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Plug-in Hybrid Systems newly developed by Hynudai Motor Company

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Abstract

As a solution for reducing fuel energy consumption and emissions of cars, hybrid electric vehicle (HEV) systems have been proposed and the development of technology has advanced by leap and bounce. Among the hybrid systems, a plug-in HEV (PHEV) which is a vehicle which combines the features of HEV and electric vehicle (EV) has significant potential to decrease fuel consumption and greenhouse gas emissions. In this paper, new PHEV systems developed by Hyundai Motor Company (HMC) will be described with the attributes of the PHEV systems. The EV driving performance and configurations of HMC's PHEV systems will be described.

Keywords: Plug-in Hybrid Electric Vehicle (PHEV), Blended PHEV, EREV (Extended-Range Electric Vehicle), Multi-mode hybrid system,

1 Introduction

As the exhaustion of fossil fuel energy sources and the exacerbation of environmental problem, various automotive technologies that have possible potential for reducing fuel consumption and emission have been proposed. The deliverables of year's long continuing research include HEV, EV, PHEV and Fuel Cell Electric Vehicle (FCEV).

In recent years, HMC introduced various types of HEVs such as a mild HEV and a full HEV and started mass scale production in automobile industry. Meanwhile, HMC has researched and developed EV, PHEV and FCEV for on sale in the global auto market. Consumers will be able to purchase these eco-friendly cars of HMC in the near future.

Among the various approaches, the PHEV is emerging as one great solution surpassing conventional HEV systems. The PHEV is expected to make up the defect of EV and scale up the merit of HEV.

According to the research for PHEV customers, PHEV customers can be classified into two types as following; a customer who prioritize actual electric driving range and a customer who prioritize overall efficiency and reducing gas expense.

The former is to satisfy pure electric drive in city and in less than 65MPH on highway and allow engine to be used during rapid acceleration and high speed on highway. The latter strongly require pure EV mode most of their driving circumstance and longer driving range than pure EVs even if engine is used. HMC has been researching and developing various types of PHEV that can meet the needs of customers.

This paper will compare the concepts between Blended PHEV and Extended-range EV (EREV), two types of PHEV classified by customers' preference and describes the configuration, features and performance of a PHEV system being newly developed by HMC.

2 Plug-in HEV

A PHEV is a vehicle which combines the features of HEV using an internal combustion engine and battery-powered electric motors and electric vehicle (EV) using a battery-powered electric motor only and charging the battery pack from external energy source. The advantages of PHEV are to enhance the fuel economy of HEV and to compensate the short driving distance of EV. As shown at Figure 1, the PHEV has different battery management mode according to the condition of battery SOC. In case of high SOC by charging from external energy source, a PHEV is operated in charge depleting (CD) mode where a PHEV drives most or all of distance in EV mode until a battery is depleted to a predefined target SOC. When the battery SOC is depleted below a predetermined minimum SOC level, the mode is switched to charge sustaining (CS) mode that sustains a target level of battery SOC. As a result, the PHEV has significant potential to decrease overall fuel efficiency and greenhouse gas emissions.

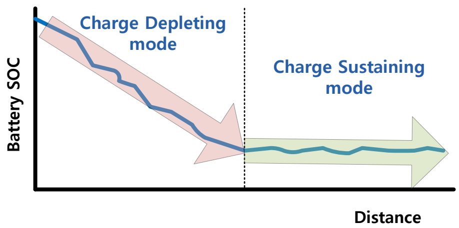

Figure 1. Battery SOC management of PHEV

2.1 Features of PHEV

A PHEV can be classified into Blended PHEV and Extended- Range EV (EREV) according to the EV driving capability on US 06 driving cycle as shown at Figure 2.

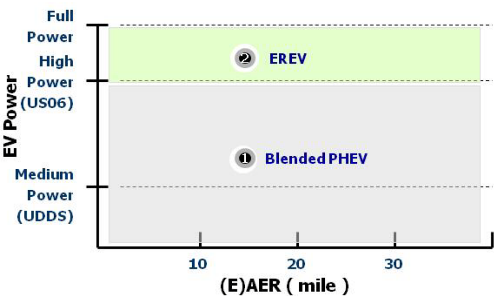

Figure 2. Classification of PHEV

- Blended PHEV: a PHEV that expands the electricification of HEV by adding the energy capacity of battery pack. Thus the engine turn-on is occasionally blended in CD area as presented at Figure 3.

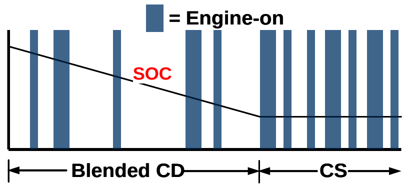

Figure 3. Driving feature of Blended PHEV

- EREV: PHEV that enhances the electric driving capability by increasing the power of electric motors and battery pack compared to blended PHEVs so that the engine does not turn on under all circumstances in CD mode period as the following Figure 4.

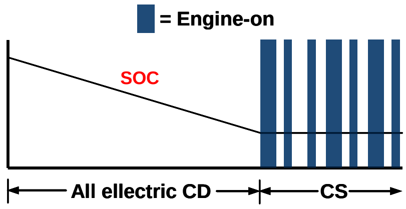

Figure 4. Driving feature of EREV

The system configuration of PHEV can be adopted among several hybrid system configurations such as parallel hybrid system, power-split hybrid and multi-mode hybrid system. However, Table 1 shows that each hybrid system configuration has different compatibility for use with HEV and PHEVs.

Table 1. Compatibility between hybrid configurations

	HEV	Blended PHEV	EREV
Parallel	Compatible	Compatible	
Power Split		Compatible	
Multi Mode		Compatible	Compatible

The feature of Blended PHEV is to be compatible with parallel, power-split and multi-mode hybrid system because of convenience of additional battery integration. On the other side, Multi-mode hybrid system of hybrid configurations is compatible with PHEV systems such as EREV and Blended PHEV.

Multi-mode hybrid system consists of a power-split mode and a parallel mode. The feature of

multi-mode hybrid system has a flexibility which can be applied for various hybrid systems.
As comparing in side of competitiveness of HEV, Blended PHEV, EREV and EV, at Table 2, EV must be the most eco-friendly technology but expensive cost and driving range make consumers to hesitate about buying EV. EREV can be decided as the most acceptable technology in cost, environment, and long driving range respect. EREV can be regarded as a practical EV and in charge of next-generation eco-friendly automotive technology.

Table 2. Competitiveness of Eco-technology

Technology	HEV	Blended PHEV	EREV	EV
Cost	☹	☹½	☹☹	☹☹☹
Environment	☺	☺½	☺☺½	☺☺☺
Long driving range	☺	☺	☺	☹
Customer Acceptance	☺	☺	☺	☹

HMC has been successfully launching YF Sonata HEV which adopted a parallel hybrid system with hybrid starter-generator (HSG). YF Sonata HEV achieved better fuel efficiency and driving performance. Furthermore, HMC has developed diverse PHEV systems and exerted all possible efforts for a new PHEV system that enhances the flexibility and extensibility into various hybrid systems.
HMC remodelled an existing HEV system to a Blended PHEV. On the other side, a new system configuration was newly developed for adopting into EREV system.
Table 3 presents the specifications of Blended PHEV and EREV being developed by HMC. Blended PHEV is descended from YF sonata HEV. EREV is created by a new-concept powertrain technology and new components.

Table 3. Specifications of HMC's PHEVs

	Blended PHEV	EREV
System configuration	Parallel	Multi-mode (Power-split+Parallel)
Engine	2.0 L Gasoline	1.6 L Gasoline
Battery power	45 kW	103 kW

Next section describes the features of a new HMC's EREV system and validation by fleet test on certified driving cycle and real world driving conditions.

3 Extended-Range EV (EREV)

3.1 Features of EREV

A new hybrid configuration has been required to make an effective and flexible system for all electric PHEV or EREV. In order to configure EREV system, the engineers of HMC decided to adopt a multi-mode hybrid system which can perform a power-split mode and a parallel mode. The feature of power-split mode has the function of ECVT (electric continuously variable transmission) which can operate engine on optimal operation line due to continuous gear ratio. However, its system efficiency tends to drop beyond the mechanical point. In order to make up that weak point, discrete gear modes like auto-transmission are selected in the area of low system efficiency to perform a parallel hybrid system.
The powertrain configuration of HMC EREV consists of one engine and two motors linked up with clutches/brakes and planetary gear sets.

3.2 Mode selection of EREV

The mode selection of EREV can be different according to the period of CD and CS.
In the CD period, EREV is operated as a pure EV in case of usual driving condition. The operation mode is divided into EV#1 and EV#2 by vehicle speed as shown at Figure 5.

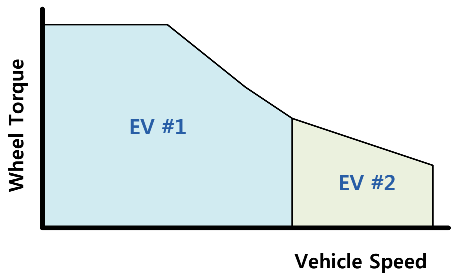

Figure 5. Operation mode in CD period

In EV #1 mode below a predefined vehicle speed, EREV system is transformed into a parallel hybrid system with propelling capacity of dual motors. This flexibility is the great merit of HMC EREV system. As shown at Figure 6, by locking up the second node on the lever, two middle different sizes of electric motors can simultaneously supply output power for EV propelling by the command of optimized control strategy. Moreover, these motors will also play an important role for ECVT in other modes in CD and CS period.

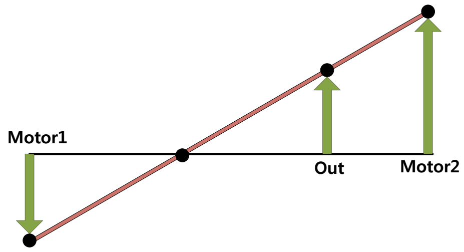

Figure 6. Lever analysis of EV#1 mode

At high speed, the mode will be switched to EV#2 which applies the mechanism of power-split mode for power distribution.
Because two motors in EV #1 mode are connected in parallel each other, the output power can be calculated uncomplicatedly by power of Motor1 plus power of Motor2 as presented in Figure 7. This fact makes it easy for optimization approach to be applied.

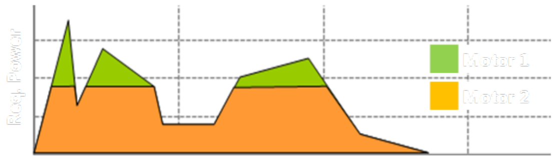

Figure 7. Power distribution strategy of EV #1

In the CS period, the operation mode consists of power-split mode and discrete gear shifting mode based on a parallel hybrid mode. The strategy for mode selection is dependent on the output speed of transmission and gear ratio including overall system efficiency. The control strategy concept of EREV in the CS resembles that of conventional HEVs.

3.3 Powertrain implementation

The powertrain of HMC EREV was designed to allow as much flexibility as possible while meeting the objective of fuel economy and driving performance.

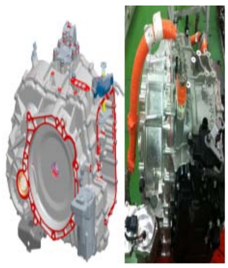

Figure 8. Prototype powertain of HMC EREV

As shown in Figure 8, HMC has done the extensive design of EREV powertrain and made a prototype powertrain of EREV. In Figure 9, the EREV vehicle was equipped with a highly efficient EREV powertrain including 1.6 L engine, electric motors and transmission designed exclusively by HMC.

Figure 9. EREV powertain equipped in vehicle

The battery pack in HMC EREV is muc larger than that of a typical HEV. The reason for such a large battery pack is to help maximize the EREV’s all-electric range (AER) and available elelctrical power for the electric motors. Lithium-ion polymer battery was chosen for HMC EREV. The peak power of 103 kWis enough power to run both electric motors in EV #1 mode during the CD period. Figure 10 shows the battery pack and on board charger (OBC) installed in HMC EREV.

Figure 10. Battery pack & OBC in HMC EREV

3.4 Performance of HMC EREV

As a practical EV, EREV must have EV driving ability on US06 cycle. That is a vehicle performance criterion. Therefore, the prototype vehicle of HMC EREV is also required to meet the performance criterion of EREV. A chassis dynamometer was used to simulate EV driving performance of HMC EREV on US06. The powertrain of EREV was automatically controlled under a powertrain control unit integrating engine, motors and transmission.

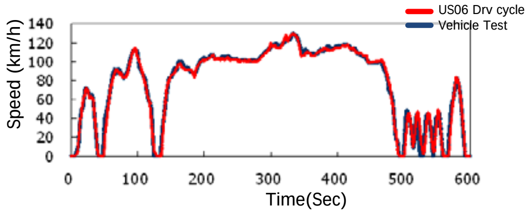

Figure 11. Test result on US06 driving cycle

In the result, during driving on US06 cycle, the operation mode of EREV transitions from EV #1 to EV #2 or from EV #2 to EV #1 depending on mode selection strategy in the CD period. Figure 11 shows that the HMC EREV successfully traced on the reference speed of US06 cycle in pure EV mode.

4 Future works

HMC will continue our efforts to improve the overall system efficiency of HMC EREV powertrain. Besides US06 cycle, the performance of fuel efficiency on the city cycle (UDDS) and the highway cycle (HWFET) will be tested. In order to verify the effluence in real life, real world driving conditions will be tested.
Eventually, one of our goals is to improve the shifting quality (SQ) under the condition of mode transition for satisfaction of consumers.

5 Conclusions

MHC has exclusively developed an EREV with a multi-mode hybrid powertrain. The resulting vehicle operates on EV mode all or most of charge-depleting (CD) period, and has minimal environmental impact on the earth. Fuel economy of HMC EREV is almost double the stock HEV even more. Its ability to use dual motors for EV driving can reduce total size of electric motors of EREV even though having a power-split mode. The increase usage of renewable electricity is able to make HMC EREV a significant contribution reducing dependence on petroleum and greenhouse gas emission.
It is believed that HMC EREV is potentially the only vehicle that can meet the demands of the consumers and automotive makers. Thanks to our hard work and accumulated knowledge for HEV/PHEV system development, HMC EREV will be a great success solution in the future.

References

[1] *PHEV Customer Requirements*, Internal Technical Report, Hyundai Motor Company

Authors

Buhmjoo Suh received a Ph.D. degree in mechanical engineering from the University of California at Davis, USA Since 2008, he has worked as a senior research engineer of Eco-vehicle system test team at Hyundai Motor Company, where he is working on the development of HEV system. His current research interest includes the PHEV and EREV system and control strategy

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