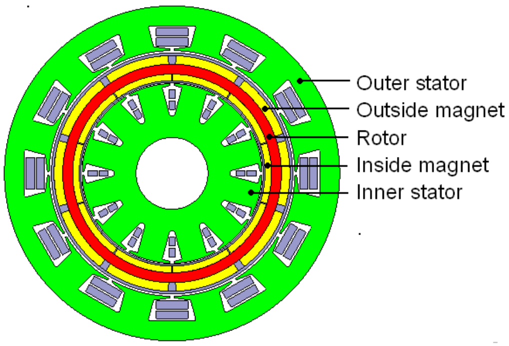


Figure 1. The structure of DSBLDC

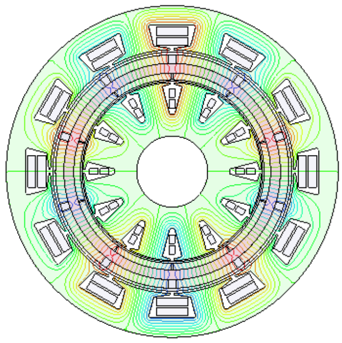


Figure 2. Magnetic field distribution of DSBLDC at no load

In this paper, a design method of DSBLDC with series magnetic circuit structure is proposed, i.e. a DSBLDC can be regarded as being consisted of an inner-rotor BLDC and an outer-rotor BLDC. Verified by FEA, it can be indicated that the proposed design method is practical. Moreover, a prototype motor designed by this method is manufactured and tested, and the experimental results of this prototype motor operating under various winding connection modes show excellent performance for EV drive.

2. Design Method and Steps

In Figure 1, the DSBLDC can be approximately treated as two BLDCs, i.e. the inner stator and the inside magnets compose an outer-rotor BLDC; the outer stator and the outside magnets compose an inner-rotor BLDC; both of the motors share the same rotor core. Due to the series magnetic circuit structure of the DSBLDC, the inside and outside magnets are oriented in the same magnetization direction and there is few flux in the rotor-yoke circumferential direction. It means that the rotor-yoke of the DSBLDC can be designed as thin as possible, whose thickness only depends on the mechanical strength of its material. Furthermore, the main flux per pole of the DSBLDC goes through two-layer airgaps, and the mutual inductance between the inner and outer stator windings can be neglected, which means that the coupling between the inner and outer stator windings can not be taken into account in the method,

Based on the descriptions above, the DSBLDC is divided into an outer-rotor BLDC called inner motor and an inner-rotor BLDC called outer motor. The structures and magnetic field distributions of the two motors at no load are respectively shown in Figure 3 and 4. Obviously in Figure 3 and 4, the main flux goes through the rotor-yoke circumferential direction, which is different from the DSBLDC. Therefore, in order to imitate the condition of no main flux in the rotor–yoke circumferential direction of the DSBLDC, it's necessary to thicken both of the BLDCs' rotor-yokes while other dimensions unchanged. Thus, both of the BLDCs are of low flux densities and magnetic pressure drops in rotor-yoke. This is a critical setting in the design method.

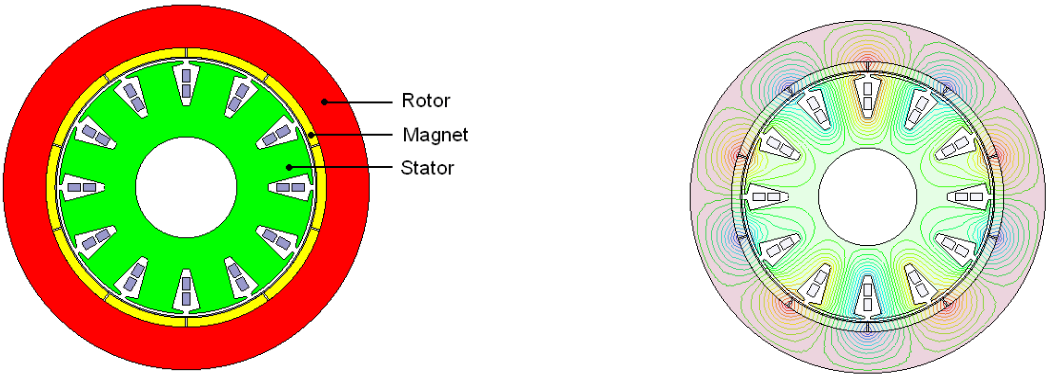


Figure 3. The structure and magnetic field distribution of the inner motor at no load

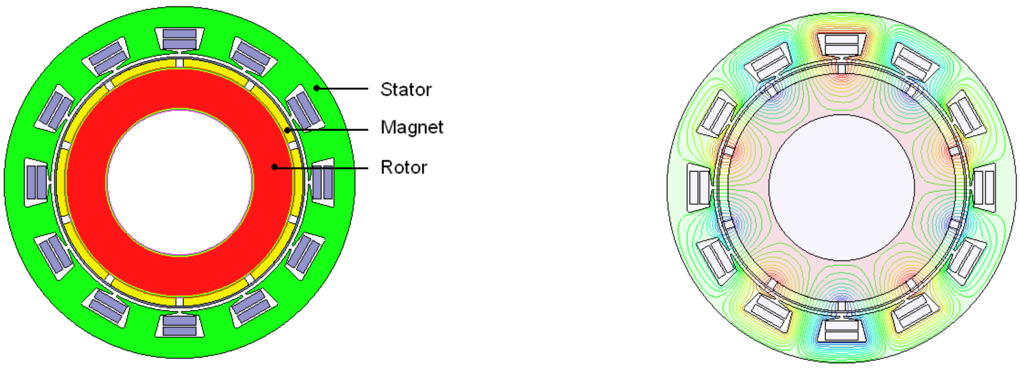


Figure 4. The structure and magnetic field distribution of the outer motor at no load

As the inner and outer stator windings of the DSBLDC can be connected in series and supplied by one inverter, both of the BLDCs are constrained as Equation 1.

$$\begin{cases} P_{N-in} + P_{N\_out} = P_N \\ U_{N-in} + U_{N\_out} = U_N \\ I_{N-in} = I_{N\_out} = I_N \end{cases} \quad (1)$$

Where, $P_{N\text{-}in}$, $U_{N\text{-}in}$, and $I_{N\text{-}in}$ are the rated power, DC bus voltage and DC bus current of the inner motor; $P_{N\text{-}out}$, $U_{N\text{-}out}$, and $I_{N\text{-}out}$ are the rated power, DC bus voltage and DC bus current of the outer motor; P_N, U_N, and I_N are the rated power, DC bus voltage and DC bus current of the DSBLDC.

The basic design steps are shown as follows:

1) It's essential to specify a large group of combinations of inner and outer motors that satisfy the constraint (1), then these motor projects are designed by conventional design methods and softwares.
2) According to the design requirements of the DSBLDC, these projects are adjusted, guaranteeing that the combinations not only satisfy the constraint (1) but also satisfy the conventional motor design principles such as suitable slot fill factor, flux density, thermal load, etc. Thus, an appropriate combination of inner and outer motors can be obtained.
3) Apply the combination of the inner and outer motors to constitute the DSBLDC.
   In particular, as DSBLDC has dual airgaps and the cooling condition of the inner stator is inferior to the outer stator, the thermal load of the inner motor should be lower than the outer motor.

3. Finite Element Analysis Verification for the Method

Referred to the design method, the DSBLDC as well as the inner and outer motors are designed according to the structures as in Figure 1, 3 and 4. The DSBLDC example is a 3 phase and 10 pole motor with rated values of 4 kW, 98 Vdc and 2100 rpm, whose main structural parameters are listed in Table 1. And the inner and outer motors are respectively with rated values of 1.2 kW/2.8 kW, 33 Vdc/65 Vdc and the same speed 2100 rpm.

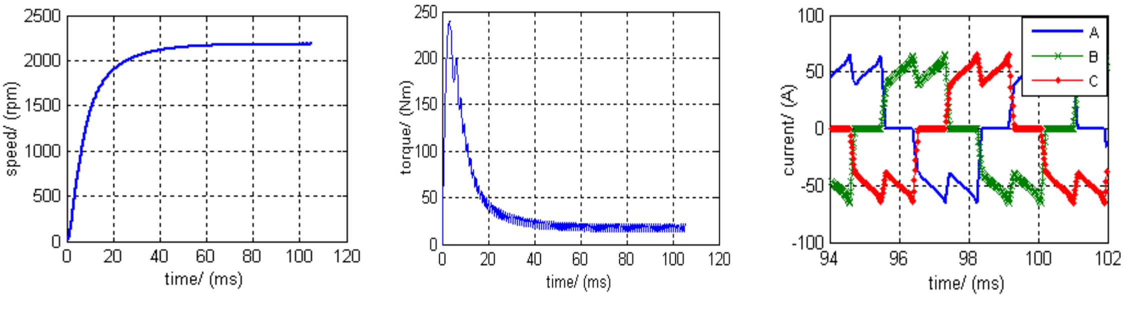
Table 1. The main structural parameters of DSBLDC

Parameter	*Value*	
	Inner Stator	Outer Stator
diameters of inner stator (mm)	36	90
diameters of outer stator (mm)	123.2	168
Length and thickness of middle rotor (mm)	55	5
Pole-arc coefficient of magnets	0.98	0.9
Numbers of stator slots	12	12
Winding pitch	1	1

In the FEA, the DSBLDC is applied its rated load, and the inner and outer stator windings are connected in series and applied the whole voltage 98Vdc. And the inner and outer motors are respectively applied their rated loads and their rated voltages of 33Vdc and 65Vdc. The performances of the three motors obtained by FEA are listed in Table 2, and the waveforms are shown in Figure 5-7. Obviously, the performances composition of the inner and outer motors are generally consistent with those of the DSBLDC. And the electromagnetic torque of the DSBLDC is a supraposition of the torques in the dual airgaps, which permits the motor starting rapidly.

Table 2. The main performance of the three motors

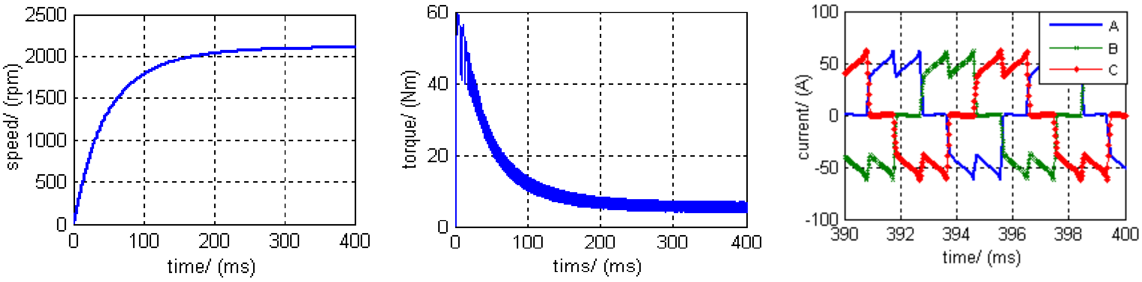
Parameter	*DSBLDC value*	*Inner motor value*	*Outer motor value*
RMS of phase emf(V)	39.81	12.58	26.02
RMS of phase current (A)	41.28	39.56	41.10
DC bus current(A)	45.90	45.99	46.11
Electromagnetic torque (Nm)	18.38	5.80	12.20
Speed(rpm)	2180	2099	2118
Power(kW)	4.194	1.275	2.705



(a) (b) (c)

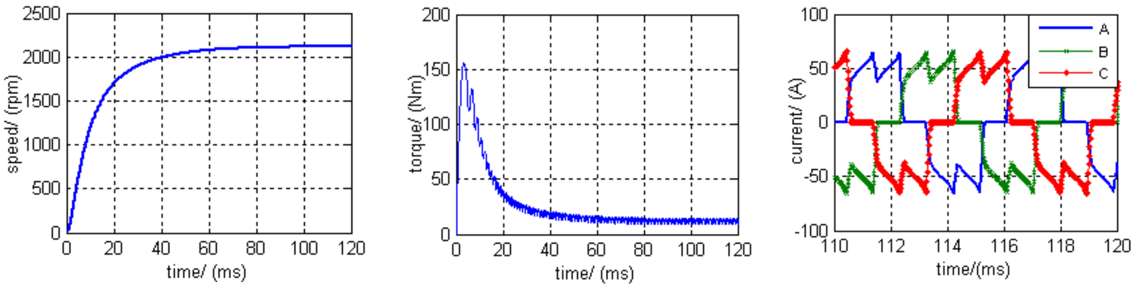
Figure 5. The FEA waveforms of the DSBLDC, (a) Speed, (b) Electromagnetic torque, (c) Steady-state current

Verified by FEA, the DSBLDC can be regarded as being consisted of an outer-rotor BLDC and an inner-rotor BLDC within the allowable error range. As a useful conclusion, the design of the DSBLDC with series magnetic circuit structure shown in Figure 1 can be simplified by using the available conventional BLDC design model.



(a) (b) (c)

Figure 6. The FEA waveforms of the inner motor, (a) Speed, (b) Electromagnetic torque, (c) Steady-state current



(a) (b) (c)

Figure 7. The FEA waveforms of the outer motor, (a) Speed, (b) Electromagnetic torque, (c) Steady-state current

4. Results of the Prototype Motor Experiment

The prototype of the DSBLDC is shown in Figure 8. In order to reduce the motor volume and cut costs, a decelerator is installed to the motor.

(a) (b) (c)

Figure 8. The prototype of the DSBLDC, (a) The whole motor, (b) The inner and outer stators, (c) The middle rotor

Figure 9 illustrates the performance of the DSBLDC with the inner and outer stator windings connected in series as well as the outer stator windings used alone when the whole voltage 98Vdc is applied. Compared with the situation that the outer stator windings work alone, the motor with the series winding connection mode can output a larger torque while requiring a smaller DC bus current, so the efficiency is higher under the same output power. However, when the outer stator windings work alone, the motor could attain a higher speed than the series winding connection mode under the same load.

Figure 10 illustrates the performance that when the outer stator windings work alone while applied the voltages of 65 Vdc and 98 Vdc respectively. When applied the voltage 65 Vdc, the motor can output a higher torque and efficiency, however it can not attain a higher speed.

Besides, the inner stator windings are generally not used alone due to the smaller output power and poor cooling condition, therefore, the experimental results of this situation aren’t presented here.

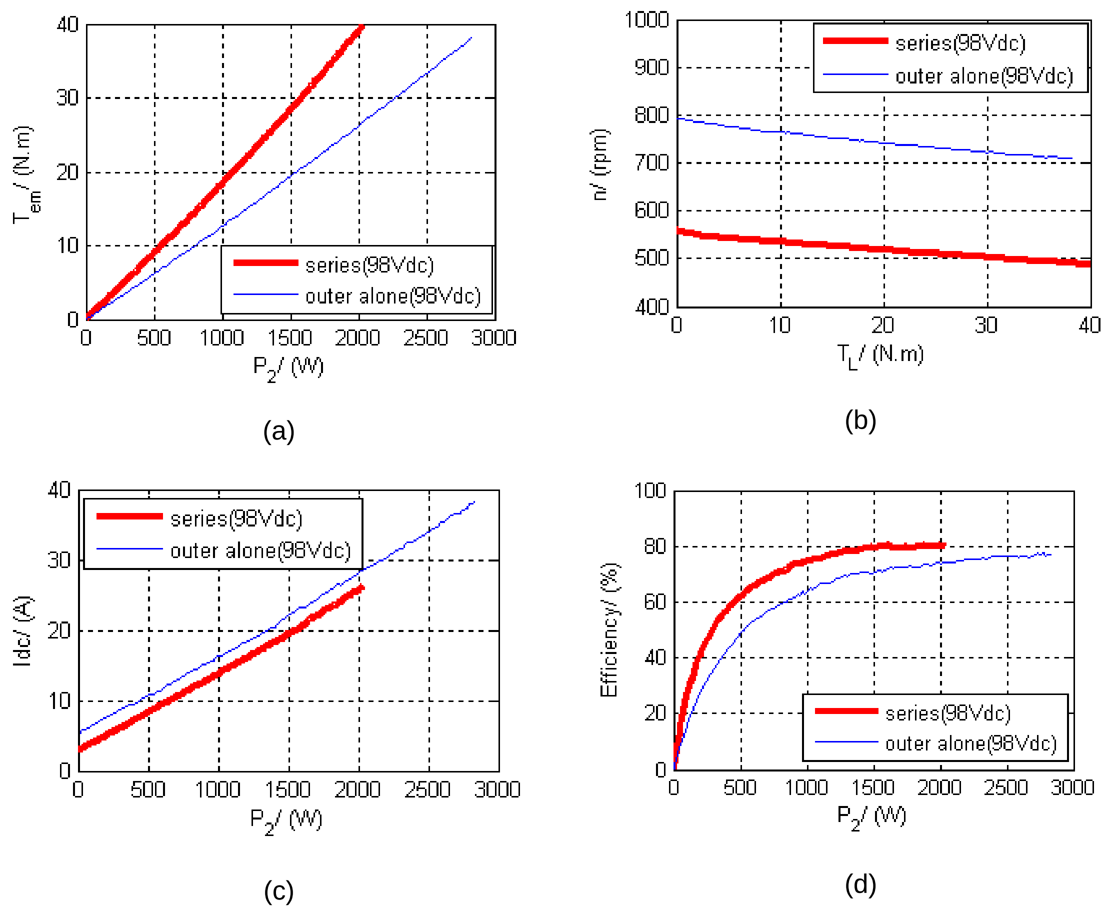


Figure 9. The curves of windings connected in series and the outer windings used alone (98Vdc), (a) Curve of output torque vs. output power, (b) Curve of speed vs. output torque, (c) Curve of DC bus current vs. output power, (d) Curve of efficiency vs. output power

Referred to the experiment, it can be confirmed that the DSBLDC can operate in multiple states according to different winding connection modes and different voltages. When the inner and outer stator windings are connected in series, a larger output torque is attained to accelerate the starting process of the EV and also improve the climbing capacity in the low speed situation. When the outer stator windings work alone, the motor can attain a higher speed which improves the high-speed running capability of EV. Moreover, various winding connection modes can provide an alternate measure in case that one set of stator windings would break down, the remaining set could work alone to maintain a fault-tolerance running.

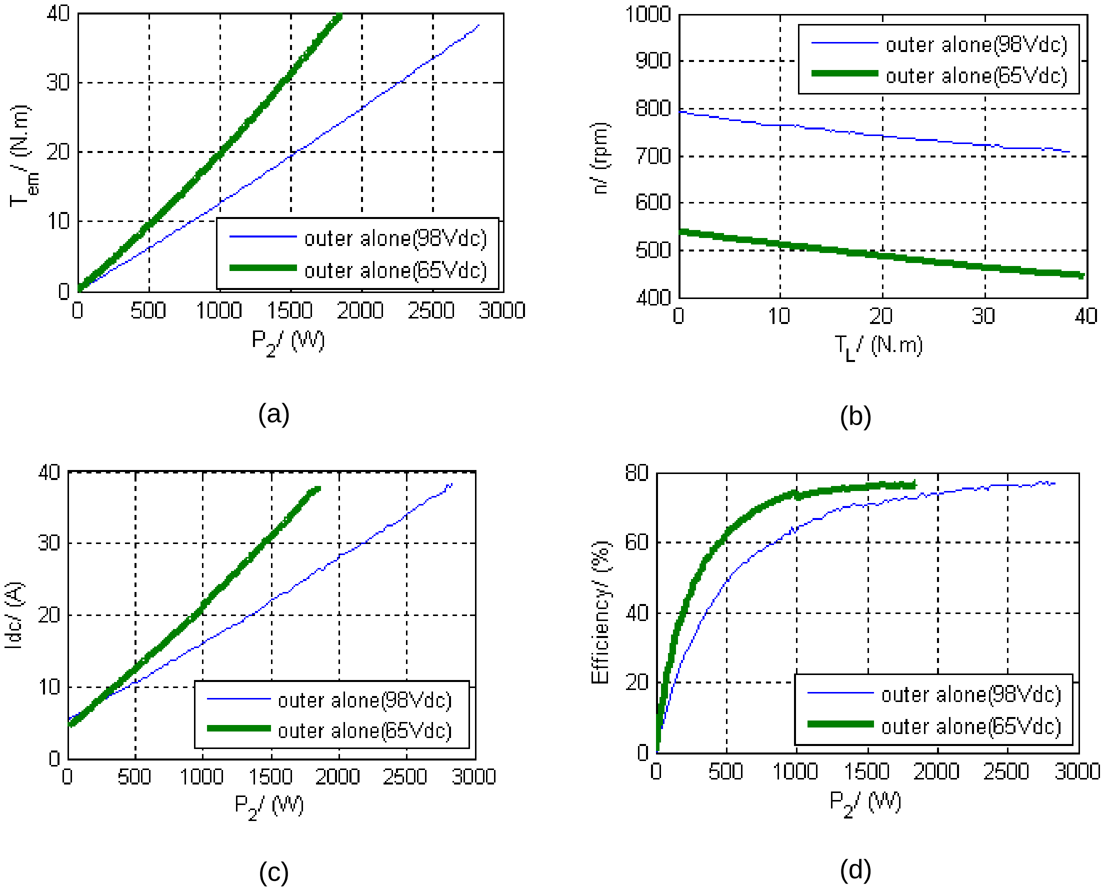


Figure 10. The curves of the outer windings used alone with the voltages of 98Vdc and 65Vdc, (a) Curve of torque vs. output power, (b) Curve of speed vs. output torque, (c) Curve of DC bus current vs. output power, (d) Curve of efficiency vs. output power

5. Conclusion

This paper focuses on the design and performance analysis of DSBLDC with the supports from the results of FEA and prototype motor experiments. Based on the works above, conclusions can be obtained as follows:

1) According to the series magnetic circuit structure of the DSBLDC, a design method is proposed. The DSBLDC can be divided into an outer-rotor BLDC and an inner-rotor BLDC which can be designed individually, therefore, the conventional BLDC model designed by available magnetic circuit design methods and sofewares can be practically used in DSBLDC design, which will simplify the design process of DSBLDC.
2) DSBLDC can output various running states with different winding connection modes, which will benefit the EV's starting, accelerating, load climbing, overtaking, etc. by winding switching.

In conclusion, the design method is practical in the DSBLDC design to achieve excellent performance of DSBLDC for EV drive.

References

[1] Niu S, Chau K T, Jiang J Z, Chunhua Liu. Design and Control of a New Double-Stator Cup-Rotor Permanent-Magnet Machine for Wind Power Generation. *IEEE Transactions on Magnetics*. 2007; 43(6): 2501-2503.

[2] Chai Feng, Zhu Chunbo, Cheng Shukang. Calculation for Electromagnetic Torque of Double-stator Permanent-magnet Synchronous motor. *Harbin Institute of Technology*. 2000; 7(2): 58-61.

[3] Zou Guotang, Cheng Ming. Electric Vehicle New Drive Technology. First Edition. Beijing. China Machine Press. 2010: 107-114.

[4] Nipp E, Norberg E. *On the Feasibility of Switched Stator Windings in Permanent Magnet Motors for Traction Drives*. Proceedings of the 1998 ASME/IEEE Joint Railroad Conference. Philadelphia. 1998: 33-39.
[5] Niu S, Chau K T, Jiang J Z. Analysis of Eddy-Current Loss in a Double-Stator Cup-Rotor PM Machine. *IEEE Transactions on Magnetics*. 2008; 44(11): 4401-4404.
[6] Wang Y, Cheng M, Chen M, Du Y, Chau K T. Design of High-torque-density Double-stator Permanent Magnet Brushless Motors. *IET Electric Power Applications*. 2011; 5(3): 317-323.
[7] Norhisam M, Norafiza M, Sia C Y. *Double Stator Type Permanent Magnet Generator*. Proceedings of 2009 Student Conference on Research and Development (SCOReD 2009). Serdang. 2009: 316-319.