OPTIMIZING POWER CONTROL STRATEGY FOR HYBRID-ELECTRIC VEHICLE

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Hybrid electric vehicles.

Automobiles, Electric.

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This dissertation is submitted in partial fulfillment of the requirements for the Master of Science (MS) Electronic Engineering with specialization in **Power and Control Systems** at Department of Electrical Engineering, Faculty of Engineering & Technology, Islamabad.

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DEDICATED TO

My Teachers,

Parents,

Sister and Brothers

CERTIFICATE OF APPROVAL

Title of Thesis: Optimizing Power Control Strategy for Hybrid Electric Vehicle

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Abstract

Today world is going to aware for sustainable reduce in fuel consumption of all future automobiles. While comparing the efficiencies, hybridization rate and emission with conventional vehicles, the hybrid electric vehicles have an added advantage of less fuel cost, great efficiency and low emissions. The conventional vehicle is driven only by the ignition combustion engine while the hybrid electric vehicle is driven by ignition combustion engine or electric motor or both. Hybrid electric vehicles plays an important role for reduction of environmental pollution. All these characteristics of the hybrid electric vehicle based on the selection of the energy management control strategy. The energy management control strategy treats with hybridization rate, fuel cost and emissions so that the vehicle is environment friendly as well as low fuel cost. Hybrid electric vehicle has great efficiency inside the cities due to low speed of the vehicles on the road as it operates on electric motor in vehicles crowd. In this thesis, three energy management control strategies i.e. sliding mode control, PID-control and heuristic computation techniques are proposed which give the real-time results of minimum fuel cost, good hybridization rate and low emissions in the environment. Moreover, the ADVISOR software is used to get results by defining the different control strategy variables and drive cycles. The ADVISOR gives the real-time results of low fuel cost and emissions by setting the optimum control strategy variables.

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(Muhammad Atiq-ur-Rehman)

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Chapter 1

Introduction

Hybrid Electric Vehicle (HEV) are those vehicles in which impulsion energy is produced from different sources. One of them is electric source. Further, hybrid electric vehicles reuse or recollect heat loss during repeated braking while in typical vehicles such type of energy is lost. Now a days, its need of time to reduce consumption of fuel to maximum extent. In conventional vehicle, internal combustion engine is used while electric motor is used in hybrid electric vehicle.

By efficiency comparison of conventional and hybrid electric vehicles (HEVs), HEVs have the following advantages over conventional vehicles:

1. Economizing of the engine to reduce friction losses and compensating for the lacking power by the electric motor.
2. Recovering kinetic and potential energy during braking phases by using the electric path instead of the conventional brakes [1]

1.1 Power Flow of Hybrid Electric Vehicle

Hybrid electric vehicle configurations are classified with respect to power flow path. During power flow, impulsion power from electric motor is converted into electric power and required amount of mechanical energy is obtained. In this way motor can be powered by different methods like generator or energy storage source. Engine generator pair has ability to power electric motor as well as energy storage source. During repeated brakes, motor works as generator that changes mechanical energy into electric energy and results in charged storage system. When engine in braked, battery gives electric energy to generator which perform like motor as shown in figure 1.1.

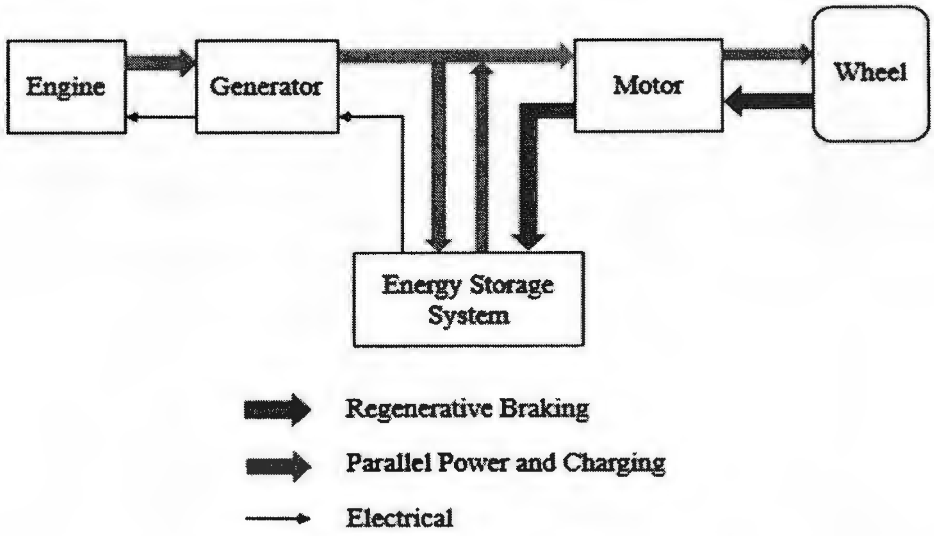

Figure 1. 1 Power Flow in Hybrid Electric Vehicle

In case of parallel hybrid vehicle, it is powered by engine or electric motor or on both sources. During repeated braking, captured energy is changed into electric energy using electric motor and it is stored in storage source. Then energy storage source powered generator as well as motor to crake the engine when get started. This path is adopted by power flow of hybrid vehicles [2].

Do hybrid electric vehicles helpful for clean environment? The conventional vehicles run on gasoline or diesel and emit CO_2 directly to atmosphere while the electric vehicles run directly on electricity. The electric vehicles are known as zero emissions. But is this true? In the Production of vehicle, more than 1/3 of life time CO_2 emissions from an electric car comes from the energy use to make the vehicle itself. The lithium battery system used in the electric vehicle is not a green activity. Electric vehicles use electricity which is produced by another fuel like fossil fuels. So, electric vehicles are said to be fossil fuels powered vehicles. Moreover, if the electricity is produced from the renewable resources like solar system or wind energy, then it is very helpful to reduce the emissions. Thus, the future electric vehicles based on renewable resources, like in

Pakistan, can play role to reduce the emissions. Another question is how much cleaner battery electric power vehicles as compared to fossil fuel power vehicles. The research about this proves that total global warming of each type of vehicle throughout every stage of its life from manufacturing to driving to disposal is a big difference.

Regarding hybrid electric vehicles, how does hybridization improve miles per gallon (MPG)? It downsizes the engine size and run more efficiently and there is a freedom of electric motor torque and efficiency. There is degree of freedom to recharge the battery system from plug in charge. It has another aspect of regenerative braking in which energy is captured while braking the vehicle. What is regenerative braking? Is it special technology added to hybrid electric vehicles? Or is it just a marketing tool? Regenerative technology is used only in electric and hybrid electric vehicles. This technology works to save the kinetic energy produced by the mass of vehicle while braking. The same motor acts as the generator and it recharges the installed battery system in the vehicle. Another question raises, are the hybrid electric vehicles worth? What is the payback by the hybrid electric vehicles? These questions are answered in chapter 2.

1.2 Motivation

Usually, non-renewable energy sources are used for working of automobile. In past, pollution produced due to heavy vehicle was increased with time. Main aim is to increase the efficiency of vehicle and reduce the usage of fuel to make process financially feasible. For this purpose, Hybrid electric vehicles (HEV) are introduced. These vehicles are producing less pollution as compared to conventional vehicles as well as best efficiency is obtained in them. However, there are few drawbacks with conventional vehicles like to attain high output in high speed conditions or to moving on a slope. These problems are solved by hybrid electric vehicles. The main aim of this research work was to use fuel in a good way as well as to enhance the efficiency of engine and to

reduce the usage of non-renewable sources. Hybrid electric vehicles have advantages over conventional vehicles as given follow

1. In these vehicles, less amount of fuel is consumed. Thus, low level pollution is produced that removes many environmental problems relevant to pollution.
2. It also reduces the usage of non-renewable sources.
3. It works well in low speed conditions

Optimal hybridization rate between both ignition combustion engine (ICE) and electric motor (EM) can be achieved by an energy management control strategy based on robust control technique [1].

1.3 Problem Statement

The major area of my research is an optimal configuration of the vehicle between the power of electric motor and the ignition combustion engine to determine economical hybridization rate using the robust non-linear control strategy approach, heuristic computational technique and advanced vehicle simulator (ADVISOR).

The following problems are considered in the development of hybrid electric vehicles power control strategy:

- **Optimizing Engine Operation:** The operation points of the engine are set on the optimal points of the torque and speed plane based on the engine mapping data of the fuel economy and emissions as well as compromising between fuel economy and emissions.

- **Optimizing Electric Motor Operation:** The motor set has a preferred operating region on the torque and speed plane in which the overall efficiency of the system remains optimum.
- **Optimizing state of change (SOC) of the Battery System:** State of charge operating window and swing rates are optimized to compromise the battery's life and fuel economy of the hybrid electric vehicle.
- **Acquisition of Maximum Regenerative Energy:** Optimum set of states of charge of the battery system to capture the maximum free regenerative energy based on the drivers' driving habits, road structure and weather conditions as well as traffic flow.
- **Optimum control of HEV Transmission System:** The most recent hybrid electric vehicle systems are not only possessing the features of the parallel hybrid vehicle but also incorporate the unique advantages of the series hybrid [2].

In hybrid electric vehicle, power is distributed between ignition combustion engine and electric motor. The only electric motor provides the power to move on the vehicle requiring power between 0KW to 8KW. While exceeding the power requirement by the vehicle, the ignition combustion engine is started to provide more power to vehicle and to charge the battery system. Above than 40KW, both ignition combustion engine and electric motor provides the power to vehicle. In braking condition, the motor which is also acting as a generator converts the braking energy to store in the battery storage system. Power requirement slab from both sources is shown in the figure 1.2.

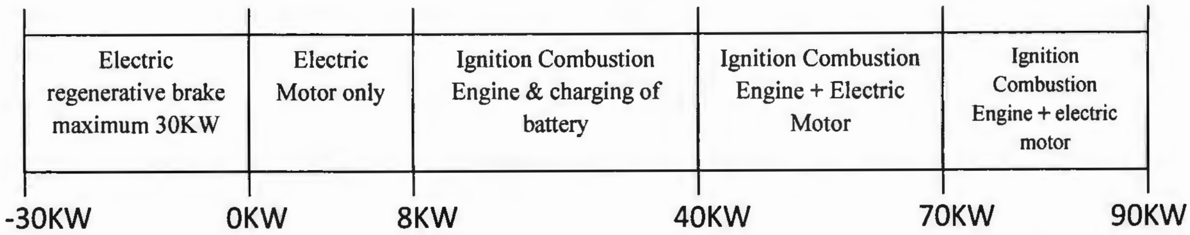

Figure 1. 2 Hybrid Electric Vehicle Power Slab

1.4 Aims and Objectives

The main objective of hybrid electric vehicle is fuel economy and low emission which is also known as environment friendly. This objective is basically effected by environment factors like road conditions, traffic flow, driving cycle and weather conditions. While driving on the road, it can't be possible to estimate the actual fuel consumption and emission. For this reason, the following objectives must be under consideration while designing an automobile:

- Standardization of drive cycles under repeated conditions
- Drivability during acceleration and deceleration
- Operational modes
- Selection of energy management control strategy
- Selection of powertrain system
- Road profiles and environmental conditions
- Monitoring of speed and torque
- Given drive cycle response optimization

1.5 Literature Review

Hybrid electric vehicle can work on two bases. One of them is usage of electrical power and second one is that of internal combustion engine. It has many advantages over conventional vehicles [3].

Main aim is to construct a hybrid electric vehicle which is powered by using battery as well as engine. It uses less amount of fuel as well as produces small amount of pollution [4]. Hybrid electric vehicles have a battery which is used to derive electric vehicle as well as a power system that have combustion engine used to reduce the usage of fuel as well as production of high amount pollution. It has also one advantage that is to have ability to recharge the battery to run generator which in tune run the turbine and alternatively internal combustion engine. In these vehicles, battery provide power to derive vehicles at low speed where efficiency of engine is enhanced. In different conditions like moving to hill, engine is assisted by electric power. In this way, hybrid electric vehicles are best to work in heavily traffic areas like urban cities [4] .

HEV consists of internal combustion engine and a motor. These vehicles show high efficiency as well as reduced fuel consumption. As a result, overall efficiency of vehicle is enhanced. These vehicles can cover large distance in same amount of fuel as compared to conventional vehicles [4]. Hybridization can decrease the usage of fuel as well as emission of pollutants with availability of other energy sources. Hybrid electric vehicles work at effective engine point and engine is downsized when maximum power is required. There are many other benefits of such vehicles like recuperation as well as energy management in two power sources. Energy management strategy (EMS) which is also called supervisory control strategy made the basic of HEV. EMS is categorized into two groups one of them is rule based control strategies while other is optimized based control way. EMS plays important role maximize power division between combustion engine and electric source. Thus, reduces the usage of fuel as well as increases the deriving power that is demand of a vehicle.

Need of time is to construct environmental benign vehicles with lowest consumption of fuel. To fulfill the need, vehicle manufacturing industries give suggestions to have electric vehicles (Ev).

Different types of vehicles are included in this category like plug in hybrid vehicles. With different technologies, a wide range of modes are available. It is always a question that which type of vehicle have best properties. Best satisfaction of maximum hybridization rate as well as the driving cycle. Optimal conditions for a vehicle cannot be defined by a single standard. It is actually the ratio of power of heat engine and electrical system that tunes to reduce the usage of fuel and total expenses for the life span of vehicle. This ratio is determined by the application of specific pattern of vehicle and required working [5].

Electric vehicles (Evs) are those vehicles in which energy is obtained by using renewable sources. Thus, it reduces the dependence on conventional vehicles. Use of Evs at large scale is not possible due to some sort of limitations. So, as a result, Plug in hybrid vehicle in which battery is used as source of power in preference of internal combustion engine is alternate solution. Both the motor and battery work efficiently yet motor can give torque at low speed only while engine works efficiently at high power. When these two sources of energy are used together, then efficient vehicles can be constructed. Energy management system (EMs) is defined as those strategies in which heuristic knowledge is used. These systems can be easily implanted. Optimum conditions for EMs can be constructed by usage of dynamic programming. In the same way, pontryagin's minimum principle and particle swarm optimization are use together to construct EMs of hybrid vehicles [6].

Plug-in hybrid electric vehicles (PHEV) use both electricity and gasoline to propel the vehicle, and is being recognized as a potential alternative to conventional vehicles. PHEVs offer opportunity to use electric energy generated by renewable resources and significantly reduce greenhouse gas emissions. The driving distance, charging times, charging locations, battery state of charge, and charging requirements of a PHEV are the key parameters [7].

Various distinct modes work together in energy management system of power split plug in hybrid vehicles. Energy reducing problem can be overcome by use of dynamic programming system. In dynamic programming system, good results can be obtained and implemented in real way [8].

A vehicle driven by usage of electric energy can also be designed by sliding mode controller [9]. High torque is required to drive line for electric motor. Thus, energy is efficiently regenerated as well as acceleration is increased in hybrid electric vehicles. Shaft and backlash elasticity is attained. Differential limits are implied at bandwidth of derive line to attain stability as well as comfort. In backlash, nonlinearity is introduced in drive line. In this way, large amount of energy is generated when vehicle is accelerated. Thus, comfort and stability is not lost as well as drive safety is also attained [10].

Hybrid electric vehicles usually assume fuel usage potential when energy control system is used to give high efficiency to the system. Controlled ways are categorized on rule based of optimal condition based. When these conditions are implied then interesting results can be obtained. Thus, results obtained will be closer to optimum conditions.

Rule based deterministic and Fuzzy Logic based approaches, as well as transient optimization based approaches such as Equivalent Consumption Minimization Strategy (ECMS) and global optimization based approaches like dynamic programming, game theory or genetic algorithm can be used [11].

Sliding mode control way can be used in conventional controller of hybrid electric vehicles. In this way, sliding mode control way is used as controller [12].

While energy is produced, used and saved in hybrid electric vehicles by implying management approach. In this way, maximum controlled way is the key point to attain or construct hybrid electric vehicles [12].

The need of non-renewable energy sources or fuel mostly in light duty vehicles are increased as progress of country. Its need is also increased with economic growth. Those vehicles in which fossil fuel are used as energy source have some drawbacks. For example, these vehicles produces financial burden and cause large scale fluctuation in fuel prices as well as also produced environmental pollution and induces harmful effects on health of human as well as other organisms. Here, different type of technologies implied in hybrid electric vehicles have been reviewed as well as their construction and various steps adopted to construct maintainable, effective and environment benign transportation system [13].

The growth in market potential of HEVs is strongly influenced by the movement of legislation. Moreover, the benefits and stringent emission legislation is common in areas where hybrid electric vehicles have been successful [13] [14].

1.6 Thesis Layout

Thesis consists of six chapters. The first chapter is about introduction of the title, problem statement, aims and objectives, motivation about the topic and the literature review. The second chapter is about the architecture of hybrid electric vehicle, control strategies and cost function used for the hybrid electric vehicles. Three control energy management strategies and heuristic computational techniques are proposed for economical fuel consumption and low emissions. The third chapter is about the power electronics devices used in hybrid electric vehicles, for example, converters and inverters. The fourth chapter is about the advanced vehicle simulator (ADVISOR) with brief explanation. The fifth chapter is about the results and discussions. Last chapter, but not least, consists of the conclusions and future works.

Chapter 2

Architecture and Energy Management Control Strategies

In this chapter, the architecture of hybrid electric vehicle and its three types are briefly discussed with mechanical and electrical flow diagrams. The types of HEV are depend upon the configuration of the its components. The main components of the hybrid electric vehicle are explained. These components are the key to its economical fuel consumption and low emissions. Moreover, the three types of control strategies are discussed i.e. sliding mode control, PID control and the heuristic computation techniques. Cost function based problem can be solved by using any one of the heuristic computational techniques. These strategies play key role for the economical distribution of energy between two energy sources.

2.1 Architecture of Hybrid Electric Vehicle

There are typically three different hybrid electric vehicle architectures.

2.1.1 Series Hybrid Electric Vehicle

The series hybrid electric vehicle is configured in such a way so that the engine is connected to generator and that engine provides the power to generator. The generator is used to provide power to energy storage system (ESS). The ESS power is used to propel the wheels of vehicle.

In this architecture, power sources are connected in series electromechanically. The electrical power train provides impulsion power to drive the wheels. An engine-generator pair unit recharges the energy storage system (ESS) and provides energy to the electrical powertrain. Hence, a series hybrid electric vehicle has an engine-generator pair unit to supply electrical energy when the vehicle's battery deficiencies sufficient energy to power the vehicle as shown in the figure 2.1 [2].

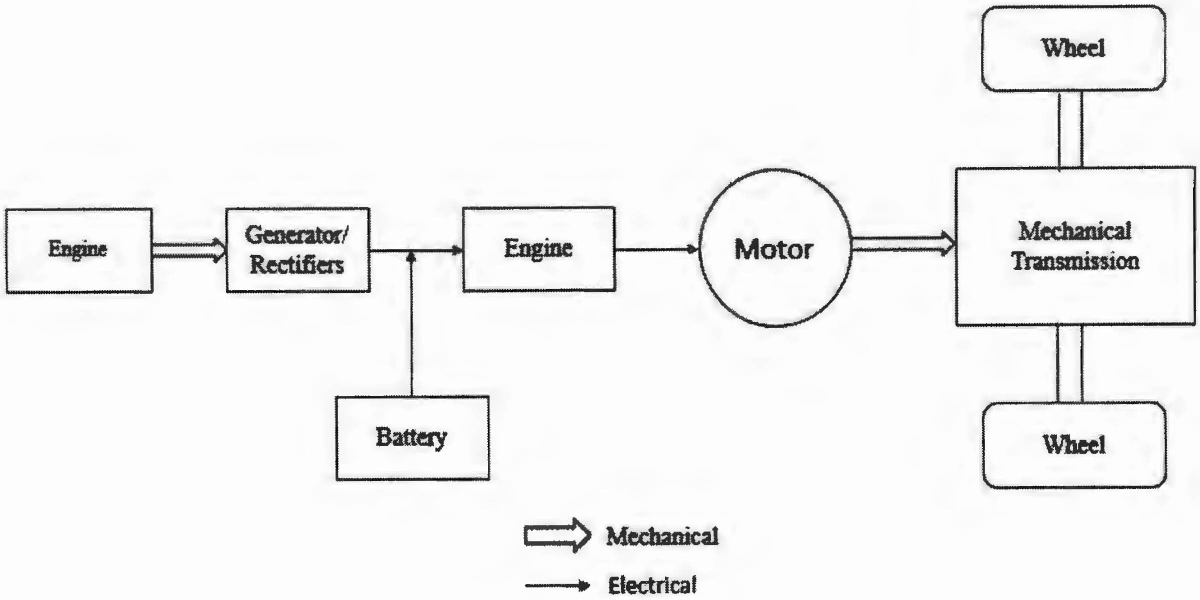

Figure 2. 1 Series Hybrid Electric Vehicle

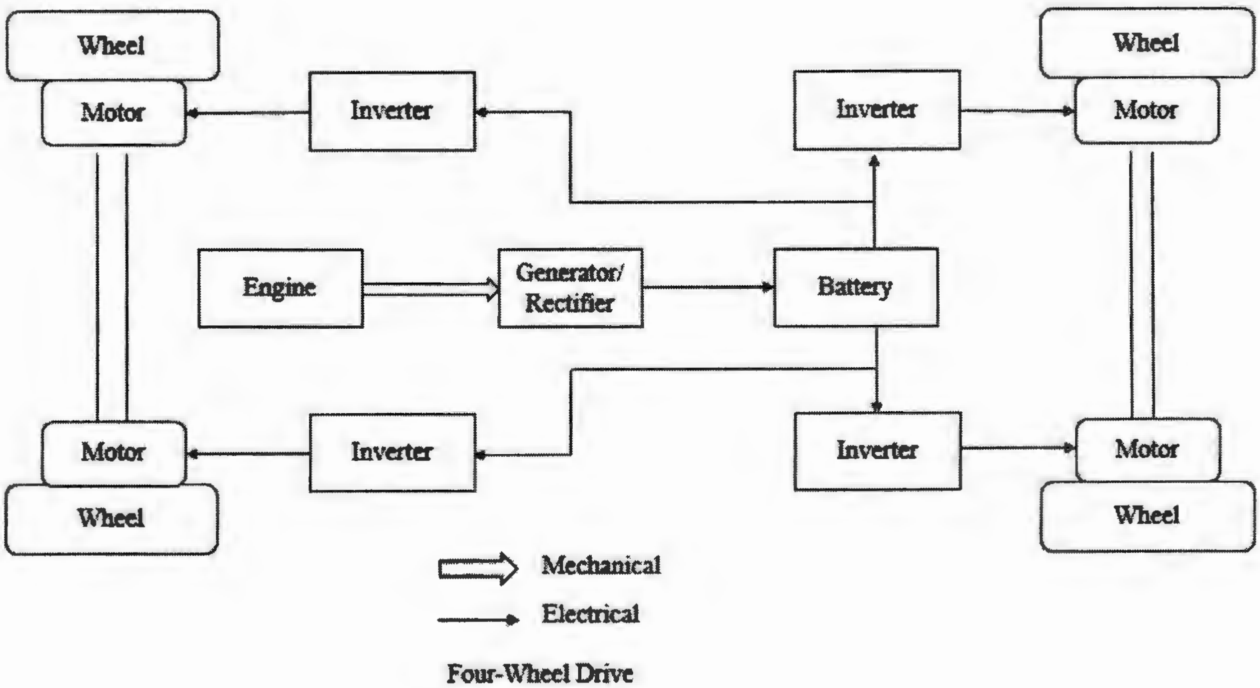

Figure 2. 2 Four Wheel Series Hybrid Electric Vehicle

The engine generator system is turned off when the battery system has adequate energy. In this case the vehicle power demand is low and it is powered only by using battery system. When the vehicle power demand is high then the engine generator system is turned on. In this case both ignition combustion engine (ICE) and energy storage system (ESS) provides the power to vehicle. When vehicle's power demand is less than the engine generator system's optimum power and the battery state of charge (SOC) is low then a portion of engine generator system power is used to charge the battery system. This is known as power splitting. Battery can also be charged from engine generator without the vehicle is being driven. The battery is also charged by regenerative braking. While braking, the electric motor operates as a generator to recharge the battery system. The vehicle's kinetic energy is converted into electric energy. The four-wheel series hybrid vehicle is shown in the figure 2.2

2.1.2 Parallel Hybrid Electric Vehicle

In this architecture, engine or electric motor or both source drive the vehicle. The electric motor acts as generator to recharge the battery system during regenerative braking. When there is extra power generation by the engine than required vehicle propulsion power then this extra power is used to recharge the battery system. The parallel hybrid electric vehicles are relatively less costly and economical as compared series and series-parallel hybrid.

There are many potential points that are used for linking both power sources to the drivetrain. An electrical power train system is linked to conventional power train system through a clutch in a parallel hybrid electric vehicle (HEV). Parallel HEV has the maximum power rating of the electrical powertrain as compared to the engine based conventional power train. The power train is designed in such a way so that the distribution of power between electric motor, internal

combustion engine and the energy storage system (ESS) is optimized. The engine may be turned on and off regularly in reply to the system control strategy as shown in the figure 2.3 [2].

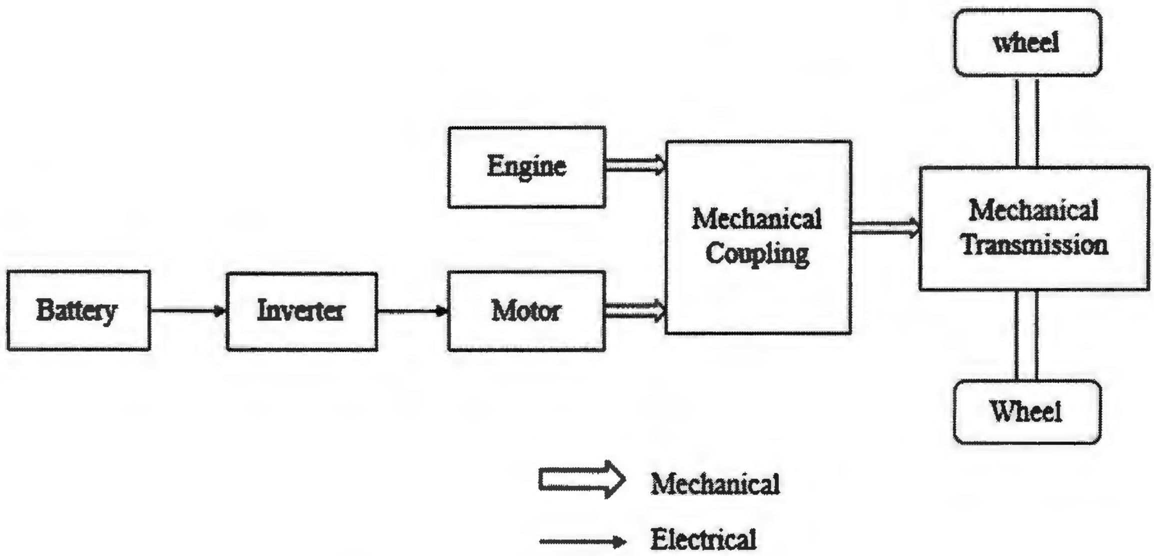

Figure 2. 3 Parallel Hybrid Electric Vehicle

The ignition combustion engine is turned off in condition of low vehicle's power demand and high SOC. The vehicle is powered only by using the battery system. This is known as motor alone mode. The ignition combustion engine is also turned on in condition of high vehicle's power demand. This is known as combined power mode. While travelling on the highway and high power demand, the engine provides the power required to drive the vehicle. The motor system remains in idle state. Even though the battery SOC is at a high level, the engine remains turned on. When the power demand of the vehicle is low and the battery SOC is also low then the engine is turned on to propel the vehicle and to recharge the battery. This is known as the power split mode. The battery system can also be charged by running the motor which acts like a generator without driving the vehicle. This is known as stationary charging mode. The electric motor is worked as a generator to convert kinetic energy into electric energy which is stored in the battery in

regenerative charging mode. In this approach, the engine and motor controllers are correctly coordinated [2].

2.1.3 Series-Parallel Hybrid

The series-parallel hybrid electric vehicle has both properties of series and parallel approaches. The fuel economy and drivability is optimized depending upon the vehicle's operating condition. The series-parallel hybrid electric vehicle is a very popular and common choice due to increase of degree of freedom in control. Moreover, it is mostly extra expensive than series or parallel hybrid electric vehicles due to increase of components and complexity [2]. The architecture of series-parallel hybrid electric vehicle is shown in the figure 2.4. The four-wheel drive series-parallel hybrid electric vehicle architecture is shown in the figure 2.5.

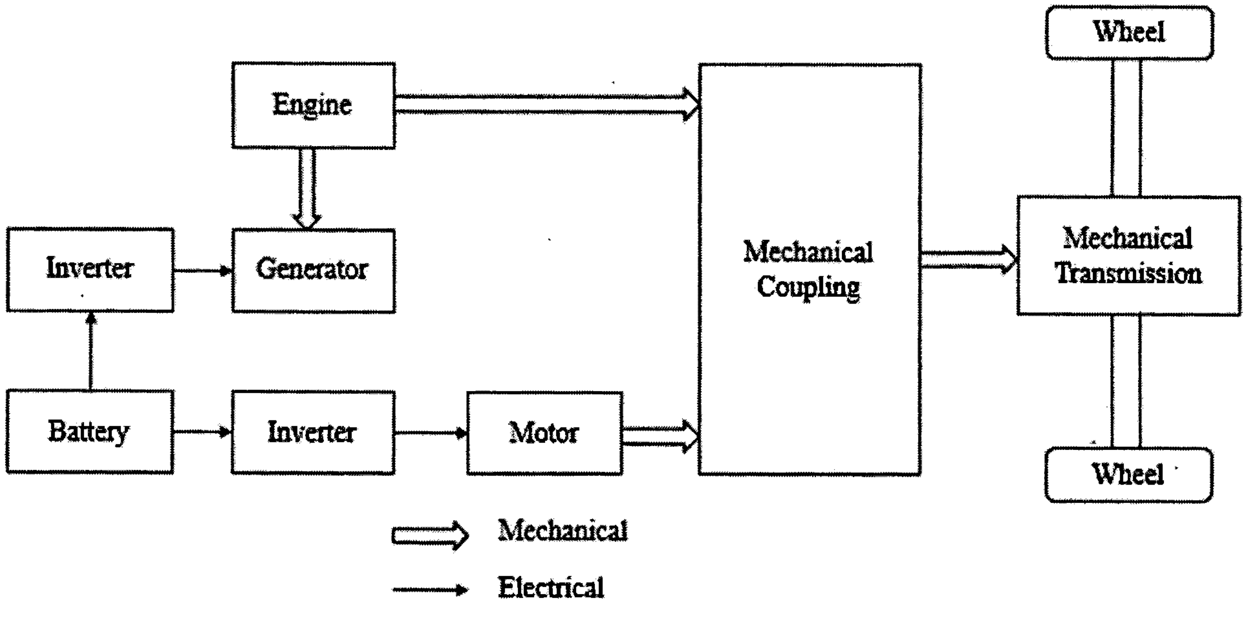

Figure 2. 4 Series-Parallel Hybrid Electric Vehicle

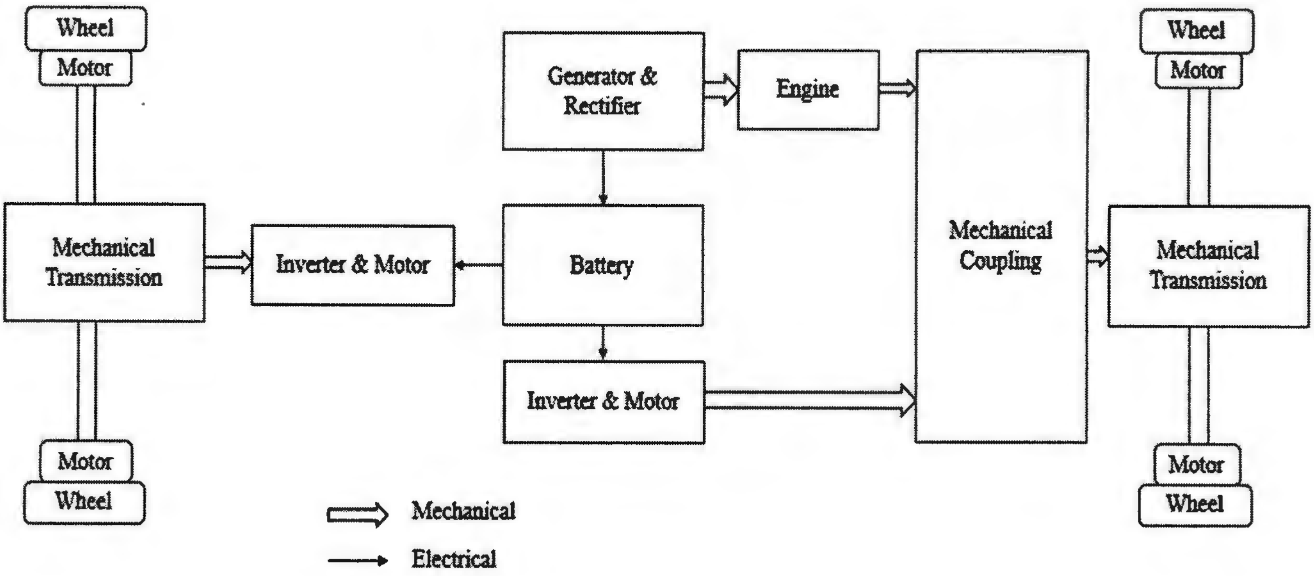

Figure 2. 5 Four-Wheel Drive Series-Parallel Hybrid electric vehicle

2.2 Hybrid Electric Vehicle Components

The HEV mostly consists of energy storage system (ESS), transmission, electric motors and power electronics units. These modules are the dc-dc converters and dc-ac inverters. These components are important in hybrid electric vehicles as compared to conventional vehicles.

1. **'Energy Storage System':** ESS is the one of the most important subsystem in hybrid electric vehicle. The energy storage system directly effects the efficiency of the vehicle. High energy density, low internal resistance, long cycle and calendar life batteries are needed for hybrid electric vehicles. Moreover, high power density batteries are mostly used for traditional HEVs while high energy density batteries are used for plug in HEVs.

2. **'Transmission':** The hybrid electric vehicle transmission can manage ignition combustion engine (ICE) only driving, electric motor only driving and mixtures of the both. Transmission has backing functions of stop start, regenerative braking and shifting ignition combustion engine working range. The transmission is also able to manage and adjust its

parameters to meet the actual driving scenarios. The hybrid electric vehicle system is mostly depending upon the transmission to a contrivance optimal performance for multiple types of drive cycles. Minimizing additional weight, cost and packaging are the major challenges for hybrid electric vehicle transmission. Hybrid electric vehicle transmission is designed for multiple drive cycles rather than a specific cycle.

3. **'Electric Motors':** Hybrid electric vehicles uses efficient, light, powerful electric motors. Electric motor (EM) selection depends on the design of hybrid electric vehicle. EM is used as peak power regulation device, load sharing device and small transient source of torque. The hybrid electric vehicle electric motors operate in two modes. The normal mode and the extended mode. When motor exerts constant torque throughout the rated speed range. It is called normal mode. When motor enters in extended mode above rated speed and the torque decreases with speed. During normal mode, the electric motor delivers the necessary torque for tolerable acceleration. Above the tolerable acceleration, the electric motor enters in extended mode for steady speed. Direct current, brushless DC and alternating current induction motors are used depending on design of hybrid electric vehicle.

   Electric motor is also capable to capture the regenerative braking energy. The EM acts as a generator when it produces negative torque by some external rotational force. This external rotational force is produced by the momentum of the vehicle. The control system of the HEV directs the EM to rotate with negative torque. In this condition, the ICE is switched off. The mechanical energy is converted into alternating current electric energy. The inverter system of the HEV is used to convert it into direct current to recharge the battery system. The control system in hybrid electric vehicle has the capacity to optimize the regenerative braking energy.

4. **'Power Electronic Units':** dc-dc converters and dc-ac inverters are used in hybrid electric vehicles. The function of dc-dc converters in hybrid electric vehicle is to convert high voltage of energy storage system to low voltage for accessories. The function of DC-AC inverters in the hybrid electric vehicle is to convert the DC voltage of the energy storage system to high AC voltage to power the electric motor. This process is reversed in case of regenerative braking. The output AC power of the electric motor is inverted to DC to charge the battery. The power electronic units used in hybrid electric vehicle have noteworthy impact on total efficiency of the vehicle [2].

2.3 Control Strategies

The strategies that control power distribution within the hybrid powertrain are often referred to as energy management strategies.

Various control strategies may be used in drive train of vehicle. The main objective of control strategies in hybrid electric vehicle is:

- To operate each component of vehicle with optimum efficiency.
- To fulfill the power requirements for hybrid electric vehicle driver.
- To recover braking energy as much as possible.
- To maintain the battery state of charge.

Control strategies are normally divided into two groups that are rule-based and model based optimal control strategies.

2.3.1 Rule-based control Strategies

The rule based control strategies are supervisory control of power flow of hybrid electric vehicle power train. It is the effective feature in real time. The basic idea behind this strategy is load leveling.

By using the actual Ignition combustion engine operating point as near as possible to predetermine value for every instant in time. The fundamental concept of operation of hybrid electric vehicle is load leveling. There are two types of rule based strategies:

- Deterministic
- Fuzzy logic

2.3.2 Model-based control strategies

There are two types of model based control strategies:

- Numerical Approach
- Analytical Approach

Hybrid electric vehicles have multiple energy storages or power storage sources, so these vehicles have the potential to reduce fuel consumption and emission as compared to conventional vehicles. The total power from battery and engine at each instant must be fulfilled so that driver's power requirement is ensured. The power distribution solutions among these sources can be derived by using energy management strategy. The energy management strategy problem is typically solved by numerical or analytical optimization techniques. λ control and predictive control strategy can also be used in hybrid electric vehicles.

The numerical approach can be categorized as dynamic programming, genetic algorithms, simulated annealing and stochastic dynamic programing.

Analytical approach can be categorized as Pontrygin's minimum principle and equivalent consumption minimization strategy.

The dynamic programming and analytical optimal control techniques are used to get the theoretical optimal solutions.

2.4 Energy Management Strategies

The energy management control strategy minimizes the vehicle fuel consumption and it maintains the battery state of charge near a desired value and required power by the vehicle to optimum value. The model of energy management has two scopes:

1. By creating the plant simulators to which is used for testing and development.
2. By creating such an embedded model that are used to set up analytical approach

Correct estimation of fuel consumption and better state of charge (SOC) can be obtained by conditions of control inputs and road structure. The prime objective in above both cases is to reproduce the energy flows within the power train [6].

In conventional vehicles, the freedom of choice of a suitable combination of power flows creates enormous flexibility compared to a single drive train [14].

The performance of an HEV depends upon the efficiency of the individual components w.r.t. fuel economy and emission minimization. In other words, we can say that energy management strategy ('Power control strategy') in hybrid electric vehicle plays a key role for optimal energy consumption [15].

The key goals of hybrid electric vehicle energy management strategies are variety of its formations which are used to achieve 'maximum fuel economy', 'minimum emissions' and 'lowest system cost'. Following key points are taken under consideration in the development of hybrid electric vehicle energy management strategy.

The operating points of the ICE are adjusted in such a way so that it meets the optimal points of the torque speed plane based on the engine mapping data of fuel economy. Any fluctuation in regulation of operating speed of an ICE is corrected by minimizing engine dynamics. To improve fuel economy and decrease emissions, minimization of the engine's idle time is needed. The engine on/off is based on driver's driving conditions, road structure and weather conditions. By setting state of charge of the battery system maximum, energy is captured from free regenerative energy. The battery's life may be increased by using swing rates. The motor system is a preferred operating points region on the torque speed plan. Zero emission policy is followed.

The Important and most challenging task of the energy management strategy is to allocate/distribute the hybrid electric vehicle demand power to the ignition combustion engine (ICE) and electric motor (EM) in real time [16].

2.5 Sliding Mode Control

Sliding mode control is used in a non-linear problem to get the solutions. This method is used to change the dynamic features by high frequency switching control action. In sliding mode control, the state trajectory is the predefined surface in state space and maintains the system on this surface for consequent time. This predefined surface is called sliding surface or switching hyperplane or sliding manifold. The switch control action keeps the system state trajectory on the surface. Then the switched control enforces the state trajectory back to the surface. In this way, the predefined surface finds how to normalize the control action. Robustness is an added advantage as the controlled system is naturally slide along the surface. It rests on the surface in finite time. The sliding mode control is described graphically in figure 2.6 [10].

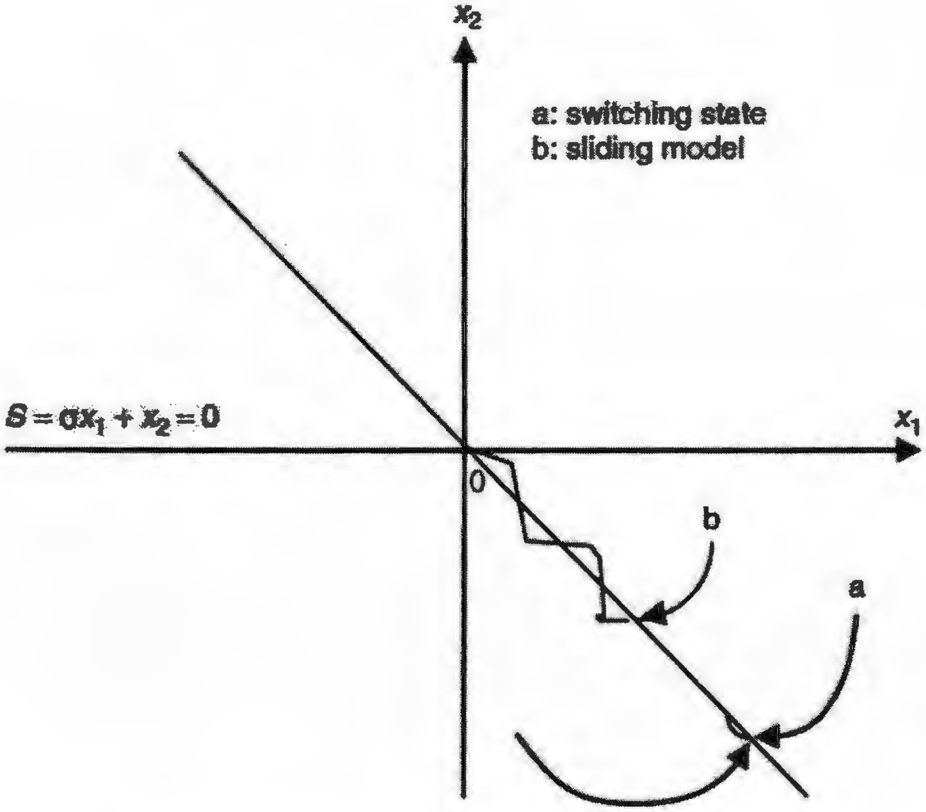

Figure 2. 6 Sliding-Mode Control and State Trajectory

There are two steps for designing the sliding mode controller:

- The selection of feedback control law depends on the verification of sliding condition. To overcome of the presence of modeling imprecision and disturbances, the control law should be discontinuous across S(t). Chattering is the undesired response in practice and can be seen in figure 2.6.
- The discontinuous control law is properly smoothed to achieve an optimal tradeoff between control bandwidth and tracking precision.

Firstly, it achieves the robustness for parametric uncertainty and secondly it achieves robustness to high frequency unmodeled dynamics [12].

Advantages

- Sliding mode techniques are perhaps original best known for their potential as robust control method.
- Sliding mode control is characterized by a suit of feedback control laws and a decision rule.
- Variable structure control system (VSCS) is designed to drive and then constrain the system state to lie within a neighborhood of the switching function.

The second order sliding mode control can be used for a hybrid control power system for electric vehicles. The main advantage of the second order sliding mode control that it does not require the upper bound of the uncertainty [17].

2.6 PID-Controller

2.6.1 Principle of PID control

The Proportional-Integral-Derivative (PID) controller has following significant operations:

- It can remove steady state counterbalances through integral action.
- It provides feedback to the system.
- It can suppose the future states through derivative action.

In industrial control systems, PID controller is used with a control loop feedback system. The PID controller measures the error value which is the difference of a desired set point and measured process variable. The PID controller algorithm is used to minimize the error value with passage of time by modification of control variable. This is done by adjusting the control valve, a damper or power supplied to heating element. The new value is determined by weighted sum[18].

The equation of PID controller can be expressed as:

$$u(t) = K(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d\frac{de(t)}{dt})$$

- *P (Proportional)* is denoted for the present values of the error. If the error is large and positive, the control output will also be large and positive.
- *I (Integral)* is denoted for past values of the error. If the current output is not sufficiently strong, error will accumulate over time and the controller will respond by applying a stronger action.
- *D (Derivative)* is denoted for possible future values of the error based on its current rate of change.

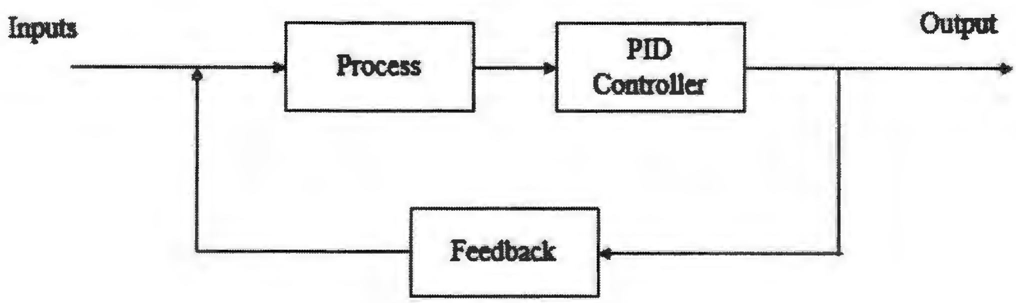

Figure 2. 7 Block diagram of PID Principle

A block diagram or a simple control loop is shown in the figure 2.7. The system has two major components:

- The process
- The controller.

The process has one input that is the manipulated variable also called the control variable.

2.6.2 PID based Model for Hybrid Electric Vehicle

The PID algorithm can be represented as the following equation:

$$u(t) = K(e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + T_d \frac{de(t)}{dt})$$

$e(t) = V_{sch}(t) - V_{vsh}(t)$ = Normal error.

$u(t)$ is the control variable which is the sum of the following three variables:

The *P* term is $ke(t)$ which is proportional to the error.

The *I* term is $K\frac{1}{T_i}\int_0^t e(\tau)d(\tau)$ which is proportional to the integral of the error.

The *D* term is $KT_d\frac{de(t)}{dt}$ which is proportional to the derivative of error.

The transfer function of the PID control algorithm is shown below:

$$G(s) = \frac{U(s)}{E(s)} = K(1 + \frac{1}{T_{is}} + T_{ds})$$

The controller's parameters are gain *K*, integral T_i, and derivative time T_d.

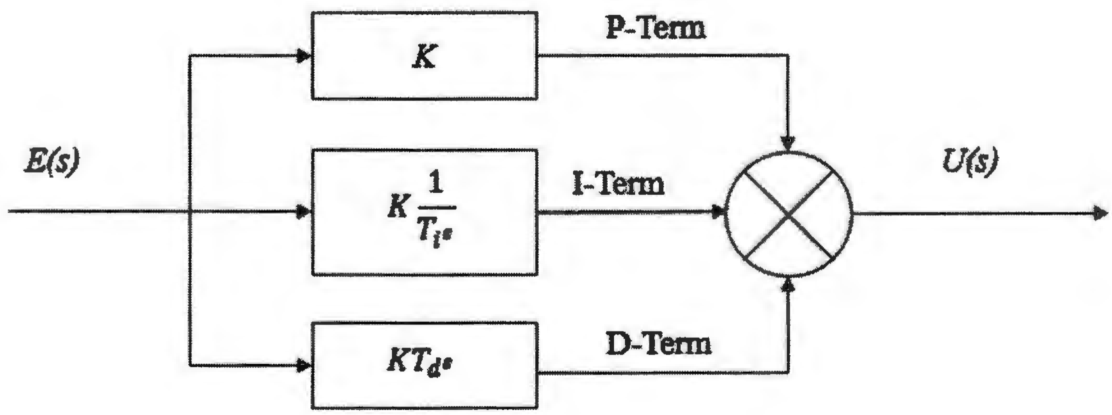

Figure 2. 8 Block Diagram of PID algorithm

According to the control theory, the feedback loop in PID controller is wrecked when control variables reaches the maximum/minimum limit. Then the system operates as an open loop[18]. The block diagram of PID algorithm is shown in the figure 2.8. The PID controller algorithm can be employed for energy management control strategy in HEV.

2.6.3 Driver Model

There are two inputs for driver model i.e. 'vehicle speed' and 'driver desired speed'. There are also two outputs for driver model i.e. percentage of driver pedal and brake pedal. PID controller can be used for driver model and the physical limitations are given below:

$$\tau_{\text{demand}} = \tau_{\text{PID\_Adjusted}} + \tau_{\text{load}}$$

$$\tau_{PID\_Adjusted} = \begin{cases} \max\left\{-\tau_{max}, K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d\frac{de(t)}{dt}\right)\right\} \; if \; K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d\frac{de(t)}{dt}\right) > 0 \\ \min\left\{\tau_{max}, K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d\frac{de(t)}{dt}\right)\right\} \; if \; K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d\frac{de(t)}{dt}\right) \le 0 \end{cases}$$

$$\tau_{load} = \left(m_v\frac{dV_{veh}}{dt} + F_{load}\right).r_{wh}$$

$$F_{load} = F_{rolling} + F_{aero} + F_{grade}$$

$$\tau_{demand\_brake} = min\{0, \tau_{demand}\}$$

$$\tau_{demand\_prop} = max\{0, \tau_{demand}\}$$

$$P_{a\_pct} = \frac{\tau_{demand\_prop}}{\tau_{\max\_prop}(V_{veh})}X100$$

$$P_{brake\_pct} = \frac{\tau_{demand\_brake}}{\tau_{\max\_brake}}X100$$

Symbols	Variable Description
V_{veh}	'Vehicle speed ($^{m}/_{s}$)'

$F_{rolling}, F_{aero}, F_{grade}$	'Rolling resistant', 'Aerodrag resistance', 'Grade weighing forces'
τ_{demand_prop}	'Demand propulsion torque from vehicle'
$\tau_{\max\_prop}$	'Maximum achievable propulsion torque at the current vehicle speed'
$\tau_{\text{demand}\_brake}$	'Vehicle's demand brake torque'
P_{a_pct}	'Position of the acceleration pedal in percentage'
P_{brake_pct}	'Brake pedal position in percent'

2.7 Cost function of Hybrid Electric Vehicle

The HEV can maximize fuel economy as well as minimize the air emissions as compared to the conventional vehicles. The main objective of HEV is to optimize as well as distribute the total power required by the vehicle between the ignition combustion engine and electric motor. Fuel economy, drivability and the emissions are the main parameters considered for decision making to economize the fuel.

The equivalent fuel consumption of ICE and electric motor (EM) is based on the cost function. The added advantage for cost function based configuration is real time as well as utilizing the regenerative braking energy. Power requirement and battery life constraints plays key role in cost minimization procedure[2].

2.7.1 Cost Function

The HEV's cost function of two sources of energy is given below:

$$J = Cost_{engine} + Cost_{motor} + Cost_{batter\_life} + Cost_{energy_{\_balance}} \tag{2.1}$$

$$J = C_{fuel}.Power_{eng} + C_{elec}.Power_{mot} + C_{bat\_life}.Power_{mot} + C_{eneg\_bal}.C_{eneg\_bat}.Power_{mot} \quad (2.2)$$

$$J = C_{fuel}.Power_{eng} + (C_{elect} + C_{bat\_life} + C_{energy\_balance})Power_{mot} \quad (2.3)$$

C_{fuel} = The weight factor for the actual real fuel cost. C_{fuel} can be expressed as below:

$$C_{fuel} = f(Temperature_{eng}, Torque_{eng}, Speed_{eng}) \quad (2.4)$$

The weight factor $C_{electric}$ = The electric energy cost.

$C_{electric}$ can be normalized by equalizing to the fuel cost of the engine at current operating points. The efficiency of electric motor and battery system is also considered as show in equation 2.5.

$$C_{electric} = \frac{\min(C_{fuel})}{\eta_{mot}.\eta_{bat}} \quad (2.5)$$

η_{bat} = Efficiency of the battery system and $\eta_{bat} = \eta_{discharge}$ if $Power_{\mathrm{mot}} \leq 0$ and $\eta_{bat} = \eta_{charge}$ if $Power_{mot} > 0$ in the cost function defined in equation.

η_{mot} = Efficiency of the motor/inverter system at the current operating condition.

C_{bat_life} = The weight factor of the cost of battery life loss and this can written as below:

$$C_{bat\_life} = f(SOC, T, P_{mot}) \quad (2.6)$$

$C_{energy\_balance}$ = The weight factor for the cost. It can understand as 'SOC of the battery system is away from the desired operating setpoint $SOC_{desired}$' and it can be represented as below:

$$C_{energy\_balance} = f(SOC, T, P_{mot}) \quad (2.7)$$

2.7.2 Essential Power

The vehicle's essential power is to drive it. It can be represented as the sum of the engine's output power and motor's output power. The positive power is given by the engine while positive and negative power (In case of regenerative braking) is given by the motor. It can be represented as below:

$$Power_{req\_veh} = Power_{engine} + Power_{motor} \qquad (2.8)$$

$$Power_{engine} \geq 0 \qquad (2.9)$$

2.7.3 Constraints

To fulfill the power demand of the HEV from the ICE and electric motor, some physical limitations/constraints must be under consideration as follows:

2.7.3.1 Energy Storage System (ESS) Constraints

There are two ESS constraints as given below:

i. Maximum Charging Power

'The maximum allowable charging power of ESS' can be expressed as:

$$Power_{\max\_charge\_bar} = f(SOC, T, SOH) \qquad (2.10)$$

$Power_{\max\_charge\_bar}$ = Maximum charging power availability by ESS.

ii. Maximum Discharging Power

'The maximum allowable discharging power availability by ESS' can be written as:

$$Power_{\max\_discharge\_bar} = f(SOC, T, SOH) \qquad (2.11)$$

$Power_{\max\_discharge\_bar}$ = Maximum discharging power availability by ESS.

2.7.3.2 Electric Motor Constraints

There are two electric motor constraints as given below:

i. Maximum Propulsion Power

'The motor' maximum propulsive power constraint' can be expressed as below:

$$Power_{\max\_prop\_mot} = f(T, Speed, Torque) \quad (2.12)$$

$Power_{\max\_prop\_mot}$ = Propulsive power constraint of the electric motor.

ii. Maximum Regenerative Power

The electric motor's maximum regenerative power can be written as:

$$Power_{\max\_regen\_mot} = f(T, Speed, Torque) \quad (2.13)$$

$Power_{\max\_regen\_mot}$ = Regenerative power constraint of the electric motor.

2.7.3.3 Engine Constraint

There is only one engine constraint as given below:

i. Maximum Propulsion Power

'The engine's maximum propulsion power' can be expressed as:

$$Power_{\max\_eng} = f(Speed) \quad (2.14)$$

2.8 Optimum Problem Solution

The overall objective function and the constraints are optimized in such a way so that there is optimal power distribution between the 'ICE' and 'EM' of HEV for best fuel economy at any instant. The overall optimization problem can be written as:

Objective Function

$$J = C_{fuel}.Power_{eng} + (C_{electric} + C_{battery\_life} + C_{energy\_balance}).Power_{motor} \qquad (2.15)$$

Subject to:

$$Power_{engine} + Power_{motor} = Power_{demand\_vehicle} \qquad (2.16)$$

Under the following constraint

i. If $Power_{demand\_vehicle} \geq 0$ $\quad (propulsion)$

$Power_{motor} \leq \min(|Power_{\max\_discha\_bat}|, power_{\max\_pro\_motor}$

$Power_{engine} \leq power_{\max\_engine}$

ii. If $Power_{demand\_veh} < 0$ $\quad (regenerative\ braking)$

$Power_{motor} > \max(-Power_{\max\_charg\_bat}, Power_{\max\_regen\_motor})$

The above defined problem with cost function and constraints can be solved by any one of the heuristic computational techniques. The heuristic computational technique solves the said problem in real time [2].

2.9 Heuristic Computational Techniques

Evolutionary Computation

The evolutionary computation can be used for automated control, gaming, system identification and other complicated and combinational problems.

The main objective is to provide feasibility for the solution of given cost function problem in previous section in real time. The heuristic optimization techniques are used to solve the real-world problems with heuristic algorithms. These techniques are used to solve and understanding of the design issues. Optimization is done by the comparison and programming of some fundamental evolutionary algorithms.

Numerous heuristic tools are proposed that facilitate solving optimization problems given in previous section. These tools are:

- 'Genetic Algorithms and Evolutionary Strategies'
- 'Particle Swarm Optimization'
- 'Differential Evolution'
- 'Stimulated Annealing'
- 'Ant Colony Optimization'

The evolutionary methods can be used for solving the energy management problems in the hybrid electric vehicles. These methods are known as good tools for solving the distribution of energy between two or more energy sources in hybrid electric vehicle. The energy distribution or control strategies problem is solved by the evolutionary techniques in real time.

2.9.1.1 Genetic Algorithms and Evaluation Strategies

The genetic algorithm optimization techniques can be used to optimize the hybrid electric vehicle control strategy. To increase the fuel economy and charge sustainability, the genetic algorithms play a key role. In other words, the hybrid electric vehicle control strategy has non-linear constraints, conflicting design objectives and large amount of coupling parameters, this can be solved by changing the multi objective optimization problem to single objective [19] [20].

Evolution strategies are the strategies with real coded variables. These rely purely on mutation search operator and population size. The main differences between these two are:

Genetic Algorithms	Evolution Strategies
GA operate on the binary strings	Evolution strategies operate directly on floating point vectors
GA mainly rely on the recombination to explore the search space	Evolution strategy uses the mutation as the dominant operator
GA maintain the genetic link	Evolution strategy is the idea of evolution at individual behavior level and the link between individual and its offspring

2.9.1.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a concept for optimizing non-linear functions.

According to the simple mathematical formulae of particle's position and velocity, the given problem can be optimized using PSO. Simplest form of PSO is only two lines of computer code which consists of the velocity and position [21]. The velocity and position equations can be written as:

$$V_{id} = V_{id} + C_1 rand(.)(P_{id} - X_{id}) + C_2 Rand(.)\left(P_{gd} - X_{id}\right)$$

$$X_{id} = X_{id} + V_{id}$$

PSO can be deployed to determine an optimal power management. The threshold parameters can be optimized by using the PSO algorithm. The real time optimal solution can be determined from the driving cycle pattern optimization [22]. As the threshold parameters are very sensitive to the driving cycle so the dynamic optimal parameter algorithm can be designed to get optimal solution. Total energy cost (oil and electricity) can be minimized by setting the objective function minimal [23].

2.9.1.3 Differential Evolution

Differential Evolution (DE) is the method that optimizes the problem by iteratively trying to improve the candidate solution regarding given measure quality. Such methods are commonly known as metaheuristic computational techniques. The metaheuristic techniques do not guarantee for optimal solution.

To increase fuel economy, reduce emissions and to maintain battery life of hybrid electric vehicle, the DE algorithm can be used. The optimal control parameter of the energy management strategy can be purely optimized by using this algorithm [24] .

2.9.1.4 Simulated Annealing

Simulated annealing (SA) refers to implement the real-life problem or process into machine. SA is a method for solving unconstrained and boundary constrained memory problem. SA aims to finding a good solution to an optimization problem. SA maximize or minimize a solution set as per the environment conditions. SA avoids being caught in local maxima. The simulated annealing algorithm have following steps:

1. Generate random solution

2. Calculate path using cost function
3. Generate the random neighboring solution
4. Calculate the new solution cost
5. Compare if $C_{new} < C_{old}$ then accept and if $C_{new} > C_{old}$ then reject.
6. Repeat step 3 to step 5 until the acceptable solution is found.

SA is used to solve the energy and pollution problems on a large context. SA algorithm can be used in hybrid electric vehicle to increase the fuel economy and reduce the emissions[21].

2.9.1.5 Ant Colony Optimization

The ant colony optimization (ACO) algorithm can be used for solving the computational problems. This is a metaheuristic technique to find the solutions. ACO studies artificial systems that take inspiration from the behavior of real ant colonies and which are used to solve discrete optimization problems. The real ants have limited individual capabilities i.e. rudimentary sight, limited visual and auditory communication and not capable of achieving complex tasks on their own. The real ants are capable of impressive group results i.e. nest building and defense, forming bridges and cooperatively carrying large items, sorting food items, foraging (Shortest path selection) for food sources. The real ants have self-organization that can produce complex, purposeful structures and behavior without the need for planning or direct communication. The communication between ants is based on the chemical produced by ants i.e. pheromones. The social behavior of the ants is driven by the trail pheromone. This can be used to mark a path because others can follow. Real ants deposit the pheromone while walking between food sources and the nest. The ants follow trails with higher pheromone levels with a higher probability than trails with lower pheromone levels. As more ants use a path, the pheromone trail grows stronger. This results in autocatalytic behavior, as more ants follow the trail, the trail becomes increasingly attractive. The probability of choosing the short path when starting at point *i* with stochastic model can be written as:

$$P_{is}(t) = \frac{(t_s + \Phi_{is}(t))\alpha}{(t_s + \Phi_{is}(t))^{\alpha} + (t_s + \Phi_{il}(t))^{\alpha}}$$

Where: $i \varepsilon$ [A, C], $t_s = \frac{l_s}{v}$ and $\Phi_{is}(t) \propto k_{is}(t)$

$\Phi_{is}(t)$ Total amount of pheromone on the branch

$k_{is}(t)$ Total amount of ants who have used the branch

As energy management control strategy of hybrid electric vehicle has a great influence on the vehicle fuel consumption as compared to the conventional vehicle. The control parameters of the hybrid electric vehicle can be optimized by using the ACO algorithm. The equivalent fuel consumption minimization strategy can be implemented by using the ACO algorithm [21].

2.10 Chapter Summary

The architecture of the hybrid electric vehicle depends on the components connectivity. The series parallel architecture is complex design while the series and parallel hybrid are simple architectures. Hybrid electric vehicle components variables are set to optimum values. The control strategies are energy management strategies which control the power distribution in the hybrid electric vehicles to get optimum solutions. The control strategies are divided into two parts i.e. rule-based and model based control strategies. The control strategies are configured in such a way so that the optimum distribution of energy is obtained from energy sources. The cost function based energy management strategy and the equivalent minimization between ignition combustion engine and electric motor are considered which operate in the real-time controlling and energy distribution. The cost function including the constraints is considered to obtain the optimum solution between the two sources of energy. The heuristic computational techniques are the alternative methods to distribute the energy demand of hybrid electric vehicle between the ignition combustion engine and electric motor. The heuristic computational techniques are considered as fast and real-time results given strategies.

Chapter 3

Power Electronics in Hybrid Electric Vehicles

The power electronics devices are widely used in the 'hybrid electric vehicle, architecture. The converters and inverters are basic devices used. In the hybrid electric vehicles, inverter and converter are used that changes the alternating current (AC) to direct current (DC) and direct current (DC) to direct current (DC).

3.1 Principle

These can be defined as the studies of 'converters' which process and tunes the power flow via electronic ways. In these devices, semiconductors tune power diodes, transistors used in insulated gates (IGBTs). While 'metal oxide field effect transistors' (MOSFETs) are used to control the flow of current. These switches play important role for controlling.

The distinctive power converter consists of four segments:

- First segment consists of switching and peripheral circuits
- Second segment consists of filtering circuits
- Third circuit consists of control circuits and feedback
- Fourth segment consists of an optional user interface

Power electronics is used to enable technologies pushing the change from typical gasoline and diesel engines runes vehicles to electronic vehicles. Hybrid electric vehicle powertrain for understanding power electronics circuits is shown in the figure 3.1.

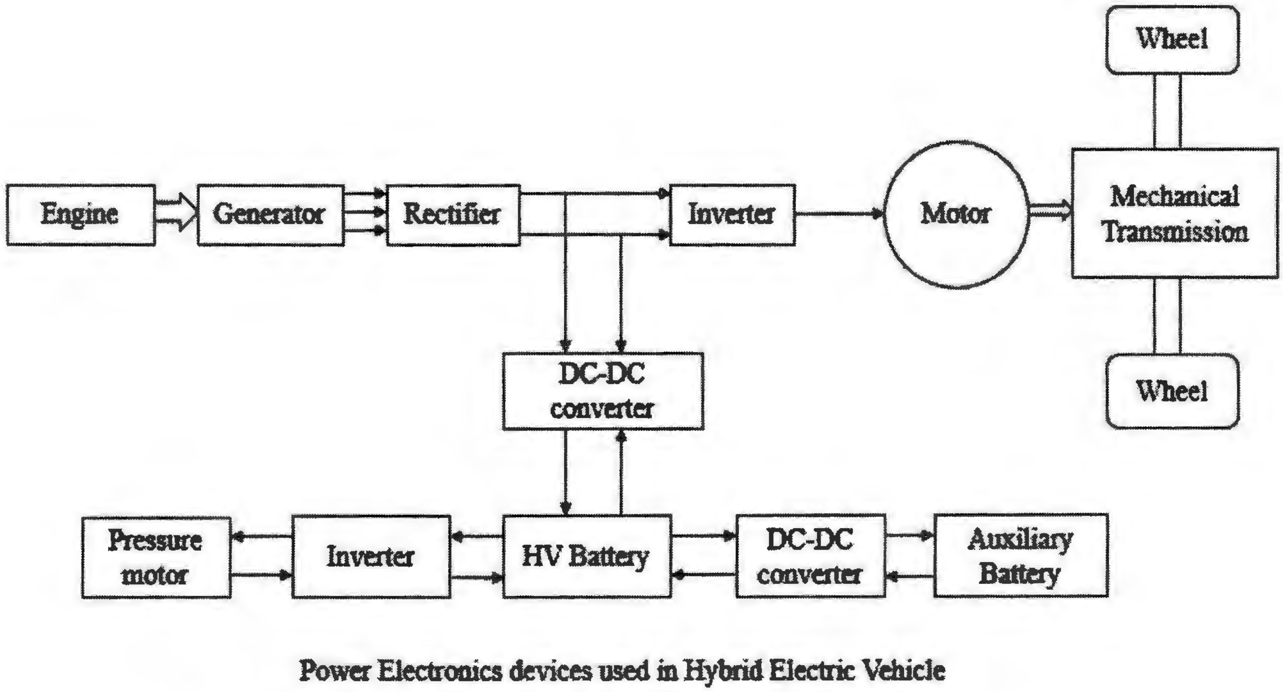

Figure 3. 1 Power electronic devices used in hybrid electric vehicles

In it, a permanent magnet produce harmony in generator used in internal combustion engine. Three form voltage in this generator produces changing voltage and frequency according to the requirement. Output required a rectifier thus changed in direct current and voltage as shown in the figure 3.1.

The induction motor drives the front wheels and induction motor. Its working is tuned a 'voltage source inverter' (VSI) or a 'current source inverter' (CSI). In this way, energy storing system (ESS) establish a connection with current bus. ESS is connected via generator and rectifier output as well as inverter. So, existence of bi-directional Dc-Dc converter tunes the charging or discharging of the battery as well as tunes the Dc bus voltage as shown in figure 3.1.

The engine drives the air conditioning compressor via a belt in conventional vehicles. While engine is shut down often and go through driving pattern in hybrid electric vehicles. When engine is in off condition then electric motor drives the air conditioner compressor by another battery. 'Vehicle's hydraulic system' consists of brakes having frictional and power tuning properties. This system is controlled and driven by the hydraulic pressure pump electronically. Motor which is air conditioned as well as of compressor are usually brushless give direction to current motors via an inverter [2].

The 14V battery runs the auxiliary components like 'headlights', 'wipers as well as entertainment system. There is no alternator exists in the advanced hybrid electric vehicles so high voltage is required to charge the 14V battery. In other words, we can say that even if an alternator exists and engine is in off condition yet 14V battery is drained rapidly. So, there must be DC-DC converter that can charge the battery in time.

There are few common feature of power converters that are implied in hybrid electric vehicles and industrial commercial or residential applications.

The design of hybrid electric vehicle power electronics circuits includes:

- **'Electrical design':** It is design that contains of switching circuit and tuned circuit as well as tuned frequency to optimize it.
- **'Control algorithm design':** It consists of inducing tuned algorithm to attain required voltage current and frequency as output source and to attain bi directional power flow according to the requirement.
- **'Magnetic design':** It consists of inductor as well as transformer and some other parts like capacitors that are required for filtering, to switch on and driving unit.

- **'Electromagnet circuit (EMC) design':** It consists of understanding the interference problems of electromagnetic issues, to analyze tuning transient as well as circuit outline that reduces inductance as well as capacitance.

- **'Mechanical and thermal design':** It contains the models of power loss devices as well as magnetic parts, cooling parts, heating sink and integration part of electronic power unit [2].

3.2 Kinds of power converters

'Power converters' can be categorized in different input and output. Power converters are typically divided into four kinds as given follow

1. Dc-Dc converter
2. Dc-Ac inverter
3. Ac-Dc rectifier
4. Ac-Ac Cyclo-converter

First three kinds of converters are utilized in hybrid electric vehicles while Ac-Ac cyclo-converter is only implied to tune the voltage and frequency magnitude in large motors. Hybrid electric vehicle contains various converters of different kinds according to the requirement. Selection of power converter depends on power train configuration and level of hybridization.

It consists of semiconductor devices required to power and peripheral parts.

In hybrid electric vehicles, semiconductors are used to turn on or at required frequency range. Both types like MOSFESts and IGBts are implied in power converters of hybrid electric vehicles depends upon the voltage of the system. Usually two type of circuits are implied [2] as given follow

- **Filter:** In converters, relevant to power electronic have usually LC low pass filter. It is used to filter high frequency parts of the required voltage. While low frequency parts or current is passed to side of the load.
- **Control and feedback:** It classically involves the application of microcontroller as well as different types of sensors. Powertrain uses of hybrid electric vehicle involves the tuned torque feedback. Current feedback is essential necessity.

3.3 Rectifiers used in Hybrid Electric Vehicles

Rectifiers are mostly implied to change alternating input to direct current output, while tuned rectifiers is present. These are usually implied in automotive uses. Uncontrolled passive rectifiers are used due to their unique aspects in hybrid electric vehicle applications. These are:

- Ideal Rectifiers
- Practical Rectifiers
- Single Phase Rectifiers
- Voltage Ripple

3.4 Buck Converter used in Hybrid Electric Vehicles

In buck converter, high voltage Dc input is converted into low voltage Dc output. Most common application of buck converter is to reduce voltage of hybrid battery in hybrid electric vehicle from 200-400 V to 14 voltage that is used in auxiliary batteries. Novelty of this converter is large input and output voltage difference as well as small duty ratio that are required according to tunced switching.

There are two topologies for regenerative braking i.e. one of them is without Dc-Dc converter and other is with Dc-Dc converter.

When Dc-Dc converter is not available then Dc bus voltage fluctuates during changes between motor and brakes. In other sense, the system which consists of Dc-Dc converter via invertor and motor bus as well as battery, can have Dc bus voltage to be maintained at constant value.

3.5 Voltage and Current Source Inverter

Voltage inverters are mostly implied in hybrid vehicles to tune electric motors as well as generators. Voltage invertor output is tuned via mean pulse changed signals to generate sinusoidal waveforms.

3.6 Thermal Management of Hybrid Electric Vehicle Power Electronics

Power electronics devices have power losses 2-4KW at power level of 100KW even with an efficiency of 98%. Heat generated in hybrid vehicles using powertrain motors, power electronic circuits as well as bi directional Dc Dc power converter is of great value.

3.7 Energy Storage System

In hybrid electric vehicles, energy storage system has great value. It usually consists of pack that store energy like voltage, temperature measurement system, a cell that balance the circuit as well as cooling system. The main aim of storage system is to change chemical energy into electrical and alternatively by use of oxidation and reduction reactions according to electrochemical series. It has also ability to give as well as take energy from hybrid electric vehicle according to the requirement. In purely electric vehicles, energy is stored from repeated brakes as well as from electric grid via plug in charger. The main necessity of storage system is safety, efficiency, reliability as well as cost effectiveness. Different need to construct hybrid electric vehicles are changed like its configuration, speed, time of acceleration as well as range to be covered. It also depends on the design operating modes.

An energy storage system can be selected by considering following variables:

- Battery Pack Capacity 'Ampere hours'
- 'Peak and continuous charge and discharge power capabilities (KW)'
- 'Maximum and minimum operating voltage (V)'
- 'Maximum and minimum operating current (A)'
- 'Maximum and minimum operating temperature (C)'
- 'Cold cranking power capability (KW)'
- 'Maximum self-discharge rate (Watt hour/day)'
- 'Allowable state of charge operating range (%)'
- 'Battery calendar life (Years)'
- 'Battery cycle life'
- 'Battery pack mass (Kg)'
- 'Current, voltage and temperature measurement sampling rate and accuracy'
- 'State of charge estimation accuracy'

3.8 Energy sources for Hybrid electric vehicle

Hybrid electric vehicle basically required a portable source of electrical energy. That source converts the mechanical energy using electric motor for vehicle driving. Energy is stored in cell in form of chemical energy. It is converted into electrical energy according to the requirement. Specific type of energy is present in different every energy source. Batteries are preferable sources of energy that are used in electric vehicles as well they are portable sources of energy.

The selection of batteries depends upon specific energy, specific power and operating life. The workable life of battery can be defined as number of discharged cycles that are attained in its life as well as number of year of service that are expected in specific applications. The required characteristics of battery in hybrid electric vehicles are need of high speed, high amount of energy, high capacity to be charged and discharged, braking regeneration as well as long life cycle. Batteries are made of unit cells. In cell energy is stored in form of chemical energy that is converted into electrical energy on requirement. Cell in battery are kept in enclosure to keep together. Meanwhile battery pack is consisting of different battery modules. Thus, battery modules are come in contact in series as well as in parallel manner to attain the required voltage and energy. Thus, give the required power to the electronic system. Amount of energy stored in battery is actually the difference of energy present in chemical components in charged state and discharged state. Amount of energy present in cell in chemical form in converted into electrical energy on need by implying the operation of components of unit cell. Components of unit cell include anode and cathode as well as separators and different electrolytes. Oxidation and reduction reactions take place at relevant electrodes and thus electrons are released or bonded according to the requirement. When chemical reactions take place at relevant electrode, it induces flow of electrons from one electrode to another electrode when battery is in working position.

Usually two types of batteries are being reported. One of them is primary battery type and other one is secondary battery type.

Primary batteries are those batteries that cannot be recharged and are constructed in such a way that only single discharge can run in them. While those batteries that can be recharged by flow of current in opposite direction to that of direction used during discharging are called secondary batteries. Secondary batteries are usually implied in hybrid electric vehicles.

3.9 Chapter Summary

The power electronics devices play an important role for architecture and design of the hybrid electric vehicles. The converters, inverters and rectifiers are the key devices used in hybrid electric vehicles. The power electronics devices technology is used to shift the conventional vehicles to hybrid electric vehicles. Generator and induction motors are installed in hybrid electric vehicles according to the design of driving i.e. front wheel drive, rare wheel drive or four-wheel drive. To keep the generator and induction motor to optimum level, the VSI and CSI are used. Control algorithm plays an important role for controlling these. The regenerative braking energy is captured in installed energy storage system by using inverters and converters devices.

Chapter 4

Advanced vehicle simulator

Advanced vehicle simulator (ADVISOR) represents the model, data and text files that are used with Matlab and Simulink. It is used to analyze rapidly the performance and fuel economy for a conventional and hybrid vehicle. It acts as backbone for analysis of user defined drivetrain parts as well as a starting point of vehicle data. This analysis takes full advantage of flexibility of Simulink as well as analytical power of Matlab. Many advantages that can be get from ADVISOR are as follow

- It can be used to estimate the fuel economy of different vehicles which have not been constructed yet.
- It can also be used to estimate the use as well as loss of energy during drivetrain of hybrid or conventional vehicles.
- It can be used for comparative analysis of tailpipe emissions produced during different cycles.
- It can be used to evaluate the way to manage fuel converter strategy of hybrid vehicles.
- Optimize the conditions so that maximum performance can be gained at expense of low fuel.

4.1 ADVISOR Working

4.1.1 File interaction and Data flow

Schematic diagram shows the data flow in the ADVISOR file system is shown in the figure 4.1.

The four main types are:

- 'Input Scripts': These define variables in the workspace and call other inputs scripts.
- 'Block Diagrams': These are Simulink files containing the equations used to compute outputs such as fuel use from inputs such as an engine map. They are the models.
- 'Output Scripts': These post process the model outputs by querying the workspace. These may include plotting routines or error checking routines.
- 'Control Scripts': These may both develop inputs and process outputs.

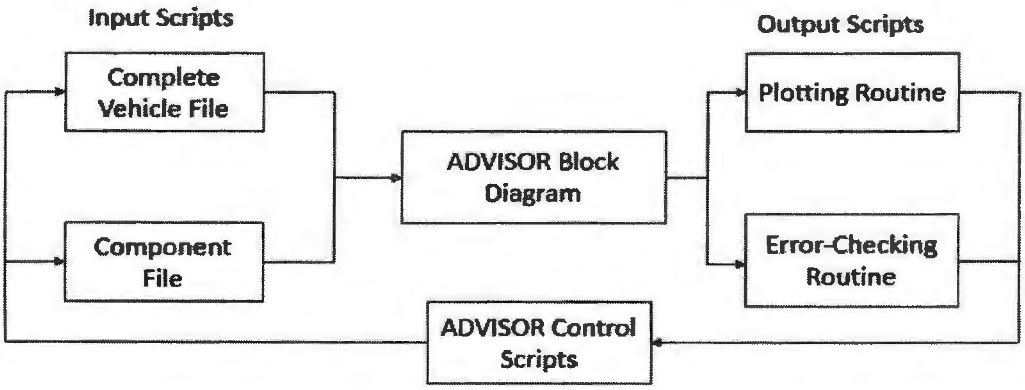

Figure 4. 1 Schematic Diagram of ADVISOR

4.1.2 Compatibility and intended applications

ADVISOR imply basics of physics to model the present of future vehicles. It gives prediction about the performance of vehicles that have not been constructed yet. It also provides the answer of such questions like that 'what will be characteristics of a car which are going to construct. ADVISOR gives prediction about use of fuel, emission tailpipe, to accelerate performance as well as ability. Usually, two steps which are taken are as such

- First, to get estimation of components as well as overall data of vehicle.

- Second is to get prescription of speed vs time along with road characteristics that cars must follow.

ADVISOR make sure that data meets the cycle to get best of its ability. It gives ability to measure or to offer ability to get data about magnitude of every torque, speed, voltage, current as well as power of all components of car. AVDISOR also provides the answer of the following questions

- Does the vehicle have ability to get the speed trace?
- How much energy or fuel will be consumed to get the required attempt?
- How the charge of batteries will undergo fluctuation during the whole cycle?
- What will be the peak powers attained by drivetrain components?
- What will be the torques and speeds distribution during working?
- What will be average transmission efficiency?

From an alternative definition of vehicle or driven cycle, user can get the answer of following questions

- At which type of road, vehicles can maintain 55 mph adequately?
- Which type of small engine can accelerate the vehicle from 0 to 60 mph per 12 seconds?
- What will be the final ratios which will minimize the fuel consumption while maintaining 40 to 60 mph within 3 seconds?
- What will be the fuel economy to mass relevant to aerodynamic drag as well as vehicle or different variables components?

4.2 Limitations

4.2.1 Limitations for analysis

ADVISOR is designed as an analytical tool rather than detailed design tool. The components of ADVISOR are quasi static in characteristics and have not ability to detect phenomenon which occur in less than tenth part of second. Advisor cannot be used to capture physical vibrations, electric field and dynamic phenomenon. As analytical tool, ADVISOR takes desired speed as input while determine the torque, speed for certain vehicle. Because of these characteristics, ADVISOR is called as backward facing vehicle simulation. While characteristics of forward facing vehicle, simulation are as model of a driver that senses the required speed and as a result show response to an accelerator or a brake position. This sort of simulation is designated as suited to the design of control system.

ADVISOR is most suitable for evaluation as well as to design controlled logic and energy management technique. It means when output torque of engine is low while state of battery charge is high results in turn off the engine. ADVISOR work with control logic that is wanted for a vehicle. The way to implant control system into control logic in hardware shows how vehicle do what is wanted to do. It is not original aim of ADVISOR applications.

4.2.2 Power bus for power transfer

When electric components come in communication with each other, ADVISOR deals with power and do not work with voltage of current. It only works with voltage bus.

4.2.3 Drive axle in single axle only

It is assumed that front axle is the only derive axle according to vehicle dynamic calculations. Simple steps can be done to correct the calculation for weight transfer in rear drive vehicles.

4.3 Hybrid Electric Vehicle Model

The hybrid electric vehicle model is shown in the figure 4.2

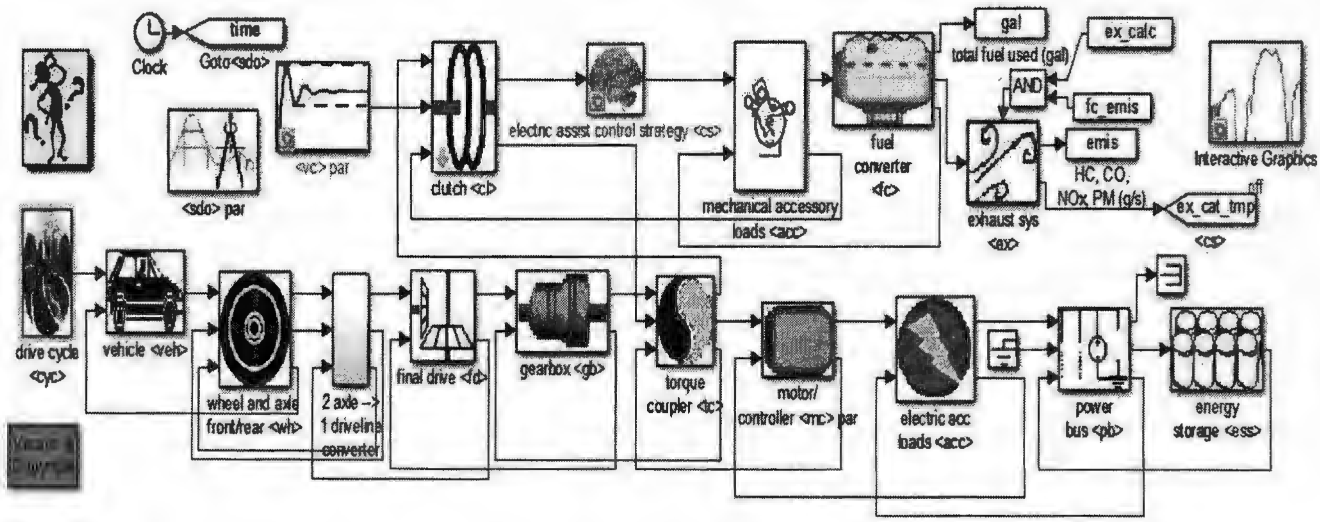

Figure 4. 2 Hybrid Electric Vehicle Model

4.3.1 Defining a vehicle

Starting window takes to the input figure where variables can be set accordingly. The input figure opens and sees the default values for a specific vehicle. Moreover, the values can be customized by using starting window.

4.3.2 Drivetrain selection

It is possible to select drivetrain configuration of vehicle from drivetrain popup Manu. This will induce schematic vehicle configuration in left part of figure to be changed accordingly. It also indicates that which component will be available for selection of drivetrain as shown in the figure 4.3.

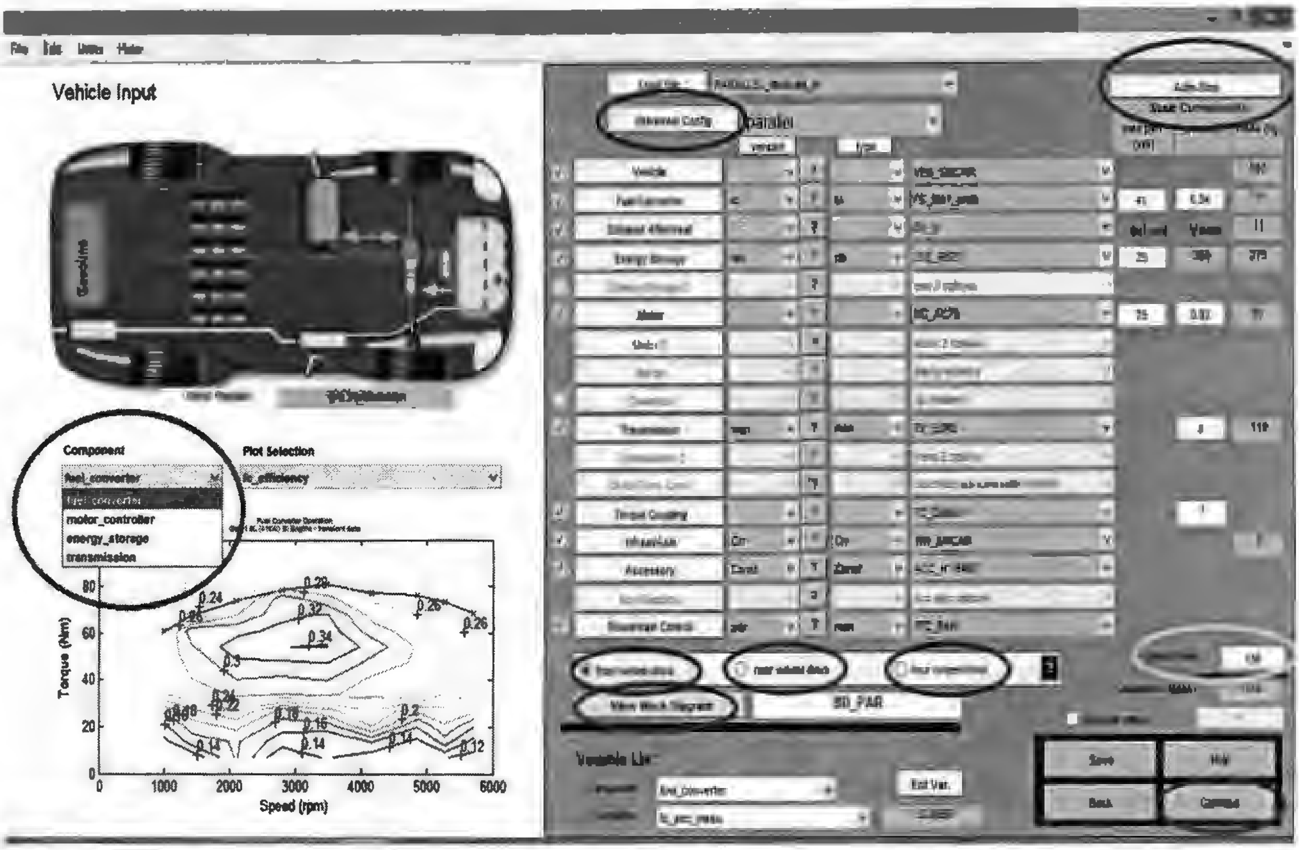

Figure 4. 3 Drive Train Selection

4.3.3 Selecting components

When drivetrain configuration is selected, then all parts of vehicle can be selected by popup manu or just click on the part in figure. On left of component popup manu pushbutton is present that permits to add or delete parts by selecting the relevant list in m-files. Access can be attained to m-files of specific part for viewing or to modify by selecting either from component pushbutton or click on the relevant part in picture.

4.3.4 Editing variables

When all required parts of vehicle in figure will be selected, scalar input variables can be modified according to the requirement. One method to do this is to do with list of variables present at the bottom of the figure or on variables edit button. First step is selection of variable and then to click on edit button to induce changes. By doing this, default value is shown as reference. All the variables being altered can be viewed by selecting view all button. This can also be done by just clicking on help button and brief description can be seen as well as units that are used for input variables.

A second way to edit variables is to put values in edit box next to the required part of figure. Another way to edit mass of vehicle is to use the override mass button. Value that is putted in edited box is used while calculated mass is ignore.

4.3.5 Loading and saving vehicle configuration

Another way that can be adopted to edit variables is to type desired value in the edit box next to required component of the vehicle figure. Left portion of the figure while at its bottom, popup manu and axes is present that have ability to show information relevant to component like maps efficiency, maps efficiencies, and maps fuel use. These values are plotted with their maximum torque envelope where suitable. By clicking on component button, component file can be viewed easily.

4.3.6 Auto size

Auto size button is used by selected vehicles to adjust vehicle parameters till it meets the required acceleration and grade ability. The parameters that can be altered by using this button are fuel 'converter torque', 'motor controller torque', 'number of energy storage systems modules' and 'mass of vehicles' as shown in the figure 4.4.

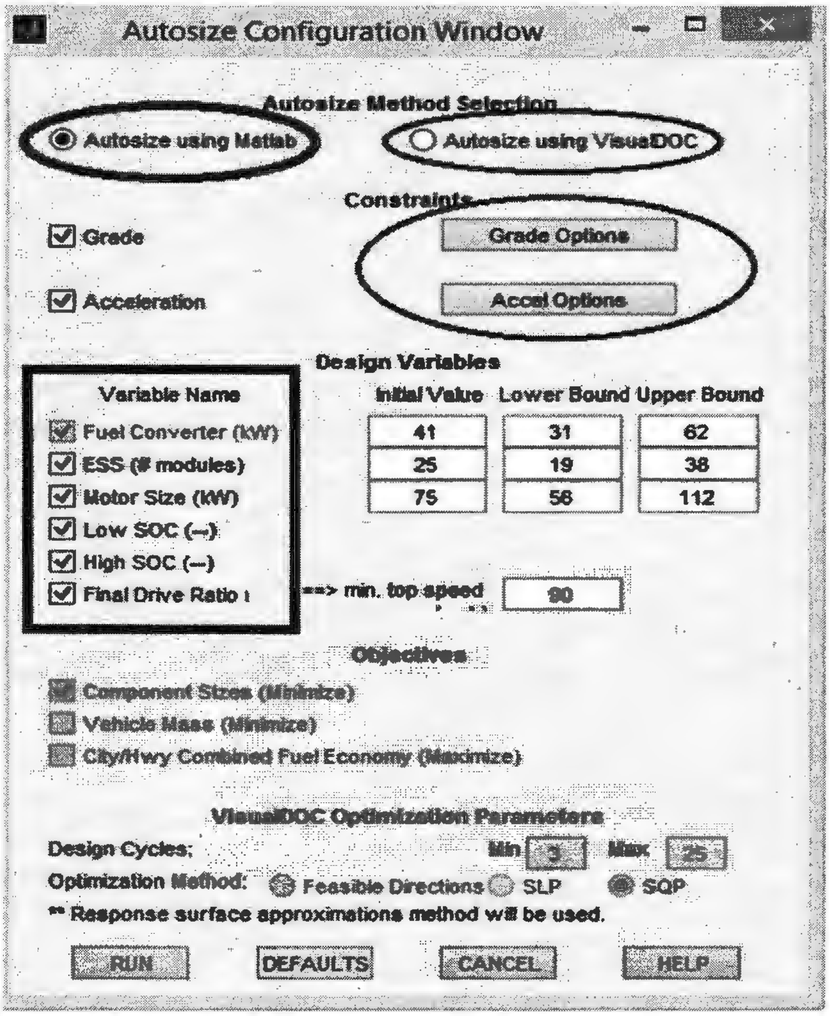

Figure 4. 4 Auto size Selection

4.3.7 Back and continue buttons

Back button takes to opening screen while all unsaved information's can be lost while continue button can lead to simulation setup in figure.

4.3.7 Running a simulation

Simulation setup in figure give many information about the method how currently defined vehicles can be tested.

4.3.8 Drive cycle selection

When drive cycle radio is selected then it uses pulldown menu from a list of available driving cycles. It can also be used to calculate that how many time cycles can be repeated along with SOC corrections. It can be used to set initial conditions. The filtering tends to smooth out the selected cycle as shown in figure 4.5.

4.3.9 Trip builder

This functionality can be used to create a cycle that combines different cycles back to back. This new formatted cycle can be saved as normal cycle and can be operated as such as shown in figure 4.5.

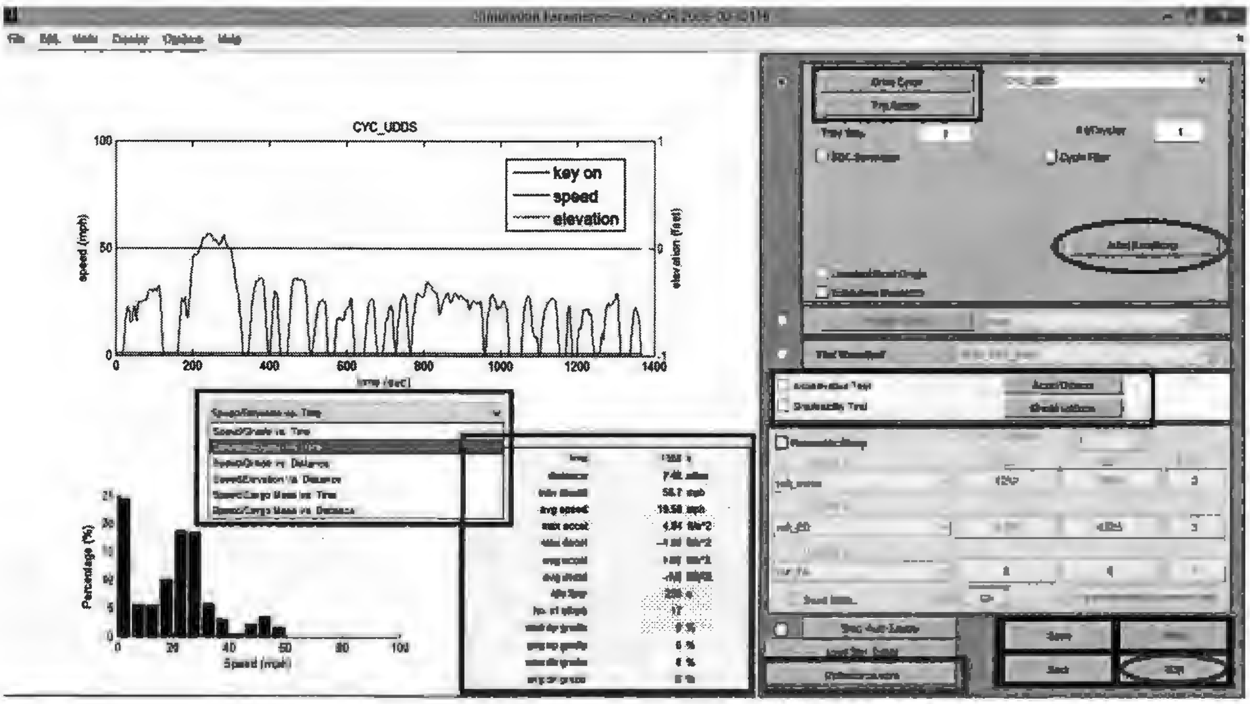

Figure 4. 5 Drive cycle and Trip builder selection

4.3.10 Auxiliary loads

Graphical interface can be brought by selecting this button and different auxiliary loads can be selected and alternatively on/off times relevant to drive cycle [25].

4.3.11 SOC correction

Two SOC correct options are reported as follow

- Liner
- Zero delta

Two simulations are run in linear SOC correction. One of them give positive change in charge state while second one gives negative change. The corrected value of variables is used to attain a linear fit between two data points. Zero delta correction sets the initial state of SOC till simulation run produces zero change in SOC while 0.5 % tolerance band is attained.

4.3.12 Constant road grade

It can be used to run derive cycle by selecting check box while constant road grade is used in place of drive cycle's elevation profile.

4.3.13 Interactive simulation

Real time interactive simulation interface can be activated by selecting interactive simulation check box.

4.3.14 Multiple cycle

Different cycles can be operated with same initial conditions while can be speed up using this cycle. Multiple cycles are used to save information relevant to setup including initial conditions. After that each cycle is operated and results are saved. From figure, different results can be attained or accessed from result list as shown in the figure 4.6.

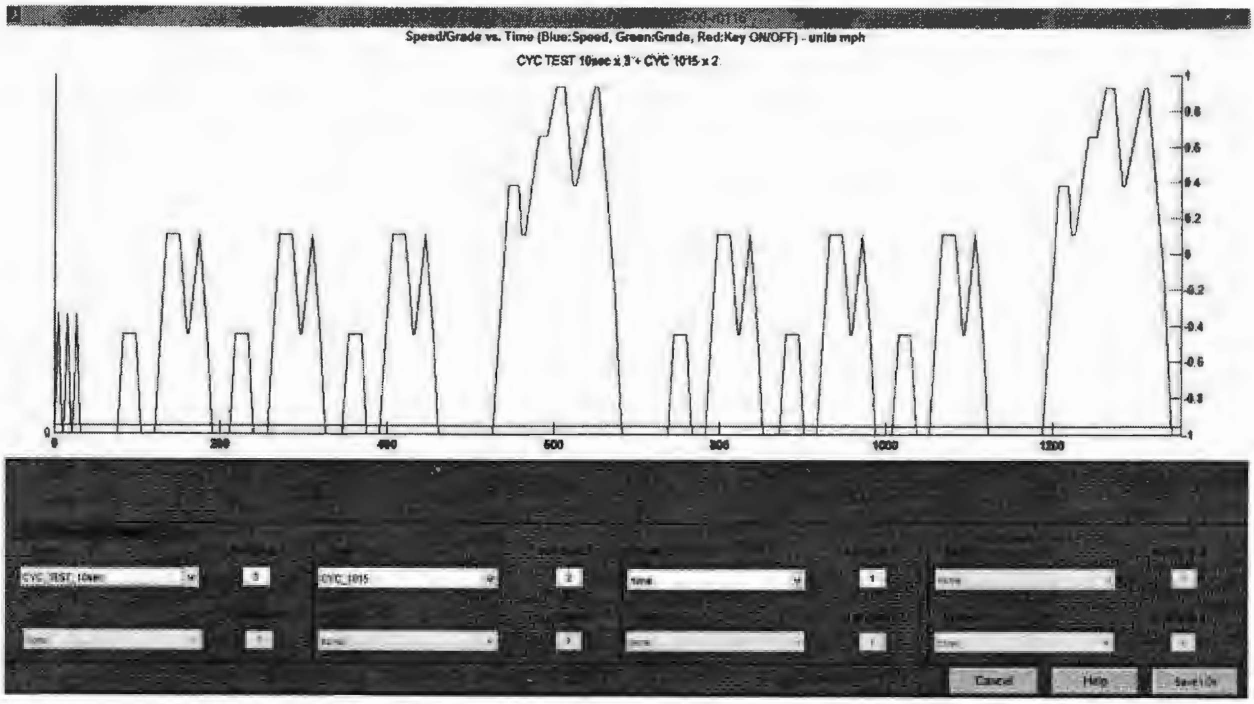

Figure 4. 6 Multiple drive cycle selection

4.3.15 Test procedure

Test procedure button can be used to pull down menu to select the kind of test to be run when test procedure button is selected.

4.3.16 Constraints

Constraints can be selected as selected as required regarding environmental conditions as shown in figure 4.7.

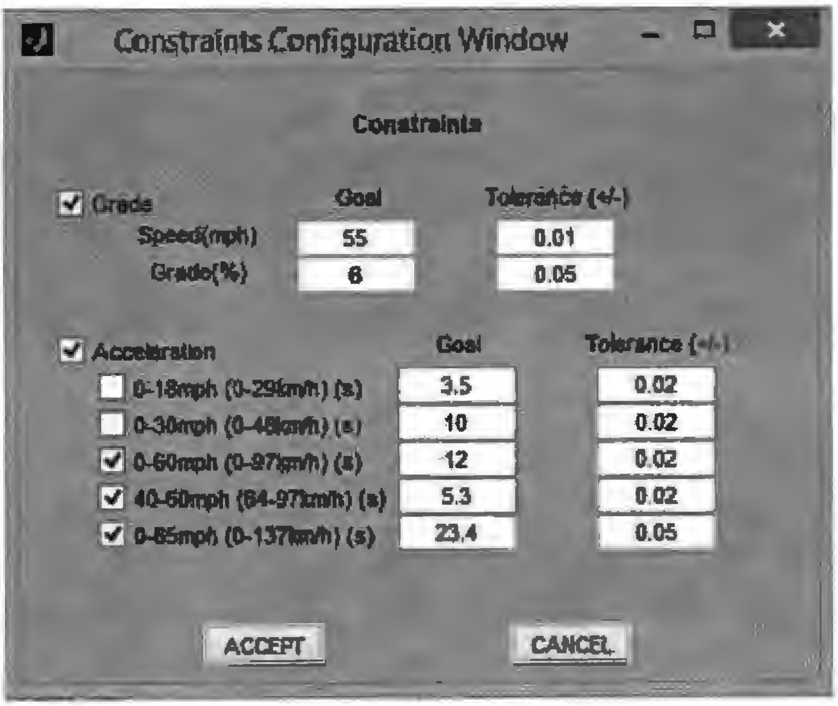

Figure 4. 7 Constraints selection

4.3.17 Acceleration test

By selecting this box, acceleration test is operated along with choose cycle. Acceleration time, maximum acceleration and travelled distance in time interval of 5 seconds can be displayed in figure. This test is used to run along with chosen cycle. To check second output of acceleration test, CYC-ACCEL is selected from cycle menu as shown in the figure 4.8.

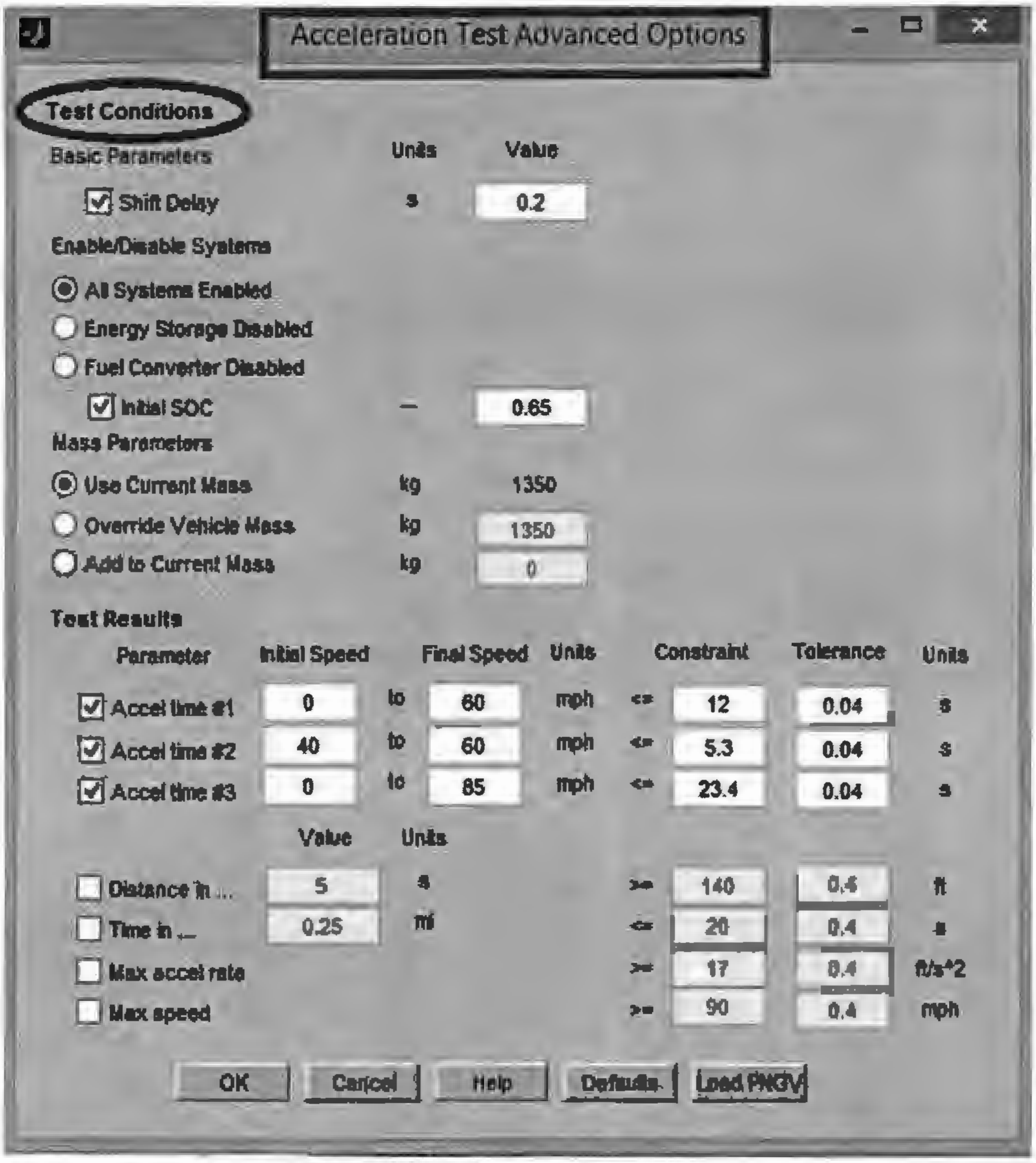

Figure 4. 8 Acceleration Test

4.3.18 Grade ability test

When grade ability test box is selected, grade ability test is operated along with chosen cycle. The grade which is displayed in results are results appeared at input with maximum grade maintainability as shown in figure 4.9.

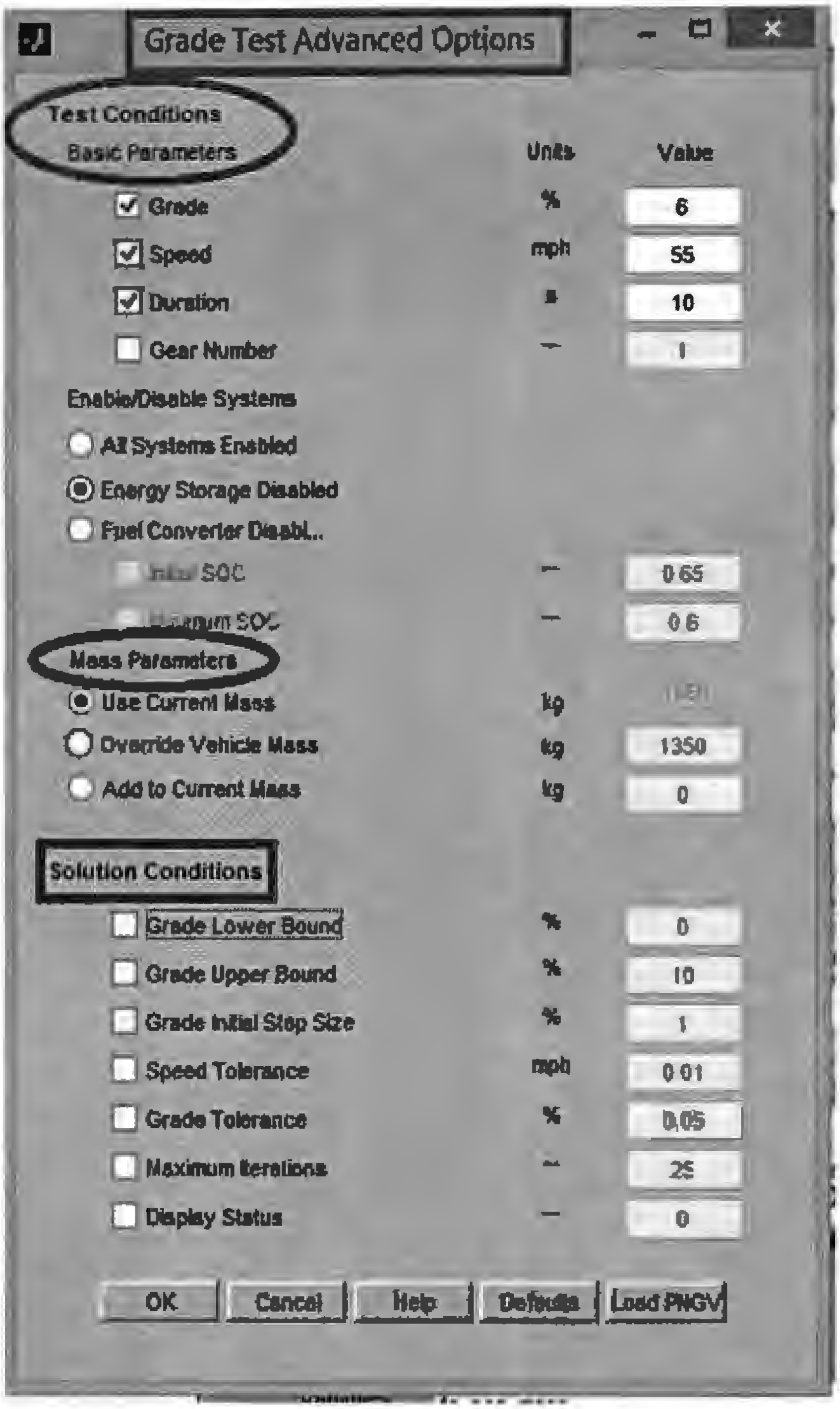

Figure 4. 9 Grade variables selection

4.3.19 Optimizing Control Strategy (CS) Variables

The main purpose of the control strategy optimization routine is to find out the set of control strategy parameters. These parameters satisfy the specified objectives and constraints. It is achieved by adjusting the control strategy parameters and reevaluating the performance procedure until the fulfillment of specified parameters. There are two types of functions in ADVISOR. The first one is Matlab based and the second one is VisualDOC optimization software. Both control strategy optimization routine provides only a single solution to the optimization problem. The control strategy optimization routine required the performance i.e. grade and acceleration test and constraint information as well as auto sizing routine. To implement the Control strategy, "optimize CS variables" push button opens the control strategy optimization setup window. Here we can set the design variable used to optimize for the selected objectives and constraints as shown in figure 4.10.

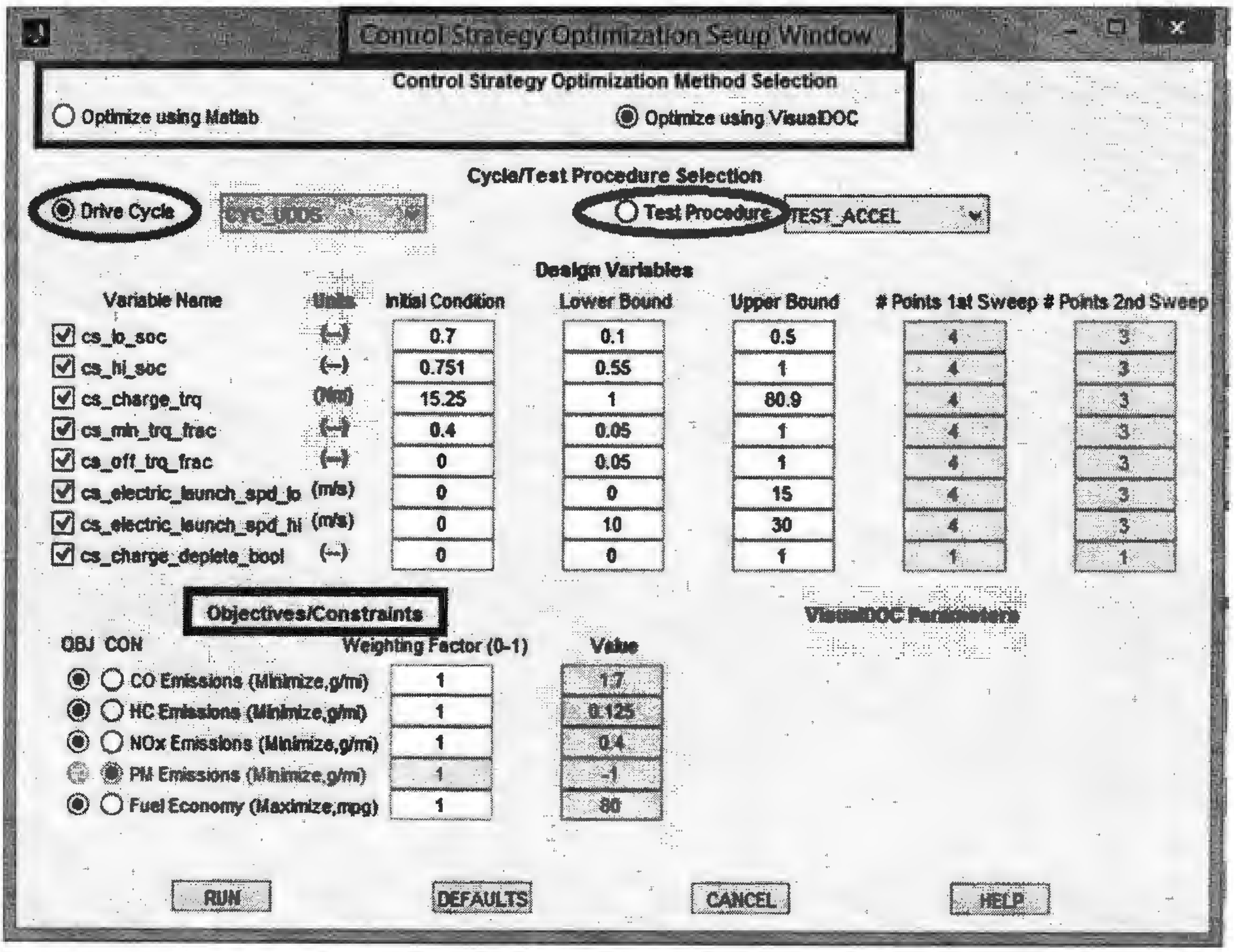

Figure 4. 10 Control Strategy Optimization variables

4.3.20 Save

This option saves the simulation setup.

4.3.21 Run

While to run simulation, the run button is pressed and wait for the results figure to popup.

4.3.22 Hybridization Rate

The hybridization rate can be selected between 0 to 1 as required as shown in the figure 4.11.

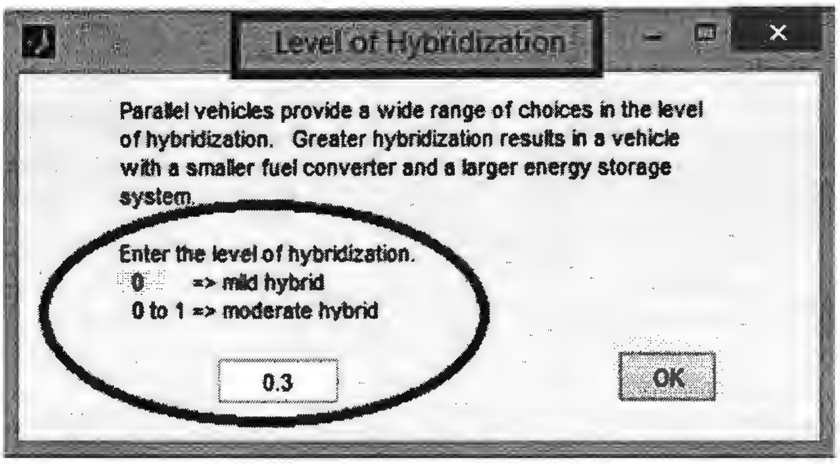

Figure 4. 11 Level of Hybridization

4.4 Chapter Summary

ADVISOR is used to analyze the performance, fuel economy low emission rapidly for the conventional and hybrid electric vehicles. It is compatible with the simulink and matlab environment. It is used to estimate the fuel economy and low emissions by selectig the desired energy management control strategy. It is used for comparative analysis of emissions produced during settled cycles. It can be used to evaluate the method to manage fuel converter strategy of hybrid vehicles. It can be used to optimize the conditions so that maximum performance can be gained at expense of low fuel.

Chapter 5

Results and Discussions

Increasing concerns about the environmental problems like in Pakistan, such as the global warming and greenhouse emissions as well as the predicted shortage of the oil supplies have made the energy efficiency and reduced emissions a primary selling point for the automobiles and concerns for many governments. The hybrid electric vehicles have become extremely popular and are known as the good technology. The hybrid electric vehicles have more advantages as compared to the conventional vehicles but the complexity and increased cost is bothering the hybrid electric vehicle engineers and these vehicles are not affordable to common man.

The total power demanded by the vehicle is split into energy sources via energy management control strategy. The effective and efficient control strategies are those which results in real-time. There are two major control strategies used in hybrid electric vehicles. The rule-based strategies and the model based strategies are proposed in this thesis. The rule based strategies are further divided into deterministic and fuzzy logic based strategies. The model based strategies are also divided into two types i.e. numerical approach and analytical approach. The numerical approach consists of the dynamic programming and stochastic dynamic programming while the analytical approach contains the pontrygin's minimum principle and equivalent consumption control strategy.

Heuristic computational techniques can also be used for optimal solution of the control strategy problem. These techniques based on the algorithm. These techniques are very fruitful for the real-time power split between the ignition combustion engine and the electric motor. So, the cost of the fuel used in hybrid electric vehicle is minimized. Further, heuristic computational techniques take short time to implement and to show results.

Advanced Vehicle Simulator (ADVISOR-Software) is used to find the optimal usage of the energy sources. It contains the predefined parameters. The control strategy optimization parameters can be selected according to the drive cycle or test procedure what is required. Further, the SOC can also be selected by using the control strategy optimization pane. The cost function and the constraint like emissions are set accordingly. Other constraints are the grade ability and the acceleration required by the driver.

5.1 Auto Size Test Results using Control Strategy of ADVISOR

The control strategy is applied to the auto size successfully. The grade test and acceleration test are successful. The results are given below:

Grade test ... SUCCESSFUL!!

Acceleration test ... SUCCESSFUL!!

Fuel converter set to minimum size!!

Fuel converter ==> 33 kW

Motor/controller ==> 56 kW

Energy storage system number of modules ==> 20

Control strategy - cs_lo_soc ==> 0.7

Control strategy - cs_hi_soc ==> 0.751

Final drive ratio ==> 1.3393 to allow max speed of 90 mph.

Total vehicle mass ==> 1250 kg.

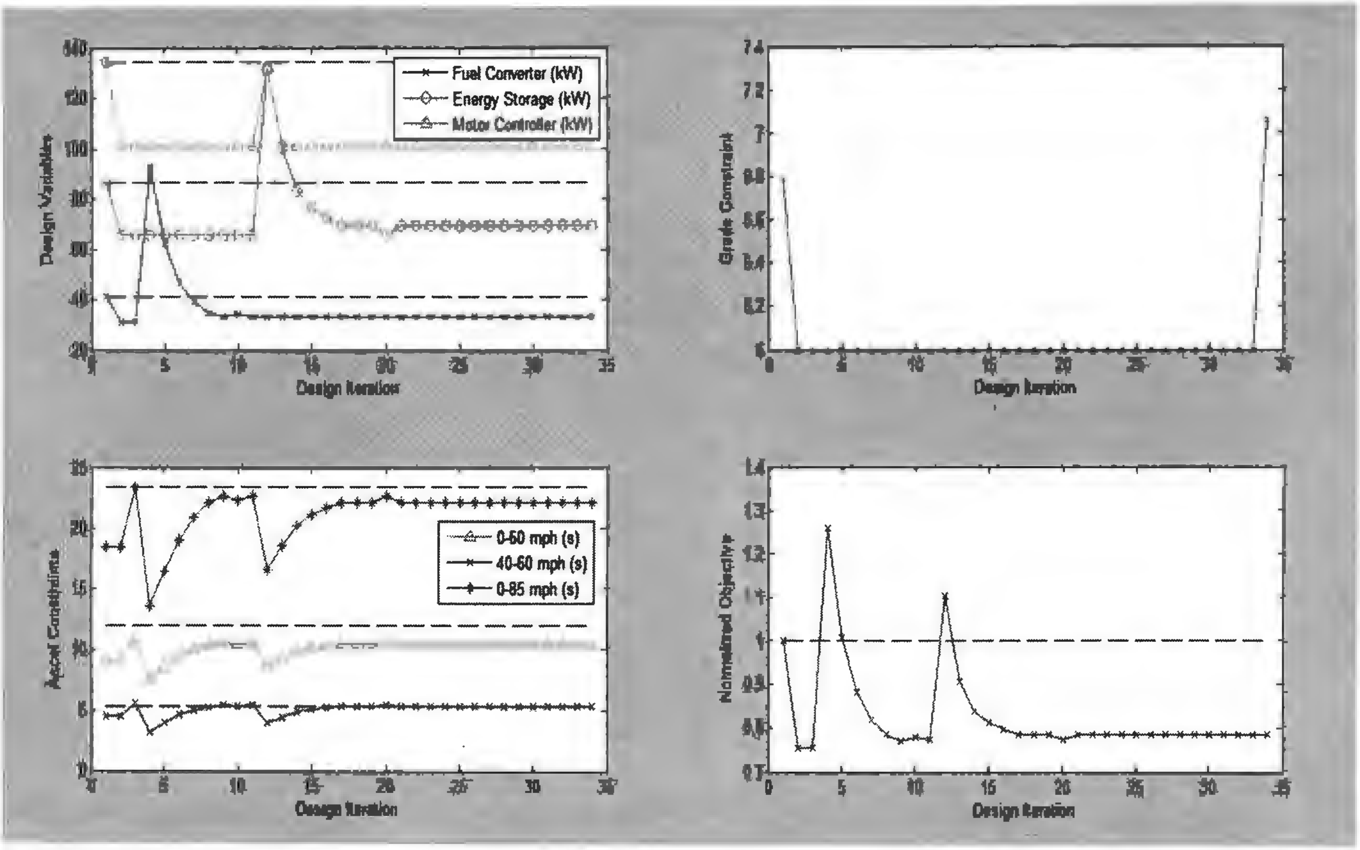

Figure 5. 1 Auto size test Results

5.2 Control Strategy Optimization Results

The control strategy can be optimized by using two methods i.e. using Matlab or VisualDoc. Initial conditions, low bounds and upper bounds variables are selected accordingly. The objective function and the emission constraints are also selected accordingly. The following are the optimum results as shown in figure 5.2.

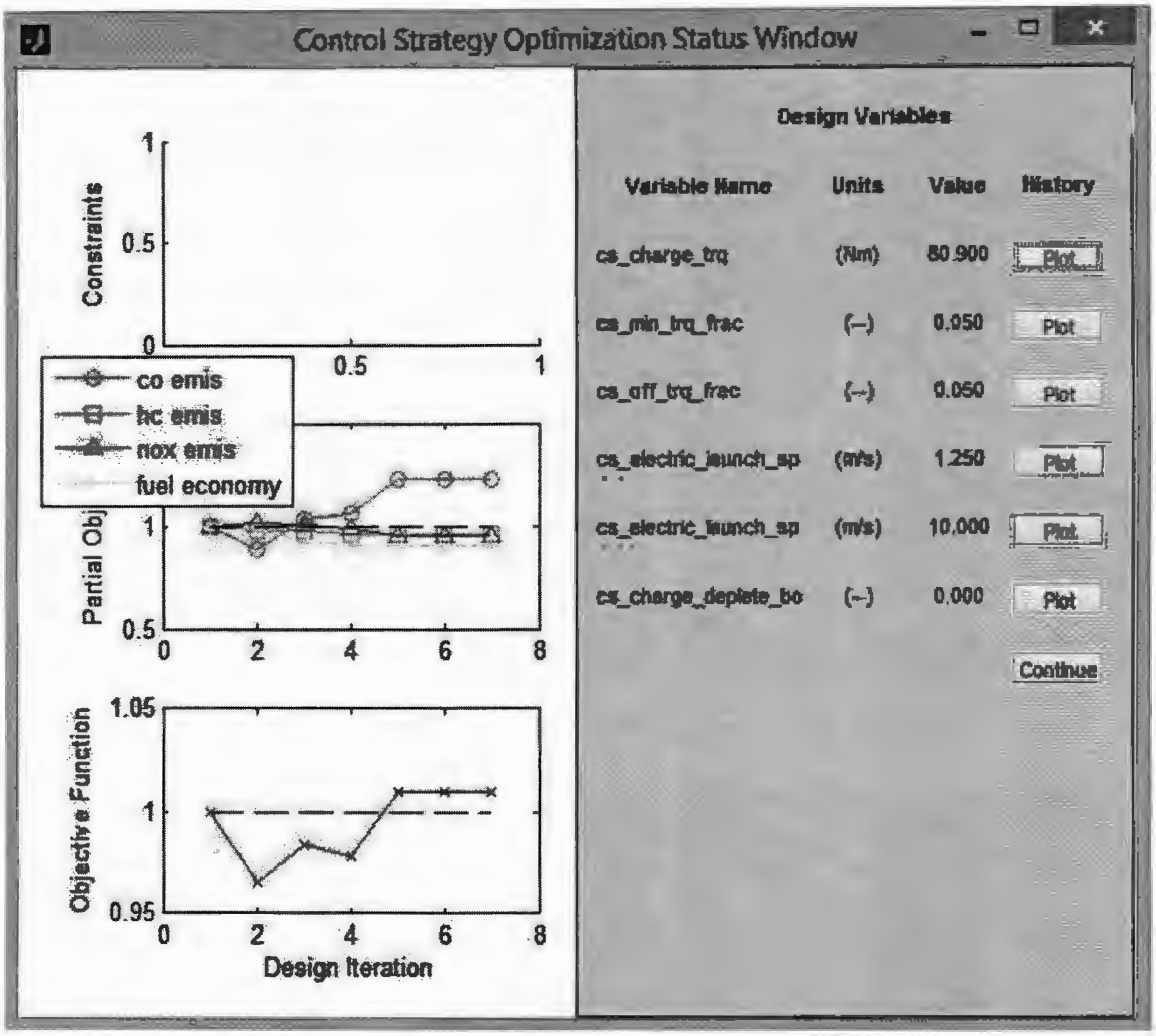

Figure 5. 2 Results of energy management control strategy

The control strategy charge torque is $SOC_{Initial} - SOC$ also known as hybrid charge torque. The Figure 5.3 shows the representation of objective function verses the control strategy minimum torque and control strategy charge torque.

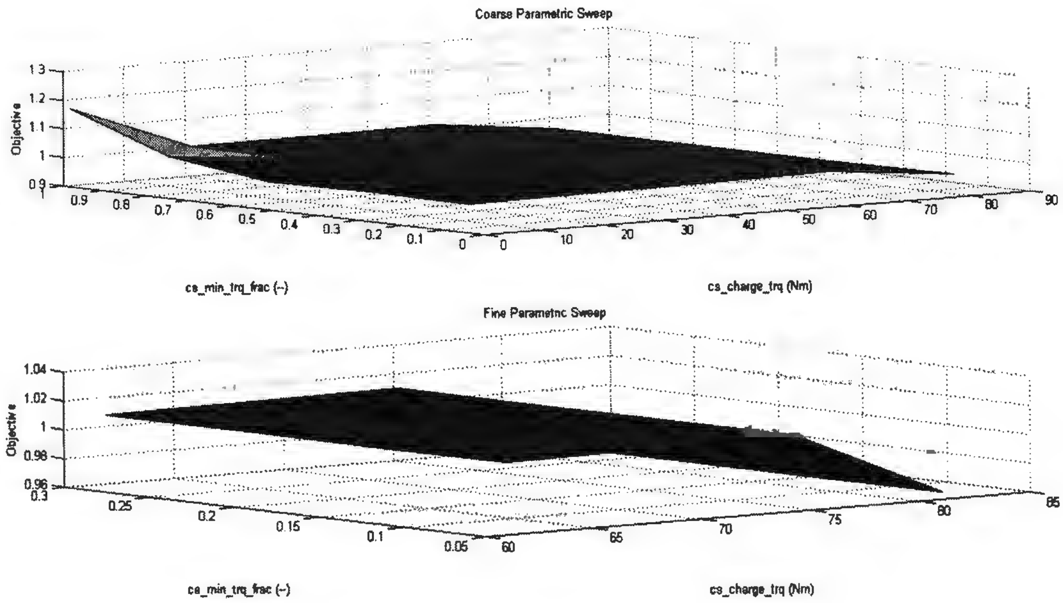

Figure 5..3 Control strategy charge torque results

The control strategy minimum charge torque is the capability of engine to operate at required operating points on current speed. The Figure 5.4 shows the relationship between the control strategy minimum charge torque and the objective function. When there is less torque required by the vehicle, then the engine operates at threshold torque and motor acts as generator to charge the batteries.

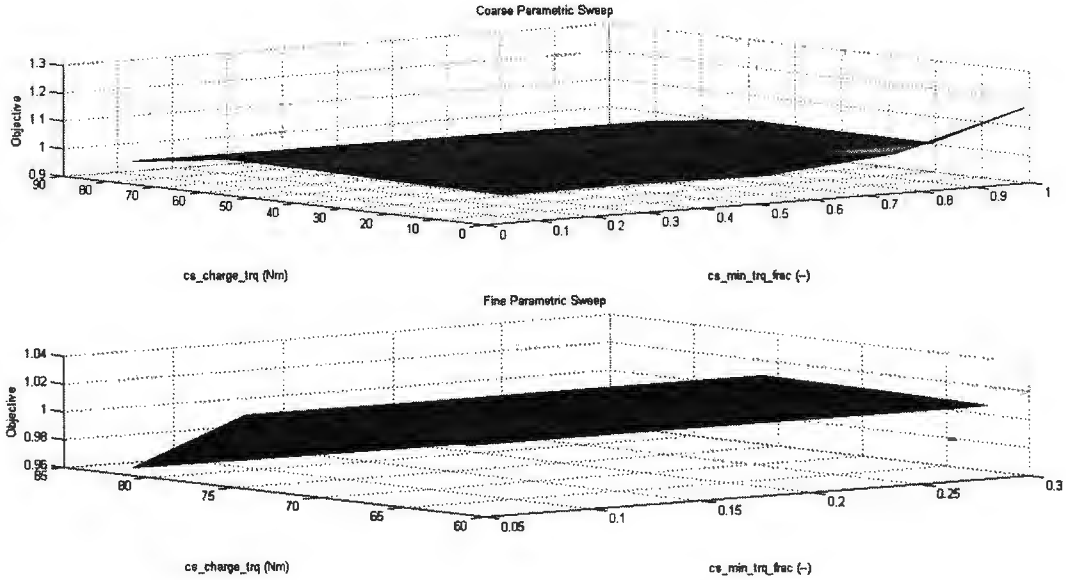

Figure 5. 4 Control strategy minimum charge torque frac*.

The control strategy off torque frac* is the torque capability of the engine for current speed which is equal to the torque threshold. When there is less torque demanded by the vehicle, the engine is turned off. The result Figure 5.5 shows the control strategy off torque verses objective function and constraint variable graph. The fine sweep and coarse sweep can be seen in the figure.

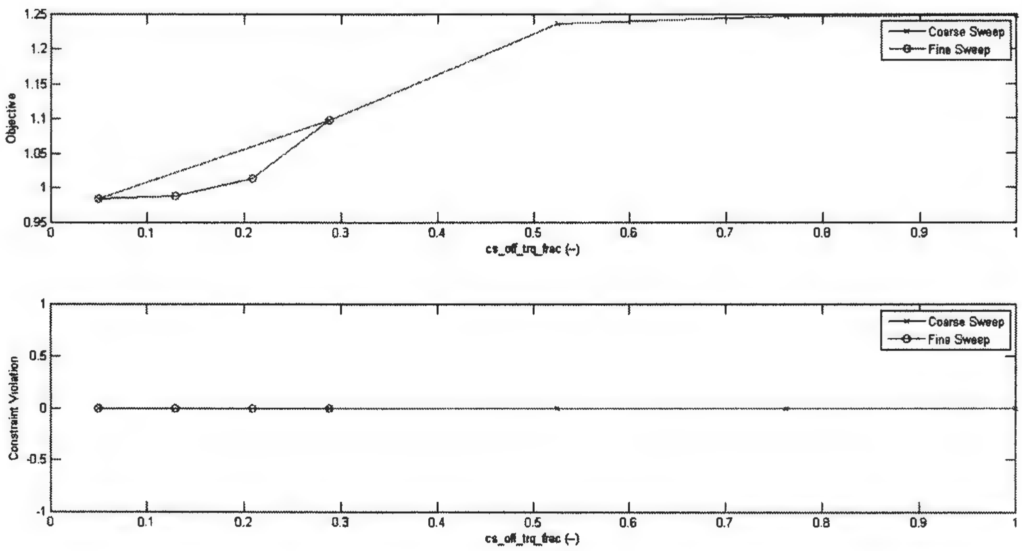

Figure 5. 5 Control strategy off torque frac*.

The control strategy electric launch speed low versus objective and constraint violation is shown in the Figure 5.6. Threshold speed is shown. The figure shows that all the constraints are fulfilled. Below the electric launch speed, the fuel converter is turned off.

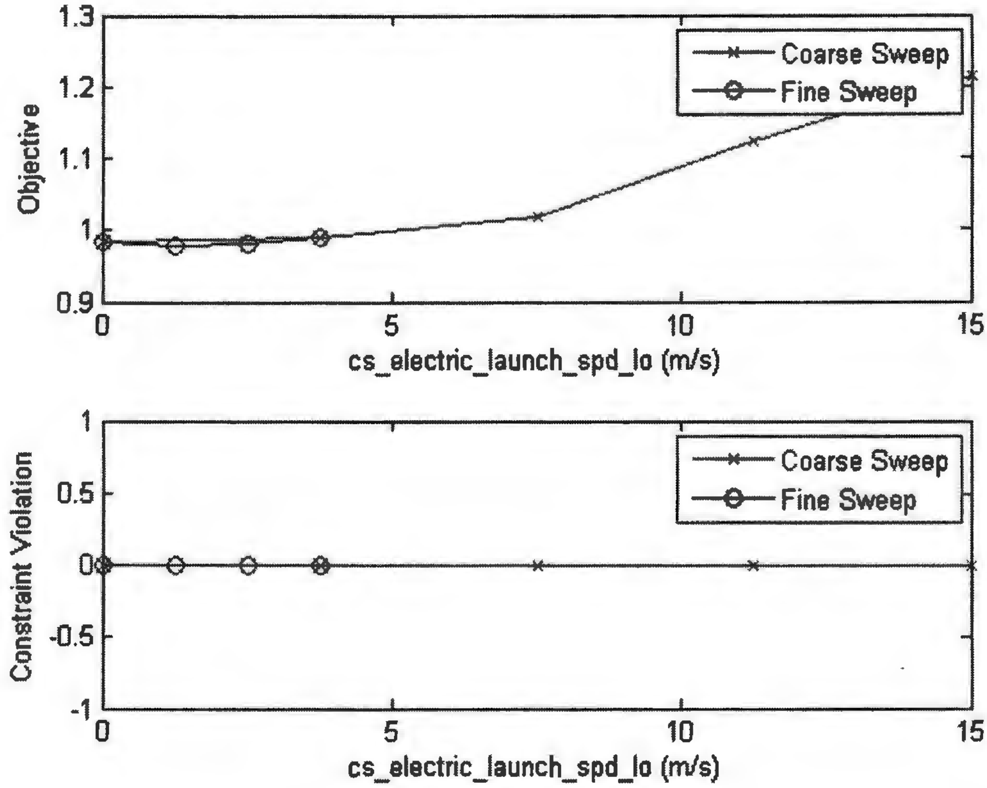

Figure 5. 6 Control strategy electric launch speed

The control strategy electric launch speed high versus objective and constraint violation is shown in the Figure 5.7. The figure shows that all the constraints are fulfilled. Above the electric launch speed, the fuel converter is turned on.

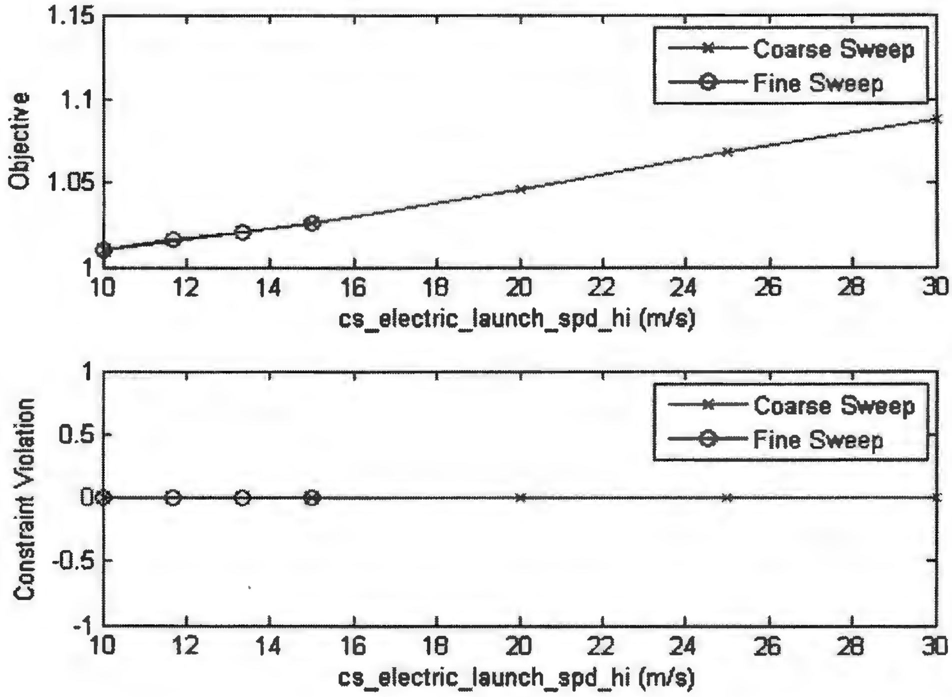

Figure 5. 7 Control strategy electric launch speed 1

The Figure 5.8 shows the graph between control strategy charge deplete Boolean versus objective and constraint violation. The high means turn on the charge deplete strategy while the low means the charge sustaining strategy.

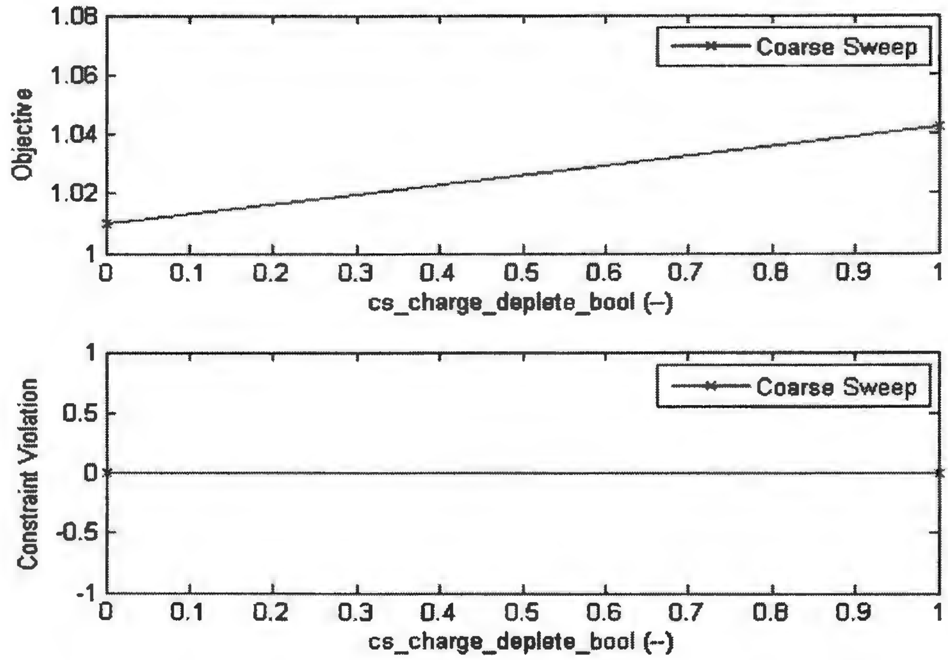

Figure 5. 8 Control strategy charge depletes Boolean

Chapter 6

Conclusions and Future Works

As hybrid electric vehicles use two or more energy sources so that the fuel distribution or hybridization rate can be economical and less emissions. Due to slow driving in the city areas, the hybrid electric vehicle can be driven on electric motor only which results in no emissions. Fuel can also be conserved by using hybrid electric vehicles. Moreover, the energy storage system can also be recharged by using the solar panels which can be fixed on the roof of the vehicle.

Many heuristic computational techniques can be used for optimal hybridization rate between ignition combustion engine and the electric motor. These techniques optimize the cost of the fuel by setting the both energy sources consumption at optimal level in real time. The fuel economy mainly depends upon the choice of the driving cycle. Moreover, new algorithms can be designed to optimize the fuel cost and emissions.

The ADVISOR software is built in SIMULINK/MATLAB environment. It is a tool which can perform analysis of some predefined models of the ignition combustion engine, electric motor and hybrid electric vehicle for fuel economy and less emissions. It has predefined driving cycles for all types of driving conditions.

The hybrid electric vehicles are environment friendly as compared to the conventional vehicles. The batteries used in hybrid electric vehicles have long life. The batteries recycling will be economical as compared to the batteries used in conventional vehicles. The research work on the new types of fuel cells and renewable fuels makes the progressive future for hybrid electric vehicles.

The figure 6.1 shows the ADVISOR model design window for different types of vehicles i.e. series hybrid, parallel hybrid, series-parallel hybrid with different drive cycles and road conditions.

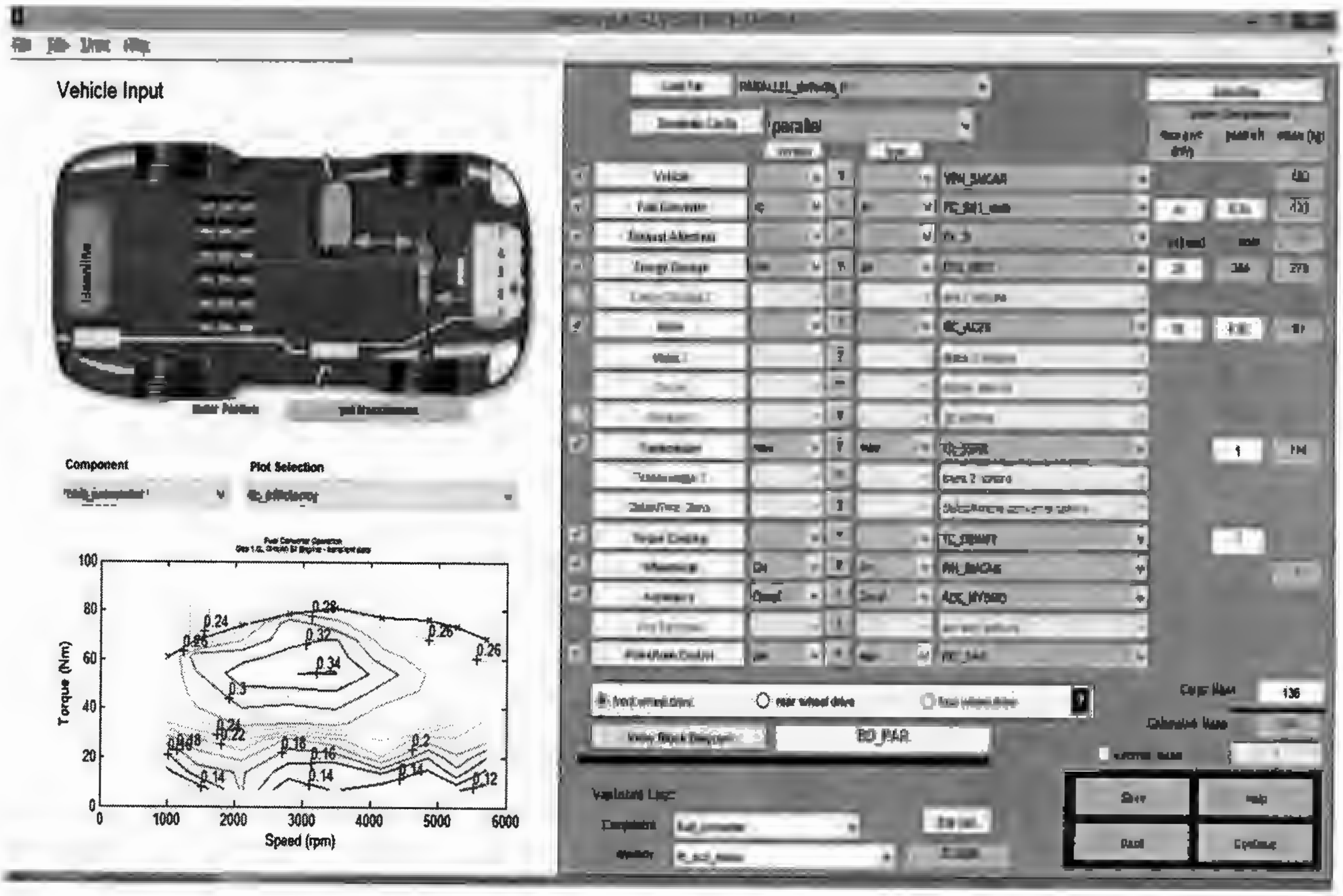

Figure 6. 1 Advisor Starting Window

References

[1] L. Serrao, "A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles," *Cent. Automot. Res.*, vol. PhD, p. 266, 2009.

[2] W. Liu, *Introduction to Hybrid Vehicle System Modeling and Control.* 2013.

[3] B. Adel and Z. Youtong, "Parallel HEV Controller Modeling for Power Management," *Fuel*, vol. 4, pp. 1–7, 2010.

[4] Z. Syed, S. Singh, S. Venkateswaran, and A. Bandiwdekar, "Hybrid engine," in *Technologies for Sustainable Development (ICTSD), 2015 International Conference on*, 2015, pp. 1–5.

[5] H. Turker, "Methodology hybridization of a vehicle," in *Transportation Electrification Conference and Expo (ITEC), 2015 IEEE*, 2015, pp. 1–8.

[6] H. Banvait, J. Hu, and Y. Chen, "Design of energy management system of Plug-in Hybrid Electric Vehicle using hybrid systems," in *American Control Conference (ACC), 2015*, 2015, pp. 1339–1344.

[7] X. Wang and R. Karki, "Exploiting PHEV to Augment Power System Reliability."

[8] H. Banvait, J. Hu, and Y. Chen, "Energy Management Control of Plug-in Hybrid Electric Vehicle using Hybrid Dynamical Systems."

[9] J. Zhang and T. Shen, "Real-Time Fuel Economy Optimization With Nonlinear MPC for PHEVs."

[10] U. Angeringer and M. Horn, "Sliding mode drive line control for an electrically driven

vehicle," in *Control Applications (CCA), 2011 IEEE International Conference on*, 2011, pp. 521–526.

[11] D. Chrenko, S. Gan, C. Gutenkunst, R. Kriesten, and L. Le Moyne, "Novel Classification of Control Strategies for Hybrid Electric Vehicles," in *Vehicle Power and Propulsion Conference (VPPC), 2015 IEEE*, 2015, pp. 1–6.

[12] B. Ganji, A. Z. Kouzani, S. Y. Khoo, and M. Nasir, "A sliding-mode-control-based adaptive cruise controller," in *11th IEEE International Conference on Control & Automation (ICCA)*, 2014.

[13] D. Sánchez-repila, J. Edgar, and W. Poxon, "Hybrid Electric Vehicles : Current Concepts and Future Market Trends," *Transportation (Amst).*, no. Imc, pp. 5–30, 2006.

[14] S. Onori, *SPRINGER BRIEFS IN ELECTRICAL AND COMPUTER Hybrid Electric Vehicles Energy Management Strategies.*.

[15] W. Zhifu, "Control Strategy of energy distribution on hybrid electric vehicle," pp. 354–357, 2009.

[16] S. S. Williamson, *Energy Management Strategies for Electric and Plug-in Hybrid Electric Vehicles*. 2013.

[17] R. Vijayan, B. K. S. Prasad, and A. T. Sriram, "Simulation of Sliding Mode Controller of Boost Converter for Fuel Cell Hybrid Electric Vehicle."

[18] K. Astrom, "PID controllers: theory, design and tuning," *Instrument Society of America*. p. 343, 1995.

[19] Y.-H. Cheng and C.-M. Lai, "Control Strategy Optimization for Parallel Hybrid Electric Vehicles Using a Memetic Algorithm," *Energies*, vol. 10, no. 3, p. 305, 2017.

[20] L. Fang, S. Qin, G. Xu, T. Li, and K. Zhu, "Simultaneous optimization for hybrid electric vehicle parameters based on multi-objective genetic algorithms," *Energies*, vol. 4, no. 3, pp. 532–544, 2011.

[21] Kawang Y. Lee, Mohamed A. Al Sharkawi, "Modern Heuristic Optimization Techniques"

[22] A. Singh and E. A. Kaur, "Speed Control of Hybrid Electric Vehicle Using Artificial.pdf," vol. 3, no. 6, pp. 6856–6860, 2014.

[23] Z. Chen, R. Xiong, K. Wang, and B. Jiao, "Optimal energy management strategy of a plug-in hybrid electric vehicle based on a particle swarm optimization algorithm," *Energies*, vol. 8, no. 5, pp. 3661–3678, 2015.

[24] L. Zhang, C. Lin, and X. Niu, "Electric Vehicle Based on Differential Evolution," 2009.

[25] G. Fiengo, L. Glielmo, and F. Vasca, "Control of Auxiliary Power Unit for Hybrid Electric Vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 15, no. 6, pp. 1122–1130, 2007.

Appendix

List of ADVISOR Version and Type

Version: This is the version of model i.e. Simulink block diagram for the component which are using to run. For example, 'ic' for fuel converter is a model of an internal combustion engine which 'fc' is the model for the fuel cell.

Type: Type is a choice for the version that has been picked. For example, if 'ic' is picked then this is for fuel converter, the types of components available for that model are spark ignition (si) and compression ignition.

Version and Type List:

Component	***Version***	***Type***	***Description***
Fuel Converter	Ic		Internal combustion engine model in Simulink with look up tables
		Si	Spark ignition
		Ci	Compressed ignition
	fcell		Fuel cell model in Simulink
		Net	Net power vs fuel consumption lookup model
		Polar	Polarization curve based model
		Gctool	Links to GCTOOL
	Ic_nn		Internal combustion engine model with neural network emissions model vis s-function
		Ci	Compression ignition
Energy storage	Rc		Resistance capacitance model
		Li	Lithium ion
		Nimh	Nickel metal hybrice
		Cap	Ultracapacitor
	Rint		Internal resistance battery model Simulink battery model consisting of a voltage source and an internal resistor to model the battery
		Pb	Lead acid
		Li	Lithium ion
		Nimh	Nickel metal hybrid
		Cap	Ultracapacitor
		Nicad	Nickel cadmium
		NiZn	Nickel zinc
	Fund		Fundamental lead acid battery model
		Fund	
	Nnet		Neural network battery model
		Nnet	
Powertrain control	Conv		Conventional
		Man	Manual transmission
		Auto	Automatic transmission
		Cvt	Continuously variable transmission

	Par		Parallel
		Man	Manual transmission
		Auto	Automatic transmission
		Cvt	Continuously variable transmission
	Ser		Series
		Man	Manual transmission
	Ev		Electric vehicle
		Man	Manual transmission
	Prius_jpn		Powertrain control for the Japanese prius
		Pg	Planetary gear continuously variable transmission
	Insight		Insight
		Man	Manual transmission
	Fc		Fuel cell
		Man	Manual transmission
Transmission	Man		Manual transmission
		Man	Manual transmission
	Auto		Automatic transmission
		Auto	Automatic transmission
	Cvt		Continuously variable transmission
		Cvt	Continuously variable transmission
	Pgcvt		Planetary gear continuously variable transmission
		Pgcvt	Planetary gear continuously variable transmission
Wheel	Crr		Constant coefficient of rolling resistance model
		Crr	Constant coefficient of rolling resistance model
	J2452		Model using SAE J2452 rolling resistance parameters
		J2452	Model using SAE J2452 rolling resistance parameters
Accessory	Const		Constant power accessory load models
		Const	Constant power accessory load models
	Var		Variable accessory models
		Spd	Variable accessory models
	Saber		Saber cosimulation on accessory loads
		DV	Dual voltage models
		SV	Single voltage models
	Sinda		Sinda/fluint cosimulation model initialization files
		Sinda	Sinda/fluint cosimulation model initialization files

List of ADVISOR File Naming Conventions

All model and data files use a prefix followed by an underscore ('_') that is the same as the prefix used for (nearly all) the variables it defines, which in turn is in pointy brackets (<>) at the end of the Simulink block in which those variables are used. Here are ADVISOR's component file types:

File Name	Function
ACC_*.M	Accessory load files
CYC_*.M	Driving cycle files, which define variables starting with cyc_, used in the block labeled <cyc>
ESS_*.M	Energy storage system data files, which likewise define variables starting with ess_, used in the block labeled <ess>
EX_*.M	Exhaust after treatment files (such as catalysts)
FC_*.M	Fuel converter data files
TX_*.M	Transmission data files (these include gearbox-gb and final drive-fd variables)
GC_*.M	Generator/controller data files
MC_*.M	Motor/controller data files
PTC_*.M	Powertrain control data files, which define engine control, clutch control, and hybrid control strategy variables starting with vc_ and cs_, used in blocks labeled <vc> and <cs>
TC_*.M	Torque coupler data files
VEH_*.M	Vehicle data files
WH_*.M	Wheel/axle data files
FC_*.M	Fuel converter data files
FD_*.M	Final drive data files
GB_*.M	Gearbox data files
GC_*.M	Generator/controller data files
BD_*.MDL	Simulink block diagrams (models)
CV_*.M	Complete vehicle files that include all necessary references to component files to define an entire vehicle

Commonly used Matlab commands

Listed below are a few commands that are frequently used to reduce and inspect ADVISOR's input and output data. Matlab help is available on these commands by entering *helpwin command, help command*, or *helpdesk* at the command line. A very useful Matlab help feature is the 'lookfor' command, which searches the one-line descriptions of all Matlab commands for the word that you enter. To use 'lookfor,' enter something like *lookfor color* at the command line.

List of ADVISOR Variable Naming Conventions

ADVISOR variable names use only lower-case letters.

All ADVISOR variables use prefixes except the three main output variables:

- emis-tailpipe emissions
- gal-total fuel use
- mpha-the actual vehicle speed.

The other input and output variables use the same prefixes used for the component data file names which are also enclosed in '<' in appropriate Simulink block on the main level of ADVISOR's block diagrams.

Variable Name	Abbreviation
cs_*	Hybrid control strategy variables
cvt_*	Continuously variable transmission variables
cyc_*	Driving cycle variables
ess_*	Energy storage system variables
ess_*	Energy storage system variables
fc_*	Fuel converter variables

gb_*	Gearbox variables
fd_*	Final drive variables
gc_*	Generator/Controller variables
mc_*	Motor/controller variables
tx_*	Transmission variables
vc_*	Vehicle control variables (engine and clutch)
veh_*	Vehicle (coast down-related) variables

ADVISOR variable names with prefixes always use the word indicating the units or value of the variable last. For example, the initial state-of-charge of the energy storage system is stored in the variable ess_init_soc.

List of ADVISOR Control Strategy Variables

Control Strategy (Input Variables)				
Name	Type	Units	Vehicle Type	Description
cs_charge_trq	scalar	N*m	par	hybrid_chargetrq*(SOCinit-SOC) = an alternator-like torque loading on the engine to recharge the battery pack; negative recharge is never requested
cs_electric_launch_spd	scalar	m/s	par	vehicle speed threshold; below this speed, the fuel converter is turned off
cs_min_trq_frac	scalar	–	par	cs_min_trq_frac*(torque capability of engine at current speed) = minimum torque threshold; when commanded at a lower torque, the engine will operate at the threshold torque and the motor acts as a generator
cs_off_trq_frac	scalar	–	par	cs_off_trq_frac*(torque capability of engine at current speed) = minimum torque threshold; when commanded at a lower torque, the engine will SHUT OFF
cs_fc_init_state	scalar	Boolean	ser	1=fuel converter (FC) is initially on; 0=FC initially off
cs_charge_pwr	scalar	W	ser	cs_charge_pwr*fc_spd_scale*fc_trq_scale*((cs_soc_hi+ cs_soc_lo)/2-SOC) is the SOC-stabilizing adjustment made to the bus power requirement
cs_max_pwr	scalar	W	ser	cs_max_pwr*fc_spd_scale*fc_trq_scale is the maximum power commanded of the fuel converter unless SOC<cs_lo_soc
cs_min_pwr	scalar	W	ser	cs_min_pwr*fc_spd_scale*fc_trq_scale is the minimum power commanded of the fuel converter
cs_max_pwr_fall_rate	scalar	W/s	ser	cs_max_pwr_fall_rate*fc_spd_scale*fc_trq_scale is the fastest the fuel converter power command can decrease (this number < 0)
cs_max_pwr_rise_rate	scalar	W/s	ser	cs_max_pw_rise_rate*fc_spd_scale*fc_trq_scale is the fastest the fuel converter power command can increase
cs_min_off_time	scalar	s	ser	the shortest allowed duration of a FC-off period; after this time has passed, the FC may restart if high enough powers are required by the bus
cs_pwr	vector	W	ser	cs_pwr*fc_spd_scale*fc_trq_scale is the vector of FC powers that define the locus of best efficiency points throughout the genset map
cs_spd	vector	rad/s	ser	cs_spd*fc_spd_scale is the vector of FC speeds in locus of best efficiency points, indexed by cs_pwr*fc_spd_scale*fc_trq_scale
cs_hi_soc	scalar	–	par/ser	highest state of charge allowed
cs_lo_soc	scalar	–	par/ser	lowest state of charge allowed
cs_fc_spd_opt	vector	rad/s	prius_jpn	optimum speed points for fc operation used along with cs_fc_trq_opt and cs_fc_pwr_opt
cs_fc_trq_opt	vector	N*m	prius_jpn	optimum torque points for fc operation used along with cs_fc_spd_opt and cs_fc_pwr_opt
cs_fc_pwr_opt	vector	Watts	prius_jpn	power values for which cs_fc_trq_opt and cs_fc_spd_opt are defined.
cs_charge_deplete_bool	boolean	–	par/ser	1=> use charge deplete strategy, 0=> use charge sustaining strategy
cs_fc_max_pwr_frac	scalar	–	par with CVT	engine power fraction below which engine would like to operate
cs_fc_min_pwr_frac	scalar	–	par with CVT	engine power fraction above which engine would like to operate
cs_hi_trq_frac	scalar	–	load/ SOC balanced par	highest desired engine load fraction
cs_lo_trq_frac	scalar	–	load/ SOC balanced par	lowest desired engine load fraction
cs_offset_soc	scalar	–	par	x-intercept of electric launch speed vs. SOC - ONLY active if cs_charge_deplete_bool=1
cs_trq_to_soc_factor	scalar	–	load/ SOC balanced par	weighting factor for the relative importance of engine operation near the goal to the SOC operation near the goal ==> low values mean that SOC is more important, large values mean engine is more important
cs_tstat_init_state	scalar	–	EV	used in EV PTC, initial FC state; 1=> on, 0=> off