UDC 621.002

MATLAB SIMULATION AND USER SATISFACTION ASSESSMENT OF PHEV

Aleh Marozka, Yury Petrenko
Belarusian National Technical University, Minsk, Belarus, o.morozko@mail.ru,
ypetrenko@bntu.by

Electric-drive vehicles (EDVs) have gained attention, especially in the context of growing concerns about global warming and energy security aspects associated with road transport. The main characteristic of EDVs is that the torque is supplied to the wheels by an electric motor that is powered either solely by a battery or in combination with an internal combustion engine. This covers hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs), but also photovoltaic electric vehicles (PVEVs) and fuel cell vehicles (FCVs). [1] So we initiated research work with a view to assess the economic impacts, engineering constraints and user needs of a future market penetration of those car technologies, with a focus on PHEVs. As a starting step, we reviewed the literature and prepared this paper which provides a summary description of the technology aspects, the current state of the research and development in the field. It also elaborates consistent sets of data about the vehicle technologies in view of the subsequent modelling work to undertake the assessment. The report also identifies a series of areas where more data and assessment are needed.

Battery Electric Vehicles refer to vehicles propelled solely by electric motors. The source of power stems from the chemical energy stored in battery packs which can be recharged on the electricity grid. The future of such vehicles strongly depends on the battery developments (performance and cost).

Plug-in Hybrid Electric Vehicles refer to vehicles that can use, independently or not, fuel and electricity, both of them rechargeable from external sources. PHEVs can be seen as an intermediate technology between BEVs and HEVs. It can indeed be considered as either a BEV supplemented with an internal combustion engine (ICE) to increase the driving range, or as a conventional HEV where the all-electric range is extended as a result of larger battery packs that can be recharged from the grid. IEEE defines a PHEV as "any hybrid electric vehicle which contains at least: (1) a battery storage system of 4 kWh or more, used to power the motion of the vehicle; (2) a means of recharging that battery system from an external source of electricity; and (3) an ability to drive at least ten miles in all-electric mode, and consume no gasoline. These are distinguished from hybrid cars mass-marketed today, which do not use any electricity from the grid." [2]

A large range of options are currently developed that vary in terms of power train architecture, energy mode management, battery type, that can influence the energy performance and costs. Figure 1 provides an illustration of the PHEV configuration.

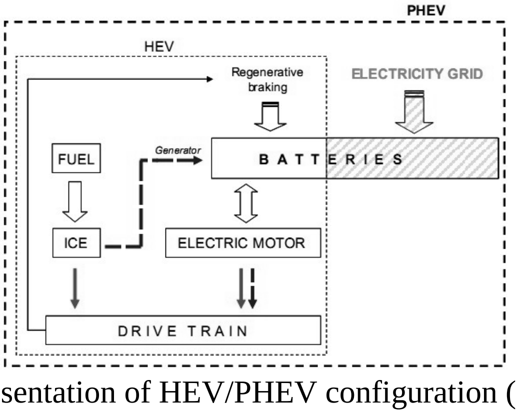

Figure 1 - Simplified representation of HEV/PHEV configuration (dash line: series; full line: parallel)

While split combines the advantages of both parallel and series hybrid concepts (dash and full lines on Figure 1). But at the same time vehicle architecture becomes relatively complex. This is for instance the architecture implemented in the Toyota Prius model (Hybrid Synergy Drive). [3, 4, 5]

The Hybrid Vehicle Control Unit (HV ECU) optimizes the power output and the torque of driving forces to reduce the fuel consumption and the pollutant of the exhaust gas [6]. The optimal required driving power of the Internal Combustion Engine (ICE), motor-generators MG1 and MG2 is based on its inputs signals which are the gas pedal position, rotation speed of the drive shaft and gear shift lever position. Also the state of charge (SOC) of the battery pack and the temperature of the motor-generators have influence on the optimal driving power. Figure 2 shows a schematic diagram of the communication between the HV ECU and the other Hybrid Synergy Drive (HSD) devices.

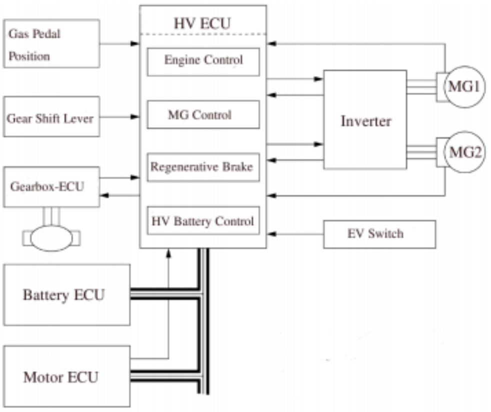

Figure 2 - Diagram of the HSD communication system [6]

The HSD operates in distinct phases depending on demanded speed and torque. Here, the most important phases of operation are listed:

– Low gear: When accelerating at low speeds in normal operation, the ICE turns more rapidly than the wheels but does not develop sufficient torque. The extra engine speed is fed to MG1. The output of MG1 is fed to MG2, acting as a motor and adding torque at the drive shaft.

– High gear: When cruising at high speed, the engine turns more slowly than the wheels but develops more torque than needed. MG2 then runs as a generator to remove the excess engine torque, producing power that is fed to MG1 acting as a motor to increase the wheel speed. In steady state, the engine provides all of the power to propel the car. During heavy acceleration or driving up a steep incline at high speed the ICE is unable to supply enough power. In this case, the battery supplies the difference.

– Reverse gear: There is no reverse gear as in a conventional gearbox. The HV ECU just feeds negative voltage to MG2, applying negative torque to the wheels. If the battery is low, the system can simultaneously run the engine and draw power from MG1.

– Silent operation: At slow speeds and moderate torques the HSD can drive without running the internal combustion engine at all. Electricity is supplied only to MG2, allowing MG1 to rotate freely (and thus decoupling the engine from the wheels). This is popularly known as Stealth Mode. Provided that there is enough battery power, the car can be driven in this silent mode for some miles even without gasoline.

– Regenerative braking: During braking the motor-generators are working in the generator mode converting much of the forward motion into electrical current flow which is used to recharge the batteries while slowing down the vehicle. Harder braking action engages standard front disk and rear drum brakes which are also provided for faster stops and emergency use.

MATLAB is widely used in academic and research institutions as well as industrial enterprises for complex systems simulation [7]. Mathematical model of PHEV was created on the base of official Matlab example presented in [8]. Developed model shows a multi-domain simulation of a PHEV power train based on SimPowerSystems and SimDriveline. The PHEV power train is of the series-parallel type (split type), such as the one found in the Toyota Prius car. This PHEV 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). The general view of the model is shown on Figure 3.

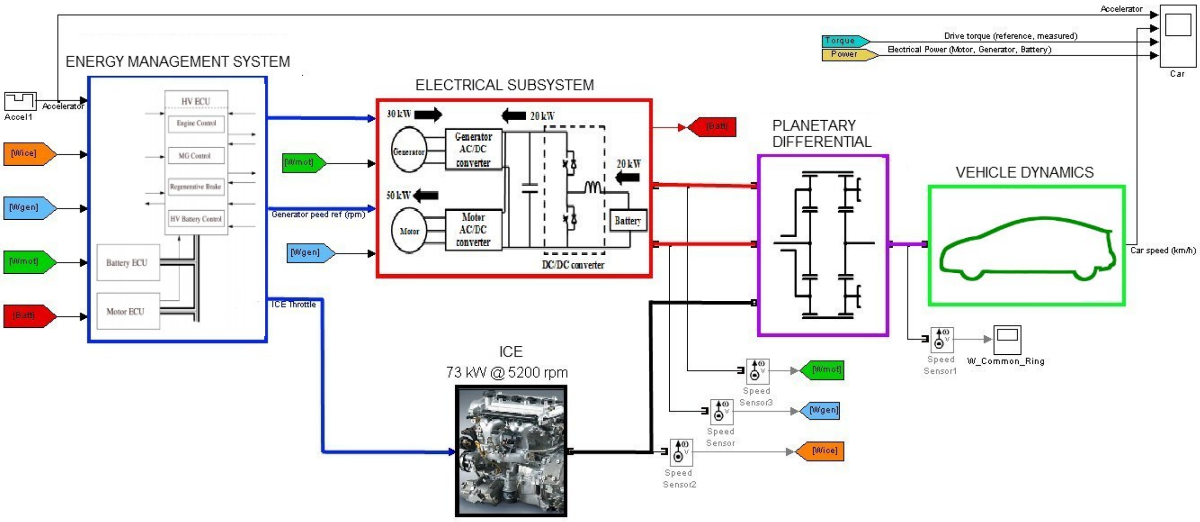

Figure 3 - Matlab based PHEV model

The Electrical Subsystem is composed of five parts: The electrical motor, the generator, the battery, the electricity grid connector 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.

The Planetary Differential models the power split device. It uses a double 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 (ICE) subsystem models a 73 kW @ 5200 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.

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.

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 PHEV 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% and “to electricity grid” connection. 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.

Satisfaction of driver needs is based on several criteria, for instance security, daily cost, reliability, performances, etc. Some criteria like performances are easily quantifiable but others like comfort are qualitative so that they can only be estimated by fuzzy description. In this study we will consider only quantitative criteria: performances, cost and security.

Performances include maximal vehicle velocity, acceleration performances and gradeability. They can be evaluated by simulation in Matlab by following standard approaches described in classical vehicle theory [17, 18].

Maximum speed is evaluated when solving equilibrium equation between propulsion power and dissipated power by resistance forces (rolling resistance, aerodynamic resistance…)

$$\eta P_{propulsion}(\omega) = P_{resis\tan ce}(\nu) = c_0\nu + c_1\nu^2 + c_3\nu^3 \qquad (1)$$

Where ω is engine speed while v is the vehicle ground speed, η is the transmission efficiency, c0, c1, c2 -coefficients of a general expression of the driving resistance forces.

Acceleration time (from V1 to V2, km/h) can be evaluated by solving integration of equation of motion of the vehicle

$$\Delta t = m_{eff} \int_{\nu_1}^{\nu_2} \frac{dV}{F_{net}(V)}, \qquad (2)$$

where m_{eff} is the equivalent or effective mass and F_{net} - the net force between propulsion force and driving resistance forces.

Gradeability: is estimated by solving the equation limiting the propulsion force that can be transmitted to the ground while taking care of mass transfer during climbing in steady sate motion:

$$F_{propulsion} = F_{resis\tan ce} \le \mu W_{f/r} \qquad (3)$$

W_f and W_r are respectively the front and rear weight under front or rear wheels.

A simple cost model is introduced to estimate the total vehicle cost which is devised into two costs: an operating cost, $C_{operating}$ and an investment cost, C_{inv}

$$C_{inv} = c_{engine} P_{engine} + c_{elec} P_{elec} + c_{bat} N_{bat} + C_{fixed} \tag{4}$$

where c_{engine}, c_{elec} are respectively the cost per kW of the IC engine and the electrical components and P_{engine}, P_{elec} are the maximum rated power output in kW. In order to account for parallel hybrid designs that have no generator (since the electric machine works reversibly as a motor or a generator), the P_{elec} is defined as:

$$P_{elec} = P_{motor} + P_{generator} \tag{5}$$

c_{bat} is the module battery cost and N_{bat} the modules number. The c_{fixed} is taken to include the bodywork and all the accessory components, and is assumed to be fixed and is the same for a hybrid or a conventional vehicle. In reality it is clear that this is a greatly simplified costing, since as engine power varies so does the cost of many associated components such as braking systems, suspension systems and tires. Operating cost is calculated as:

$$C_{op} = c_{fuel} M_{fuel} + C_{ma\,\mathrm{int}\,enance}, \tag{6}$$

where c_{fuel} is the cost per litre of fuel and M_{fuel} is the volume of fuel used over the assumed life of the vehicle. The maintenance costs have been neglected because we assume that the maintenance cost is more or less similar for the hybrid and conventional vehicles, which is again a rough approximation.

Security: It is the capability of the vehicle to ensure both the passengers and other road users safety. Safety can be based on several criteria like security equipment available on the vehicle, crash test results (e.g. Euro NCAP [15]), static stability factor estimating rollover resistance [13], etc. But the vehicle mass is the main factor for road security, especially for security of collision partners. Based upon the FARS (Fatal Analysis Reporting System) database, Joksch et al. [16] have estimated the relationship between the mass ratio of collision partners, and the fatality ratio of collision partners to be:

$$\frac{F_2}{F_1} = \left(\frac{m_1}{m_2} \right)^4, \tag{7}$$

where m_1 and m_2 are the mass of vehicle 1 and 2, F_1 and F_2 are the fatalities in vehicle 1 and 2. As an example, for a mass ratio of 2:1, the formula (4) predicts a fatality ratio of 16:1 between the lighter car and the heavier one. This mean that for vehicle-to-vehicle collisions in which one vehicle weighs twice more than its collision partner, for every fatality unit in the heavier car there would be sixteen in the lighter car. Because of this we decided to focus on the security criteria to evaluate security solely by formula (4) of the mass ratio between the considered vehicle and a reference one. In MatLab, the vehicle mass is a function of used components of vehicle.

CONCLUSION

In this paper an overview of electrical-drive vehicles systems and their control systems was created. Mathematical model of PHEV was developed. Further use of the model is helpful for any optimization according to such requirements as fuel consumption minimization, driving patterns unification, charging speed increasing, charging station market location, user satisfaction criteria etc. [9, 10, 11]

In addition use of developed model will sufficiently reduce time and financial costs in future development and design.

REFERENCES

1. Nemry, F. Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency / European Commission, Joint Research Centre, Institute for Prospective Technological Studies, Luxembourg // Office for Official Publications of the European Communities © European Communities. – 2009.

2. Plug-in Hybrid Electric Vehicle Definition / Board of Directors. – 2007. - Mode of access: http://www.ieeeusa.com/policy/POSITIONS/PHEV0607.pdf. – Date of access: 24.01.2013.

3. Meisel, J. An analytic foundation for the Toyota Prius THS-II powertrain with a comparison to a strong parallel hybrid-elecric powertrain / SAE 2006 // World Congress. - 2006. Detroit, MI. - Mode of access: http://www.toyota.com/prius/specs.html. – Date of access: 24.01.2013.

4. Toyota Prius Plug-in Earns 2012 Urban Green Vehicle Award. Toyota USA Newsroom. - 2011-10-27. - Retrieved 2011-10-29.

5. Voelcker, J. 2012 Toyota Prius: GreenCarReports' Best Car To Buy 2012 / Green Car Reports. - Retrieved 2011-12-04.

6. Toyota Motor Corporation (TMC) Manual, Prius NHW20.

7. Лазарев, Ю.Ф. Начала программирования в среде MATLAB: Учебное пособие. – К.: НТУУ «КПИ». - 2003. – 424 с. - Режим доступа: http://www.mathworks.com/products/simmechanics/download_smlink_confirmation.html. - Дата доступа: 01.02.2011

8. Patrice, B. Hybrid Electric Vehicle (HEV) Power Train Using Battery Model. – Mode of access: http://www.mathworks.com/matlabcentral/fileexchange. – Date of access: 24.01.2013.

9. Kim, M.-J. Peng, H. Power management and design optimization of fuel cell/battery hybrid vehicles / Journal of Power Sources. - Vol 165, Issue 2. - March 2007.

10. Van Mierlo, J. Comparison of the environmental damage cuased by vehicle different alternative fuels and drivetrains in Brussels context / Proceedings of the Institution of Mechanical Engineers // Part D Journal of Automobile Engineering 217. – 2003. – P. 583-593.

11. Pagerit S., Karbowski D. PHEV Control Strategy Optimization Using MATLAB Distributed Computing: From Pattern to Tuning / S. Pagerit, D. Karbowski, S. Bittner, A. Rousseau, Ph. Sharer // MathWorks Automotive Conference Proceedings. - Stuttgart, Germany, June 2008. Mode of access: http:// www.mathworks.com. - Date of access: 23.09.2013.

12. Coello Coello, C. A. Evolutionary Algorithms for Solving, Multi-Objective Problems / Kluwer Academic Publishers. - New York, 2002.