MODELING AND SIMULATION OF A SERIAL – PARALLEL HYBRID ELECTRICAL VEHICLE

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ABSTRACT

This study provides information about series parallel hybrid electrical vehicle's technology and defines tools for modeling the vehicle. The components of the vehicle; including internal combustion engine, driving machine, generator machine, batteries and transmission, and also vehicle's load model and control logic is modeled in Matlab/SIMULINK and the simulation is run in some urban and highway driving cycles. The results are discussed in respect to energy efficiency and potentials of the series parallel vehicle benefits due to probable driving conditions.

I. INTRODUCTION

A series-parallel hybrid electrical vehicle utilizes an internal combustion engine (ICE), electrical machines (EM) for driving the vehicle and generating electricity, power electronic components (PE), advanced electronic control units (ECU), a complex transmission and high voltage battery packs. As the combination of these different components, hybrid electrical vehicle engineering is the integration of automotive engineering, electrical and electronic engineering, computer hardware and software engineering and also chemical engineering. Increase in the number of components also makes the integration and optimization of the working of these components more important and challenging.

While hybridizing a vehicle, performance demands, fuel economy/emission reduction criteria and proper and safe use procedures should be defined clearly. While defining the optimal working of these components, the driving cycle of the vehicle should also be considered, too. The level of hybridization should be defined here. As all new components in a hybrid vehicle bring more weight, complexity and cost to the system, defining of the level of hybridization and investigating the amortization of the investment is an important part in the hybridization of a vehicle. A flexible computer modeling and simulation tool is important in optimization of the hybrid vehicle [1 – 5].

In this work, a series parallel hybrid vehicle will be considered. In modeling of series-parallel hybrid electrical vehicle, the electric motor and generator, the size of the battery pack, level of voltage and the new ICE can be chosen by the help of the above mentioned criteria. The proposed model is flexible that it can be diversified and the control logic can be different for each driving cycle. While building the model, components' performances are modeled, load model is derived, transmission and wheel models are built, operation modes are defined and control logic to realize this modes are derived, models are integrated and run in highway and urban driving conditions, so, energy and driving performance of the vehicle is tested.

II. MODELING

The considered vehicle is a series parallel vehicle and the schematic view of the vehicle can be seen in Figure 1.

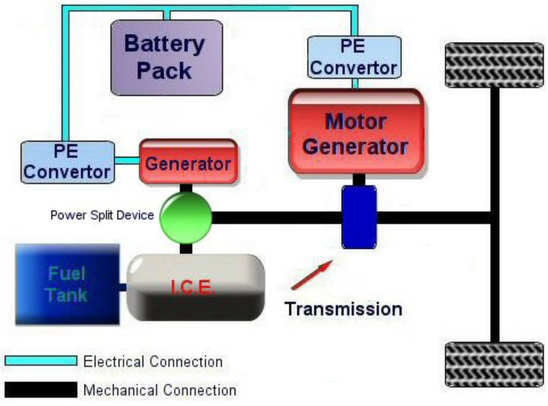

Figure 1. Series – Parallel HEV

INTERNAL COMBUSTION ENGINE

In this work, the engine is modeled as a torque source that has a variable output due to the engine speed. Engine speed is defined with the help of a MATLAB function. The function defines the maximum and minimum probable engine speed. The minimum speed values are taken into account while the vehicle is decelerating whereas the maximum values are calculated for acceleration. The maximum and minimum speed values of the generator and the ratios of the planetary gear are the parameters while calculating engine speed. The other part of the planetary gear is the driving shaft, which is proportional to the vehicle's actual speed so it is taken as a definitive value for engine speed. So, the engine speed is defined as seen in Table 1.

A lookup table containing the ICE's torque – speed characteristics is built. The calculated speed value is used as the input, thus the output is the torque of the engine in that speed. All the proposed working conditions for ICE are defined in the control logic block. Calculated torque value is given to output incase the ICE is working due to the developed control logic.

Table 1: Engine Speed

Vehicle Speed in Acc. (km/h)	Max. ICE speed (rpm)	Vehicle Speed in Dec. (km/h)	Min. ICE speed (rpm)
0-12	1600	0-89	1250
12-31	2000	89-100	1550
31-50	2500	100-110	1810
50-69	3000	110-120	2100
69-87	3500	120-130	2350
87-150	4000	130-140	2610

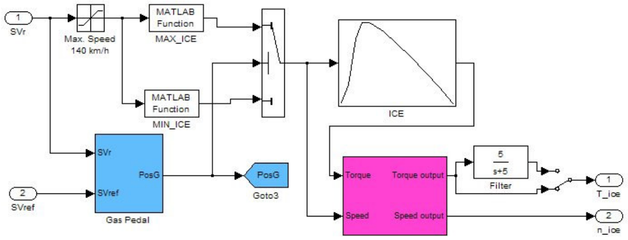

Figure 2. Simulink block diagram of ICE

In this work, the engine performance is considered thus a comprehensive engine model including emissions and fuel consumption is not built. The acceleration signal is defined by comparing reference speed by the vehicle speed. If reference is bigger than real, output of this block, which is the gas position, is "1". Simulink model for ICE, including the block for gas pedal position, can be seen in Figure 2.

DRIVING ELECTRICAL MACHINE

Driving electrical machine is modeled as a power and torque source. Torque – speed and power – speed characteristics are used in lookup tables for modeling. The speed input of these blocks is derived from vehicle's actual speed.

The driving electrical machine is actually used for two purposes: Electrical driving motor and regenerative braking generator. The calculated speed and torque values are given to output after control block which checks the conditions of control logic and decides whether the vehicle is accelerating or regenerative braking. Torque output is given to transmission whereas the power output is sent to battery pack after it is added to or subtracted from generator machine's power. The Simulink model can be seen in Figure 3.

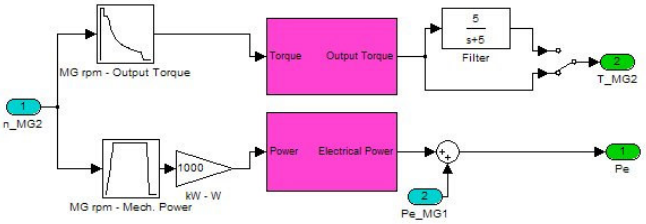

Figure 3. Simulink block diagram for driving electrical machine

GENERATOR MACHINE

Generator machine is used for starting up the engine, generating power from engine's excess power and also adjusting the gear ratio. It is modeled as a power and torque source. Torque – speed and power – speed characteristics are used in lookup tables. Speed input of this block set is calculated in the planetary gear block set. Output is connected to driving electrical machine's power input then the share of the battery is calculated. The starter action of this machine is also modeled. The model can be seen in Figure 4.

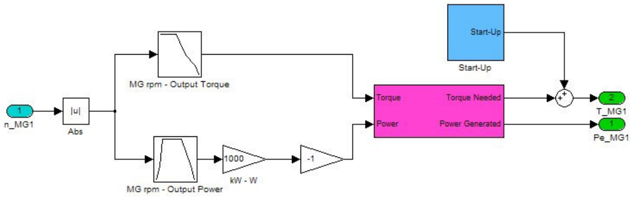

Figure 4. Simulink block diagram for generator machine

PLANETARY GEAR

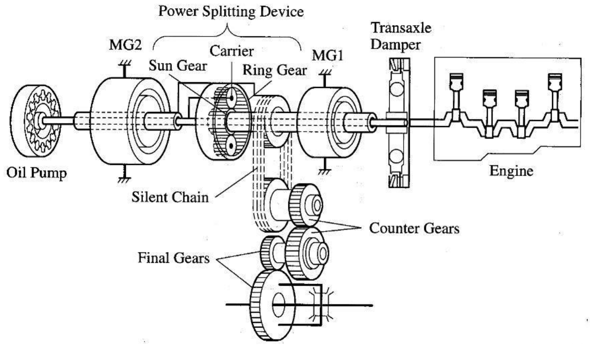

Figure 5. Power split device (by Toyota Corporation)

The planetary gear is used for splitting the engine's output power between driving shaft and generator machine and also used as an electronically controlled continuous variable transmission. The engine shaft is connected to planetary carrier, generator is connected to sun gear and the driving shaft is connected to ring gear. The gear ratios are taken as same as it is in Toyota Prius. The power split device in Prius is seen in Figure 5.

The ratio between three components is seen below:

$$n_{engine} = \left(n_{generator} + 2.6 \cdot n_{driving}\right)/3.6 \tag{1}$$

By using above equation, torque coefficients for defining the torque affected on wheels by engine and generator can be calculated as:

$$C_{T\_MG1} = \frac{(n_{ice} \cdot 9.36) - (n_{MG2} \cdot 6.76)}{(n_{ice} \cdot 3.60) - n_{MG1}} \tag{2}$$

$$C_{T\_ICE1} = \frac{(n_{ice} \cdot 3.6)}{0.722 \cdot (n_{MG1} + (n_{MG2} \cdot 2.6))} \tag{3}$$

While calculating these, the reduction gears' ratio between driving shaft and wheels are taken 3.905. The Simulink block is seen in Figure 6.

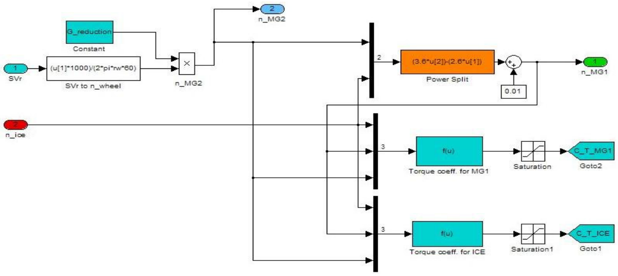

Figure 6. Simulink block diagram for planetary gear

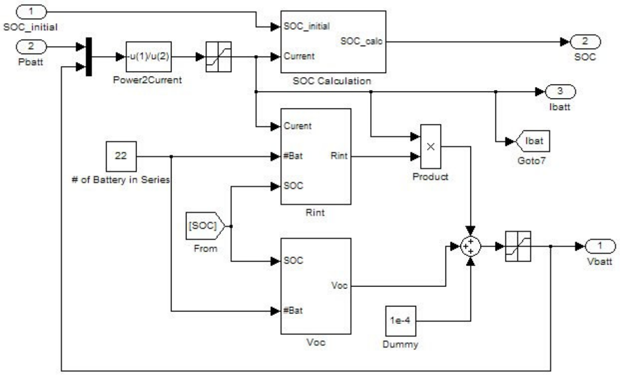

Figure 7. Simulink block diagram for battery pack

BATTERY

Battery is modeled as a voltage source and a resistance, which changes with the power flow and load. Battery values are taken from a simulator program named Advisor [3]. SOC calculation, resistance and open circuit voltage are calculated in the sub-blocks. In the model, there are serially connected 55 Ah batteries. Number of batteries is set to 22 to obtain 274V of voltage. It is possible to adjust initial value of state of charge (SOC). Battery power demand is used to find out the current demanded or supplied per hour. Integration of this value is added to available capacity of the batteries and new capacity level is determined. By dividing it with the full capacity, state of charge is found. The battery model is seen in Figure 7.

LOAD MODEL AND TRANSMISSION

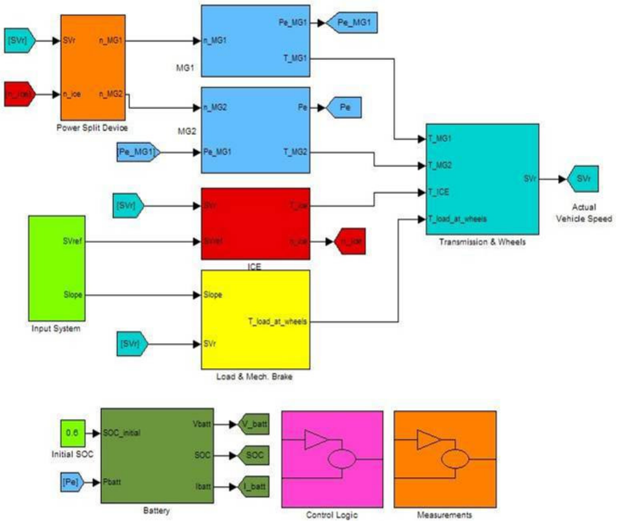

Figure 8. Simulink model for Series Parallel HEV

Load model and vehicle dynamics are calculated in the related blocks. Load torque on wheels is subtracted from driving machine and ICE torques on wheels. Also, generator machine torque is subtracted, too. The calculated value is the torque that turns the wheels and runs the vehicle. The overall system model can be seen in Figure 8.

III. DRIVING MODES AND CONTROL LOGIC

Vehicle's driving modes are defined as follows:

Vehicle start up and low speeds: As the internal combustion engine is inefficient in this range, acceleration with electrical machine is suitable.

Normal working: To avoid the battery flat-outs and excessive performance losses in this range, vehicle is driven by both internal combustion engine and electrical machine.

Sudden acceleration: In this mode, full throttle acceleration of the vehicle is considered. With the help of the extra energy from the generator, electrical machine runs in its full performance. So, internal combustion engine and electric motor together produce the maximum available power.

Regenerative braking: During deceleration, vehicle generates energy from its kinetic energy by running the electric machine in generator mode.

Battery recharge at rest: When the state of charge is below certain levels, it is possible to run the internal combustion engine in its efficient ranges and recharge the batteries with the help of the generator.

Control logic is developed to realize good driving performance and good battery energy management in these driving modes. Thus, control logic tries to keep the SOC in a narrow band around 50% to avoid overcharge or undercharge. Thus, SOC is divided into 5 levels and in each level, proper energy management algorithms are utilized. Between 40% and 60%, the SOC is considered to be in adequate level. In this level, vehicle runs in silent mode below 40km/h, electric assist on full throttle is available, engine is run in its optimum point and excess power is used by the generator machine to charge up the batteries. When the SOC increase above 60%, up to 90%, electric consuming modes continue to operate as it was in the adequate level but energy is only saved by regenerative braking. This means that engine excess power is used by the generator only to power the driving electrical machine. When SOC increase above 90% critical overcharge level is reached. After this level, no regenerative braking or any energy generation occurs. The vehicle uses energy as usual. When SOC is below 40% but more than 10%, silent mode is cancelled. As the ICE is not efficient in low speeds, it is run in its efficient points but the excess power is obtained and used in generator to charge up the batteries. This occurs both in low speeds and at rest. Electric assist and regenerative braking occur as usual. When the SOC is below 10%, critical undercharge level is reached. In this level energy management system cancels all the electric assist and concentrate on regaining the proper SOC levels [1].

By considering speed, driver demand and SOC issues, various driving conditions are modeled in the control logic block in the simulation.

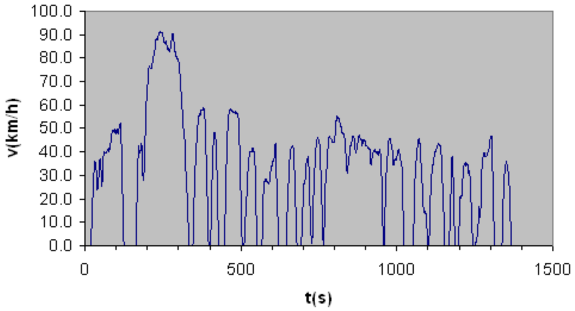

Figure 9. UDDC Urban Driving Drive Cycle

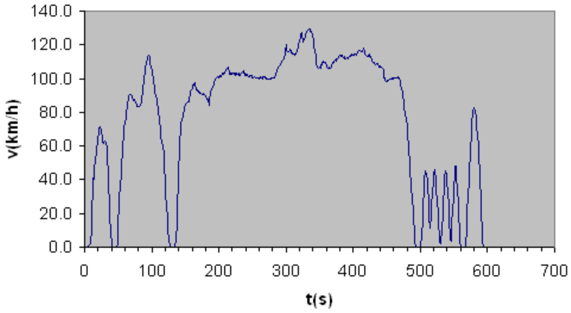

Figure 10. US06 Highway Driving Cycle

IV. SIMULATION

The series parallel hybrid electrical vehicle model has been built on Matlab R13 using Simulink 5. Initial SOC has been taken 60%. Model has been run on UDDC and US06 driving cycles. The cycles can be seen in Figure 9 and Figure 10.

During the UDDC, which is 12 km, the propulsion system has conducted 39.53 kWh of mechanical energy to the vehicle. From this energy, 3.77kWh of electrical energy has been recovered from regenerative braking and electric machine has conducted 2.87kWh of mechanical energy to the system. The SOC has reduced from 60% to 47% because vehicle has run in silent mode in low speeds, consuming battery energy. SOC pattern during UDDC can be seen in Figure 11.

While the overall vehicle performance is considered, it can be said that the vehicle was powerful enough to follow up the reference speed pattern. As this cycle is not very performance demanding, we should look at the highway driving cycle to comment on chosen motor and engine, whether they are able to meet the demands or not.

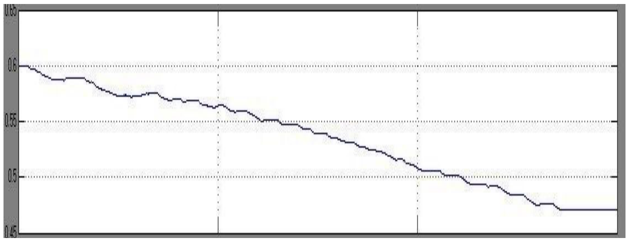

Figure 11. SOC pattern in UDDC

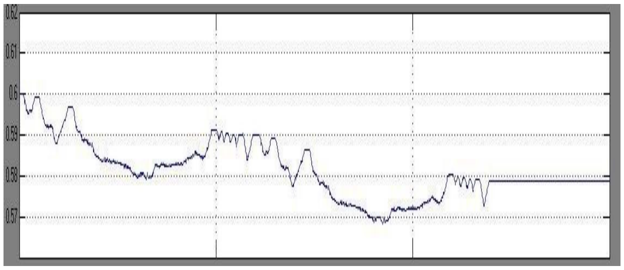

Figure 12. SOC pattern in US06

US06 cycle has been run twice and 26km is driven. During this cycle, propulsion system has conducted 54.06 kWh of mechanical energy to the system, 4.36kWh of this energy is recovered electrically through regenerative braking and electric machine has conducted 2.43kWh of energy to the system. The SOC has been dropped only 2.5% because vehicle generally used electrical energy in full throttle accelerations by using the driving electrical machine as an assist motor. The SOC pattern can be seen in Figure 12. When overall driving performance is considered, it could be said that vehicle was able to meet this driving cycle's aggressive demands so motor and engine is thought to be adequate in performance.

Developed model has saved 9.50% of the total mechanical energy used for driving the vehicle in UDDC by regenerative braking. In US06, recovered amount is 8.07% of the total mechanical energy given. These values are calculated by taking the amount of regenerative electrical energy that has been stored in the batteries. Actual saved energy could be calculated by subtracting battery losses from this amount, which has negligible effect on overall energy calculations.

In order to obtain total energy saving of series-parallel hybrid vehicle, other components should be considered. The rates calculated above are a part of the possible energy save of the vehicle. Besides this recovered energy, there are some potential parameters that should affect energy saving of the series parallel hybrid electrical vehicle. These parameters are: optimal operation of engine, downsizing of the engine, idling stop – start and silent mode driving [6]. By developing more sophisticated internal combustion engine model, fuel savings and emission reductions can also be calculated.

V. CONCLUSION

The commercial and educational vehicle simulation programs are not flexible and being presented as closed boxes, thus it not possible to build up an innovative energy management system by using them. The developed simulation can be diversified by installing new type of engine, electrical machine and battery models; also it can be run on any driving cycle developed. Also, it offers a base to complicated models, which can utilize more detailed engine models, defining the fuel consumptions and calculating the emissions. The developed model can be optimized to introduce new topologies as well as building up energy management strategies. Resulted simulation is thought to be an optimized full series parallel hybrid electric vehicle. By obtaining proper results for two different characterized driving cycles, this claim is supported.

Until a breakthrough in fuel cell or battery technology occurs, hybrid electrical vehicles will be the most popular new vehicle trend for some decades. Increase of the prices in petroleum is also supporting this trend. These vehicles are controlled by computer programs and it is possible to develop tailor made energy management systems for each vehicle in each driving conditions. So, it is best to describe different and optimized energy management systems for different drive cycles. For a further work, an optimization tool for different drive cycles, including Istanbul drive cycle can be built and more effective amortization scenarios, for a certain region and certain driving habits, can be developed. It is thought to be a good information source for automotive producers and users, and even governmental or civil organizations to realize the potentials of hybrid electrical vehicle benefits.

VI. REFERENCES

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