Design and Analysis of a Novel Flux-Switching Permanent Magnet Integrated-Starter-Generator

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Abstract

This paper presents a flux-switching permanent magnet machine for application of automotive integrated-starter-generator (ISG). Firstly, a typical three-phase flux-switching permanent magnet machine topology and its advantages are introduced. Secondly, optimal design of the machine to maximise torque capability is studied and final design data is given as the global optimisation for the target ISG. Finally, the performance simulation results are obtained and analysed.

1 Introduction

A typical three-phase flux-switching permanent magnet (FSPM) machine, as shown in Fig. 1, was proposed in [4,5,11]. It has a doubly-salient structure, similar to a switched reluctance motor with 12 poles on the stator and 10 poles on the rotor. Moreover, a magnet is embedded in each stator pole. The magnets in the adjacent poles have the same polarity facing each other. The stator winding comprises concentrated coils, each coil being wound around a pole which is formed with two adjacent laminated segments and a magnet.

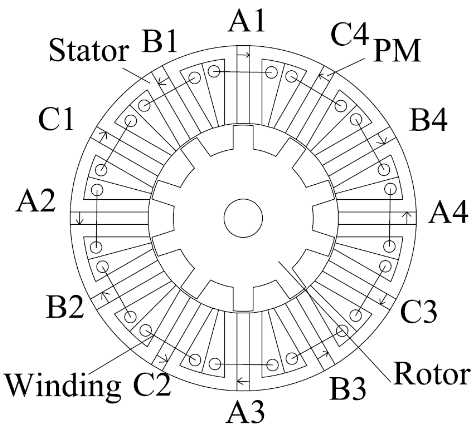


Fig.1: Machine topology

Fig. 2 shows that the flux-linkage and back-electromotive force (back-EMF) in each phase winding of the FSPM machine are both bipolar. Hence, its torque capability is significantly higher than that of a doubly salient PM machine, in which the magnets are embedded in the stator yoke and the flux-linkage is unipolar. The sinusoidal back-EMF also makes it suitable for brushless AC operation, which can reduce the torque ripple, and vector control and direct torque control can be performed for the motor.

Further, since the windings and the magnets are effectively magnetically in parallel, rather than in series as in conventional PM machines, the influence of the armature reaction field on the working point of the magnets is almost eliminated and the irreversible demagnetization withstand capability of the magnets is high [10]. Thus, such machines can have a high flux-weakening capability, which is suitable for constant power operation over a wide speed range.

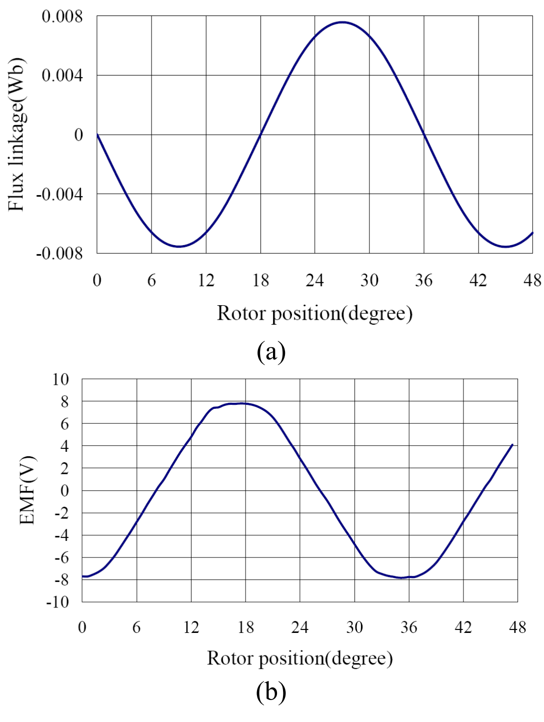


Fig.2: (a) Phase flux linkage waveform, (b) Phase back EMF waveform

In addition, flux focusing may be readily utilised because of the unique topology, and low-cost ferrite magnets might be employed [5]. Besides, since the windings and the magnets are both on the stator, it is easier to dissipate heat from the stator and to limit the temperature rise of the magnets. This is desirable for the aerospace and EV applications where the ambient temperature of the machine may be high.

The integrated starter generator (ISG) is an electric subsystem in which the functions of starting internal combustion engine and generating electric power are fulfilled with one electric machine onboard vehicle, instead with two separated machines in a traditional automotive vehicle. Due to its significant advantage over the separated machines for cold cranking and battery charging, ISG attracts considerable interest in modern automobiles and mild hybrid electric vehicles(HEVs) [1].

However, the performance specification of the ISG requires a very high starting torque for cold cranking, and a constant output voltage over a very wide speed range for battery charging. Recently, several types of machines have been proposed for ISG applications including PM brushless DC machine, induction machine, and switched reluctance machine (SRM), etc. [3]. Although the PM brushless DC machine has higher efficiency than induction machine and the SRM, its flux-weakening capability does not meet the specifications at motoring of the ISG [3]. The SRM can run very fast and even be used as aerospace ISG at speed up to 60,000 rpm or higher. The main disadvantages of the SRM are torque ripple, vibration and acoustic noise despite its simple structure and control [2, 3]. Induction machine is also an ISG machine candidate because of its low cost, high reliability and low maintenance, however, its power capability decreases with speed increase at constant voltage operation by flux weakening, and constant power operation can only be valid within the speed variable ratio of 3~5 [3,6].

In this paper, the flux-switching PM machine which has the advantages of high power/torque density, high efficiency, and high flux-weakening capability, is proposed for application to the automotive ISG. Structure design considerations will be investigated and performances simulation will be given based on finite element analysis.

2 Machine Design Considerations

Fig. 3 shows the original machine design in which the stator segment teeth, slot openings, PM magnets, and rotor poles have an identical width. The available literatures indicate that such a dimension is not optimal to maximum the torque capability while ISG requires a high starting torque [8,10]. Moreover, it is desirable to design the FSPM machine having the back-EMF waveform as sinusoidal as possible in order to eliminate the torque ripple. The optimisation of back-EMF waveform and maximum torque capability is studied and the balance between them is investigated for the ISG application.

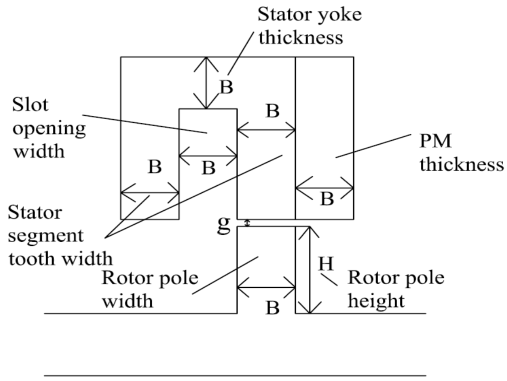


Fig.3: Original design

The research on optimisation of the machine design has been done in [10] and the influence of rotor pole width on the back-EMF waveform has been investigated in order to reduce the harmonics [9]. It is found that the phase back-EMF waveform is very close to sinusoidal when the ratio of the optimal design to the original design of rotor pole width is 1.4 [10].

Since the FSPM ISG which is designed in this paper needs changing windings connection to limit the starting current and reach rated speed, different connection styles are studied. The back-EMF waveform of the winding which is serially composed of coil A1 and A3 (or A2 and A4) has more harmonics than that of the winding which is serially composed of coil A1 and A2 (or A3 and A4)[9]. To eliminate the torque ripple as soon as possible, coil A1 and A2 are serially connected as a phase branch winding which is connected in parallel with the other phase branch winding (composed of coil A3 and coil A4 in series).

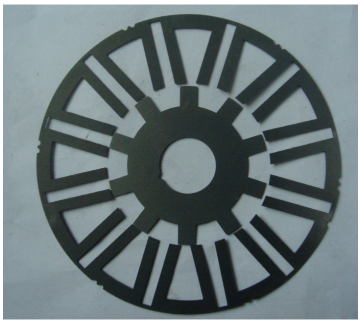
The split ratio, the ratio of the inner to outer diameter of the stator, is an important design parameter, as the motor torque is usually proportional to the square of the rotor diameter while the stator slot area reduces as the rotor diameter increases. Under the condition of a fixed copper loss, maximum electromagnetic torque is usually achieved when the split ratio is 0.55–0.6 [10].

Influence of the stator tooth width and the width of the slot opening on the torque when the split ratio and rotor pole width are fixed are also investigated in [10]. Although the slot area for accommodating the coils could be increased by reducing the stator segment tooth width, the teeth would become more heavily saturated and the phase flux linkage would be reduced [8]. Considering the saturation effect, the optimal stator segment tooth width is 1.1 times the original value and the width of the slot opening is approximately equal to it [10]. The rotor pole width is chosen 1.6 times the original design to maximise the torque capability as the global optimisation while the waveform of back-EMF is also essentially sinusoidal as shown in Fig. 2 (b).

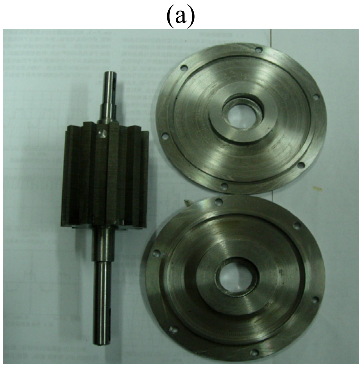
As the rated torque density of the ISG designed in this paper is high, NdFeB is applied. Table.1 shows the final design data of the machine, whilst the prototype is shown in Fig. 4.

Items	Design data
Rated speed	2000rpm
Rated power	1.5kw
Rated torque	7.2Nm
Dc-link voltage	24V
Active stack length	60mm
Stator tooth number	12
Rotor pole number	10
Number of phases	3
Air gap length	0.5mm
Stator outer diameter	90mm
Stator inner diameter	49.5mm
Rotor inner diameter	17mm
Stator tooth width	3.2mm
Rotor tooth width	5.1mm
Rotor pole height	6.2mm
Number of turns per armature coil	6
Generator speed range	800rpm-5000rpm

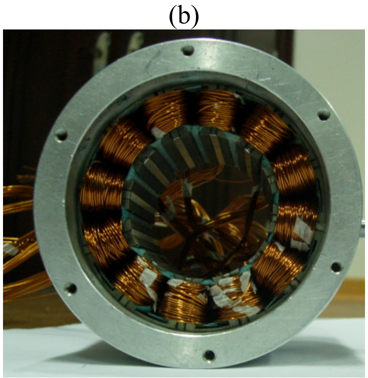
Table.1 Design data



(a)



(b)

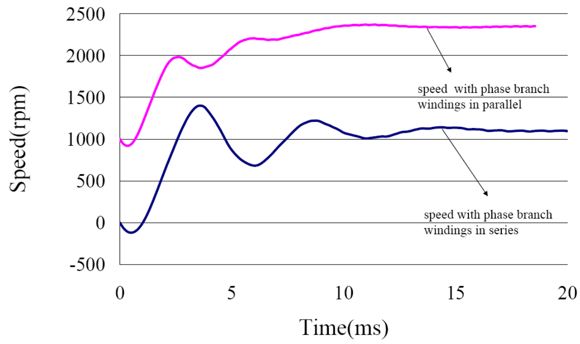


(c)

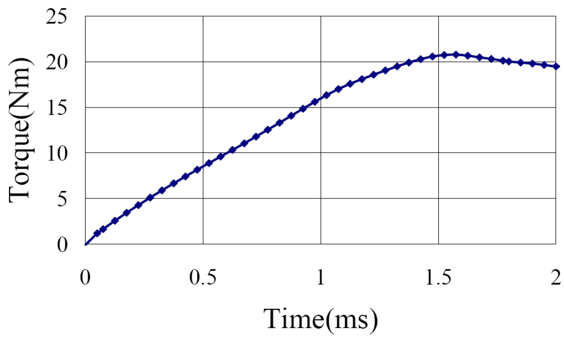
Fig.4. (a) Stator and rotor laminations, (b) Rotor and end-caps, (c) Stator armature installed in housing

3 Performance Simulation and Analysis

Fig.5 shows the starting speed under rated torque operation and the starting torque .When the FSPM ISG starts, two phase branch windings are connected in series to limit the starting current. By changing the windings connection (phase branch windings connected in parallel) when the machine reaches the speed 1000 rpm, it can reach the rated speed and meet the rated power requirement in the steady state. It can be also seen that the machine can reach steady operation under rated load in twenty milliseconds, which is desirable for ISG applications.



(a)



(b)

Fig. 5 (a) Starting speed under rated torque operation, (b) Starting torque

Fig. 6 shows the current waveforms during the starting procedure with different winding connections, where the effect of current limit can be seen.

A factor K_{fw} is defined to reflect the flux-weakening capability of the machine [7],

$$K_{fw} = L_d i_m / \psi_m$$
$$= [(\Lambda_d N^2)(\sqrt{2} J_s A_{hs} K_p) / N] / (N\phi_m) \quad (1)$$
$$= \sqrt{2}\Lambda_d J_s A_{hs} K_p / \phi_m$$

where J_s, A_{hs}, L_d, K_p, ϕ_m and N are the rated current density, area of half slot, d-axis inductance, slot filling factor, PM flux-linkage and wind turns per coil, respectively. Λ_d, A_{hs} and ϕ_m can not vary if the machine has been designed. Thus the variable parameters can only be J_s and K_p. Due to the rated current density of the FSPM ISG designed is high (about 12

A/m^2), the machine can exhibit high flux-weakening capability. The slot filling factor K_p of the investigated FSPM ISG is 0.46. It has been revealed that the machine can run over a wide speed range via flux-weakening, which is realised with advancing the inverter firing angle. Fig. 7 describes the two extended speeds under rated torque with phase branch windings in parallel and in series, where the advanced firing angle is 60°. It can also be seen that the FSPM ISG has the overload capability for short period of time (1.5 times rated power).

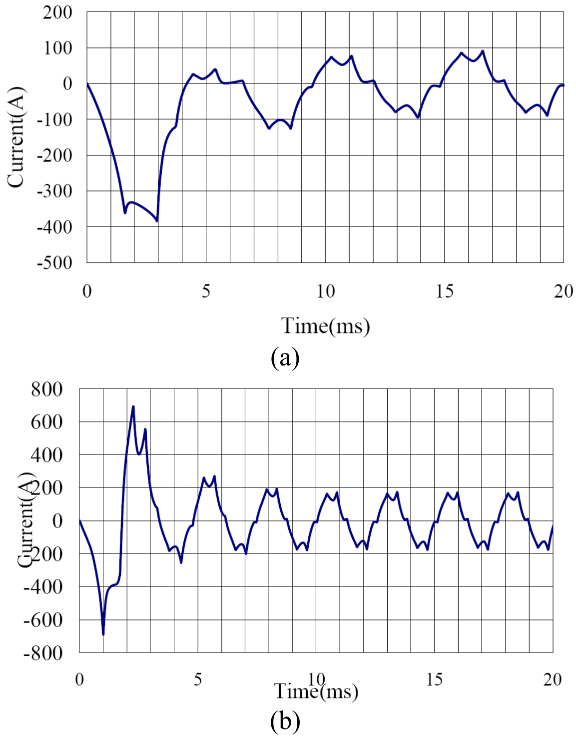


Fig. 6 (a) Starting current with windings in series, (b) Starting current with windings in parallel

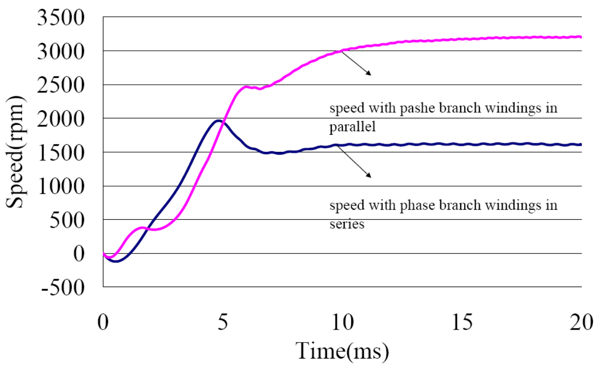


Fig.7. Extended speeds under rated torque operation

By advancing the inverter firing angle and changing windings connection, the machine can reach higher speed under constant power operation, as shown in Fig .8, which is obtained from finite element analysis, verifying the flux-weakening capability of the machine.

When the ISG is operating in the generating state and charging up the power battery of the electric vehicle, there is no strict requests for the sinusoidal EMF waveform. Fig. 9 shows the output voltage of the machine at the speed of 5000 rpm, which can be adjusted to 24V by adding a DC/DC converter between electronic inverter bridge and battery.

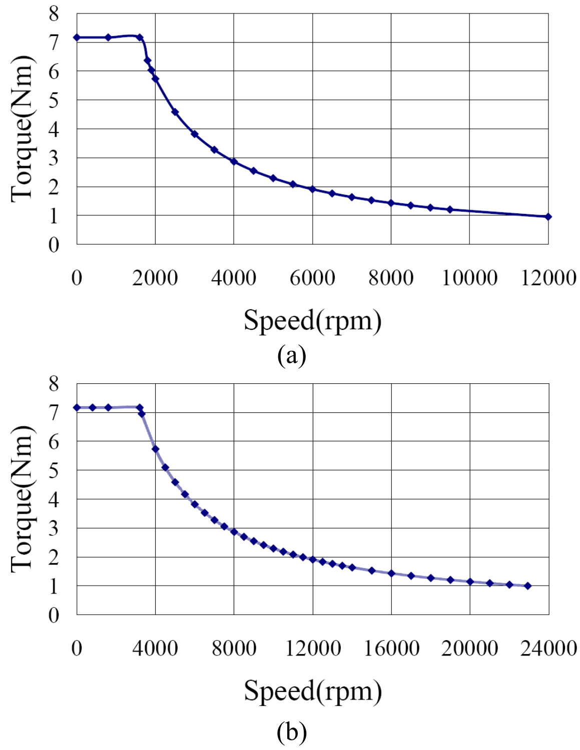


Fig. 8(a) Extended speed under constant power operation with windings in series, (b) Extended speed under constant power operation with windings in parallel

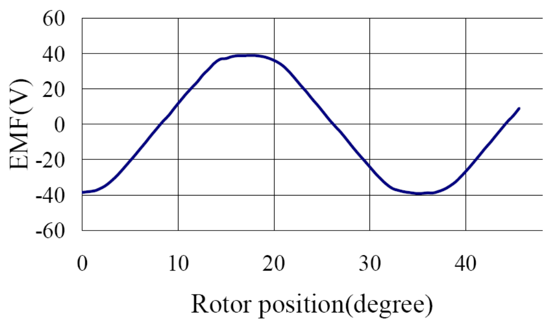


Fig.9. Back-EMF waveform at 5000 rpm

4 Conclusion

A design of FSPM ISG has been proposed and analyzed. Duo to its high power(torque) density, high efficiency and high flux-weakening capability, the research in the paper indicates that the FSPM can meet the performance requirements of the ISG such as high starting torque, high speed range when acting as a motor and overload capability for short period of time. The performance simulation results are given and analysed. Experiment validation and further research will be given in future papers.

Acknowledgements

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