MODELLING AND SIMULATION OF HYBRID ELECTRIC VEHICLE

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Abstract

Conventional vehicles with IC engines provide good performance and long operating range by utilizing the high-energy-density advantages of petroleum fuels. However, conventional IC engine vehicles have the disadvantages of poor fuel economy and environmental pollution. Battery-powered Electric Vehicles, on the other hand, possess some advantages over conventional IC engine vehicles, such as high-energy efficiency and zero environmental pollution. However, the performance, especially the operation range per battery charge is far less competitive than IC engine vehicles Due to the much lower energy density of the batteries than that of gasoline .Hybrid Electric Vehicles which use two power sources have the advantages of both IC engine vehicles and EVS and overcome their disadvantages. A vehicle that has two or more power trains is called a hybrid vehicle. A hybrid vehicle with an electrical power train is called an HEV. After designing of any vehicle, the design is implemented as a prototype and then that prototype is tested on different roads to check its performance. prototyping is needed if faults are identified during prototype testing. In order to save this cost of prototyping, modeling of mechanical system can be performed on available software's like Matlab Simulink to minimize number of faults in prototype. There is a need of development of model of hybrid electric vehicle, so that that model can be simulated to behave like actual prototype. That vehicle model can be tested on different drive cycles, which is equivalent to test a prototype on real road traffic conditions. Once the model is finalized and tested, next step is to proto type it and that prototype is unlikely to have faults compare to prototype which is directly developed without its simulated model. The model developed in software can be easily modified to implement different hybrid electric vehicle. The HEV model developed is based on the Honda Integrated Motor Assist power-train which is utilized by Honda in its all the HEVs. In order to check the accuracy of the developed MATLAB-SIMULINK HEV model, the simulation is carried out on three different standard international drive cycles (NYCC, HWFET, WVU5), and the data is compared with the published data. Three major performance parameters are compared to validate the developed model: fuel consumed, energy regenerated and energy consumed. After comparing the performance parameters the MATLAB-SIMULINK HEV model developed is validated against published data.

1. Introduction

As the global crisis of energy is increasing day by day, the scientists are researching the alternate sources of energies. As the automobiles also one of the key consumers of energy in the form of fossil fuels the researches are also made to improve the efficiency of the vehicles. The solution for this problem is the Hybrid Electric Vehicles (HEV). The HEV utilizes the basic internal combustion engine with the electric motor. The main advantage of internal combustion engine is that the fossil fuels on which they run contain high energy in lower mass. But the disadvantage of the internal combustion engine is the hazardous emissions. On the other hand the main advantage of electric vehicles is that they don't cause any emissions. But the power content in electric energy storage systems (batteries) is low with higher mass as compare to the internal combustion engines. So the HEV combines the advantages of both internal combustion engine and electric motors and remove the disadvantage of higher emissions in conventional vehicles.

Another advantage of HEV is the regenerative braking. This is the basic difference between the braking system of a conventional vehicle and HEV. In addition to normal braking system, in HEV the electric motor is utilized to produce negative torque at the axle in order to stop the vehicle. During regenerative braking the part of energy which is dissipated in the form of heat energy from disc or drum in conventional braking systems, is recaptured and fed back to batteries.

In order to increase the efficiency and accuracy of automotive design, computer aided engineering is playing a vital role. With the increase in computing powers, manufacturers are now able in designing, testing and optimization using computer simulation prior to the real time implementation of design. Similar to other areas of automotive researches such as vehicle dynamics and crash worthiness, many software's are developed in order to evaluate the energy efficiencies of conventional vehicles. These software's are used to simulate conventional vehicles by customizing the power components such as engines and other vehicle components but this software is not good enough for HEV. So there is a need of developing a simple tool dedicated to HEV which can be utilized to simulate complete HEV.

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The Matlab/simulink model consists of a simple HEV system based on power components and mechanical components of Honda Insight with Integrated Motor Assist (IMA) architecture, in which motor act as an auxiliary power source which assists the engine when engine torque reaches to threshold value. The Honda Insight is chosen as it is the basic power-train utilized by Honda in its all HEV, including Honda Insight (2000), Honda Civic (2005) and it is also used in Honda Insight Second Generation. And it is also least complex of all hybrid power-train architectures.

2. Objective

The purpose of this thesis is to create a Matlab/Simulink HEV model. Second objective is to simulate HEV model. Simulation is parametric analysis of HEV performance. The major parameters which are to be simulated are energy regenerated per driving cycle and fuel consumed per driving cycle. Other parameters are also evaluated. The driving cycles on which simulation is performed are international driving cycles such as EPA NYCC (New-York city cycle), EPA HWFET (Highway Fuel Economy cycle), and WVU5 (West Virginia University 5 peak cycle). This is achieved in following steps:

A) Modeling of all the following modules:

1) Drive cycle module

2) **Driver Controller module**
3) **Power management controller module**
4) **Engine module**
5) **Motor/Generator module**
6) **Transmission module**
7) **Battery module**
8) **Vehicle module**

B) Combining all the modules to form HEV model.

C) Model Simulation to evaluate the major performance parameters i.e. energy regenerated per drive cycle, fuel consumed, energy consumed per drive cycle.

3. Overview of hybrid electric vehicle

Conventional vehicles with internal combustion engine (ICE) provide good performance and long operating range by utilizing the high energy density advantages of petroleum fuels. However conventional ICE vehicles bear disadvantages of poor fuel economy and environmental pollution. The main reasons for their poor fuel economy are: 1) engine fuel efficiency characteristics are mismatched with real operation requirements. 2) Dissipation of vehicle kinetic energy during braking.

On the other hand, battery powered electric vehicle (EV) posses some advantages over conventional ICE vehicles, such as high energy efficiency and zero environmental pollution. However, the major disadvantage of EV performance as compare to the ICE vehicles is poor specifically the range per battery charge due to lower energy content of the batteries VS energy content of the fossil fuel.

Hybrid Electric Vehicle (HEV) by definition runs on two power sources: Primary power source and Secondary power source. It has the advantage of both ICE vehicles and EV. And it also overcomes the disadvantage of both ICE vehicles and EV and during regenerative braking the electric motor is utilized to apply the brakes and it recaptures the energy during deceleration which otherwise has lost in conventional vehicle in the form of heat dissipated.The block diagram of a normal HEV power-train is given in figure 2.1.

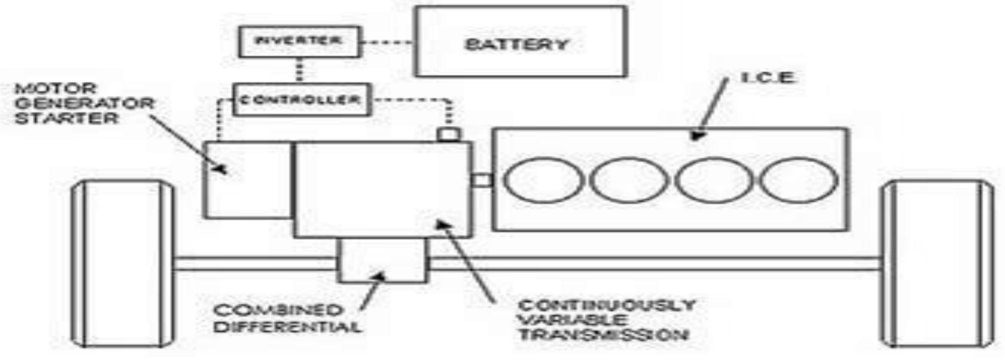

Fig. 2.1 Schematic diagram of HEV

In order to combine two power sources: ICE and electric motor there are various configurations possible. But all these configurations are basically divided in to two categories: Series hybrid power train and Parallel hybrid power train. According to the power train utilized the HEV also called as series HEV and parallel HEV.

Series Hybrid Configuration

The block diagram of a Series hybrid power- train is shown in figure 2.2.

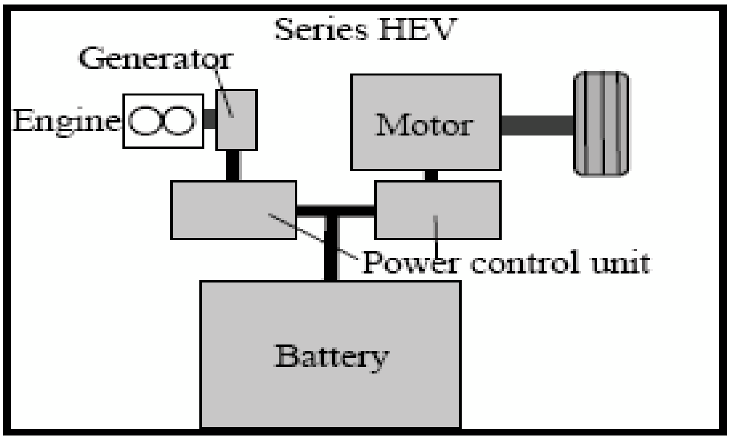

Fig. 2.2 Schematic Diagram of series HEV

In the series hybrid System the engine runs the generator, which produces electricity. That electric energy is stored in the battery. The battery then supplies the electric energy to the electric traction motor, which in turn drives the wheels and propels the vehicle. The advantage of the Series configuration is that: the engine runs at the optimum efficiency point and hence the produces less emissions and also increases the overall efficiency of the vehicle.

Parallel Hybrid Configuration

The block diagram of parallel HEV power-train is shown in figure 2.3.

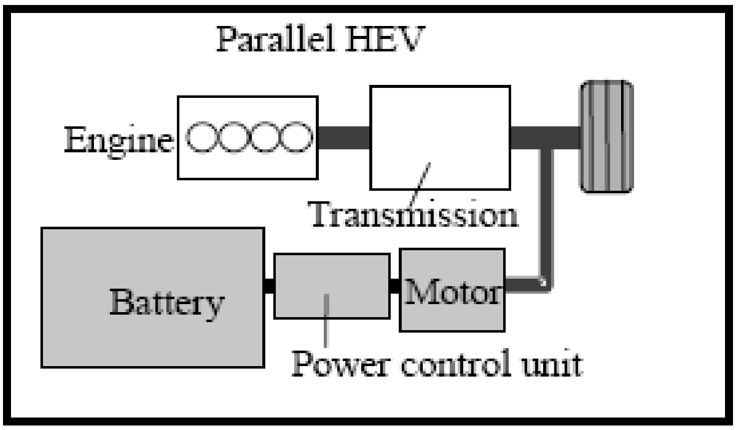

Fig. 2.3 Schematic diagram of Parallel HEV

The parallel HEV power-train configuration switches between two power sources: ICE and electric motor powered by battery. The high efficiency range of two power sources is utilized. Both power sources can also be used simultaneously in order to achieve the power requirement of vehicle. During stop-go drive cycle or city drive cycle as the electric motor can produce high torque at lower speeds, it is utilized for stop-go drive cycle

Existing Design

Various automakers have successfully developed HEV which are currently in the market. Some of these designs will be discussed in the following section:

Honda HEV

Honda motors currently have two HEV in the market. One is Honda Insight and another Honda Insight Second Generation. All the Honda HEV are based on only one power- train which is called as Integrated Motor Assist (IMA) Technology. Honda have first introduced this power-train technology in Honda Insight, then they have utilized same power train in Honda Civic and now they utilize same power-train in second generation Honda Insight.

Integrated Motor Assist (IMA) system:

The block diagram of IMA system developed by Honda is shown in figure 2.4

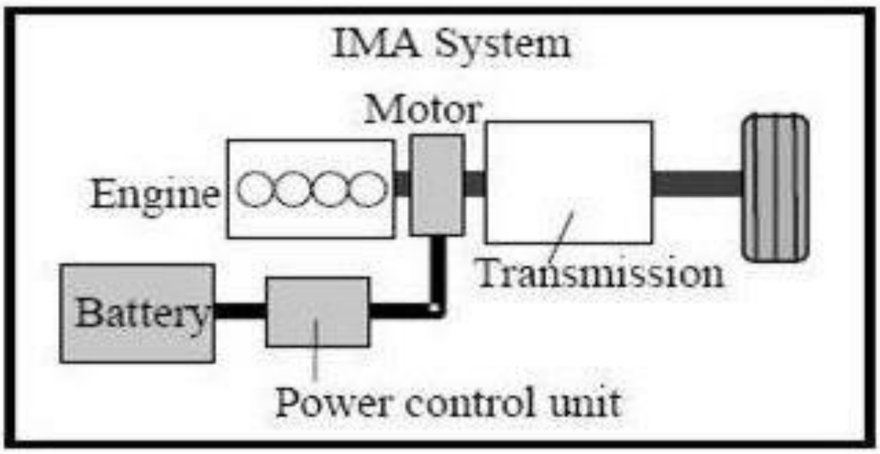

Fig. 2.4 Schematic diagram of IMA

IMA is a parallel hybrid configuration. In IMA hybrid power-train, A Permanent Magnet DC brushless motor is placed between the engine and the transmission, with motor shaft directly connected with the engine crank-shaft. In IMA, engine act as a main power source where as motor act as an auxiliary power source. During normal operation the engine is utilized to full-fill the power required by the vehicle. But during high acceleration, hill climbing when high torque is required and engine is unable to provide enough power then electric motor is utilized. During deceleration the electric motor is used to apply the brake in the regenerative mode in order to recapture the braking energy as much as possible. The major advantage of the using motor as an assist is that the less power rated motor is required. And hence the overall power-train becomes very much compact, light weight and weight of the power control unit and battery is also decreased. In order to improve the fuel economy in Honda Civic, engine idle stop system is also included.

The Specifications of the Honda Insight are given in table.2.1

Table2.1 Specifications of Honda Insight

Engine	50 KW
Motor	10 KW
Transmission	5 speed manual
Battery	Nickel Metal Hydride (capacity 6.5 Ahr, rated voltage 144 V)

Regenerative Braking for HEV:

One of the most important features of EV and HEV is their ability to recover significant amount of braking energy. The electric motors in EV and HEV can be controlled to operate as a generators to convert the kinetic or potential energy of the vehicle mass into electrical energy that can be stored in the energy storage and reused.

The braking performance of a vehicle is undoubtedly one of the major factors that affect vehicle safety. A successfully designed braking system for a vehicle must always meet two distinct demands. Firstly, in emergency braking, it must bring the vehicle to rest in shortest possible distance. Secondly, it must maintain control over the vehicle"s direction. The former requires that the braking system be able to supply sufficient braking torque on all the wheels. The later requires braking force to be distributed on all the wheels equally. Generally, the braking torque required is much larger than the torque that an electric motor can produce. In EV and HEV, mechanical frictional braking systems must coexist with electric regenerative braking. Thus, the proper design and control of both mechanical and electric braking systems are major concerns to the armature, hence feeding energy to the source. 2.5.1 Energy consumption in braking

A significant amount of energy is consumed by braking. For example, braking a 1500 kg vehicle from 100 km/hr to 0 speed consumes about. 16 kW hr of energy (.5 M V^2). When vehicles are derived in stop-go driving cycles in urban areas, a significant amount of energy is consumed by frequent braking. This results in high fuel consumption, so in urban areas the use of regenerative braking recaptures the energy as much as possible and increases the overall efficiency of the vehicle

4. Hybrid electric vehicle model in matlab/simulink

The model is constructed in MATLAB/SIMULINK (7.5.0 – R2007b) software package, runs on operating system Windows XP. The power-train components and vehicle dynamics modules are modeled. The overall structure of the HEV model is shown in figure 4.1.

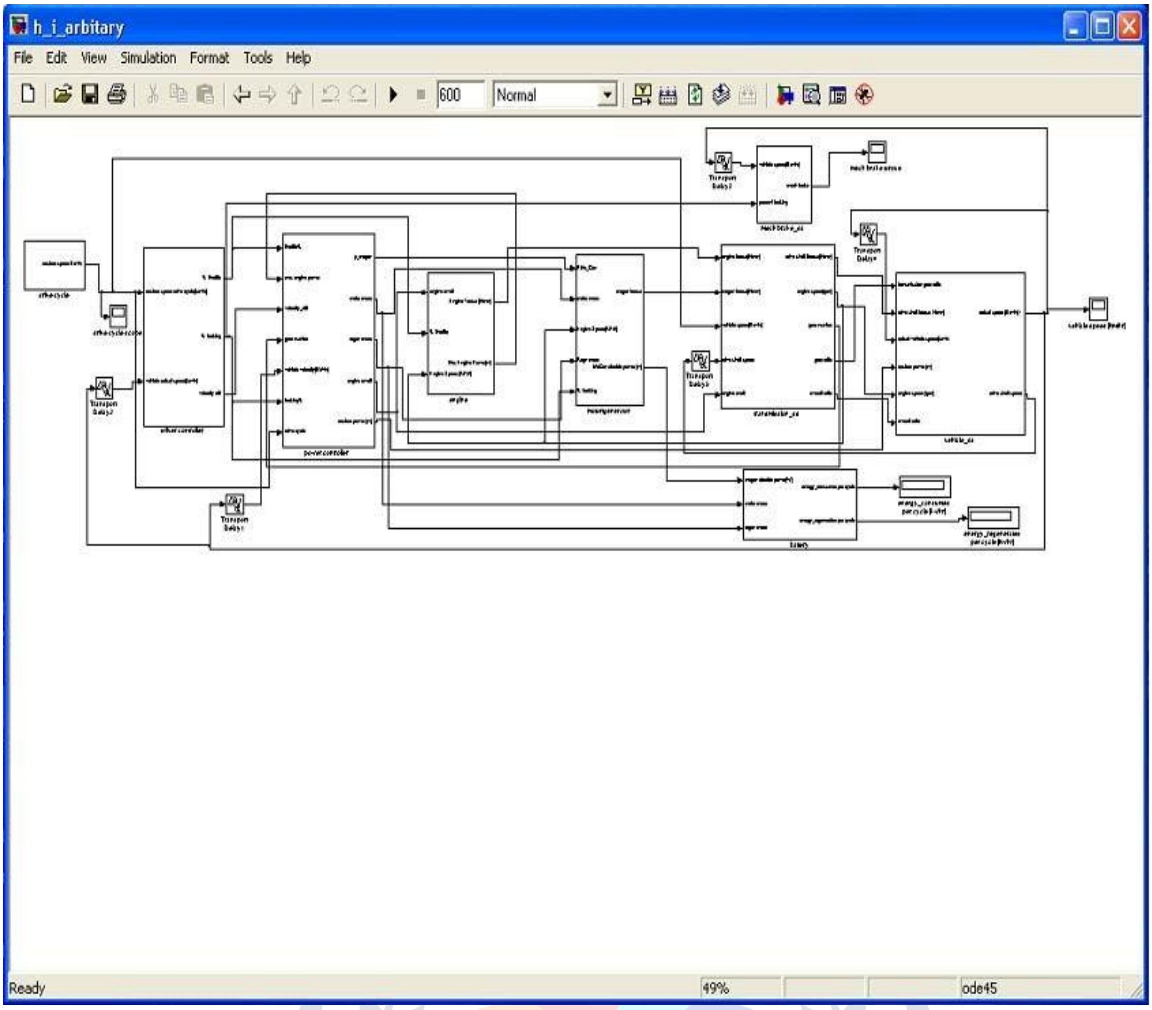

Fig. 4.1. Overall Structure of HEV model

In order to make the model more visible, two more diagrams are shown. First one shows first half of the model and second one shows second half of the model. The diagrams are shown in figures 4.2 and 4.3 respectively.

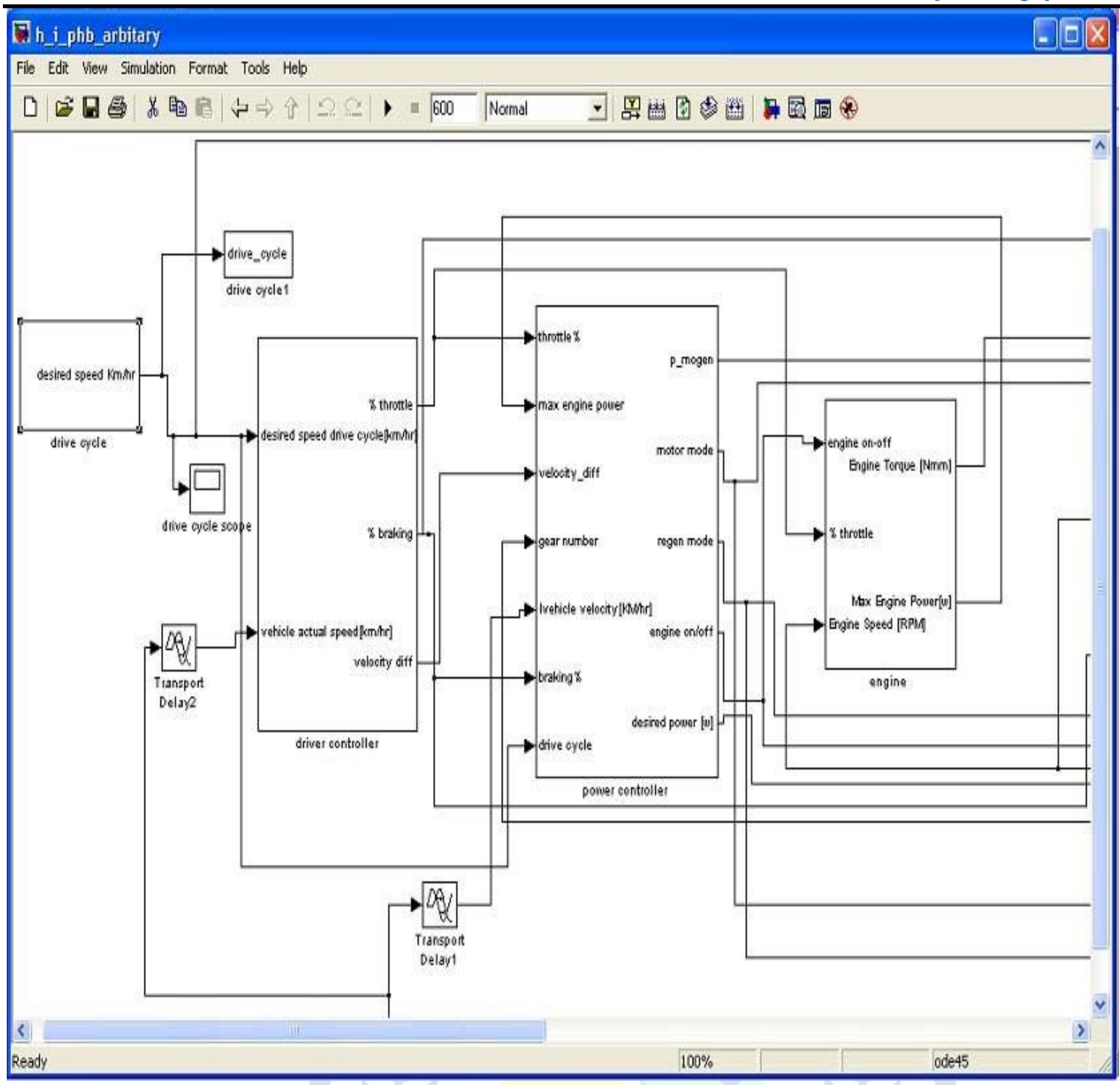

Fig. 4.2. First half of HEV model

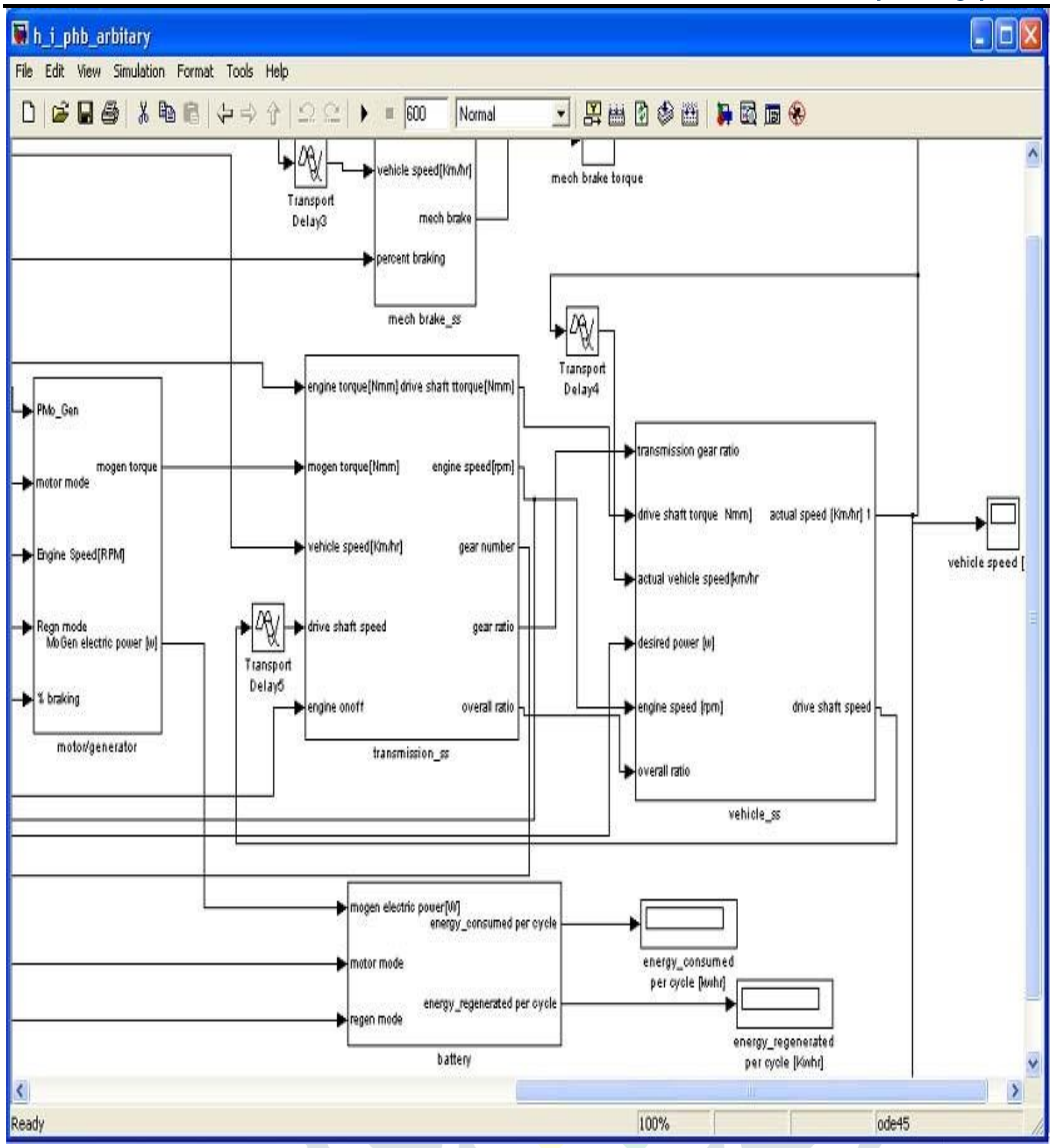

Fig. 4.3. Second half of HEV model

The MATLAB/SIMULINK model shown in above figures is formed by connecting each and every module constructed separately. Each one will be discussed in this chapter. All the modules constructed are arranged in chronological order. The input ports of the modules are on left side, and output ports are on right side. The appropriate ports are connected with each other.

The following section will discuss all the individual modules developed separately:

DRIVE CYCLE MODULE

The drive cycles means the average speed data which varies with time. There are some drive cycles developed for some common international cities like, New York. Some drive cycles are developed specifically for particular kinds of driving patterns like, driving on high ways, or in traffic etc. and some drive cycles are virtually developed for specific uses. The use of drive cycles is that, without actually driving the real car on that drive cycle, we can simulate our developed model of vehicle on these drive cycles in order to analyze vehicle‟s behavior on that driving condition. Similarly, in order to simulate the HEV model developed in this project, three important drive cycles are modeled in the drive cycle Module. The drive cycles are modeled by using look-up tables indexed by the simulation time. The look- tables consists of speed points for every second.

Due to unavailability of accurate speed points, the speed points are being taken from the available graphs. So the drive cycles utilized in this project are approximate drive cycles.

The output of the drive cycle module is desired speed, which is the input to the driver controller, which compares the desired vehicle speed with actual vehicle speed and controls the throttle position and brake pedal. The drive cycles used to simulate the model are EPA-NYCC (New York City drive cycle), EPA-HWFET (Highway Fuel Economy Drive Cycle), West Virginia University 5 peak Drive Cycle (WVU5). The drive cycle module is shown in figure 4.4.

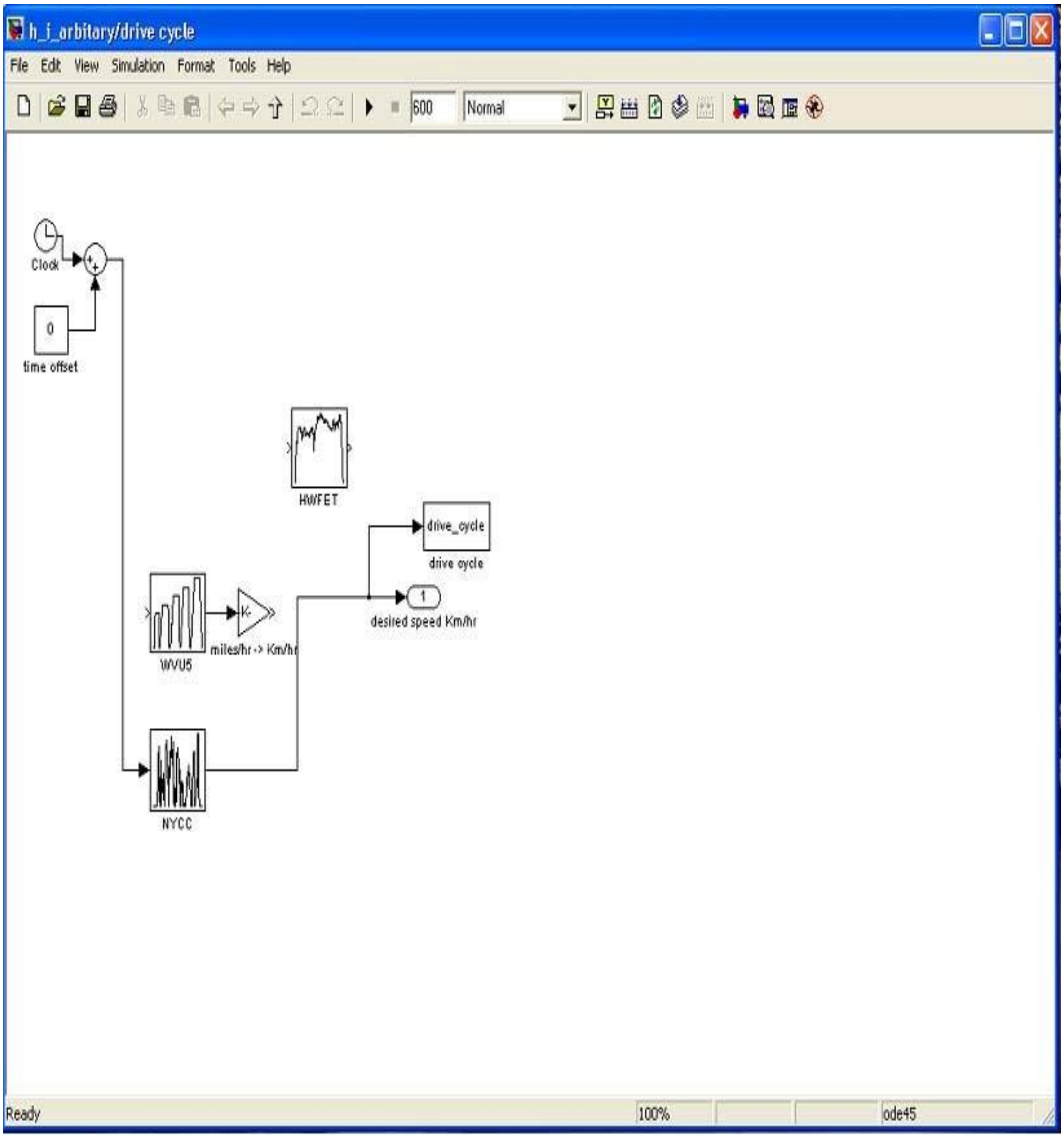

Fig. 4.4. Drive Cycle Module

DRIVER CONTROLLER MODULE

As discussed in section 3.5.1, the driver controller module is modeled in order to mimic the behavior of the real life driver. The inputs for the Driver Controller are desired speed from the drive cycle module and the actual vehicle from the vehicle module. The driver controller compares the desired speed and the actual vehicle speed to calculate the percentage throttle and percentage braking. The driver controller module is shown in figure 4.5.

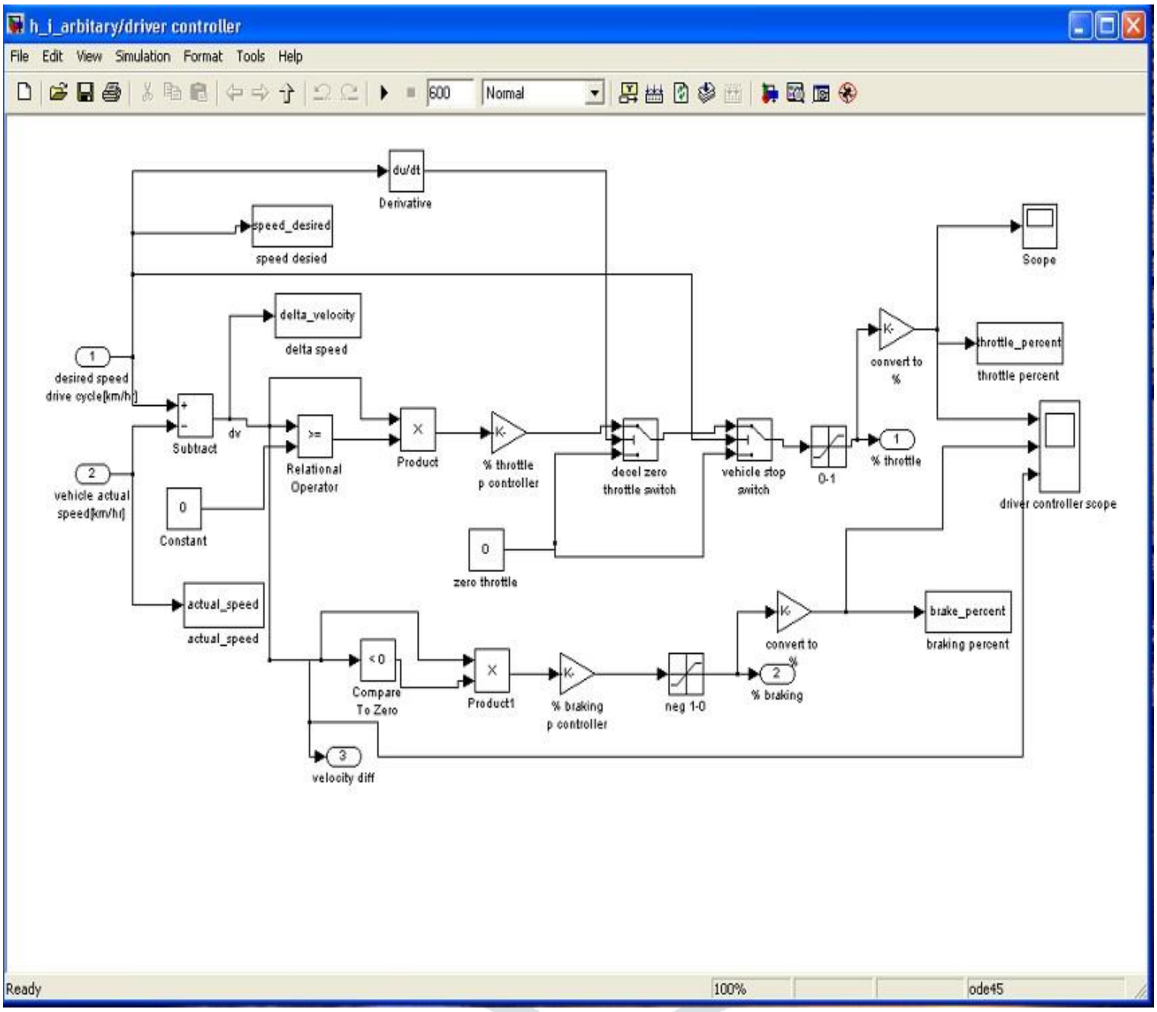

Fig. 4.5 Driver Controller Module

The driver controller module calculates the difference between the desired speed and the actual vehicle speed. This differential speed also called as delta speed. The differential speed is then checked whether it is positive or negative by using relational operator. If it is positive then it is fed to the throttle proportional controller otherwise it is fed to braking controller after negating. The saturation switch is provided to limit the percentage-throttle (PT) and brake-percentage (BP) between 0% - 100%. The percentage throttle corresponds to the throttle position (TP). Here the throttle position is proportional to the gain of throttle proportional controller and percentage braking corresponds to the desired deceleration (0g – 1g), which is obtained by brake pedal position sensor. In this model brake pedal position is proportional to the gain of the brake proportional controller. In this model two switches are also provided. One is to check whether acceleration is positive or not, to identify whether vehicle is accelerating or decelerating. When vehicle is accelerating then only the throttle will be open otherwise throttle remains closed. Second switch is provided to check whether the desired speed is greater then zero or not. If it is less then zero, then throttle remains closed, if it is greater then zero, then only throttle will be opened. The output of the driver controller is given to the power management controller which calculates other parameters.

POWER MANAGEMENT CONTROLLER (PMC) MODULE

As discussed in the Section 3.6.2, the power management controller is used to control the two power sources (engine and electric motor) to achieve the required power from the vehicle while increasing the overall vehicle efficiency.

The power management controller is shown in figure 4.6.

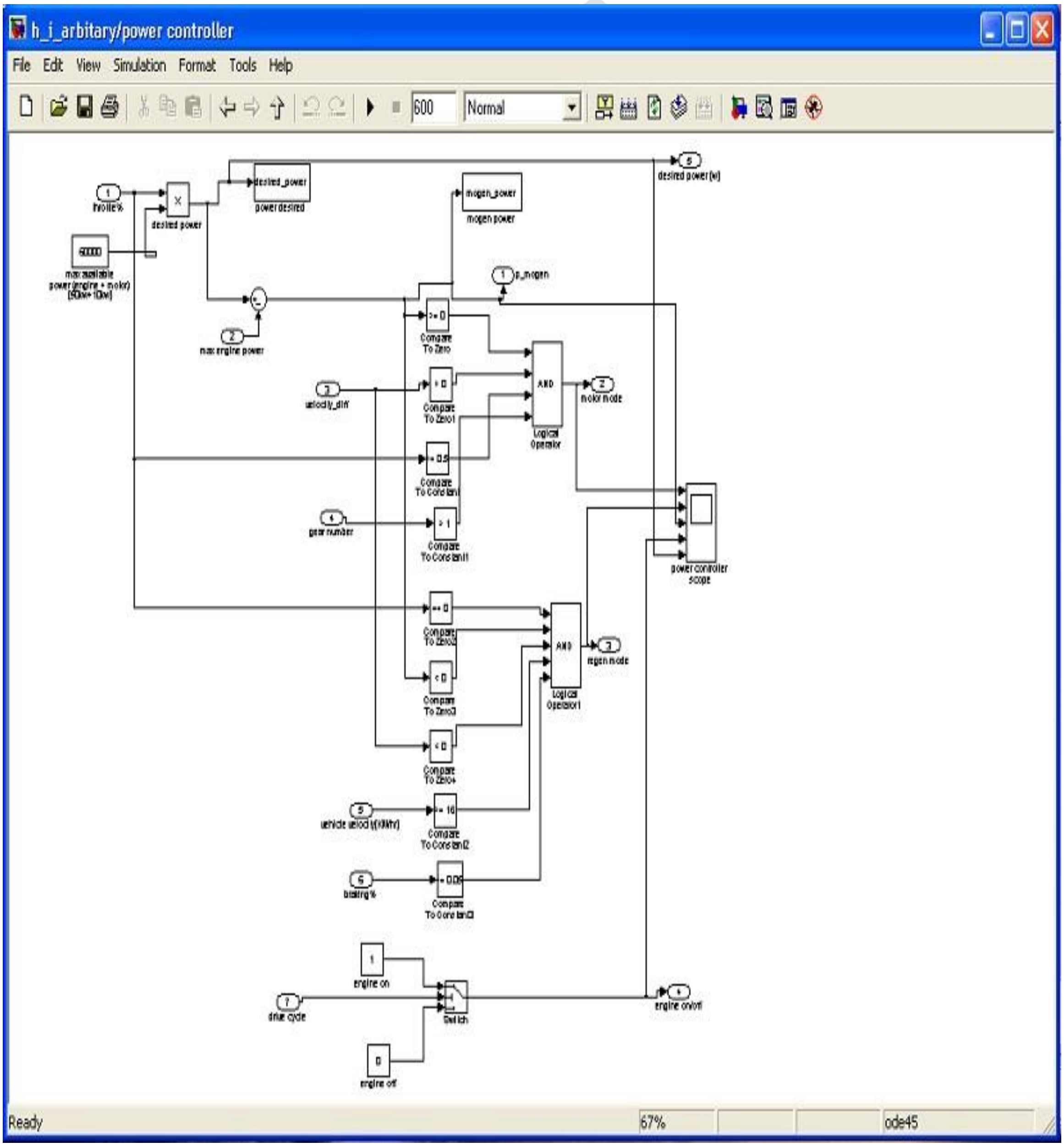

Fig. 4.6 Power Management Controller Module

In order to make PMC module more visible, two more diagrams are shown in figures 4.7 and 4.8.

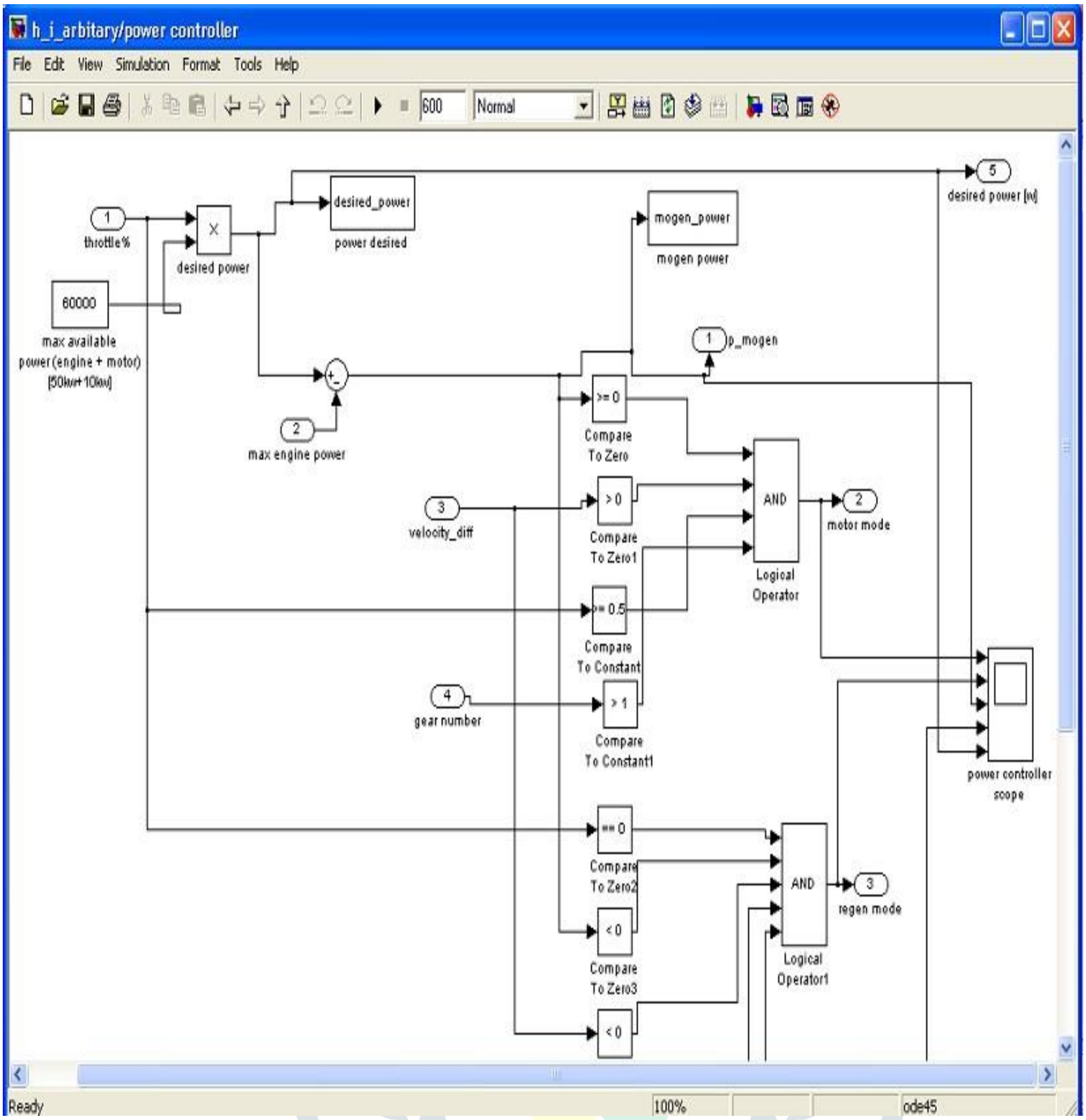

Fig. 4.7 upper half of PMC

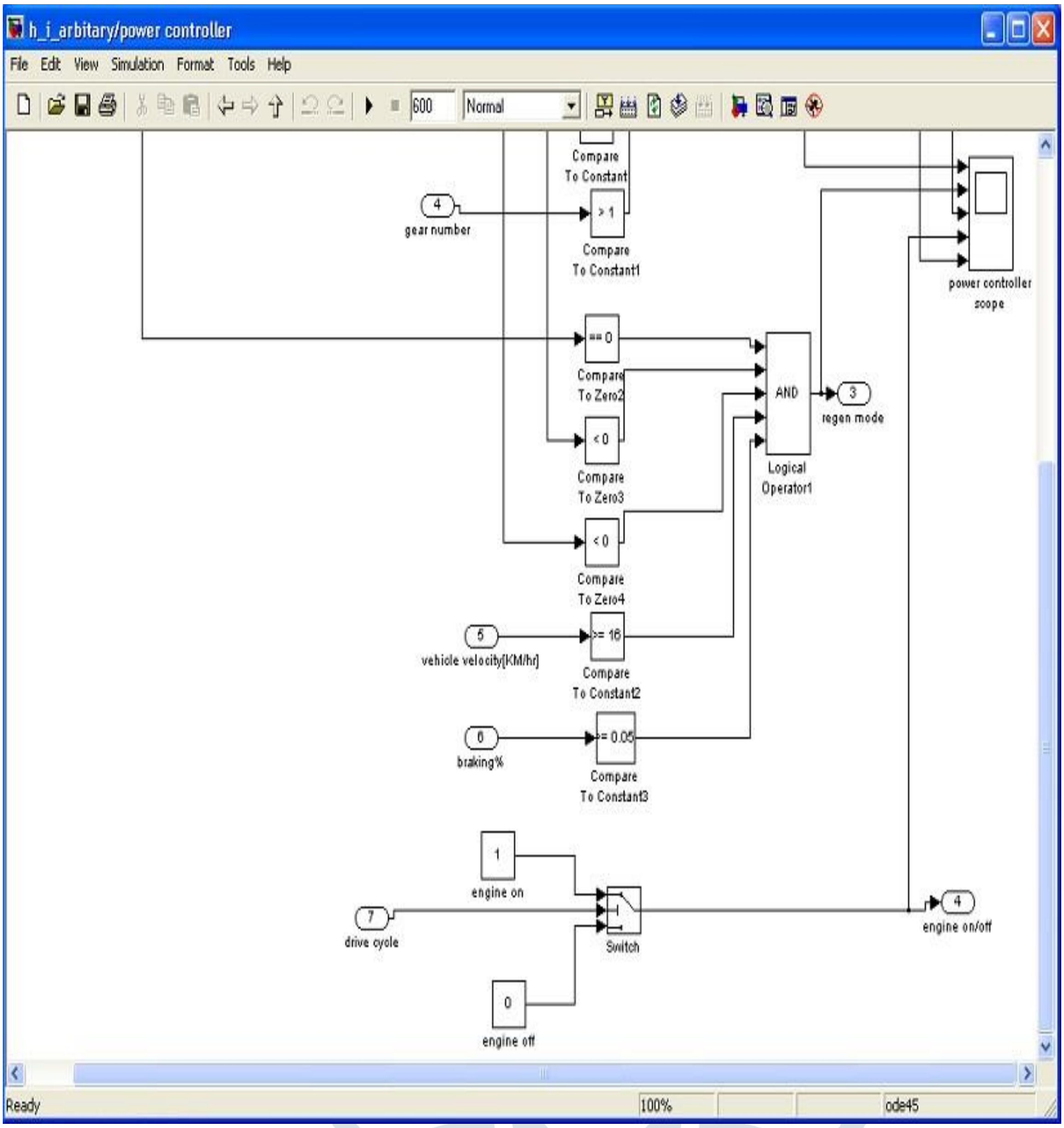

Fig. 4.8 lower half of PMC

In order to model the PMC Module some assumptions are made. It is assumed that the desired vehicle power is directly proportional to the throttle percentage. Therefore the desired vehicle power is calculated by scaling the maximum available power from the two sources. The net power available from the two sources is calculated by adding power ratings of two power sources i.e. engine (50 kW) and motor (10 kW).

The maximum available power (W) is calculated as:

$$P_{max} = P_{e,max} + P_{mo,max} \quad \ldots\ldots (1)$$

Where **Pe,max** (W) is maximum engine power and **Pmo,max** (W) is maximum motor power.

The desired vehicle power (W) is calculated as:

Pdes = PT . Pmax …..(2)

Where **PT** (0 - 1) is percentage throttle, which is obtained from driver controller.

The power required from the motor-generator is calculated by subtracting the engine maximum power from the vehicle desired power. If the difference between the vehicle desired power and the engine maximum power is positive, it means motor assist is required and the motor will provide the power which is equal to the difference between the desired vehicle power and the maximum available power of the engine. If the difference between the desired vehicle power and the maximum engine power is negative then regenerative mode can be turned on if other conditions are also satisfied. The two modes
i.e. motor assist mode and regenerative mode are modeled by using AND Boolean functions. When all the conditions are true or „1" then corresponding mode will be turned on. If any condition is not satisfied then that mode will not be turned on.

The required motor-generator power (W) is calculated as:

Pmo-gen = Pdes – Pe,max…..(3)

As discussed in section 3.6.2.1, In order to turn on the motor-assist mode following conditions have to be satisfied:

1) **Pmo-gen > 0**

2) **dv > 0**, where dv is difference between desired speed and actual vehicle speed. 3) **PT > 50%**

4) **GN > 1**, where GN is gear number.

Similar to the motor-assist mode, regenerative mode is also modeled by using AND Boolean function. The regenerative mode will be turned on when all the following conditions will be satisfied:

1) **Pmo-gen < 0**
2) **dv < 0**
3) **PT = 0**
4) **V > 16 km/hr**, where V is vehicle actual speed.
5) **PB > 5%**, where PB is percentage braking.

In addition to the motor control, the PMC also controls the engine on-off. One switch is provided to check whether the vehicle desired speed is greater then zero or not. If desired speed is greater then zero then only engine will turn on otherwise engine remains off.

The signals obtained from the power management controller are fed to the motor module and engine module in order to control their operation.

ENGINE MODULE

The engine utilized is Honda Insight engine, which is 1.0L, V-Tec, SI engine. The engine is modeled by using look-up tables and empirical formulations. The engine module calculates the engine output torque, maximum engine power and fuel consumed. The engine module is shown in figure 4.9.

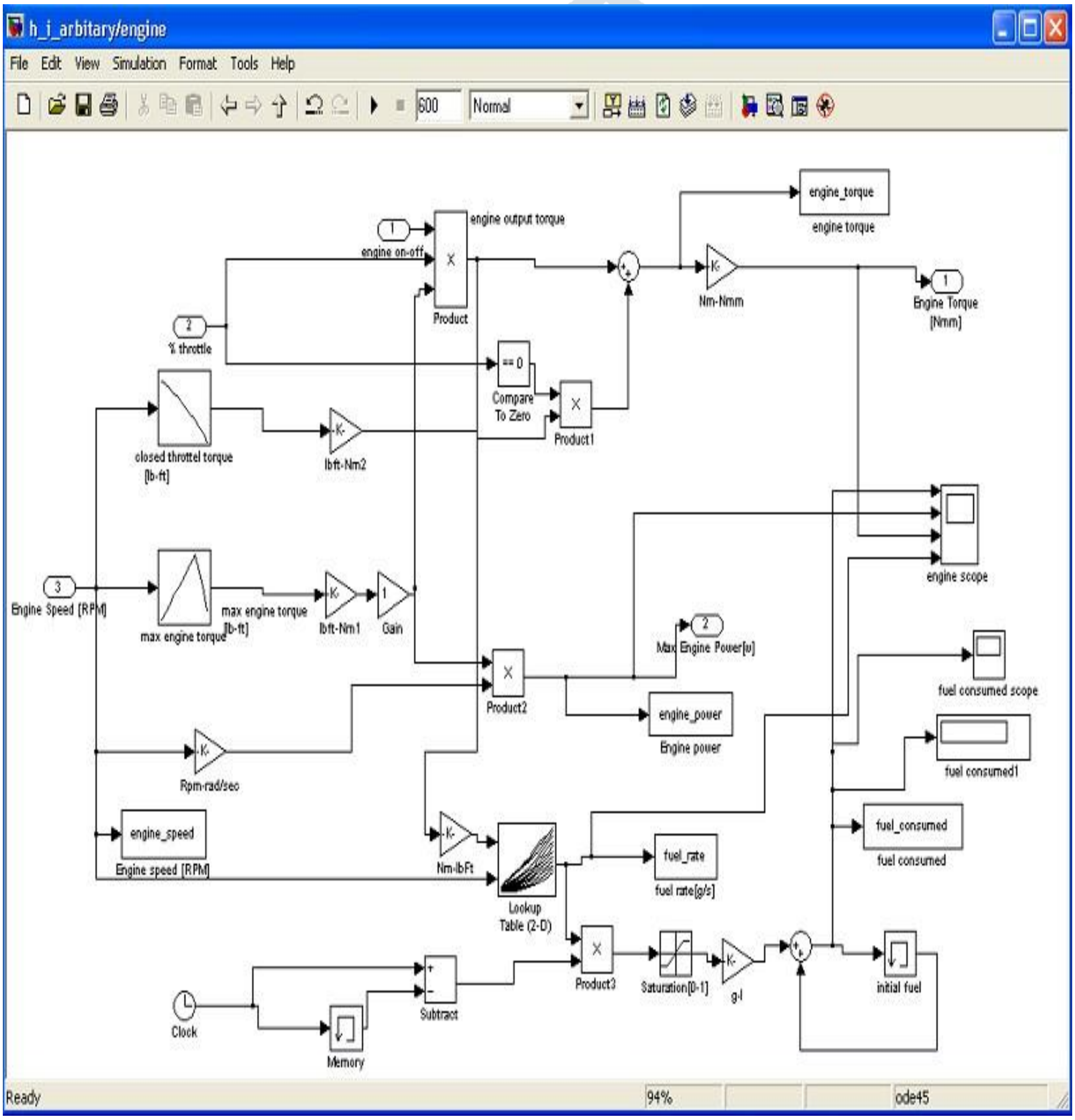

Fig. 4.9 Engine Module

As discussed in the section 3.4.1, engine module is modeled by using look up tables for close throttle torque and maximum throttle torque. Both these look-up tables are indexed by the engine speed which is obtained from the transmission module.

The engine output torque (Nmm) is calculated as:

$$T_e = PT \cdot (T_{e,max} + T_{e,c}) \quad \text{.....(4)}$$

Where PT (0-1) Is percentage throttle, Te,max (Nm) is maximum engine torque and Te,c (Nm) is close throttle torque.

The maximum engine power (W) is calculated by multiplying maximum engine torque and current engine speed:

$$P_{e,max} = T_{e,max} \cdot W_e \quad \text{.....(5)}$$

Where Te,max (Nm) is maximum engine torque and We (rad/sec) is engine speed

The engine fuel flow rate is modeled as two dimensional look-up table indexed by two parameters i.e. engine output torque and engine speed. The look-up table gives the output fuel flow rate according to these two parameters. The fuel flow rate is then interpolated to calculate the total fuel consumed. The fuel consumed at every step size is calculated and then stored in the memory. It is added with the new fuel calculated at next time step and stored in the memory. The same process continues until simulation time completes and the output is total fuel consumed per cycle.

The fuel consumed per drive cycle is calculated as:

$$F_{c\text{-}c} = F_r \cdot S_s \quad \text{.....(6)}$$

Where Fr is fuel rate and Ss is step size.

MOTOR – GENERATOR MODULE

As discussed in the section 3.4.2 the motor-generator module is also modeled by using look- up tables similar to the engine module. The motor torque and generator torque (negative of motor torque) are modeled as look-up tables indexed by engine speed, as discussed the engine speed is same as that of motor speed because the motor shaft is directly connected to the engine crank shaft. The motor module is shown in figure 4.10.

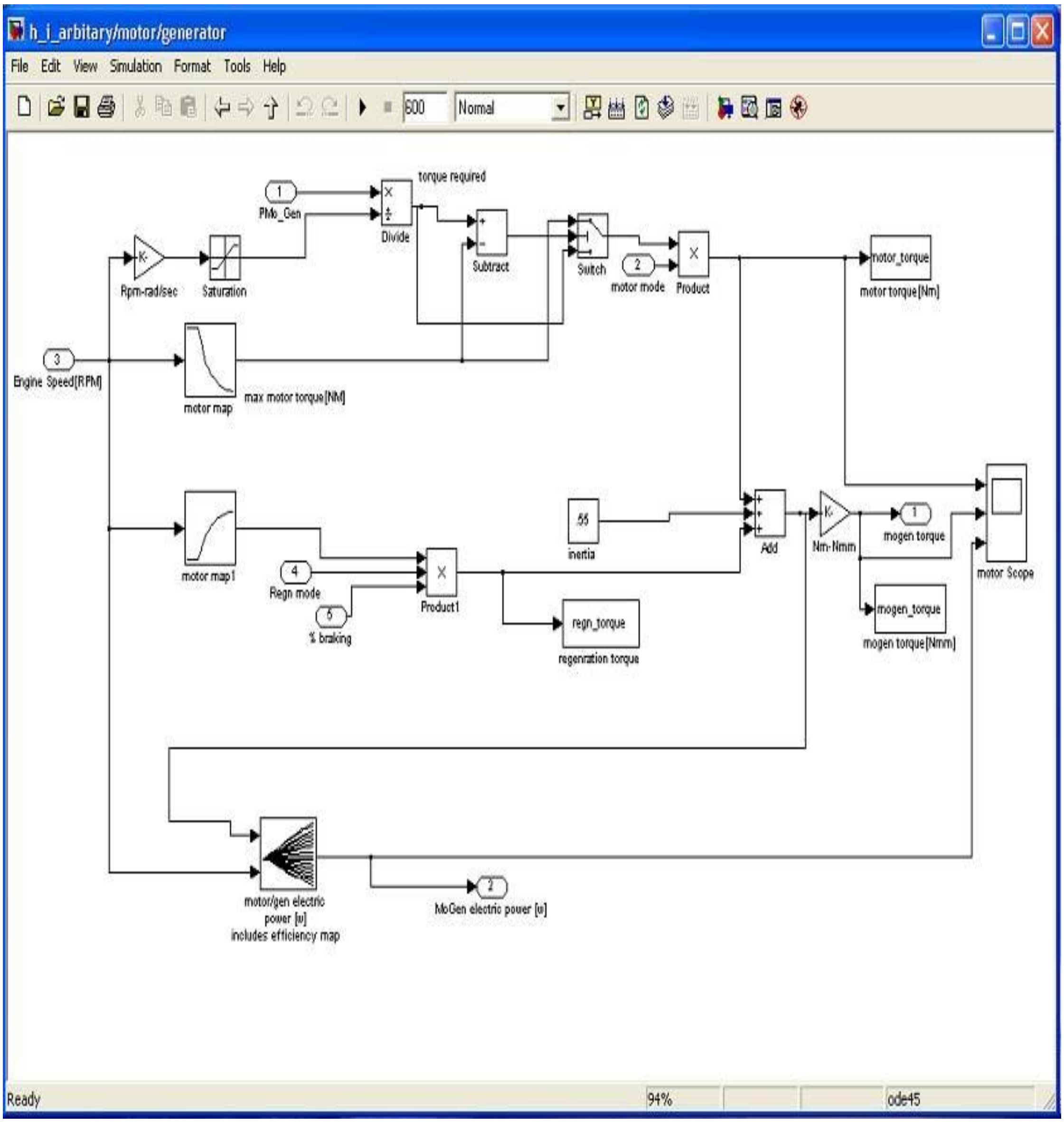

Fig. 4.10 Motor-Generator Module

The required torque is calculated by dividing the required motor-generator power obtained from the power management controller by engine speed. The required motor-generator torque (Nm) is calculated as:

$$Tr = Pmo\text{-}gen / We \quad \text{.....(7)}$$

Where Pmo-gen (W) and We is engine speed (rad/sec).

The required motor-generator torque is then checked whether it is greater or less then maximum motor torque. Accordingly the motor output torque is calculated.

If the maximum motor torque available is greater then the required torque then output motor torque will be equal to the required torque. If the maximum motor torque available is less then the required torque then motor output torque will be equal to the maximum torque available from the motor.

The motor output torque is calculated as:

If (**Tr - Tmo,max**) > 0 Then, **Tmo = Tmo,max…..(8)**

Else, **Tmo = Tr …..(9)**

Where Tr is required motor torque (Nm), Tmo,max (Nm) is maximum motor torque, Tmo (Nm) is motor output torque.

The motor also acts as generator in regenerative mode. The modes are controlled by the power management controller. During deceleration, the regenerative mode will be turned on. In order to simplify the modeling it is assumed that relationship between generator output torque and the percentage braking is linear. Therefore during the regenerative mode, the generator output torque is calculated by the scaling the maximum generator torque by percentage braking.

The generator output torque (Nm) is calculated as:

Tgen = PB . Tgen,max…..(10)

Where PB (0g – 1g) is percentage braking and Tgen,max (Nm) is maximum generator torque.

The net motor-generator torque (Nm) is calculated by adding the motor torque and generator torque:

Tmo-gen = Tmo + Tgen + Im…..(11)

Where Tmo (Nm) is motor output torque, Tgen (Nm) is generator torque, Im is motor inertia.

In addition to the torque calculations, the motor-generator module also calculates the motor-generator electric power. This power is calculated by multiplying motor-generator torque and engine speed. The power is also scaled by the efficiency. The motor efficiency map is included in appendix [2].

The motor-generator power (W) is calculated as:

Pmo-gen = N (Tmo-gen . We)…..(12)

Where N is motor efficiency, Tmo-gen (Nm) motor-generator torque and We is engine speed (RPM).

This motor-generator power calculated is input to the battery module, which calculates the energy consumed and energy regenerated.

TRANSIMISSION MODULE

As discussed in the section 3.4.4, the transmission utilized in this project is the Honda Insight, 5-speed manual transmission. Transmission module calculates the driveshaft torque from engine and motor torque. It also calculates the engine speed from driveshaft speed. The transmission module is shown in figure 4.11.

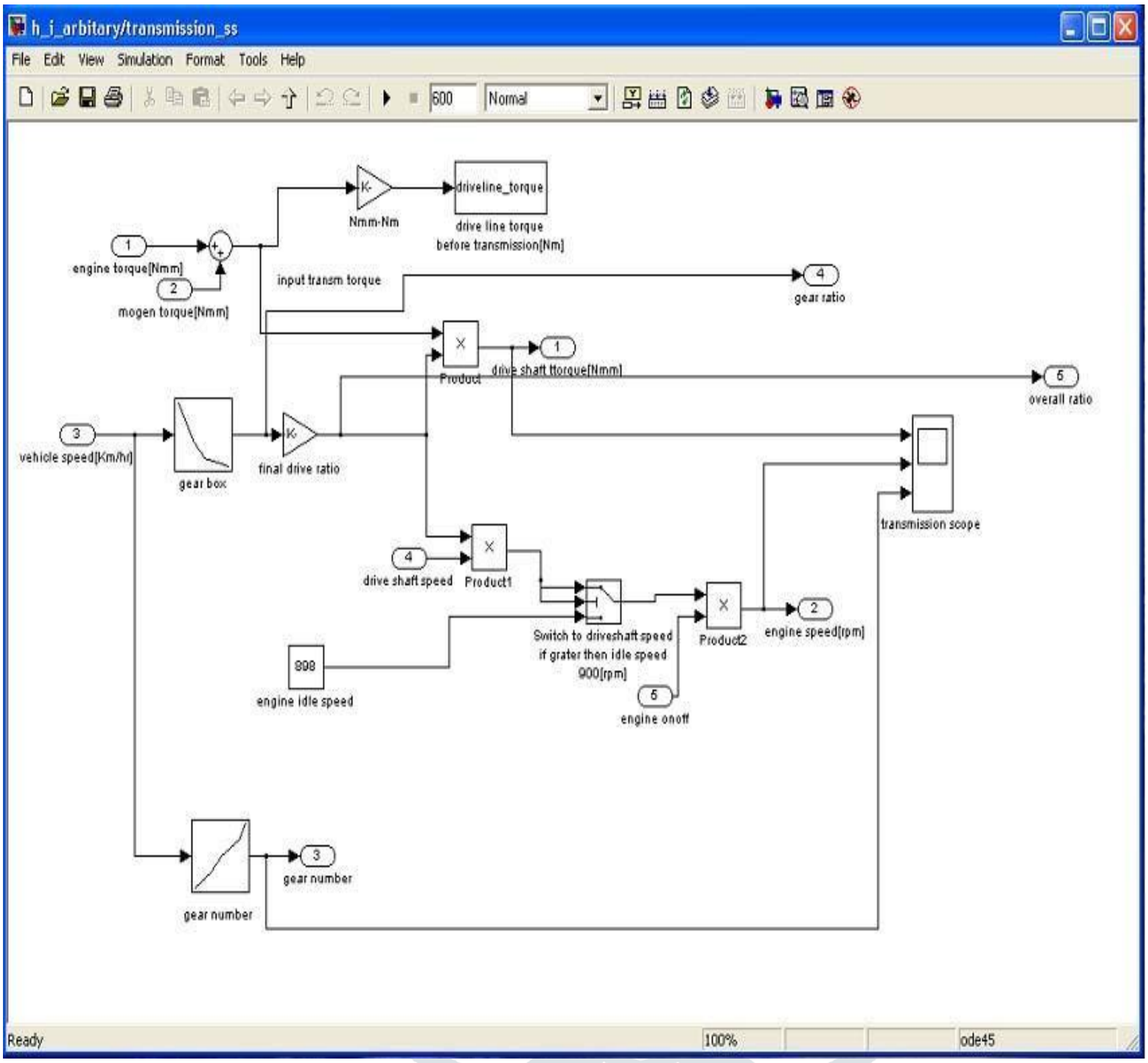

Fig. 4.11 Transmission Module

In the transmission module simple logic is used for gear shifting. The gear-ratios are modeled as look-up tables indexed by the vehicle actual speed. The overall gear ratio is calculated by multiplying the gear-ratio with the final drive ratio. Final drive ratio is modeled as constant.

The overall gear ratio is calculated as:

Ntf = Nt . Nf …..(13)

Where Nt is gear ratio and Nf is final drive ratio.

The net torque (Nmm) to the transmission is calculated by adding the engine output torque and motor-generator output torque:

Tnet = Te + Tmo-gen…..(14)

Where Te (Nmm) is engine torque and Tmo-gen (Nmm) is motor-generator torque.

The driveshaft torque is calculated by using net torque by multiplying net torque with the overall gear ratio which is calculated in equation 13 and this driveshaft torque is applied to the vehicle (vehicle module).

The driveshaft torque (Nmm) is calculated as:

$$Td = Ntf \cdot Tnet \ldots\ldots (15)$$

Where Ntf is overall gear ratio and Tnet is net transmission torque.

In addition to the driveshaft torque calculation, the transmission module also calculates the engine speed by multiplying the driveshaft speed obtained from the vehicle module with the overall gear ratio.

The engine speed (RPM) is calculated as:

$$We = Wd \cdot Ntf \ldots\ldots (16)$$

Where the Wd (RPM) is driveshaft speed, Ntf is overall gear ratio.

As discussed in the previous sections, the Integrated Motor Assist (IMA) Technology also consists of an engine idle stop system. When the engine speed is less then the idle speed (900 RPM) then the engine will be stopped. In order to model this system, a three way switch is used to check whether the engine speed is less then engine idle speed. If it is less then idle speed then engine will be stopped. In addition gear numbers are also modeled as look-up tables in transmission module. Which are utilized by power management controller to select the mode of traction motor.

BATTERY MODULE

As discusses in the section 3.4.3, the battery modeled in this project is based on the ratings of Ni-Mh battery utilized in the Honda Insight. The battery is modeled as simple energy calculation by integrating the power consumed or power generated obtained from the motor module. The energy calculated at each time step of simulation time and stored in the memory. Then the energy for next time step is calculated and added or subtracted to the energy calculated in previous time step and new energy is stored in the memory. After complete simulation time the results are obtained for energy consumed and energy calculated. In order to simplify the battery modeling some assumptions are made: 1) no- load voltage is equal to rated voltage. 2) no-load voltage is constant for different state of charge. 3) The internal resistance of the battery is zero.

The vehicle consumes the energy from the battery when vehicle runs in motor-assist mode. At this time the motor-generator power is positive. The energy consumed (kW-hr) by the vehicle is calculated as:

Ec = Integration (+ Pmo-gen)…..(17)

Where + Pmo-gen (kW) is power consumed by vehicle when traction motor is operating in motor-assist mode.

When the vehicle is decelerating, then the traction motor behaves as generator in regenerative mode. The kinetic energy of the vehicle is converted in to electric energy through regenerative braking and stored in the battery. The motor-generator power in regenerative mode is negative because the vehicle is applying the torque in reverse direction. The energy which is generated due to regenerative braking is called regenerated energy.

The regenerated energy (kW-hr) is calculated as:

Er = Integration (-Pmo-gen)…..(18)

Where –Pmo-gen (kW) is negative power during deceleration.

In addition to energy calculation the battery module also calculates the state of charge. The SOC is the most important parameter of the battery. In order to calculate the SOC, firstly the maximum battery capacity has to be calculated.

The maximum energy capacity is calculated as:

Cb,max = Cr . Vr…..(19)

Where Cr is Rated Capacity of the battery (6.5 A-hr) and Vr is Rated Voltage of the battery (144 V).

The Sate of Charge (SOC) is calculated as:

SOC = E / Cb,max…..(20)

Where E is total energy consumed and regenerated. The battery module is shown in figure 4.12.

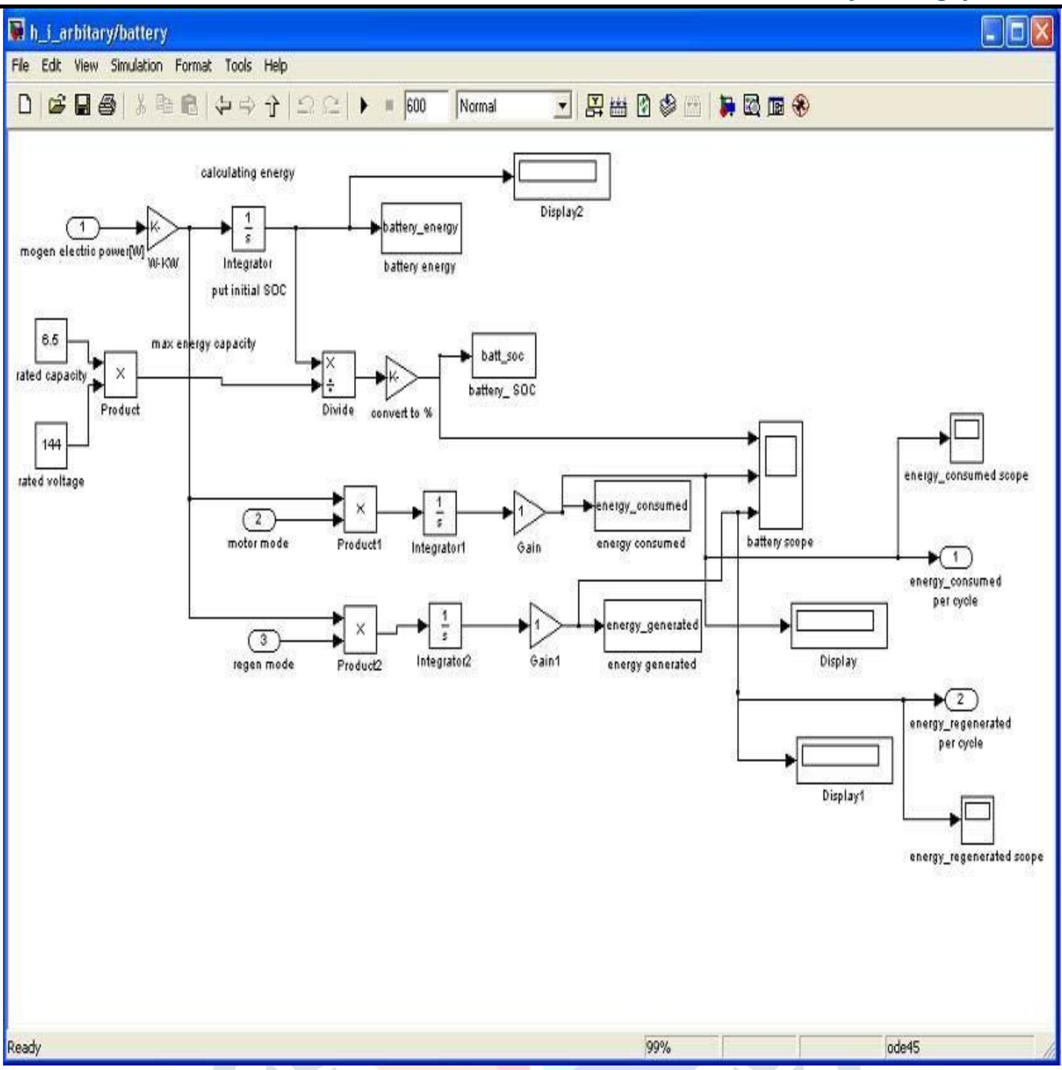

Fig. 4.12 Battery Module

VEHICLE MODULE

The vehicle module, as discussed in the section 3.5, corresponds to the vehicle dynamics. Its tough to exactly model the dynamic behavior of the vehicle by equations as so many parameters have to take in accounts. But for this project a simple vehicle module is enough to perform the functions of vehicle dynamics. The major inputs to this module are the driveshaft torque and engine speed from transmission module with other inputs. The power-train modeled gives the driveshaft torque to the wheels through the differential and final drive. The major parameters are modeled as follows:

The acceleration [m/s^2] of the vehicle is calculated as:

$$\mathbf{Ax = [1 / (M . Mf)] . [(Td . ntf) / r - Rx - Da] \ldots..(21)}$$

Where Mf is mass factor.

Td [Nm] is the drive shaft torque obtained from the transmission module. ntf is the transmission efficiency.

r (m) is the tire rolling radius.

Rx (kN) is rolling resistance of the tire. Da (kN) is aerodynamic drag.

The mass factor is calculated as:

$$Mf = 1 + .04 + .0025\ Ntf^2 \quad .....(22)$$

Where Ntf is the overall gear ratio obtained from transmission module. The rolling resistance (Rx) (kN) of the tire is calculated as:

$$Rx = Fr\ .\ (M\ .\ g) \quad .....(23)$$

Where Fr (.013) is rolling resistance coefficient modeled as constant. For concrete and asphalt road the value of Fr is taken as .013.

M (1500 kg) is the mass of the vehicle, which is also modeled as constant. The mass of Honda Insight is taken which is 1500 kg.

g (9.8 m/s^2) is acceleration due to gravity also modeled as constant.

The aerodynamic drag (Da) (kN) is calculated as:

$$Da = .5\ .\ (d\ .\ Af\ .\ Cd\ .\ V^2) \quad .....(24)$$

Where d (1.205 kg/(m^3)) is the air density which is modeled as constant.

Af (1.9 m^2) is the frontal area of the car, which is also modeled as constant. The value taken is of frontal area of Honda Insight.

Cd (.25) is aerodynamic drag coefficient modeled as constant.

V (m/s) is the actual vehicle speed which is fed back from the vehicle module after delay. The vehicle velocity is calculated as:

$$V = K\ .\ (\ Pdes\ /\ (\ Ax\ .\ M\ )\ ) \quad .....(25)$$

Where K is constant. K = 904.54.

Pdes (W) is desired vehicle power which is obtained from power management controller. Ax (m/s^2) is acceleration of the vehicle.

M (1500 kg) is the mass of vehicle, modeled as constant.

In addition to these calculations the vehicle module also calculates the driveshaft speed (RPM) from engine speed:

$$Wd = K\ .\ (\ We\ /\ Ntf\ ) \quad .....(26)$$

Where K (.93) is constant.

We (RPM) is engine speed obtained from the transmission module Ntf is overall gear ratio obtained from the transmission module.

The vehicle module is shown in figure 4.13.

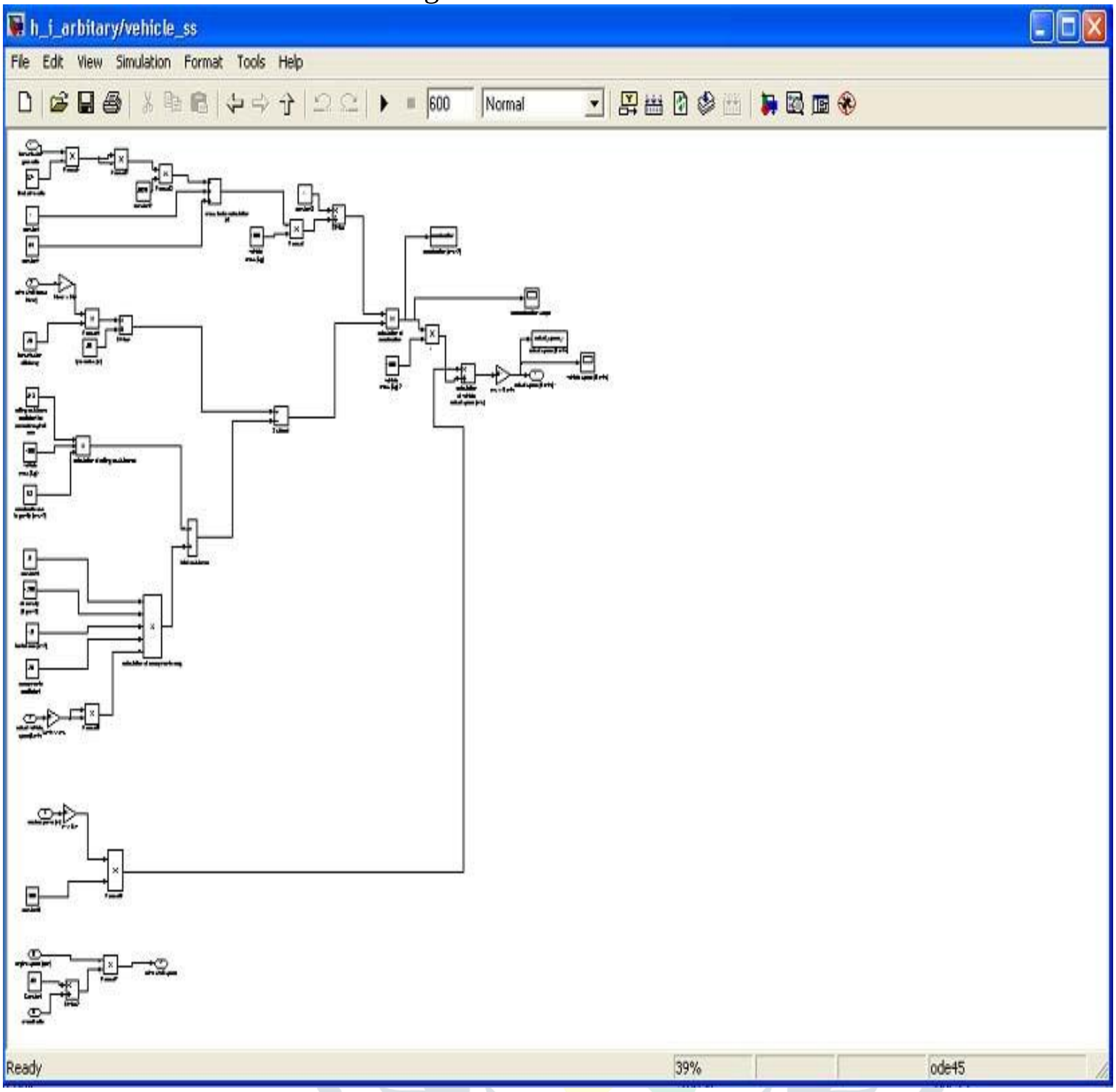

Fig. 4.13 Vehicle Module

In order to make vehicle module more visible, three more diagrams of the vehicle module are shown. The diagrams are shown in figures 4.14, 4.15, .4.16.

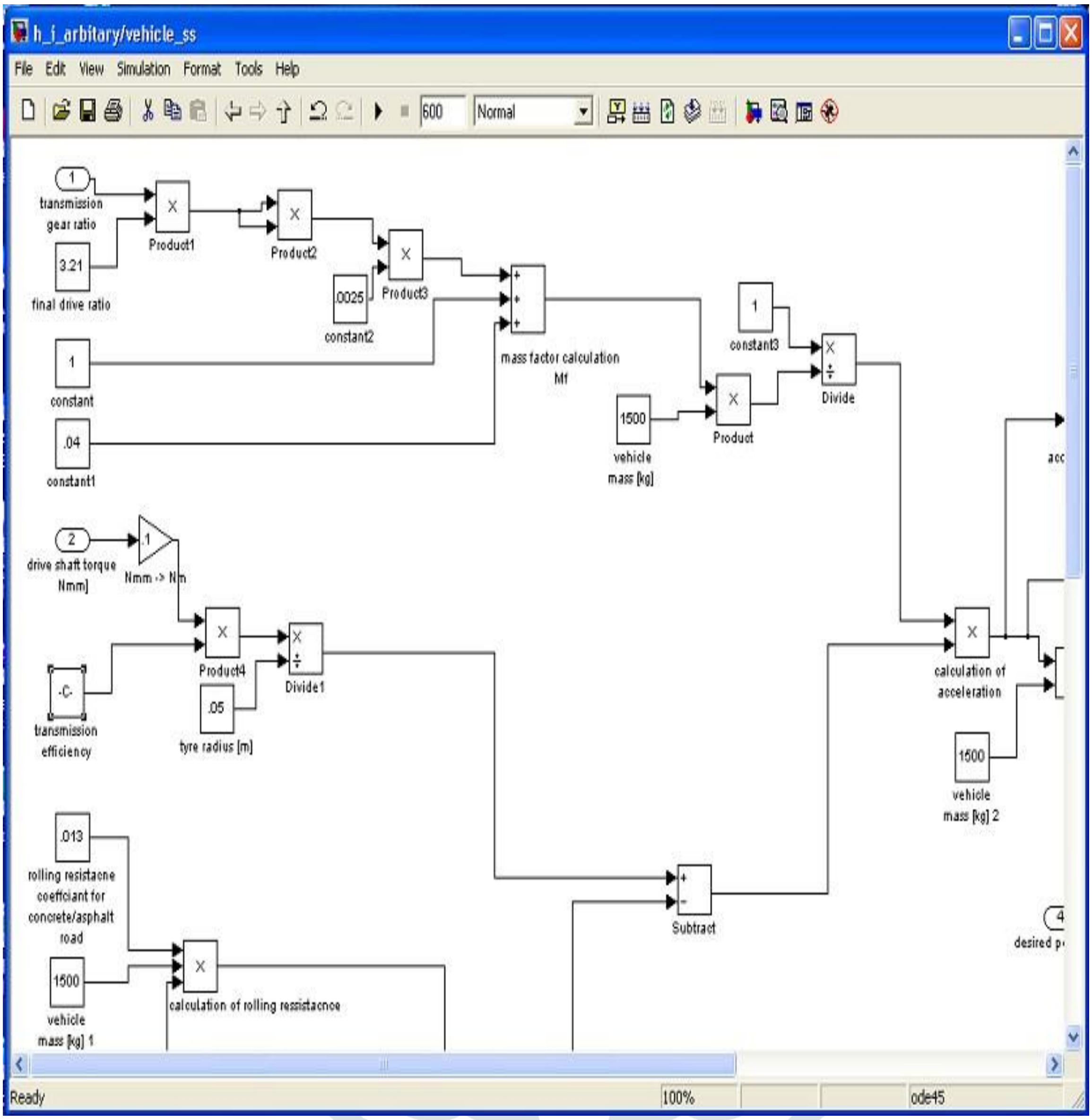

Fig. 4.14 upper half of Vehicle Module

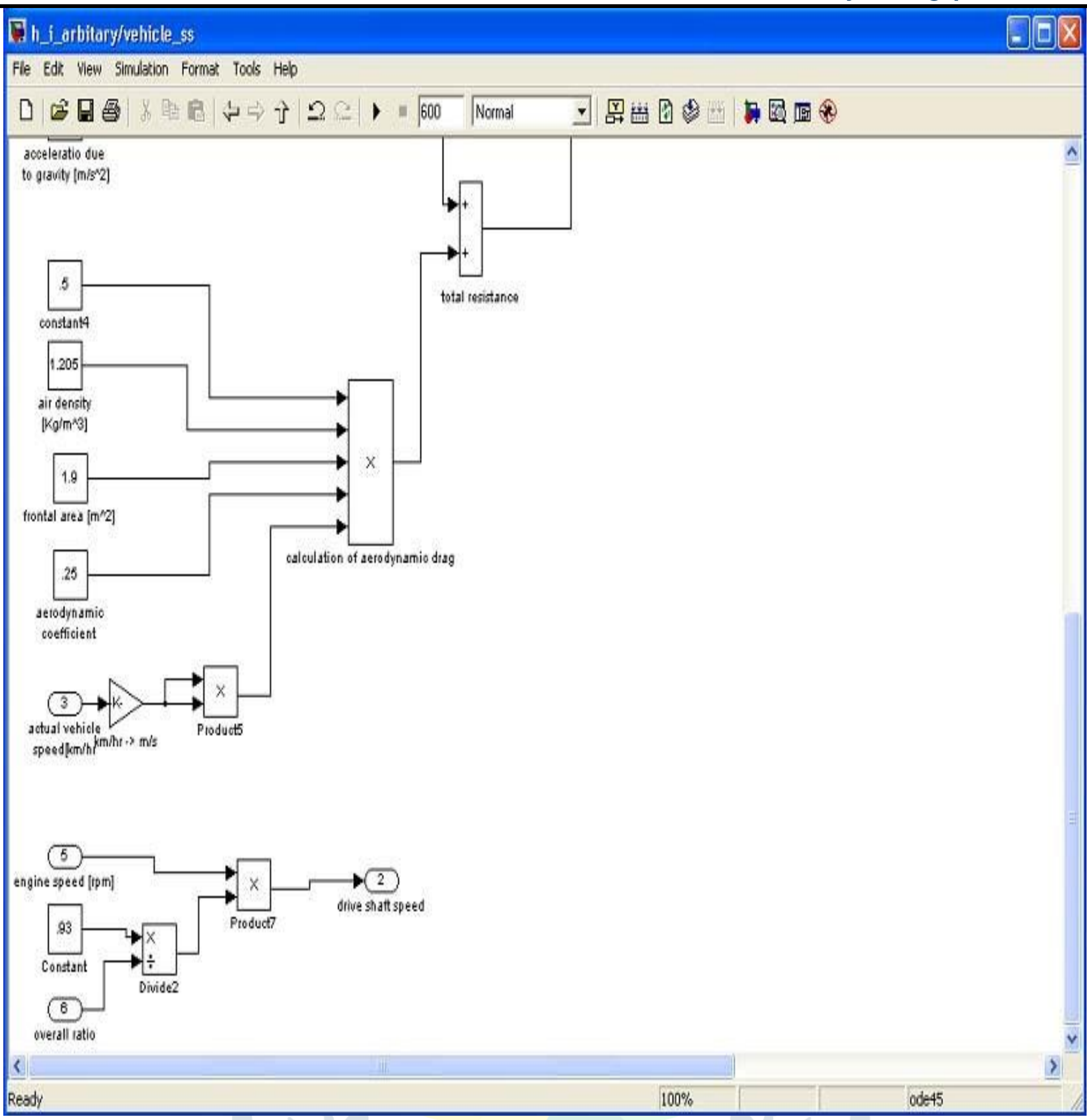

Fig. 4.15 Lower half of Vehicle Module

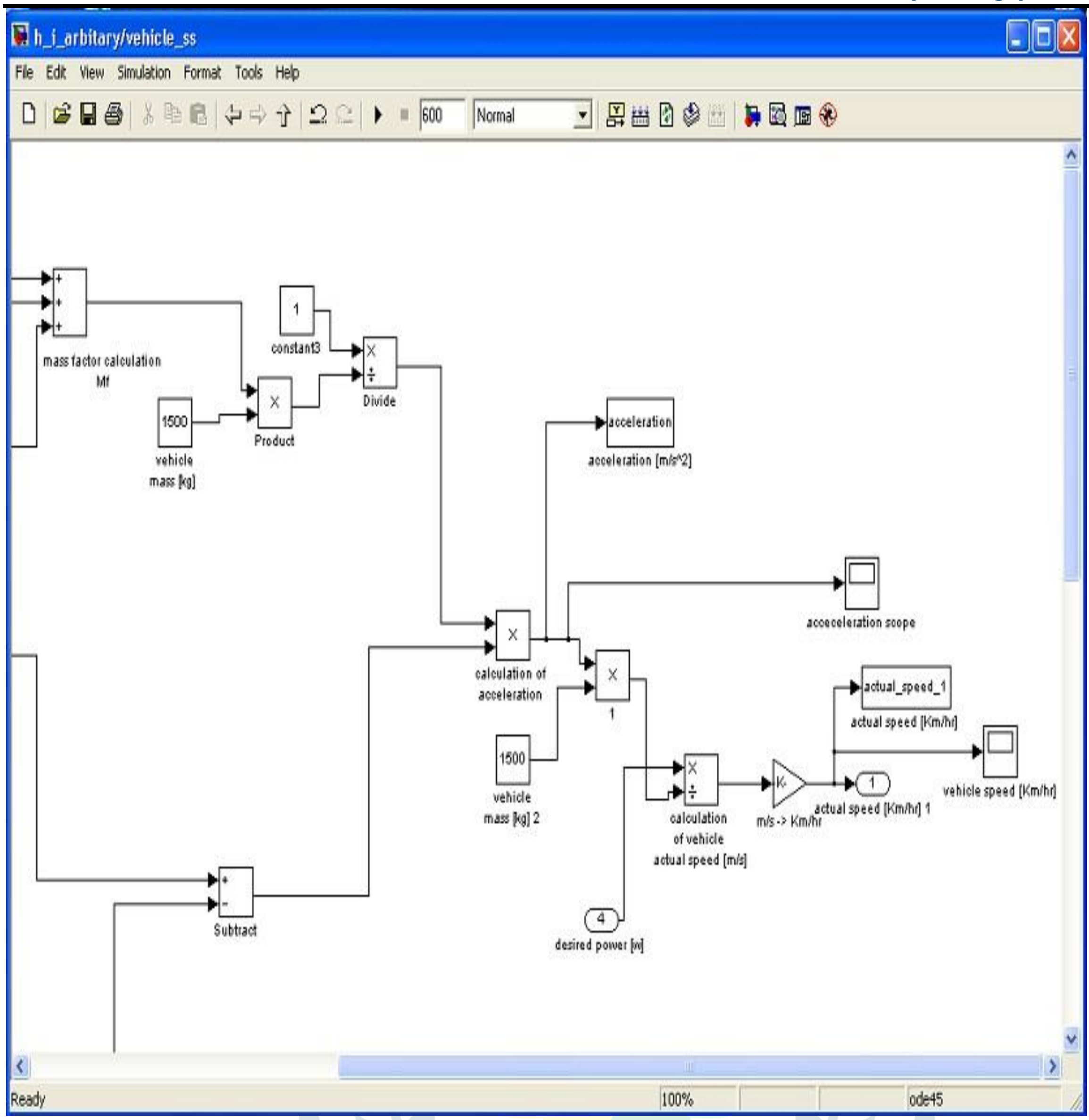

Fig. 4.16 right most of Vehicle Module

CONSTRUCTION OF HYBRID ELECTRIC VEHICLE (HEV) MODEL

As discussed in the section 4.1 the HEV model is constructed by connecting all the eight modules developed as discussed in previous sections. All the individual modules developed are drag into new MATLAB/SIMULINK model and arranged in chronological order. The output ports are connected to the corresponding input ports of the other modules.From the last module i.e. vehicle module two parameters (actual vehicle speed and driveshaft speed) are fed back to the HEV model. But in order to stabilize the complete power-train components a delay of 10ms is provided when output parameters of the vehicle are fed back to the corresponding HEV model. The HEV model is already shown in figures 4.1, 4.2, 4.3.

MODEL VALIDATION

In order to validate the HEV model developed in MATLAB/SIMULINK, the data evaluated from the HEV model is compared with the published data of the Honda Insight and the data published in the reference paper [1]. The fuel consumed per drive cycle is compared with the published fuel consumed per drive cycle data of the Honda Insight and energy regenerated and energy consumed data is compared with the published data in reference paper..

Model validation by comparing fuel consumed data with published data of Honda Insight

The fuel consumed per 100 km for Honda Insight is obtained from the site. The published data is in gallons per 100 km so it is converted into liters per 100 km. The fuel consumed is given on drive cycles NYCC. The published fuel consumed data is given in table 4.1.

Table 4.1 published fuel consumed data of Honda Insight

Drive cycle	Km	Fuel economy (miles / gallon)	Fuel consumed (liters / 100 km)
NYCC (600 sec)	1.89	60	3.9

After simulating the HEV model developed, the fuel consumed by that HEV model is evaluated. The fuel consumed data is shown in table 4.2

Table 4.2 fuel consumed by HEV model

Drive cycle	Km	Fuel economy (miles/gallon)	Fuel consumed (liters / 100 km)
NYCC (600 sec)	1.89	82	3.42

As discussed in the section 4.2 that the drive cycles utilized in this project are approximate drive cycles. So the discrepancies in evaluated data after simulation are expected.

As shown in the tables 4.1 and 4.2, the Honda Insight published fuel consumed per 100 km in NYCC (New York City cycle) is 3.9 liters. And the fuel consumed by MATLAB / SIMULINK HEV model of Honda Insight is 3.42 km. so small variation is there as it is due to the approximate drive cycle utilized for the simulation not the accurate one.Table 4.3 energy comparison of HEV model with published data

Drive cycle	Energy regenerated per drive cycle (kW-hr) (published)	Energy regenerated per drive cycle (kW-hr) (HEV model)	Energy consumed per drive cycle (kW-hr) (published)	Energy consumed per drive cycle (kW-hr) (HEV model)
NYCC (600 sec)	.2425	.3992	.2960	.2968

So after comparing two data; energy regenerated and energy consumed obtained from published data and obtained by simulating the HEV model in NYCC, it is clear that the model is almost validated against the published data. Normal discrepancies are obtained because the drive cycle utilized to simulate the HEV model is approximate drive cycle not the accurate one utilized by researchers.

Therefore the HEV model developed is MATLAB/SIMULINK is validate against the published data and can be utilized to evaluate the other performance parameters of the HEV.

4. Simulation of hev model developed in matlab / simulink

As discussed in the previous chapter, a HEV model is developed based on the Honda Insight Integrated Motor Assist (IMA) system. The HEV model is also validated against the published data of Honda Insight and published data of reference paper [1]. The simulation is the parametric analysis of performance of the HEV. The HEV model developed is simulated on three drive cycles. NYCC (New York City Cycle) drive cycle is utilized to simulate the behavior of city traffic driving pattern. HWFET (Highway Fuel Economy Cycle) drive cycle is utilized to simulate the behavior of Highway and third drive cycle utilized is WVU5 (West Virginia University five peak cycle), which includes the constant acceleration and constant velocity driving pattern. The major parameters which are evaluated are energy regenerated, energy consumed and fuel consumed. As discussed in the previous chapter,

SIMULATION RESULTS FOR HEV MODEL

The New York City Cycle (NYCC) is utilized so that the vehicle can be tested on traffic conditions. The approximate NYCC is shown in figure 5.1. The HEV model is simulated on this drive cycle and major parameters are evaluated. The graphs obtained for energy regenerated and energy consumed are shown in figures 5.2 and 5.3 respectively.

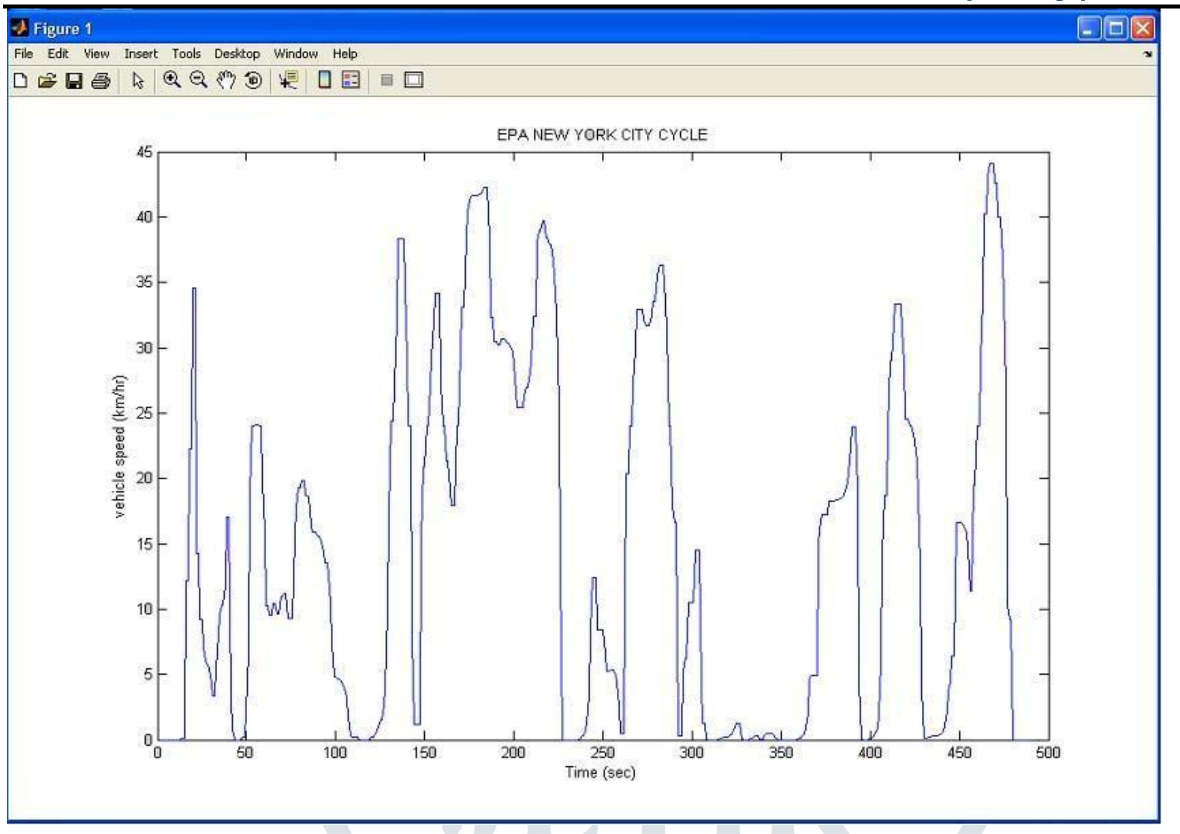

Fig. 5.1 New York City standard drive cycle

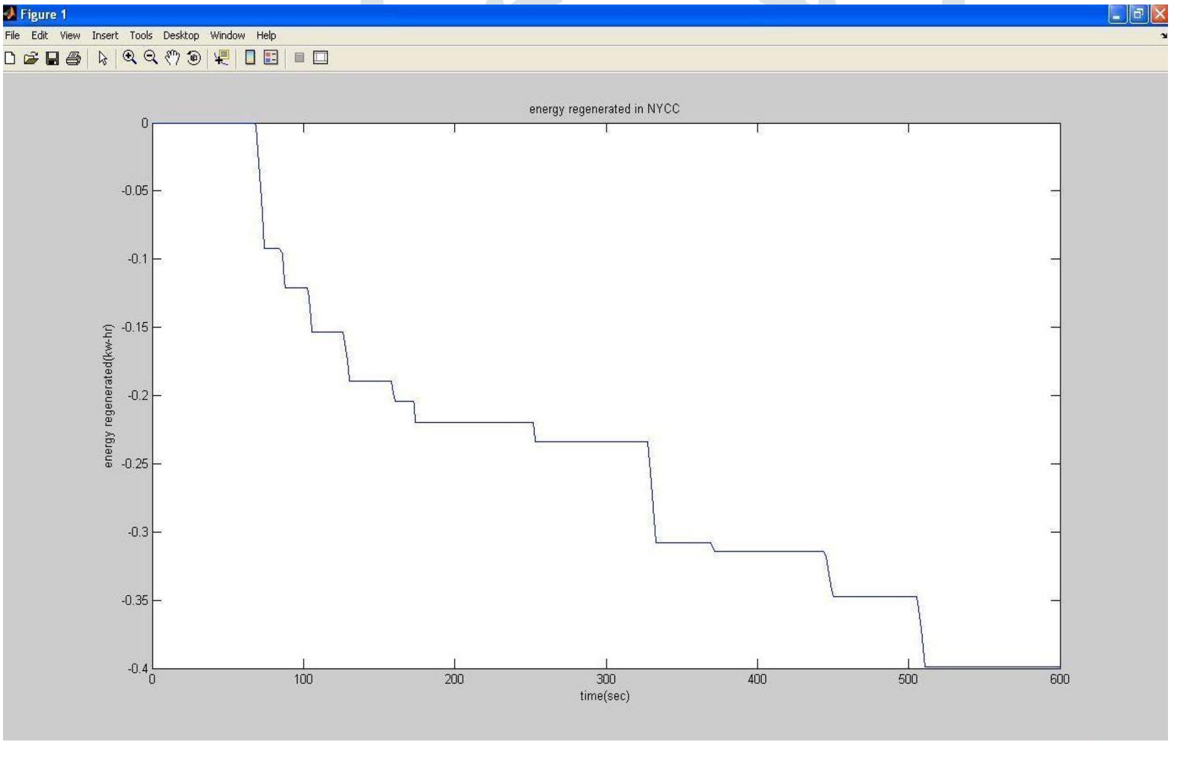

Fig.5.2 energy regenerated by HEV in NYCC

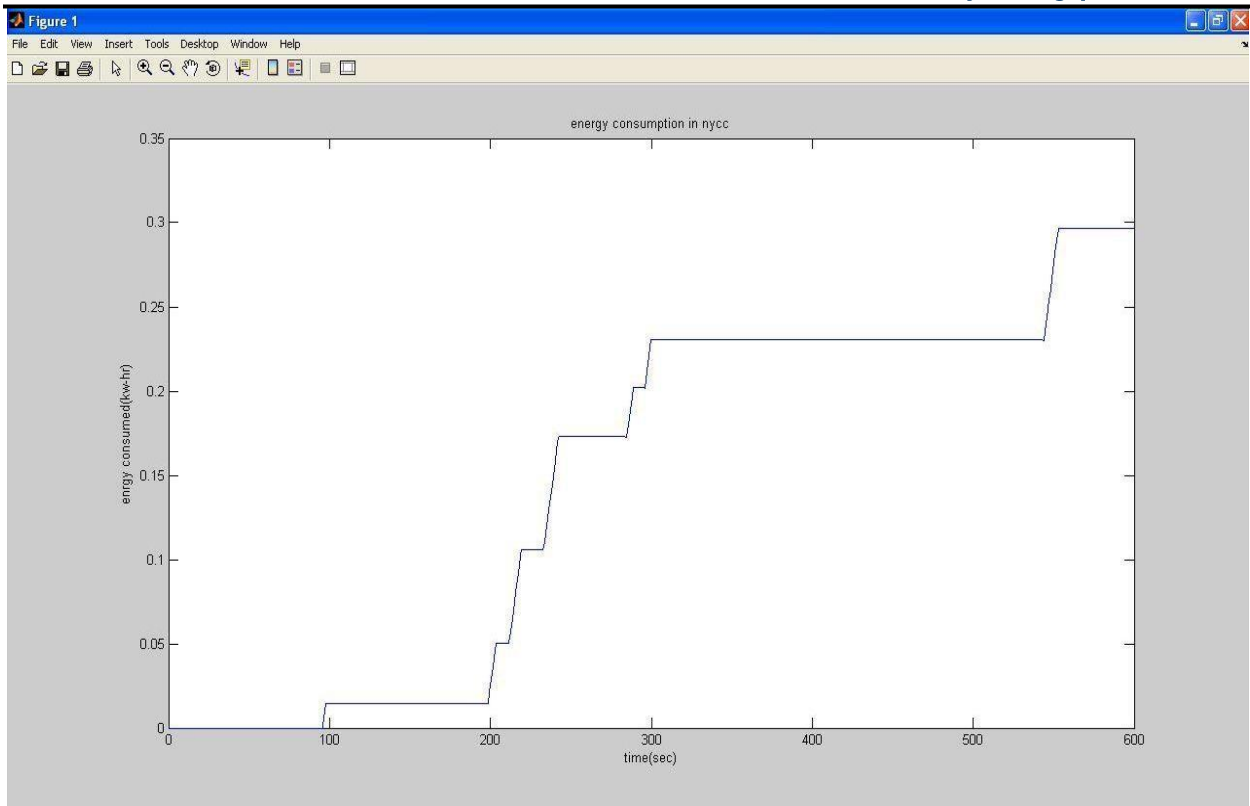

Fig.5.3 energy consumed by HEV in NYCC

The values of parameters (energy regenerated, energy consumed and fuel consumed) are evaluated after simulating the HEV model are given in table 5.1.

Table 5.1 major parameters evaluated after simulating HEV model

Drive cycle	Energy regenerated (kW- hr)	Energy consumed (kW-hr)	Fuel consumed (liters)
NYCC (600 sec)	-.3992	.2968	.06464
WVU5 (820sec)	-.5994	.7934	.09908

After evaluating the energy parameters, it is clear that the HEV model developed in MATLAB / SIMULINK is working fine; the energy regenerated in highway cycle is lesser then that of energy regenerated in city cycle, because the application of the brake during highway is less then application of brakes during city cycle due to traffic. Less application of brakes means less regenerative braking used, and hence less energy is regenerated during highway cycle as comparison to the city drive cycle.

On the other hand if fuel consumed data is compared; the fuel consumed in highway drive cycle is more then in city drive cycle. Because as discussed in previous chapters, during highway drive cycle, the power required by the vehicle is more, which can not be full-filled by the electric motor as motor can not produce high power at high RPM. Therefore during highway driving, the engine is utilized by the vehicle to obtain the required power. Hence more fuel is consumed. Whereas, during city driving, the power requirement of the vehicle is less and electric motor can provide that power. Therefore, during city driving less engine is used and hence fuel consumption during city drive cycleis less.

5. Conclusion

The hybrid electric vehicle (HEV) model is constructed in MATLAB/SIMULINK based on the Honda Insight Integrated Motor Assist (IMA) power train. The engine utilized is

1.0 L, V-Tec, SI engine and motor utilized is 10 kW permanent magnet DC brushless motor. The data are obtained from the published data of Argonne National Laboratory (ANL) site. The model consists of 8 modules namely: Drive cycle, Driver Controller, Power Management Controller, Engine, Motor-Generator, Transmission, Vehicle and Battery Module. The simulation of HEV model is conducted to evaluate the major performance parameters: energy regenerated, energy consumed, fuel consumed. In order to validate the model, the parameters evaluated after simulating the HEV model are compared with the published data of the Honda Insight.

The MATLAB / SIMULINK hybrid electric vehicle (HEV) model provides modular, flexible and easily modifiable platform so that different kind of HEV can be modeled and simulate to virtually investigate there performance prior to the actual manufacturing of the HEV.

6. Future scope

The MATLAB / SIMULINK HEV model can be utilized in the future to investigate the performance of the other HEV. New HEV can be designed theoretically to find out power sources (engine, motor, battery) specification and then the MATLAB / SIMULINK HEV model can be used to evaluate the other performance parameters of that HEV on different driving cycles. In future new driving cycles can also be included for example Indian metropolitan cities driving cycles, and the performance of the HEV can be analyzed on these new driving cycles. The power management controller (PMC) module can be developed more sophisticated to model other sophisticated HEV power-trains like, series, parallel, complex and mild hybrid power-trains. The driver controller module can be made more sophisticated to include the real-life behavior of the driver like its timing to react to sudden accidental circumstances. The engine module and the motor generator module can be made not only by look-up tables but also by equations so that there performance can be checked more dynamically. The Transmission module can also modified for automatic transmission and can also contain the clutch logics. The vehicle module can be made more complex to include more vehicle dynamics parameters. Finally the Battery module can be made more sophisticated to include more parameters like variation of internal resistance with battery state of charge.

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