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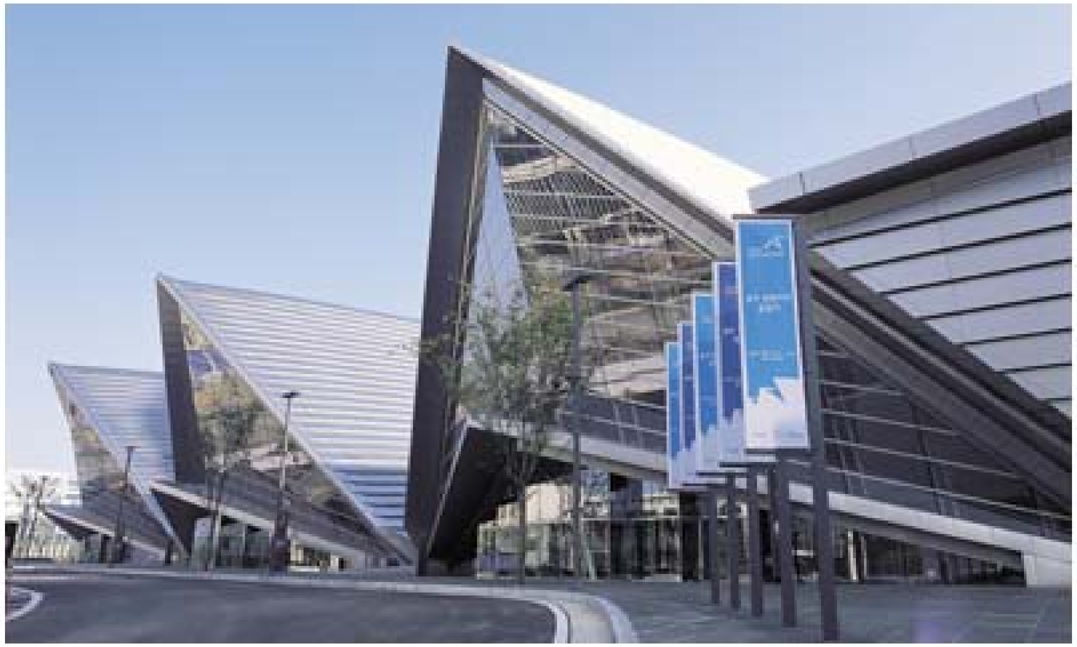

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Effect of Vibration and Noise on IPMSM type Integrated Starter and Generator According to Number of Slots

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Abstract — Integrated starter and generator (ISG) is one of the important component for hybrid electric vehicle (HEV). The main function of ISG is starting of engine after idle stop and generating during vehicle driving. When ISG starts engine, acoustic noise can be detected inside a vehicle. Many of such electric noise of the motor are produced by electro-magnetic exciting force and it is amplified to meet resonance frequency of system. Based on these faces, two kinds of method to reduce noise and vibration of system can be considered. The one is reduction of electro-magnetic exciting force. The other method is that frequency of exciting force avoids resonance frequency of system. This paper deals with second method to reduce vibration and noise of interior permanent magnet synchronous motor (IPMSM) type ISG by changing of number of slots. Exciting force of prototype and designed model is calculated by finite element analysis (FEA) and motor's 'product-level' and 'vehicle-level' experiment are performed to verify design method.

I. INTRODUCTION

Idle stop is one of the most important functions in hybrid electric vehicle (HEV) driving in the downtown especially. Idle stop ceases the engine operation in order to eliminate emission when vehicle is temporally stopped. After the idle stop, engine is started automatically by electric motor which is called by integrated starter and generator (ISG).

The operating speed is different between conventional engine starter and ISG which is rotating about 4000rpm with maximum power because it operates engine to reach over the idle speed to avoid a vibration of initial starting of engine. In that time, acoustic noise can be detected inside a vehicle. Many of such electric noise of the motor are produced by electro-magnetic exciting force and it is amplified to meet resonance frequency of system [1]. Based on these facts, two kinds of method to reduce the vibration and noise of system can be considered. Firstly, reduction of electro-magnetic exciting force is one of the method [2]. The other method is that frequency of exciting force avoids resonance frequency of the system. This paper deals with second method to reduce vibration and noise of interior permanent magnet synchronous motor (IPMSM) type ISG by changing of number of slots because frequency of exciting force can easily changed with least degradation of performance [3].

Prototype is designed by 6-pole and 36-slot with short pitch (5/6) distributed winding. In order to improve characteristics of acoustic noise, different number of slot, 18slot is investigated and optimized. Two kinds of experiment are performed to verify the effect on vibration and noise of IPMSM type ISG according to number of slots in same condition of pole number. One is motor's 'Product-level' experiment. We can find the effects on the vibration by changing of number of slots without any effects of mechanical changes. The other is 'Vehicle-level' experiment which is performed to evaluate vibration and noise with considering whole system effects. The experiment results may show a correlation on vibration and noise as changing the slot number.

TABLE I
SPECIFICATION OF PROTOTYPE

List	Value	Note
Number of pole and slot	6 /36	
Operating speed range	4000rpm	Starting mode
Maximum power	6.4kW	-
Winding method	Distributed winding	Short pitch (5/6)
Driving method	Sinusoidal current	SV PWM

II. INVESTIGATION OF SOURCE OF ACOUSTIC NOISE

A. *Specification of prototype*

The specifications of prototype, IPMSM, are shown in Table I. Prototype consist of 6-pole and 36-slots, and is wound by distributed winding. Slot pitch of armature winding is set to 5 to obtain sinusoidal back electro-motive force (EMF). In order to increase power density, permanent magnet of Nd-Fe-B type is inserted in the rotor. The rotor core below the permanent magnet is punched to reduce total weight of the rotor.

B. *Experimental results of prototype*

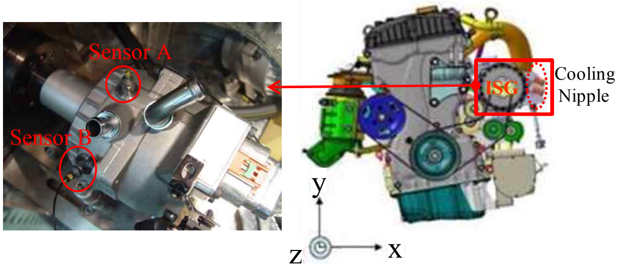
The prototype mounted beside the engine is connected with shaft of engine by pulley, and experimental conditions and results are shown in Fig. 1.

In order to measure the vibration of prototype, 3-axis G-sensors (accelerometer) are attached on the housing nearby cooling nipple in the radial direction and it is shown in Fig. 1 (a). In addition, noise is measured 1 m away from the prototype in the direction of z-axis using microphone.

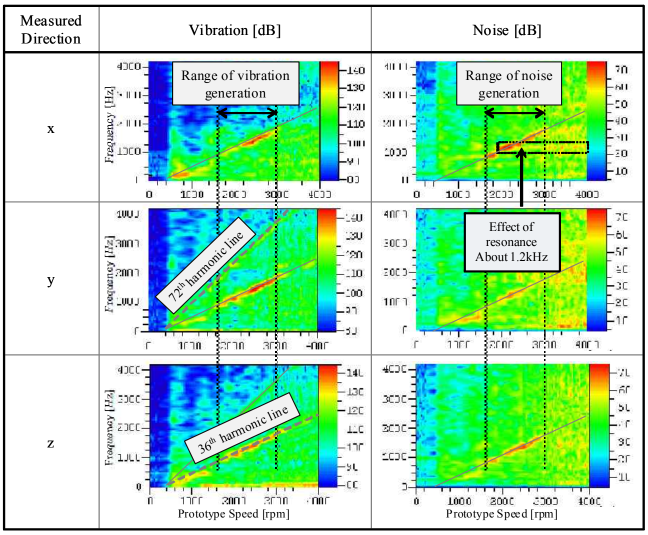
Fig. 1 (b) shows color map of the measured vibration and noise of prototype. The vibration and noise are measured in the direction of x, y, and z-axis, and the tendency of two results is almost similar in all directions. Because maximum torque is produced in the prototype rotation speed range from 1600 to 3000 rpm, the vibration and noise mainly occurred in this speed range. Especially, noise around 1.2 kHz after 2000 rpm is generated by resonance of engine assembly. This frequency of vibration and noise has maximum value. Therefore, main harmonic order of vibration and noise should be moved away from resonance frequency by changing the main harmonic order of exciting force. In order to change the main harmonic order of exciting force, changes of slot number is considered in this paper. For reference, mode analysis is performed as shown in Fig. 2. Frequency of mode 2 is 1289 Hz which is similar value with resonance frequency shown in Fig. 1.

Harmonic orders of electro-magnetic exciting forces are shown in Table II. The fundamental component of cogging torque, 2nd harmonic component of torque ripple and 6th harmonic component of radial, tangential force are matched with 36th harmonic component of the measured vibration and noise. Generally, torque ripple is produced 6-times as single electric cycle. However, torque ripple of prototype is likely produced by 12-times as a single electric cycle because 2nd harmonic component is mainly contained in the torque ripple.

In the earlier research, the 2nd harmonics of torque ripple regard as source of acoustic noise of ISG [4]. Therefore, 2nd harmonic component of torque ripple may remove to avoid resonance frequency by changes the number of slot.

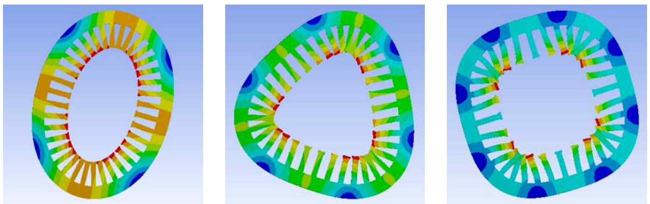


(a) Position of accelerometer



(b) Experimental result of vibration and noise

Fig. 1. Experimental results of prototype.



(a) Mode2=1289Hz (b) Mode =3330Hz (c) Mode4=5534Hz

Fig. 2. Mode analysis of prototype.

TABLE II
HARMONIC ORDERS OF ELECTRO-MAGNETIC EXCITING FORCES

Electro-magnetic exciting forces		Harmonic orders	
Global force	Cogging torque	$N/60 \times LCM_{PS} \times h$	$h=1,2,3,\cdots n$
	Torque ripple	$N/60 \times 6 \times pp \times h$	
Local force	Radial force	$N/60 \times 2 \times pp \times h$	
	Tangential force	$N/60 \times 2 \times pp \times h$	

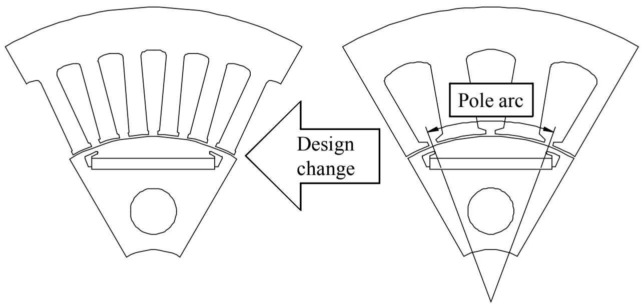
LCM_{PS}: Least common multiple of number of pole and slot, pp: Pole pair
N: Rotational speed of ISG, h: Harmonic order

III. DESIGN OF 18-SLOT MACHINE

A. Concept of design

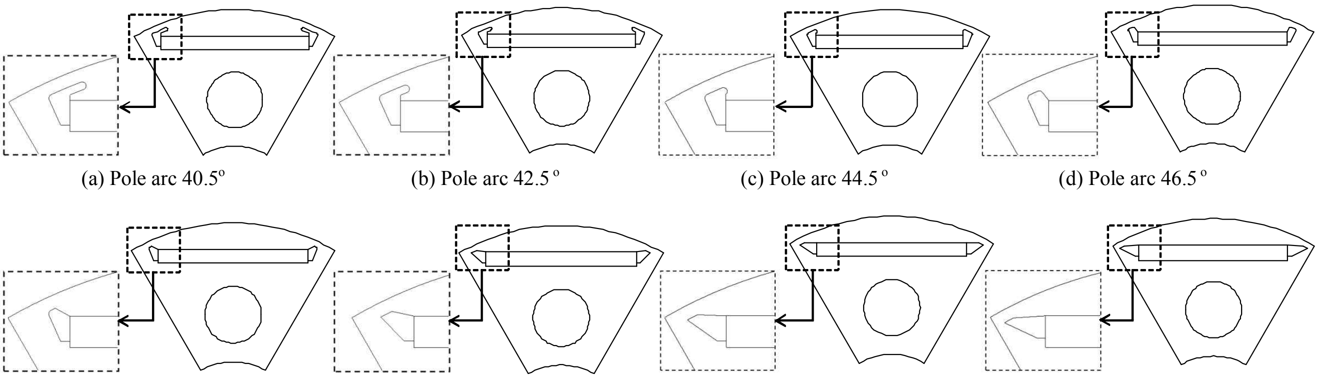
Design for changing of slot number is performed to avoid source of acoustic noise due to resonance frequency. Tooth width of 18-slot model can make thicker than prototype as shown in Fig. 3 which make more high stiffness in stator tooth. Winding pitch is also changed from short pitch (5/6 slot pitch) to full pitch because slot per pole per phase is reduced to one. In this case, there is no option to select a short pitch with distributed winding.

In order to optimize the characteristics of 18-slot model, several analyses using finite element analysis (FEA) is performed as variation of pole arc of rotor. Generally, wining pitch determine the winding coefficient under the same rotor structure [5]. It means back EMF of 18-slot model could have higher value than prototype under the same rotor. Moreover, cogging torque, torque ripple, average torque and total harmonic distortion (THD) of back EMF are changed due to number of slot changes. Fig. 4 shows analysis models according to pole arc which are from 40.5° to 54.5° within 2° step. Because flux from permanent magnet affects motor performance, the volume of permanent magnet is set to concentrated condition in the analysis.



(a) 36-slot model (b) 18-slot model

Fig. 3. Concept of design changes.



(a) Pole arc 40.5°　(b) Pole arc 42.5°　(c) Pole arc 44.5°　(d) Pole arc 46.5°

(e) Pole arc 48.5°　(f) Pole arc 50.5°　(g) Pole arc 52.5°　(h) Pole arc 54.5°

Fig. 4. Analysis models of rotor according to pole arc.

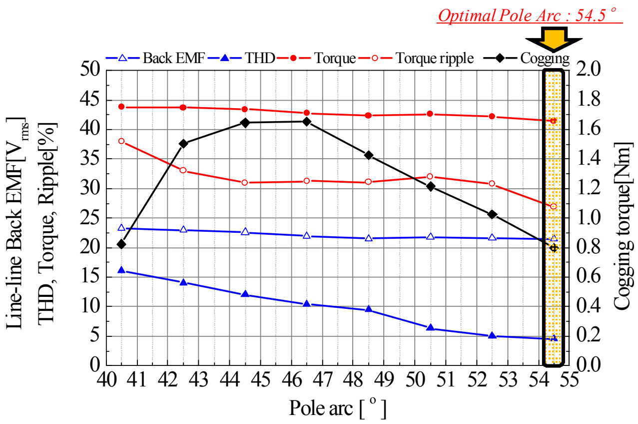
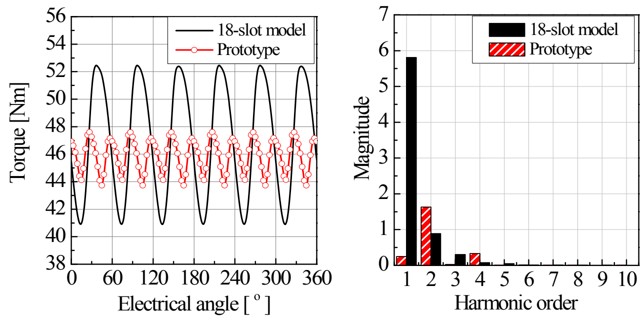
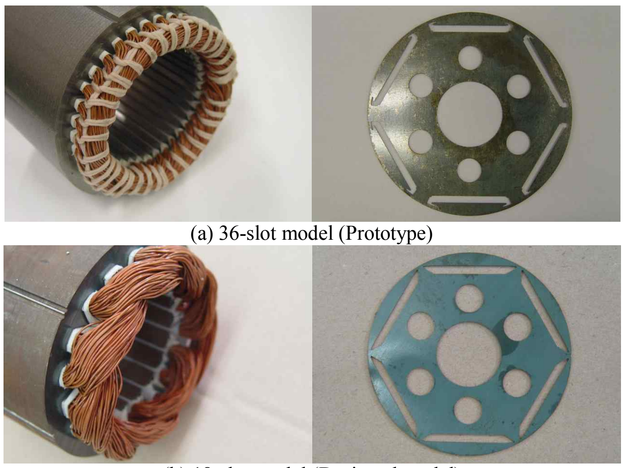


Fig. 5. Characteristics versus pole arc.



(a) Torque waveform　(b) FFT result

Fig. 6. FEA results of torque



(a) 36-slot model (Prototype)

(b) 18-slot model (Designed model)

Fig. 7. Configuration of prototype and designed model.

B. Determination of optimal pole arc

Eight-number of analysis models which have different pole arc are considered to determine optimal model. Pole arc 40.5° is considered to optimal pole arc of prototype. Based on this model, seven-number of models are designed and analyzed.

Fig. 5 shows several characteristics of analysis models such as line to line back EMF and its THD, average torque, torque ripple and cogging torque. Average torque and torque ripple are calculated with maximum current condition. Back EMF decreases as pole arc increases due to leakage flux which occurs in flux bridge of the rotor. Cogging torque and THD of back EMF and torque ripple start to decrease from the pole arc 46.5°. The pole arc of motor is limited by rotor structure as shown in Fig. 4, and the optimal pole arc has been determined as 54.5° considering such structural limitation.

C. Comparison of torque wave

Torque waveform of two models, prototype and 18-slot model which have optimal pole arc are calculated by FEA and results are compared as shown in Fig. 6. Average torque of both models has almost same value. However, peak to peak value of torque wave of 18-slot model is quite higher than prototype. Whereas, frequency of torque wave of 18-slot model is twice lower than prototype. Generally, most of the 3-phase machine produces torque wave 6-times during single electrical period. In other words, fundamental frequency of both waveforms is same but torque waveform of prototype mainly has 2nd harmonics component as shown in Fig. 6 (b). Therefore, frequency of torque ripple which is regarded as an exciting force of vibration and noise can be moved away from the system resonance, 1.2 kHz during the engine starting mode of ISG.

IV. EXPERIMENTAL RESULTS

In order to verify the design method, two kinds of experiment have been performed. Firstly, motor's 'Product-level' experiment is performed. Secondly, 'Vehicle-lever' experiment is conducted to verify ultimate effect of motor on vehicle in reality.

A. 'Product-level' experiment

Fig. 8 shows the 'Product-level' experimental set-up with the ISG. The ISG is connected with dynamometer by pulley. Two G-sensors are attached on ISG as shown in Fig. 1 (a). In the experiment, ISG operates with 3000rpm. Fig. 9 shows the measured acceleration of both prototype and 18-slot model. The frequency is 1.8 kHz as the highest acceleration value of prototype reaches to 0.792 m/s^2. This value is 36^{th} harmonic component of mechanical frequency of rotor rotation. Experimental results of 18-slot model exhibit different trend compared to prototype. The maximum acceleration occurs at 0.9 kHz and value of this point is 2.19 m/s^2, which mean that exciting force of vibration and noise, is reduced to half of that of prototype.

B. 'Vehicle-level' experiment

In order to verify the design method for reduction of vibration and noise in vehicle, 'Vehicle-level' experiment is performed. The experiment is performed with a condition when ISG starts engine after idle stop which is short time, about 1 second. Fig. 10 shows the experimental results of two models. Maximum values of vibration of prototype and 18-slot model are 138 dB and 136 dB, respectively. Therefore, vibration of HSG in the vehicle, 2 dB is reduced by changes of number of slot. However, noise which measured inside a vehicle is increased because there is very sensitive frequency, 600 Hz to vehicle vibration. The 18^{th} harmonic component of noise is induced by vibration which meets sensitive frequency ranges of vehicle.

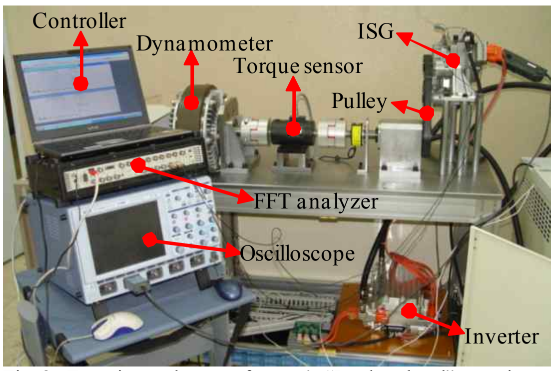
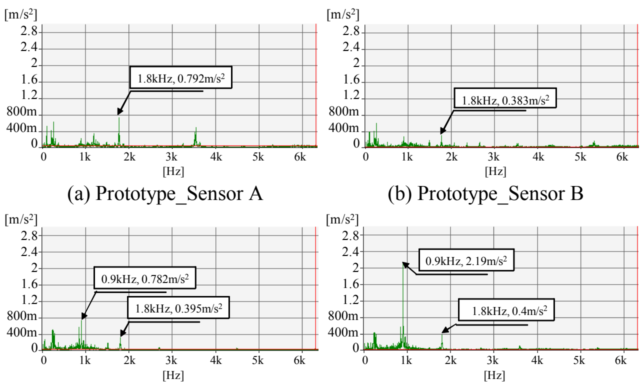


Fig. 8. Experimental setup of motor's "Product-level" experiment



(a) Prototype_Sensor A (b) Prototype_Sensor B

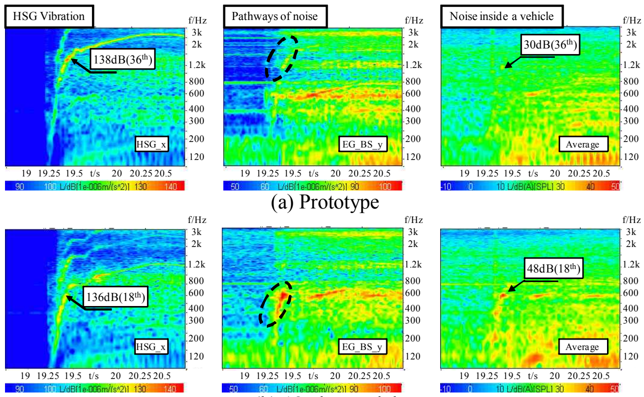
(c) 18-slot model_Sensor A (d) 18-slot model_Sensor B

Fig. 9. Motor's 'Product-level' experimental result (Vibration).

V. CONCLUSION

This paper deals with the design method for reduction of the vibration and noise in IPMSM type ISG for HEV. In order to change the frequency of exciting force which matches system resonance, changes of number of slot is introduced. Firstly, designed model which is 18-slots model is optimized to reduce the torque ripple as much as low. Then, torque ripple and its harmonic components are compared with prototype's one. Lastly, two kinds of experiment which are motor's 'product-level' and 'vehicle-level' experiment have been performed. In the experiment result, main frequency of vibration of 18-slot model is reduced to half of that of prototype. In the 'vehicle-level' experiment, HSG vibration is reduced by 2 dB. In spite of reduction of vibration in 18-slot model, maximum noise inside a vehicle is increased by 18 dB because the noise along the pathways of vehicle system is matched with main noise component of 18-slot model.

Even if noise inside a vehicle is increased by changes of number of slot, vibration level is obviously reduced. The method for vibration and noise reduction of ISG dealt with in this paper is sufficient to utilize to other ISG application with consideration of system resonance and sensitive noise frequency of vehicle system.



(a) Prototype

(b) 18-slot model

Fig. 10. Motor's 'Vehicle-level' experimental result (Vibration&Noise).

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