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Study Power Management of Hybrid Electric Vehicle Using Battery Model Simulation

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Abstract This paper discusses the need for modeling and simulation of hybrid electric vehicle (HEV) Different modeling methods are presented with powertrain component and system modeling examples. The mattlab/simulink modelling and simulation of the hybrid electric vehicle (HEV) are represented in this paper. This simulation tool is meant as a help in the design and evaluation of the hybrid electric vehicle. Components in the driveline can be varied and the effect on the hybrid electric vehicle efficiency can be investigated. Both simulation tools are consist of a simulink vehicle model, where the driveline components are represented as interconnected blocks that are communicating physical signals between each other in the level of seconds. The demonstration shows different operating modes of the HEV over one complete cycle: accelerating, cruising, recharging the battery while accelerating and regenerative braking.

Keywords: *hybrid electric vehicle simulation, hybrid vehicles, modeling and simulation, physics-based modeling*

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1. Introduction

Hybrid electric vehicle are propelled by an internal combustion engine (ICE) and an electric motor/generator (EM) in series or parallel configurations. The ICE provides the vehicle an extended driving range, while the EM increases efficiency and fuel economy by regenerating energy during braking and storing excess energy from the ICE during coasting. Many HEV projects reported fuel economy improvement from 20% to 40% [1]. Therefore, HEV provides a promising solution to relieve the energy shortage as shown Figure 1. Design and control of such powertrains involve modeling and simulation of intelligent control algorithms and power management strategies, which aim to optimize the operating parameters to any given driving condition. [1]. Traditionally there are two basic categories of HEV, namely series hybrids and parallel hybrids [1]. In series HEV, the ICE mechanical output is first converted to electricity using a generator. The converted electricity either charges the battery or bypasses the battery to propel the wheels via an electric motor. This electric motor is also used to capture the energy during braking. Aparallel HEV, on the other hand, has both the ICE and an electric motor coupled to the final drive shaft of the wheels via clutches. This configuration allows the ICE and the electric motor to deliver power to drive the wheels in combined mode, or ICE alone or motor alone modes. The electric motor is also used for regenerative braking and for capturing the excess energy of the ICE during coasting. Recently, series-parallel and complex HEV have been developed to improve the power performance and fuel economy [2]. The HEV powertrain design process is aided by modeling and simulation. Several models and control algorithms were proposed and implemented [3,4,5,6]. Issues such as battery modeling, torque management, control algorithms and vehicle simulation, were addressed by using simulation tools such as Matlab/Simulink. Computer models are readily available for these purposes [7]. In this study, two general issues of hybrid electric vehicles were reviewed, including the state-of-the-art powertrain configurations and advanced energy storage systems. Comparisons were made to find optimal design for certain application. A review of vehicle simulation tool was carried out. Two modeling platforms introduced in detail were Matlab/Simulink and Modelica/Dymola. These simulation packages were used extensively through this study.

2. Modes of Operation

With the architecture depicted various operating modes for the vehicle can be achieved. These operating modes have been summarized in Table 1. During a typical driving mission, the HEV operates in both hybrid, and conventional modes [2]. This can be seen in the table below from the battery and assist the ICE with motoring the vehicle during four-wheel drive situations. The ISA shares similar options during Normal mode. Basically, the 4WD mode is merely a derivative of the Normal mode with the EM motoring and the ISA generating the electrical power needed (a series/parallel hybrid combination). The vehicle enters Deceleration mode when the driver uses the brakes to slow the vehicle. Here the concept of “Regenerative braking” is implemented.

Regenerative braking involves the process of using the resistance between the field and armature of the EM to generate power to replenish the battery. As the driver applies the brake, for a set distance of pedal travel, the mechanical braking system does not activate and the EM absorbs torque off of the rear axle. This mechanical energy is converted to electrical energy and sent to the battery [6].With each of these, the fuel efficiency increases and the emissions decrease immensely. During the idle mode, and decelerating cases the ICE is be turned off, unless recharging of the battery requires this to drive the ISA to provide the necessary power (series HEV). The fuel efficiency can increase by as much as 10% simply by eliminating fuel flow to the ICE during braking and idling situations [5]. This concept accompanies the general rule that the EM should be used during launch and immediate power request situations [6]. This is because electric actuators can deliver high torque at low speeds while emitting no environmentally harmful by-products. This general rule is satisfied during Electric Launch mode when the EM motors (MOT.) the vehicle. After a set speed, the ICE turns on during the Engine Start mode [8]. Once the ICE is up to speed, the automatic transmission engages and the ICE becomes the primary actuator for vehicle propulsion. At this point, the vehicle enters the Normal mode. Between the Electric Launch and Normal mode, the HEV satisfies the constraints of being a parallel HEV as previously defined. Note that during Normal mode, the EM can be used to supply regenerative power to the battery; moreover, the EM can draw power.

Table 1.Vehicle Operating Modes [2]

MODE	ICE	ISA	EM	TRAN.
Idle	Off	Off	Off	Neutral
ICE, EM, AND, ISA ARE SHUTOFF, ELECTRICAL ACCESSORIES.				
ELECTRIC LAUNCH	OFF	MOT.	OFF	NEUTRAL
VEHICLE STARTED FROM WITH EM.				
ENGINE START	START	MOT.	MOT.	NEUTRAL
ATA CERTAIN VEHICLE, ICE QUICKLY STARTED BY ISA.				
NORMAL	ON	MOT. OR GEN.	MOT. OR GEN.	DRIVE
TORQUE REQUESTS DETERMINED BY PRIMARY CONTROL STRATEGY.				
DECELERATION	ON OR OFF	GEN.	GEN.	DRIVE OR NEUTRAL
REGENERATIVE BRAKING BY EM AND ISA AS BATTERY ALLOWS.				
4WD	ON	GEN. OR OFF	MOT.	DRIVE
EM RECEIVE CONTINUOUS POWER THROUGH DC BUS FROM ISA.				

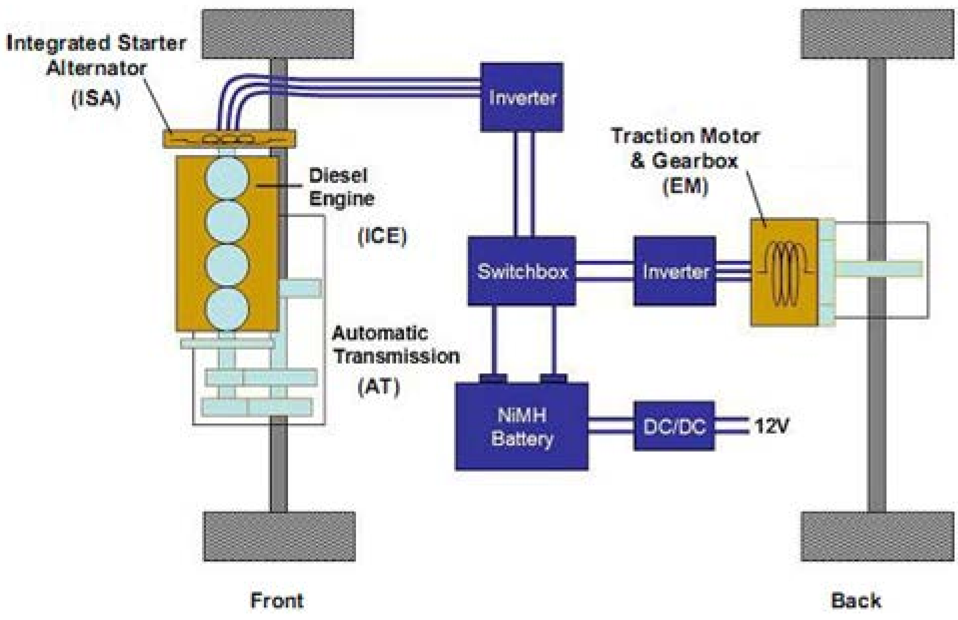

Figure 1. Ohio State Challenge X Vehicle Architecture [5]

3. Model of the Driveline

The dynamic model of the driveline is displayed in Figure 2. Refer to Table 2 of the Appendix for a list of the nomenclature. Only the necessary inertias are included in the model.

The inertias of the smaller components (the axles, brake assemblies, and wheels) do not have a drastic effect on the dynamics of the system and can be ignored for simplicity. Unnecessary damping and spring effects such as those intrinsic to the automatic transmission and rear gearbox are also eliminated to further simplify the model. Disregarding these dynamic effects does not alter the accuracy of the model since they are insignificant in comparison to other driveline components (i.e. ICE, EM, and ISA) [9]. The equations that follow are developed by the author, as well as separately.

Table 2. VW ICE microbus technical specification

Body type	Body on frame	
Dimensions	Overall length (mm)	4360
	Wheelbase (mm)	2560
	Overall width (mm)	1700
	Front tread (mm)	1430
	Rear tread (mm)	1422
	Overall height (mm)	1920
	Curb weight (kg)	1500
	Cross weight (kg)	2200
Engine	Capacity (CC)	1584
	Fuel system	Solex 30 PICT-3 carburetor
	Fuel	Gasoline
	Number of cylinder	4
	Max. power (HP @ rpm)	57 @ 4400
	Max. torque (Nm @ rpm)	114 @ 2400

Figure 2. Hybrid microbus

There are different between the hybrid microbus performance and the ICE microbus this difference will be shown in the plot of the relation between the speed & power for two microbuses and the speed & Torque relation Figure 3.

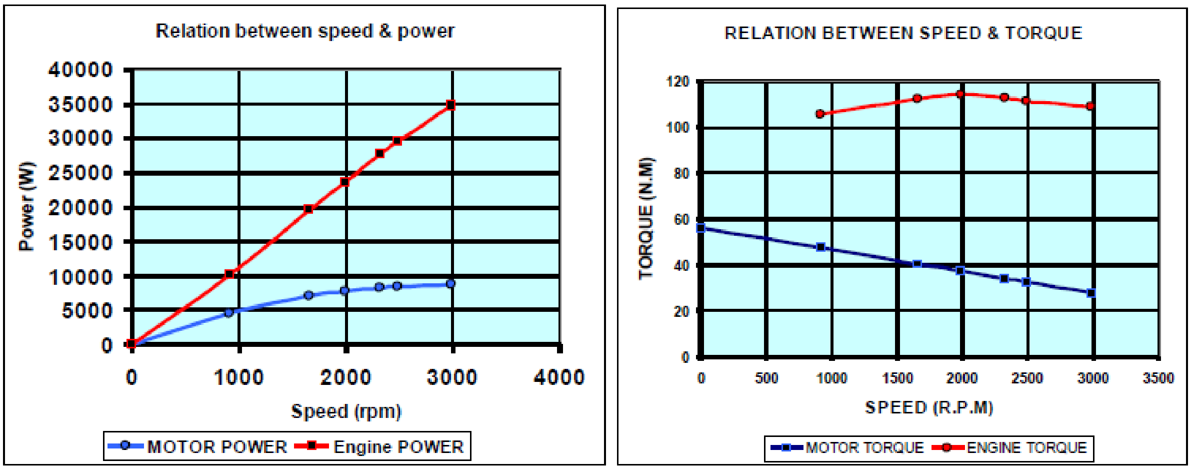

Figure 3. performance for hybrid and IC engine

4. Vehicle Simulation Tools

Simulation based analysis on vehicle performance is crucial to the development of hybrid powertrain since design validation using costly prototype is impractical. Due to the in convenience of the many separated modeling methods, integrated modeling tools are required to speed up the modeling process and to improve the accuracy. Vehicle simulation is a method for fast and systematic investigations of different design options (fuel choice, battery, transmission, fuel cell, fuel reformer, etc.) in vehicle design and development. At present, several simulation tools based on different modeling platforms are available, although none of them is sufficient to model all design options. These tools always focus on a specific application with focused concerns [1]. After years of continuing improvements, a fast, accurate and flexible simulation tool is still under development. Among the most widely used vehicle modeling and analysis platforms are MatLab/Simulink and Modelica/Dymola [10].

5. Hybrid Electric Vehicle Power Train Using Battery Model

This example shows a multi-domain simulation of a HEV power train based on Sim PowerSystems and SimDriveline. The HEV power train is of the series-parallel type [2]. This HEV has two kinds of motive power sources: an electric motor and an internal combustion engine (ICE), in order to increase the drive train efficiency and reduce air pollution. It combines the advantages of the electric motor drive (no pollution and high available power at low speed) and the advantages of an internal combustion engine (high dynamic performance and low pollution at high speeds).

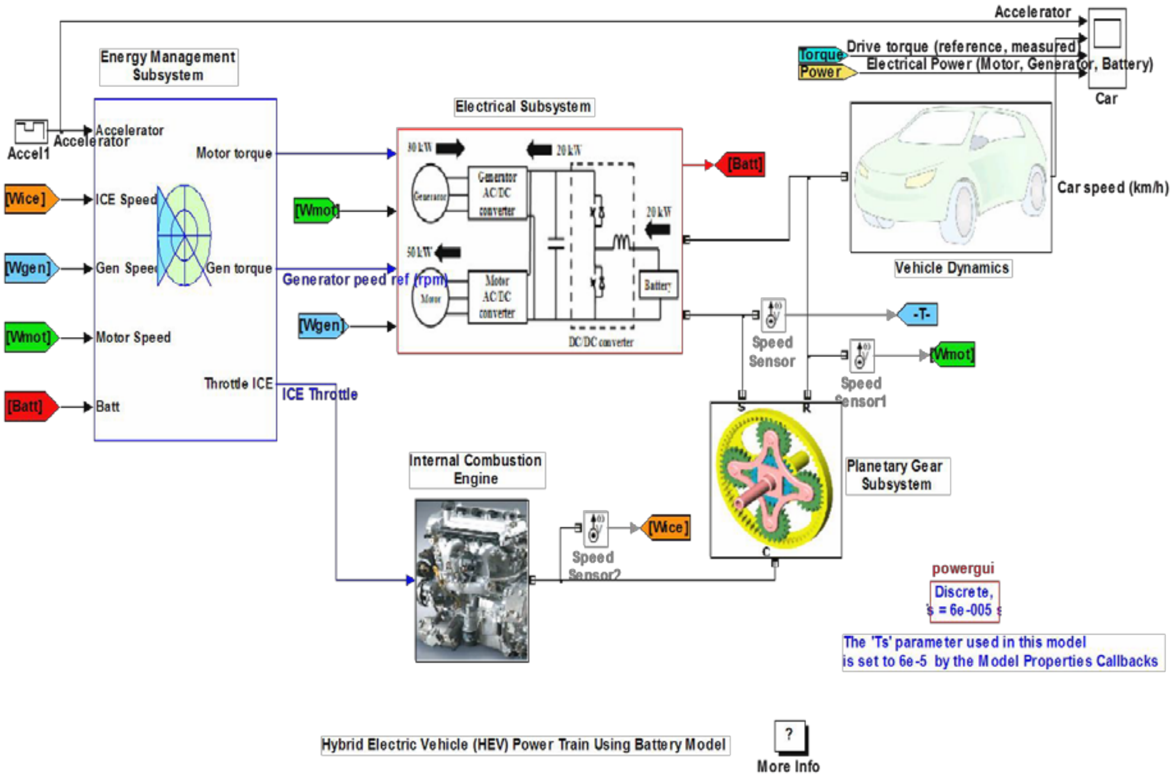

Figure 4. Simulation Model in SIMULINK for Hybrid Electric Vehicle Power Train Model

a- Electrical Subsystem

The **Electrical Subsystem** is composed of four parts: The electrical motor, the generator, the battery, and the DC/DC converter.

- The electrical motor is a 500 Vdc, 50 kW interior Permanent Magnet Synchronous Machine (PMSM) with the associated drive (based on AC6 blocks of the SimPowerSystems Electric Drives library). This motor has 8 pole and the magnets are buried (salient rotor's type). A flux weakening vector control is used to achieve a maximum motor speed of 6 000 rpm.
- The generator is a 500 Vdc, 2 pole, 30 kW PMSM with the associated drive (based on AC6 blocks of the SimPowerSystems Electric Drives library). A vector control is used to achieve a maximum motor speed of 13000 rpm.
- The battery is a 6.5 Ah, 200 Vdc, 21 kW Nickel-Metal-Hydride battery.
- The DC/DC converter (boost type) is voltage-regulated. The DC/DC converter adapts the low voltage of the battery (200 V) to the DC bus which feeds the AC motor at a voltage of 500 V.

b- Planetary Gear Subsystem

The **Planetary Gear Subsystem** models the power split device. It uses a planetary device, which transmits the mechanical motive force from the engine, the motor and the generator by allocating and combining them.

c- Internal Combustion Engine

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

d- Vehicle Dynamics subsystem

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

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

e- Energy Management Subsystem

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

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

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

There are five main scopes in the model:

- The scope in the **Main System** named **Car** shows the accelerator position, the car speed, the drive torque and the power flow.
- The scope in the **Electrical Subsystem** named **PMSM Motor Drive** shows the results for the motor drive. You can observe the stator currents ia, the rotor speed and the motor torque (electromagnetic and reference).
- The scope in the **Electrical Subsystem** named **PMSM Generator Drive** shows the results for the generator drive. You can observe the stator currents ia, the rotor speed and the motor torque (electromagnetic and reference).
- The scope in the **Electrical Subsystem/Electrical measurements** shows the voltages (DC/DC converter, DC bus and battery), the currents (motor, generator and battery) and the battery SOC.
- The scope in the **Energy Management Subsystem/Power Management System** shows the power references applied to the electrical components.

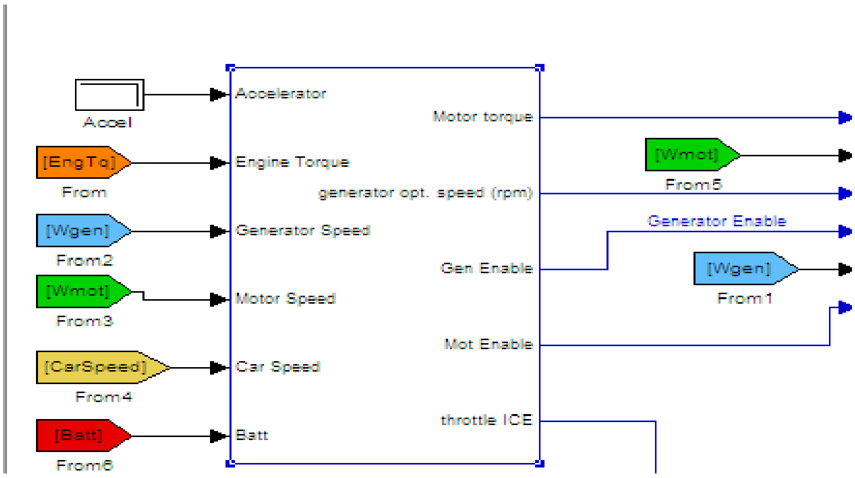

Figure 5. Energy management subsystem

Figure 6. Internal combustion engine Subsystem

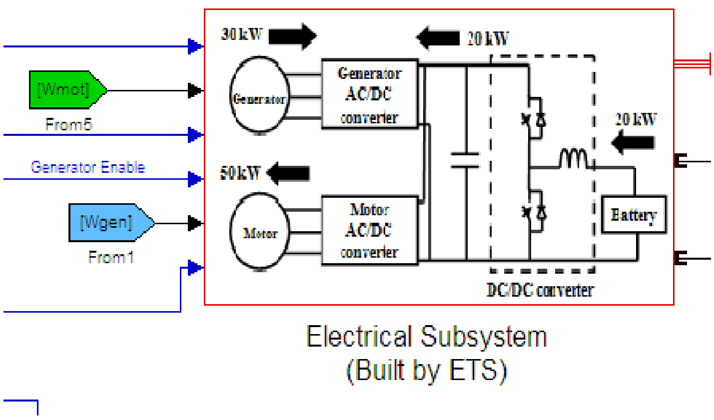

Figure 7. Electrical Subsystem

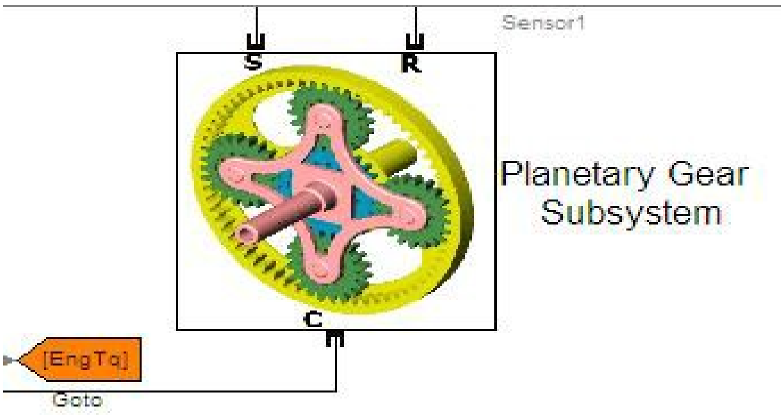

Figure 8. Planetary gear subsystem

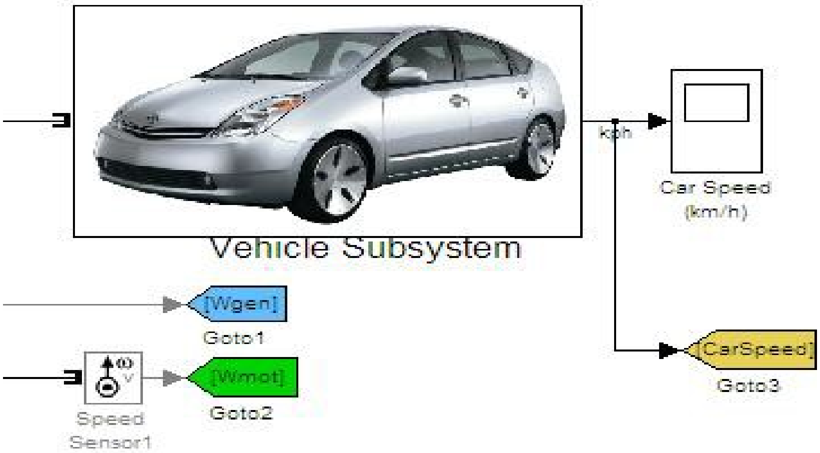

Figure 9. Vehicle dynamic subsystem

6. SIMULATION RESULTS

The demonstration shows different operating modes of the HEV over one complete cycle: accelerating, cruising, recharging the battery while accelerating and regenerative braking. Start the simulation. It should run for about one minute when you use the accelerator mode. You can see that the HEV speed starts from 0 km/h and reaches 73 km/h at 14 s, and finally decreases to 61 km/h at 16 s. This result is obtained by maintaining the accelerator pedal constant to 70% for the first 4 s, and to 10% for the next 4 s when the pedal is released, then to 85% when the pedal is pushed again for 5 s and finally sets to -70% (braking) until the end of the simulation. Open the scope-Car|| in the main system. The following explains what happens when the HEV is moving:

- At t = 0 s, the HEV is stopped and the driver pushes the accelerator pedal to 70%. As long as the required power is lower than 12 kW, the HEV moves using only the electric motor power fed by the battery. The generator and the ICE provide no power.
- At t = 1.4 s, the required power becomes greater than 12 kW triggering the hybrid mode. In this case, the HEV power comes from the ICE and the battery (via the motor). The motor is fed by the battery and also by the generator. In the planetary gear, the ICE is connected to the carrier gear, the generator to the sun gear and the motor and transmission to the ring gear. The ICE power is split to the sun and the ring. This operating mode corresponds to acceleration.
- At t = 4 s, the accelerator pedal is released to 10% (cruising mode). The ICE cannot decrease its power instantaneously; therefore the battery absorbs the generator power in order to reduce the required torque.
- At t = 4.4 s, the generator is completely stopped. The required electrical power is only provided by the battery.
- At t = 8 s, the accelerator pedal is pushed to 85%. The ICE is restarted to provide the extra required power. The total electrical power (generator and battery) cannot reach the required power due to the generator-ICE assembly response time. Hence the measured drive torque is not equal to the reference.
- At t = 8.7 s, the measured torque reaches the reference. The generator provides the maximum power.
- At t = 10 s, the battery SOC becomes lower than 40% (it was initialised to 41.53 % at the beginning of the simulation) therefore the battery needs to be recharged. The generator shares its power between

the battery and the motor. You can observe that the battery power becomes negative. It means that the battery receives power from the generator and recharges while the HEV is accelerating. At this moment, the required torque cannot be met anymore because the electric motor reduces its power demand to recharge the battery.

- At t = 13 s, the accelerator pedal is set to -70% (regenerative braking is simulated). This is done by switching off the generator (the generator power takes 0.5 s to decrease to zero) and by ordering the motor to act as a generator driven by the vehicle's wheels. The kinetic energy of the HEV is transformed as electrical energy which is stored in the battery. For this pedal position, the required torque of -250 Nm cannot be reached because the battery can only absorb 21 kW of energy.
- At t = 13.5 s, the generator power is completely stopped

Some interesting observations can be made in each scope. During the whole simulation, you can observe the DC bus voltage of the electrical system well regulated at 500 V. In the planetary gear subsystem, you can observe that the Willis relation is equal to -2.6 and the power law of the planetary gear is equal to 0 during the whole simulation.

The power system has been discretized with a 60 us time step. In order to reduce the number of points stored in the scope memory, a decimation factor of 10 is used. The AC6 blocks of SimPower Systems (representing the motor and the generator) and the DC/DC converter use the average value option of the detailed level. This option allows to use a larger simulation time step. The Electrical Subsystem is composed of four parts: The lectrical motor, the generator, the battery, and the DC/DC converter. The Planetary Gear Subsystem models the power split device. It uses a planetary device, which transmits the mechanical motive force from the engine, the motor and the generator by allocating and combining them. The Internal Combustion Engine subsystem models a 57 kW @ 6000 rpm gasoline fuel engine with speed governor. The Vehicle Dynamics subsystem models all the mechanical parts of the vehicle. No torque before acceleration > 1 m/s2 and No torque before velocity > 60 km/h.

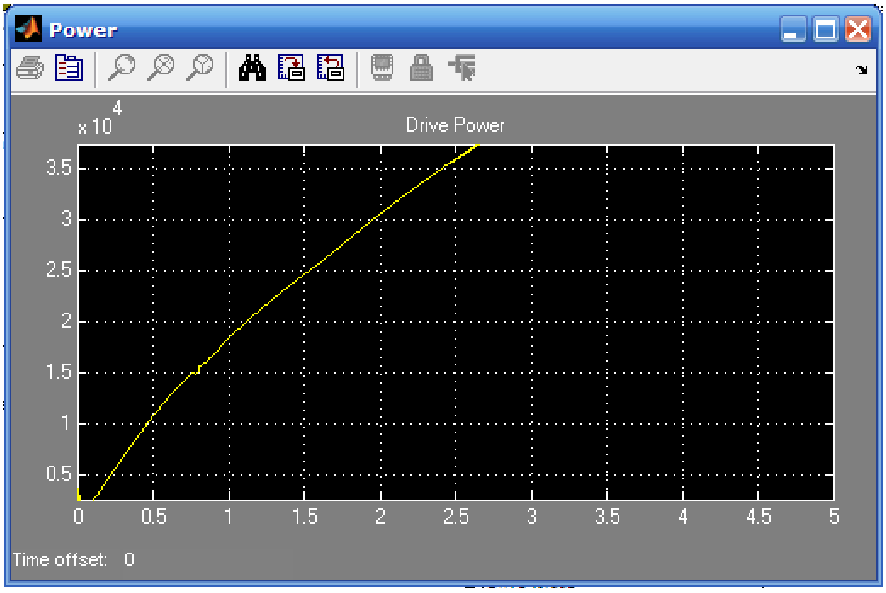

Figure 10. Relationship between drive power and time at Speed range 0:60Km/h

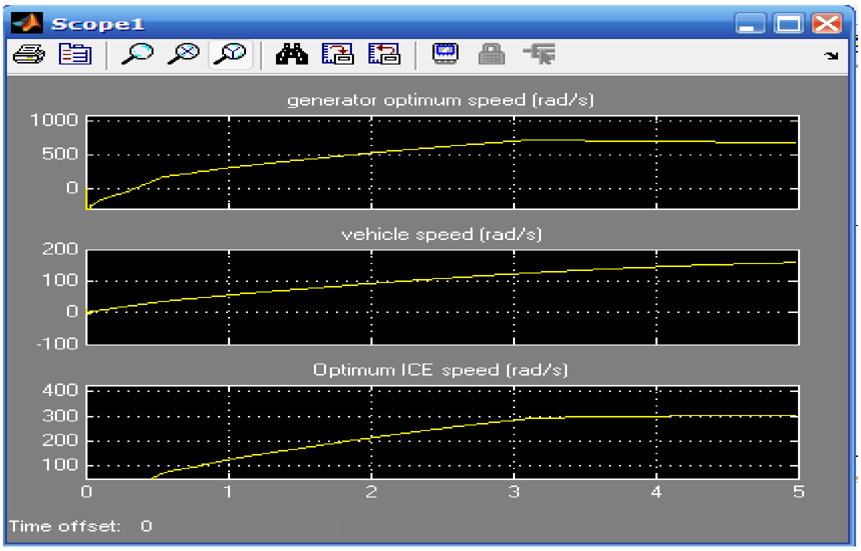

Figure 11. generator optimum speed, Vehicle speed and Optimum ICE speed (rad/s)

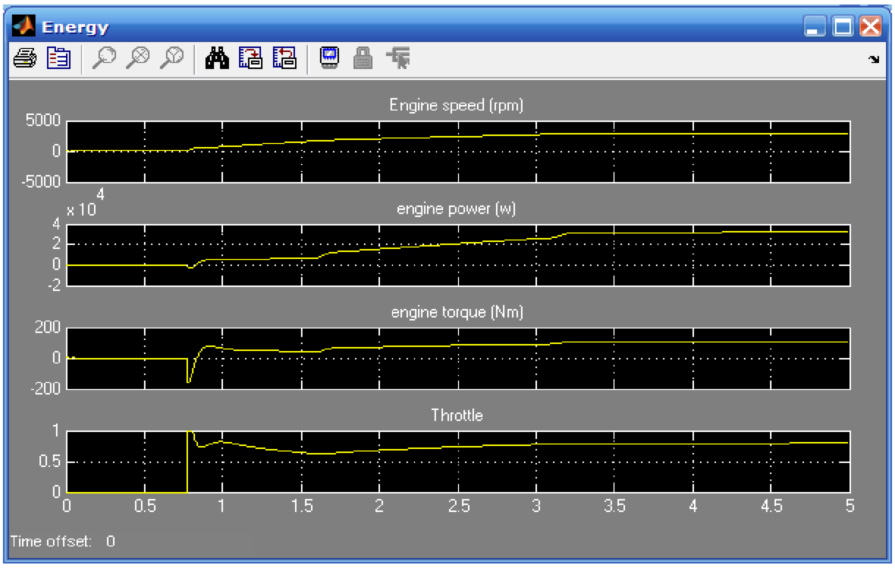

Figure 12. Engine speed, engine power, engine torque and throttle valve

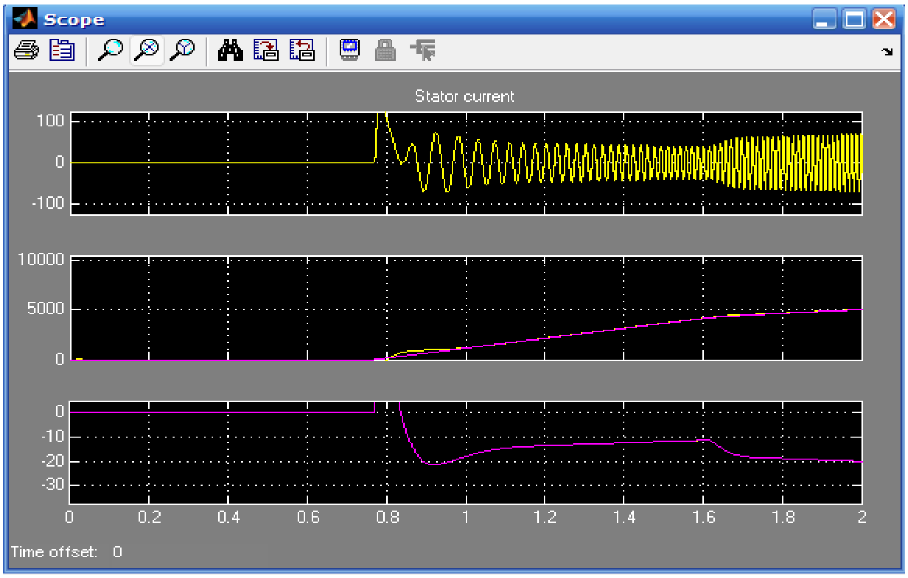

Figure 13. Electrical Subsystem result

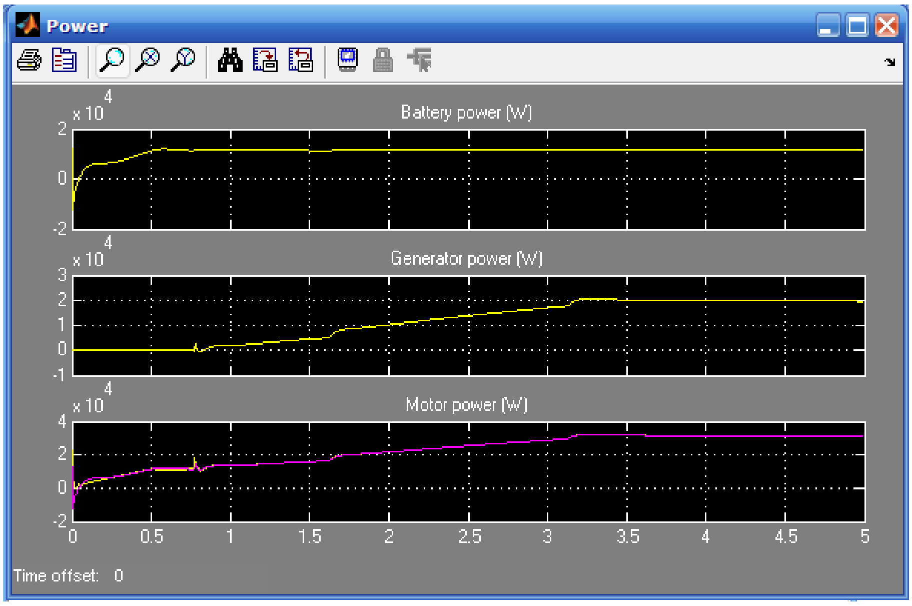

Figure 14. Electrical measurements

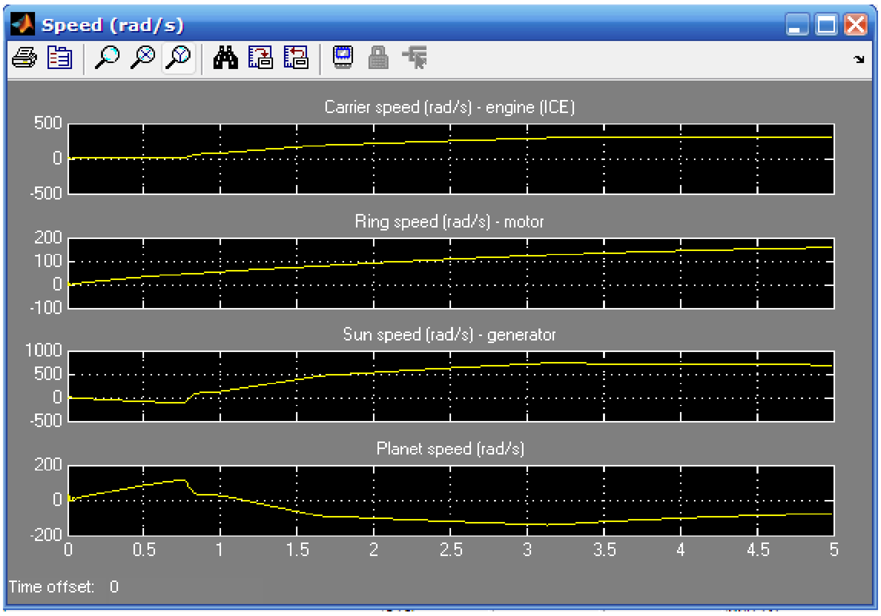

Figure 15. Planetary Gear Subsystem result

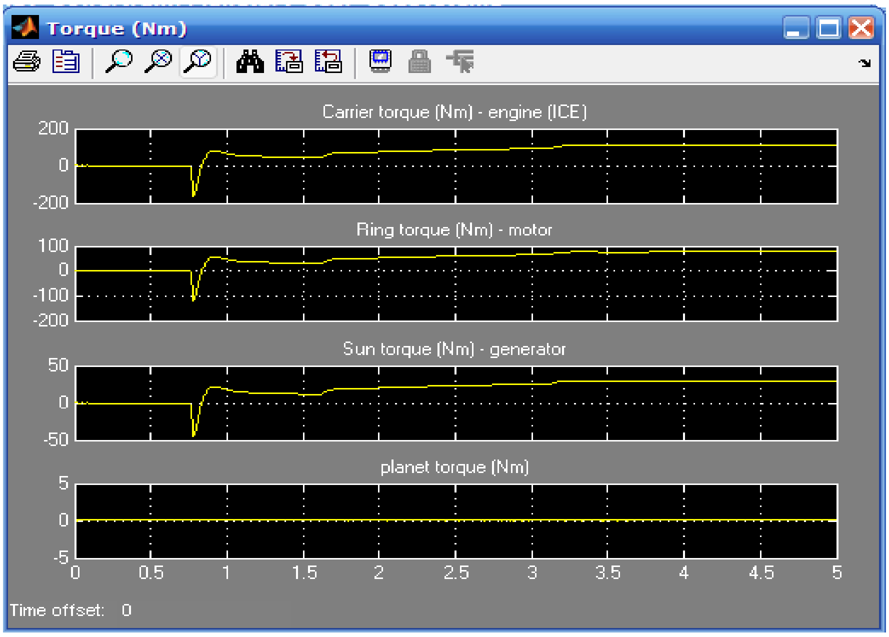

Figure 16. Planetary Gear torque, power Subsystem result

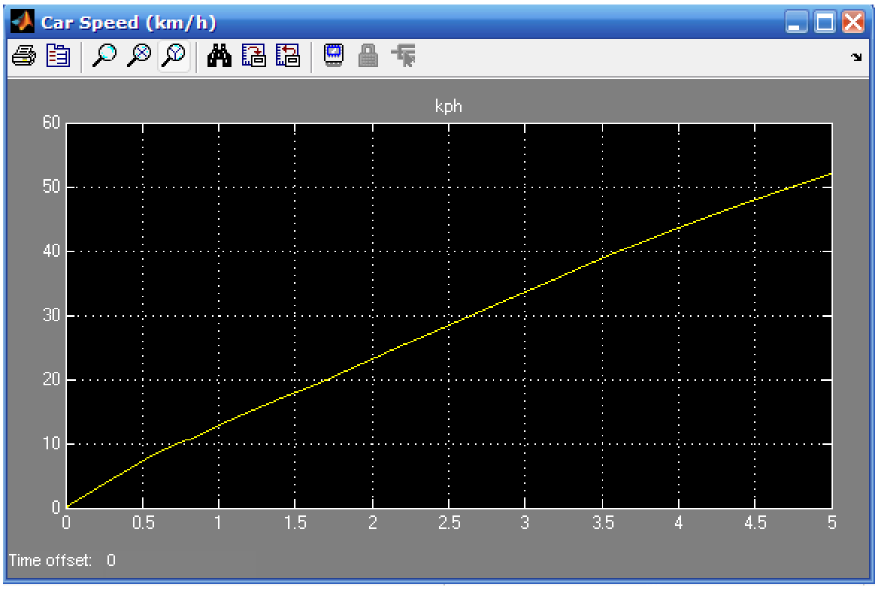

Figure 17. ICE Vehicle Subsystem result

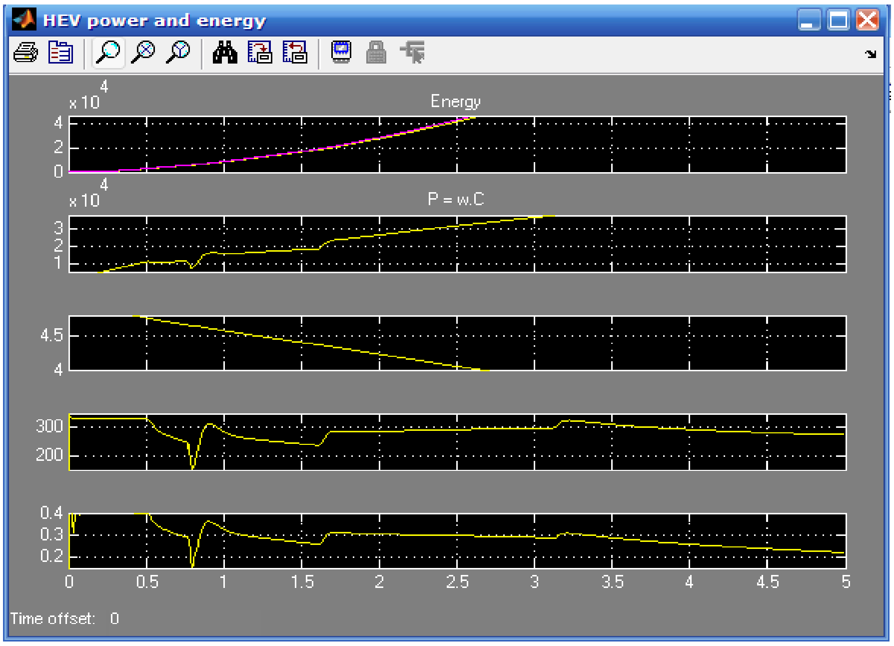

Figure 18. Relationship between -energy and time-power and time

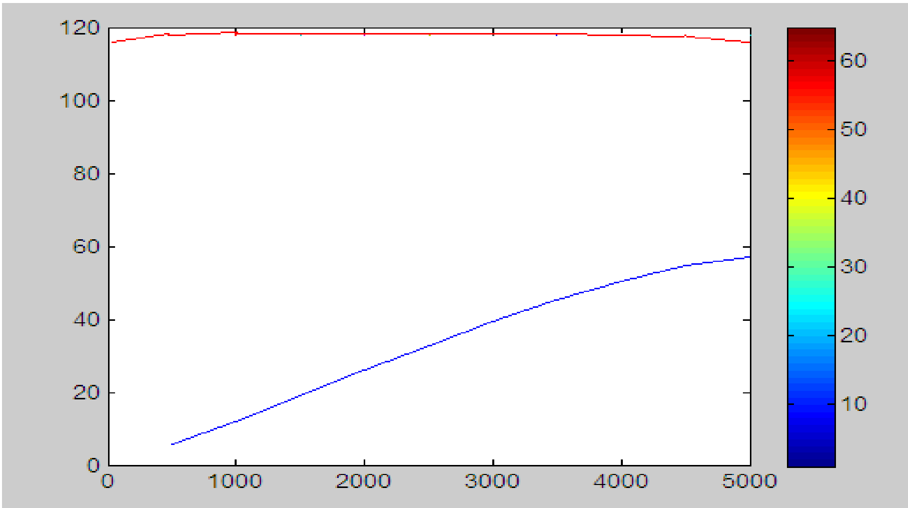

Figure 19. Relationship between Power engine and time, Torque engine and time

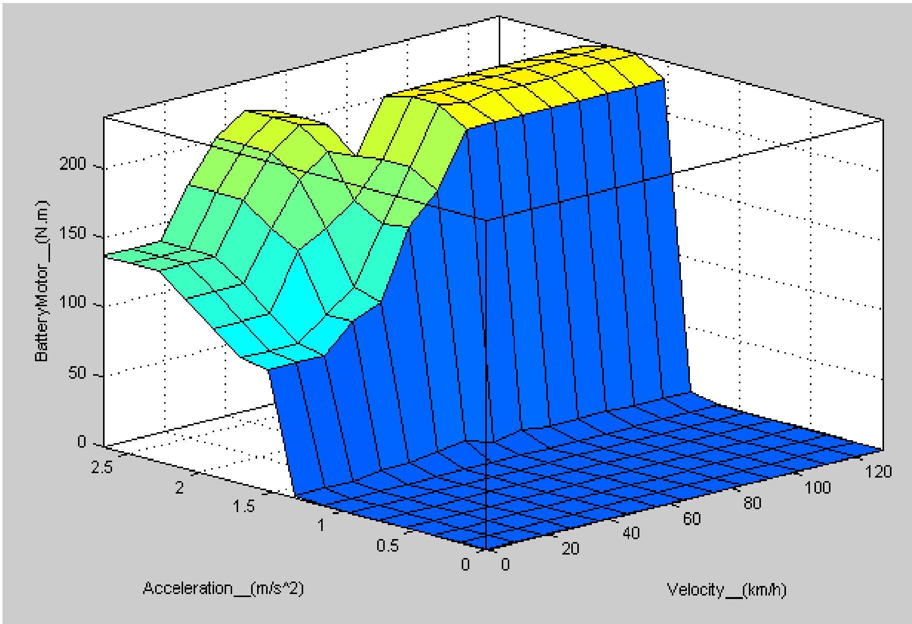

Figure 20. Electric Motor Torque vs. Acceleration and Velocity

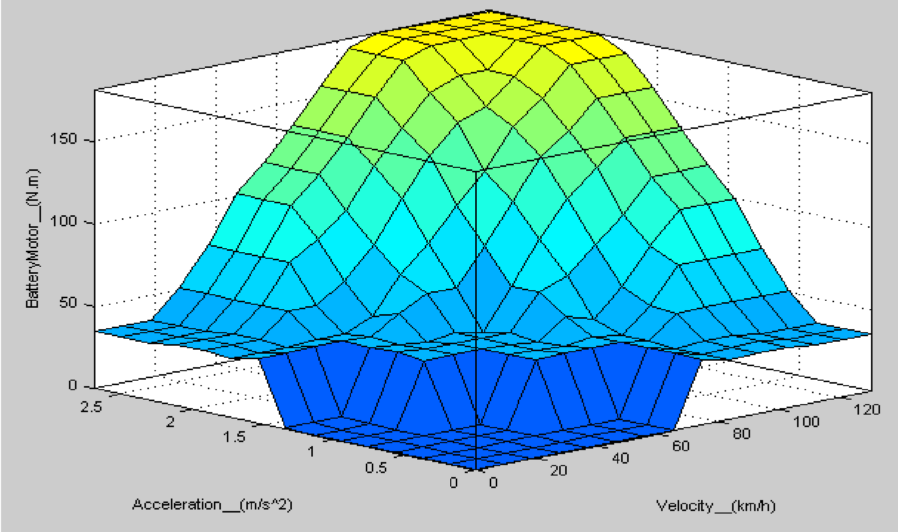

Figure 21. Hill shape: Torque increases with velocity and acceleration

7. Conclusion

This paper has presented an overview of the modeling and simulation of hybrid electric vehicle (HEV) Different modeling methods are presented with powertrain component and system modeling examples. This simulation tool is meant as a help in the design and evaluation of the hybrid electric vehicle. Components in the driveline can be varied and the effect on the hybrid electric vehicle fuel efficiency can be investigated. Both simulation tools are consist of a Simulink vehicle model, where the driveline components are represented as interconnected blocks that are communicating physical signals between each other in the level of seconds. The simulation input is a vector containing the vehicle reference speed as a function of time. The output can be any desired simulated signal. Some interesting observations can be made in each scope. During the whole simulation, you can observe the DC bus voltage of the electrical system well regulated at 500 V. In the planetary gear subsystem, you can observe that the Willis relation is equal to -2.6 and the power law of the planetary gear is equal to 0 during the whole simulation.

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