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A novel design and driving strategy for a hybrid electric machine with torque performance enhancement both taking reluctance and electromagnetic attraction effects into account

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Abstract

A novel design, the hybrid electric machine, that owns improved competence for the output torque regulation as well as enlarged power density comparing to the conventional brushless machines by making use of the simultaneous performance overlapping concept based on magnetism is proposed in this paper. The developed design concept is focused on electric machine structure and its counterpart drive for applying two main magnetic-power transmitting paths by combination of both features of magnetic tendencies of flux generation that may flow in the path with minimum reluctance and direction owning the electromagnetic motive attraction. The verifications demonstrate that the outputted torque owns effective improvement by the presented concept of the electric machine based on the equivalent 3-hp frame than the conventional brushless motors.

Keywords: Hybrid electric machine; Reluctance; Electromagnetic attraction; Torque

1. Introduction

The permanent-magnet brushless motor is becoming widely used in small-horsepower applications due to its high efficiency, small size, and low cost. However, applications of these brushless motors utilizing the magnets in rotor within certain limits in speed and power rating, described in Refs. [1–3]. Switched reluctance motor (SRM), the electrical machine utilizing reluctance torque with rugged structure, is an inherently four-quadrant variable speed drive machine and gaining acceptance in industrial applications worldwide.

Though the efficiency of SRM is lower while the comparison is made with permanent-magnet brushless motor in general cases, introduced in Refs. [4,5], the construction of rotor is simpler and robust, as it merely consists of laminated steel with neither permanent magnets, nor electrical windings, while the stator can be easily manufactured as the windings are not distributed but concentrated around the salient poles.

Efforts on design of modified machine structure for combining these two types of electric machines own complementary advantage to each other. Research of allocations of the permanent magnet is one of the crucial approaches for combining their features, such as structures of interior permanent magnet (IPM), and surface permanent magnet (SPM), respectively, addressed in Refs. [6,7]. Opinions based on parallel driving concept are also presented in Refs. [8,9]. However, both of the considerations may apparently involve issues of growth of manufacturing sophistication and cost as well as rating of applied power modules in driving topologies. Hence, an effective concept to tackle the above restrictions, which conforms to the application requirements in a simpler way, is highly expected.

2. Basic characteristics of the torque generation

The design of a novel electric machine, hereafter being named as hybrid brushless motor (HBLM), is proposed

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herein by utilization of the combination of output torque composing of reluctance force except for the original production by the electromagnetic attraction force. Followings will arrange a brief introduction on the torque production for the proposed HBLM.

2.1. Electromagnetic torque

Based on the torque generation concept of the conventional brushless motor, the electromagnetic torque in a three-phase scheme can be expressed in the form of

$$T_B = \frac{P}{2}\lambda_m\left[\left(i_{as} - \frac{1}{2}i_{bs} - \frac{1}{2}i_{cs}\right)\cos\theta_r + \frac{\sqrt{3}}{2}(i_{bs} - i_{cs})\sin\theta_r\right], \quad (1)$$

where T_B means the output electromagnetic torque of the electric machine. P, λ_m, i_{as}, i_{bs}, i_{cs}, and θ_r are, respectively, pole number, flux linkage, phase currents in stator winding of phase a, b, and c, and angle between $\boldsymbol{q}$-axis and magnetic phase $\boldsymbol{a}$-axis in $\boldsymbol{d}$–$\boldsymbol{q}$-axis analysis basis, and all these former parameters belong to part of the related conventional brushless motor design in HBLM.

2.2. Reluctance torque

The definition of reluctance can be described as "magnetic resistance", being equal to the ratio of magneto-motive force to magnetic flux. Reluctance torque, taken for the other output torque source of the HBLM, can be expressed as

$$T_{\mathrm{R}} = \sum \frac{1}{2} i_r^2 \frac{\partial L_r}{\partial \theta}, \quad (2)$$

where T_{R}, i_r, L_r, and θ denote reluctance torque, activating current, equivalent magnetic inductance, and rotor angle, respectively. Torque production in reluctance machines is achieved by the tendency that the rotor would move to a position where the reluctance of the excited winding is minimized.

3. Hybrid design concept of electric machine

Overlapping of simultaneous performance is the main concept of the novel design of the HBLM. Based on the following description of space flux relation and its simple counterpart driving circuit, the presented design can be put into practice.

3.1. Structure feature

The structure of the HBLM applies the space allocation of the SRM and permanent-magnet brushless motor for making the two flux paths of the former two torque generation sources, constructed in the path with minimum magnetic resistance as well as the direction owning motive attraction. The two torque sources are formed in orthogonal disposing and they are operated simultaneously. The illustration of the HBLM for depiction of magnetic force composition is shown in Fig. 1.

As shown in Fig. 1, the HBLM owns two salient reluctance poles in rotor from part of the structure concept of the SRM. Based on this design opinion, two schematic structures can be illustrated in Fig. 2 for a three-phase HBLM.

In HBLM's stator, the reluctance stator salient poles are set to be separated by the poles of original brushless motor in basis of three phases, say, a, b and c, respectively. From

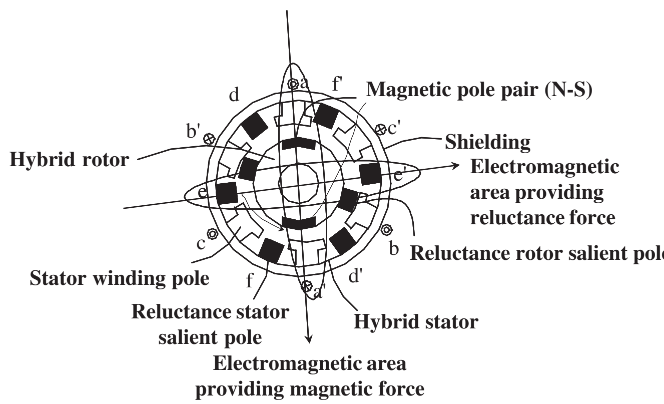

Fig. 1. The space allocation of the two torque generation sources.

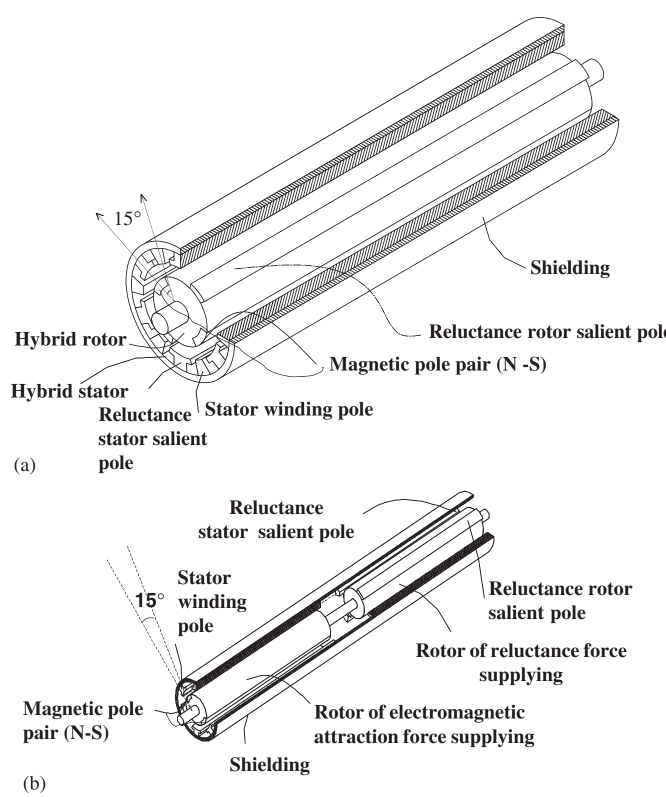

Fig. 2. The schematic view for the implementation of the HBLM: (a) structure overlapping scheme; (b) axial connection scheme.

Eqs. (1) and (2), the output torque of the HBLM can be obtained as the following form of

$$T_e = k_1 \cdot \left[\frac{P}{2} \lambda_m \left[\left(i_{as} - \frac{1}{2} i_{bs} - \frac{1}{2} i_{cs} \right) \cos\theta_r + \frac{\sqrt{3}}{2} (i_{bs} - i_{cs}) \sin\theta_r \right] \right] + k_2 \cdot \left(\frac{1}{2} \cdot i_r^2 \cdot \frac{\partial L_r}{\partial \theta} \right), \quad (3)$$

where T_e means output torque of the HBLM. Both k_1 and k_2 are adjusting parameters, between 0 and 1, related to the weighting of the two power sources for the torque and can be decided by the driver circuit.

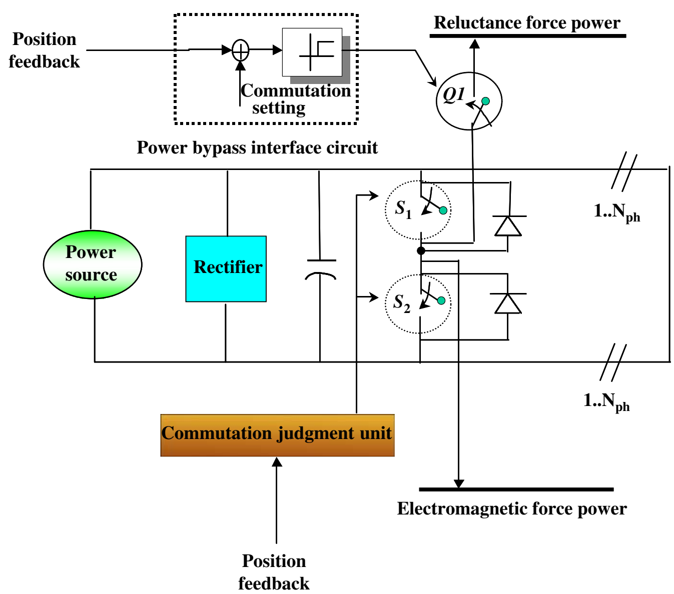

Fig. 3. The modified driving circuit.

3.2. Driving strategy

The modified driving circuit based on the conventional inverter topology, which merely one adding switch is needed for each activating phase for regulating the current of the reluctance power source, as shown in Fig. 3.

The position driving scheme for the reluctance force power control is shown in Fig. 3, deciding the torque ratio factors, k_1 and k_2, by the sharing period related to duty cycle of electric activation signal.

4. Experimental setup and performance demonstration

The HBLM scheme based on Fig. 2(b), combined with the 2-hp brushless motor and the 1-hp SRM, is taken to set up a driving system as shown in Fig. 4 for verifying the effectiveness by the comparison to a conventional 3-hp brushless drive system.

By this test arrangement, Fig. 5 shows the measuring results of the torque response at rated speed. An improvement ratio of power density can be generated with about 61.2% by the HBLM based on an equivalent 3-hp frame for larger torque being applicable compared to the conventional brushless motor.

A verification model with permanent magnet of Nd–Fe–B of the 3-hp HBLM scheme based on Fig. 2(a) is also constructed by Ansoft Maxwell EM software and the evaluation information is arranged in Fig. 6.

As illustration of Fig. 6, the increasing of torque of 31.2%, 16.1% and 25% under ratios of 0.3, 0.5, and 1.2 rated speed is achieved, respectively.

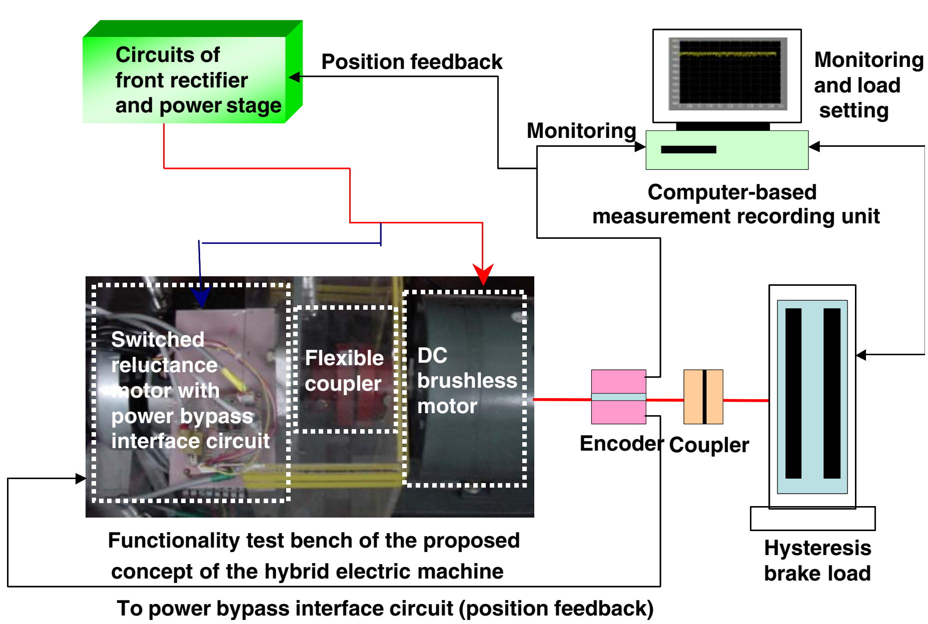

Fig. 4. The experimental setup of the HBLM drive.

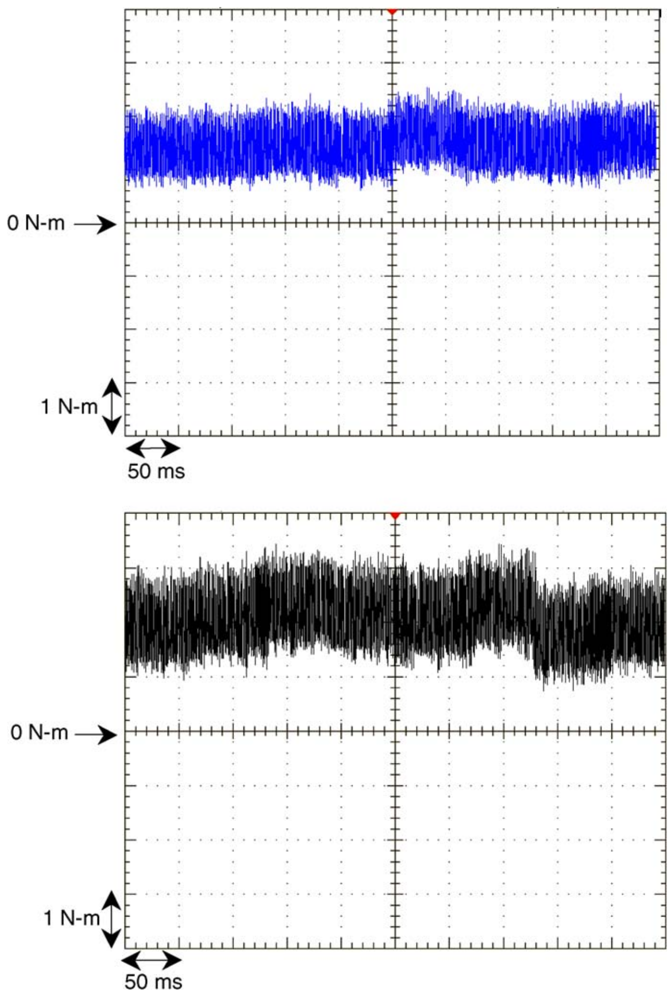

Fig. 5. Comparison of torque response: (a) by conventional motor drive; (b) by the proposed HBLM drive.

The power density can be enhanced with significant improvement by the HBLM compared to the conventional brushless motors, which also means lowering magnet requirements in the same power rating.

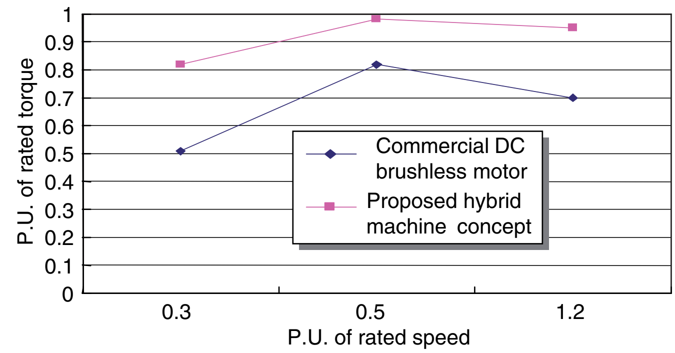

Fig. 6. The evaluation result under specific speed settings.

5. Conclusions

The proposed concept of the HBLM is focused on electric machine structure and its counterpart drive for applying two main magnetic-power transmitting paths. The related structures of the HBLM have been granted as number of 216,627 in the Intellectual Properties office of the Republic of China. By this novel design, the enhancement of torque performance can be achieved and it provides an effective solution for dilemma considerations between high power rating application and limitations of applicable magnets for brushless motors.

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