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Development of GENSET Module Technology of Plug-in Hybrid Electric Vehicles

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Abstract
The main purpose of this paper is to develop the on-board generator (named “GENSET”), equipped on the Plug-in Hybrid Electric Vehicles (PHEVs) in Industrial Technology Research Institute (ITRI), Taiwan. Based on the developed electric power components such as battery integration, DC/DC converters, traction motor and control units, ITRI hybrid powertrains were thereby established by combining above items and existing engine technologies. Therefore, a power-assist 100kW powertrain for a SUV and an 18 kW full-hybrid powertrain in a light-duty vehicle were built. Several techniques of key subsystems such as a 50 kW PMSM traction motor, a GENSET, enhanced vehicle controllers, an 8 kWh/150A battery module, and battery management systems (BMSs) from the powertrains mentioned were utilized to integrate the prototype PHEV. From the experimental results, the 20 kW generator with a 1.2L 4-cylinder engine integrated into a GENSET can reach 20 kW output power and has a good performance in the narrow domain. Finally, we raised briefly several directions for future study.

Keywords: HEV, PHEV, Generator, GENSET.

1 Introduction

The design goal of a Plug-in Hybrid Electric Vehicles (PHEVs) is to increase the stored energy in battery modules to raise the all-electric range (AER) for the series Hybrid Electric Vehicles (HEVs). This design allows a PHEV, as an Electric Vehicle (EV), to be driven in daily life, especially in the urban area. For moving a long distance, the PHEV’s module GENSET (Integrated Engine/Generator) can charge the vehicle on board to extend the driving range through compensating the constraint battery range of pure EVs [1].

Key modules and technology trends of various types of EVs are similar. They mainly include electric propulsion system, high-power battery modules, DC/DC converters, and/or the range-extender system. From the viewpoint of global trends and status, the cost, reliability and safety of battery modules, as well as the battery management systems (BMSs) are the key issues for EV promotion within the next decades [2]. For this purpose, a large amount of global automakers and research institutes have put lots of efforts on the research of reducing the battery weight, enhancing the control algorithms to raise battery performance, decreasing the operation voltage to save cost of power ICs, and increasing safety for batteries. To improve the battery module and to extend the traveling distance of EVs and PHEVs, an engine/generator range-extender system has ben regarded as one of the best solutions. Different design characteristics of green vehicles are listed in Table 1.

Table1: Comparison of the characteristics for various EV (Source: SAE 2008-01-0458)

Toyota Prius

GM EV1

Vehicle Type	Electric Power	Onboard Electric Storage	Grid Conn.	Electric Driving
Mild HEV	low	low	no	no
Full HEV	med	low	no	very limited
PHEV	med	med	yes	limited
E-REV	high	high	yes	Full
EV				

Tate et al., "The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles", SAE 2008-01-0458

From Table 1, it is found that the design of green vehicles for Toyota is to gradually enlarge the electrical part from the traditional engine vehicles. Vehicle types are changed from the Mild HEV (with the electric power-assisted system), Full HEV, PHEV to the Extended-Range EV (E-REV). For GM, they produced a pure electric vehicle, EV1, in the past decades. However, they consequently integrated an engine/generator module to extend the driving range due to the limited battery performance [3]. Although E-REV and PHEV are both EVs with high-power battery system, charging system, engine/generator module, there are still different in some ways. In electric propulsion, both the size of electric motors and battery power of E-REVs are higher than those of the PHEV. An E-REV is always designed mainly for the pure electric mode, while a PHEV can be regarded as an HEV with charging function. For the aspect of energy storage, the energy storage capacity of E-REV is higher than that of the PHEV. Moreover, both E-REV and PHEV are able to be interconnected to the electric grid network.

2 The Specification of GENSET Module

The configuration of the ITRI (Industrial Technology Research Institute) PHEV system is illustrated in Figure 1, where the GENSET, traction motor, energy unit and related controllers are shown.

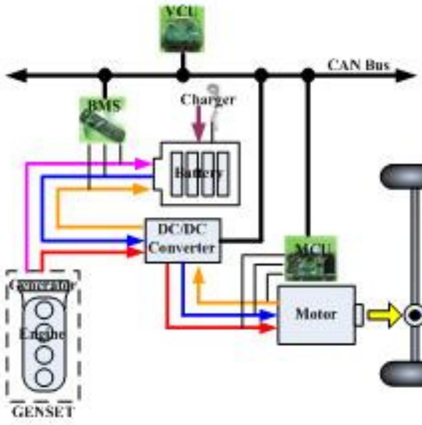

Figure 1: Configuration of the ITRI PHEV systems

The first stage for designing the GENSET is to analyze the mileage and vehicle dynamic performance by reliable analyzing tools. Meanwhile, the system architecture, component specifications and control strategies are carried out. To achieve the goal of a 40 km AER, and a 250 km extending range, the GENSET is integrated with a 1.2 liter engine and a 20 kW generator as shown in Figure 2, where the energy storage device is a 8 kW-hr high performance Li-ion battery package, and the traction motor is a 50 kW Permanent Magnet Synchronous Motor (PMSM).

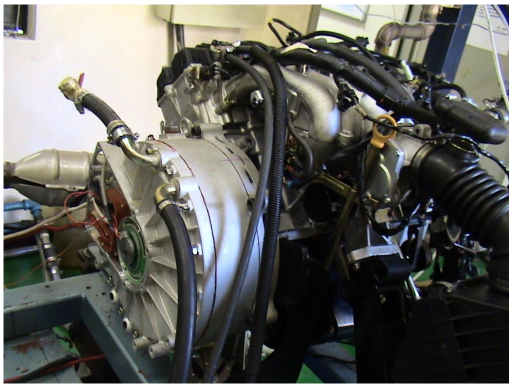

Figure 2: GENSET structure

2.1 High Performance Engine

The chosen engine is a 1.2L 4-cylinders/16 valves multipoint injection engine whose maximum torque is 100 N-m and maximum output power is 50 kW as shown in Figure 3. We had modified it's the original control strategies of the Engine Management System (EMS) and related diagnostic functions have been tuned in order to meet the requirements of a PHEV, including start/stop, high-output power, speed control, torque control and power conversion.

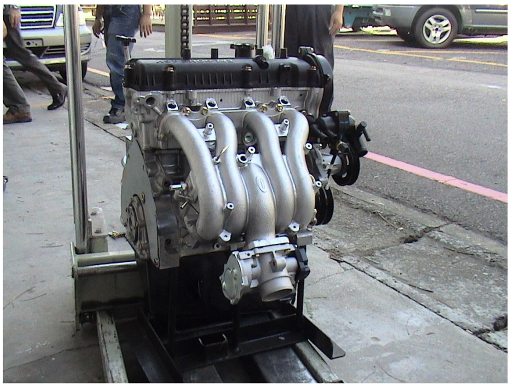

Figure 3: 1.2L 4-cylinders/16 Valves Multipoint Injection Engine

Measured by dynamometer, the experimental results were plotted in Figure 4, where the maximum torque output is 105 N-m occurred between 4000 ~ 4500 rpm. The maximum output power is 51 kW at 5000 rpm. Also, the optimal brake specific fuel consumption (BSFC) is less than 250 kW-hr/g. Currently, the engine operates in Miller cycle, while the next stage will explore at the Atkinson cycle and fix the operation points around the optimal BSFC area in generator mode, which is to improve the combustion efficiency.

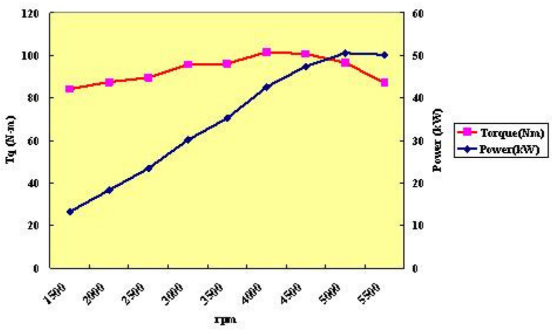

Figure 4: Engine Performance: Torque vs. rpm

2.2 20 kW Generator

According to the preset requirements such as good thermal treatment, minimized noise, and vibration, the light stator winding is necessary. Moreover, the connection interface with the engine allows the GENSET to be placed in the original engine room as shown in Figure 5 (a). The power stage module of the controller integrates the intelligent power module (IPM), the DC/DC module, logic components and the Optocoupler module. Therefore, the controller, as shown in Figure 5 (b), has the properties of initial state protections, complex signal reduction by logic circuits, intelligent system protection, and high stability.

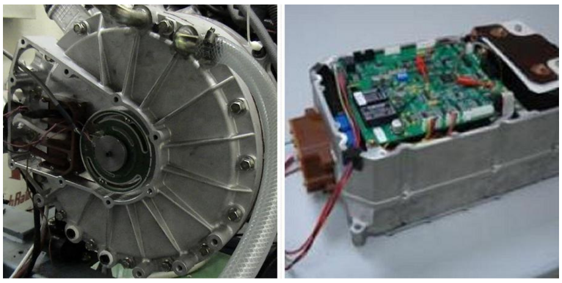

Figure 5: (a) 20kW Light Generator and (b) its Controller

In order to properly operate the engine, the controller must equip with the functions of quick start, fixed speed control, constant power control, and variable power control the maximum output power can be reached over 20 kW after 3250 rpm, and the maximum efficiency can be raised to 93% as illustrated in Figure 6. Moreover, we conducted a rigorous test for this light generator under different duration requirements. The output performances have similar results within 100 hours duration, and the maximum torque ripple error does not exceed 5%, as shown in Figure 7.

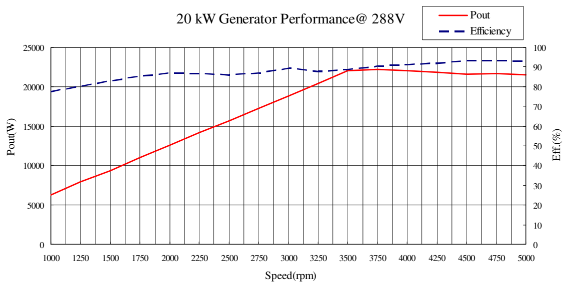

Figure 6: Output Power and Efficiency of Generator

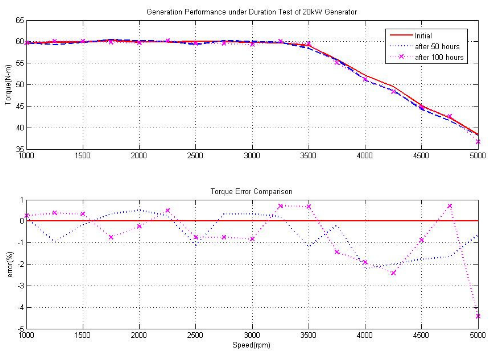

Figure 7: Generator Performance

3 Relational Interface and Power Linkage

3.1 Traction Motor

We adopted a 50 kW PMSM as the traction unit in our PHEV system as illustrated Figure 8 (a) and (b). The rating power of this motor is 35 kW between 2700 ~ 4200 rpm, and peak power is 52 kW at 3600 rpm. The power linkage of the traction motor has high power energy unit and GENSET module.

Figure 8: (a) a 50 kW Traction Motor and (b) its Controller

The measured performance of traction motor is shown in Figure 9, where the base load speed of the traction motor is before 2500 rpm, the maximum speed is at 7000 rpm, and the continuous torque is 120 N-m before 3300 rpm, and the peak torque is 200 N-m before 2000 rpm.

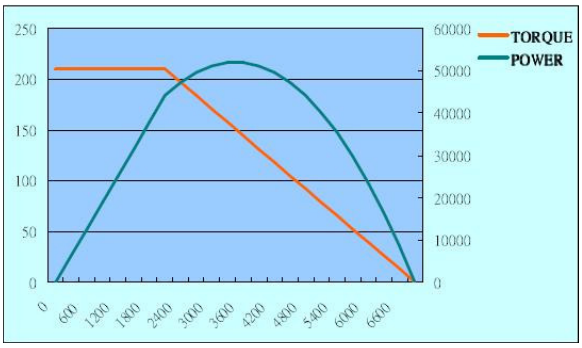

Figure 9: Measured Traction Motor Performance Map

3.2 Integrated Power System

Based on performance requirements of ITRI PHEV, the integrated power system included lithium-ion batteries, the DC converter and the battery management system as shown in Figure 10. The battery of integrated power system is an 8 kWh/288 V/150 A battery module. And the BMS has functions of the cell voltage detection and the temperature protection by Controller Area Network (CAN) bus. Different operating modes, such as charge-depleting mode, charge-sustaining mode and mixed mode, are also included in the BMS for driving needs.

Figure 10: Integrated Power System

3.3 DC Converter

In addition to the high-voltage part for the traction motor, the vehicle is operated by a number of auxiliaries at 12-V low-voltage. Therefore, the 288-V high voltage has been converted into the 12 V low-voltage through a DC converter for controller power, relays, and other components. From a simple test results shown in Figure 11, the same results under different high-voltage inputs are obtained.

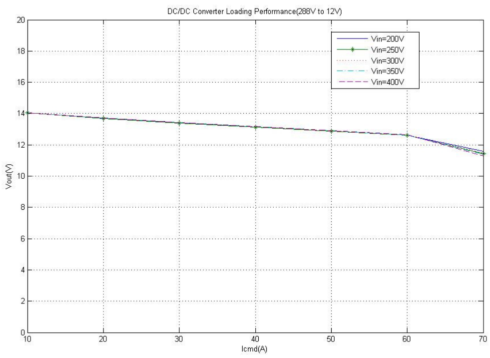

Figure 11: Performance of DC/DC Converter

3.4 Vehicle Control Unit

To replace the real PHEV, a real-time vehicle simulation systems was constructed and integrated with the Vehicle Control Unit (VCU) to form a hardware-in-the-loop platform through the CAN interface as shown in Figure 12. The optimal energy management can be found according to the quantitative simulation results. The simulator contains the engine, the traction motor, the GENSET and the battery module. Aimed to run at ECE 40 driving cycle, the vehicle simulator includes the driving cycle model, driver model, battery model, engine model, motor model and the powertrain model.

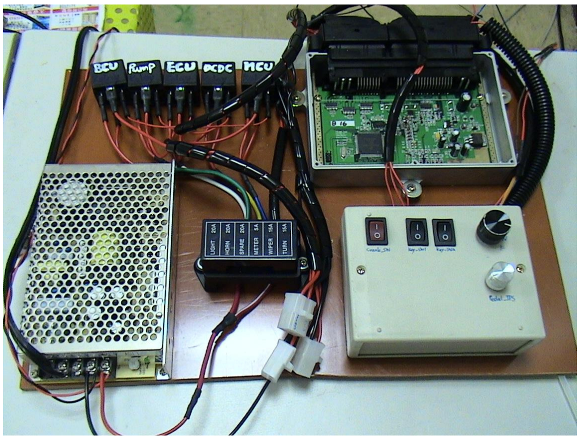

Figure 12: Vehicle Control Unit

4 Experimental Results

Experiments were conducted for the generator of GENSET natural generation under different engine speed conditions, as a strategy for future development. The results are illustrated in Figure 13. Without loading, from the engine idle (about 850 rpm) to mid-high speed (about 4500 rpm), the air-intake negative pressure of engine maintains almost within 40 ~ 50 kpa, as shown in Figure 13. The engine throttle opening at about 50% in mid-high speed, the generator of GENSET does not produce any power in the synchronic running with engine.

Starting from the high speed 4500 rpm, the air-intake negative pressure of engine move upwards, and the throttle opening is also climbing. In the same time, the generator of GENSET begins to produce some powers. Finally, the air-intake negative pressure of engine reached 100% at about 5800 rpm, and the Engine Control Unit (ECU) is off automatically at once.

In the process, the generated natural power has to ensure the balance of battery's State of Charge (SOC) when it operates more than 4500 rpm, as considering in the vehicle strategic development.

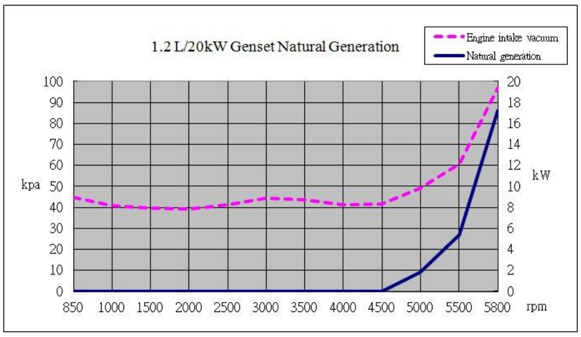

Figure 13: GENSET Natural Generation

In figure 14, we experiment the generation function of GENSET, the system operation voltage is 300Vdc, when the system starts, the generator can generate about 65 amps stably immediately. Therefore, integrated power system can obtain a long stable and sustainable high-power generated line to fall in the 20 kW (take about 5 minutes) from GENSET.

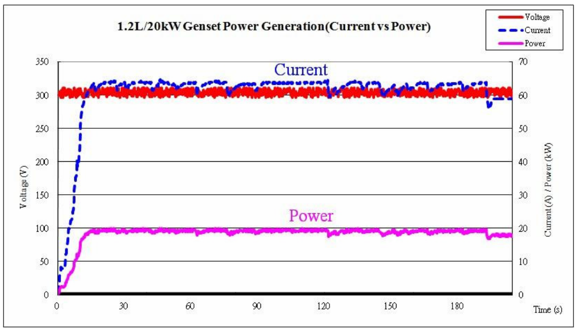

Figure 14: GENSET Power Generation

In Figure 15, the engine is operated between 2000 ~ 4000 rpm and carry out in every 500 rpm intervals in order to observe the relation between the engine torque and generator torque. The narrow domain of 2000 ~ 4000 rpm is selected due to its high efficient area and small noise for PHEV. Finally, the ideal power generation is compared to the actual power generation and is shown in Figure 16. It observed that they have a similar generation performance except for when the engine is idling.

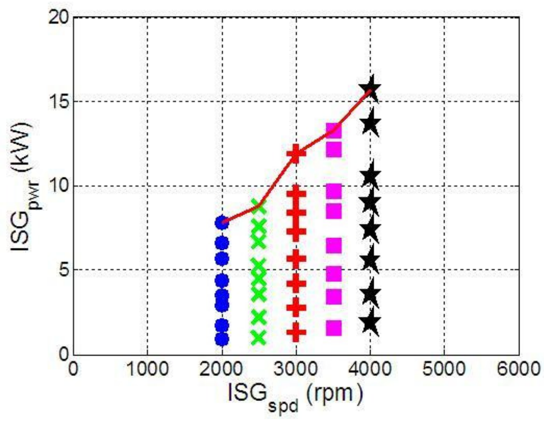

Figure 15: Narrow Speed Generation

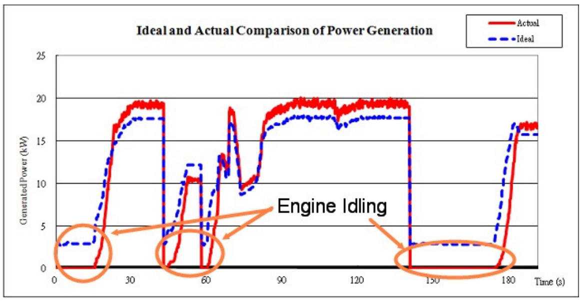

Figure 16: Compare Ideal with Actual Generation

5 Conclusions

In this work, the 20 kW generator with a 1.2L 4-cylinder engine integrated into a GENSET can reach 20 kW output power and has a good performance in the narrow domain.

A proportional relationship for the maximum output power and the engine speed is rpm : kW≒ 3000:10. That is, when the engine speed is at half loading (throttle opening at 50%), the maximum generating output power about 10 kW, while the engine speed is at full loading (throttle opening at 100%), the maximum generating output power about 20 kW. Consequently, it is known that the maximum output power is 6.7 kW at 2000 rpm, and 13.3 kW at 4000 rpm, according to the relationship.

Several directions for future study:

(1) The output power can be raised to at least 10 kW in the narrow domain without changing any conditions.

(2) For 6.7 ~ 13.3 kW, how to specify the smaller engine and generator, in order to meet the small PHEV configuration design.

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