Design of a Permanent Magnet Assisted Synchronous Reluctance Motor For Integrated Starter and Generator in 42 Volt System of Vehicles

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Abstract — In this paper, the rotor design of a permanent magnet assisted synchronous reluctance motor (PMa-SynRM) for integrated starter and generator (ISG) in 42 Volt system of vehicles are introduced and their effects are studied. In the design process, response surface methodology coupled with design of experiment is used for optimization. The effects of design variables are investigated on the object function considering induced voltage at maximum speed. The reason is critical system requirements for safety of vehicles. Basic parameters such as induction voltage, inductance profiles are calculated by finite element method, and equivalent circuit analysis is used for characteristic analysis. The characteristic analysis results will be compared with experimental results.

I. INTRODUCTION

ISG could produce lower system cost as well as extra functionality, achieve almost twice the efficiency at 80% compared to the alternator at 50%, fuel consumption is reduced, reduction in cyclic irregularities and engine vibrations by more than 70%. For example, higher power capability of the ISG allows the engine to start rapidly and smoothly. This machine could allow the engine to be automatically stopped when it would otherwise be idling and then "instantly" restarted [1].

Despite the many advantages, there are many things to be considered in the design of ISG that is not using flux-weakening control. Particularly, ISG with high torque is designed by the relationship between maximum current and maximum back-EMF. The reason is the current capacity is in inverse proportion to the voltage capacity on the characteristics of power device as shown Fig. 1. This design point make system unstable by large a mount of back-EMF.

This paper proposes the improved rotor shape that is effective to solve the above problem. The function of multi-flux barrier, as like the PMa-SynRM, is to produce high saliency ratio, which is used for the increase of reluctance torque and the reduction of back EMF. ISG of the PMa-SynRM type is designed with optimal design process consists of DOE and RSM.

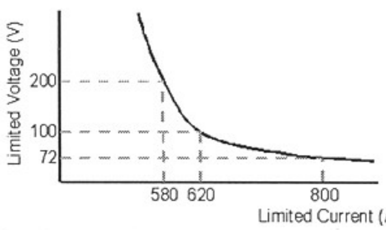


Fig. 1. The voltage capacity on the characteristics of power device

TABLE I
BASIC SYSTEM SPECIFICATION OF DESIGNED ISG

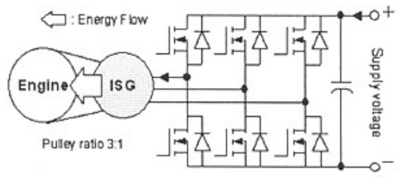
Mode	Contents	Value
Motoring	Input Voltage (V_{dc})	42
	Input Limited Current (A_{rms})	550
	Max. Output Power (kW)	8.0
	Rated Torque (Nm)	200
Generating	Max. Output Power (kW)	8.0
	Main Generating Region (rpm)	2500 ~ 7500
	Limited Induction Voltage (V_{pk})	120

The performance of improved model is calculated by using equivalent circuits consists of electric parameters [2]. The inductance and back-EMF, sensitively influenced by magnetic saturation, are obtained by FEA. Basic system specification of designed ISG is shown in Table I. Especially the critical specification is a limited back EMF at generating mode for the safety of the system.

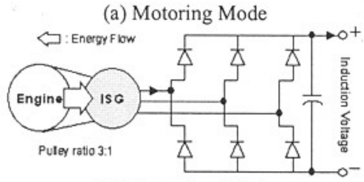
II. REVIEWING SYSTEM CONFIGURATIONS

A. Control Logic on Operating Mode

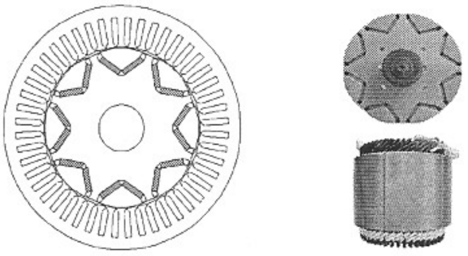
Usually the ISG is operated by maximum torque control to ensure the cranking torque at motoring mode and it operates as a generator with flux weakening control to have constant power. However the ISG dealt in this paper generates larger torque than other systems, so that it is designed to reduce magnetic torque by back-EMF for safety of system. From vehicle control point of view, using the flux-weakening control or relay at the output terminal of the drive circuit to reduce or eliminate back-EMF at the high speed is concerned inappropriate method. Therefore, the control logic in this paper consists of a maximum torque control at the starting and the three-phase full wave rectifier at the high speed as shown Fig. 2.



(a) Motoring Mode



(b) Generating Mode
Fig. 2. Control logic diagrams on operating mode



(a) Section Drawing (b) Proto Sample

Fig. 3. Configuration of Conventional Model

B. *Conventional ISG*

The rotor and stator of conventional model is indicated in Fig. 3. The conventional model has the V-shaped single layer permanent magnet in the rotor and consist 8 poles 48 slots. Even though this machine satisfies the desired specifications such as output power 8.05kW and rated torque 205Nm, back EMF exceeds 135V_{pk} that is the limitation of system at high-speed region. Moreover, its saliency ratio is too small by 1.18.

III. Improved Design

Improved design is performed using DOE and RSM. Improvement of saliency ratio is chosen for the objective function to minimize the back EMF in generating mode satisfying the output torque. Design variables are shown in Table II. RSM is performed with analysis of main effect and interactions of variables chosen by FFD [2].

Initially, main effects of design variables on the saliency ratio and value of back-EMF are observed by DOE result. Among eight variables, 1st layer offset, PM thickness, and Number of flux barrier are chosen for RSM, since all of them have significant effects on the saliency ratio and value of back EMF. From RSM result, improved model are shown in Fig. 4.

TABLE II
DESIGN VARIABLES

Section	Mark	Description
Rotor	A	PM thickness
	B	PM width
	C	1st layer offset
	D	Bridge width
	E	Web width
	F	Number of flux barrier
Stator	G	Yoke thickness
	H	Tooth width

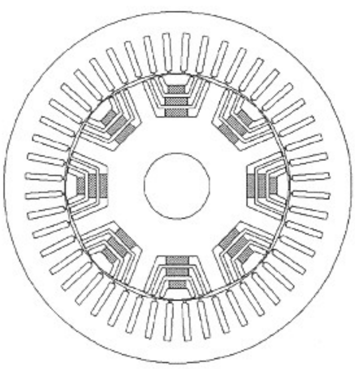


Fig. 4. Configuration of improved Model

IV. Comparison of Motor Parameters

D, q-axis inductances and saliency ratio according to current angle comparison are shown in Fig. 5. D-axis inductance variations of the two models are different to each other and there is a significant difference in the value of q-axis inductance. This results in higher reluctance torque of improved model. Saliency ratio is shown in (b), due to triplex flux barrier layer, higher saliency ratio of improved model is resulted.

Fig. 6 is comparisons of back EMF and total torque of two models. The magnitude of back EMF in the improved model is lower than conventional model about 50%. The required torque 200Nm is satisfied at current angle 45°. Equivalent circuit is solved with calculated parameter and Fig. 7 shows the speed versus output torque and power characteristics of both models.

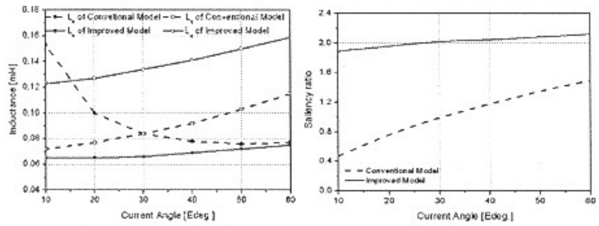
V. Conclusion

This paper deals with optimum design of ISG which offers a better system solution. It has been revealed that back EMF amplitude constraints can have a significant impact on the ISG machine design, as PMa-SynRM. From the results, the improved rotor structure is proposed to increase the saliency ratio, to reduce back EMF.

VI. References

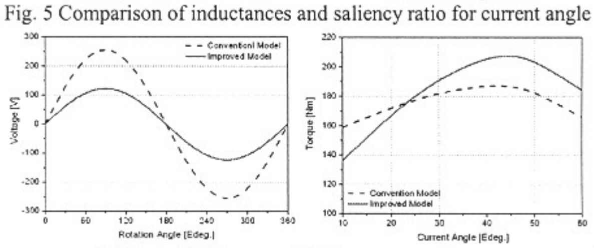
[1] C.Peter Cho, David R. Crecelius, "Vehicle Alternator/Generator Trend Toward Next Millennium," *Vehicle Electronics Conference*, vol 1, 443-438, 1999.

[2] J.Y.Lee, S.O.Kwon, J.W.Jung, J.P.Hong, Y.S.Lim, Y.Hur, "The Comparison Study of Distributed and Concentrated Winding type in Interior Permanent Magnet Motor for Integrated Starter Generator," *CEFC Conference*, vol. 2., 2006.



(a) d, q-axis inductance (b) Saliency ratio

Fig. 5 Comparison of inductances and saliency ratio for current angle



(a) Back-EMF (b) Torque according to current angle

Fig. 6 Comparison of induction voltage and total torque

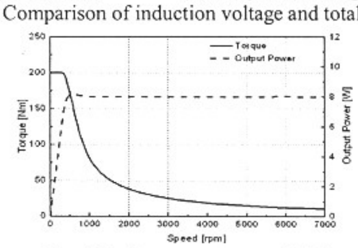


Fig. 7 Performances curve of ISG

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