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Enhancing the Hybrid-Electric Vehicle Efficiency through Advanced Configuration Strategies

Journal of Electrical Systems

Abstract: - Fuel consumption will play an important role with the recent rapid expansion of hybrid electric vehicles in the transportation sectors due to the progressive depletion of oil sources. It indicates changing the conventional usage of vehicles into alternative solutions. To optimise the fuel consumption in hybrid electric vehicles, the well-predefined configurations of the powertrain will be introduced to precise coordination between the actuators and the sources of energy required to save the benefits of energy. This proposed methodology concentrates on the design and development of the hybrid electric vehicle (HEV) that targets the optimisation of fuel consumption. The parallel HEV configuration will be adopted for the dynamic model of the HEV to estimate the vehicle response for medium-range frequency. This parallel configuration gives an idea of the different modes of driving like engine or electric or a combination of both. To define the HEV drive system characteristics, a special control approach has been developed to smoothen the operation of the electric vehicle during the changes of modes in terms of switching conditions. In the context of the HEV control issue, this goal typically entails reducing fuel usage.

Keywords: *Fuel consumption, Hybrid electric vehicle, control approaches, Parallel Hybrid power train, Supervisory algorithms*

INTRODUCTION

According to a recent study conducted by the United States Energy Information Administration [1], the transportation sector used 68% of all available petroleum resources in the U.S. in 2006. 66% of these resources were imported. The automotive industry is pursuing alternative propulsion technologies to reduce fuel consumption and emissions, including hybridization of conventional and electric powertrains. Hybrid-electric vehicles (HEVs) use electrical energy storage and drive systems in combination with ICEs, a concept that dates back to 1898 when Porsche built the first hybrid car. [2]. Hybrid vehicles have been overlooked due to ICE technologies. Hybrid vehicles are becoming increasingly important due to rising fuel costs and population growth. Hybrid vehicles are entering the mainstream, but cautious organisation of powertrain functions is vital to increase efficiency of energy conversion, emission reductions, and drivability improvement. These goals are equally important and often conflicting from a control engineering standpoint. As an example, ICEs operate with greater efficiency at moderate speeds and loads, whereas drivability and emissions constraints generally favour low-load operation. A control framework that appropriately combines these objectives by making optimum use of the hybrid powertrain is highly desirable. In order to address the control issues related to vehicle drivability, the dynamic behaviour of a hybrid vehicle should be carefully analysed [3]. A dynamic vehicle simulator facilitates this analysis and enables the design of model-based control strategies with the objective of reducing controller calibration effort. The simulator should be designed such that it accurately represents the vehicle behaviour within the frequency bandwidth of interest and without imposing excessive complexity. HEVs have additional drivability issues due to the hybrid nature of their drivetrains and control strategies. A subset of hybrid systems, that is relevant to this study, is the class of switched systems [4] in which the

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continuous phases of a system's dynamics are interrupted by a switching signal that is either supervised by a high-level logic or is a result of the dynamics of the plant. A relatively unexplored problem in the area of switched systems, which is of great practical interest, is the analysis and control of *mode-switching-induced transients*. In the case of HEVs, the negative impacts of switching modes are induced the transients in manifest as undesirable drivability features. Control mode transitions are observed in multi-mode combustion engines [5], [6], gear control shifting in automated-manual gearboxes [7], and control of soft-landing in variable valve actuated engines are explained as best automotive applications. Because of the framework's broad application, the final goal of this research is to investigate alternative control solutions for systems that exhibit switching mode will caused transients. This paper also shows applications to hybrid-electric automobiles.

A. Contributions of the Paper

The primary goal of this work is to examine and identify control solutions to drivability challenges caused by the essential characteristics of HEV drivetrains, and also to manage the control systems. To fulfil this goal, the main contribution of this research is to design and develop the parallel HEV model for predicting low-to-mid frequency vehicle, and to identify the dynamic behaviour that affects longitudinal drivability. This proposed method will simplify this model which will be utilised to design the control algorithms. These control algorithms are designed for the purpose of the HEV to optimise the fuel economy which will cause, and known as the energy management controllers. This proposed method seeks to solve shortcoming [8], identifying the main drivability difficulties and proposing various techniques for the improvement of ECMS. This method purposes to address the methods [8], identifying significant drivability problems and providing solutions for energy management systems. The suitable research solution for this complexity of drivability in a HEV with a multi-mode control architecture, so that it can be utilise the proper engine start-stop function. This observation inspired further investigation into the control of systems characterised by induced transients with the switching mode.

PROPOSED METHODOLOGY

As mentioned in [9], the propulsion of hybrid-electric vehicles is dependent on a number of energy storage and conversion systems. These elements when combined produce a vast variety of architectures, each with a multitude of options. Many factors, including application type, budgetary limits, weight restrictions, and target market preferences, affect the particular configuration of a hybrid-electric vehicle. A hybrid-electric vehicle's architecture is based on essential components of its propulsion system, which include a fuel tank, internal combustion engine (ICE), one or more electrical energy carriers (like batteries or supercapacitor), electric machines, power converters, gearbox, and various driveline connections [10].

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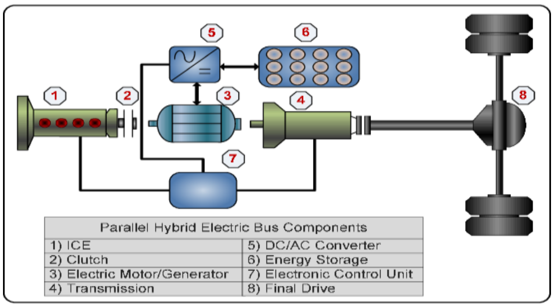


Figure 1: Common hybrid-electric vehicle architectures

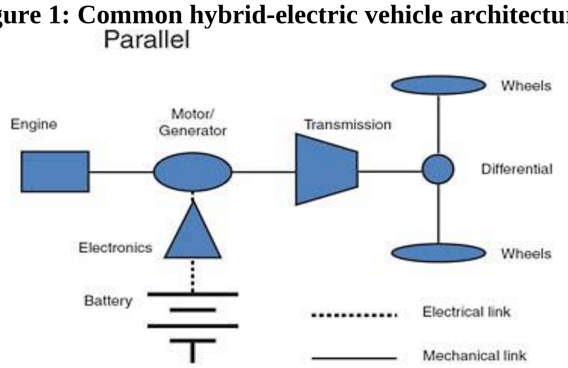


Figure 2: Schematic of parallel hybrid power train configuration.

DESIGN OF PARALLEL CONFIGURATION OF HEV

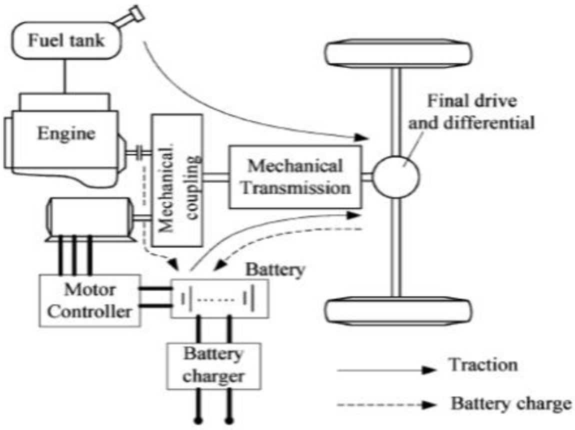


Figure 3: Block diagram of parallel configuration of HEV

Parallel Hybrid Drivetrain: Figure 3 provides a clear depiction of the architecture of a hybrid-electric vehicle (HEV). The power flows within the system are illustrated by arrows in the diagram, while a dotted line indicates battery charging, allowing for additional energy to be returned to it. In this design, the generator is positioned between the power splitter and the battery. In a parallel hybrid drivetrain, depicted in Figure 2, both the engine and electric motor can deliver torque directly to the driven wheels via a mechanical coupling [11]. This coupling could take the form of a gearbox, pulley-belt unit, sprocket-chain unit, or a single axle, as shown in Figure 1. Conceptually, a hybrid electric vehicle combines features of both electric and internal combustion engine (ICE) vehicles [12]. At lower speeds, it functions as an electric vehicle powered by the battery. As speeds increase, the engine and battery cooperate to meet the demand for drive power [13]. The efficient sharing and distribution of power between these two sources are critical factors in achieving fuel efficiency.

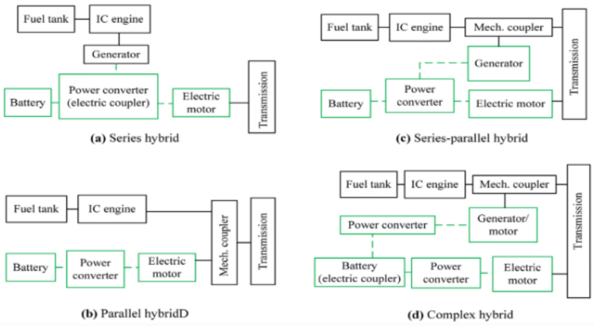


Figure 4: A comprehensive review on hybrid electric vehicles: architectures and components

A Supervisory Level Controls

The primary functions of the vehicle's supervisory controller are: Scheduling engine start-stop: Several conditions affect scheduling of the engine start-stop events to fulfil performance, fuel economy, and drivability and emissions requirements. The vehicle functions such as traction control and driveline control require individual controllers to be stimulated as required. The supervisory controller handles these functions based on predefined transition conditions. If the normal operation is denied by the driver manually, then the supervisory controller involves the vehicle into the required mode of operation.

Safe vehicle operation: The supervisory controller reconfigures the control system, if a responsibility of powertrain is distinguished. A finite state machine representation of the experimental vehicle's operating modes is given in Figure 5. The operating modes that are related to the safety features of the vehicle (such as the engine mode) are not shown in this figure. Therefore, this mode has an unconditional branch as shown in Figure 5. Also, the hybrid and regenerative braking modes share a parent state that branches out to cruise control and traction control modes if the corresponding transition conditions are satisfied. If the controller exits one of the two modes, it defaults back to the hybrid mode.

The supervisory controller is implemented in the MATLAB environment. it provides diagnostics features to help detect issues such as transition conflicts and cyclic behaviour. In this work, the supervisory controller is tested in the loop with the vehicle simulator over an extensive number of driving cycles.

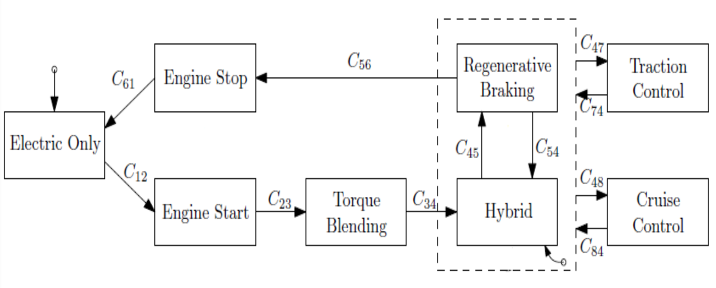


Figure 5: A state machine representation of the vehicle supervisory controller.

B. Design Steps

The major problems like multilayer, malty complexities of HEV design [14] are identified as a typical of classical engineering problems will be discussed in the below section in view of design

Engine design:

The dynamic HEV model, CX-DYN, can be configured in a variety of ways according to the objectives of the simulation. If the objective is to follow a desired velocity profile to predict the vehicle performance and fuel economy, the simulator can be executed using driver feedback.2 If the objective is to verify the correct operation of a control strategy, the simulator can be executed using only the control strategy in the feedback loop. In this scheme, actual accelerator and brake pedal commands are fed to the simulator and the corresponding vehicle states are obtained. A third possibility involves executing the vehicle simulator in an open-loop fashion using torque commands obtained from actual driving conditions. This scheme is most suited for model validation using experimental data. CX-DYN simulator uses the MATLAB *ode23tb* routine for the numerical integration of differential equations. This routine implements a variable-step solver that is suited for stiff dynamic systems.

To represent the aforementioned effects, those that significantly impact the engine behaviour are implemented in the vehicle model. The engine torque request ($T_{ice;req}$) is calculated as a function of the percentage-based torque request ($T_{ice;per}$), the engine speed (T_{ice}), and other modifications resulting from the idle speed controller ($T_{ice;\,idle}$) and the transmission controller ($T_{ice;tr}$):

$$T_{ice;req} = f_{ice,trq}\left(\omega_{ice}, T_{ice,per}\right) + T_{ice,Idle} + T_{ice,tr}$$

ii. Battery Design:

Capacity, discharge characteristics, and safety are the three most important factors to consider when designing a battery. Historically, higher capacity has been connected with increased size and weight. Discharge characteristics govern the dynamic response of electrical components to withdraw or provide energy to the battery [14], [15]. The battery state-of-charge (SOC) is known as a control strategy feedback signal which affects the actuators to the power split, the model of the battery has an indirect influence on vehicle drivability. A simple zeroth order model of battery is employed to evaluate the charge of the battery in order to predict this effect [16].

The battery power supply P_{batt}, is derived as:

$$P_{batt} = P_{acc} + \sum_k T_k \omega_k \begin{cases} \frac{1}{\eta_k(\omega_k T_k)} & T_k \geq 0 \\ \eta_k(\omega_k T_k) & T_k < 0 \end{cases} \quad (k = \{em,\ bsa\})$$

iii. Designing of Motor:

The electrical machines like motor will be used in HEV as engines namely DC Motors, AC Motors, Permanent Magnet Synchronous Motors (PMSM), and also Brushless DC Motors [17]. All the type of motors have specific limitations in terms of its usages. But the HEV are mostly implemented and designed by the Permanent Magnet Synchronous Motors (PMSM) because of its maximum power density compare to others [18]. The mathematical modelling for the rear driveline can be explained with the help of output of the shaft which gives the considerable inertia using the lumped network.

$$\omega_{em} = \frac{1}{J_{em} + J_{gb} + \frac{1}{\mu_{gb}^2} J_{rd}} \left(T_{em} \eta_{gb} \eta_{rd} - T_{em,fr} - \frac{2}{\mu_{rd} \mu_{gb}} T_{hs,r} \right)$$

where *Jem* is the EM inertia of the rotor, J_{gb} is the output shaft inertia of the gearbox, J_{rd} is the differential input shaft inertia at the rear, μ_{gb} is the speed of the gearbox in the form of reduction ratio, μ_{rd} is the differential speed of the rear in the form of reduction ratio, η_{gb} is the gearbox mechanical efficiency, η_{rd} is the rear differential mechanical efficiency, T_{em} is the torque of the EM output, and $T_{hs;r}$ is the reaction torque of rear axle on a single half shaft. $T_{em;fr}$ is a various types of the friction losses and parasitic losses, bearing frictions.

iv. Power Splitter

A planetary gear is an efficient power splitter that allows power to flow to the driveshaft from two power sources. Typically, the engine is linked to the sun gear, while the motor is linked to the ring gear.

v. Dynamics of the Vehicle

The Hybrid electric vehicle has divided into two types of sources that are Electric motor and Internal combustion engine for which those are used for improving the efficiency of drive train and minimising the air pollution, it will combine for the advantages of minimising the air pollution at low speeds and high dynamic performance means high speed with low air pollution [19].

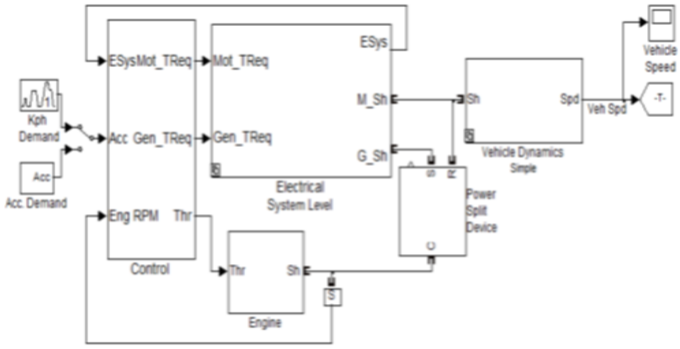


Figure 6: Block diagram of Energy Management Systems

1. The permanent magnetic synchronous motor with the ratings of 600 V and 55 kW is connected to internal drive and it has 8 pole salient type structure. To gain the maximum speed of 6500 rpm of a motor, the flux weakening is used in the vector control method.
2. Then the PMSM is connected to a generator worth of 500V DC, 21 kW power, and 2 pole, and it has been designed to achieve the maximum speed of 13000 rpm
3. The type of battery which we can use in hybrid electric vehicle is with the rating of 6,8 Ah, 250 V DC, 22 kW nickel metal frame in this architecture
4. The boost type of voltage regulator will be used to regulate the converter voltage
5. The low voltage of 200 V DC-DC is converted into 500 V AC through the bus

The Planetary Gear Subsystem and Internal Combustion Engine subsystem are responsible for modelling the power split device, which consists of a set of carrier, ring, planet, and sun gears that constrain the connected driveline axes [20]. The ratio between the ring and sun gears must exceed one for the internal combustion engine to function properly. In relation to the carrier, the ring and sun gears rotate with a fixed gear ratio but in opposite directions. The Internal Combustion Engine subsystem emulates a petrol fuel engine equipped with a speed governor, generating 55 kW of power at 6500 rpm. The throttle input signal ranges from zero to one, indicating the demand for maximum torque from the engine. Additionally, this throttle input signal governs the engine speed.

Table 1: Various type of motors and its density of torque

Type of a machine	Torque/ Envelop E Nm/M^3	Torque/Copper mass Nm/kg Cu
Permanent Magnetic(PM) motor	28760	27.7- 48.5
Induction (IM) motor	4270	6.62
Switched Reluctance(SR)motor	6680	6.17

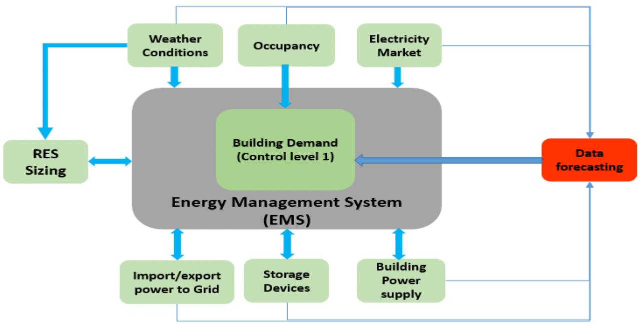


Figure 7: Block diagram of Energy Management Systems

The main power will be distributed precisely from the three different sources like internal combustion engine, the motor and generator drives to maintain the perfect energy management system. The figure 7 shows the accelerator position will be calculate by the three sources signals in between 100% with the measurement of hybrid electric vehicle speed. This paper will be discussed in the results analysis with the hybrid mode of the HEV.

RESULTS ANALYSIS

HEV Operating Modes: Hybrid

The hybrid operating mode is initiated after the engine start event [21]. In this mode, the control strategy has the ability to use the engine and the two electric machines in combination to satisfy the driver's power request. This mode is active for the majority of the vehicle's normal operating conditions. Therefore, the performance of the controller that is active in the hybrid operating mode greatly influences the overall performance of the vehicle. Among the practically feasible optimization techniques, the Equivalent (fuel) Consumption Minimization Strategy (ECMS) [22] is used in this dissertation for the implementation of the hybrid operating mode. In fact, this approach is preferred even for the two-way split case if the control strategy is intended for real-time operation. In the case of the actual implementation, an online driving cycle estimation scheme is usually used to update the equivalence factor in order to achieve a near-optimum performance for a variety of driving cycles.

The energy management system of the battery will works on the State-Of-Charge (SOC) mode with the 40 to 80% and the battery will control the power from many voltage issues [23]. The power demand of a motor and generator will be split in the available power so that the total system reference power will be in control. The engine speed and the generator torque will be controlled by the power of the HEV.

1. At t = 0 sec, the total power required to HEV is less than 12 kW, then the HEV will be turnoff with 70% of acceleration by the pedal. So the HEV the HEV runs with the help of motor fed by the battery. The no power will be provided to the generator and the engine.
2. At t = 1.5 sec, the power of HEV triggered more than 12 kW which is known as hybrid mode. Then the power flow from the engine to the battery through the motor. Here the motor is fed by the battery in association with the generator. The carrier gear is connected among the planetary gear and IC engine, and the ring gear is connected in between motor and sun gear. The power IC engine is split to the sun and the ring gears. This is the acceleration mode.
3. At t = 4.1 sec, the cruising mode will works due to the pedal of accelerator is released to 10%. Then the IC engine cannot decline its power immediately; consequently, the generator power will be engrosses the battery to minimise the essential torque.

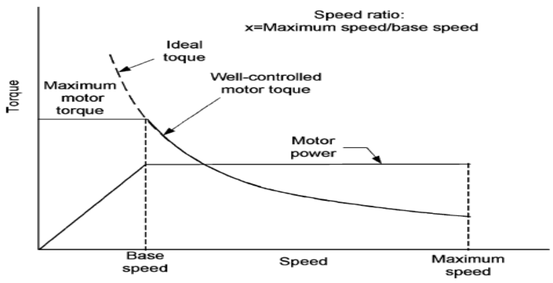
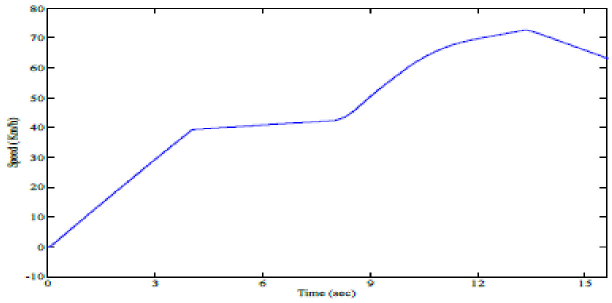
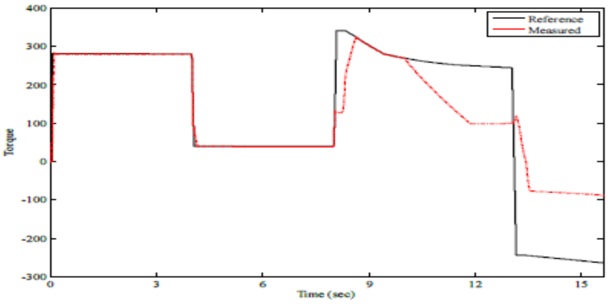


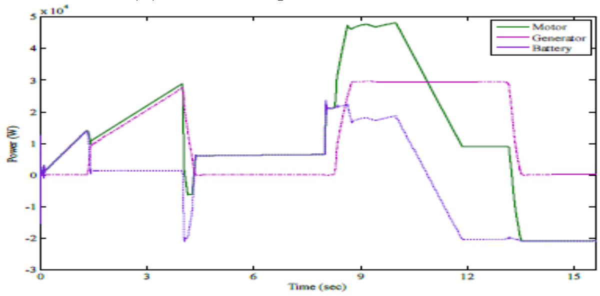
Figure 8: Motor ideal torque-speed characteristics.



(a) Motor speed characteristics.



(b) Motor torque- characteristics.



(c) Motor power characteristics.

Figure 9 a, b, c: Response of accelerator profile

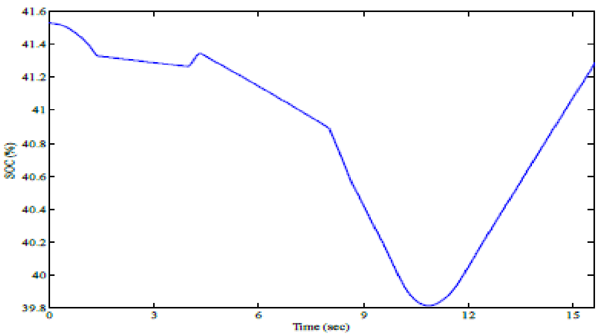


Figure 10: variations of electrical subsystem.

4. At t = 4.5 sec, the battery will provide the maximum power then the running state of the generator is fully stopped.
5. At t = 8.4 sec, the IC engine resumed to offer the additional required power to the accelerator pedal which is moved to 85%. Then the total battery and generator power will not meet the desired power because of the assembly of generator and IC engine response time. Henceforth the restrained drive torque is not same as to the reference torque.
6. At t = 8.7 sec, the reference torque is equal to the measured torque. Then the maximum power provided by the generator.
7. At t = 10 sec, the battery needs to be recharged, and the generator shares its power between the battery and the motor, resulting in a decrease in torque.
8. At t = 12.9 sec, the simulation of regenerative braking is reaches to 70% where the accelerator pedal is to be set. At this condition the machine will be act like motor to drive wheels of the electric vehicle. The battery will stores the kinetic energy of the HEV and transfer to electrical energy. Then the battery can be absorbed the 21 kW of energy with the desired torque of -250 Nm, then the pedal position is set.
9. At t = 13.7 sec, the running state of the generator is fully stopped. The figures 9 and 10 illustrate the speed, torque, power and acceleration. The different variations of the electrical subsystem are observed from the figure 10. It is also observed that, throughout the complete simulation part, the electrical system of the DC bus voltage is well regulated at 500 V.

CONCLUSION

This proposed method delivers a proper ESS module design and sizing which can be improve the fuel economy and cost of HEVs. This design will be provide the suitable energy management system for optimising the fuel consumption. The optimised module of ESS and the sizing of the motor show the impact on the vehicle cost. The main aim of the proposed design is to achieve improvements in fuel economy while maintaining good drivability. This objective is met by the control strategy by first converting the accelerator/brake pedal position into a power/torque demand, then determining the suitable vehicle operating mode, and finally computing a torque split to achieve the control objectives defined in a particular operating mode. Finally it can be determined that the HEV will attract the consumers towards the automotive industry in rigorous limitations on energy resources and environmental concerns. Modelling and simulation are essential factors for design and development of HEV. In this method discovers a drive train modelling, simulation, and analysis using Mat lab/Simulink to meet high efficiency of energy, fuel economy for the hybrid electric vehicle.

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