Modelling and Simulation of Series Parallel Hybrid Electric Vehicle

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Abstract. The present paper intends to discuss the architectural structure and the different modes of operation of a series parallel hybrid electric vehicle during a drive cycle. Here an attempt has been made to simulate a standard series parallel HEV using the MATLAB and SIMULINK software to estimate the consumption of fuel for the different drive cycles. The results obtained from the model in terms of the fuel consumption have also been compared with that of a conventional internal combustion engine based vehicle. The study thus reinforces the need and viability of the use of hybrid electric vehicles as an intermediate transition and a pre-requisite to the full electric vehicle for the developing countries like India.

Keywords: Series Parallel Hybrid Electric Vehicle (SP HEV), Power Split Device (PSD)

1. Introduction

Automobile industry has seen rigorous boom in developing countries like India in the last two decades and the prognosis of this sector states even higher rise in manufacturing in the coming time. This results in an increase in the amount of fossil fuel consumption, dramatically followed with subsequent rise in emission of pollutant gases. One of the primary purposes to introduce the concept of a hybrid vehicle is to improve the fuel economy of the vehicle. Development in this area began, with Toyota launching its first Hybrid Electric Vehicle (HEV) under mass-production, gaining much market interests in Japan, named Toyota Prius long back in 1997. [1] Koichiro Muta from Toyota Motor Corp carried out performance study in 2004 of SP HEV, where an improvement of car mileage of 7-8% was obtained. [2] This augmentation in the fuel economy is much higher than that of the previous modifications, which mainly focused on improvement in fuel injection and at most led to an enhancement ranging from 0.5 to 1%. [2]. Regardless of such significant benefits, attention towards this modification by Indian car manufacturers has not been as expected. Moreover, the uncompromising emission norms lay by Govt. of India (Bharat Stage VI) [9] demands automobiles to reduce emission level furthermore. Thus, it is important to address the developments in HEV till date and the ways to inculcate the benefits of this model in our country.

In any hybrid vehicle (series or parallel or series-parallel), the main objective is an attempt to operate the IC engine only in its most efficient band range. In series HEV the mechanical output from IC
engine is converted to electricity by the generator and this electric power can be used to charge the battery or operate motor and drive the vehicle. But for short trips IC engine is downsized, which sizes the motor. This makes the system expensive and economically not feasible. In parallel HEV, IC engine and motor output independently supplies power to the wheels. This design implies a mechanical coupling between the engine and the transmission, inhibiting the engine to always operate in its most efficient band, thus also not feasible for short ride passenger vehicles. [13]

In a Series-Parallel HEV model, both the power sources (electric and fuel based) are combined at the transmission (Epicyclic planetary gear) and then supplied to the wheels. This paper explains the modelling of the series parallel HEV model, supposed to be the most efficient design for the passenger vehicle. [3] The model discussed here has been referred from Mathworks official website [10]. The analysis of the model has been done using the parameters like fuel type and the drive cycle corresponding to that of Indian scenario to obtain the improvised fuel economy of the HEV.

2. Architectural Overview

The main components of a series parallel (SP) HEV are:-

1. Internal Combustion engine
2. Motor Generator 1 (MG1) - acting as generator
3. Motor Generator 2 (MG2) - acting as motor
4. Power Split Device (PSD) - an Epicyclic compound planetary gear set

As illustrated in Fig.1, the architectural structure of a series parallel HEV comprises of the carrier of ring gear connected to the output of an IC engine, followed by the sun gear connected to the shaft from the generator and lastly the ring gear is connected to the shaft from the motor. The motor and the generator are further connected, via an electric circuit, to a battery source. The ring gear is finally connected to the differential of the front drive axle, which has wheels mounted connected via a set of gears and shafts, inhibiting certain inertia and rotational damping. [4].

3. Modelling of SP HEV

A Series Parallel HEV model in MATLAB and SIMULINK version 2013a is shown in Fig. 2. It comprises of several sub-systems which are connected to each other by means of mechanical and electrical linkage. [6] All of these subsystems operate in synergy for the vehicle to deliver the desired speed and acceleration from the driver, and minimize the fuel consumption while doing so. The blocks in Fig.2 depict the following subsystems:

- Combustion Engine
- Electrical Systems
- Power Split Device
- Control System
- Vehicle Dynamics
- Input from the Drive Cycle
Each of the sub-systems is discussed in the following section:

**A. Engine:**

Based on input from control logic value, the engine produces torque and speed and the values are sent back to the control logic as feedback. The engine is connected to the carrier and the same drives the generator via Carrier-Sun gear connection. During the drive cycle, when the power demand is low, only the motor is operated to meet the driver requirements and engine is shut off. This is advantageous because the motor operates on DC current from the battery and is agile, unlike that of the engine, under unsteady load conditions.

However, during the high power demands (such as during sudden acceleration of the vehicle), the motor falls short to meet the driver demands and thus the engine needs to be operated. The amount of power to be delivered by engine is calculated by the control logic by subtracting power demand from the driver and the maximum power motor can provide. The torque demands of the vehicle are met by motor and hence, the engine only has to supply the balance torque such that the fuel economy is maximized. Also when the battery state of charge falls below the permissible level, the engine is operated to run the generator and charge the battery. [10]

In contrast to SI engines of conventional vehicles operating on Diesel cycle, the IC engine in HEV operates on Atkinson cycle. This is because of the fact that the engine in HEV does not operate on its full load capacity as compared to that in conventional passenger vehicles, but operates at part loads corresponding to maximum efficiency. Due to this phenomenon the engine cannot operate in Diesel cycle but on Atkinson cycle, which caters to the part load during engine operation in HEV, giving a 10% better fuel efficiency than SI engine. [12]

However the power density is reduced in operation of the Atkinson cycle due to reduction in input load. This is compensated by power input from the motor during cycle operation.

| Cycle       | Atkinson Cycle          |
|-------------|-------------------------|
| Idling Speed| 800 rpm                 |
| Hp          | 98 hp 1.8L 4cylinder    |

**B. Electrical System**

The electrical sub-system comprises of the following:

i. Generator: Synchronous servo generator and drive
ii. Motor: Synchronous servo motor and drive
iii. DC-DC converter and battery
Similar to that of the engine, the generator and the motor have input ports connected to the mode logic of the hybrid electric vehicle sending signals to it. The output shaft from the generator is connected to the Sun and that of the motor to the Ring gear of the Power Split Device (PSD).

| Properties          | Generator | Motor |
|---------------------|-----------|-------|
| Stator Resistance   | 0.0048    | 0.091 |
| Shaft Inertia       | 0.2 kgm$^2$ | 0.2 kgm$^2$ |
| Stator Mass (kg)    | 8.58      | 16    |
| Rotor Mass (kg)     | 3.93      | 6.7   |
| Magnet Mass (kg)    | 0.448     | 0.768 |
| Efficiency          | 91%       |       |

For operation of motor in between 2000 RPM to 6500 RPM, high mechanical efficiency is available from 96-99%. [7]

C. Power Split Device (PSD):

Negligible meshing losses between the sun and the planet and between the ring and the planet gears have been considered in this model, for purpose of simplification. However values of (0.96 0.98) losses exhibit on-road characteristics. [7]. The equations governing the torque and speed (RPM) of the sun, planet and carrier in PSD are discussed here in brief. The transmission efficiency is given as

$$ \eta_t = \frac{1}{\eta_m + \eta_g} + \left(1 - \frac{1}{\eta_m + \eta_g}\right) \frac{1}{\rho + SR} $$

where $\eta_m$ and $\eta_g$ are motor-generator efficiency and SR is ratio of speed of engine and motor and $\rho$ is gear ratio. [14]

The axle power $P_a$, which is the sum of power from battery and the mechanical power from the IC Engine can be given by:

$$ P_a = T_e \omega_e + P_B + T_C \omega_C $$

where, $P_B$ denotes Battery power, $T_e$ and $\omega_e$ denotes Engine torque & speed

And angular velocity as,

$$ \omega_C = \frac{\rho \omega_S}{\rho+1} + \frac{\omega_T}{\rho+1} $$

where $\omega_C$, $\omega_S$ and $\omega_T$ is velocity of carrier, sun and ring gear respectively. [4]

D. Control System

The control system is a continuous closed loop feedback system sub-divided into several components, as stated below

i. Controllers

a) Engine speed controller
b) Motor speed controller
c) Generator speed controller
d) Battery charge controller

4. Simulation of SP HEV

Consider the below drive cycle for simulation of the above modelled SP HEV [10]
The scopes in the model provide detailed plots for speed and torque of different components in the vehicle like generator, engine and motor, as shown below.

**A. Motor and Generator**

![Fig 5: Speed of motor and generator](image)

It can be clearly seen from the above plot graph that the motor traces a similar path as that of the drive cycle (Fig. 4). When the motor falls short to supply the required power, the generator traces a peak at its power production. As the generator is driven by the IC engine, from the graph it can be seen that the motor encompasses majority of power supply and IC engine is driven only when necessary.

**B. ICE**

![Fig 6: Speed, Torque and Power of the ICE](image)

Comparing Fig. 5 (operation of motor and generator) with Fig. 6 (operation of IC engine) for the given input drive cycle (Fig. 4), it is seen that the engine operation peaks only when the motor falls short of the required supply. Moreover, from Fig 6, engine can be seen to be operated only at the most efficient points.

As a result, the fuel economy of the engine improves significantly and results in less pollutant emissions.
C. Battery

Comparing the battery output voltage with that of engine operation and the drive cycle, the peak of the drive cycle corresponds to peak of power demand. Here the battery supplies maximum power to motor for its operation. During vehicle retardation or constant speed movement, battery output is invariant and traces minor dips, as seen in Fig. 7.

For the considered drive cycle, we obtain the fuel economy as:-

Table 3: Fuel economy of vehicle

| litre /100 km | 3.124 |
|---------------|-------|
| km / litre    | 32.01 |
| Total fuel used (L) | 0.03106 |

As it can be inferred from Table 3, the mileage obtained for the considered drive cycle is 32 km/litre for diesel. An average of 22 km/litre is observed in a conventional vehicle which corresponds to an increase of 50-65% This rise is due to the fact that the mode logic sends input to the engine such that it operated in its band of maximum efficiency as much as possible.

5. Conclusion

Thus in this paper, architectural structure and the modelling of a series parallel HEV has been discussed, in which the different major components and their individual roles were illustrated. The simulation performed was based on a model referred from Mathworks, while the input parameters for the analysis like fuel calorific value followed by engine and motor parameters and the drive cycle were corresponding to that of Indian scenario. It can be revealed from the study that:

1. The fuel economy (32 km/litre) is significantly improved compared to that of a conventional IC engine based vehicle (diesel engine). The improvement is of the order of 50-65%.

It is being addressed that these developments have been established in the early 2000s in Japan and U.S however they still have not been explored in our country by automobile manufacturers to the needful extend.

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