2010

Optimal power management of hybrid electric vehicles through drivetrain analysis

Ashim Raj Das
University of Windsor

Recommended Citation

Das, Ashim Raj, "Optimal power management of hybrid electric vehicles through drivetrain analysis" (2010). *Electronic Theses and Dissertations*. 8239.
https://scholar.uwindsor.ca/etd/8239

OPTIMAL POWER MANAGEMENT OF HYBRID ELECTRIC VEHICLES THROUGH DRIVETRAIN ANALYSIS

By

Ashim Raj Das

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2010

Library and Archives
Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-62726-6
Our file Notre référence
ISBN: 978-0-494-62726-6

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

DECLARATION OF PREVIOUS PUBLICATION

This thesis includes two original papers that have been previously published and two papers are in process of being submitted which have been used in the thesis as follows:

Thesis Chapter	Publication Title	Publication Status
Chapter 2, 4	Power Management of a Series-Parallel Hybrid Electric Vehicles Through Optimized Operation of Electric Motor and Engine	Published
Chapter 2, 3, 5	Efficient Power Management Through Optimized Speed and Torque Operation of Drivetrain Components	Published
Chapter 2, 6	Distribution of Power in a Series-Parallel Drivetrain Through Variable Speed-Torque Operation of Engine and Motor	To be submitted
Chapter 3,7	Effect of Diesel Hybridization on Vehicle Performance for Urban (city) Driving Condition	To be submitted

I certify that I have obtained a written permission from the copyright owners to include the above published materials in my thesis. I certify that the above material describes work completed during my registration as graduate student at the University of Windsor.

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owners to include such materials in my thesis.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

The inefficient performance of gasoline-engine based vehicles along with high emissions and fuel consumption can be improved through utilization of hybrid electric vehicles (HEVs). The multiple power and energy sources in the hybrid drivetrain can be well managed through an appropriate control strategy that supervises the power distribution. While doing so, the control strategy needs to operate every component optimally in addition to overseeing controlled charge-discharge of battery to obtain efficient energy usage.

In this thesis an algorithm has been developed for efficient power division among the various components of a series-parallel (S-P) drivetrain. It has been designed to manage the power flow with the least possible losses while keeping fuel economy at an optimum level and maintaining battery state-of-charge (SOC) in a pre-defined range. The importance of optimizing both engine and motor has been discussed. Analysis has also been presented to show possible benefit of using diesel instead of gasoline engine for hybrid vehicles.

DEDICATION

To My Family and
Well Wishers

ACKNOWLEDGEMENT

I am extremely thankful and grateful to my loving family whose love, support and sacrifice has made me what I am today. I wish to express my sincere gratitude to my advisor Dr. Narayan Kar for his assistance has been vital at every step of the way. His valuable guidance has had an immense influence on my professional growth and without his technical expertise, reviews, and criticism it would not have been possible to shape this thesis. I would also like to thank my committee members, Dr. Mirhassani and Dr. Lee for their valuable suggestions and guidance in the completion of this work.

I would also like to thank my fellow colleagues at the Centre for Hybrid Automotive Research & Green Energy for their support and encouragement during the time I spent here. Working in their friendly and encouraging company was an unforgettable and terrific experience.

In addition I would like to thank University of Windsor for providing me the opportunity to be a proud member of its successful graduate student fraternity. Special thanks to the faculty and staff for providing assistance whenever I required it.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

NOMENCLATURE

The important symbols that have been utilized in this document have been listed down:

ω_e : Angular speed of engine in rpm

ω_g : Angular speed of generator in rpm

ω_m : Angular speed of electric motor in rpm

τ_m : Motor torque in Newton-meter (N-m)

τ_e : Engine torque in Newton-meter (N-m)

P_b : Power output of battery in kilowatts

P_g : Input to generator in kilowatts

P_e : Engine power in kilowatts

P_m : Motor power in kilowatts

P_{req} : Power requirement of the vehicle in kilowatts

P_{ava} : Mechanical power available from wheels

E_e : Energy content of fuel (gasoline or diesel) in kJ

E_b : Electrochemical energy of battery in kJ

η_t : Transmission efficiency in %

η_m : Motor efficiency in %

η_g : Generator efficiency in %

η_e : Engine efficiency in %

η_b : Efficiency of the battery in %

V_f, V_0 : Final and initial speed

V_{avg} : Average speed of the vehicle

SOC_f : Final State-of-charge of battery

SOC_0 : Initial State-of-charge of battery

$Fuel_f$: Final fuel tank level (gasoline)

$Fuel_0$: Initial fuel tank level

D : Distance travelled by the vehicle

t, Δt : Journey duration and time step in seconds

x : Recirculation factor

F_{aero} : Aerodynamic drag experienced by vehicle in Newton

F_{roll} : Force for overcoming rolling resistance in Newton

F_{grad} : Force required to overcome the gradient component in Newton

R_t : Tire resistance coefficient

m : Mass of vehicle in kilograms

g : Gravitational constant in m/s^2

θ : Angle of inclination with the horizontal in degrees

C_d : Coefficient of drag

A_f : Frontal area in m^2

ρ : Air density in kg/m^2

G_r : Gear ratio between the wheel and motor

E_{acc}, P_{acc} : Energy & power required during acceleration

E_{ss}, P_{ss} : Energy & power required during steady-state

E_{dec}, P_{dec} : Energy & power available during deceleration

t_{acc}, t_{ss}, t_{dec} : Duration of vehicle accelerating, travelling at constant speed or decelerating in seconds

1 BACKGROUND STUDY

1.1 Hybrid Electric Vehicles: A Step towards a Cleaner Future

The increasing gasoline prices and fuel emissions coupled with the reducing fossil fuel reserves necessitates an interest in the field of alternative power options. Presently, the rate of gasoline consumption has an increasing exponential trend and recent studies have shown that oil production is likely to peak within a foreseeable future. The ever escalating demand for gasoline has put strain on almost every single economy in the world, be it a developing or developed economy. In addition to that the fluctuating prices have put the automobile corporations and consumers at the mercy of the economics of gasoline. A feasible option for reducing the consumption and dependence on gasoline is through application of electric vehicles (EVs) and hybrid electric vehicles (HEVs) [1]. Electric vehicle technology is an attractive option that can help reduce the dependency on gasoline, however due to the limited range of battery and present day technological constraints it requires more research and development to become more practical [2]. The transition from conventional vehicle to electric vehicle is a multi-step process as the capacity and size of the battery need to be considerably high in order to reduce fuel consumed as demonstrated in Figs. 1.1 and 1.2 [3]-[5]. Hence there is a big void that needs to be filled between electric vehicles and conventional vehicles; this is where HEVs step in. As a result of battery constraints, HEVs can prove to be a viable alternative to commercial vehicles and will be quite vital until the drawbacks of electric vehicles have been minimized through further advancement in battery technology [1].

The biggest motivation behind the need for hybrid vehicles is the inefficiency and high fuel consumption rate, conventional vehicles suffer from [1], [6]. The maximum efficiency an average engine can achieve ranges from 30 to 34 % [7], [8], which is only

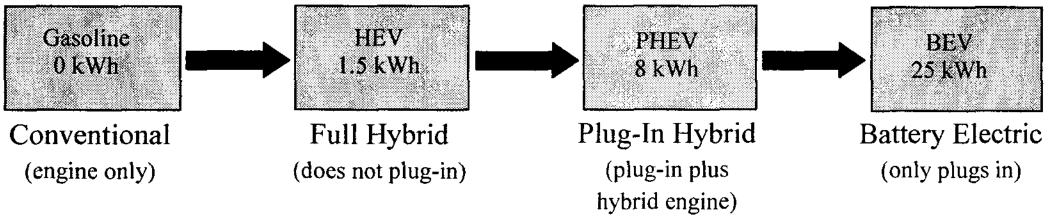


Fig. 1.1 Variation in battery capacity for EVs, HEVs, plug-in HEVs and conventional vehicle [3]-[5].

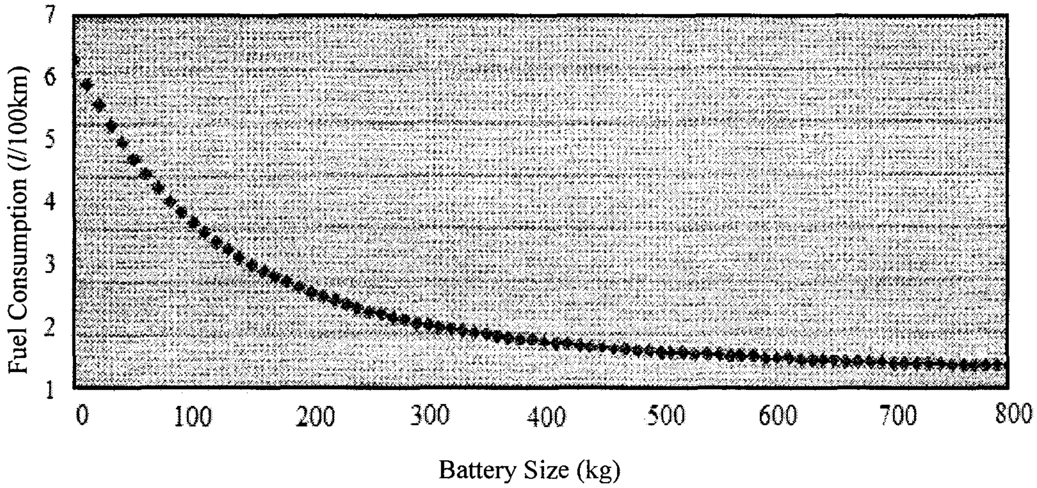


Fig. 1.2 Effect of battery size on fuel consumption [4], [5].

possible for a very narrow region. This inadequacy of the engine to operate optimally pushes the vehicle operation into inefficient operation [9]. Due to this, conventional vehicle can offer a very limited scope of control of speed-torque of engine. The average utilization of fuel can go up by 10-15 % through hybridization of the drivetrain which is able to achieve better speed-torque control [10], [11]. Hence HEVs have emerged as the technology that has provided the much needed transition from conventional to electric vehicles especially in the past decade or so [2].

Another important reason for this transition has been the ever increasing concerns over the greenhouse emissions and depleting gasoline reserves. The immediate solutions to these problems are HEVs [12]. Not only do HEVs provide higher fuel economy and fewer emissions as compared to a conventional vehicle but they have also been seen to reduce the size of the engine which helps in reducing consumption of gasoline [13]. The drivetrain efficiency is improved by up to 30-40% in HEVs as compared to their counterpart conventional vehicles [8], [9].

A basic HEV drivetrain consists of at least one electric motor, a battery pack and an engine (ICE). It combines the advantages of each of these devices while reducing the individual drawbacks of the motor and engine to a great deal [2], [14]. HEVs employ two or more energy sources to meet the power requirement and therefore, their drivetrain is a hybridization of two or more power sources rather than just one, as is the case of conventional vehicles. Hence the mechanical power required to drive the vehicle is a combination of engine power and motor power. Hybridization of the drivetrain immediately provides the advantage of a downsized engine, two sources to meet the energy requirements of the vehicle, reduced fuel consumption among many others [15]. The hybridization results in an increased fuel economy and lesser fuel emissions. Due to presence of multiple energy and power sources it can get quite unmanageable to split the driver power demand. This could result in engine operating inefficiently making the hybrid drivetrain completely redundant and also an additional negative effect could be complete disregard for the state-of-charge (SOC) of the battery resulting in deep discharge. In addition to this there is power available during deceleration which can be utilized to charge the battery. An efficient power management strategy can address all the issues mentioned above [16]. In the next sub-section an overview of the various control strategies has been provided.

1.2 Control Strategies and Algorithms for Efficient Power Distribution

As the HEV powertrain structure combines the electric motor and engine either in series or in parallel or a combination of both, the understanding of the drivetrain architecture necessary for formulating control strategy.

Hybrid vehicles can be classified into three major categories depending upon their power-train configuration namely: series HEV, parallel HEV and series-parallel HEV. The control strategy needs to be designed quite differently for the three configurations as their power distribution is different. As for the series-parallel, it has the most intricate control strategy as its configuration is a combination of the series and the parallel drivetrains [17], [18]. Vehicle design complexity increases significantly with hybrid configurations especially for more complex architectures, because optimum controls and other support systems are needed for internal combustion engine (ICE), electric motor and other components to blend the power coming from the two sources. The increased complexity needs to have an equally efficient control mechanism that optimizes the working of the components in accordance with each other. The control strategy of these systems is an important issue that determines the success of the vehicle. Thus the vital issues that need to be addressed by control strategies are:

(1) Efficient performance of drivetrain components

(2) Reduction in the total fuel consumption

(3) Reduction in the gross amount of emissions (CO_2+NO_X+CO+...)

(4) Improving the drivability

(5) Maintenance of battery SOC

(6) Reduce the total cost function associated with the vehicle

While attaining the above mentioned objectives the control strategy has to see to it that the vehicle performance does not degrade. At any instant the control strategy should be able to determine the power distribution between the primary energy source (gasoline-engine) and the renewable energy storage system. The driver's power demand should be met by managing the power from different power sources. The optimal behavior of a vehicle can be defined in terms of its reduction in fuel consumption.

Implementation of a power management system is usually done through a central controller based on an algorithm that works on a principle of regulating the drivetrain power distribution. The multiple energy and power sources are managed through this control algorithm. In case of hybrid vehicles, the power flow is controlled for electrical and mechanical paths. In short, the primary function of the control algorithm is to either generate appropriate on and off decisions to engage and disengage drivetrain components respectively or to modify their regions of operation for the best possible solution.

An accepted classification of the control strategies [19] can be seen to be subdivided into three categories as shown in Fig. 1.3. It can be observed that a control strategy can be classified into three categories, rule-based, optimization based or neural network based, which have been further explained in this section in detail:

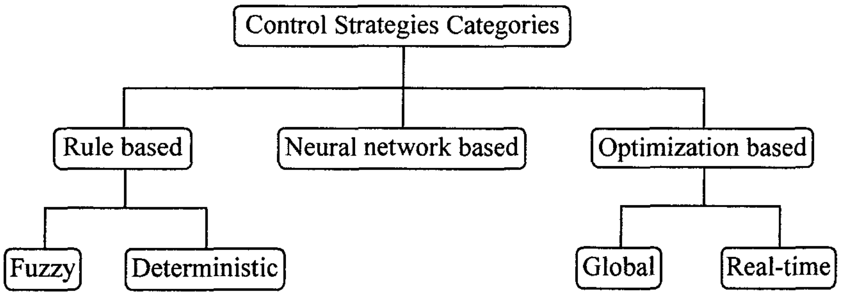


Fig. 1.3 Classification of control strategies used for power management [19].

A. Rule based strategy: This approach manages the power management based on their capability to solve real-time supervisory control of drivetrain power flow. The basis for forming the rules of this approach is based on intuition, heuristics, and human expertise. The mathematical models are created without any prior information of previous driving cycle. It is based on the concept of load-leveling. Through the use of this strategy actual operating point of engine is shifted to an extremely close value of the optimal value of fuel efficiency, fuel emission and economy rate for a certain value of the engine speed. When the result of this is analyzed, it is observed that maximum fuel economy is achieved for a system which is being operated at a low torque and engine speed value than the most efficient one. So high fuel economy is achieved when there is less amount of accelerator commands [20].

   The difference in power demanded by the driver and that provided by engine is compensated by the motor or it is used in replenishing the battery based on the value of SOC. If the actual operating region on the efficiency map is changed then the engine speed and the engine torque have to be changed as well. The engine speed can be determined through the gear ratio and speed of vehicle. There are two kinds of rule based strategies:

   a. Deterministic rule based methods: These are based on heuristic approach which involves analysis of power flow in the drivetrain, efficiency/fuel or emission maps of an engine, and human experiences. This is done using the look-up tables, which is being utilized to divide the requested power between the power sources.
   b. Fuzzy rule based methods: The powertrain of hybrid vehicle is dependent on multi-domain, non linear and time varying parameters due to which the fuzzy logic based methods are suitable. Fuzzy logic is able to exploit the decision making capability that the system has, which can be used to realize the real time and sub-optimal power demand. Hence from the above discussion it can be inferred that the controller for a fuzzy logic based method has a definite edge over the conventional rule based one.

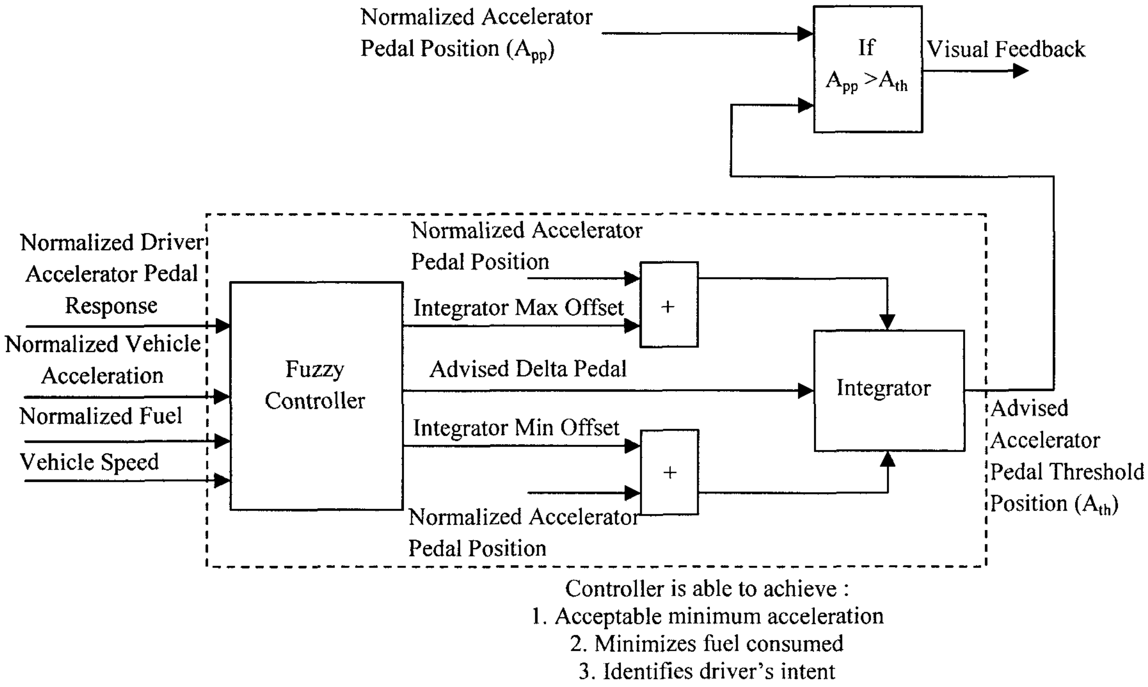


Fig. 1.4 Rule-based fuzzy advisory controller [22].

The main advantages of fuzzy rule based method being [19]:

1) Robust: tolerance to imprecise measurements and component variations.
2) Adaptation: fuzzy rules can be easily varied depending upon the needs of drivetrain.

Fuzzy based techniques [21] have proved to be of great help and have proved to provide more efficient controllers. A recently developed fuzzy-based controller explained in [22]-[25], is shown in Fig. 1.4.

B. Optimization based strategy: This method is quite different from rule based strategy as unlike it, this control strategy requires the complete knowledge of the driving cycle beforehand [19]. In this, the approach is to generate optimal torque references for various power sources and then optimal gear ratios are calculated by minimization of a cost function which is a function representing the fuel emissions and efficiency. The optimization based control strategies are again subdivided into two which have been discussed in brief.

a. Global optimization: This kind of optimization is usually applied for a fixed driving schedule. This can be used to compute the reduction in fuel consumption for the given drivetrain. In order for employing this strategy the primary knowledge that the system needs to have is of the future driving conditions. This control strategy is quite useful for assessment, analysis and comparative studies with the existing control strategies [26]. Some methods of this kind of optimization in use are, game theory, dynamic programming and genetic algorithm [27]-[29].

b. Real-time optimization: As the global optimization strategies need to have knowledge of the entire driving schedule beforehand, they prove to be quite unrealistic for real-time implementation. In order to counter this problem a real time control strategy needs to be developed.

   In real-time optimization, the cost function needs to be reduced for every time step and corresponding change in SOC [30]. Hence on the basis of equivalent fuel consumption, the global criterion is replaced by a local one that is creation of an instantaneous cost function. This cost function is a weighted sum of the fuel consumption and equivalent fuel consumption related to the SOC variation equivalent consumption minimization strategy (ECMS).The equivalent fuel consumption can be defined as extra fuel consumption that will be required to charge battery in the near future.

C. Neural network based strategy: This is a relatively new kind of control strategy which has found application in the automotive drivetrain control recently. This is mainly due to its ability of being adaptive in nature that is its ability to dynamically update itself. Through the artificial neural networks precise non-linear modeling can be obtained which makes it an ideal option for providing solution for controlling a non-linear system. An example of this strategy is the recurrent neural network controller explained in [31]. This strategy employs a closed-loop control method in order to train the neural network controller, which has been observed to enhance performance of the system and is shown in Fig.1.5.

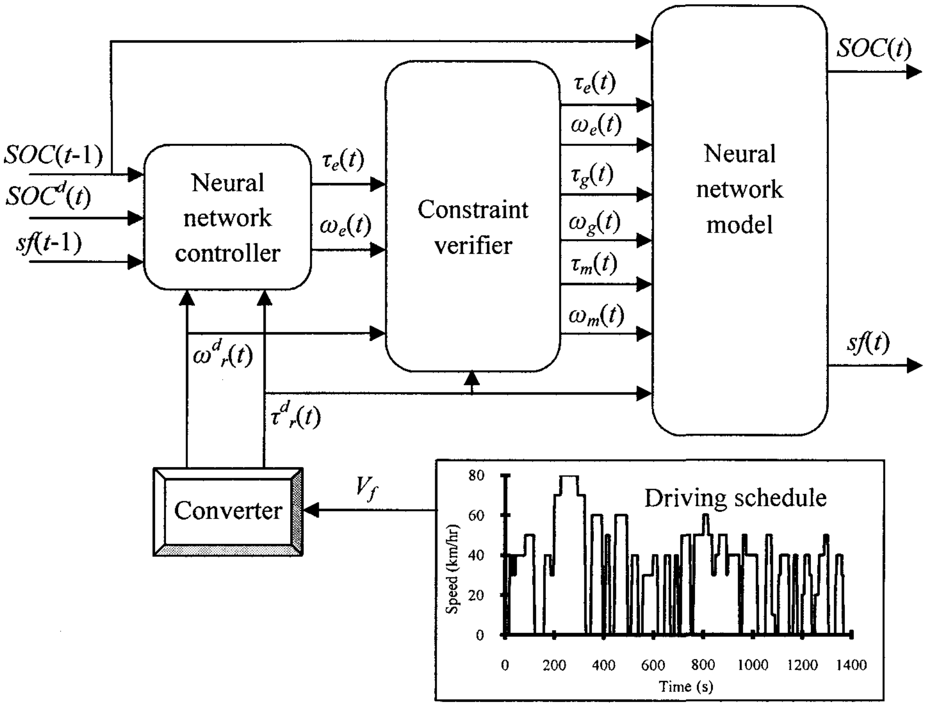


Fig. 1.5 Closed-loop controller for training neural network controller [31].

Based on the complexity, efficiency and other factors a comparison has been provided in Table 1.1 for the various strategies discussed. Table 1.1 presents the comparative advantages and disadvantages of the various control strategies

When it comes to robustness capabilities of the system, fuzzy rule-based and optimization based strategies are apparently superior. As for the online implementation, fuzzy logic based and real time methods are best possible choices. Neural network control strategy is an appropriate method for non-linear optimal control. Neural network controller can get a better efficiency on the same vehicle than the fuzzy rule-based optimization [32]. But due to the high computations and complexity, the neural network poses a serious setback when comes to implementation and overall cost. Overall, the rule based techniques have been seen to provide least complexity and computational intensity. With the proper technique, this strategy can provide an optimal overall solution with efficiency comparable to the other strategies (optimization and neural network based).

TABLE 1.1

COMPARISON OF VARIOUS CONTROL STRATEGIES

Control Strategy	**Method**	**Computation intensity**	**Robust**	**Real-time**	**Complexity**	**Efficiency**
Rule-Based	Thermostat	*	***	****	*	*
	Modified Power Follower	***	***	**	*	*
	State Machine-Based	***	***	**	*	*
	Conventional Fuzzy	*	****	****	*	**
	Fuzzy Adaptive	*	****	****	***	**
	Fuzzy Predictive	*	****	****	***	***
Optimization-Based	Dynamic Programming	***	****	*	***	***
	Generic Algorithm	*	***	***	****	***
	Real time	****	***	****	***	***
	Decoupling	****	***	****	***	****
Neural Network		****	****	***	****	****

1.3 Aim of the Research Conducted

HEVs have emerged to be quite beneficial in further enhancing and improving the performance of the engine as compared to its performance in a conventional drivetrain. Through the addition of an electric path to the drivetrain, not only the overall efficiency increases but also considerable reduction in the fuel consumption is achieved. But with increasing hybridization, complexity of powertrain also goes up; the inescapable consequence of this is the need for efficient control over power distribution and various components. This is where research needs to be conducted in order to design a control strategy which provides an optimal solution that takes into account factors like: cost, complexity, fuel emissions, robustness etc.

The focus of research work conducted and presented in this thesis would be dealing with the design of a control algorithm for managing the power flow while keeping the fuel consumption low, reduce emissions and cost. The objectives are achieved by following the procedure defined below:

- Utilization of various drivetrain configurations
- Obtain the speed and torque constraints for optimal performance
- Develop a control strategy to optimally operate motor and engine
- Optimal operation of drivetrain components
- Manage battery charge/discharge to maintain SOC over a certain limit

The novelty of the strategy demonstrated in this thesis, stems from the manner in which an optimal solution is obtained for managing power flow through the drivetrain. In the various literatures reviewed, few [8], [9], [12] have shown to either employ or further explain the various possible modes. But further enhancement can be achieved in these modes through there mathematical modeling. These models would be able to represent the power and energy relationship for the various components for different drivetrain paths and driving conditions. Through application of drivetrain models, the control algorithm would be able to improvise upon the existing techniques. This is mainly due to considerations of higher number of control variables which have a dynamic relationship between the various components. The reason for this dynamic relation is due to consideration of efficiency maps for speed-torque characteristics. Although efficiency maps have been seen to be employed in research work carried out earlier [1], [9] but through utilization of both the engine and motor characteristics at the 'same instant' makes it unique. Through power solution obtained at every time step for a correlated efficiency based selection of speed and torque of engine and motor will be capable of yielding power output for maximized and appropriate utilization of various components. In addition to the above the battery charge-discharge characteristics are regulated based on the battery's state of charge. This is done as research carried out until now has not fully integrated the idea of the need to vary the control algorithm's operation based on lower or higher state of charge [10], [16].

1.4 Overview of Thesis

This thesis has been organized into the following chapters:

Chapter 2: This chapter talks about the various kinds of architectures that are available for hybrid vehicles. These are then compared and importance of drivetrain architecture to the power management has been explained. Next the power model for the various configurations considered have been developed which is followed by models required to analyze energy and power sources.

Chapter 3: This chapter shows the steps involved in the development of a rule based algorithm for managing power distribution of a series-parallel drivetrain. The optimization procedure has been explained and analyzed in detail. In addition power and energy demands of the vehicle based on various parameters and specifications that are vital to achieve control has also been discussed

Chapter 4: In this chapter the power management for a random journey has been discussed. The analysis is presented for low and high SOC conditions in order to understand effectiveness of algorithm in managing power distribution and its ability to control charge-discharge pattern of battery.

Chapter 5: The focus of this chapter is to demonstrate the application of the algorithm for an urban driving schedule. The optimization achieved for various driving states while applying appropriate drivetrain has also been enumerated.

Chapter 6: This chapter primarily presents an in-depth analysis of effect of optimizing the power sources while a study is conducted to evaluate the drivetrain performance for different factors.

Chapter 7: This chapter presents the scope of improvement that can be achieved in the drivetrain performance through incorporation of a diesel engine.

Chapter 8: The research findings of this detailed analysis have been presented in this section. The implications of this research have been discussed and the scope of future improvements has been duly proposed.

2 DRIVETRAIN ANALYSIS AND SYSTEM MODELLING

2.1 Hybrid Drivetrain Architecture

There have been various kinds of drivetrain architectures proposed but out of these the ones that are usually demonstrated in literature and that are being implemented to manage different components for hybrid vehicles are: series, parallel and series-parallel [14], [33]-[37]. These architectures are based on the arrangement of various power and energy sources in different manner in the drivetrain through application of clutches and gears. The objective of these architectures are to provide electrical and mechanical connection among the various components which helps in managing routes for energy flow while achieving appropriate control of the system.

As the number of components go up, the complexity of the drivetrain also increases proportionally if not exponentially. Even though series-parallel has a more complex architecture as compared to series or parallel drivetrains, this drivetrain has the capability to combine the benefits of both these hybrid drivetrains. In a latter section, a brief comparative analysis would be presented to highlights its advantage. In the series parallel drivetrain, the power demanded can be satisfied by either the engine, the battery-motor combination or, by both engine and battery-motor combination usually for high power demands. The three main architectures discussed above have been explained in the forthcoming section with diagrammatic representation of the drivetrain.

2.1.1 Series Architecture

In the case of a series hybrid drivetrain, a single power source (motor) is responsible for propelling the vehicle. This power source can be fed through two power paths as shown in Fig. 2.1. The energy requirements of these power paths can be met through either a unidirectional energy source (gasoline) using the ICE as a power converter coupled to a generator or the bi-directional electrochemical energy source connected through the means of a power electronics converter [17]. The electric motor acting as the power source can be operated in backward motion for operating as a generator in order to recharge the battery. Also the ICE has been observed to act as a prime mover to drive an electric generator that delivers power to electric motor to provide the propulsion power.

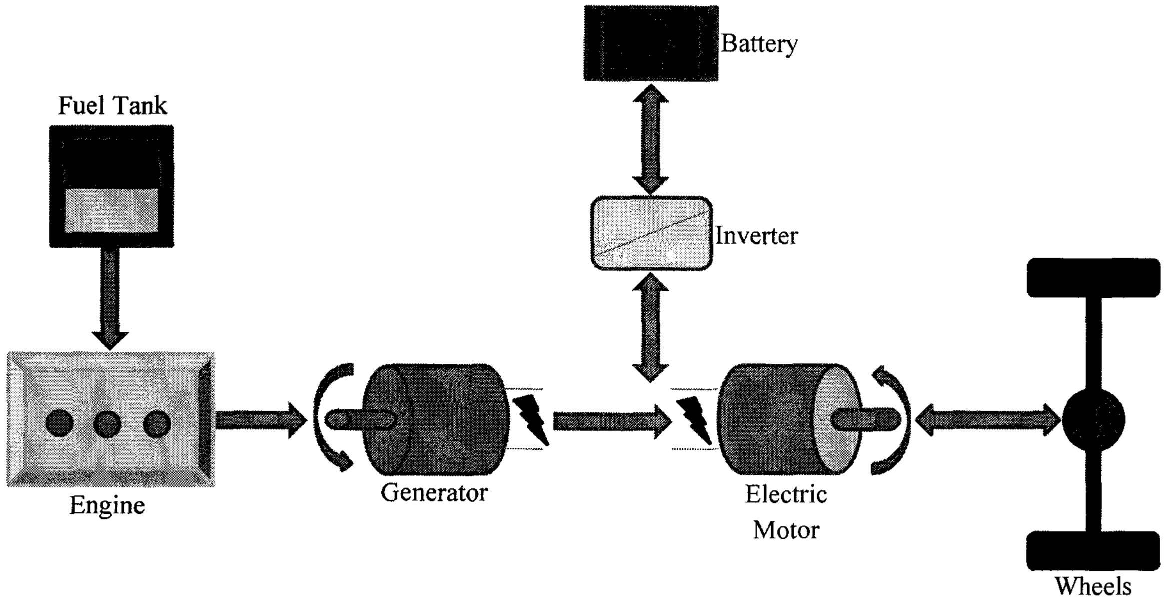


Fig. 2.1 Power distribution for series drivetrain architecture.

The benefit achieved from the series drivetrain is its simplicity which enables flexibility in the design and implementation of control strategy. But due to requirement of three power sources (ICE, generator and motor) the efficiency of the vehicle significantly reduces. In addition if the proportion of brake energy that can be absorbed by the batteries needs to be increased, an unwanted consequence is that the battery and ICE have to be sized bigger (this is due to low scope of power acceptance).

The transmission for series hybrid configuration is all electrical, via DC link. It normally requires a power converter for each element of the system in order to control the power flow in the form of direct current (DC) from element to element. The biggest advantage of this configuration is the bi-directional power flow between the vehicle drive motor and the energy storage this enhances the capability of regenerative braking.

There are quite a few modes in which the series drivetrain is known to operate based upon the driver's need and other factor. The possible modes of operation for this drivetrain have been listed below:

1) Battery alone mode: In this mode the engine is disengaged from the drivetrain. The vehicle is powered by the motor which is supplied energy by battery.

2) Engine alone mode: In this mode the battery neither charges nor discharges. Only the energy of fuel is employed by the use of ICE-generator and motor.
3) Combined mode: Both the ICE-generator and battery provide power to motor which propels the vehicle using dual energy sources.
4) Power split mode: The ICE-generator power is divided into two parts, major portion used to run the vehicle while the rest charges the battery.
5) Regenerative braking mode: The mechanical energy of wheels used to charge the battery through motor working in generating mode.

2.1.2 Parallel Architecture

The parallel drivetrain is quite different in concept from the series one. In this drivetrain, the power is supplied by the engine mechanically to the wheels, the same as a conventional vehicle. Also the motor is observed to assist the engine and is also mechanically coupled to the transmission. The parallel drivetrain is shown in Fig. 2.2. The ICE and motor are mechanically connected to the driveshaft through two different clutches [17]. Due to mechanical coupling of the power sources they can be coupled in various ways speed, torque or speed-torque coupling [8]. The motor output is considerably lower for this drivetrain as compared to series drivetrain, the reason being that the engine provides the major portion of the power demanded from the vehicle.

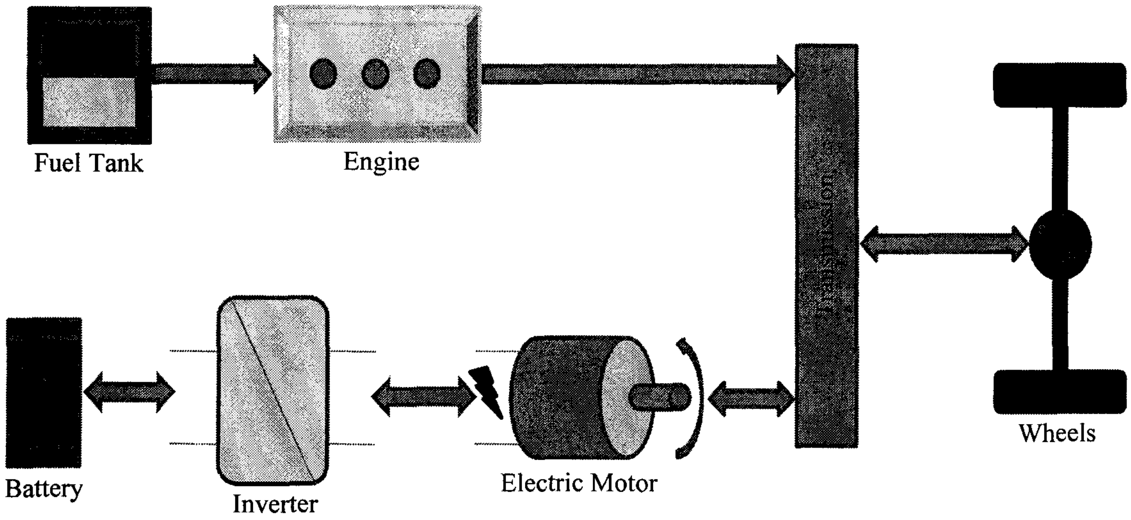


Fig. 2.2 Power distribution for parallel drivetrain architecture.

Hence propulsion power can be met through engine only, motor energized through the battery or a combination of both in parallel as the name of the drivetrain indicates. The motor which can also act as a generator depending upon situation is quite vital addition to this drivetrain as it has the functions discussed below [18]:

1) To start the engine
2) In order to supplement the engine output when vehicle is accelerating.
3) Utilize the brake energy during deceleration through regenerative braking.
4) Recharge the battery
5) To supply vehicle auxiliaries

The biggest advantage of having a motor/generator is to start the engine, which not only removes the need for a conventional starter motor but also enables rapid, quiet and smooth restarting. Thus it is able to disengage the engine when it is not required for propelling the vehicle. The possible modes of operation for parallel hybrids while employing speed coupling are as follows [8]:

1) Hybrid traction: Both the engine and motor run at positive speed and torque to provide power to the wheels.
2) Engine alone traction: The engine meets the power demand while the motor is mechanically disengaged from the wheels.
3) Motor alone traction: The motor meets the power demand of the vehicle while engine is disengaged from the drivetrain.
4) Regenerative braking: The electric motor is controlled to operate as a generator that is providing negative torque which can be employed to charge battery.
5) Engine charging battery: The energy of fuel is used to charge battery. The electric motor provides negative torque.

2.1.3 Series-Parallel Architecture

The arrangement of the series-parallel is a combination of the series and parallel drivetrains. This makes the configuration relatively more complicated which results in the control strategy being more complex but as the drivetrain is a combination of series and parallel drivetrains it is able to extract the benefits of both these architectures [38]-[40]. Through observation of the drivetrain in Fig. 2.3 the only major drawback of series parallel architecture is its requirement of two electric machines. This architecture uses a

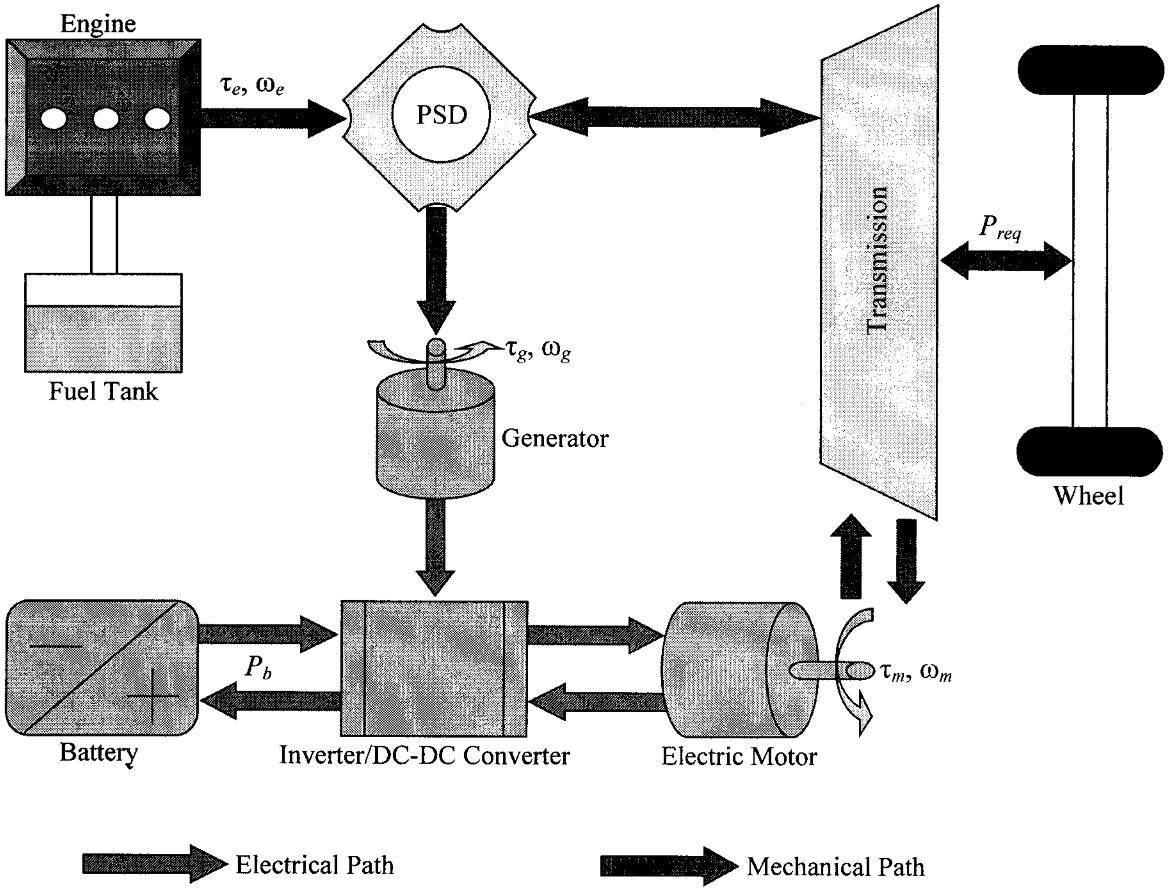


Fig. 2.3 Power distribution for series-parallel drivetrain architecture.

power split device for splitting the engine power; this component is responsible for allocation of engine power to the wheels using a driveshaft and the generator. The electricity produced by generator can be either used to charge the battery or to run the motor. This is mainly dependent upon the SOC of battery and driver's power demand. The motor has the capability to deliver power in parallel with the engine to the wheels. A converter/inverter is utilized to either make the output voltage of the generator suitable for charging the battery (AC to DC conversion) or to appropriately condition the output power to produce electricity in order to run the motor. The engine speed can be operated at its optimal value by controlling the speed of the generator and motor.

In case of the series-parallel hybrid, the power split device plays a vital role in the power division procedure, for this purpose a planetary gear unit is employed which acts like a simple gear box with a fixed gear ratio. This planetary gear employs mechanical

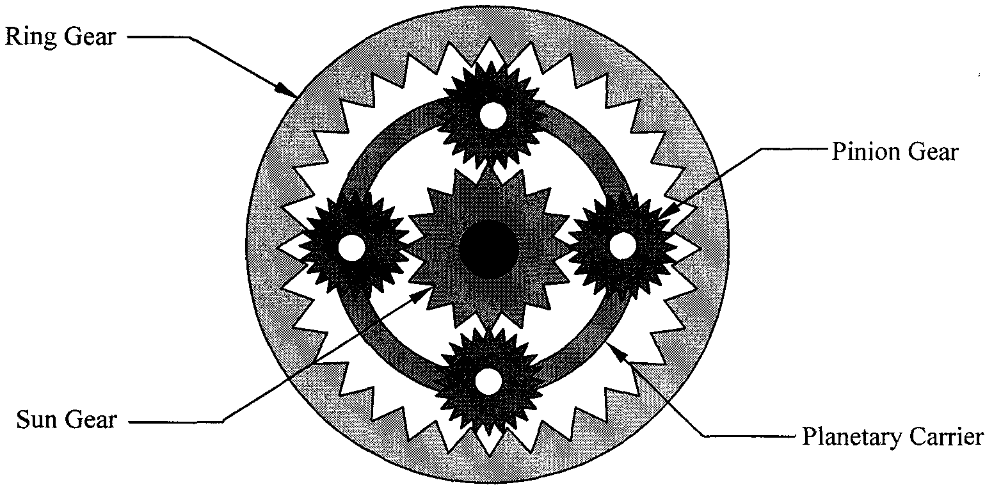


Fig. 2.4 Speed coupling through use of planetary gear arrangement.

coupling between the three power sources namely the engine, motor and generator [8]. Speed coupling is employed in Toyota Prius [41] and due to its specifications and parameters is being considered for the research work demonstrated in this thesis. Therefore speed coupling has been further explained in brief.

In case of speed coupling two or more power sources are coupled together using a planetary gear; this is done via coupling of their angular speeds [40], [42]. A planetary gear as the one shown in Fig. 2.4 is employed in order to split the engine output. The engine has a direct connection to planetary carrier through pinion gears, while the generator and motor are connected to the sun gear and ring gear respectively. Due to speed coupling the various gears would have the same speed value corresponding to the component they are connected with. Depending upon the number of gear teeth certain gear ratios are obtained which provide a relationship between the speeds of the various power sources which is defined as follows:

$$\omega_g = \omega_e(1+G) - \omega_m G \tag{2.1}$$

$$G = Z_r / Z_s \tag{2.2}$$

Where, G: Gear ratio of the planetary gear

Z_r: The number of teeth on the ring gear

Z_s: The number of teeth on the sun gear

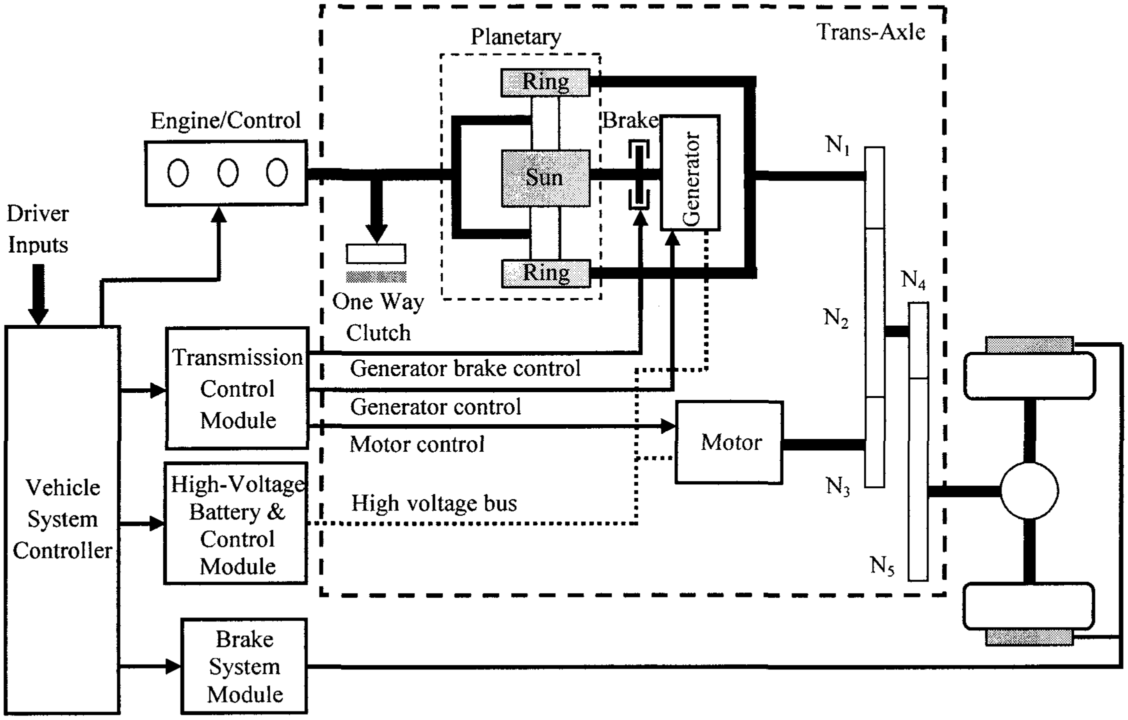


Fig. 2.5 Basic control structure for a planetary gear based S-P drivetrain [39].

Hence power split device employing planetary gear provides the opportunity for the engine to operate at or near its optimal operating speed, irrespective of speed of vehicle, while still being able to efficiently deliver power to the wheels and at the same time drive the generator. The general control technique for a power split drivetrain has been further explained in [25], [39] based on which a representation of the system is obtained which is shown in Fig. 2.5. Similar to the other architecture there are some modes in which the series-parallel drivetrain operates [35], [43]. Based on the driving characteristics various kinds of modes possible have been enumerated below:

1) For vehicle accelerating initially and mid-range speeds driving, as the engine has been observed to operate inefficiently, the traction power is met through the motor alone using energy of the battery.
2) For standard driving conditions, drivetrain efficiency is kept at optimal level by keeping major portion of the engine output to drive the vehicle while using the rest to turn the generator in order to generate electricity.

3) In a high speed acceleration scenario, the generator supplements the electrical energy provided by battery in order for the motor to generate sufficient mechanical energy.
4) During vehicle decelerating or braking, the motor would act as a generator in order to recover kinetic energy of the wheels in order to charge the battery.
5) When the battery SOC is low or when enough electricity can be produced by generator then a portion of engine power used to charge battery

The various modes that have been utilized for achieving optimization of the series-parallel drivetrain have been explained and discussed properly later sub-sections of this chapter. Also power models obtained for these modes have been presented.

2.2 Comparative Study of Various Drivetrains

The most commonly used drivetrain architectures for hybrid vehicles are the series and parallel drivetrain, another architecture that has been found to be quite beneficial is the series-parallel drivetrain. As the series-parallel drivetrain combines the advantages of series and parallel architectures it is quite important to understand the inherent benefits and drawbacks of these systems.

2.2.1 Benefits and Drawbacks of Series Architecture

The main advantages of using series configuration can be summarized as:

- ✓ Engine is almost always running at its optimal speed and torque values.
- ✓ Engine and generator are sized to meet the average propulsion power requirements
- ✓ Mechanical separation of engine and generator from the wheels results in ability of running the engine at its maximum efficiency.
- ✓ Simplicity of drivetrain means reduced control strategy complexity

The drawbacks inherent to this architecture have been listed down below:

- ✗ Multiple energy conversions are required that is mechanical to electrical (using generator) and electrical to mechanical (using motor).
- ✗ It has two electric traction devices.
- ✗ The electric motor has to be sized bigger in order to propel the vehicle.

2.2.2 Benefits and Drawbacks of Parallel Architecture

The major benefits of utilizing parallel configuration can be given as:

- ✓ Requirement of only one electric machine in the drivetrain.
- ✓ The peak power requirement for electric motor is significantly reduced as compared to a series hybrid.
- ✓ The engine power can be delivered to the wheels directly hence no energy conversion losses.
- ✓ The motor, engine or both can be used to meet the power demand.

The drawbacks of the system are as follows:

- ✗ The mechanical coupling of the engine and motor to the wheels places a restriction on the level of speed-torque optimization of the engine.
- ✗ An extra mechanical link is required.

2.2.3 Series-Parallel versus other Architectures

As the series-parallel configuration is developed as a combination of the series and parallel drivetrain architectures, it is able to take advantage of both these drivetrains with minimal drawback [44]. A feature common to series and this drivetrain is the requirement of two electric machines. However unlike series both machines are not required to be sized for large power requirement, which results in one electric machine, generator, to be sized considerably smaller. The utilization of more components does lead to complexity but through implementation of the appropriate control algorithm the overall level of improvement can outweigh the complexity of the system. The comparison based on various literature studies for all the 3 drivetrain architecture has been shown in Table 2.1.

2.3 Series-Parallel Modes and Corresponding Power Flow Models

In a series parallel hybrid system there are various modes in which the drivetrain can be configured [34]. Drivetrain configuration plays a pivotal role in how efficiently the power is distributed among the various components. It is through apposite arrangement of the drivetrain components that the best possible utilization of power and energy sources can be obtained. But in order to obtain efficient operation out of the energy/power sources the selection of the right mode becomes a primary concern. The optimal mode

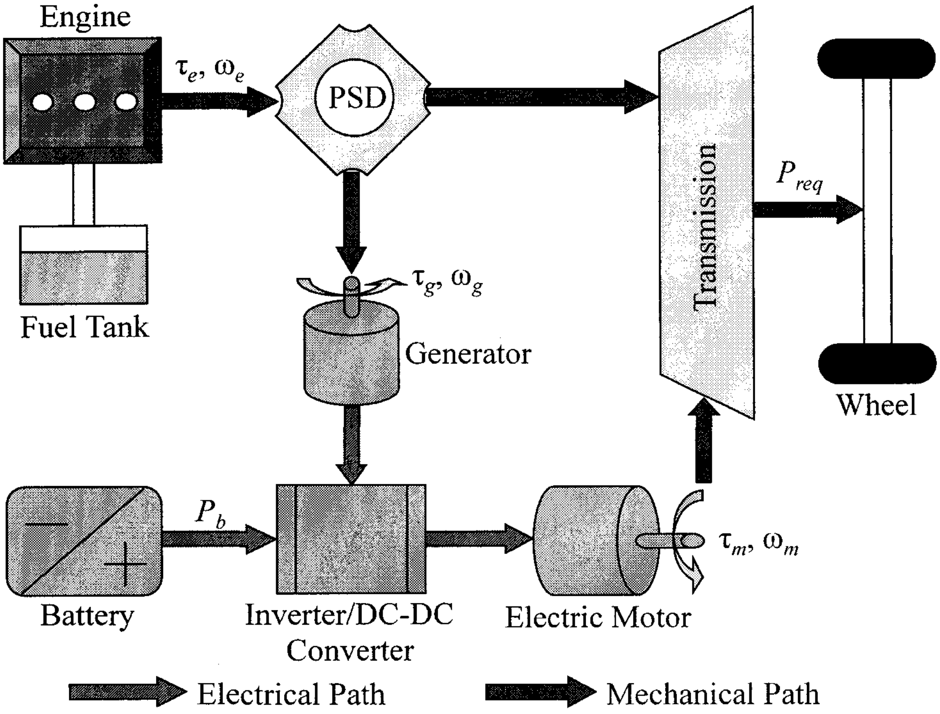
TABLE 2.1

COMPARISON OF VARIOUS DRIVETRAIN ARCHITECTURES

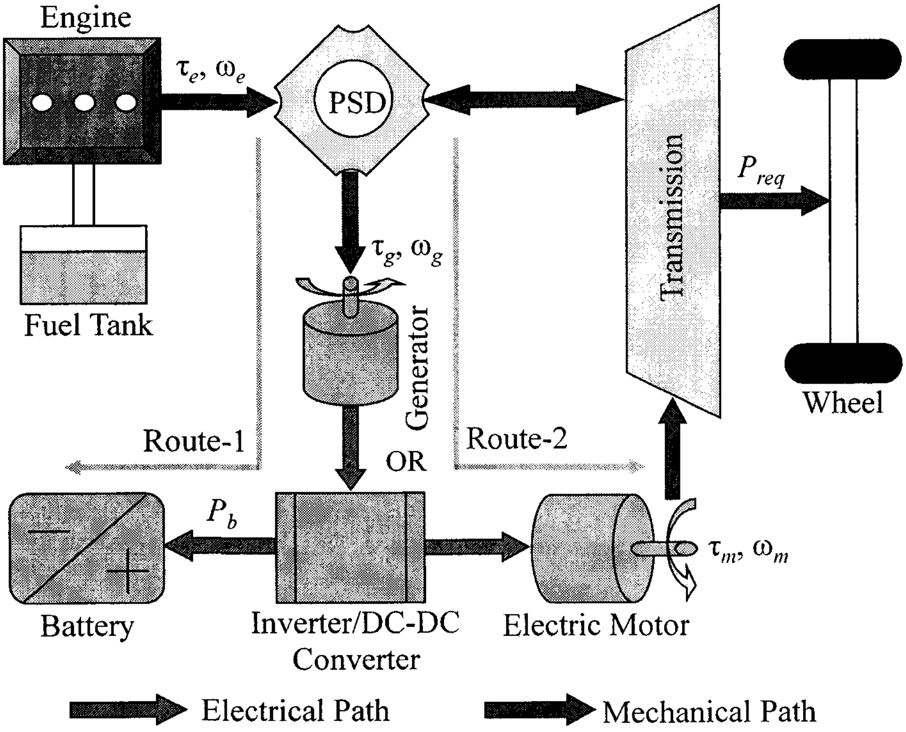
Type of Drivetrain	**Fuel economy Improvement**			**Driving performance**	
	Energy gained by Regenerative braking	**High efficiency operation control**	**Total efficiency**	**Acceleration**	**Continuous High output**
Series	***	**	**	*	*
Parallel	**	*	**	**	*
Series-parallel	***	***	***	**	**

should be chosen to obtain high fuel efficiency and efficient energy distribution among the energy sources. For this purpose certain modes of operation have been selected and some mathematical power flow models have been obtained. The concept of these models can be understood from [12], [37]. Depending upon the vehicle requirements the mode selection and power flow changes. Through the reconfiguration of the drivetrain optimal operation of the components can be attained based upon the driver's power demand [12].

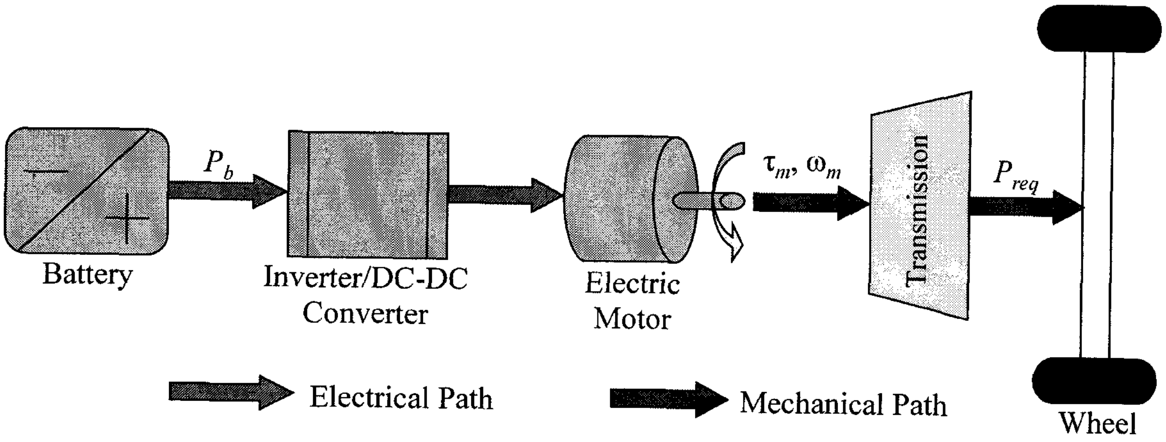
Based on the driving state, power requirement, SOC and other important parameters, the drivetrain can be modeled for optimal performance based on the situation. Although there are various possible arrangements [43], [45], only the types that have been utilized have been explained. There are four modes that are primarily used to achieve optimal performance out of the drivetrain. Out of these modes only two of these modes have the engine actively engaged in the drivetrain in order to power the vehicle. Fig. 2.6 shows a physical representation of drivetrain components being engaged in order to manage power distribution during each of the modes being modeled and explained.



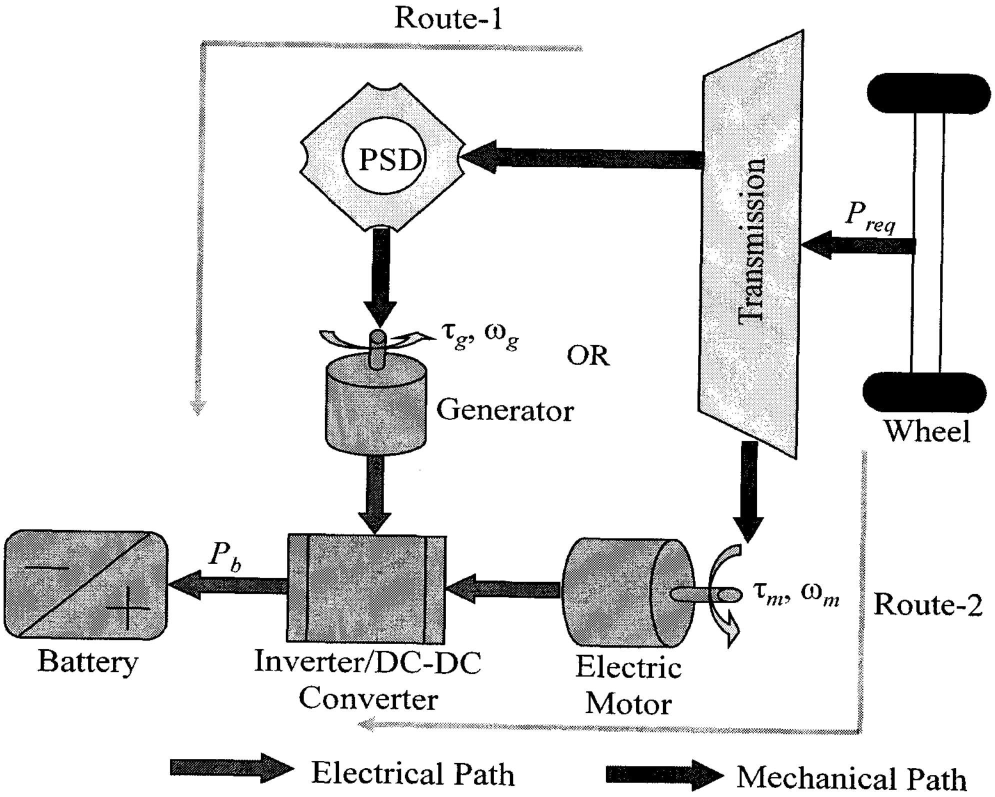
(a) All drivetrain components are actively engaged.



(b) Motor does not power vehicle for route-1 and battery neither charges nor discharges for route-2.



(c) All electric drivetrain, only motor powers vehicle.



(d) Generator utilized for route-1 and motor used for route-2.

Fig. 2.6 Various modes utilized for a series-parallel powertrain: (a) Series-parallel mode, (b) Engine only mode, (c) Electric mode, and (d) Regenerative mode.

2.3.1 Electric Mode (EM)

This is the most preferable configuration with zero emissions, since the vehicle runs as a purely electric vehicle. The electrochemical energy of the rechargeable battery is utilized to power the electric motor which drives the vehicle. In this mode the engine, generator and power split device are disabled from the drivetrain. Since the engine is not utilized it is therefore an all electric drivetrain and has been shown in Fig. 2.6 (c).

The utilization of this mode is primarily for low to mid speed driving conditions. It is commonly the first choice drivetrain configuration for low to mid speed acceleration. Also based upon factors like the SOC, the distance travelled and elevation, it can also be used for mid-speed steady state vehicle driving. Therefore it can be employed during steady-state driving for a speed of up to 40 km/hr. These constraints have to be considered so as to avoid deep discharge of the battery in order to keep it above a certain SOC. Due to direct relation between the vehicle and motor speed, the motor is seen to operate at lower speed. As power required at low speed is less than that at a higher speed, the motor operates at a lower torque and speed which makes it operate at lower efficiency, typically 70-80 %. Even though this is true the utilization of electric mode offers much higher drivetrain efficiency as compared to any other mode due to the fact it disables the engine. The engine is known to be least efficient at lower speed and torque range. Hence rendering engine inoperative would result in saving fuel as well as evading inefficient engine operation. Through mathematical modeling the dynamics of this mode can be explained. These equations also help in understanding the power flow in the drivetrain. The battery and motor power can be represented through the following:

$$P_b = \frac{P_{req}}{\eta_t \eta_m} \tag{2.3}$$

$$P_m = \eta_m P_b; \qquad \left(\text{where } P_m = \omega_m \tau_m\right) \tag{2.4}$$

The electric power provided by battery has to be converted to mechanical power which is done by the use of an electric motor. Electric motor is designed for frequent stop and start driving conditions [46]. In short the primary objective achieved through EM is operating the vehicle at low speed steady-state conditions and for low acceleration demands. Through this configuration high drivetrain efficiency can be achieved for city conditions as the vehicle frequently starts and stops.

2.3.2 Series-Parallel Mode (SPM)

This mode utilizes the energy from gasoline and battery to meet power demand. The drivetrain does not have to be reconfigured in this mode as can be observed by looking at the representation provided in Fig. 2.6(a). All the components are operational during the entire operation of the mode. Since none of the components have to be disengaged from the drivetrain, the power distribution algorithm has an immense amount of work due to presence of multiple energy and power sources. The engine and motor speed-torque range needs to be varied in order to obtain optimal performance.

As the name of the mode suggests, the power distribution is a combination of both the series and parallel paths. The parallel path consists of the engine and the electric motor providing power to the wheels in parallel. Also the series path comes into play when a small portion of the engine power is routed through the generator to provide power for the electric motor.

This mode is used to meet power needs of the vehicle mainly for acceleration and sometimes during steady-state. As the battery by itself is not able to meet the power demand during speeds over 50 km/hr, the proportion of electric to engine power is kept as high as possible while keeping SOC in consideration. Based upon the electric proportion this mode can be sub-divided in two parts:

- High electric ratio: When the battery is in a higher SOC range of 60 to 85%. Due to the availability of battery energy, the electric power, from the battery powered motor, is higher and therefore less engine power is required. As a result the proportion of electric power is higher.
- Low electric ratio: When the battery is in a lower SOC range of 30 to 60%. Due to a lack of available battery energy, the electric power (battery powered motor) is lower and more engine power is utilized to meet power demands. As a result, the proportion of electric power goes down.

The operation of the EM and SPM modes are similar, except that the speed and torque range that the motor, engine and generator operate are different. There are two main factors that influence the operation of this mode:

- Selection of the appropriate speed-torque range of the motor and engine through the use of efficiency maps.

- Varying the recirculation factor, x in order to control the generator output power and angular speed.

The recirculation factor is a variable that specifies how the engine power is split into two paths: the mechanical path that is directly connected to the wheels and the electrical path through the motor-generator. Through varying the power that passes through the electrical path the efficiency of not only engine but also the motor can be increased. The recirculation factor and the battery output can be varied in order to enhance performance of the power sources while keeping the power lost through recirculation as low as possible. Initially the speed-torque range of motor and engine are selected based upon the information fed from the look up tables created using efficiency maps. After this in order to maximize drivetrain optimization, through control of the amount of engine power going through the electrical path the motor's region of operation is managed. This is done while keeping the power through this path as low as possible. These operations are better understood by looking at the representative model of power flow for this mode:

$$P_m = x(\eta_g \eta_m P_e) + \eta_m P_b \tag{2.5}$$

$$P_{req} = \eta_t (1-x) P_e + \eta_t P_m \tag{2.6}$$

$$P_e = \eta_t P_{req} + P_g \tag{2.7}$$

$$P_g = (1-x) P_e \tag{2.8}$$

The primary aim of utilization of SPM is to distribute the energy between the primary energy source (gasoline) and the battery in an optimized manner such that both the engine and the motor operate in a region of high efficiency.

2.3.3 Engine Only Mode (OEM)

The requirement of this mode is quite vital for two chief reasons: to utilize the engine power efficiently so that the fuel consumption and emissions are as low as possible and secondly to charge the battery whenever the SOC is below pre-defined limit. Based upon the application of engine power to drive vehicle or to drive vehicle and charge battery either battery or motor is disengaged from the drivetrain respectively. Through utilization of this mode engine can be operated in higher efficiency points (η_e>25%).

This mode comes into action when the vehicle is in steady-state. The power requirement during steady-state usually is low to medium. For lower speeds, as the power requirement is quite low, the modes discussed earlier are preferred over this mode. When the speed is over 50 km/hr and either the SOC is too low or there is reason for utilizing a small portion of engine power to charge the battery, this mode proves quite effective. While a major portion of the engine power is used to meet the power requirement, a small portion (10 to 30%) is routed through the generator to generate electricity which can either be used to charge the battery when the SOC level is low or to run the vehicle when SOC is in a certain range. On the basis of the utilization of the engine this mode can be classified into the following:

- Drive the vehicle only: Medium to high power demand, higher speed (>50 km/hr) and medium SOC range (50 to 70%). The vehicle power distribution can be explained from the power model developed:

$$P_{req} = \left(\eta_t(1-x) + \eta_t\eta_m\eta_g x\right)P_e \tag{2.9}$$

$$P_m = x\eta_g\eta_m P_e; \quad \left(\text{where } P_e = \omega_e\tau_e\right) \tag{2.10}$$

The power passing through the electrical path is kept at a minimum level to reduce the conversion losses while operating engine at high efficiency.

- Drive vehicle and charge battery: Medium power demand, medium speed range (40-60 km/hr) and low SOC (<50%). Power management for this mode can be represented mathematically as follows:

$$P_{req} = \eta_t(1-x)\omega_e\tau_e \tag{2.11}$$

$$P_b = x\eta_g\omega_e\tau_e \tag{2.12}$$

The output of the motor in this scenario is zero. The battery is charged in a constant power manner. Both kinds of implementation of the mode can be seen in Fig. 2.6(b).

In order to have absolute optimization there are other factors that have been considered. The distance traversed by the vehicle, the elevation and amount of driving time spent during steady-state other control parameters. Based upon the driving schedule information, all these parameters can play a pivotal role in deciding how this mode is utilized. A portion of the engine power can be used to run the generator whose output can be utilized to charge the battery which has been represented by (2.12). Hence this mode is quite vital for optimal engine operation and maintenance of SOC.

2.3.4 Regenerative Mode (RM)

When the vehicle decelerates there is no power being consumed but since the wheels are in motion there considerable amount of kinetic energy available [47]. There is a substantial amount of power that can be captured through regenerative braking. In order to maximize the power captured there is need for control of the component responsible for it. Due to this, the regenerative mode is used to manage effective power capture through component selection. This mode is employed during deceleration when the power requirement is zero. In this mode the engine is not required hence it is disengaged in order to avoid idling. The main objective of this mode being:

- Selection of either motor or generator in order to capture energy through regenerative braking.
- Choosing optimal speed-torque characteristics of motor/generator for maximized power capture rate.
- Safely monitoring the power fed back to battery.

The drivetrain can be configured in two ways depending upon the power available from the wheels and the vehicle speed as shown in Fig. 2.6(d):

- Regenerative braking through motor (route-2): The motor acts like a generator. This configuration is utilized usually for higher speeds as more power can be captured. The amount of power fed back through the motor to charge battery can be represented by:

$$P_b = \eta_m \omega_m \tau_m \tag{2.13}$$

- Regenerative braking through generator (route-1): The generator is utilized instead of the motor at lower speed when there lower power available. This is done as it has higher overall efficiency then the motor. This is done as the generator has a higher efficiency as compared to the motor functioning as a generator. Generator output available for charging the battery can be represented by:

$$P_b = \eta_t \eta_g P_{req} \tag{2.14}$$

$$P_g = \eta_t P_{req} \tag{2.15}$$

This mode is quite vital when the vehicle is decelerating. It's responsible for disengaging the engine and the other components from drivetrain if they are not required.

Identifying these modes of operation and there power modeling are quite essential in order to select the design parameters for optimized power distribution. Based on these equations it can be inferred what range and value of different parameter have to be taken in order for efficient operation of the various energy and power sources. Through optimal mode configuration selection the following objectives that can be achieved:

- Efficient electric motor and engine operation
- Optimal drivetrain performance
- Regenerative braking through motor or generator
- Speed and torque optimization of components

2.4 Assessment of Vehicle Energy and Power Sources

Drivetrain hybridization is achieved through utilization of multiple energy and power sources. Hence when a power distribution strategy is being designed there is a need to evaluate status of the key components in the drivetrain in order to analyze effectiveness of the control strategy. The information about the average efficiency of the engine and the motor during the driving schedule can shed light upon the optimization of these components. Based on various equations obtained for various configurations (2.5)-(2.15) and the input-output dynamics of engine, motor, generator etc., generalized series have been developed for obtaining average motor and engine efficiencies illustrated below:

$$\eta_m(avg)=\frac{\begin{gathered}\left\{\left[\sum_{t=t1}^{t2}\omega_m\tau_m+\sum_{t2+1}^{t3}\omega_m\tau_m\right]\vee\left[\sum_{t=t1}^{t3}\omega_m\tau_m\right]_E\right\}_{acc}\wedge\left\{\begin{matrix}\left[\sum_{t3+1}^{t4}\omega_m\tau_m\right]_{SP}\vee\left[\sum_{t3+1}^{t4}\omega_m\tau_m\right]_E\\ \vee\left[\sum_{t3+1}^{t4}\omega_m\tau_m\right]_{OE}\end{matrix}\right\}_{ss}\\ \wedge\left\{\left[\sum_{t4+1}^{t5}P_b\right]_R\right\}_{dec}\wedge\ldots\ldots\end{gathered}}{\begin{gathered}\left\{\begin{matrix}\left[\sum_{t=t1}^{t2}P_b+\sum_{t2+1}^{t3}\left(P_b+x\eta_g\omega_e\tau_e\right)\right]_{SP}\\ \vee\left[\sum_{t=t1}^{t3}P_b\right]_E\end{matrix}\right\}_{acc}\wedge\left\{\begin{matrix}\left[\sum_{t3+1}^{t4}\left(P_b+x\eta_g\omega_e\tau_e\right)\right]_{SP}\\ \vee\left[\sum_{t3+1}^{t4}P_b\right]_E\vee\left[\sum_{t3+1}^{t4}x\eta_g\omega_e\tau_e\right]_{OE}\end{matrix}\right\}_{ss}\\ \wedge\left\{\left[\sum_{t4+1}^{t5}\omega_m\tau_m\right]_R\right\}_{dec}\wedge\ldots\ldots\end{gathered}} \quad (2.16)$$

$$\eta_e(avg) = \frac{\left\{\left[\sum_{t2+1}^{t3}(1-x)\omega_e\tau_e + \left(\frac{\omega_m\tau_m}{\eta_m\eta_g} - \eta_m P_b\right)\right]_{SP}\right\}_{acc} \wedge \left\{\begin{array}{c}\left[\sum_{t3+1}^{t4}(1-x)\omega_e\tau_e + \left(\frac{\omega_m\tau_m}{\eta_m\eta_g} - \eta_m P_b\right)\right]_{SP} \\ \vee \left[\sum_{t3+1}^{t4}(1-x)\omega_e\tau_e + \left(\frac{\omega_m\tau_m}{\eta_m\eta_g}\right)\right]_{OE}\end{array}\right\}_{ss} \wedge \ldots\ldots}{\left\{\left[\frac{\sum_{t2+1}^{t3} E_e(t)}{\sum_{t2+1}^{t3} t}\right]_{SP}\right\}_{acc} \wedge \left\{\left[\frac{\sum_{t3+1}^{t4} E_e(t)}{\sum_{t3+1}^{t4} t}\right]_{SP} \vee \left[\frac{\sum_{t3+1}^{t4} E_e(t)}{\sum_{t3+1}^{t4} t}\right]_{OE}\right\}_{ss} \wedge \ldots.} \tag{2.17}$$

These values take into consideration the various configurations utilized based upon the power requirements and driving state. The various terms in the series show the different driving states and corresponding modes possible. Using (2.16) a general power series is obtained to calculate average motor output power which is shown in (2.18). The motor output can be observed to be a weighted average of the motor outputs from different modes corresponding to driving states. Similarly average engine output can also be obtained in order to analyze the level of engine optimization.

$$P_m(avg) = \frac{\left[\left\{\left[\sum_{t=t1}^{t3}\eta_m P_b\right]_E \vee \left[\begin{array}{c}\sum_{t=t1}^{t2}\eta_m P_b + \\ \sum_{t2+1}^{t3}(x\eta_m\eta_g P_e + \eta_m P_b)\end{array}\right]_{SP}\right\}_{acc} \wedge \left\{\begin{array}{c}\left[\sum_{t3+1}^{t4}(x\eta_m\eta_g P_e + \eta_m P_b)\right]_{SP} \vee \\ \left[\sum_{t3+1}^{t4}\eta_m P_b\right]_E \vee \left[\sum_{t3+1}^{t4}x\eta_m\eta_g P_e\right]_{OE}\end{array}\right\}_{ss} \wedge \ldots\ldots\ldots\right]}{[(t3-t1)+(t4-t3-1)+\ldots\ldots.]} \tag{2.18}$$

In order for power management system to function properly it requires information on the energy storage sources that is the SOC of the battery and the fuel level [48]. This information can help in calculating the fuel consumption and battery discharge which can help in controlling the power sources. Due to this, certain equations have been developed to demonstrate the charge/discharge activity of the battery and the gasoline consumption during a particular duration:

$$SOC_f(t+\Delta t) = SOC_0(t) + \frac{\eta_b P_b \Delta t}{E_b} \tag{2.19}$$

$$SOC_f(t+\Delta t) = SOC_0(t) - \frac{P_b \Delta t}{\eta_b E_b} \tag{2.20}$$

$$Fuel_f(t+\Delta t) = Fuel_0(t) - \frac{P_e \Delta t}{\eta_e E_e} \tag{2.21}$$

These equations aid in monitoring the battery and fuel tank and help in understanding the energy distribution. Through the development of these mathematical models for power flow in the drivetrain and energy consumption accountability, an algorithm can be designed for control of power and energy sources.

3 DESIGN CONSIDERATIONS AND DEVELOPMENT PROCEDURE OF A RULE BASED ALGORITHM

3.1 Vehicle Dynamics for Various Driving States

In order to successfully implement the algorithm to manage the power distribution the most important prerequisite is the calculation of the power and energy requirements of the vehicle, which requires knowledge about the vehicle dynamics. The vehicle driving state plays a very vital role in the design of the algorithm [6], [48]. The driving state provides the algorithm with the initial information required about how much is the power required at a certain speed and whether vehicle is accelerating or not. The state of the vehicle is quite important in taking the necessary steps needed in order to decide the power flow among the components. Even during deceleration the information fed back from the vehicle is helpful in gathering information about the amount of braking power that can be useful. In this section the importance of why knowledge of various driving states is important has been explained. Also equations that have been considered for the calculation of power and energy with regard to the various driving state have been demonstrated.

3.1.1 Vehicle at Rest

The vehicle is in a state of rest when power demand is zero, this happens when the vehicle is at standstill or as soon as vehicle comes to rest just after decelerating. The control strategy plays a small role even for this state; this is during the transient phase when the vehicle is just about to accelerate. Its job is to see to it that the engine is shut off during the initial start up and battery does not discharge before the vehicle actually starts to accelerate that is when vehicle is idle.

3.1.2 Acceleration

The vehicle power and torque demands are relatively higher during acceleration as compared to steady-state or deceleration. This happens due to requirement of a large amount of energy in a very short interval which can range from 1 to 10 seconds. This creates a high power requirement. This high power need is a combination of both, power required in order to overcome the forces opposing the motion of the vehicle and power required in order to maintain speed. The forces acting on the vehicle are caused due to a combination of frictional forces between the wheels and the aerodynamic shape of the vehicle. The power and energy requirement for acceleration are based upon certain forces acting on the vehicle [8], [47], [49], [50]:

$$F_{aero} = 0.5C_D A_f \rho V_f^2 \tag{3.1}$$

$$F_{roll} = R_t mg \tag{3.2}$$

$$F_{grad} = mg\, sin\theta \tag{3.3}$$

The energy and power requirements can be calculated utilizing (3.1)-(3.3) based on explanation obtained from [8], [50]:

$$E_{acc} = \left[0.5mV_f^2 + \left(F_{aero} + F_{roll} + F_{grad}\right)D\right] \tag{3.4}$$

$$P_{acc} = {E_{acc}}/{t} \tag{3.5}$$

3.1.3 Steady-State

During this driving state the vehicle travels at a constant speed; hence there is no need for vehicle to accelerate. Therefore the power requirement during this driving state is lower as compared to acceleration. The power demanded during this driving state to a certain extent is a function of distance travelled and the elevation. The reason for above being that the vehicle only requires power to maintain speed as it has already overcome the opposing forces. Based upon (3.1)-(3.3), vehicle dynamics for steady-state can be obtained [8], [50] as follows:

$$E_{ss} = \left(F_{aero} + F_{roll} + F_{grad}\right)D \tag{3.6}$$

$$P_{ss} = {E_{ss}}/{t} \tag{3.7}$$

3.1.4 Deceleration

Power management system even plays a crucial role even during deceleration It is quite important that the deceleration state being considered separately, this is due to fact that during vehicle decelerating, even though the engine is turned off and battery's not discharging the mechanical energy of the wheels which would otherwise be wasted can be used to charge the battery. Certain portion of this energy is wasted as friction but there is a significant amount of kinetic energy of the wheels that can be captured through regenerative braking. This is given as:

$$E_{dec} = \left|\left\{md - \left(F_{roll} + F_{grad} + F_{aero}\right)\right\}D\right| \tag{3.8}$$

$$P_{dec} = {E_{dec}}/{t} \tag{3.9}$$

3.2 Use of Efficiency Maps to Obtain Conditions and Constraints

3.2.1 Efficiency Map Utilization

A hybrid drivetrain has been able to achieve better fuel efficiency and economy at the expense of introduction of more components in the drivetrain which influence the system efficiency. Due to this reason it becomes vital to consider efficiencies especially for the engine, motor and generator. Through utilization of efficiency maps, information on speed and torque can be gathered which can be employed to optimize the operation of the component. The knowledge obtained can thus be used to develop a strategy to manage the power distribution of the system. In order to obtain the speed-torque range of the motor, the efficiency characteristic of the Prius motor has been considered which is based on motor map information obtained from [51] and has been illustrated in Fig. 3.1.

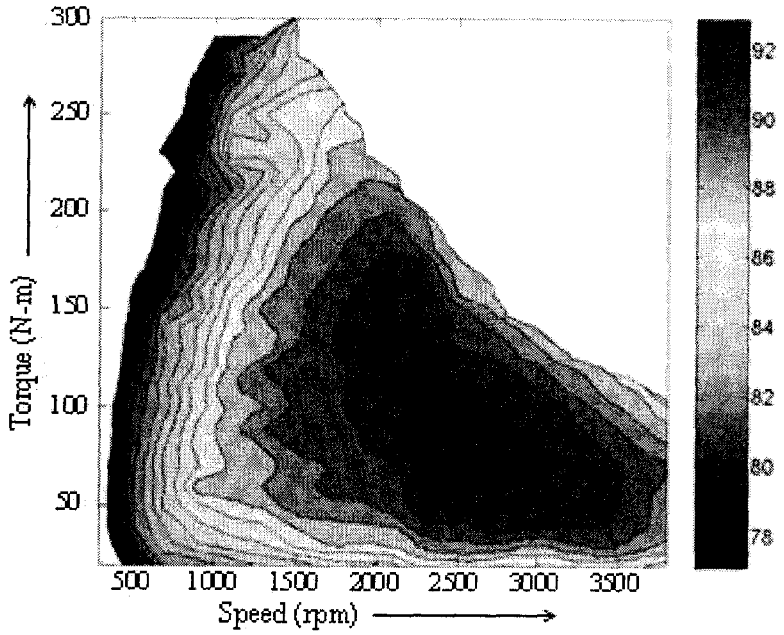


Fig. 3.1 Speed-Torque characteristics with efficiency information for motor-inverter [51].

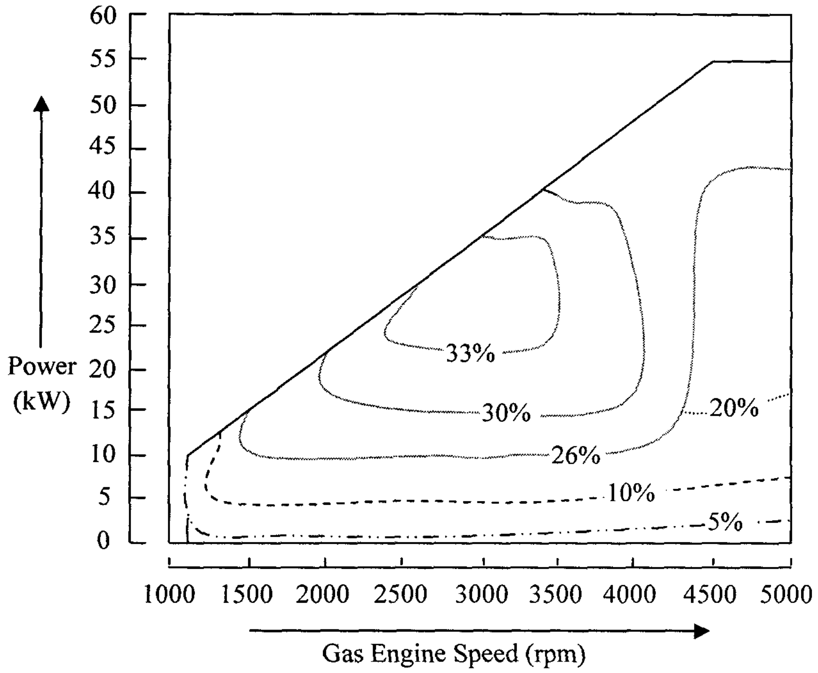


Fig. 3.2 Engine efficiency map based on generalized engine map [7], [8], [41].

From the motor efficiency map the torque and output power of motor can be selected to operate in an optimal region. This map takes inverter characteristics into consideration as well. Besides motor map, a generalized efficiency characteristic of an ICE is employed to an actual power versus speed plot of Prius engine in order to consider an engine map [7], [8], [41] as shown in Fig. 3.2. From these maps, optimal speed and torque operation can be achieved [1], [42]. Even though generator efficiency has been taken to be constant, its power and speed have still been accounted for. The speed relationship between the electric motor, engine and generator obtained from speed coupling [37], [51] is useful for calculation of angular velocities and defined earlier in (2.1).

3.2.2 Formation of Conditions and Constraints

In order to develop a robust optimization technique, a vital design requirement is the defining of conditions and constraints that need to be considered. In the previous section the importance of efficiency maps has been stressed, especially for obtaining efficiency related speed-torque values and this is where their utilization becomes quite vital. Through the information gathered about the speed-torque characteristics of the engine and motor [8], [51] look-up tables can be created which in turn are responsible for obtaining the

TABLE 3.1
VEHICLE CONTROL CONDITIONS

Control variable	**Test condition:**
Vehicle power demand (kW)	$P_{req}(t) < P_{req}(min)$
	$P_{req}(t) > P_{req}(min)$
Vehicle speed (km/hr)	$V(t) < V(min)$
	$V(t) > V(min)$
SOC (%)	$SOC(t) < SOC(min)$
	$SOC(t) > SOC(min)$
Distance travelled (km)	$D < D(min)$
	$D > D(min)$

conditions and constraints based on which appropriate power split solution is obtained. As the efficiency characteristics of motor and gasoline engine are used hence this requires formation of different conditions and constraints.

The various types of conditions that might be required to obtain optimization based upon driving situation have been listed in Table 3.1. The Power requirement has been calculated using (3.4)-(3.7) mentioned in the previous sub-section and then based on this various boundary conditions are set, similarly other boundary conditions have also been formed from vehicle data fed back (speed, SOC etc.). The utilization of these conditions will be demonstrated when control algorithms would be explained.

In addition to the conditions, there are various constraints that help in limiting the engine and motor operation within acceptable limit. These constraints are based upon minimum and maximum value of the speed and torque of the motor, generator and engine, in addition to this maximum output capability of the battery also needs to be considered. Constraints that are vital to design of the control strategy are shown below:

$$\left.\begin{array}{l}\omega_e(\min) \le \omega_e \le \omega_e(\max) \\ \tau_e(\min) \le \tau_e \le \tau_e(\max)\end{array}\right\} @ \eta(\max)$$

$$\left.\begin{array}{l}\omega_m(\min) \le \omega_m \le \omega_m(\max) \\ \tau_m(\min) \le \tau_m \le \tau_m(\max)\end{array}\right\} @ \eta(\max)$$

$$\omega_g(\min) \le \omega_g \le \omega_g(\max)$$

$$P_b < P_b(\max)$$

$$\text{Where } \eta(\max) = f\{\eta_e(\max), \eta_m(\max)\}$$

As enumerated above these constraints are created based on analytical investigations of the efficiency maps and they are selected for most optimal drivetrain performance. Both the engine and motor efficiency are considered while finding the constraints range. Hence knowledge of these conditions and constraints combined with power models of various drivetrain modes would be quite vital in order for constructing the algorithm for managing power distribution during each driving state.

3.3 General Methodology for Design of Algorithm

The power distribution for hybrid drivetrain will be managed though the appropriate selection of the speed and torque of the power sources. An additional feature obtained from the application of this strategy will be the selection of the generator over electric motor for regenerative braking based upon the power availability scenario. The efficiency maps discussed before are utilized for selection of the operational range of speed and torque of the power sources. Through range selection, the speed-torque characteristics can be obtained for the driving cycle considered for simulation. The optimization procedure has been sub-divided into three sections based upon the driving states.

3.3.1 Managing Power Distribution during Acceleration

The vehicle power demand is significantly higher during acceleration as compared to the other driving states. The high power demand necessitates a need for balanced distribution of power between the engine and motor. This management of power needs to done in an efficient manner such that the drivetrain components operate in a region of high efficiency. The proposed strategy for acceleration optimization is illustrated in Fig. 3.3. As it can be seen in this figure, optimized output is obtained based upon the input control parameters. These control parameters are divided into two sub groups: control inputs and the constraints of motor and engine. The range of torque and speed for efficient operation is important for optimal drivetrain performance. The final speed of vehicle in addition to vehicle power required act as conditional control inputs. These values are obtained via feedback paths which are responsible for delivering driver requirement information.

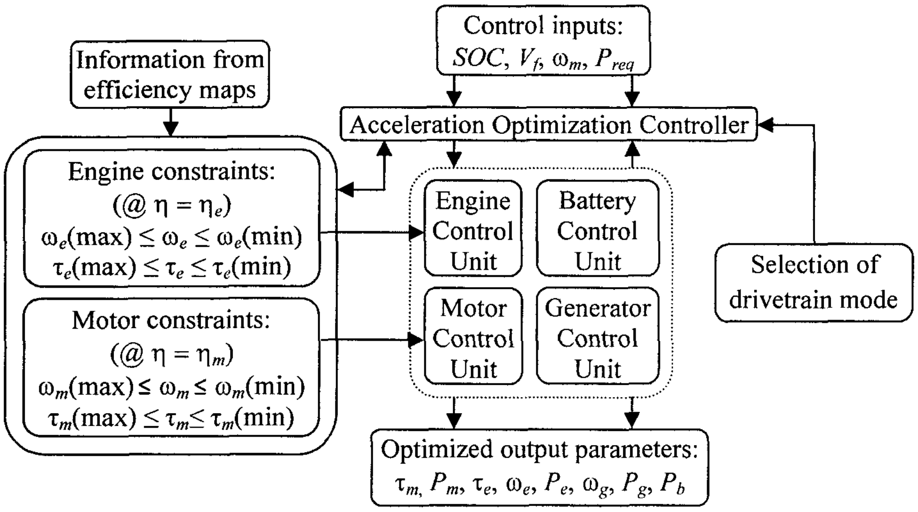


Fig. 3.3 Basic control strategy for acceleration.

3.3.2 Managing Power Distribution during Steady-State

The fact that power requirement is lower when vehicle travels at more or less constant speed as compared to it accelerating; the optimization procedure for steady-state requires different parameters in order to obtain efficient power distribution. Fig. 3.4 illustrates the basic theory behind the proposed optimization procedure. The battery SOC plays an even more important role for steady-state power distribution as compared to acceleration. Through a combination of efficiency maps discussed before and information obtained about the urban driving pattern the optimization process is designed. Depending upon the SOC level and distance travelled the optimization strategy decides what proportion of power is obtained from the battery. Steady-state optimization focuses on operating the engine in the highest possible region of efficiency while operating the electric motor at a reasonably high efficiency. The strategy involves using a minor portion of engine power to charge the battery while optimally operating engine. The input parameters are chosen such that the battery does not discharge quickly while meeting a minor share of the power demand through battery. At lower constant speed, the vehicle is operated as an electric vehicle this is done only when the power demand is lower.

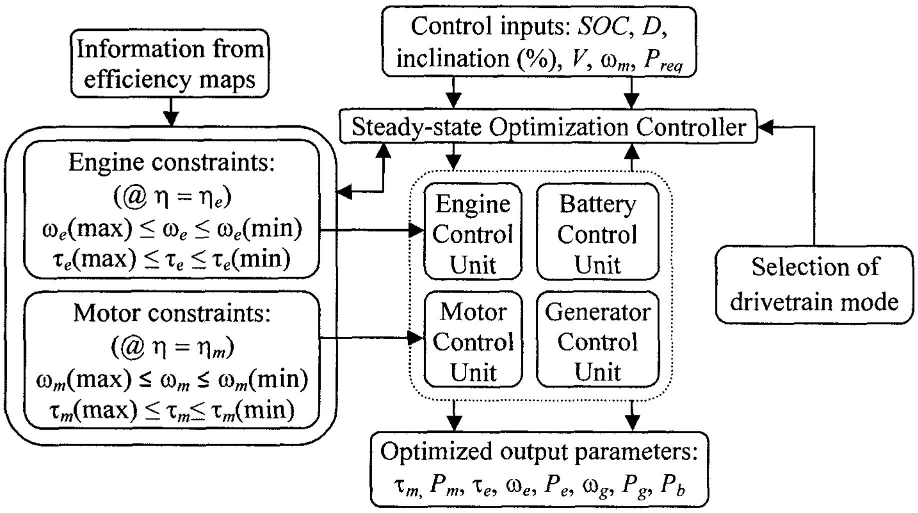


Fig. 3.4 Basic control strategy for steady-state.

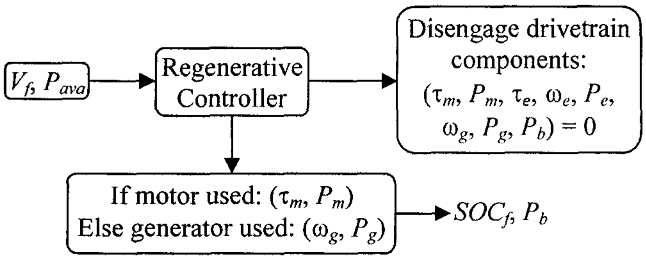


Fig. 3.5 Strategy used for regenerative braking control.

3.3.3 Maximizing Energy Capture during Deceleration

Through regenerative braking significant amount of energy can be captured during deceleration. The basis for achieving controlling regenerative braking is shown in the block diagram in Fig. 3.5. The electric motor can be operated as a generator in order to capture this energy to charge the battery. The battery can be charged in a safe manner through regulation of the motor power. This can be done through an adaptive strategy that depending upon the power available and wheel speed would be able to decide how much power from the wheels reaches the battery. An important feature of this strategy is the utilization of the generator for regenerative braking when the power to be captured is low. The generator is utilized instead of motor as it has much higher efficiency as compared to the electric motor.

3.4 Optimal Drivetrain Performance through Efficient Operation of Engine and Motor

In order to augment the vehicle's efficiency, an effective control strategy has to be in place. This necessitates the need for algorithm that controls the drivetrain operation for maximum efficiency at every time step. Hence a rule-based algorithm is developed based on shifting the region of operation of the engine and motor from a less efficient region to a region of higher efficiency. This is essentially done through implementation of procedure mentioned below:

- Consideration of the correct control parameters and constraints.
- Selection of the best possible mode based upon the vehicle driving state.
- Appropriate mathematical model for computing the power distribution among components.
- Choosing optimal speed-torque region operation for the motor, engine and generator based on data obtained from efficiency maps [6]-[8], [51].
- Maintaining the SOC over a certain level through control of charge/discharge activity of battery.

On the basis of the steps mentioned above, algorithms have been developed for control of the powertrain for acceleration, steady-state and deceleration. Control for each of the driving state requires a different approach due to need for different control parameters; this has been demonstrated in the forthcoming sub-sections.

3.4.1 Optimized Power Management for Acceleration

The manner in which a vehicle accelerates has a considerable amount of impact on the power demand which in turn dictates the selection of the optimal solution for power distribution. A vehicle's acceleration phenomena can be split into two categories on the basis of its previous driving state:

- Normal Acceleration: When the vehicle is initially at rest, but after a period of time the vehicle accelerates. The EM and SPM are the preferred modes of operation. It usually lasts for 4 to 8 seconds.

- Instantaneous Acceleration: The vehicle was either travelling at a constant speed or decelerating before sudden need to accelerate. Due to a high power requirement, the SPM is utilized. It can last for up to 4 seconds.

The algorithm for power management during acceleration is shown in Fig. 3.6. The most vital aspect of control strategy is the creation of a control function based upon which the optimal power solution is obtained.

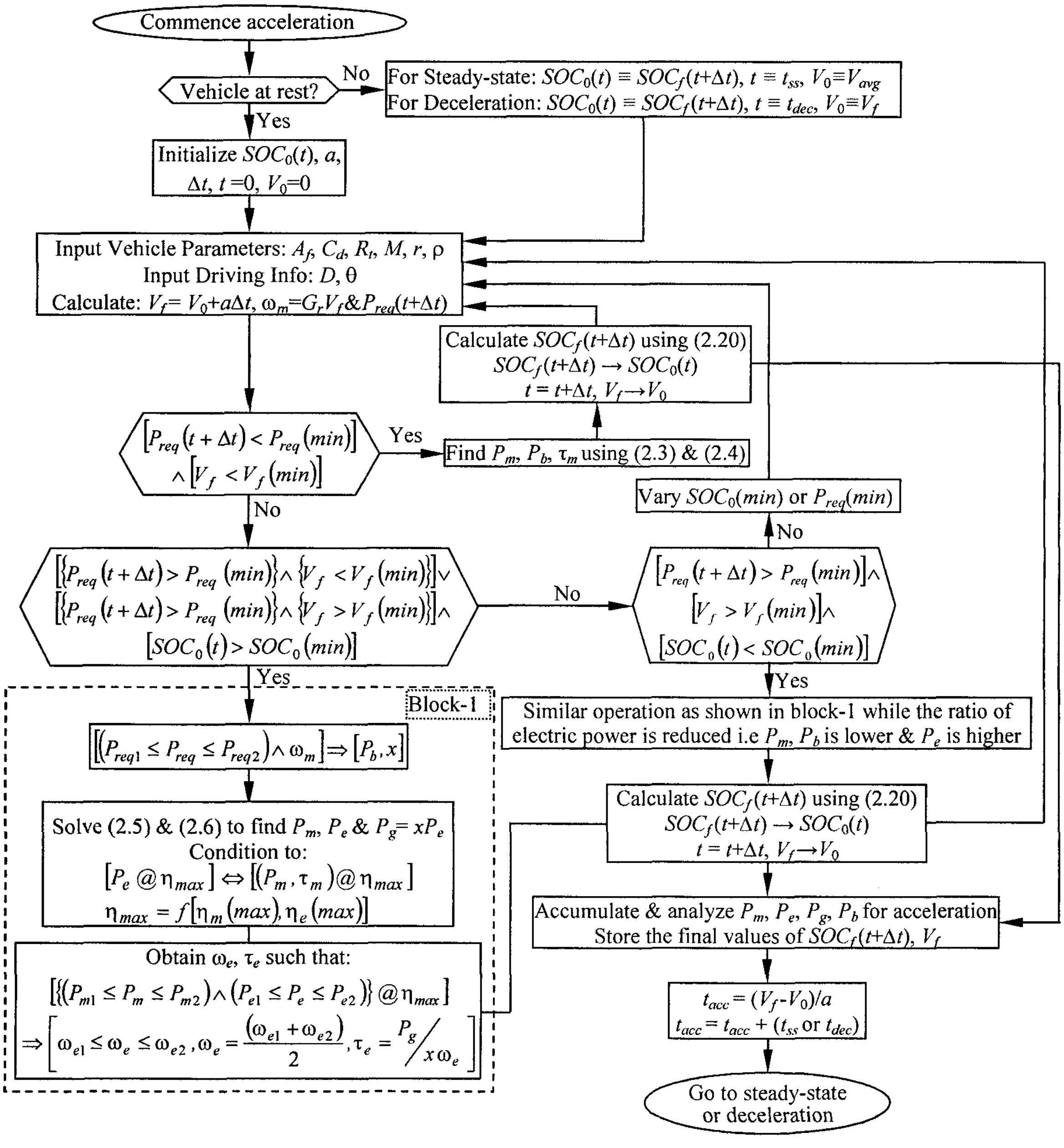


Fig. 3.6 Control algorithm for optimal distribution during acceleration.

The control function is a combination of the following two sets of criterions:

- Component constraints (CC): There are 2 kinds of constraints: system limitations and control constraints. System limitations are boundary conditions within which drivetrain components, especially the engine and motor operate, such as minimum and maximum values of speed, torque and power. The control constraints on the other hand is the information gathered from efficiency maps that demonstrates the relationship of efficiency to the corresponding speed-torque characteristics. This helps in determining the optimal regions of operation for the motor and engine which directly influence the conditional statements.
- Conditional statements (CS): The optimal mode selection is based upon fulfillment of the conditional statements applicable for the driving scenario. The conditional statement can comprise 1-3 conditions, which are based upon the power demand, vehicle speed and battery's SOC. The condition is tested against a pre-defined minimum value to see whether it is less or more in comparison to it.

Hence, on the basis of information about vehicle acceleration, various modes and control functions, an algorithm is developed for efficient power distribution.

3.4.2 Optimized Power Management for Steady-State

The control developed for steady-state driving differs to an extent from that of acceleration. This is due to the following reasons: firstly time spent travelling at a constant speed is usually higher, secondly power demand is much less and lastly, the need to avoid deep discharge of the battery. Similar to acceleration a control function is created which consists of component constraints and conditional statements. Due to these reasons, few additions have been made:

- Modify control function: In constructing the component constraints, similar approach is applied but there are few additions made to the conditional statements; in addition to power required and SOC, conditions for average speed and distance travelled are also considered as a conditional statement.

- Selecting modes: The EM and OEM modes are predominantly used to achieve optimal performance. EM is used to substitute engine operation when η_e<25%. OEM is used only for η_e>25%, either when the power requirement is higher or/and SOC is below a pre-defined point.

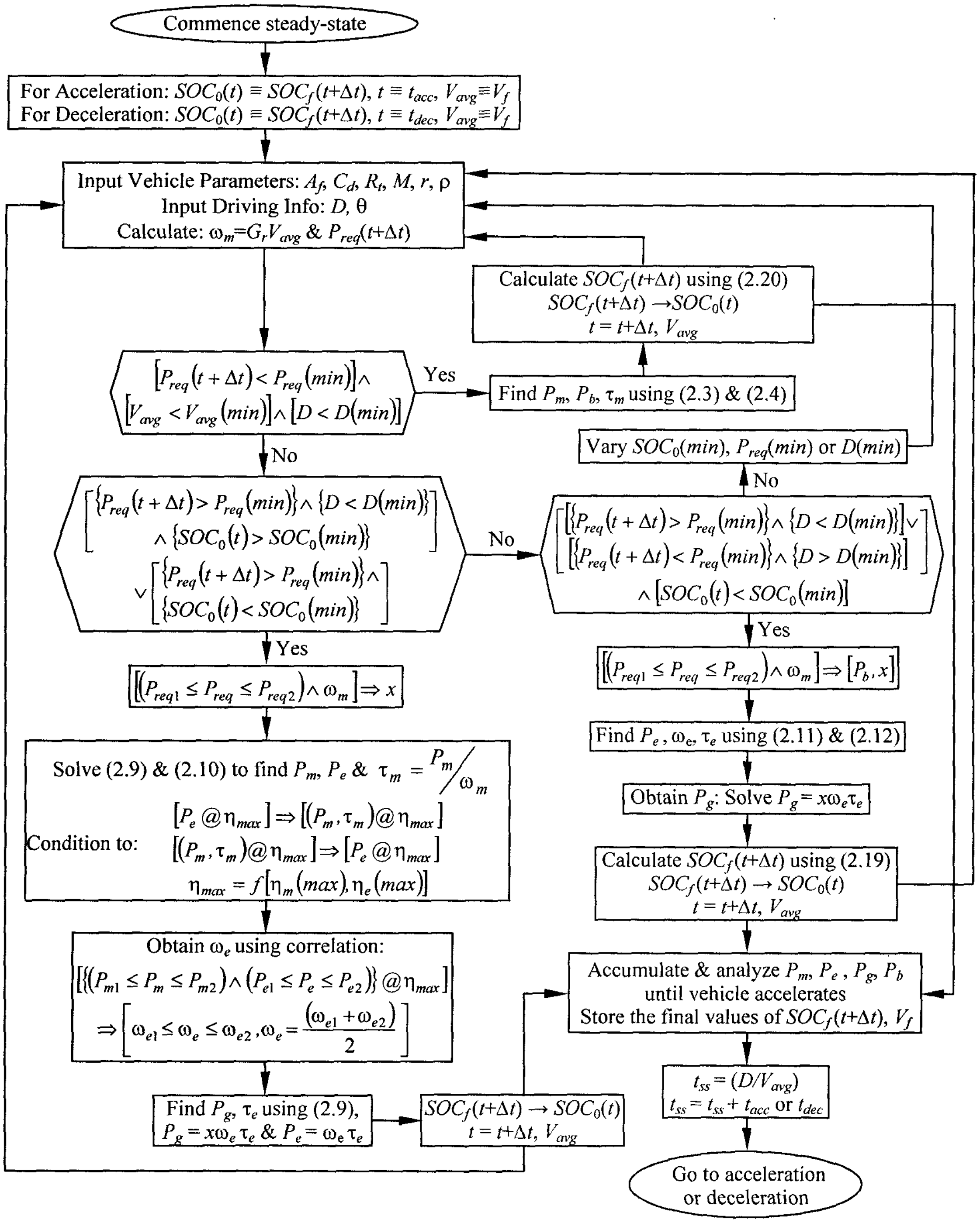


Fig. 3.7 Control algorithm for optimal power distribution during steady-state.

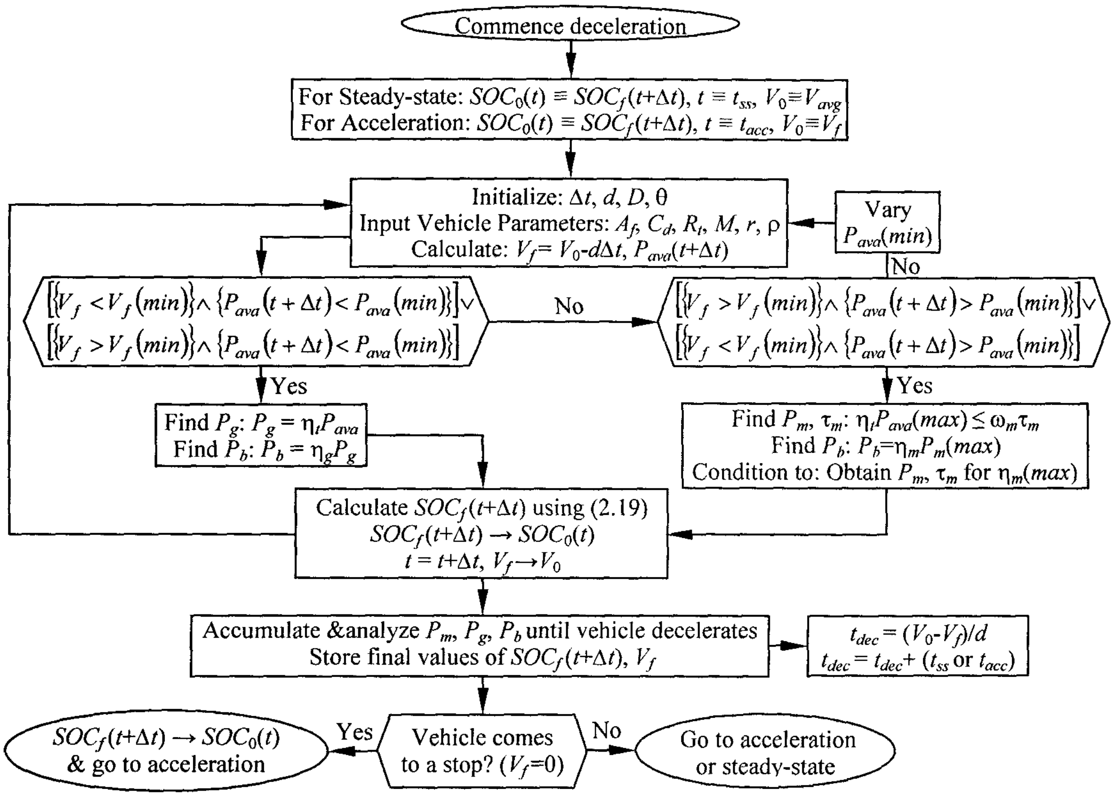


Fig. 3.8 Control algorithm for maximal power capture during deceleration.

The above methodology is utilized to construct a control algorithm for power management, which is shown in Fig. 3.7

3.4.3 Maximized Power Regeneration during Deceleration

The power that can be captured during deceleration can be maximized through control of regenerative braking which is developed based on:

- Control function: As before it consists of CS and CC. The CC is obtained either through motor or generator characteristics depending upon which is used. The CS formed by considering conditions for power available from wheels and wheel speed to check for its value against a minimum value.

The RM mode is utilized to obtain optimal path for power capture. Through the implementation of the control function and the mode selection an algorithm is developed which is demonstrated in Fig. 3.8.

3.5 Vehicle Specifications and Parameters

After developing strategy for optimizing power flow for different driving scenarios in the previous section, the next logical step would be to analyze and investigate the effect it has on the performance of drivetrain from different angles. Hence simulations have to be carried out to validate the effectiveness and capability of the algorithm. In order to simulate there is a need to consider the various parameters and other important factors (efficiency of the components) about the vehicle being considered. For the results obtained from simulation and presented in this thesis, specifications of Toyota Prius 2009 have been considered [51], [52]. Table.3.2 lists the values considered for this vehicle. It is quite important to have this information as these values have to be taken into consideration when energy and power demand are calculated.

The efficiencies of generator (permanent-magnet) and battery (NiMH) are considered to have an average value of 88-90% [53], [54] and 65-70% [8], [55], [56] respectively. Initial SOC and fuel level are taken as 70% and 100% respectively.

An important consideration for calculation of the power requirement of the vehicle is the acceleration performance. The time taken for Prius to accelerate from 0 to 100 km/hr is approximately 10 seconds. So rate of acceleration is obtained as 2.778 m/s^2. The vehicle is assumed to decelerate at the same rate as acceleration. In analysis conducted the vehicle during steady-state it is assumed to achieve a maximum average speed of 80 km/hr as urban driving characteristics are taken. The specifications of drivetrain component have been enumerated in Table 3.3. All the simulative analyses have been performed on visual basic platform.

TABLE 3.2

COEFFICIENTS AND EFFICIENCY INFORMATION

Mass of vehicle, M	1335 Kg
Wheel radius	0.1905 m
Coefficient of drag, C_d	0.26
Air density, ρ	1.204 Kg/m^2
Resistance coefficient of tires, R_t	0.013
Transmission efficiency, η_t	92%
Generator efficiency, η_g	88-90%
Battery efficiency, η_b	70%

TABLE 3.3

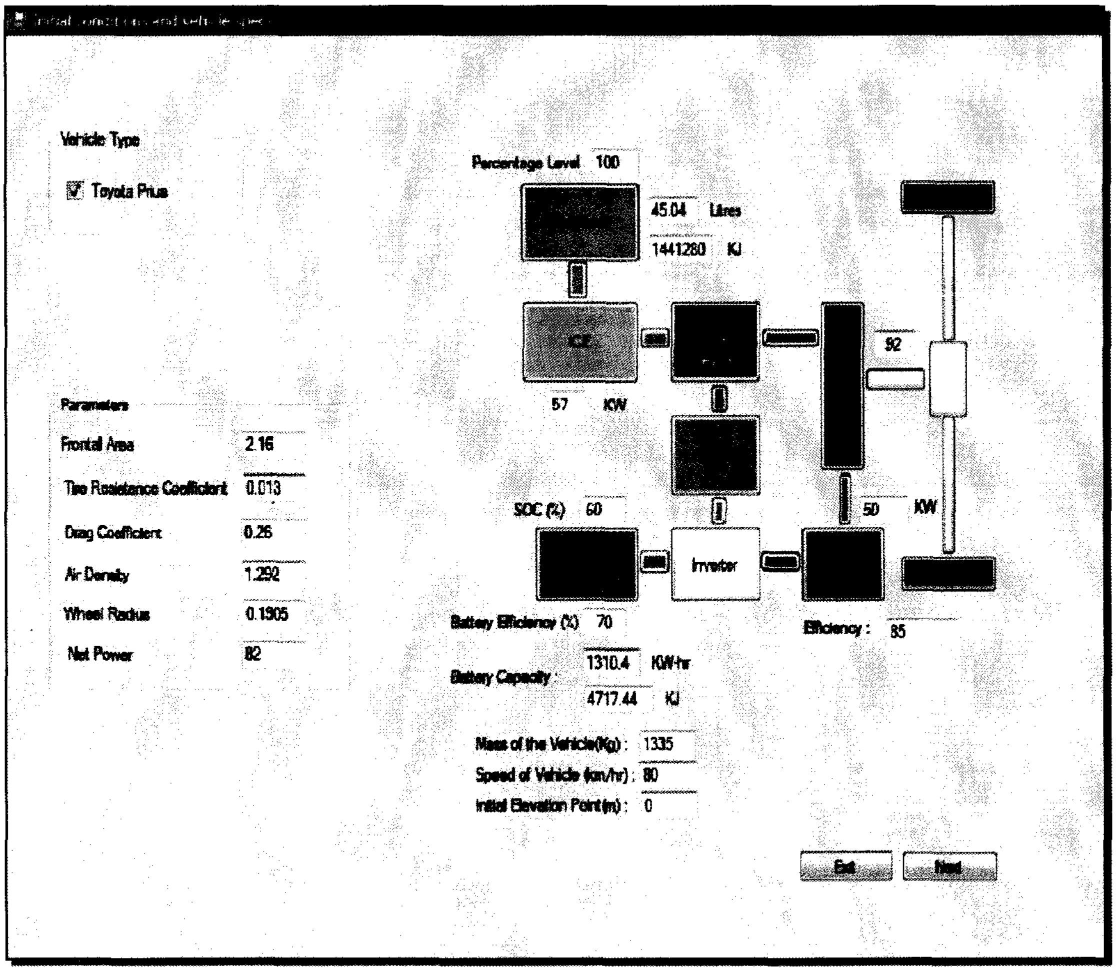
ENERGY AND POWER SOURCES UTILIZED IN TOYOTA PRIUS

Engine	1.5LAtkinson cycle based gasoline engine	Power:57 kW @ 5000 rpm Torque:111 N-m @ 4200 rpm
Electric Motor	PM synchronous machine	Power:50 kW @ 1200 -1520 rpm Torque:400 N-m @ 0-1200 rpm
Generator	PM synchronous machine	Power:10 kW Maximum Speed:10,000 rpm
Battery	NiMh battery	Peak Power:21 kW Capacity:6.5 Ahr

4 ANALYSIS OF POWER DISTRIBUTION DURING A RANDOM DRIVING SCHEDULE

4.1 Initialization and Generation of Random Driving Cycle

In order to simulate the power management for a random journey has been generated to replicate the urban driving condition driving conditions with an average speed of 80 km/hr during steady-state driving. The optimization is carried out for a distance of 26.82 km for duration of 1,260 seconds. The entire journey is segmented into different sections based on the type of driving state: acceleration, steady-state or deceleration. Distance travelled during a single steady-state phase has been taken for a range of 1 to 5 km after


Vehicle Type

☑ Toyota Prius

Parameters

Frontal Area: 2.16
Tire Resistance Coefficient: 0.013
Drag Coefficient: 0.26
Air Density: 1.292
Wheel Radius: 0.1905
Net Power: 82

Percentage Level: 100
45.04 Litres
1441280 KJ
57 KW
92
SOC (%): 60
50 KW
Battery Efficiency (%): 70
Efficiency: 85
Battery Capacity: 1310.4 KW-hr
4717.44 KJ
Mass of the Vehicle(Kg): 1335
Speed of Vehicle (km/hr): 80
Initial Elevation Point(m): 0

Fig. 4.1 Initialization interface for vehicle specification and other parameters.

TABLE 4.1

POWER AND ENERGY REQUIREMENTS FOR VARIOUS DRIVING STATES

Driving state	Journey segment	Total distance	Time	Energy available from regenerative braking	Average power requirement
Acceleration	1	88.93	8	0	30.23
Steady-state	2	1230.6	55	0	12.5
Deceleration	3	88.93	8	307.90	0
Acceleration	4	88.93	8	0	18.39
Steady-state	5	4477.7	201	0	10.37
Deceleration	6	88.93	8	30.90	0
Acceleration	7	88.93	8	0	28.39
Steady-state	8	4991.05	225	0	12.9
Deceleration	9	88.93	8	307.88	0
Acceleration	10	88.93	8	0	30.23
Steady-state	11	2768.93	125	0	12.60
Deceleration	12	88.93	8	304.88	0
Acceleration	13	88.93	8	0	32.07
Steady-state	14	3687.93	166	0	10.37
Deceleration	15	88.93	8	307.81	0
Acceleration	16	88.93	8	0	32.07
Steady-state	17	3997.2	180	0	8.64
Deceleration	18	88.93	8	307.90	0
Acceleration	19	88.93	8	0	24.71
Steady-state	20	4510.32	203	0	11.64

which vehicle decelerates at a constant rate. The change in elevation is taken to be from 0 to 100 m during steady-state. During acceleration elevation varies from -5 to 5 m. The driving pattern generated for simulation purpose consists of frequent starts and stops.

The Energy and power requirements of the vehicle for the journey are calculated through the various equations mentioned earlier, (3.4)-(3.7). The developed optimization strategy has been applied through simulation for two different SOC conditions, based on the situation algorithm operates accordingly to meet the power demand. The first case deals with a scenario where the initial SOC is in a lower range (55-65%) while in the second case optimization is carried out for the same driving pattern as the one used in the first case except the SOC has a higher range this time (80-85%).

Fig. 4.1 illustrates the interface through which the initial conditions and specifications of vehicle that have been input for the generation of journey in the simulation. Through this interface initial SOC level, fuel level and elevation can also be fixed. After this power and energy requirement, distance travelled, time taken and amount of energy available from regenerative braking during deceleration are calculated for the purpose of vehicle simulation which is shown in Table. 4.1.

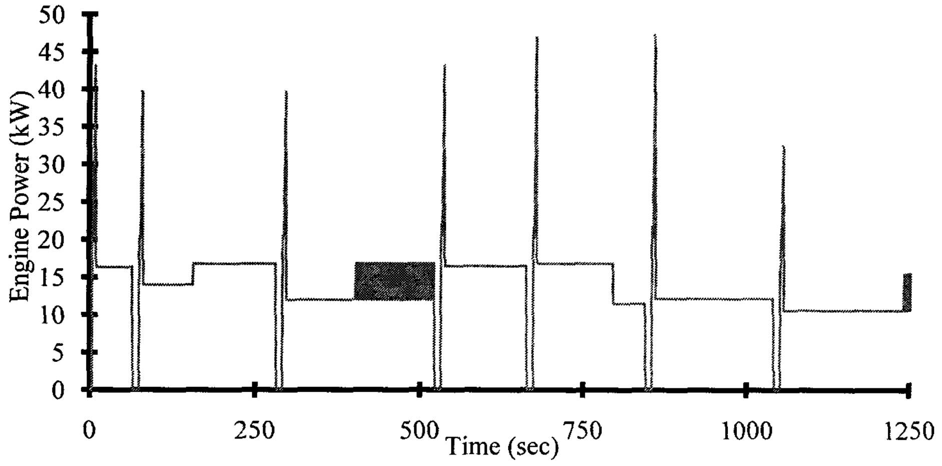
4.2 Evaluation of Power Distribution at Different SOC Levels

The simulation has been carried out for the same journey but at different SOC levels in order to demonstrate that the algorithm would work differently in order to obtain optimal operation through management of different components.

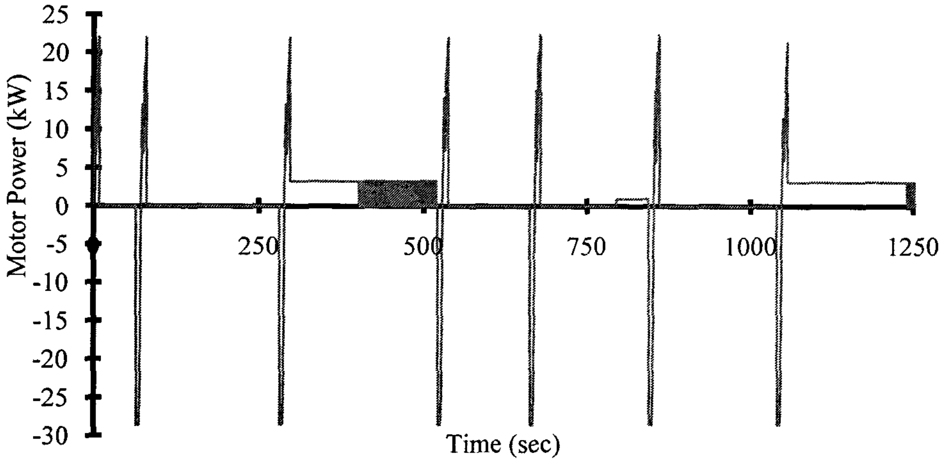
4.2.1 Analysis of Power Management for Low SOC

The vehicle starts with a 100% gasoline tank and an initial SOC of 60% at the beginning of journey. When the simulation results are plotted certain graphs are obtained as shown in Fig. 4.2. Fig. 4.2(a) shows the power provided by engine. The peaks in engine power shows that the vehicle is accelerating hence power requirement is high. Even though these peak looks like a singular point it represents a duration of 8 seconds. During this duration the battery power is varied in order for the motor and the engine to operate efficiently while keeping the battery power in a proportionate quantity to engine power. From Fig. 4.2(c) it is seen that the battery meets power demand of the vehicle usually during acceleration at lower speed. The generator power is varied in a manner such that motor operation shifts to a higher efficiency region as shown in Fig 4.2(e).

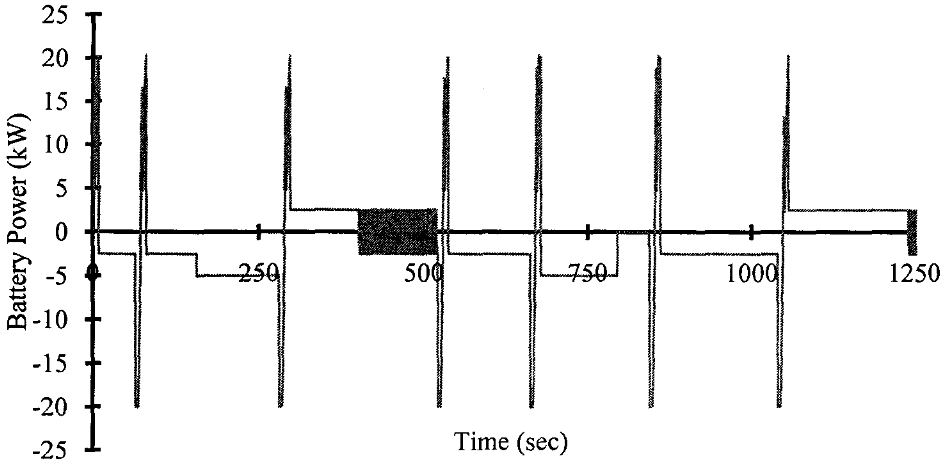
Through observation of the motor plot in Fig. 4.2(b) it seems as if the motor does not have a lot of work but this is not true as its operation is particularly essential when vehicle accelerates or decelerates as can be noticed from the peaks and dips in the plot.



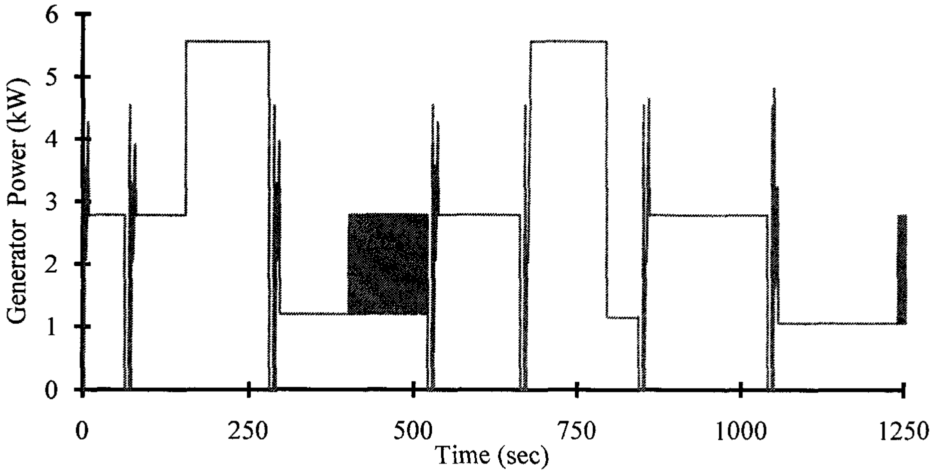
(a)Engine output during acceleration and staedy-state.



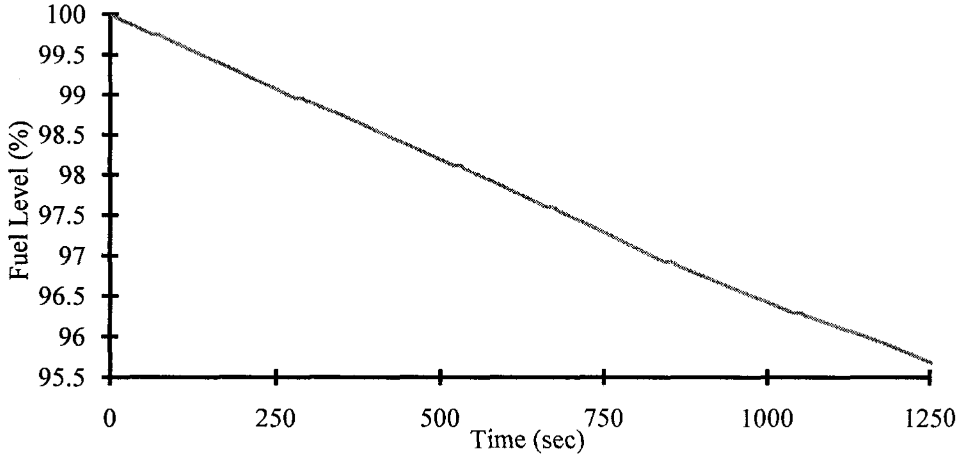
(b) Postive torque for acceleration and steady-state while negative torque for deceleration.



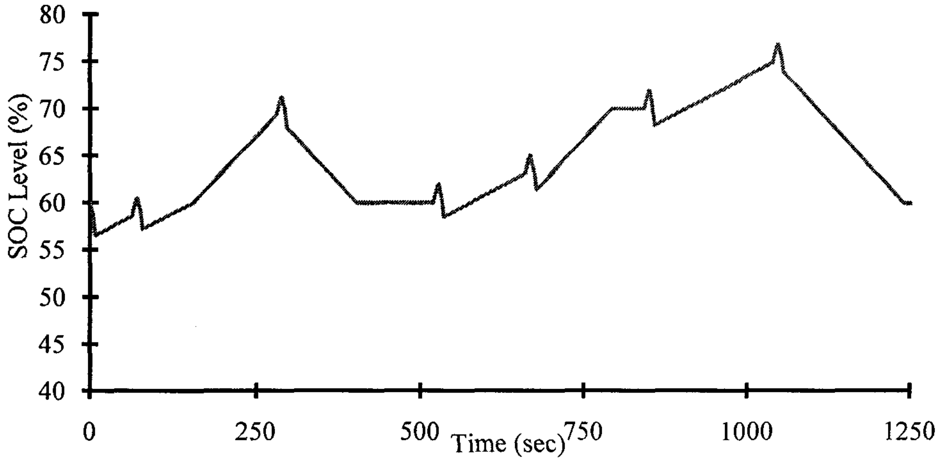
(c) Power fed to or obtained from battery during charging and discharging.



(d) Power fed to the generator.



(e) Rate of fuel consumption over time.



(f) Charge-discharge activity of battery.

Fig. 4.2 Simulation graphs for battery SOC=60% (a) Engine output power (b) Motor power (c) Battery power (d) Generator input power (e) Fuel level (f) SOC level.

TABLE 4.2

IMPORTANT RESULTS FOR SOC=60%

Parameter	Value
Final SOC level (%)	59.961
Final Fuel level (%)	95.74134
Peak SOC level (%)	76.83
Fuel consumption (*l*)	1.81
Peak engine power (kW)	46.36
Peak motor power (kW)	22.23
Steady-state engine power (kW)	13.975

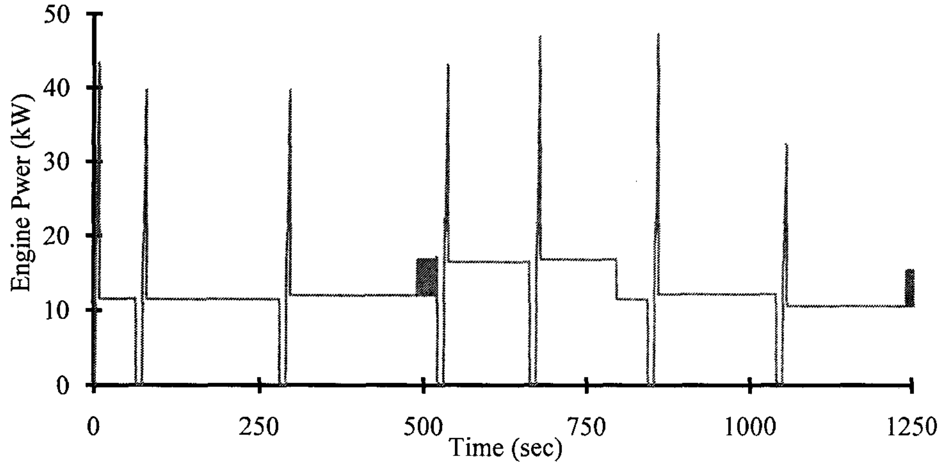
Also during steady-state motor providers a small amount of power usually when the battery is also supplying energy in addition to the engine, this can be observed to happen during the time period of 300-400 seconds and also during 1,050-1,240 seconds. It can also be seen that between 400-520 seconds and towards the very end,that is the last 20 seconds of the simulation, the graphs for all power and energy sources consists of a shaded region of curves. This can be explained from Fig. 4.2(f) which shows the change in SOC level. It is observed that battery has been charging/dicharging at a constant rate during this period, this is due to the fact that the battery is fluctuating between charging and discharging mode very quickly. Due to which the engine, motor and generator power have to be varied continously to maintain the battery SOC around 60%.

In this case the strategy works in more of a charge sustaining mode. The battery SOC is maintained in a range of 55 to 75%. Although the SOC goes above 75% for a small time intermission, 1,041-1,048 seconds, as during deceleration power is available to charge the battery which should not be wasted. In Fig. 4.2(f) there are two peaks at time, t =300 seconds and 1,050 seconds during which the vehicle works in charge depleting mode. There is a good balance between engine power and electric power. The important characteristics of this simulation have been summarized in Table. 4.2.

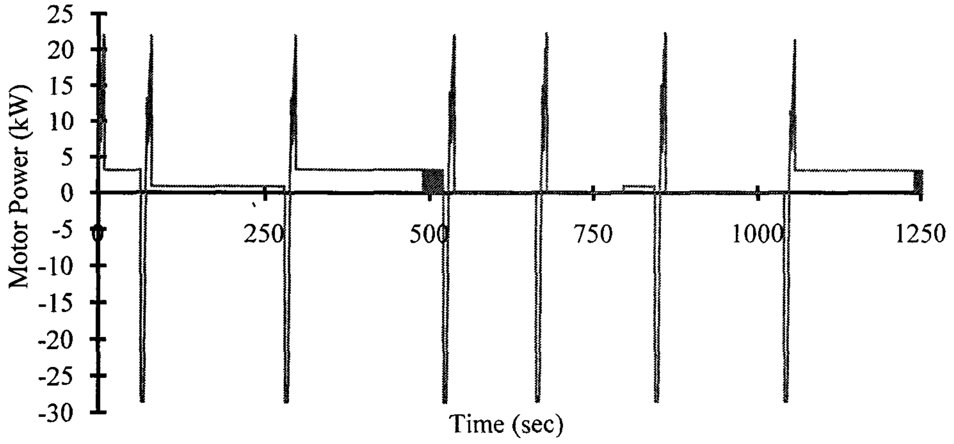
4.2.2 Simulation of Power Management for High SOC

This time simulation is once more carried out for 100% fuel tank with battery having an initial SOC level=85%. The graphs for engine, electric motor, generator and battery provide the similar kind of information as the previous case. The various graphs for this case are shown in Fig. 4.3.

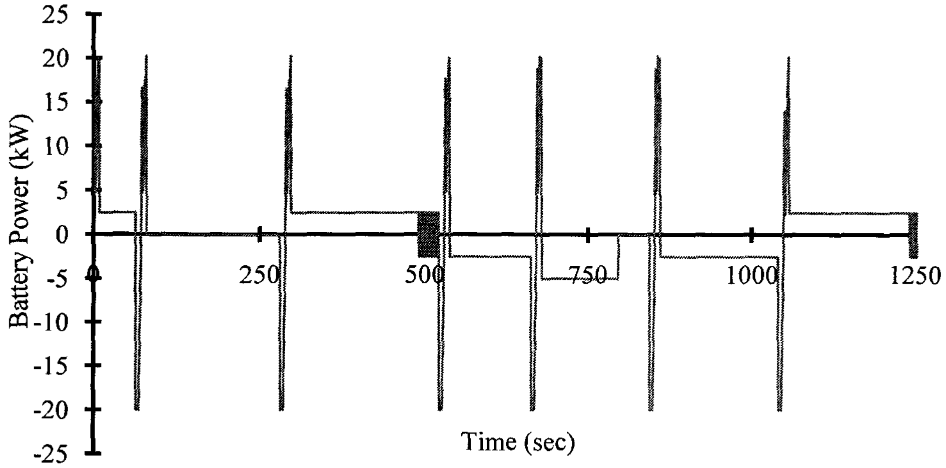
Through careful observation of Fig. 4.3(a) it can be observed that the average power provided by the engine is lower as compared to engine output provided in case of previous scenario. Also the motor utilization increases significantly. Also battery is being charged during steady-state driving conditions as seen in Fig. 4.3(b). During the period, 520-1,040 seconds the generator input is higher showing that significant amount of engine power is used to charge the battery, as seen in Fig. 4.3(e). This can be understood from SOC graph in Fig. 4.3(f). The battery output is significantly higher as compared to previous case. The average output of generator is also lower.



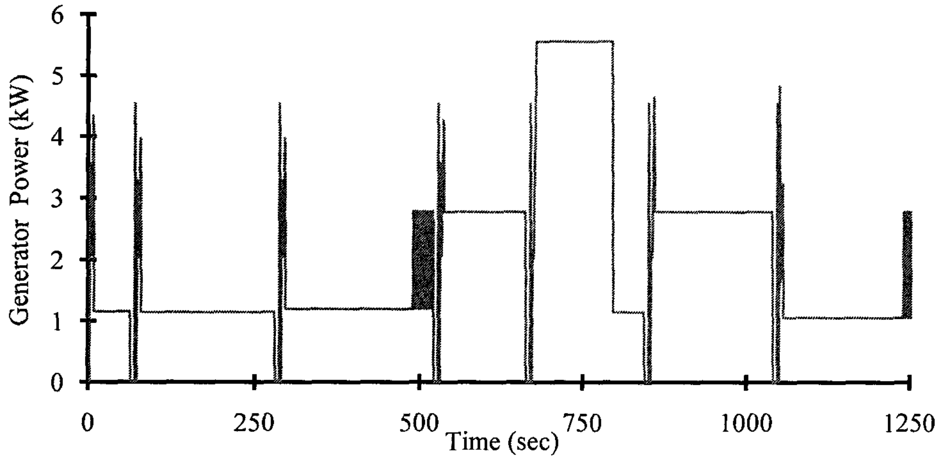
(a) Engine output during acceleration and staedy-state.



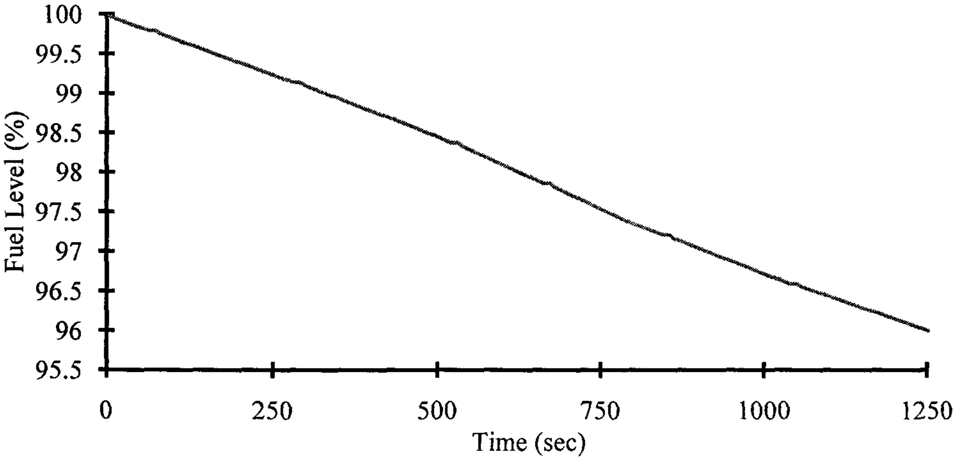
(b) Postive torque for acceleration and steady-state while negative torque for deceleration.



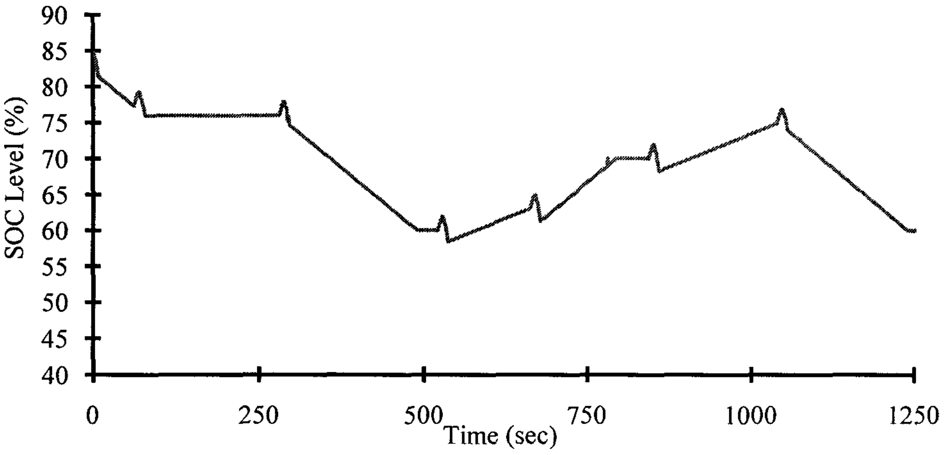
(c) Power fed to or obtained from battery during charging and discharging.



(d) Power fed to the generator



(e) Rate of fuel consumption over time



(f) Charge-discharge activity of battery

Fig. 4.3 Simulation graphs for battery SOC=85%. (a) Engine output power. (b) Motor power. (c) Battery power. (d) Generator input power. (e) Fuel level (f) SOC level.

TABLE 4.3

IMPORTANT RESULTS FOR SOC=85%

Parameter	**Value**
Final SOC level (%)	59.979
Peak SOC level (%)	76.83
Fuel consumption (liters)	1.72
Peak engine power (kW)	46.26
Peak motor power (kW)	22.23
Steady-state engine power (kW)	2.776

At *t* =520 seconds the battery SOC falls below 60% due to this the strategy works to increase the SOC as shown in Fig. 4(f). For initial 520 seconds the vehicle operates in a charge depleting mode after which it switches to charge sustaining until 1,040 seconds. After 1,040 seconds the strategy switches back to charge depleting mode. Hence in this case the algorithm works in a way such that the share of electric power increases as compared to before. During deceleration the energy of the wheels is used to charge the battery. The important observations of this simulation have been listed in Table. 4.3.

4.2.3 Summarization of Results

Through simulation it is seen that a high level of optimization is achieved for electric motor and engine when vehicle was accelerating. Electric motor operates in a reasonably efficient region of operation during steady-state driving with optimal performance obtained for engine. The fuel consumption at an average is obtained in a range of 1.6 to 1.8 *l* for distance of 25 kilometers while taking the SOC into account. At lower SOC the strategy essentially works in a charge sustaining manner while at higher SOC it utilizes high amount of battery in the first phase of journey followed by sustaining battery SOC later on in the journey. The strategy would work well for city conditions in a speed range of 60 to 80 km/hr during steady-state driving and provides high optimization during acceleration when higher proportion of electric power is utilized.

Also an important result of this work is that the battery is charged and discharged at either constant power or at certain pre-defined levels most of the times hence increasing the battery life and reducing the work of power electronics.

5 ANALYSIS OF POWER DISTRIBUTION FOR A REAL-TIME URBAN DRIVING SCHEDULE

5.1 Simulation for Urban Cycle

5.1.1 Consideration of FTP-72 Cycle

In order to obtain optimization results for a real time driving situation, an actual driving pattern for a vehicle needs to be considered. The driving pattern can be obtained through a real time test run of a vehicle under city conditions consisting of frequent start and stops. An alternate practice is to consider one of established driving standards available as has been shown in various research literatures [57], [58]. The federal test procedure (FTP-72) UDDS driving cycle [59] consists of frequent acceleration and deceleration of the vehicle besides steady-state condition and represents city conditions quite well. The frequent variation of velocity in FTP-72 cycle is an ideal choice for carrying out simulation in order to validate the speed-torque optimization technique proposed in this thesis. Fig. 5.1 illustrates FTP-72 driving cycle.

5.1.2 Examining Power Management for Urban Driving Cycle

The optimization strategy has been implemented for the FTP-72 cycle and then results have been obtained for power distribution among the components which would be further explained. Figs. 5.2 and 5.3 illustrate the optimized power distribution among the

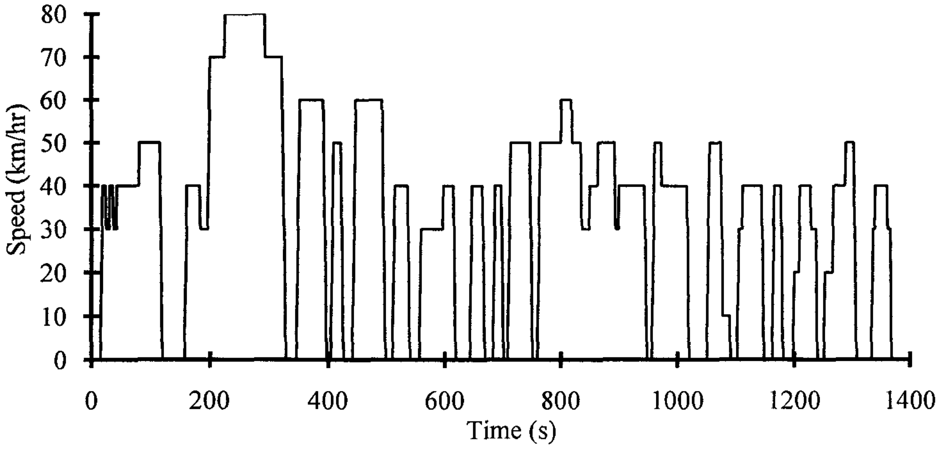


Fig. 5.1 UDDS FTP-72 driving schedule [59].

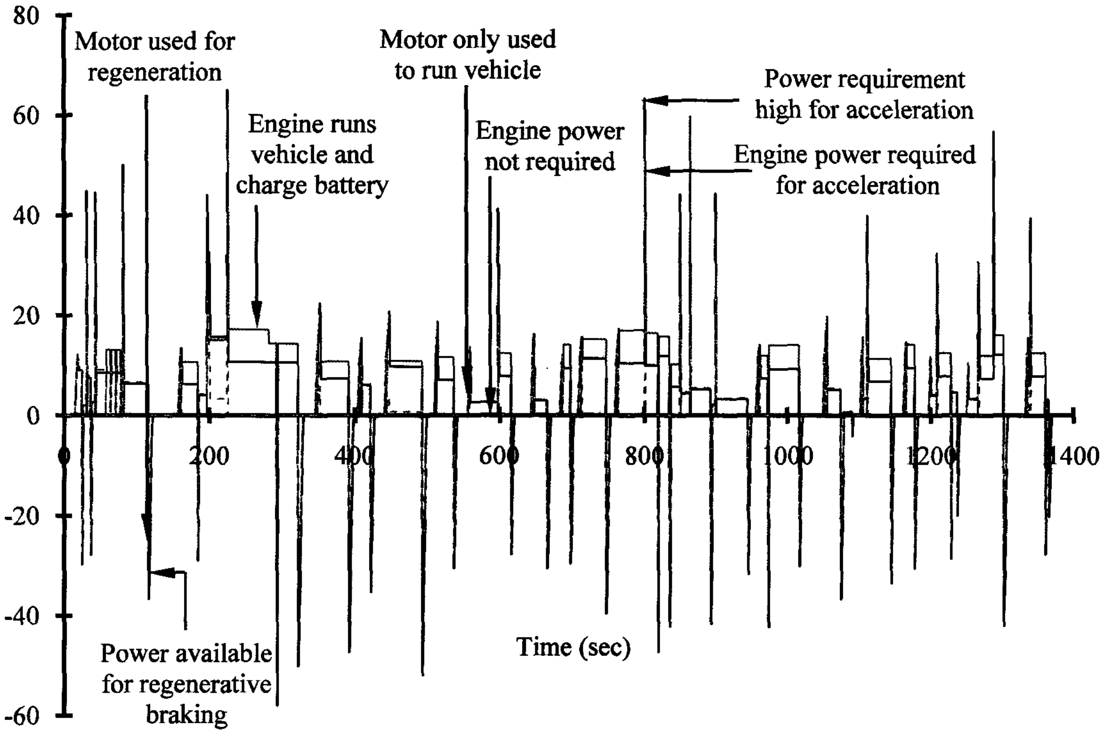


Fig. 5.2 Optimized operation of electric motor and engine for the journey.

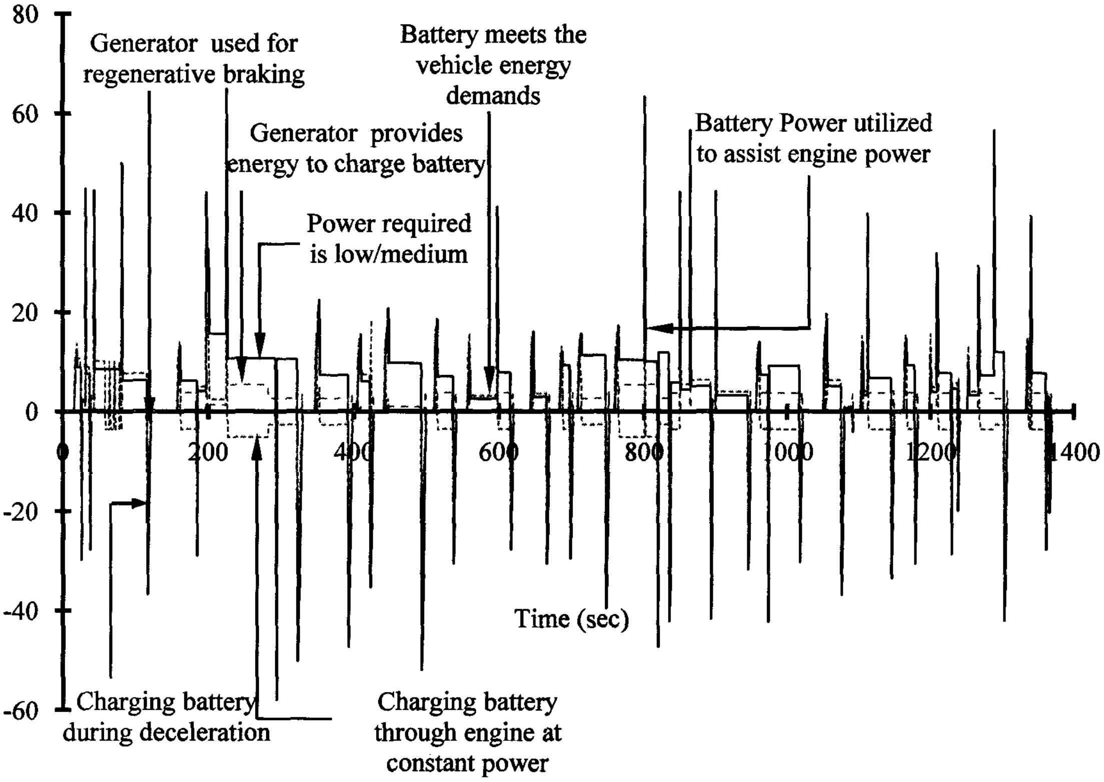


Fig. 5.3 Optimized operation of generator and battery for the entire journey.

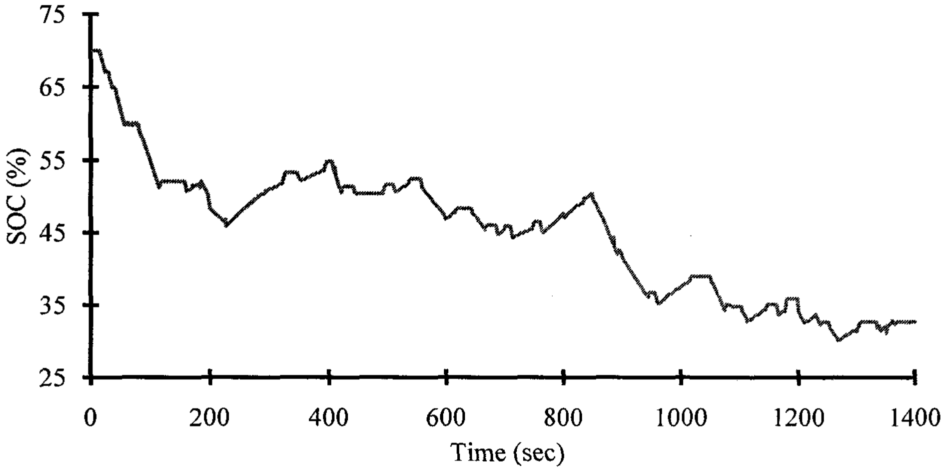


Fig. 5.4 Rate of reduction in SOC over time for the journey.

TABLE 5.1

CHARGE-DISCHARGE BEHAVIOUR OVER THE ENTIRE CYCLE

No.	Time duration (sec)	Variation of SOC (%)	Battery activity
1	0-230	45-70	High proportion of electric power
2	230-860	45-55	Maintenance of charge
3	860-950	35-50	Moderate proportion of electric power
4	950-1,400	30-40	Maintenance of charge

various drivetrain components. Negative 'power requirement' indicates power that is available for charging the battery which can be managed through regenerative mode (RM). The optimization strategy manages the power distribution while taking into consideration the SOC of the battery. The SOC charge-discharge activity for the entire duration has been shown in Fig. 5.4. For the initial 200 seconds of journey the proportion of the electric power is quite high as can be observed from the decrease seen in SOC, from 70 to 45%. After this the battery SOC is maintained within a range of 45 to 55% till about 800 seconds of the journey. This is managed through control of charge and discharge pattern of the battery in a constant power manner. The battery is recharged primarily by utilizing a small portion of the engine power, while engine is operating in an efficient region through engine only mode (OEM). For acceleration at lower speed, electric mode (EM) is utilized, while at higher speeds series parallel mode (SPM) is used. During the next 200 seconds duration the battery is operated in a discharging mode until it reaches a SOC of 35%. At about t=1,000 seconds the proportion of engine power is increased in order for the vehicle to start operating in a charge balanced mode in a SOC range of 30 to 35% till the end of journey (1,400 seconds). The charge-discharge characteristics during the entire cycle have been summarized in Table 5.1. Examples of OEM, SPM, EM and RM have been shown in Figs. 5.5, 5.6, 5.7 and 5.8, respectively which are obtained from Figs. 5.2 and 5.3 for analyzing each component. On the basis of implementation of the various drivetrain modes a brief explanation is provided for each of the driving states in order to provide an insight in to the working of the power management for the hybrid vehicle drivetrain.

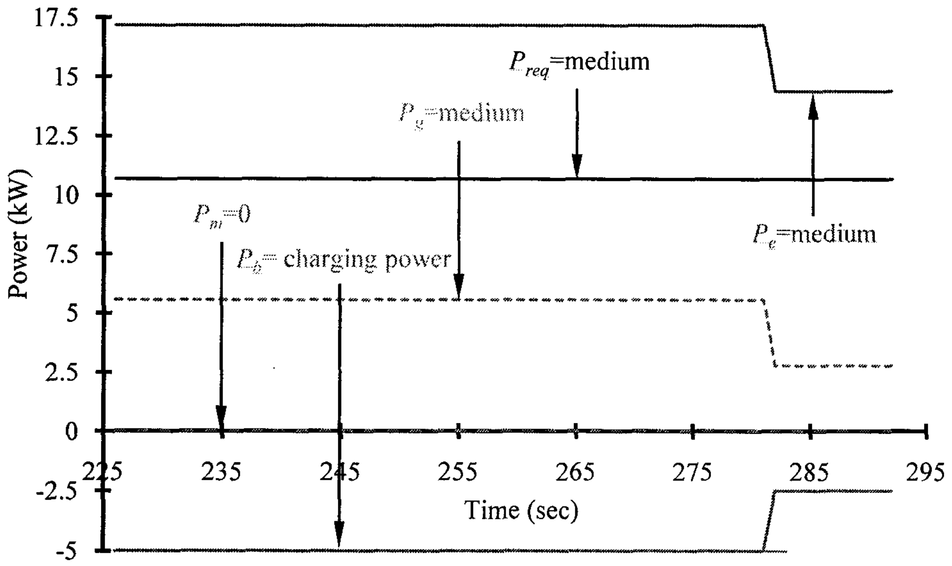


Fig. 5.5 Optimal utilization of components for engine-only mode (OEM).

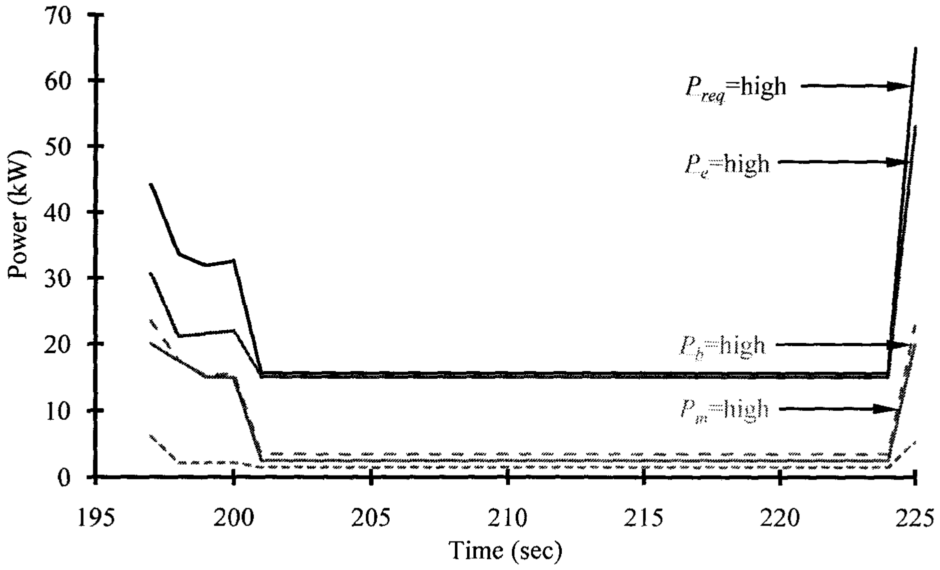


Fig. 5.6 Optimal utilization of components for series-parallel mode (SPM).

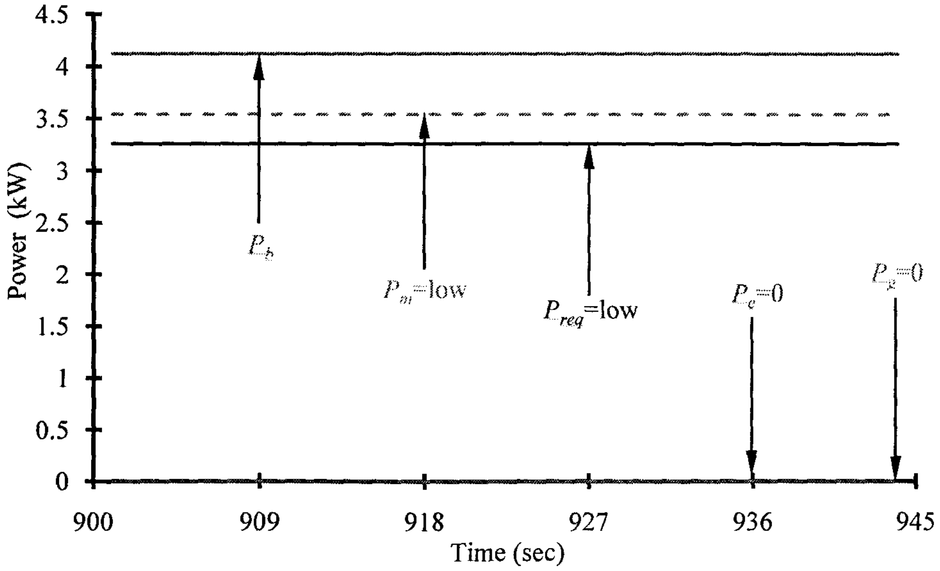


Fig. 5.7 Optimal utilization of components for electric mode (EM).

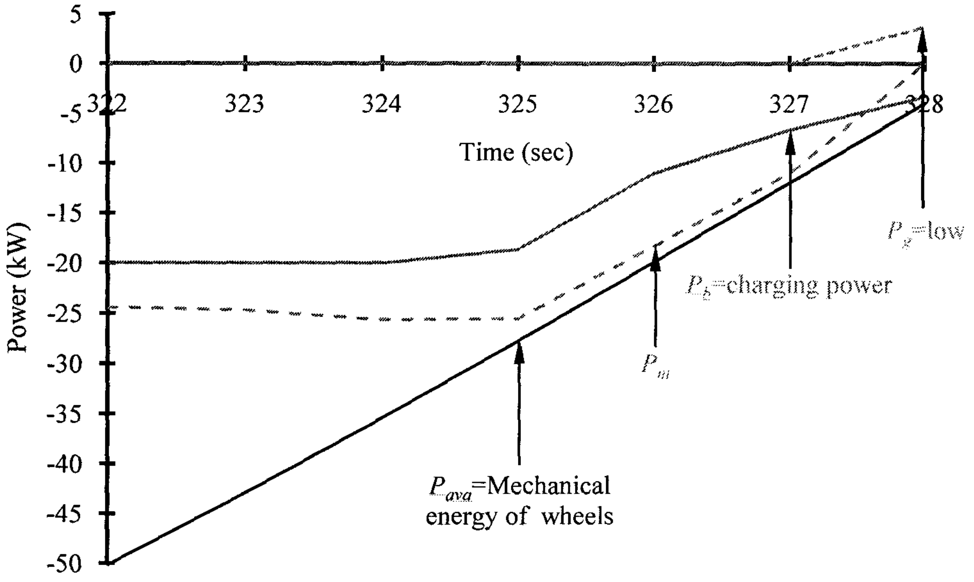


Fig. 5.8 Utilization of regenerative mode when vehicle decelerates.

5.1.3 Optimization for Acceleration

The variable power requirement observed in the initial and final seconds of Fig. 5.5 indicates that the vehicle is accelerating for that duration of the journey. For a time interval of 197 to 200 seconds the vehicle accelerates from 30 to 70 km/hr. As vehicle power demand is high hence the optimization procedure works such that the requirement is met through a combination of engine and battery power. The proportion of battery power is kept high while operating motor and engine efficiently. The portion of engine power passing through the generator-motor path is kept as low as possible; this can be inferred by observing the value of generator power which is quite low. Same is true for last second that is at t=225th second, when vehicle accelerates from 70 to 80 km/hr.

5.1.4 Optimization for Steady-State

In case of vehicle travelling at constant speed various configurations have been employed in order for optimized operation of the motor and engine, this can be explained by analyzing Figs. 5.5 to 5.7. The vehicle requires 3.26 kW in order to travel at a constant speed of 40 km/hr for the duration of 901-944 seconds, as seen in Fig. 5.5. As the vehicle is travelling at low speed and power requirement is low hence EM is utilized to manage the power needs. The strategy works in a way that it disables the engine and generator from the drivetrain therefore the respective powers are zero. SPM is employed such that a small amount of power (2.5 to 5 kW) at constant rate is supplied by the battery-motor while the major portion of power needs is met through engine power for t = 201 to 224 seconds as shown in Fig. 5.6. The vehicle speed for this time period is 70 km/hr. This configuration is employed as the SOC is over a safe value (>45%) and the power requirement is on the higher side (15.05 kW). In the time interval, 226 to 292 seconds at a speed of 80 km/hr as the power requirement is lower (10.5 kW) compared to previous time interval the strategy takes the opportunity to charge the battery from 45.94% to 50.43%. This can be inferred by observing Figs. 5.4 and 5.7. A small portion of engine power is utilized to charge the battery through efficient operation of engine. At *t*=282th second the amount of engine power utilized to charge the battery is reduced from 5 to 2.5 kW. This happens as the SOC increases above 50% and strategy works differently for this SOC range (50 to 60%) as compared to 40 to 50%.

5.1.5 Optimization for Deceleration

Figure 5.8 demonstrates the power captured through use of RM for drivetrain when vehicle decelerates from 70 to 0 km/hr during 322 to 328 seconds. The motor behaves like a generator and the amount of power passing through the motor is regulated for maximal capture of the available power from regenerative braking. When the power available is quite low (<10 kW) then the generator is utilized instead of the motor to capture power as the generator losses are observed to be lower than motor. This is implemented for the last second of the vehicle deceleration that is at *t*=328th second. The engine is completely disabled from the drivetrain and battery is operated safely.

5.2 Summarization of Results

The proposed optimization has been demonstrated through simulation for the entire 1,400 seconds of the FTP-72 driving cycle. Based upon application of mathematical model for the various modes the power management strategy has been developed that takes into consideration the speed and torque of the various drivetrain components. Furthermore analysis for this actual driving cycle has shown even better fuel efficiency and lesser fuel consumption although the SOC at the end of the cycle is somewhere close to 30%. The FTP-72 driving schedule presents a more realistic representation of power demands in addition to frequent acceleration and deceleration hence the battery activity has been obtained to be different from earlier case of random journey. The simulation for this cycle is able to demonstrate the power distribution system's ability to utilize the energy of battery to higher extent, which results in reduced engine operation, higher drivetrain efficiency and increase in the electric to gasoline ratio. In the forthcoming section the importance of engine and motor optimization has been explained in detail.

6 EFFECT OF OPTIMIZATING ENGINE AND MOTOR ON THE DRIVETRAIN PERFORMANCE

Numerical assessment has shown that power demand is met through appropriate selection of modes and efficient utilization of power sources. There are certain intervals and instants shown in Figs. 6.1 and 6.2, which have been considered in order to demonstrate drivetrain improvement through engine and motor optimization. At low and medium power demand and speed, utilization of engine is minimized. At higher speeds, the high power demand necessitates engine output to be high. The SOC is maintained either through a portion of engine power or regenerative braking to charge the battery, as seen during the intervals: 1,303-1,306 and 865-892 seconds respectively. In addition to the above, for the time interval 1,002-1,016 and 1,348-1,360 seconds, a rapid transition in engine and battery power can be seen. This happens due to charging and discharging of

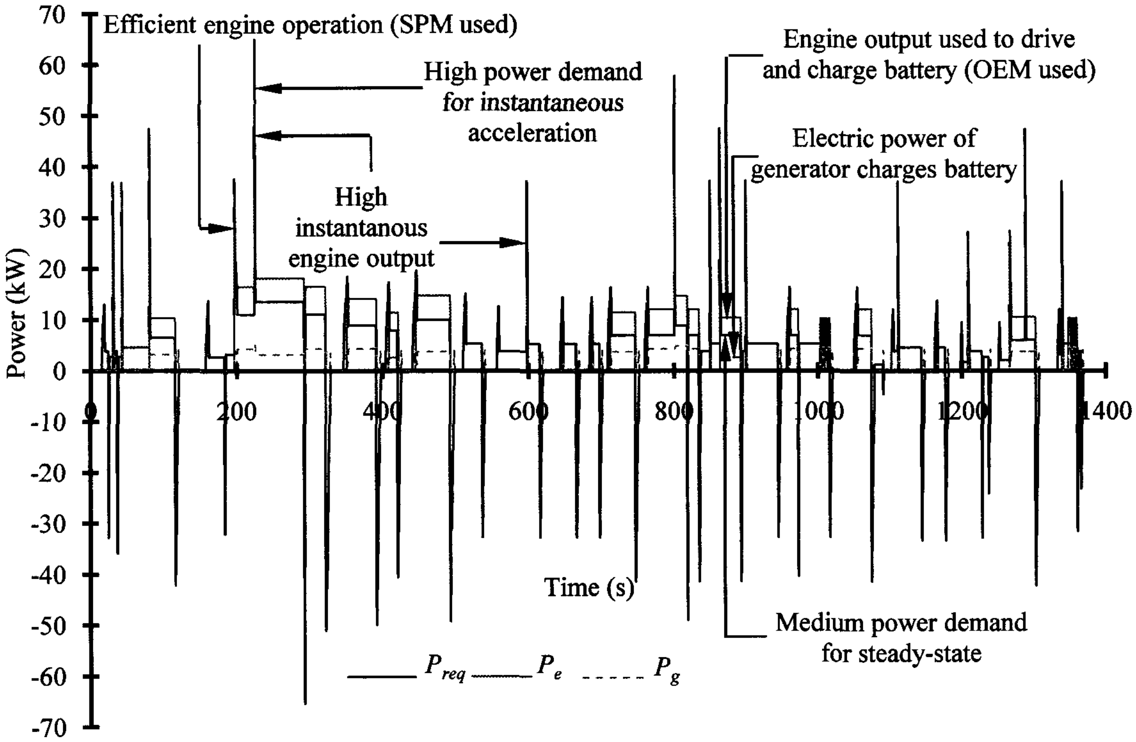


Fig. 6.1 Optimal engine power output for various driving states utilizing different modes.

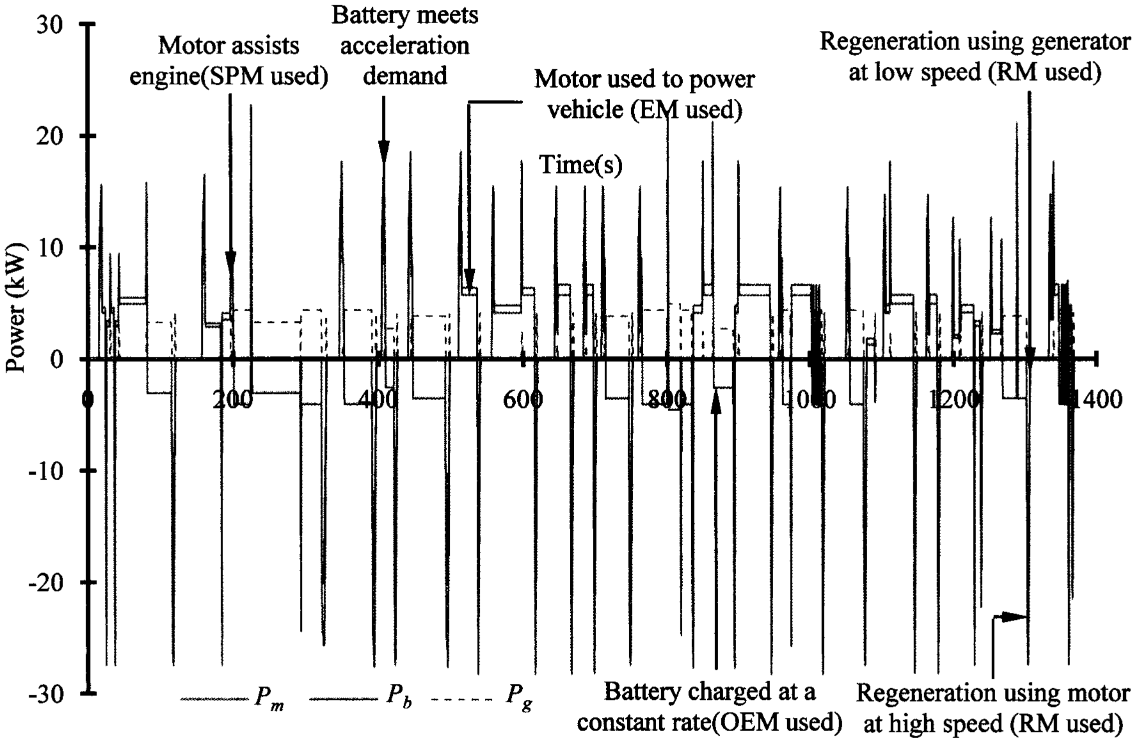


Fig. 6.2 Optimal motor operation for various driving states utilizing different modes.

battery in quick succession in order to maintain the SOC above a pre-defined limit. In-depth analysis of the method and type of optimization achieved has been explained in the forthcoming sub-sections.

6.1 Effect of Engine Optimization on Drivetrain Efficiency

6.1.1 Optimization for Acceleration Utilizing SP-mode

The time interval of 197 to 200 seconds is considered as the vehicle accelerates from an initial speed of 30 to 70 km/hr in 4 seconds. As the vehicle is not accelerating from rest, the initial power requirement is quite high. Use of E-mode is not possible as battery power is not sufficient to meet vehicle power demands. Either SP or OE mode can be employed but based on the optimization algorithm, the SP-mode with high electric ratio is chosen. Table 6.1 gives a comparative analysis of SP and OE modes. It is observed that the total energy consumption, which is a function of battery and gasoline energy, for OE would be

15-40% higher than the corresponding SP-mode for first 3 seconds. This occurs due to the engine operating at a lower efficiency which results in higher amount of emissions. As for the last second of the acceleration, OE achieves similar engine efficiency or even a little higher. However as only the engine would be powering the vehicle during OE-mode it would result in higher emissions being produced. The above reason justifies the use of SP over OE-mode. The choice of optimal mode is quite vital, but combined with that efficient engine operation yields better results as can be observed from Fig. 6.3. It is observed, that for the same power demand and corresponding engine output, the amount of gasoline spent is higher for inefficient engine operation. In Table 6.2 detailed information on the optimal speed-torque operation of engine is tabulated. Also it shows the speed-torque range that needs to be avoided in order restrict engine from operating inefficiently.

Table 6.1

Drivetrain Improvement Through use of SP-Mode Over OE-Mode

Mode of operation	**Power demand**	**Total energy consumed**	**Engine efficiency (%)**	**CO_2 emissions (g)**
Series-parallel	37.11	114.44	33	0.16696
	24.25	72.50	33	0.0995
	19.98	63.28	30	0.0847
	17.85	57.77	30	0.0816
Engine only	37.11	162.49	26	0.262
	24.25	91.85	30	0.148
	19.98	75.25-87.28	26-30	0.121-0.141
	17.85	61.12-77.57	26-33	0.098-0.125

Table 6.2

Advantage of Optimizing Engine (Acceeration)

Level of optimization	**Power demand**	**Total energy consumed**	**η_e(%)**	**Torque range (N-m)**	**Speed range (rpm)**
Optimized Engine	37.11	114.44	33	93-105	3100-3500
	24.25	72.50	33	55.6-77.8	2500-3500
	19.98	63.28	30	37.6-75.25	2000-4000
	17.85	57.77	30	48.3-72.48	3000-4000
Un-optimized Engine	37.11	123.7	30	85.92.8	3500-3800
	24.25	78.68	30	48.6-55.60	3500-4000
	19.98	71.36	26	33.44-37.62	4000-4350
	17.85	65.56	26	32.2-36.2	4000-4500

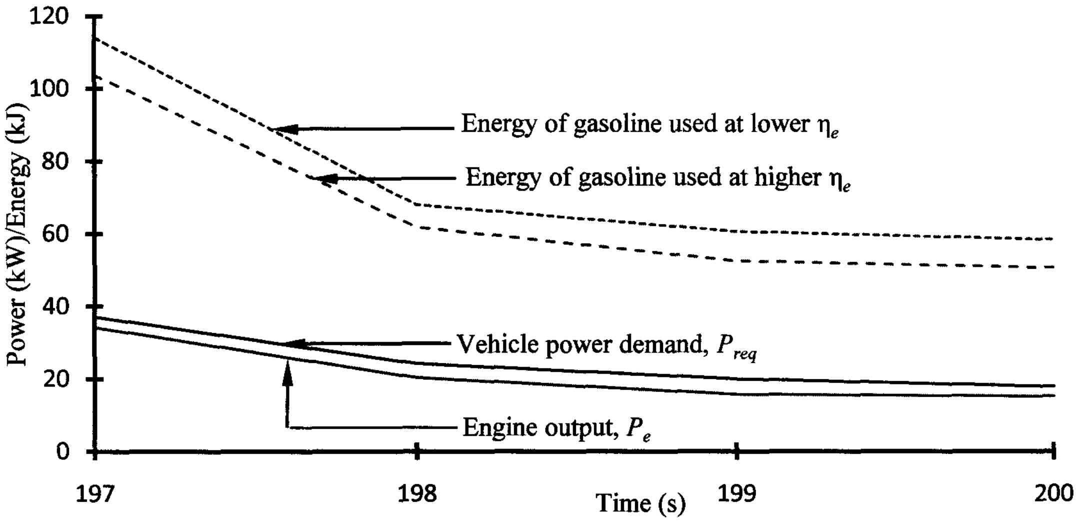


Fig. 6.3 Effect of optimizing engine using SP-mode.

6.1.2 Optimization for Steady-State Utilizing OE-mode

For analyzing steady-state optimization, time interval of 865-892 seconds has been considered during which the vehicle travelled at an average speed of 50 km/hr. This interval has been taken as an instance to demonstrate the benefit of engine optimization during steady-state. The average power demand of the vehicle is 6.97 kW for the duration. In order to meet this power demand either the OE or E-mode can be employed. Since the SOC was around 50% which is a lower range, charging the battery was given a priority over using E-mode, which would have otherwise discharged battery to below 45%. Hence, the OE-mode was preferred which could be implemented in two ways: either engine can be used to run the vehicle only or it can run the vehicle and charge the battery simultaneously by diverting about 10-30% portion of engine power through the generator. The advantage that the latter option presents is significant and can be observed in Table 6.3. It is seen that despite meeting both, the power demand and charging requirements of the battery, the engine utilizes less energy in the process due to its operating at a much higher efficiency of 26% in contrast to 15-20%. Due to higher efficiency, the engine's capability to output increases from 7.92 to 10.36 kW while at the same time the ability to do more amount of work. But as was the case earlier in acceleration, it is only through correct selection of the speed-torque range of the engine in addition to the choice of the

TABLE 6.3

BENEFIT OF DIVERTING A PORTION OF ENGINE POWER TO CHARGE BATTERY

Mode of operation:	OE (Drive vehicle and charge battery)	OE (Drive vehicle only)
Average engine output (kW)	10.36	7.92
Fuel/energy consumed (kJ)	1115.7	1108-1478.5
Engine efficiency (%)	26	15-20
CO_2 emissions (g)	1.799	1.78-2.384

TABLE 6.4

ADVANTAGE OF OPTIMIZING ENGINE (STEADY-STATE)

Level of optimization:	Optimized Engine	Un-optimized Engine
Average engine output (kW)	10.36	10.36
Total energy consumed (kJ)	1115.7	1450.5-1934.3
Engine efficiency (%)	26	15-20
CO_2 emissions (g)	1.799	2.33-3.11
Speed range	2000-4100	1350-2000
Torque range	24.11-49.44	49.44-73.24

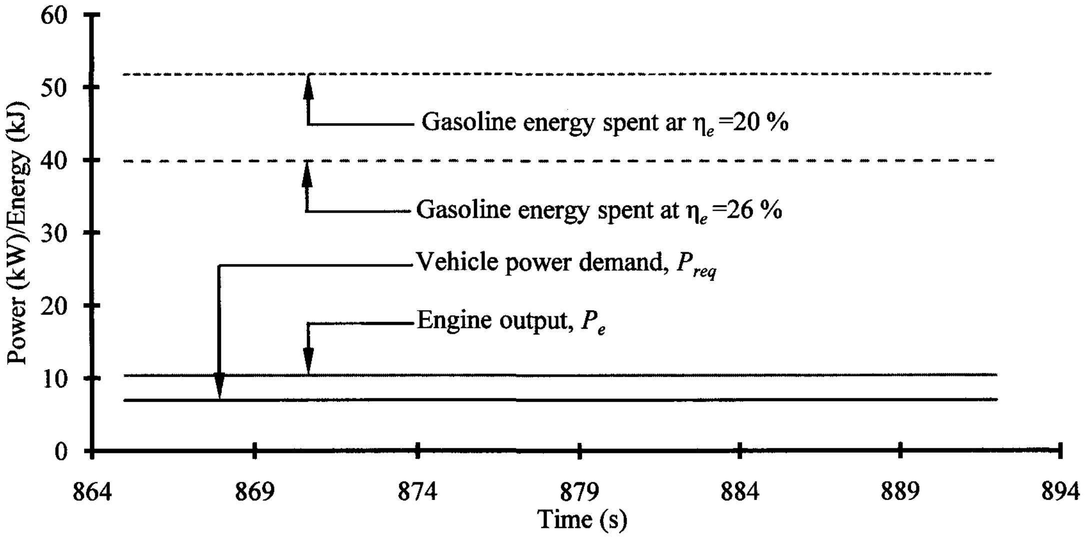


Fig. 6.4 Effect of optimizing engine using OE-mode.

mode that a solution for efficient engine operation is obtained as demonstrated in Table 6.4. Fig. 6.4 graphically plots the energy saving that can be obtained from the right speed-torque operation. As can be seen, due to a decrease in engine efficiency there's a significant increment in the amount of gasoline consumed for every second of the journey with energy consumed going up from 39.82 to 51.78 kJ for similar engine output.

6.2 Effect of Motor Optimization on Drivetrain Efficiency

6.2.1 Optimization for Acceleration Utilizing E-mode

The vehicle accelerates from a state of rest to a speed of 40 km/hr from 405 to 408 seconds. During the initial 2 seconds of the journey the speed and power requirement was too low for the engine to be engaged or operated efficiently due to which only the E-mode was feasible. Therefore the battery meets the power demand for this time period as observed in Fig. 6.5. After this duration either the SP or E-mode can be employed for 407th and 408th second, even though either mode can be applied, best possible motor optimization can be only obtained through utilization of E-mode. Observing the power curves from Fig. 6.5, the ratio of electric power is seen to go down drastically if the SP mode is used. Also, pointless usage of engine power would takes place even though battery has the capability to meet the energy demands and has sufficient SOC at this instant of 74%. As the motor output goes down there will be a corresponding reduction in torque when SP-mode is used instead of E-mode. This reduction in torque can result in the motor shifting from a region of high to low efficiency. A numerical analysis of the SP versus E-mode has been presented in Table 6.5. It can be observed that the E-mode was able to achieve 3-4% increase in the motor efficiency and no emissions as compared to SP-mode. E-mode is seen to provide the optimal motor solution for this driving scenario.

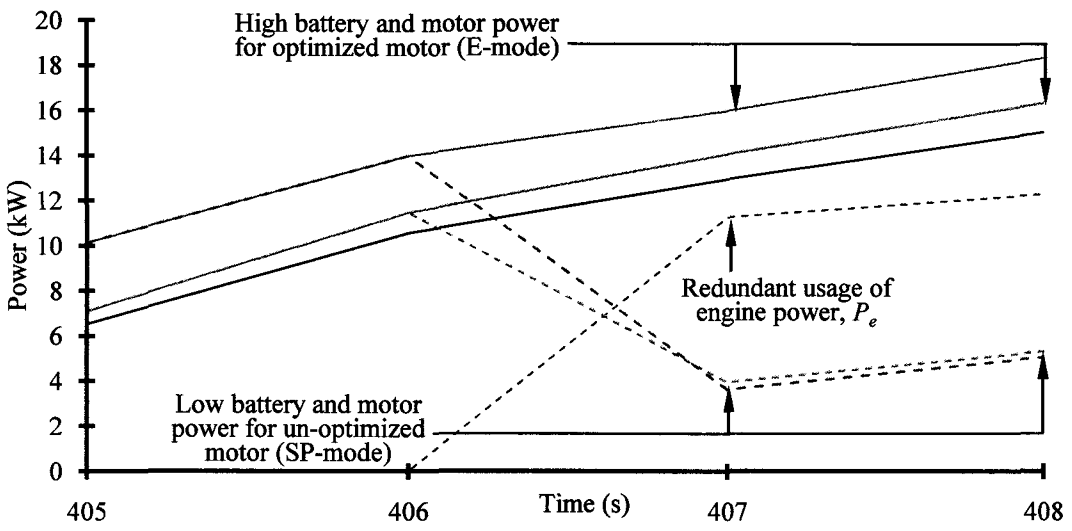


Fig. 6.5 Efficient operation of motor through use of E-mode.

TABLE 6.5

IMPROVED MOTOR PERFORMANCE ACHIEVED BY USE OF E-MODE OVER SP-MODE (ACCELERATION)

Mode of operation	Power demand (kW)	Total energy consumed (kJ)	Motor efficiency (%)	CO_2 emissions (g)	Electric proportion (%)
Electric mode	12.94	22.83	88	0	100
	15.03	26.23	90	0	100
Series-parallel	12.94	48.39	85	0.0699	24.5
	15.03	54.39	86	0.076	29.25

TABLE 6.6

OPTIMIZED VERSUS UNOPTIMIZED MOTOR USING SP-MODE (ACCELERATION)

Mode of operation	Power demand (kW)	Total energy consumed (kJ)	Motor efficiency (%)	CO_2 emissions (g)	Electric proportion (%)
Optimized motor	37.11	114.44	90	0.167	18.2
	24.25	72.5	90	0.099	27
Un-optimized motor	37.11	118.87	86	0.18	11.9
	24.25	75.55	87	0.108	21.4

6.2.2 Optimization for Acceleration Utilizing SP-mode

In the previous section it was seen that E-mode was favored mode for efficient motor performance but this is not the case for every instance as can be observed from analysis of time period: 197-198 seconds. Due to the instantaneous nature of the acceleration, the power demand for this period is 37.11 and 24.25 kW at speeds of 40 and 50 km/hr respectively, which is quite high. Therefore utilization of SP-mode is preferable as it has a balance of battery and engine power while operating engine efficiently. In order to optimize motor and maintain a higher electric ratio, the battery output was kept high. Table 6.6 shows the effect of varying battery output. It was seen that if motor and battery output are not regulated then it would not only result in lower motor efficiency but also higher emissions and energy consumption. This phenomenon occurs as a result of an increase in gasoline consumption with a corresponding decline in motor- battery output.

6.2.3 Optimization for Steady-State Utilizing E-mode

Figure 6.6 shows the power management for the vehicle travelling at an average speed of 40 km/hr for a time period of 22 seconds as it travels 244 m. Due to low power requirement of 5.3 kW) and high SOC of 73.5%, the battery-motor combination has been employed (E-mode) to power the vehicle. As the vehicle travels a short distance so the battery does not deplete quickly. Also, E-mode provides an increase in motor utilization from a mere 0.93 to 5.76 kW and, assists in evading inefficient engine output. Table 6.7 shows a comparative study of electric and engine only operation, from which it can be clearly seen that, 20 times less energy was consumed in addition to zero emissions.

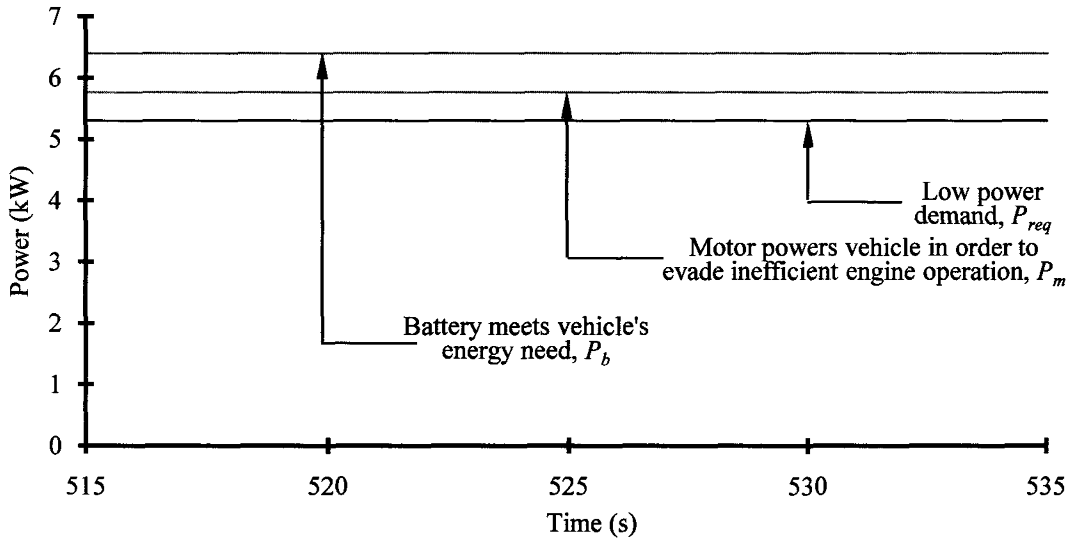


Fig. 6.6 E-mode used to meet low power demand during steady-state.

TABLE 6.7

IMPROVED MOTOR UTILIZATION

Mode of operation	Total energy consumed (kJ)	Electric proportion (%)	Emissions (g)
Electric	201.14	100	0
Engine only	884.4	0	1.43

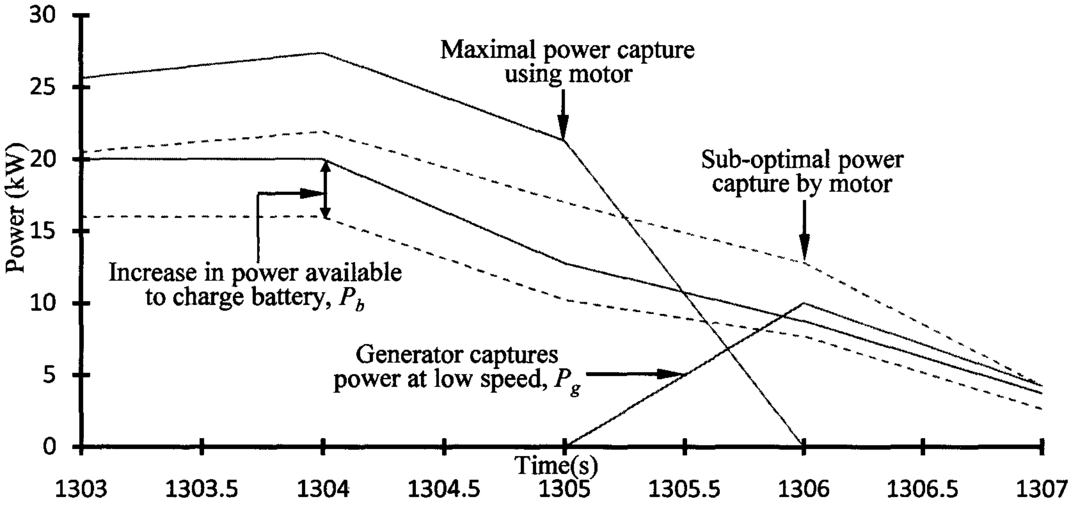


Fig. 6.7 Optimizing motor through proper component utilization.

6.2.4 Optimization for Deceleration Utilizing R-mode

In order to demonstrate the relevance of motor optimization for regenerative braking the time interval 1,303-1,307 seconds has been considered. During this 5 second period, the vehicle comes to a stop from a speed of 50 km/hr. For the initial 3 seconds, due to availability of more power, the motor was used for charging the battery while for the final 2 seconds the generator was used as can be observed from Fig. 6.7. Also, motor was utilized at a higher speed while generator kept at lower speed. At higher speeds the role of motor optimization was to generate the right motor torque in order to maximize the power being fed back to the battery, Table 6.8 lists the benefit of optimizing motor torque. It can be seen in Table 6.8 that there is a 20-25% increase in the energy available for charging, this can be graphically validated by looking at the difference in power available to charge the battery. At lower speeds, the role of motor optimization was to disengage the motor and utilize the generator to charge the battery as seen for the last 2 seconds in Fig. 6.7. The generator as a whole has a higher efficiency then the motor when in a generating mode and as a result generator is able to capture more energy as shown in Table 6.9. In Table 6.9 it is also seen that when the generator is used instead of the motor the amount of energy captured increased by 14%. The dotted lines in Fig. 6.7 show un-optimized state of motor and the effect it has on the amount of power captured for recharging battery.

TABLE 6.8

BENEFIT OF MOTOR OPTIMIZATION AT HIGHER SPEED

Level of optimization	P_m (kW)	Energy fed to battery (kJ)	τ_m (N-m)
Optimized motor	25.64	14	132.27
	27.4	14	176.69
	21.27	8.92	182.88
Un-optimized motor	20.51	11.2	105.81
	21.92	11.2	141.35
	17.01	7.15	146.41

TABLE 6.9

BENEFIT OF MOTOR OPTIMIZATION AT LOWER SPEED

Level of optimization	Drivetrain component used	P_m/P_g(kW)	Energy fed to battery (kJ)	η_m/η_g (%)
Optimized motor	Generator	10	6.12	85-90
		4.26	2.61	85-90
Un-optimized motor	Motor	12.79	5.37	60-65
		4.26	1.86	60-65

6.3 Benefit of Optimizing Engine and Motor

The Comparative analysis of optimized versus un-optimized engine and motor operation for the complete driving cycle has been graphically represented in Figs. 6.8 and 6.9. In these graphs various instances have been taken into account in order to illustrate that optimization that has been obtained for various driving states based on different control conditions and then a brief explanation has been provided to further validate the importance of efficiently operating the engine and motor. Table 6.10 presents a summary of the comparison of the power management on the basis of the level of optimization.

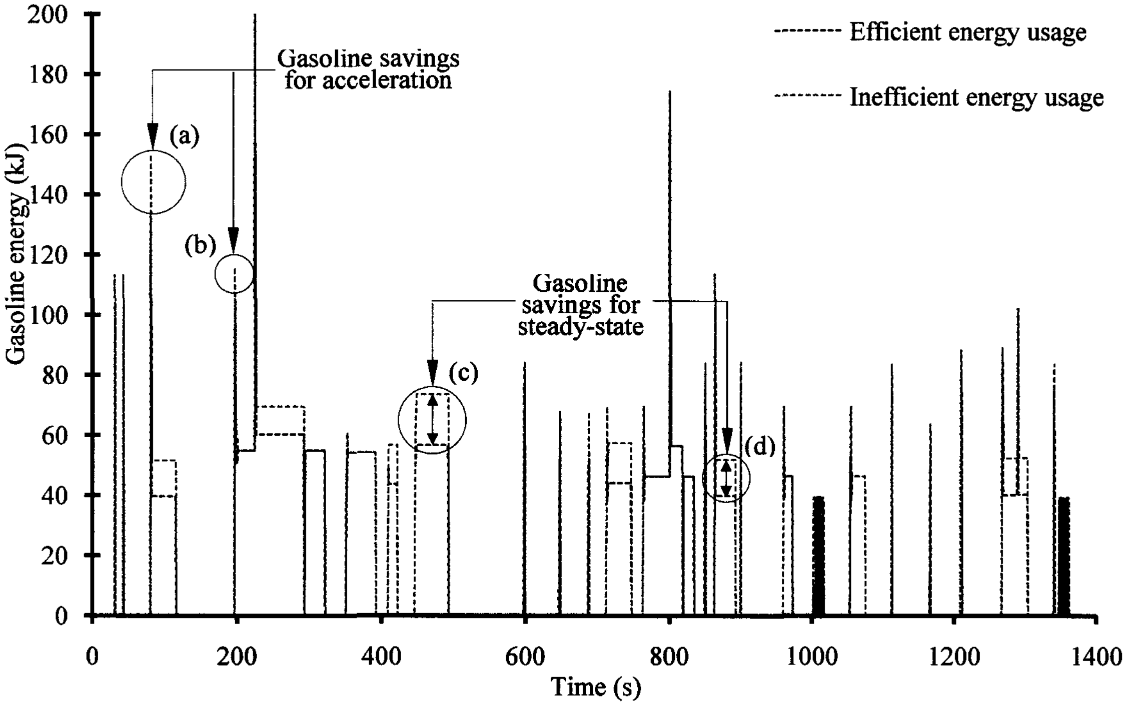


Fig. 6.8 (a) SP-mode used for high power demand (47.42 kW) and medium speed (50 km/hr) achieves an increase in fuel savings by 15.4% and efficiency by 4%; (b) SP-mode used for medium power requirement (17.85 to 37 kW) and medium to high speed (40 to 70 km/hr) achieves increase in fuel savings by 27% and efficiency by 3-6 %; (c) OE-mode utilized for high power requirement (9.97 kW), medium average speed (60 km/hr) and short interval achieves increase in fuel savings by 30.4% and efficiency of 6%; (d) OE-mode utilized for medium power demand (6.97 kW), medium average speed (50 km/hr) and short time achieves an increase in fuel savings by 30% and efficiency by 6%.

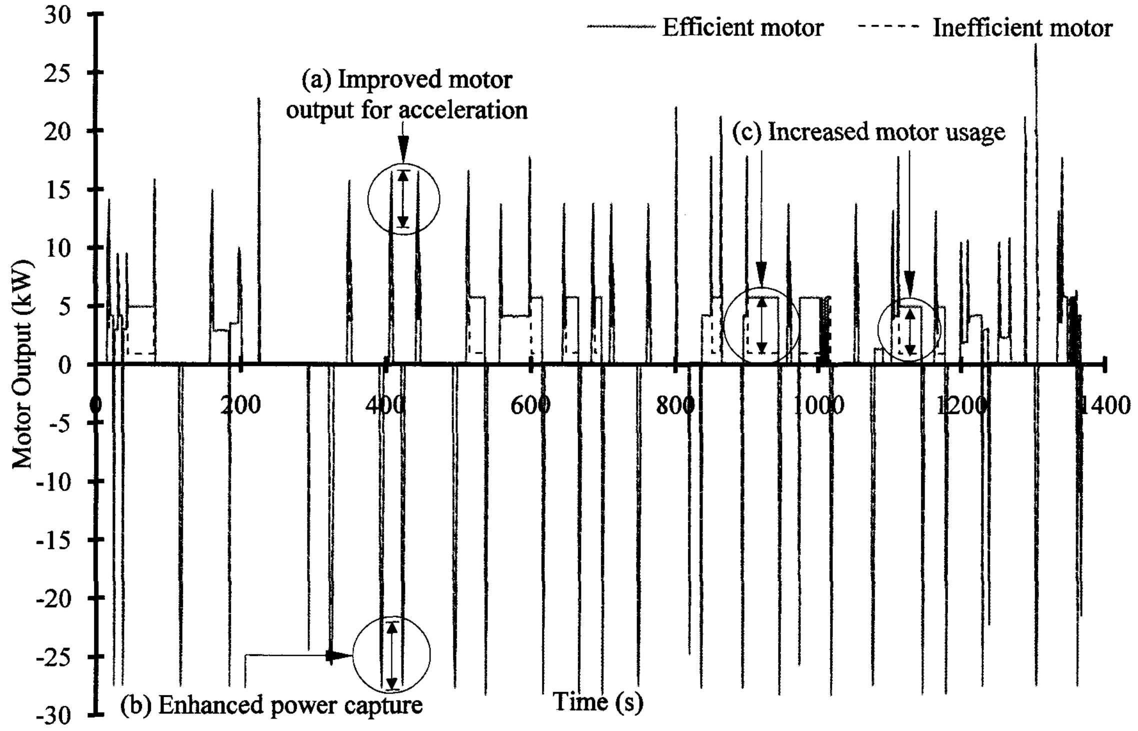


Fig. 6.9 (a) E-mode used for low power (13.06-16.14 kW) and low speed (30-40 km/hr) to attain 100% electric drivetrain and increased motor efficiency (3-4%); (b) R-mode utilizes motor at higher speed (30-50 km/hr) for higher power availability (> 20 kW) through motor torque control and generator at lower speed (10-20 km/hr) for lower power availability (< 15 kW) as it is able to capture 25% more power; (c) E-mode used for low power demand(4.57-5.3 kW) and low speed (40km/hr) attains 100% electric drivetrain and huge increment in motor utilization (5 to 6 times more).

TABLE 6.10

IMPROVEMENT IN VEHICLE PERFORMANCE ACHIEVED THROUGH PROPOSED CONTROL STRATEGY

Level of optimization	Average motor efficiency (%)	Average engine efficiency (%)	Electric ratio (%)	Fuel consumption (*l*)	CO_2 emission (kg)	NO_X emission (kg)	CO emission (kg)
Motor & Engine	86.16	27.45	32.69	.7933	1.87	.00625	.0941
Engine only	84.98	27.42	31.50	.8063	1.9	.00635	.0956
Motor only	85.55	24.14	32.65	.9059	2.14	.00713	.1074
No optimization	85.18	24.11	31.44	.9149	2.16	.00721	.1085

Through application of the control algorithm for different states, a combined optimization strategy for motor and the engine yields the best all round solution. The average values of engine and motor efficiency have been computed using (2.16) and (2.17). Through implementation of the algorithm to control distribution a 15.34% reduction in fuel consumption and correspondingly a decrease in the emissions by 16.4% is achieved. Fuel emissions are calculated based on statistics obtained from [60].

7 IMPROVEMED DRIVETRAIN PERFORMANCE THROUGH DIESEL ENGINE INCORPORATION

In this chapter analysis has been obtained to examine the benefits that can be achieved through the utilization of a diesel engine instead of an internal combustion engine for the series parallel hybrid vehicle. A comparative study has been conducted for similar optimization being applied to both the diesel and its counterpart gasoline hybrid in order to analyze the driving performance through a comparable perspective. After that information is gathered about fuel consumption, power division among components, energy efficiency and other driving characteristics. Through evaluation of data gathered the effect of employing a diesel engine over a gasoline engine has been demonstrated to signify the improvement that can be achieved in the gross energy efficacy and reduction in the overall emissions.

7.1 Why Diesel Engine Based Hybrid?

Through the application of optimal power management for gasoline-based HEVs, considerable reduction in fuel consumption has been obtained earlier. But due to gasoline having lower fuel heating value and low compression ratio (air to fuel) among others drawbacks [8], [61], the maximum efficiency of an average gasoline engine is limited to a range of 30-33%. Also the optimal region is quite small due to which limited region is available for utilization. This is where diesel engine can provide an edge over gasoline engine in obtaining higher level of optimization to the existing hybrid drivetrain. The diesel engine has better compression ratio and a superior fuel heating value which results in it providing better efficiency [61]. Diesel engines can operate in a range of up to 33-36% efficiency. Also the resultant emissions, especially CO_2, can be significantly reduced as analysis obtained from earlier works has demonstrated [50] [58]. The NO_X levels were seen to be quite high for diesel engine as compared to their gasoline equivalent [62] but that can soon become a thing of past through some reduction techniques such as the ones explained in [63]-[65]. At present there have been very few instances of research being done in diesel hybrid as the main focus is on gasoline-powered hybrid electric vehicles (HEVs), but there is a huge potential that exists for further enhancement in hybrid powertrain performance through use of diesel engines.

TABLE 7.1

FUEL CHARACTERISTICS OF DIESEL AND GASOLINE

Fuel Properties	Diesel	Gasoline
g/*l*	843.2	739.2
Percentage carbon content	85.8%	86.2
mJ/*l*	38.653	34.68
g CO_2/kWh	68.6	67.4

Also due to considerably lower heating value diesel engines are relatively safer [62]. The comparative analysis for gasoline and diesel has been provides in Table 7.1 [3]. In this chapter an optimized gasoline hybrid has been compared with a similarly optimized diesel hybrid. The analysis provides an expansive category of studies which encompasses various viewpoints, such as: vehicle fuel consumption, effect on environment, and cost dynamics and most importantly improved hybrid drivetrain performance. In the following sub-sections the effect on drivetrain performance through various kinds of analyses of diesel and gasoline hybrid has been presented.

7.2 Modifications to Drivetrain Modes

The series-parallel architecture's capability to be configured into various modes has been seen to play a crucial role in the creation of the optimization strategy. The control strategy to manage power distribution among drivetrain components designed and explained earlier was observed to employ four modes mainly in order to attain appropriate power split and avoid idling of the engine. Out of these modes only for 2 of the modes the engine was seen to be engaged in the drivetrain, which being the SP and OE-mode. Few changes and additions have been made to the power models of these modes which have been described below in brief:

7.2.1 Additional Changes to SP-mode

The functional role of SPM is to distribute the energy demand between gasoline/diesel and battery in a proportionate manner. The power demand is split in such a manner that the electric ratio is kept no less than 20% in order to keep the drivetrain as much electric as possible. Keeping the appropriate ratio is quite beneficial not only in reduction of fuel consumed but even proper utilization of the battery that is controlled discharge of battery; the electric power ratio (E.P.R) is defined as:

$$\text{E.P.R} = \frac{\eta_b E_b}{\eta_b E_b + \eta_e E_e} \tag{7.1}$$

In order to maintain high electric proportion, the battery energy is used in a way such that motor output is kept high (as motor generally is found to be more efficient at higher torques [8], [51]) while efficiently operating engine. The power distribution among the motor and engine has been modeled to provide an insight into power flow dynamics of the drivetrain. The design procedure for power flow analysis of SPM is based upon various factors like: power requirement, efficiency of components, speed-torque characteristics and SOC. Efficiency of the engine can be primarily obtained from information about its fuel heating value (fhv) and its basic specific fuel consumption (bsfc) [8], [66], the latter being obtained from fuel efficiency maps, this relation is defined as:

$$\eta_e = \left[{}^{1}\!/\!_{(\text{fhv} \times \text{bsfc})} \right] \times 100 \tag{7.2}$$

The bsfc gives an idea of the amount of power output capability relative to equivalent rate of fuel consumption. Based upon all these factors, certain power models taking into account efficiency have been obtained as shown:

$$P_{req} = \frac{\eta_t \eta_e (1-x) E_e + \eta_t \eta_m \eta_g \eta_e x E_e + \eta_t \eta_m \eta_b E_b}{\Delta t} \tag{7.3}$$

$$P_m = \frac{\eta_m \eta_g \eta_e x E_e + \eta_m \eta_b E_b}{\Delta t} \tag{7.4}$$

These models not only give an overview of the power flow through the system but also help in computing motor, engine and battery output for maximal drivetrain efficacy.

7.2.2 Additional Changes to OE-mode

OEM only uses the energy content of fuel (gasoline/diesel) to meet the vehicle power demands; it is employed due to two main reasons:

- Utilization of engine power to run the vehicle in order to avoid depletion of battery or whenever SOC is low.
- In order to draw upon a small amount of fuel energy in order to charge battery and maintain SOC.

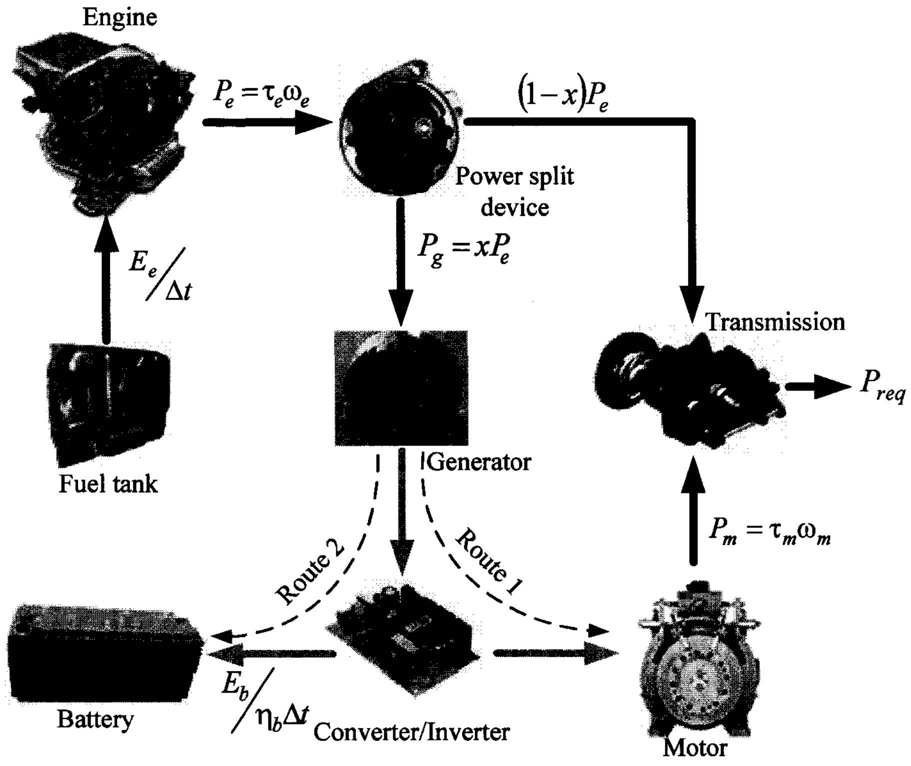


Fig. 7.1 Distribution of power for diesel/gasoline engine only operation.

Through the incorporation of efficiency maps only efficient points are selected for operating engine in an optimal speed-torque range. Even though engine is only powering the vehicle, motor still needs to be optimized. This necessity arises out of the fact that a portion of engine power is passing through the generator-motor path as can be observed route 1 in Fig. 7.2. As motor output torque would be in the lower range which usually results in inefficient performance. Route-1 is prone to losses due to power passing through multiple traction sources which reduce the overall drivetrain efficiency and in turn increasing fuel consumption as power becomes dependent on η_m, η_g and η_t. This can be effectively countered through combination or individual application of the following:

- Control the amount of power passing through route 1 by regulating the value of x.

- Eliminate route 1 instead use route 2 to divert the rest of the engine power to charge the battery (Fig. 2).

The system modeling for route 1 and route 2 have been obtained in a similar manner as SPC represented by (7.5) and (7.6) respectively.

$$P_{req} = \frac{\eta_t \eta_e (1-x) E_e + \eta_t \eta_m \eta_g \eta_e x E_e}{\Delta t} \tag{7.5}$$

$$P_{req} = \frac{\eta_t \eta_e (1-x) E_e}{\Delta t} \ \& \ \eta_g \eta_e x E_e = \eta_b E_b \tag{7.6}$$

In a lot of cases through the use of route 2 not only is the SOC maintained over a safe level but also considerable savings in energy can be achieved. The loss model created utilizing (7.5) and (7.6) yields numerical data about the savings obtained through the use of route 2 over route 1 represented as:

$$\text{Energy loss}(\%) = \left(\frac{1 - \eta_t \eta_m}{\eta_t \eta_m} \right) \times 100 \tag{7.7}$$

Hence in order to evaluate performance of gasoline based hybrid with that of its diesel counterpart, a hypothetical diesel engine based on a generalized efficiency map and calculations based on efficiency and power considerations using (7.2)-(7.6), has been assumed in place of the gasoline engine for the above mentioned modes.

7.3 Comparative Results Analyzing Effect of Diesel Hybrid over Gasoline Hybrid

In the following sections results have been presented from a various standpoints to divulge the effect, the use of diesel engine has on the performance of hybrid drivetrain.

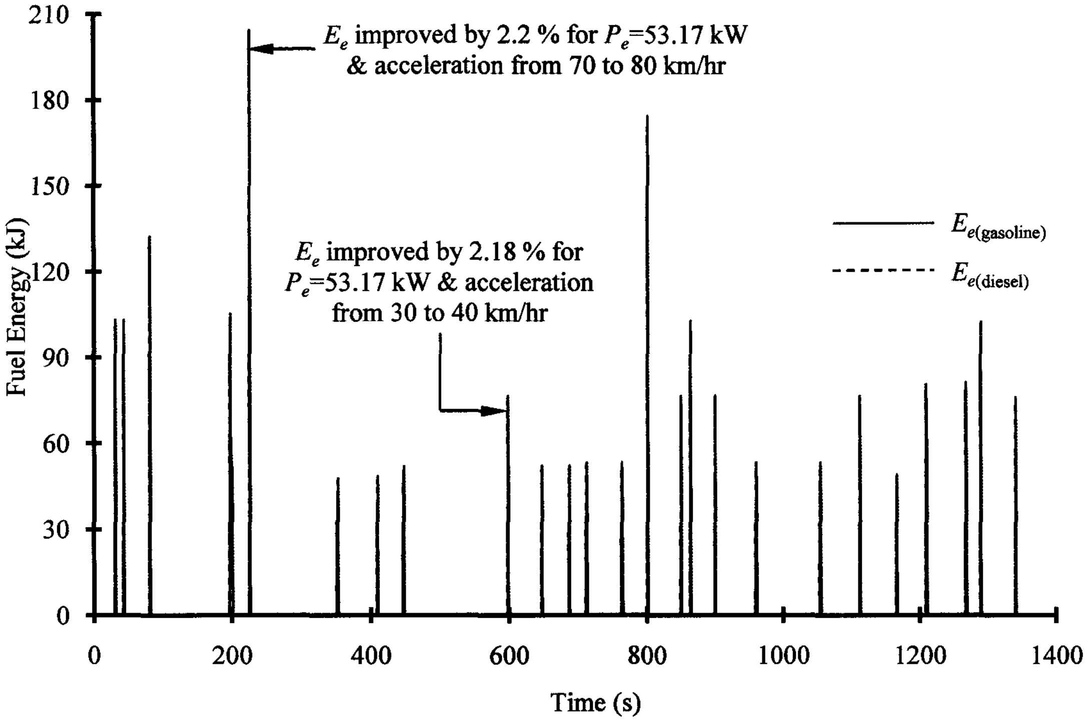


Fig. 7.2 Fuel consumed for diesel and gasoline hybrid during acceleration.

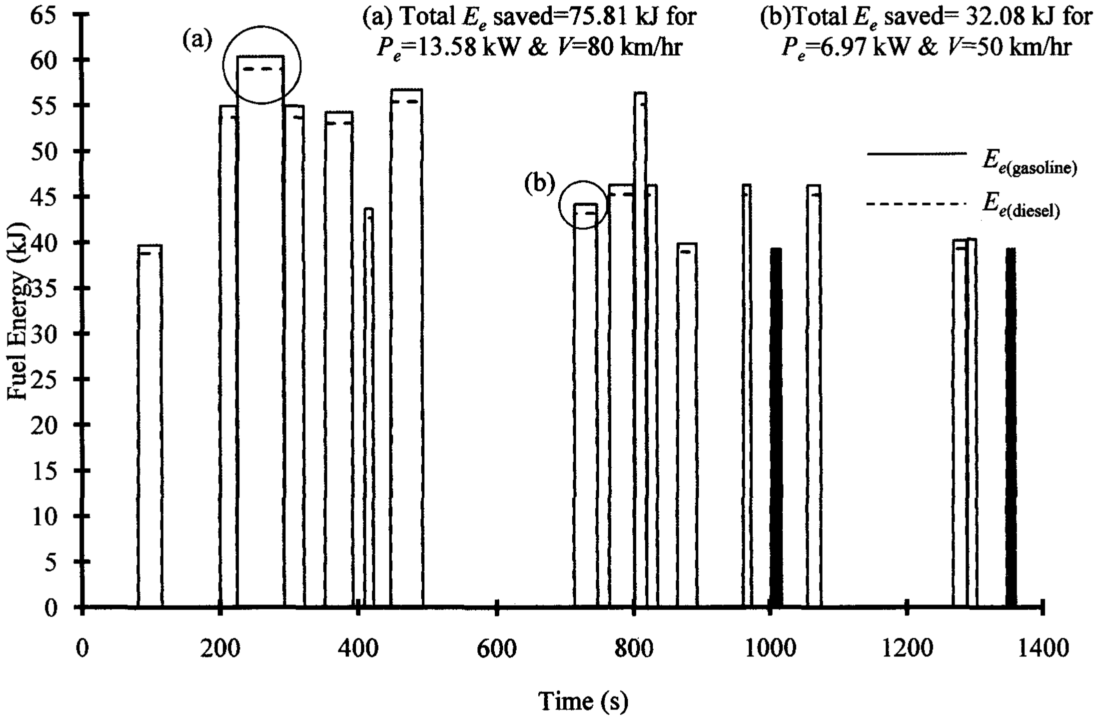


Fig. 7.3 Fuel consumed for diesel and gasoline hybrid during steady-state.

TABLE 7.2

ENERGY CONSUMPTION FOR VARIOUS DRIVING STATES

Driving state	Parameters	Gasoline	Diesel
Acceleration	Total energy spent (kJ)	2607.90	2550.41
	Average efficiency (%)	29.55	30.22
Steady-state	Total energy spent (kJ)	22818.13	22315.52
	Average efficiency (%)	27.20	27.92
Combined	Total energy spent (kJ)	25426.38	24865.94
	Average efficiency (%)	27.45	28.07

7.3.1 Energy Consumption while Accounting for Efficiency

Figs. 7.2 and 7.3 demonstrates the rate of fuel consumption of a gasoline hybrid against that of diesel hybrid for the same amount of engine output power during acceleration and steady-state of the vehicle respectively. By observing these energy consumption data plots it can be seen that the diesel engine is able to achieve better operation. The reason why diesel engine achieves superior performance is because it is able to operate at a higher efficiency therefore for the same amount of work produced by either a diesel or gasoline engine, the diesel engine consumes less fuel. The numerical analysis is broken down in order to show the effect for the different driving state and then combined to get data for complete cycle which has been presented in Table 7.2.

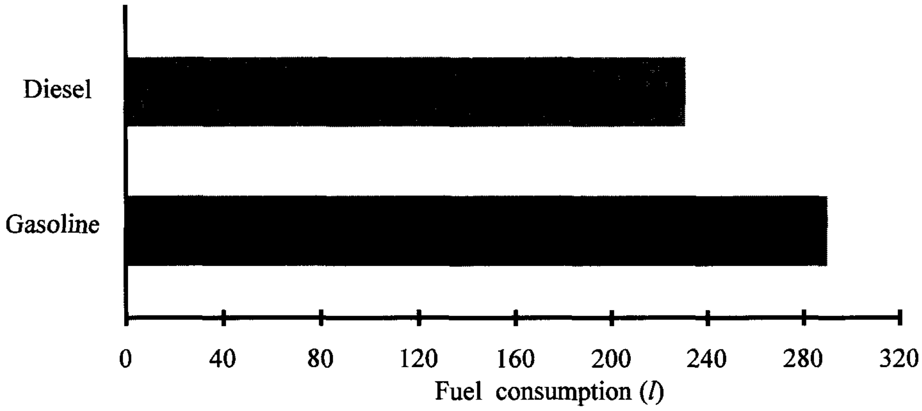


Fig. 7.4 Fuel consumption for 12-months for similar optimization of gasoline and diesel hybrid.

The energy savings for acceleration and steady-state through use of diesel engine are observed to be quite significant. The overall engine efficiency is seen to increase by 2.25% while obtaining a reduction of 560 kJ in amount of energy spent.

7.3.2 Effect on Fuel Savings for Short and Long-term Period

In order to compare diesel and gasoline hybrid the total fuel consumption over a period of time has been calculated. The gross fuel consumption for both gasoline and diesel can be obtained as:

$$\text{Fuel Consumed}(l) = \frac{\text{Energy spent}(\text{kJ}) \times \text{No. of days}}{\text{Energy density}(\text{kJ}/l)} \tag{7.8}$$

The daily energy consumed for the FTP-72 cycle has been calculated in Table 7.1. Based on the statistics from Table 7.1, the amount of fuel consumed over a day and duration of 12 months is obtained by running the FTP-72 cycle everyday for the same initial battery SOC and shown for the optimal operation of gasoline and diesel hybrid in Fig. 7.4. It's observed that through the use of diesel instead of gasoline engine in the hybrid drivetrain the daily consumption of fuel goes down from 0.794 to 0.632 *l*, which is a fuel reduction of over 20%. In fact for the 12 months period the effect is even more profound as there is a reduction in amount of fuel by 58 *l*. The slightly higher energy density of diesel also plays an important role in achieving fuel savings.

7.3.3 Improvement in Electric Drivetrain

Even though electric ratio (E.P.R) remains same for both diesel and gasoline hybrid for every time step based upon the corresponding power split, the electric ratio in terms of energy is seen to improve for diesel hybrid, defined as:

$$\text{E.E.R} = \frac{E_b}{E_b + E_e} \tag{7.9}$$

In Fig. 7.5 a step by step assessment, especially applicable for acceleration illustrates substantial increase in the E.E.R. for diesel hybrid. The reason for this phenomenon can be understood by observing Fig. 7.2, where it is seen that more fuel energy is used up to meet the power demands during the SPM for gasoline hybrid in contrast to diesel hybrid. For steady-state E.E.R does not have much relevance as either E or OE-mode is employed for which ratio would always be 1 and 0 respectively hence in either case there would be no

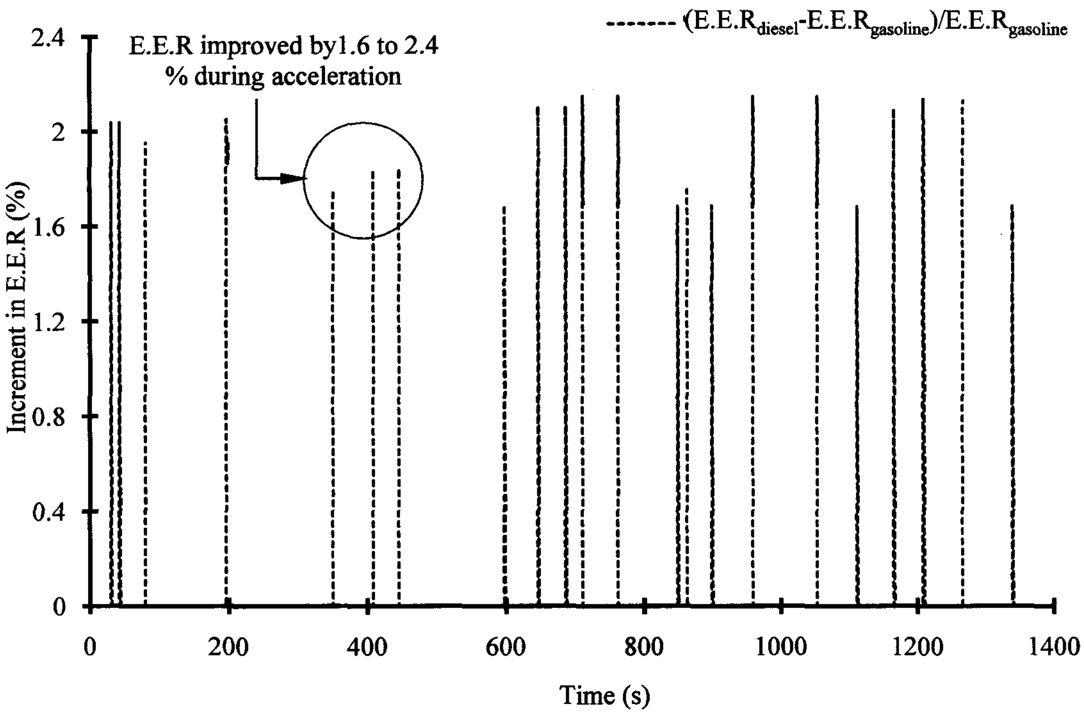


Fig. 7.5 Improvement in E.E.R through use of diesel hybrid.

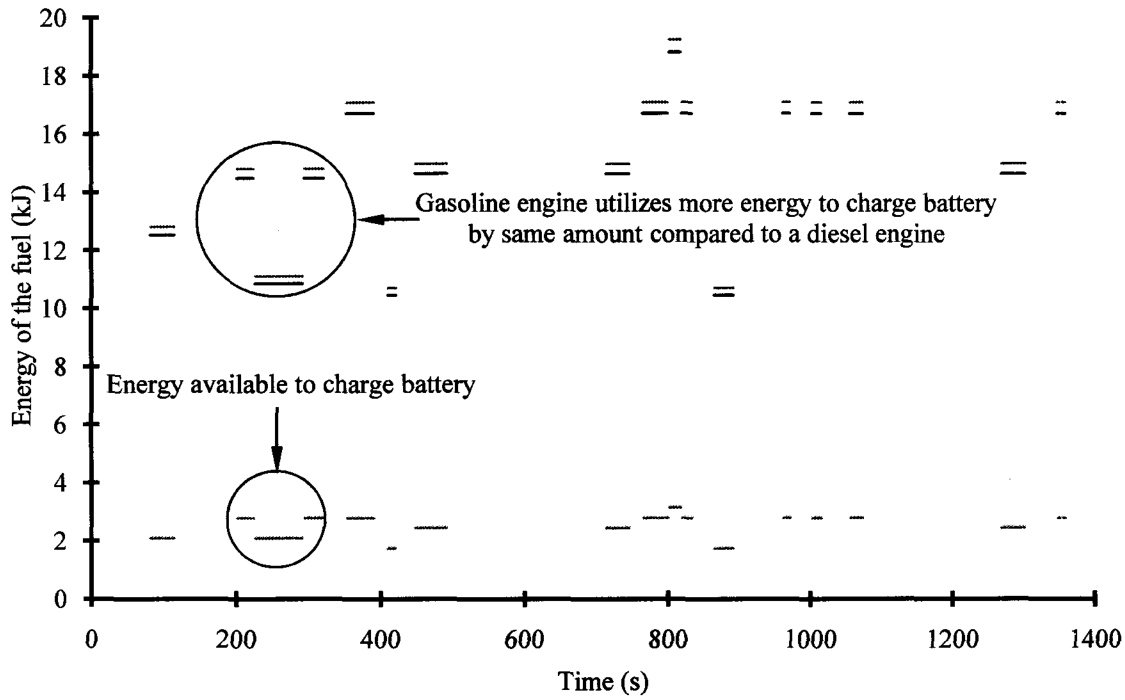


Fig. 7.6 Efficient battery charging through use of diesel instead of gasoline.

effect on the E.E.R. Therefore as E_e decreases the proportion of electric energy increases this makes the drivetrain more efficient and electric. There is a rise in average E.E.R from 0.1585 to 0.1625 for an average E.P.R. of 0.325.

An indirect consequence of using diesel instead of gasoline engine is ability to obtain enhanced utilization of energy of fuel for generation of electric energy by using a portion of engine power through OEM to charge the battery. This improved usage of energy to charge the battery can be observed by examining the energy savings shown in Fig. 7.6.

7.3.4 Effect on CO_2 and NO_X Emissions

The reduction in energy and fuel consumption explained earlier point to the fact that there will be additional benefit of reduced CO_2 emissions even though the CO_2 emissions for diesel is 2.67 kg/*l* which is slightly higher than gasoline at 2.33 kg/*l* [15]-[16]. These emissions can be calculated by:

$$\mathrm{CO_2 Emissions(kg)} = \begin{pmatrix} \mathrm{Fuel\,Emission\,rate\,of}(\mathrm{kg}/l)\times \\ \mathrm{Fuel\,Consumed}(l)\times \mathrm{No.of\ days} \end{pmatrix} \tag{7.10}$$

Based on (7.8) and (7.10) the CO_2 emissions are calculated and shown in Table 4. A 10.12% drop in emissions is observed and the long term analysis shows reduction in the level of pollutants. The NO_X emission has been calculated in a different manner as it is a function of total distance travelled and detection limit obtained from [58], expressed by:

$$\mathrm{NO_X\ Emissions}\ (\mathrm{g}/l) = \frac{\begin{pmatrix} \mathrm{Detection\ Limit\ (g/km)}\times \\ \mathrm{Distance\ (km)}\times \mathrm{No.\ of\ days} \end{pmatrix}}{\mathrm{Fuel\ Consumptio\ n}(l)} \tag{7.11}$$

Although a fall has been observed in levels of CO_2, the corresponding NO_X emissions for the same journey of a diesel hybrid would be 19.6% higher as shown in Table. 7.3.

7.3.5 Economic Benefit to the Consumer

Expenditure is of prime importance to consumer. Hence it's vital to highlight upon the cost benefit that end user can obtain through incorporation of diesel hybrid. The recent Canadian fuel market statistics [67], [68] have been consider in order to compute the overall cost savings, which is calculated based on:

$$\mathrm{Cost\ Benefit}(\$) = \mathrm{Fuel\,Consumed}(l)\times \mathrm{Cost\ of\ fuel}(\$/l) \tag{7.12}$$

The economic advantage of hybridization achieved employing diesel engine has been expressed in Table 7.4 which is based on fuel-facts from Fig. 7.4 for a single vehicle during a one year time period, which shows capability of reducing cost by up to 26%.

TABLE 7.3

CO_2 AND NO_X EMISSION COMPARISON

Duration	**Emissions for gasoline hybrid**		**Emissions for diesel hybrid**	
	CO_2 (kg)	NO_X (g/*l*)	CO_2 (kg)	NO_X (g/*l*)
Daily	1.845	0.0082	1.69	0.0102
12 months	673.55	2.993	615.92	3.723

TABLE 7.4

ANALYSIS FROM ECONOMIC POINT OF VIEW

Type of hybrid	**Fuel Consumed (*l*)**	**Fuel cost ($/*l*)**	**Cost ($)**
Gasoline	289.81	1.34	388.34
Diesel	230.86	1.23	283.95

7.4 Significance of Comparative Studies

The comparative study has been able to demonstrate that diesel hybrid would be capable of achieving even higher degree of improvement for a similar kind of gasoline hybrid for the control algorithm demonstrated in this thesis. The lower energy consumption obtained for diesel hybrid can be explained as an outcome of better energy density and average efficiency which been responsible for significant drop in fuel spent for the same amount of power demanded by the vehicle. The better utilization of the fuel also means that the proportion of electric to the engine energy also goes up as less amount of fuel energy is used up. Also higher utilization of engine energy has led optimal charging of the battery through the engine. In the emission segment there are mixed results attained, while the CO_2 emissions are seen to reduce substantially, the NO_X emissions are a little bit higher for diesel compared to gasoline hybrid. Since the major chunk of emissions is due to CO_2, the diesel engine will be able to have better overall emission performance. Finally when the cost factors was analyzed it was seen that lower prices coupled with reduced fuel consumption for diesel hybrid would prove to be a cost-effective solution for the consumer over a long period of time.

8 CONCLUSION AND FUTURE SCOPE

8.1 Conclusion

While the gasoline reserves have been on the decline for quite a while, its demand and prices have been on the upswing. This widening gap between demand and supply has put a lot of strain on the world economics. The afore mentioned factor in addition to increasing emissions causing damage to environment have proved to the driving force behind research for alternative to the conventional vehicles, which has led to development of HEVs. The HEVs have managed to not only reduce fuel consumption and emissions but also increased overall drivetrain efficiency. Through hybrid drivetrains the engine performance has been maximized while reducing dependence on gasoline. But in order to control various power and energy sources there has to be an effective power management strategy; this strategy should be able to maximize operation of each component while keeping drivetrain efficiency high.

In this thesis an effective power distribution strategy has been designed and explained for the series-parallel hybrid vehicle by developing distinct control approaches to obtain optimal power management solution for various driving states. Hence this control strategy achieves optimized operation of motor in addition to engine by shifting their regions of operation through appropriate speed-torque selection and selecting the appropriate mode. The major analytic results that have been obtained through the research conducted are as follows:

- The implementation of algorithm for urban driving conditions has been shown through analytical simulation to provide data about managing power division, which is achieved based on the characterization of various modes by developing of power models and varying speed-torque properties of engine and motor.
- An important outcome of the optimization process is variation of region of operation which leads to considerable increase in the system efficiency. Through the right speed-torque operation of engine & motor considerable amount of fuel savings and reduction in emissions have been achieved.

- The proposed control strategy manages to optimally distribute the power demand among the drivetrain component while maintaining a healthy proportion of electric power (almost 33%).
- Regulating the generator output has shown to provide substantial role in controlling operation of the engine and motor as well as in the maintenance of the battery SOC.
- In addition the algorithm keeps a check over charge-discharge pattern of the battery which helps in deciding when and where electric energy needs to be utilized.
- Optimal utilization of motor or generator in order to maximize the amount power captured during regenerative braking.
- Last of all comparative analysis from various aspects has been provided to examine the augmentation in the drivetrain performance, that can be achieved through diesel engine incorporation.

8.2 Future Scope

There are a few additions that can be made to the research work discussed in this thesis in order to further improve algorithm and real-time implementation of the algorithm:

- Consider efficiency characteristics of generator and battery instead of considering constant efficiency for these components.
- Optimize the speed-torque operation of generator based on control maps.
- Obtain and incorporate the look-up table created utilizing speed-torque characteristics of a comparable diesel engine.
- Implement the algorithm onto a vehicle power distribution controller and test the applicability of algorithm for actual city driving.
- Based on the design methodology of the algorithm demonstrated in this thesis develop a similarly structured control strategy for other driving condition such as e.g. highway driving.

APPENDIX A
EFFICIENCY TABLES

TABLE A1.1

MOTOR SPEED AND TORQUE RANGE AS A FUNCTION OF EFFICIENCY

ω_m (rpm)→	250-500	501-750	751-1000	1001-1250	1251-1500	1501-1750	1751-2000	2001-2250	2251-2500	2501-2750	2751-3000
↓ τ_m (N-m)↓	**Motor efficiency (η_m)**										
0-50	80	82	84	85	86	86	87	88	90	90	90
51-75	80	84	86	88	90	90	90	90	92	92	92
76-100	80	84	87	88	90	90	90	90	92	92	92
101-125	80	84	85	88	89	90	91	92	92	91	91
126-150	70	82	85	87	89	90	91	92	91	90	89
151-175		80	83	86	88	89	90	91	89	89	
176-200		70	83	85	87	89	90	90	89		
201-225		70	83	83	85	87	89	89			
226-250			82	84	85	87	89				
251-275			70	82	85	86					
276-300				70	83						

TABLE A1.2

ENGINE SPEED AND POWER RANGE AS A FUNCTION OF EFFICIENCY:

ω_e (rpm) →	1200-1500	1501-2000	2001-2500	2501-3000	3001-3500	3501-4000	4001-4500	4501-5000
↓ P_e (kW) ↓	**Engine efficiency (η_e)**							
0 to 5	5	5	5	5	5	5	5	5
5.01 to 10	5	10	10	10	10	10	10	10
10.01 to 15	5	26	26	26	26	26	26	10
15.01 to 20		30	30	30	30	30	26	20
20.01 to 25			30	33	33	30	26	20
25.01 to 30				33	33	30	26	20
30.01 to 35					33	30	26	20
35.01 to 40					30	30	26	20
40.01 to 45						26	26	26
45.01 to 50							26	26
50.01 to 55								26

APPENDIX B

LIST OF PUBLICATIONS

[1] A. R. Das and N. C. Kar, “Efficient power management through optimized speed and torque operation of drivetrain components,” in *Proc. IEEE Energy and Power Conference,* pp. 1-6, 2009.

[2] A. R. Das and N. C. Kar. “Power management of a series-parallel hybrid electric vehicle through optimized operation of electric motor and engine,” in *Plug-in Hybrid Electric Vehicle Conference*, pp. 1-12, 2009.

APPENDIX C

COPYRIGHT RELEASE

I authorized Ashim Raj Das to use the following publications in his thesis:

(1). A. R. Das and N. C. Kar, “Efficient power management through optimized speed and torque operation of drivetrain components,” in *Proc. IEEE Energy and Power Conference,* pp. 1-6, 2009.

(2). A. R. Das and N. C. Kar, “Power management of a series-parallel hybrid electric vehicle through optimized operation of electric motor and engine,” in *Plug-in Hybrid Electric Vehicle Conference*, pp. 1-12, 2009.

NKar

Narayan Kar
Department of Electrical & Computer Engineering

REFERENCES

[1] S. M. Lukic and A. Emadi, "Effects of drivetrain hybridization on fuel economy and dynamic performance of parallel hybrid electric vehicles," *IEEE Trans. on Vehicular Technology*, vol. 53, pp. 385-389, Mar. 2004.

[2] A. Sciarretta and L. Guzzella, “Control of hybrid electric vehicles: optimal energy-management strategies,” *IEEE Control Systems Magazine*, pp. 60-70, Apr. 2007.

[3] L. Zhou, J. Wise, S. Bowman, C. Crawford, and Z. Dong, “Design, modelling and hardware implementation of a next generation extended range electric vehicle,” *SAE Advanced Hybrid Vehicle Powertrains Conf.*, pp. 57-66, Apr. 2010.

[4] SAE J1711 fuel consumption standard.

[5] R. A. Scholer, A. Maitra, E. Ornelas, M. Bourton, and J. Salazar, “Communication between plug-in vehicles and utility grid,” *SAE Advanced Hybrid Vehicle Powertrains Conf.*, pp. 155-161, Apr. 2010.

[6] S. Zoroofi, "Modeling and simulation of vehicular power systems," Master’s thesis, Dept. Electric Power Eng., Chalmers University of Technology, Sweden, 2008.

[7] D. W. Gao, C. Mi, and A. Emadi, “Modelling and simulation of electric and hybrid vehicles,” *in Proc. 2007 IEEE Conf.*, vol. 95 pp. 315-320.

[8] M. Ehsani, Y. Gao, S. E. Gay, and A. Emadi, "Modern electric, hybrid electric and fuel cell vehicles," *in Fundamentals, Theory, and Design*, 1st ed., CRC press, 2005, pp. 15-64.

[9] A. Emadi, K. Rajashekara, S. S. Williamson, and S. M. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and comfigurations," *IEEE Trans. on Vehicular Technology*, vol. 54, pp. 763-770, May 2005.

[10] F. U. Syed, M. L. Kuang, J. Czubay, and H. Ying, "Derivation and experimental validation of a power-split hybrid electric vehicle model," *IEEE Trans. on Vehicular Technology*, vol. 55, pp. 1731-1747, Nov. 2006.

[11] M. Ehsani, K. M. Rahman, and H. A. Toliyat, "Effects of drivetrain hybridization on fuel economy and dynamic performance of parallel hybrid electric vehicles," *IEEE Trans. on Vehicular Technology*, vol. 44, pp. 19-27, Feb. 1997.

[12] T. Katrasnik, F. Trenc, and S. R. Opresnik, "Analysis of energy conversion efficiency in parallel and series hybrid powertrains," *IEEE Trans. on Vehicular Technology*, vol. 56, pp. 3649-3660, Nov. 2007.

[13] A. Sciarretta, M. Back, and L. Guzzella, "Optimal control of parallel hybrid electric vehicles," *IEEE Trans. on Control Systems Technology*, vol. 12, no. 3, pp. 352-363, May 2004.

[14] M. Ehsani, Y. Gao, and J. M. Miller, "Hybrid electric vehicles: Architecture and motor drives," *in Proc. 2007 IEEE*, vol. 95, pp. 719-728.

[15] R. Ghorbani, E. Bibeau, P. Zanetel, and A. Karlis, "Modeling and simulation of a series parallel hybrid vehicle using REVs," *in Proc. 2007 IEEE American Control Conf.*, pp. 4413-4418.

[16] F. R. Salmasi, "Control strategies for hybrid electric vehicles: evolution, classification, comparison, and future trends," *IEEE Trans. on Vehicular Technology*, vol. 56, pp. 2393-2404, Sep. 2007.

[17] Iqbal Husain, *Electric and Hybrid Vehicles: Design Fundamentals*, FL: CRC, 2003, pp.243-246.

[18] C. M. Jefferson and R. H. Rarnard, *Hybrid Vehicle Propulsion*, Boston: WIT Press, 2002, pp. 27-30.

[19] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *in Proc. 2007 IEEE Conf.*, vol. 95, pp.704-718.

[20] M. Baumann, G. Washington, B. C. Glenn, and G. Rizzoni, "Mechatronic design and control of hybrid electric vehicles," *IEEE/ASME Trans. Mechatronics*, vol. 5, pp. 58–71, Mar. 2000.

[21] N. J. Schouten, M. Salman, and N. Kheir, "Fuzzy logic control for parallel hybrid vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 10, pp. 460–468, May 2002.

[22] F. Syed, S. Nallapa, A. Dobryden, C. Grand, R. Mcgee, and D. Filev, "Design and Analysis of an adaptive real-time advisory system for improving real world fuel economy in a hybrid electric vehicle," *SAE Advanced Hybrid Vehicle Powertrains*, pp. 131-141, Apr. 2010.

[23] Y. Hao, "Fuzzy control and modeling," IEEE Press: New York, 2000.

[24] R. Yager and D. Filev, *Essentials of Fuzzy Modeling and Control*, John Wiley & Sons, New York, 1994.

[25] Chiang-Ju Chien, Chun-Te Hsu, and Yao Chia-Yu, "Fuzzy system-based adaptive iterative learning control for nonlinear plants with initial state errors," *IEEE Trans. on Fuzzy Sysems*, vol. 12, pp. 724–732, Oct. 2004.

[26] Z. X. Fu, "Real-time prediction of torque availability of an IPM synchronous machine drive for hybrid electric vehicle," *in Proc. 2005 IEEE Int. Conf.*, pp. 199–206.

[27] M. J. Gielniak and Z. J. Shen, "Power management strategy based on game theory for fuel cell hybrid electric vehicles," *in Proc. 2004 60th IEEE Veh. Technol. Conf.*, pp. 4422-4426.

[28] C.-C. Lin, H. Peng, J. W. Grizzle, and J.-M. Kang, "Power management strategy for a parallel hybrid electric truck," *IEEE Trans. Control Syst.Technol.*, vol. 11, no. 6, pp. 839-848, Nov. 2003.

[29] I. Kolmanovsky, M. Nieuwstadt, and J. Sun, "Optimization of complex powertrain systems for fuel economy and emissions," *in Proc. 1999 IEEE Int. Conf. Contr. Applicat.*, pp. 833-839.

[30] G. Paganelli, S. Delpart, T. M. Guerra, J. Rimaux, and J. J. Santin, "Equivalent consumption minimization strategy for parallel hybrid powertrains," *in Proc. 2002 IEEE/VTS Fall VTC Conf.*, pp. 2076–2080.

[31] D. Prokhorov, "Toyota Prius HEV Neurocontrol," *in Proc. 2007 Int. Joint. Conf. on Neural Networks*, pp. 2129-2134.

[32] D. Prokhorov, "Training recurrent neurocontrollers for real-time applications," *IEEE Trans. Neural Networks*, vol. 18, pp.1003-1015, Apr. 2007.

[33] F. R. Salmasi, "Control strategies for HEVs: Evolution, classification, comparison and future trends," *IEEE Trans. on Vehicular Technology*, vol. 56, no. 5, pp. 2393-2404, Sep. 2007.

[34] J. Liu and H. Peng, "Modelling and control of a power-split hybrid vehicle," *IEEE Trans. on Control System Technology*, vol. 16, pp. 1242-1251, Nov. 2008.

[35] C. Pronovost and J. Xu, "A reconfigurable series-parallel hybrid drivetrain for plug-in vehicles," *in EVS24 International Battery, Hybrid and Fuel cell Electric Vehicle Symposium*, pp. 1-8, May 2009

[36] V. Sezer et al., "Design and implementation of a series-parallel light commercial hybrid electric vehicle" *in EVS24 International Battery, Hybrid and Fuel cell Electric Vehicle Symposium*, pp. 1-8, May 2009.

[37] J. Park, J. Oh, Y. Park, and K. Lee, "Optimal power distribution strategy for series-parallel hybrid electric vehicles," 1st *International Forum on Strategic Technology*, pp. 37-42, Oct. 2006.

[38] F. U. Syed and J. Czubay, "Improving the efficiency of production level algorithm development for an SUV HEV powertrain," *SAE Conf.*, 2004.

[39] F. U. Syed, M. L. Kuang, J. Czubay, and H. Ying, "Derivation and experimental vslidation of power-split hybrid electric vehicle model," *IEEE Trans. on Vehicular Technology*, pp. 1731-1747, Nov. 2006.

[40] M. Bertoluzzo, P. Bolognesi, G. Buja, and P. Thakura, "Role and technology of the power split apparatus in hybrid electric vehicles," *in Proc. 2007 IEEE Industrial Electronics Conf.*, pp. 256-261.

[41] Hybrid synergy drive webpage (2010) [Online]. Available: synergydrive http://www.hybridsynergydrive.com/.

[42] Y. Gao and M. Ehsani, "A torque and speed coupling hybrid drivetrain-architecture, control and simulation," *IEEE Trans. on Power Electronics*, vol. 21, pp. 741-748, May. 2006

[43] J. T. B. A. Kessels, M. W. T. Koot, P. P. J. Bosch, and D. B. Kok, "Online energy management for hybrid electric vehicles," *IEEE Trans. on Vehicular Technology*, vol. 57, pp. 3428-3440, Nov. 2008.

[44] D. W. Gao, C. Mi, and A. Emadi, "Modelling and simulation of electric and hybrid vehicles," *in Proc. 2007 IEEE IECON Conf.*, pp. 256-261.

[45] J. M. Miller, "Hybrid electric vehicle propelsion system architectures of the e-CVT type," *IEEE Trans. on Power Electronics*, vol. 21, pp. 756-767, May 2006.

[46] S. S. Williamson, A. Emadi, and K. Rajashekara "Comprehensive efficiency modeling of electric traction motor drives for hybrid electric vehicle propulsion applications," *IEEE Trans. on Vehicular Technology*, vol. 56, no. 4, pp. 1561-1572, Jul. 2007.

[47] T. V. Keulen, G. Naus, B. Jager, R. molengraft, M. Steinbuch, and E. Aneke, "Control strategy for a two mode hybrid electric vehicle using EVT mode and fixed gear mode," in *EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, pp. 1-11, May 2009.

[48] S. Ali and N. C. Kar, "An energy based model for optimization of motor runtime in plug-in hybrid electric vehicles," in *Plug-in Hybrid electric Vehicle Conf.*, pp. 1-12, 2007.

[49] W. C. Morchin, "Energy management in hybrid electric vehicles," *in Proc. 1998 IEEE Conf.*, pp. 141-146.

[50] J. Larminie and J. Lowry, *Electric Vehicle Technology Explained*, John Wiley & sons, 2003, pp. 15-60.

[51] M. Olszewski, Evaluation of 2004 Toyota Prius Hybrid Electric Drive System, Oakridge National Lab, May 2005.

[52] Toyota Prius webpage (2009) [Online]. Available: http://www.toyota.com/prius-hybrid/specs.html.

[53] G. Cvetkovski and L. Petkovaska, "Efficiency maximization in structural design optimization of permanent magnet synchronous motor," *in Proc. 2008 IEEE Electrical Machines Conf.*, pp. 1-6.

[54] T. Higuchi, J. Oyama, and E. Yamada, "Optimization procedure of surface PM synchronous motors," *IEEE Trans. on Magnetics*, vol. 33, pp. 1943-1946, Mar. 1997.

[55] J. P. Aditya and M. Ferdowsi, "Comparison of NiMH and Li-ion batteries in automotive applications," *in Proc. 2008 IEEE Vehicle Power and Propulsion Conf.*, pp. 1-6.

[56] A. F. Burke, "Batteries and ultracapacitors for electric, hybrid and fuel cell vehicles," *in Proc. 2007 IEEE Conf.*, pp. 806-820.

[57] M. Bassett, N. Fraser, T. Brooks, G. Taylor, J. Hall, and I. Thaatcher, "A study of fuel converter requirements for an extended range electric vehicle," *SAE Advanced Hybrid Vehicle Powertrains Conf.*, pp. 79-87, Apr. 2010.

[58] L. A. Graham, "Greenhouse gas emissions from light duty vehicles under a variety of driving conditions" *in Proc. 2002 IEEE EIC climate Change Technology Conf.*, pp. 1-8.

[59] EPA (US) Urban Dynamometer Driving Schedule, FTP-72 Standard.

[60] EPA webpage (2010) [Online]. Available: http://www.epa.gov.

[61] U. Bossel, "Well-to-wheel studies, heating values and the energy conservation principle," *in Proc. 2003 European Fuel Cell Forum*, pp. 1-5.

[62] I. J. Albert, E. Kahrimanovic, and A. Emadi, "Disel sport utility vehicles with hybrid electric drive trains," *IEEE Trans. on Vehicular Technology*, vol. 53, pp. 1247-1256, Jul. 2004.

[63] F. Williems and D. Foster, "Integrated powertrain control to meet future CO2 and Euro-6 emissions targets for a diesel hybrid with SCR-deNOX system, " in *Proc. 2009 American Control Conf.*, pp. 3944-3949.

[64] M. Young et al., "The design and development of a through the road parallel diesel electric hybrid," in *Proc. 2007 IEEE Vehicular Power and Propulsion Conf.*, pp. 511-518.

[65] J. Y. Wong, *Theory of Ground Vehicles*, , John Wiley & sons, 4th ed., 2008, pp. 15-64.

[66] M. T. Al-Atabi and T. F. Yusuf, "Experimental investigation of a single cylinder diesel engine as a hybrid power unit for a series hybrid electric vehicle," in *Proc. 2002 IEEE Student Conference on Research and Development.*, pp. 261-264.

[67] National Resources Canada webpage (2010) [Online]. Available: http:// www2.nrcan.gc.ca.

[68] M. Khan, "Study of Challenges in Technology Development and Market Penetration of Hybrid Electric Vehicles in Canada," MASc. Thesis, Dept. ECE, University of Windsor, Canada, 2009.

VITA AUCTORIS

Name: Ashim Raj Das

Place of Birth: Orissa, India

Year of Birth: 1986

Education: *University of Windsor, Windsor, Ontario*
2008-2010
M.A.Sc.

University of Windsor, Windsor, Ontario
2007-2008
M.Eng.

Uttar Pradesh Technical University, India
2003-2007
B.Tech