

Review on the Configurations of Hybrid Electric Vehicles

Edward W C LO¹

Department of Electrical Engineering, The Hong Kong Polytechnic University
Email: eewclo@polyu.edu.hk

Abstract – This paper presents an introduction to hybrid electric vehicles, the commonly used configurations of the driving chains, the comparisons among these configurations, and then finally the possible developments of hybrid electric vehicles in the near further. Plug-in hybrid electric vehicles are also included in the discussion.

Keywords – electric vehicle, hybrid vehicle, plug-in hybrid.

I. INTRODUCTION

Now there are great concerns on green house gas (GHG) emissions in the whole world, deployment of zero/low emission cars can surely help in reducing GHG emission, hence the developments of electric and hybrid vehicles have accelerated in a number of car manufacturer companies. Purely electric vehicles (usually referred as battery electric vehicles BEV) basically have zero GHG emission and should have better impacts in terms of reducing GHG. However, generally BEVs seem to have lower popularity due to the main reason that their range and acceleration performance are far behind the internal combustion engine (ICE) powered cars. Therefore, before a great breakthrough in battery technology, hybrid electric vehicles (HEV) are good compromise between performance and environment protection. In fact, as of the end of 2007, over a million HEVs have been sold worldwide. This paper will review and comparison different possible configurations of HEV currently being in different car manufacturers and will predict the possible directions of development of HEV in the near future.

II. WHAT IS AN HYBRID VEHICLE

The Technical Committee 69 (Electric Road Vehicles) of the International Electrotechnical Commission (IEC) suggested that an HEV is a vehicle in which propulsion energy is available from two or more kinds or types of energy stores, sources or converters and at least one of them can deliver electrical energy [1]. Based on this there many types of HEV. However, in order to limit the scope of discussion in this paper, we will only discuss those HEVs which have an ICE and electric motor(s) in their driving chain. Even with this simplification, there are still many ways one can arrange the relative positions (in terms of driving chain topology) of the ICE and the electric motors(s) in the HEV, these will be detailed in Section 4.

III. ADVANTAGES OF HEVS

An ordinary ICE car uses its maximum kW power rating only for about 1 % of the time [2]. The large engine put on more weight and fuel consumption. In addition, when ICE operates under highly varying load conditions, its overall energy efficiency will be greatly reduce.

On the other side, an HEV usually has a smaller ICE. The ICE can operate under less varying load; hence can be optimized for efficiency. While the electric motor can assist when required (or in some conditions) to power the car. In addition, regenerative braking can be applied to recover energy during braking or down-slope driving; these further improve the fuel economy of the car.

As an example on an impressive fuel consumption value of HEV, Toyota Prius Hybrid (2004-2009 model) achieved 4.0 litre/100 km in City driving cycles, and 4.2 litre/100 km in Highway driving cycles (source: Natural Resources Canada EnerGuide 2006).

IV. CONFIGURATIONS OF HEVS

The main challenge for HEV design is on how to manage multiple energy sources, which is highly dependent on driving cycles, ICE sizing, battery sizing, motor sizing, and battery management. The ultimate aim is to maximize the efficiency of the whole driving system, while providing reasonable (as compared with ICE car) performance in terms of acceleration, range, dynamic response, comfortness, etc.

The configurations of drive chain of HEV can be roughly divided into 3 types: Series, Parallel and Complex HEVs

1) *Series HEV*: it can be regarded as a simple extension of BEV by adding an ICE (as shown in Figure 1) to charge the battery set in order to extend the driving range of the vehicle, hence it eliminates one of the major drawbacks of BEV. The configuration is just like diesel-electric locomotives used in railway systems.

Usually, the ICE is kept in off mode in urban driving, in order to reduce the GHG emissions in city centers. In this case, the power to the motor is only from the battery. Of course, the converter has regeneration capability, much that significant amount of energy can be recovered during down-slope driving and braking. This not only enhances the fuel economy, it also extends the lift the braking system.

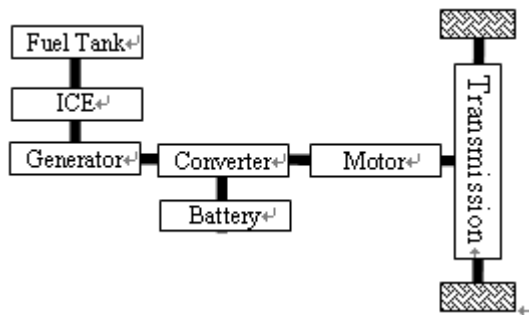


Fig 1: Series HEV

The ICE is turned on only when the battery energy storage level is low or in country side driving. In this case, as shown in Figure 1, the converter can divert the power from the generator to the motor or the battery or both, depends on the power demand of the motor. In general, the control strategy is that: the ICE is operating at a more-or-less constant output power level such that its efficiency is maximum, the surplus power will be used to charge the battery when the power demand of the motor is lower than the generator output power. On the other hand, when the power demand of the motor is higher than the output power of the generator, all the power from the generator will be used to drive the motor, plus additional power from the battery to meet the need of the motor.

Therefore, the ICE is either off or operates at its highest efficiency point, and hence greatly improves the fuel economy of the vehicle as compared with conventional ICE. The power rating of the ICE-generator set can be designed differently depends on the application characteristics of series HEV.

Examples of series hybrids include the Renault Kangoo Elect'Road (2003), Toyota's Japan-only Coaster light-duty passenger bus, Daimler AG's hybrid Orion bus, the Chevrolet Volt (Figure 2) production car and the Opel Flextreame concept car.



Fig 2: Chevrolet Volt, a Series HEV

2) *Parallel HEV*: it parallels the mechanical power outputs from the electric motor and the ICE to drive the transmission, as shown in Figure 3. There are a number of control strategy can be used for parallel, one of the common ways is: the ICE is basically always in on mode and operates at almost constant power output at maximum efficiency point.

When the demand power from the transmission is higher than the power output of the ICE, the motor will be turn on and supplement the difference in power. When the demand of the transmission is lower the power output from the ICE, the motor will become a generator and the surplus power will be used to charge

the battery set. In this way, this can be regarded as an electric-assisted ICE vehicle; the electric motor is simply acts as a buffer to smooth the appeared loading to the ICE, such the ICE can maintain at almost constant output power level of maximum efficiency, such that it greatly improve the fuel economy.

Again regenerative conversion in down-slope driving and braking can be applied in this type of vehicle to charge the battery.

The Insight model, a three-door hatchback car (Figure 4), introduced by Honda in 1999 is a specific implementation of parallel HEV. Other examples are: Ford Escape Hybrid SUV and Lexus Hybrid SUV.

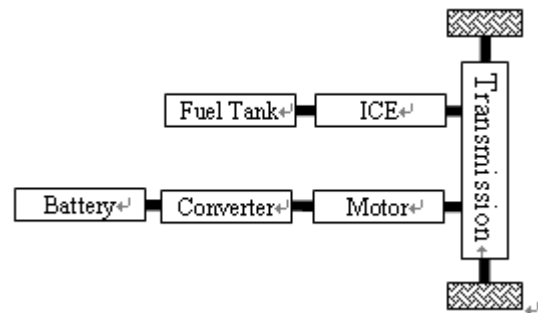


Fig 3: Parallel HEV



Fig 4: Honda's Insight, a Parallel HEV

When comparing series HEV and parallel HEV, series one needs 3 rotating machines (ICE, generator and motor), while parallel one needs 2 only (ICE and motor). The other advantage of the parallel one over the series is that: the parallel HEV needs a smaller ICE and a smaller motor for the same vehicle performance (in terms of peak acceleration and maximum up-slope capability), as at maximum power/maximum torque output, the ICE and motor are operating in parallel to provide the power/torque together.

For long trip operation, in all types of HEVs (except plug-in hybrid, which will be discussed later), all the consumed energy ultimately are from the on-board fuel tank. For series hybrid, one can see that the number of conversions from the fuel tank to the transmission (by the ICE, then by the generator, then by the motor) is more than that of parallel hybrid (by ICE only). This suggests that parallel hybrids should have a better fuel economy in long range operation.

On the other hand, the mechanical design of the transmission design of parallel HEV is far more complicated than series HEV, as it needs to accept 2 mechanical inputs (with one of this is bidirectional) and

one mechanical output (again bidirectional). In addition the location of the ICE in series HEV is more flexible, as it is decoupled mechanically from the transmission.

3) *Complex HEV*: all other configurations different from the above two types of series and parallel HEV can be referred as complex HEV, hence there are many variations within this type. All these variations try to compensate for some of the drawbacks in the above 2 types of HEV with some additional complications and cost. Three sub-types will be discussed below:

3a) *Series HEV with peak-power unit*: This is a simple extension of the series HE. In series HEV, in order help the motor to cope with the peak power/torque requirements without using a large motor, a flywheel may be added and coupled to the output of the motor (say, via continuous variable transmission), as shown in Figure 5. This is referred as Series HEV with peak-power unit.

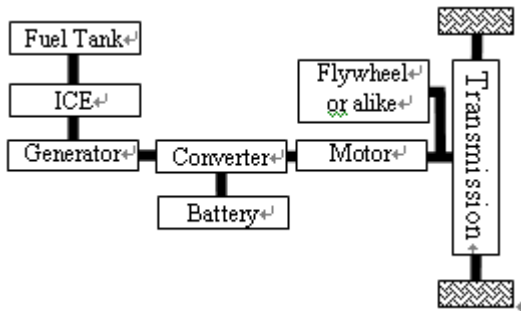


Fig 5: Series HEV with peak power unit

3b) *Series/parallel HEV*: by adding an additional mechanical linkage and a generator between the ICE and converter in a parallel HEV will allow both series and parallel operations of the ICE and the motor, as shown in Figure 6, and hence results in series/parallel HEV. Obviously, it allows for more flexible operations, but it is also complicated in structure and costly in price. The popular Toyota Prius (model NHW20, 2004-2009, as shown in Figure 7) adopted this configuration

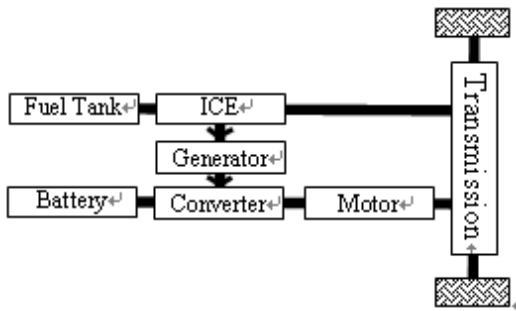


Fig 6: Complex HEV – series/parallel



Fig 7: Toyota's Prius (2004-2009 model), A Series/Parallel HEV

3c) *Bidirectional Series/parallel HEV*: If the power flow in the link between the ICE and the battery in

series/parallel HEV is bidirectional, such as that the generator can also act as motor, and hence there can be 2 electric motors to drive the transmission, if needed. This results in Bidirectional series/parallel HEV as shown in Figure 8. Therefore there is even more high flexibility in operation modes, but of course more higher complexity and costliness.

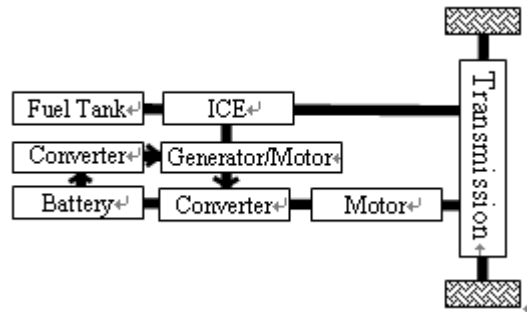


Fig 8: Complex HEV – bidirectional series/parallel

Table 1 summarizes a brief comparison among the 3 types of HEVs.

In each of the above types of HEVs, 2 or 4 wheel motors may be used, instead of only one main electric motor. Then each of these wheel motors will be controlled to achieve the desired speeds and hence eliminates the transmission and differential gears. This can further improve the overall system efficiency and hence the fuel economy.

Another possible ways of variations is the type of motor used. Three-phase induction motor, brushless DC motor and switch reluctance motor are the three commonly used motors in HEVs applications.

Table 1: Comparison among 3 types of HEV

	Series HEV	Parallel HEV	Series/Parallel HEV
Fuel economy Improvement:			
Idling stop	Superior	Superior	Excellent
Energy recovery	Superior	Superior	Excellent
High efficiency operation Control	Superior	Somewhat Unfavorable	Excellent
Total efficiency	Somewhat unfavorable	Superior	Excellent
Driving Performance:			
Acceleration	Somewhat unfavorable	Superior	Superior
Continuous high output	Somewhat unfavorable	Somewhat unfavorable	Superior

V. PLUG-IN HYBRIDS

Plug-in hybrid electric vehicle (PHEV) is a subset of HEVs, which according to the IEEE have at least the following:

- A battery system of 4 kWh or more used to power motion

- A means of recharging from an external electrical source
- An ability to drive 10 miles (16 kilometer) without using fuel (i.e. in all-electric-mode).

The power chain arrangement of PHEV can be any one of the above described configurations. Of course its main difference, as compared with normal HEVs, is recharging from an external source and then do not require conventional fuel for short trips. Hence, it usually has an on-board charger to allow easy recharging from a normal electric socket. Hence the main advantage is further reducing the GHG emissions (especially when the electricity in the grid is generated from non-fossil fuels, such as solar or wind), which implies improved air quality, particularly in urban areas with high levels of vehicle-related pollution. While the main disadvantage is that, it needs the vehicle user to take care of the battery charging procedure, which one may easily forget. In addition, usually a large battery set is used than normal HEV, in order to ensure a longer driving range in all-electric-mode. This will imply a higher initial cost of PHEVs.

One new model of PHEV is the Toyota's plug-in Prius which is expected to enter the market by the end of 2009. A photo of it is shown in Figure 9.



Fig 9: The Plug-in version of Toyota Prius

One can make a rough estimation on the financial saving of using a PHEV (say, plug-in Prius) in Hong Kong, with the following typical data:

Gasoline cost = HK\$13.5/liter (Price in May 2008)
 Fuel consumption of a normal mid-size sedan with gasoline ICE = 9.5 liter/100km (City driving)
 Distance travelled in a year = 5,200 km (20 km per day, 5 days per week)

Then the fuel cost of gasoline /year = HK\$6,669

Electricity price = HK\$1.00/kWh
 Practical electricity consumption (in all-electric mode) of HEV = 0.3 kWh/km

Then the electricity cost /year = HK\$1,560

Therefore, the saving is more than HK\$5,000 per year.

While this saving may not easily offset the cost of battery replacement after the battery life time, one has to consider, other than financial saving, a large amount of GHG will also be saved.

PHEVs were included in the Energy Independence and Security Act of 2007 in U.S. On October 3, 2008, the U.S. Government enacted the Energy Improvement and

Extension Act of 2008 as part of the bailout of the U.S. financial system. The law, as amended by the American Recovery and Reinvestment Act of 2009, provides tax credits for purchases of PHEVs until less than a year after the first 200,000 per manufacturer are sold, worth US\$2,500 plus US\$417 for each kilowatt-hour of battery capacity over 4 kilowatt-hours, up to US\$7,500 for cars under 10,000 pounds (4,536 kg), or more for larger vehicles up to 14,000 pounds (6,400 kg).

VI. CONCLUSIONS

HEV is expected to be more popular in coming years, before there are great breakthroughs in battery technology for BEV. Large scale production of HEVs starts to appear in the market. There are a number of drive chain configurations available for HEVs. The adoption of a particular configuration on to a model of HEV depends on a number of factors, such as expected driving performances, targeted fuel economy, allowable complexity in the system, cost of maintenance, total initial cost of the whole vehicle, and type of application of the model of vehicle etc. While complex hybrid in general gives better driving performance and lower fuel consumption than series or parallel HEV, but it is at the expense of higher initial and maintenance cost, because of the greater system complexity.

Currently it seems that, even with PHEV technology, the saving in fuel cost may not easily offset the cost of the battery set. However, with the consideration of saving in GHG emission, it should be still worth to adopt HEV to a larger extent.

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