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Design and Control of Series Parallel Hybrid Electric Vehicle

Pankaj R. Patil[1], Shivani S. Johri[2]
Department of Electrical Engineering, Sri Balaji College of Engineering and Technology, Jaipur, India

Abstract

This paper deals with the mathematical modelling, analysis, and simulation results of a series–parallel hybrid electric vehicle (SPHEV). The detailed models of four major types of components: electric motors, internal combustion engines, batteries, and support components that can be integrated to model and simulate drive trains having all electric, series hybrid, and parallel hybrid configurations is presented. The simulation has been done graphical simulation language Matlab/Simulink and is portable to most computer platforms. This paper also discusses the methodology for designing vehicle drive trains. A series HEV, parallel HEV, series-parallel HEV and a conventional internal combustion engine (ICE) driven drive train have been discussed. Simulation results such as fuel consumption, vehicle emissions, and complexity are compared and discussed for each vehicle.

1. Introduction

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It is today widely known that the fuel consumption of a vehicle clearly affect the surroundings where it is used. It is also widely known that the affects of the emissions are not only local but also affecting the climate globally. As a reason to this increasing and today widely spread problem, this report will propose a working solution to lower the emissions and fuel consumption and thereby increasing the overall efficiency. Compared to conventional vehicles, there are more electrical components used in electric, hybrid, and fuel cell vehicles, such as electric machines, power electronics, electronic continuously variable transmissions (CVT), and embedded power train controllers [1], [2].

Advanced energy storage devices and energy converters, such as Lion batteries, ultra capacitors, and fuel cells, are introduced in the next generation power trains. In addition to these electrification components or subsystems, conventional internal combustion engines (ICE) and mechanical and hydraulic systems may still be present. The dynamic interactions among various components and the multidisciplinary nature make it difficult to analyze a newly designed hybrid electric vehicle (HEV). Each of the design parameters must be carefully chosen for better fuel economy, enhanced safety, exceptional drivability, and a competitive dynamic performance at a price acceptable to the consumer market. Prototyping and testing each design combination is cumbersome, expensive, and time consuming. Modeling and simulation are indispensable for concept evaluation, prototyping, and analysis of HEVs. This is particularly true when novel hybrid power train configurations and controllers are developed. Furthermore, the complexity of new power train designs and dependence on embedded software is a cause of concern to automotive research and development efforts. This results in an increasing difficulty in predicting interactions among various vehicle components and systems [3].

An HEV power train generally includes an ESS and a traction electric motor in addition to the components one can find in traditional power trains. Efficiency improvements are due to internal combustion engine (ICE) downsizing, optimal operation of the ICE, and regenerative braking. Increasing the ESS capacity of an HEV results in a drive train that substantially relies on the traction force of the electric motor as long as its ESS is not completely depleted. Such a vehicle can be plugged in and charged off the grid. When completely charged, a HEV mostly relies on its ESS module for the first several miles of its drive cycle. Afterwards, it operates like a regular HEV. The ESS module energy capacity of HEVs is larger than present HEVs, though not as large as the ESS modules in EVs. The performance of ESS that consists of different battery modules is very important in this context. The parameters in an ESS module design are discussed in [4].

Due to their flexibility in chemical or electric fuel consumption, HEVs are expected to have better fuel economy when compared to conventional HEVs. HEVs could also be used as distributed energy storage (DES) units to serve the grid when they are parked and plugged-in. In this way, HEVs can be recharged during the night (when demand for the electric energy is low) and used in the afternoon as DES units (when the demand for energy is high). This could help in peak load shaving of the grid [5], [6].

However, to provide these benefits, HEVs need an ESS with a high energy capacity, and the vehicle must have prior knowledge of intended driving use so as not to deplete energy needed for the vehicular operation. It should be noted that the ESS associated with these vehicles have a limited number of battery cycles and that DES activities for these vehicles should be accomplished in such a way that the consumer is adequately compensated for the degradation in battery life associated with providing an energy storage capability. Batteries or ESS with such high energy capacities are costly; this is the largest barrier in the mass production of HEV [7], [8].

This paper is organized as follows. Section II deals the block diagram of series parallel type hybrid electric vehicle. In section III, modelling of HEV using Simulink has been presented. Section IV gives simulation results of series parallel type HEV. Paper is concluded with section V.

2. Hybrid Electric Vehicle

A. Series-Parallel HEV Architecture

A block diagram of one possible hybrid electric vehicle (HEV) architecture is shown in Figure 1. The arrows represent possible power flows. Designs can also include a generator that is placed between the power splitter and the battery allowing excess energy to flow back into the battery.

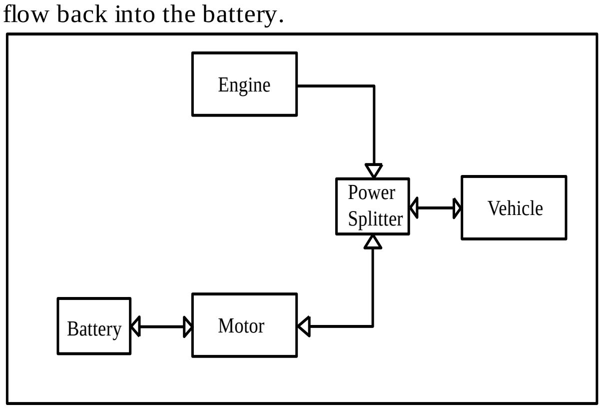

Fig. 1 Components of a hybrid electric vehicle.

Conceptually, the hybrid electric vehicle has characteristics of both the electric vehicle and the ICE (Internal Combustion Engine) vehicle. At low speeds, it operates as an electric vehicle with the battery supplying the drive power. At higher speeds, the engine and the battery work together to meet the drive power demand. The sharing and the distribution of power between these two sources are key determinants of fuel efficiency. Note that there are many other possible designs given the many ways that power sources can work together to meet total demand.

B. Design Steps

The key issues in HEV design [2] are typical of classical engineering problems that involve multilayer, multi-domain complexity with tradeoffs. Here, we discuss briefly the key aspects of the component design:

i. Engine design

The key elements of engine design are very similar to those of a traditional ICE. Engines used in an HEV are typically smaller than that of a conventional vehicle of the same size and the size selected will depend on the total power needs of the vehicle.

ii. Battery Design

The main considerations in battery design are capacity, discharge characteristics and safety. Traditionally, a higher capacity is associated with increase in size and weight. Discharge characteristics determine the dynamic response of electrical components to extract or supply energy to the battery.

iii. Motor

Motors generally used in HEV systems are DC motors, AC induction motors, or Permanent Magnet Synchronous Motors (PMSM). Each motor has advantages and disadvantages that determine its suitability for a particular application. In this list, the PMSM has the highest power density and the DC motor has the lowest [3].

iv. Power Splitter

A planetary gear is an effective power splitter that allows power flows from the two power sources to the driveshaft. The engine is typically connected to the sun gear while the motor is connected to the ring gear.

v. Vehicle Dynamics

The focus is on friction and aerodynamic drag interactions with weight and grade ability factors accounted in the equations.

3. Modelling of Series Parallel Hybrid Electric Vehicle using Simulink

In this section, HEV power train of the series-parallel type, such as the one found in the Toyota Prius car has been presented [9]. Fig. 2 shows overall block diagram of series parallel HEV using Simulink.

This HEV has two kinds of motive power sources: an electric motor and an internal combustion engine (ICE), in order to increase the drive train efficiency and reduce air pollution. It combines the advantages of the electric motor drive (no pollution and high available power at low speed) and the advantages of an internal combustion engine (high dynamic performance and low pollution at high speeds).

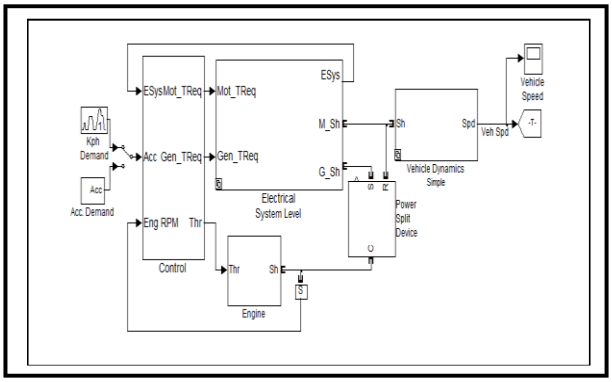

Fig. 2 Series Parallel HEV using Simulink.

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The Electrical subsystem is composed of four parts: The electrical motor, the generator, the battery, and the DC/DC converter as shown in Fig. 3.

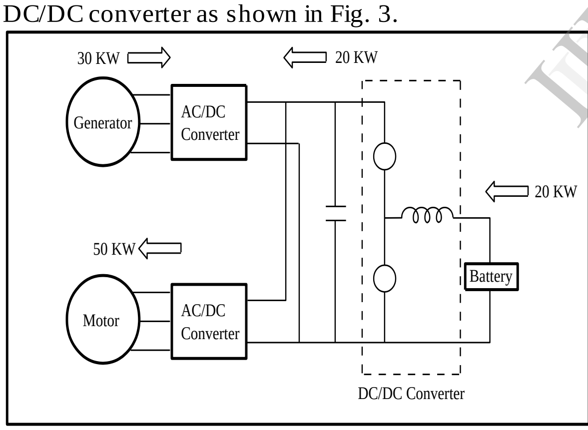


Fig. 3 The Electrical System.

1. The electrical motor is a 500 V dc, 50 kW interior Permanent Magnet Synchronous Machine (PMSM) with the associated drive. This motor has 8 pole and the magnets are buried (salient rotor's type). A flux weakening vector control is used to achieve a maximum motor speed of 6000 rpm.
2. The generator is a 500 V dc, 2 pole, 30 kW PMSM with the associated drive. A vector control is used to achieve a maximum motor speed of 13000 rpm.
3. The battery is a 6.5 Ah, 200 V dc, 21 kW Nickel-Metal-Hydride battery.
4. The DC/DC converter (boost type) is voltage-regulated. The DC/DC converter adapts the low voltage of the battery (200 V) to the DC bus which feeds the AC motor at a voltage of 500 V.

The Planetary Gear Subsystem models the power split device. It uses a planetary device, which transmits the mechanical motive force from the engine, the motor and the generator by allocating and combining them. It represents a set of carrier, ring, planet, and sun gears constraining the connected driveline axes. The gear ratio is the ratio of gear teeth (ratio of gear radii). The ring and sun co-rotate with a fixed gear ratio and in opposite directions, with respect to the carrier. The ring-sun gear ratio must be strictly greater than one.

The Internal Combustion Engine subsystem models a 57 kW @ 6000 rpm gasoline fuel engine with speed governor. The throttle input signal lies between zero and one and specifies the torque demanded from the engine as a fraction of the maximum possible torque. This signal also indirectly controls the engine speed. The engine model does not include air-fuel combustion dynamics.

The Vehicle Dynamics subsystem models all the mechanical parts of the vehicle:

1. The single reduction gear reduces the motor's speed and increases the torque.
2. The differential splits the input torque in two equal torque for wheels.
3. The tires dynamics represent the force applied to the ground.
4. The vehicle dynamics represent the motion influence on the overall system.
5. The viscous friction models all the losses of the mechanical system.

It is assumed that the vehicle is moving on flat terrain. No bearing friction or gear losses are included. The EMS with controller is as shown in Fig 4.

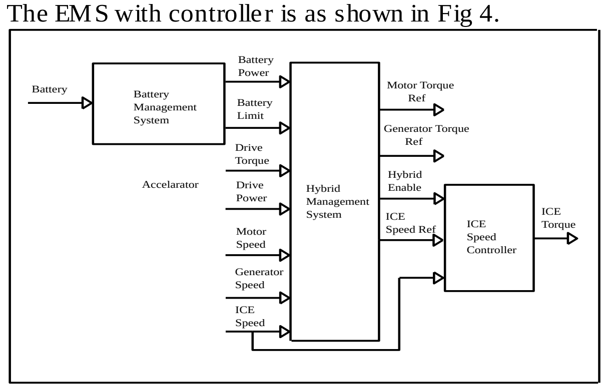


Fig. 4 Energy Management System.

The Energy Management system (EMS) determines the reference signals for the electric motor drive, the electric generator drive and the internal combustion engine in order to distribute accurately the power from these three sources. These signals are calculated using mainly the position of the accelerator, which is between -100% and 100%, and the measured HEV speed. Note that a negative accelerator position represents a positive brake position.

The Battery management system maintains the State-Of-Charge (SOC) between 40 and 80%. Also, it prevents against voltage collapse by controlling the power required from the battery.

The Hybrid Management System controls the reference power of the electrical motor by splitting the power demand as a function of the available power of the battery and the generator. The required generator power is achieved by controlling the generator torque and the ICE speed.

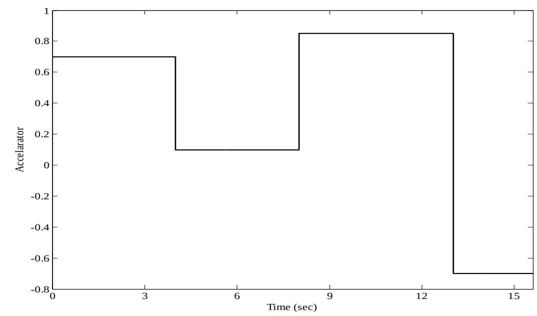
4. Test Results

The simulation shows different operating modes of the HEV over one complete cycle:

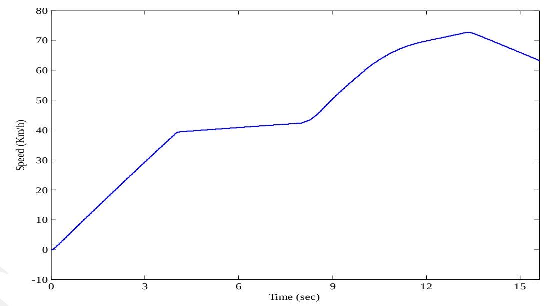
1. Accelerating,
2. Cruising,
3. Recharging the battery while accelerating
4. Regenerative braking.

The HEV speed starts from 0 km/h and reaches 73 km/h at 14 s, and finally decreases to 61 km/h at 16 s. This result is obtained by maintaining the accelerator pedal constant to 70% for the first 4 s, and to 10% for the next 4 s when the pedal is released, then to 85% when the pedal is pushed again for 5 s and finally sets to -70% (braking) until the end of the simulation. The following steps will explain operation of the HEV

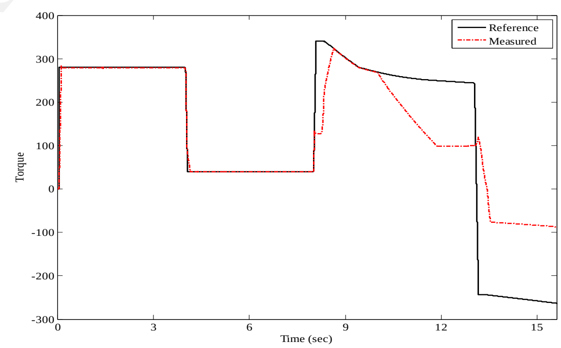
1. At t = 0 sec, the HEV is stopped and the driver pushes the accelerator pedal to 70%. As long as the required power is lower than 12 kW, the HEV moves using only the electric motor power fed by the battery. The generator and the ICE provide no power.
2. At t = 1.4 sec, the required power becomes greater than 12 kW triggering the hybrid mode. In this case, the HEV power comes from the ICE and the battery (via the motor). The motor is fed by the battery and also by the generator. In the planetary gear, the ICE is connected to the carrier gear, the generator to the sun gear and the motor and transmission to the ring gear. The ICE power is split to the sun and the ring. This operating mode corresponds to acceleration.
3. At t = 4 sec, the accelerator pedal is released to 10% (cruising mode). The ICE cannot decrease its power instantaneously; therefore the battery absorbs the generator power in order to reduce the required torque.



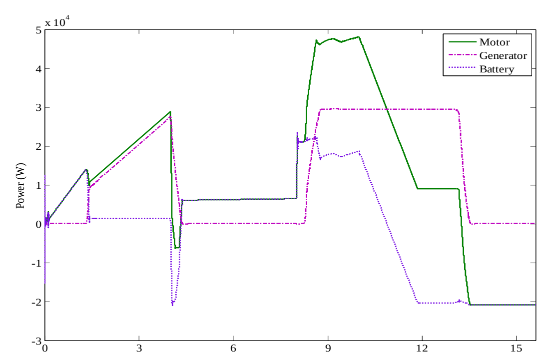
(a) Accelerator Profile



(b) Speed

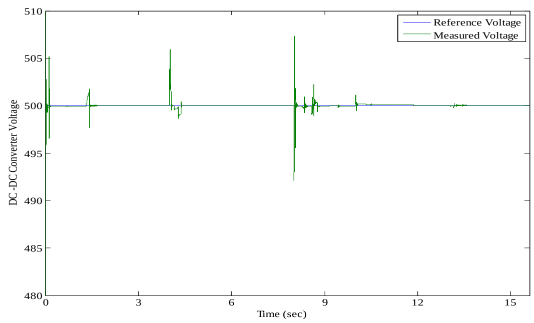


(c) Torque

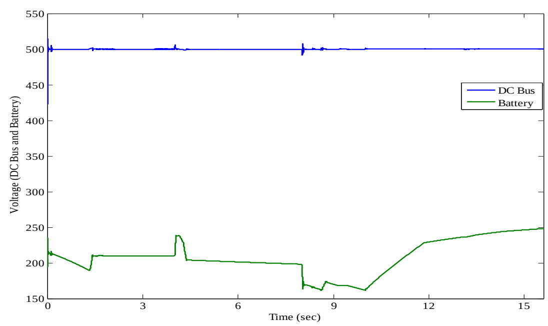


(d) Power

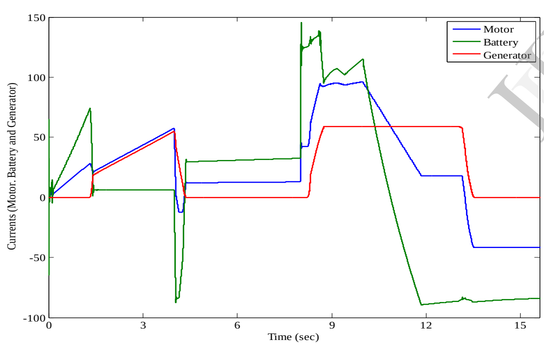
Fig. 5 Car Response for given accelerator profile



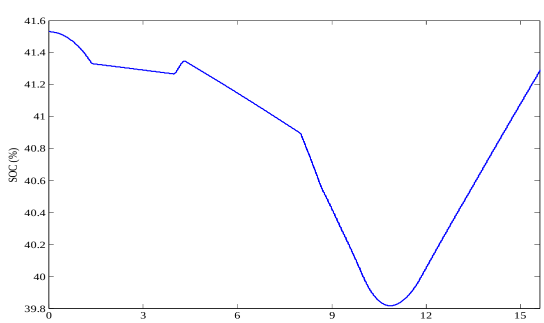
(a) DC-DC Converter Voltage



(b) Voltage



(c) Currents



(d) Battery SOC

Fig. 6 Electrical subsystem variations for Battery, Generator and Motor.

4. At t = 4.4sec, the generator is completely stopped. The required electrical power is only provided by the battery.
5. At t = 8 sec, the accelerator pedal is pushed to 85%. The ICE is restarted to provide the extra required power. The total electrical power (generator and battery) cannot reach the required power due to the generator-ICE assembly response time. Hence the measured drive torque is not equal to the reference.
6. At t = 8.7 sec, the measured torque reaches the reference. The generator provides the maximum power.
7. At t = 10 sec, the battery SOC becomes lower than 40% (it was initialized to 41.53 % at the beginning of the simulation) therefore the battery needs to be recharged. The generator shares its power between the battery and the motor. It is observed that, the battery power becomes negative. It means that the battery receives power from the generator and recharges while the HEV is accelerating. At this moment, the required torque cannot be met anymore because the electric motor reduces its power demand to recharge the battery.
8. At t = 13 sec, the accelerator pedal is set to -70% (regenerative braking is simulated). This is done by switching off the generator (the generator power takes 0.5 s to decrease to zero) and by ordering the motor to act as a generator driven by the vehicle's wheels. The kinetic energy of the HEV is transformed as electrical energy which is stored in the battery. For this pedal position, the required torque of -250 Nm cannot be reached because the battery can only absorb 21 kW of energy.
9. At t = 13.5 sec, the generator power is completely stopped.

The trends for accelerator, speed, torque and power is illustrated in figure 5 while variations for electrical subsystem are shown in figure 6. It is also observed that, during the whole simulation, DC bus voltage of the electrical system well regulated at 500 V.

5. Conclusions

This paper has presented modelling and control of series parallel type HEV, with specific focus on modelling. Simulation results for car and electrical subsystem are provided.

It can be concluded that with the ever more stringent constraints on energy resources and environmental concerns, HEV will attract more interest from the automotive industry and the consumer. Modelling and simulation will play important roles in the success of HEV design and development.

In this paper, we have discussed a drive train modelling, simulation, and analysis using Matlab/Simulink to study issues related to EV and HEV design such as energy efficiency, fuel economy, and vehicle emissions. The software uses visual programming technique, allowing the user to quickly change architecture, parameters, and to view output data graphically. It also includes detailed models of electric motors, internal combustion engines, and batteries.

This paper provides an insight into the design and sizing of the ESS module for SPHEV. ESS module design and sizing are important criteria in the design of an HEV. Proper design of the ESS module coupled with an appropriate energy management strategy could improve the fuel economy of PHEVs considerably. The selection of an energy management strategy would play a key role in the design of the electric drive train of the vehicle. Sizing of the ESS module and the electric motor would influence the cost of the vehicle. HEV like the Toyota Prius can be converted to SPHEV by increasing the ESS storage capacity. This could improve the fuel economy of the vehicle and the use of the blended mode of operation.

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Biography

Pankaj Patil has done his B.E. from North Maharashtra University in 2009. He is doing M.Tech in Power Systems from Sri Balaji College of Engineering and Technology, Jaipur. His research interests include Power Electronics, Hybrid Electric Vehicle, Control systems etc.

Shivani Johri has done her B.E. degree from Rajasthan University, Jaipur in 2009. She has completed M.Tech. in Power Systems from Rajasthan Technical University in 2013. She has published and presented a number of research papers in international and national conferences and journals.

Her areas of interest are power quality enhancement, FACTS devices, optimization techniques etc.