

Reduction of Cranking Noise from High Voltage Starter for One-Motor Two-Clutch Hybrid Systems

Kousuke Baba, Yuuki Kubo, Toyoji Yagi, and Akihiro Imura
 DENSO Corporation

ABSTRACT

In this paper, we propose a high voltage brushless AC starter that contributes to improved fuel efficiency and a reduction in the cost of the one-motor two-clutch hybrid system, which we call a 1MG2CL system. We have named it the HV starter, and it is composed of an AC motor, inverter and pinion with a shift mechanism. One of the issues with the 1MG2CL system is the high electrical energy when starting an ICE as it switches over from EV drive to HEV drive. While the ICE is starting, the main motor has to crank the ICE via the clutch; the clutch slips to absorb the main motor power, so the main motor has to output a high power to overcome the loss. Therefore, to contribute to reducing the electrical power by eliminating clutch slip losses, we developed an HV starter as a dedicated ICE starting device. Thanks to the reduction in electrical power, the HV starter is able to improve fuel efficiency and reduce system costs.

However, the major issue is the cranking noise generated by the pinion mechanism of the starter. We have developed a noise control strategy to solve this issue. The concept is to reduce the dependency of the pinion operation on the starter. We aim to utilize the ICE inertia energy in the later cranking process instead of starter cranking. Using the HV starter, which is a high power and controllable AC motor, we have managed to control the cranking noise to the target level, which is equal to the road noise during EV driving.

CITATION: Baba, K., Kubo, Y., Yagi, T., and Imura, A., "Reduction of Cranking Noise from High Voltage Starter for One-Motor Two-Clutch Hybrid Systems," *SAE Int. J. Alt. Power*, 6(2):2017, doi:10.4271/2017-01-1167.

INTRODUCTION

DENSO CORPORATION's policy is to contribute to a society that focusses on the environment, security & safety. Based on our environmental policy, we develop and produce various components for electric vehicles, including start-stop systems, HEV, PHEV, EV and FCEV. To achieve further reductions in CO₂ in the future, the popularity of electric vehicles must be improved, and improvements in fuel efficiency and cost reductions will be significant in reaching this target. We are focusing on the 1MG2CL system, which will form part of this trend. This 1MG2CL system is composed of an ICE, electric motor/generator, inverter, high voltage battery and two mechanical clutches. The MG has several functions that include driving the EV, starting the ICE, regeneration during deceleration and so on. One of the issues with the 1MG2CL system is the high electrical energy needed to start the ICE when the vehicle switches over from EV driving to HEV driving. When starting the ICE, the MG cranks the ICE through the clutch, which slips at first to absorb the MG's power. [Figure 1](#) shows the reduction in electrical power achieved by using a dedicated starting device. In the middle of this

figure shows the high electrical starting power of the MG. At the bottom of this figure, we convert the ICE starting with MG to the dedicated ICE starting device. The starting device concentrates on the ICE starting only without clutch slip losses. [Figure 2](#) shows a comparison of the electric energy required for starting. The electric energy required for starting is reduced by approximately 90% when using a dedicated starting device. This reduction will give us a 2% improvement in fuel efficiency in FTP75 mode.

The benefit of adding a starting device is not only in fuel efficiency. [Figure 3](#) shows two selectable additional benefits. The 1MG2CL system, which does not have a starting device, must be assigned to EV driving and the ICE starting power to the MG. Therefore, the output for EV driving is greatly limited. However, this restriction disappears if we use a dedicated starting device, and the EV driving region is enlarged dramatically. On the other hand, we can also choose to reduce the battery output and battery cost if we select EV performance to maintain the conventional model.

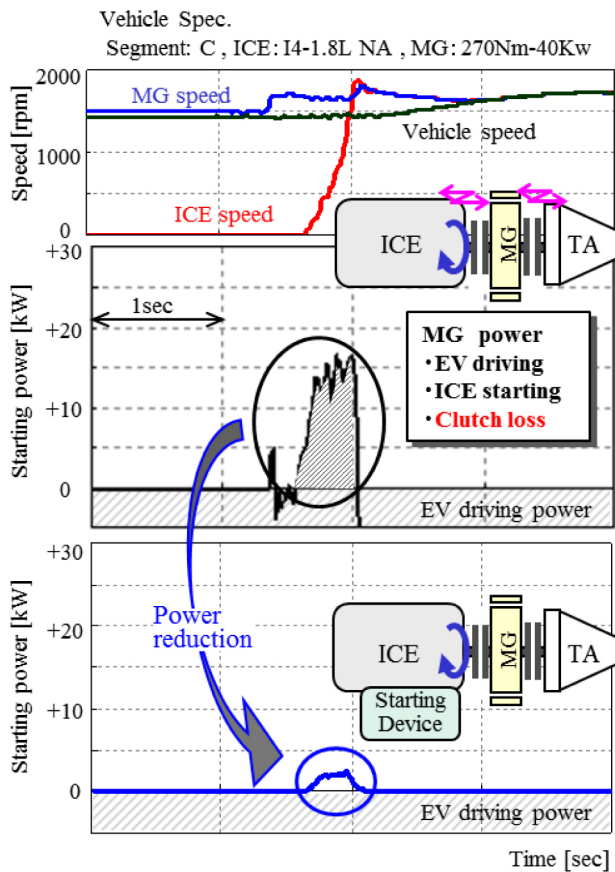


Figure 1. Evaluation results for the experimental vehicle

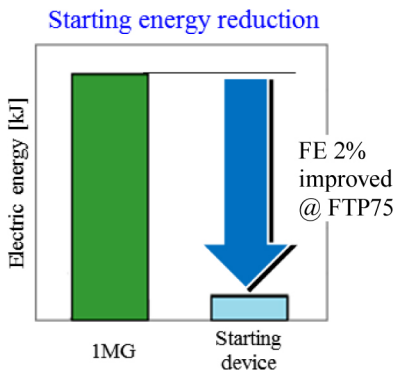


Figure 2. Comparison of electric energy required for starting

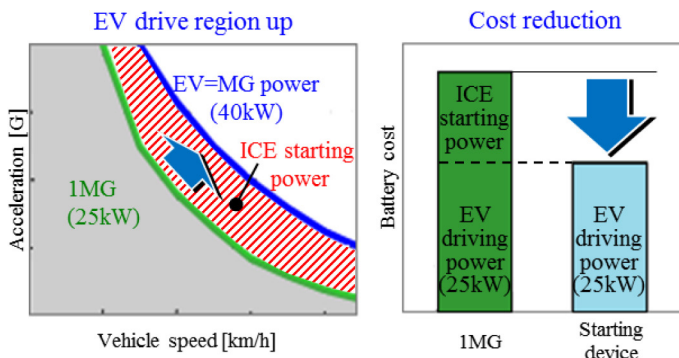


Figure 3. Selectable benefits from adding a starting device

IDEAL STARTING DEVICE

We have categorized the characteristics of the ideal starting device and the functions necessary to enable selection of the starting system. Table 1 show the requirements for each starting device. For a hybrid system, fuel efficiency is the most important function. In addition, long life is necessary, because the system starts the ICE frequently. Our study shows that a pinion shift starter using a high voltage must be one potential solution.

However, the major issue is the cranking noise generated by the pinion mechanism of the starter. In this paper, we introduce the development of low noise cranking control.

Table 1. Comparison of Starting Devices

Ideal Starting Device Characteristics	Requirement	Starting Device			
		12V		High voltage	
		DC Starter	ISG	ISG	AC Starter
F.E.	No clutch loss	Dedicated device	✓	✓	✓
	No drag loss	Disengage function	✓	Belt friction	Belt friction
Quality	Long life (1 million times)	Enhanced brush /Brushless	Limited brush life	Brushless	Brushless
	Stable voltage at 12	2-12V batt. /HV batt.	Additional 12V batt. increase in cost installation issue	Additional 12V batt. HV Batt.	HV Batt.
	NVH	Belt driven /Silent control	Gear noise	Belt driven	Belt driven
	Cold start	High torque	High reduction gear drive	Belt slip	Belt slip

FEATURES OF THE HV STARTER

Figure 4 shows an overview of the HV starter. The motor is a high-voltage brushless AC motor with an inverter. The mechanism was converted from a conventional starter's parts. The operating voltage is designed for 120–450 V. The motor torque is assumed to be 5 Nm.

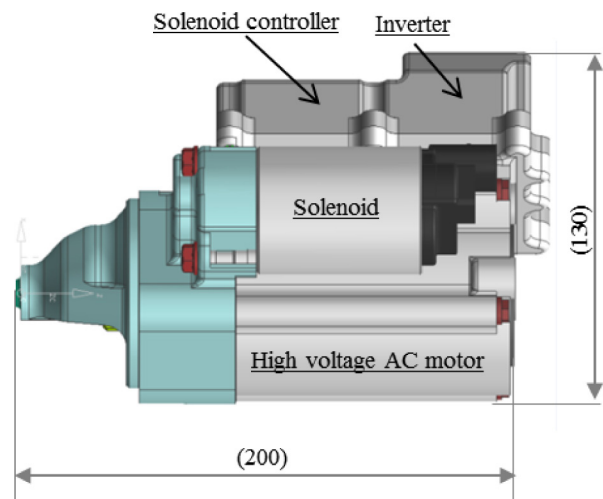


Figure 4. Overview of the HV starter

SYSTEM OUTLINE OF THE EVALUATION VEHICLE

Figure 5 shows the evaluation vehicle. It is based on a 1MG2CL parallel full hybrid system. This hybrid system is composed of a gasoline ICE, one MG, an inverter, a high voltage battery and two mechanical clutches.

In addition, this vehicle has two starting devices; one is a 12 V belt ISG and the other is a pinion shift starter. This starter can be converted to a conventional 12 V DC starter and HV starter. We compared the NVH using the same vehicle to evaluate accurately without the influence of the vehicle condition.

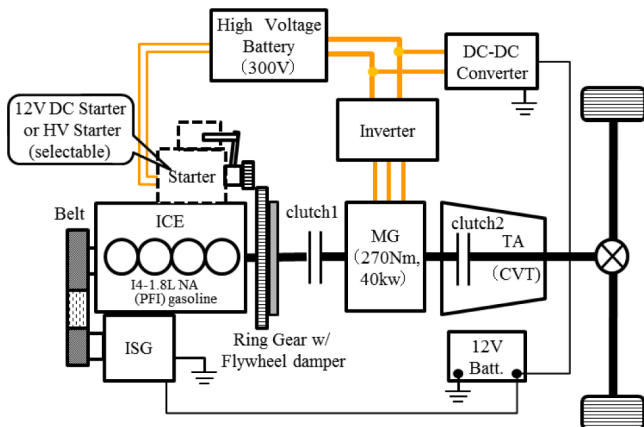


Figure 5. System outline of the evaluation vehicle

BENCHMARK FOR THE CRANKING NOISE

To determine the characteristics of the 12 V DC starter, we measured the cranking noise for a 12 V DC starter and a 12 V Belt-ISG in the cabin of the test vehicle. Figure 6 shows the test results for the cranking noise. It includes the speed of the ICE and starter, overall noise and an FFT analysis of the noise. In the case of a 12 V DC starter, there are at least three noise peaks at the pinion engagement and re-engagement points for the ICE with a starter. Conversely, in the case of a 12 V Belt-ISG, there are no noise peaks on starting except for the noise of the tensioner moving. We set the target level at the road noise level in the EV driving mode. The 12 V DC starter was over the target level, but the 12 V Belt-ISG did not exceed it.

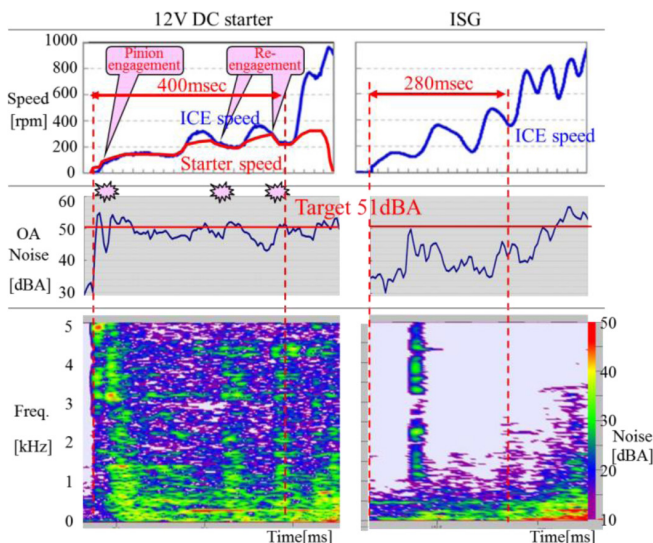


Figure 6. Benchmark results for cranking noise in the cabin

CONCEPT OF CRANKING NOISE REDUCTION

Figure 7 shows the 12 V DC starter's behaviors in the starting ICE phase/period and factors affecting the cranking noise. We analyzed the cranking noise from the 12 V DC starter into three mechanisms.

1. Collision and engagement of the pinion gear with the ring gear
2. Meshing of the pinion gear and the ring gear
3. Re-engagement of the pinion gear with the ring gear

The noise shown at 2. (2. Gear meshing) depends on the hardware; i.e., the ring gear and pinion gear. Consequently, we decided to develop a noise control strategy to reduce the engagement noise (1. Pinion engagement), the re-engagement noise (3. Re-engagement), and the overall operating time.

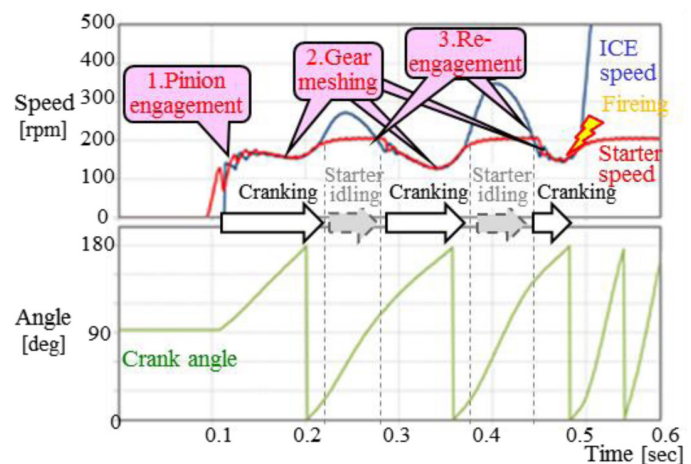


Figure 7. Noise mechanism of the 12 V DC starter

APPROACH TO A CONTROL METHOD

We developed three control strategies as follows.

- A. Preset the pinion for a soft engagement**
To reduce the collision and engagement noise, we developed soft engagement control of the pinion by presetting the position. In addition, to reduce the noise of engagement, we changed the timing of the pinion engagement just after ICE shutdown. In contrast to a 12 V DC starter, it is possible to control the solenoid current and rotation speed of the HV starter independently. We designed the minimum parameters that would satisfy a soft engagement. Thus, the pinion engagement noise when the ICE starts disappeared after presetting the pinion, and this also shortened the starting time.
- B. Pre-positioning the ICE to eliminate one cranking period**
To reduce the noise from one cranking period, we optimized the stop position of the ICE. After presetting the pinion, the HV starter rotates the crankshaft at low speed via the ring gear to the optimum position for the next restart. The optimal position for this is to set the piston to TDC, thereby eliminating the first cranking period in Figure 7.