Testing Possibilities of Control Algorithms for Hybrid Electric Vehicles

GHEORGHE LIVINȚ, VASILE HORGA, MIHAI ALBU and MARCEL RĂȚOI
Faculty of Electrical Engineering
"Gh.Asachi" Technical University of Iaşi
Blvd. D. Mangeron, nr. 53, 700050, Iaşi
ROMANIA

Abstract: - This paper presents a methodology of rapid testing for different control algorithms of electrical drives with inverter-fed induction motors used for the propulsion of hybrid electric vehicles. For analysis, modeling and off-line simulation of the vehicle operations conditions, and also for the testing in real time of the control algorithm performance certain hardware/software products COTS (ADVISOR, DS1104, ControlDesk) are used. The emulation of the real traffic conditions, obtained by off-line simulations, are replicated with a torque controlled dc machine, which load the induction machine under test.

Key-Words: - Control algorithms, real time simulation, hybrid electric vehicle, SOC measurement

1 Introduction

Any vehicle that has more than one power source can be classified as a hybrid electric vehicle (HEV), but most frequently the term is used for a vehicle which combines electric drive with a heat engine using a fossil-fuel energy source. HEVs can be classified in: a) all-electric vehicles using two different types of battery, or a fuel-cell and a battery, or a battery and a supercapacitor, b) electric vehicles (EV) in which the main electric-drive battery is supplemented in peak-load condition by power stored in a flywheel or in a hydraulic accumulator, c) hybrid vehicles in which the battery is used together with a heat engine to provide high efficiency drive.

There are also two major configurations in which the components of a hybrid system can be arranged: the series hybrid in which the drive wheels are propelled only by the electric machine, and the parallel hybrid in which the drive wheels transmission power is obtained from electric and/or heat engine.

Development of hybrid electric vehicle has been focusing on reducing emission gas and on operation with better fuel economy. With HEVs, fuel economy is achieved in two major areas: a) regenerative braking recovers a significant fraction of the vehicle kinetic energy in the battery. When the driver accelerates later, this energy is returned as essentially free power. In stop-and-start driving, the energy recovered can boost efficiency by about 20 percent [1]; b) the engine shuts down during stops and low-power driving, and so increases the average efficiency in urban driving. It improves overall efficiency by about 40 percent.

In today HEVs the induction and permanent magnet synchronous machines are used the most. The electrical machine is capable of both producing and absorbing mechanical power. Based on the driver's power request and the state of charge (SOC) of the battery, the power management algorithm determines whether electrical machine should contribute power to, or absorb power from the crankshaft.

In order to derive benefits from a hybrid powertrain, the power management becomes a major concern and deals with the decision making regarding the power split between the thermal and electrical path, taking into account the current SOC of the energy storage unit. The objective is to minimize fuel consumption while the driving schedule on demand is satisfied. A number of algorithms have been proposed in the literature based on a priori knowledge of the driving schedules.

The pressure of increased complexity in the design and verification process, involved with the testing of complex electronic and component systems, forced the automotive industry to investigate and invest in better testing methodologies. Recently, the automotive industry has seen a great change in the implementation process of new control systems, with the integration of rapid development tools for new ideas and products. Perhaps the bigger change, however, is the adoption of some rapid-prototyping concepts for vehicle and component testing and validation.

In this paper the testing possibilities of the electric drive in its operational environment and the determination of the battery SOC after the measurements of the electrical quantities are presented. Also our aim is to test the control algorithm in order to optimize the motor-inverter structure on HEV applications and for the management of energy sources. In this sense, we have combined the numerical off-line simulation techniques with the emulation techniques in real time of the vehicle behavior, reflected by requested speeds and torque at the input of transmission elements of the powertrain.

2 Model of the Parallel Hybrid Electric Vehicle

For a parallel hybrid configuration, the propulsion power can be provided by both the thermal and electrical paths, as depicted in Fig. 1.

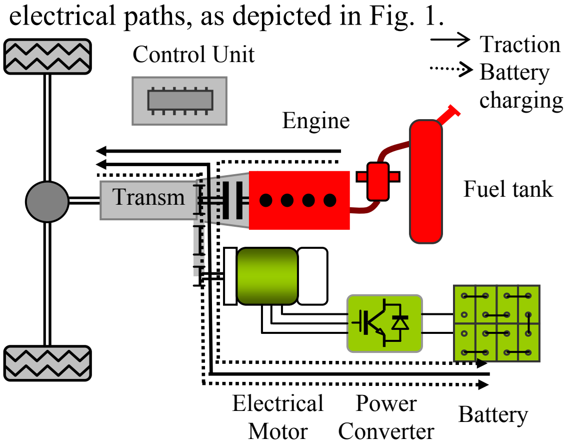

Fig.1. Parallel hybrid electric vehicle

The additional available power to the electrical machine can be regulated only by adjusting the electric torque. The latter can be either positive or negative contingent upon the mode in which the electrical machine is operating, as designated by the power management algorithm presented in Fig. 2. In motor mode, the electrical machine contributes power to the driveline by drawing electrical energy from the battery. In the generator mode, the electrical machine absorbs power from the driveline and charges the battery.

In the peak-loads conditions, when the requested torque by the driver, T_{DRIVER}, is greater that the heat engine torque, T_{HE}, a positive amount of torque, T_{EM} is provided by electrical machine:

$$T_{DRIVER} = T_{HE} + T_{EM} \quad (1)$$

When the driver demands braking, the power is expressed by a negative torque T_{DRIVER}:

$$T_{DRIVER} = T_{HE} + T_{EM} + T_{BRAKE} \quad (2)$$

where T_{BRAKE} is the friction brakes torque. The electrical machine absorbs the maximum absolute amount within the constraints imposes by the battery. Consequently, the electrical machine can recover the energy, that otherwise would be lost by means of friction brakes, so as to charge the battery.

The power management algorithm comes to a decision regarding the electrical machine torque, T_{EM}, based on the current SOC, in order to utilize the most proper engine operating point as far as fuel consumption is concerned (Fig.2).

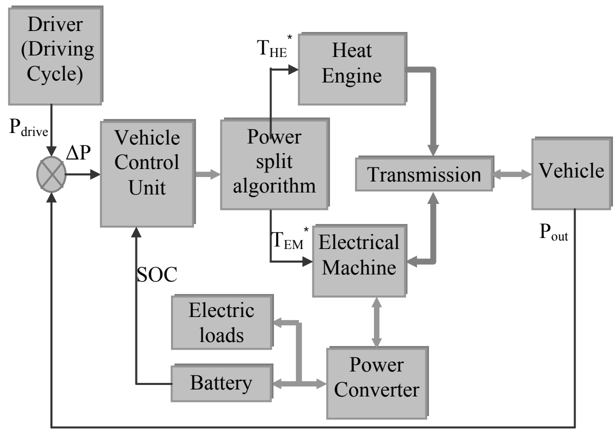

Fig.2. The model of a parallel HEV

3 Off-Line Simulation of Vehicles Dynamics

Modeling and simulation are indispensable when dealing with complex engineering systems. It makes it possible to do essential assessment before systems are built, it can alleviate the need for extensive experiments and it can provide support in all stages of a project from conceptual design through commissioning and operations. The models of HEVs are multi-engineering models. Mechanic, electric, hydraulic or thermodynamic components are often coupled together in one model.

The simplified vehicle and transmission model can be described as

$$m_{in}\frac{dv}{dt} = \frac{T_v G_r}{r} - \frac{1}{2}\rho C_d A v^2 - m_v g \mu \quad (3)$$

$$m_{in} = m_v + \frac{J_{wh} + J_m G_r^2}{r^2} \quad (4)$$

where m_{in} - inertial mass including rotational inertia, m_v - vehicle mass, J_{wh} - wheel inertia, J_m - motor inertia, G_r - transmission gear ratio, r - wheel radius, v - vehicle speed, T_v -vehicle torque, A - front area , ρ - air density, C_d - aerodynamic drag coefficient, μ - rolling friction, g - gravity.

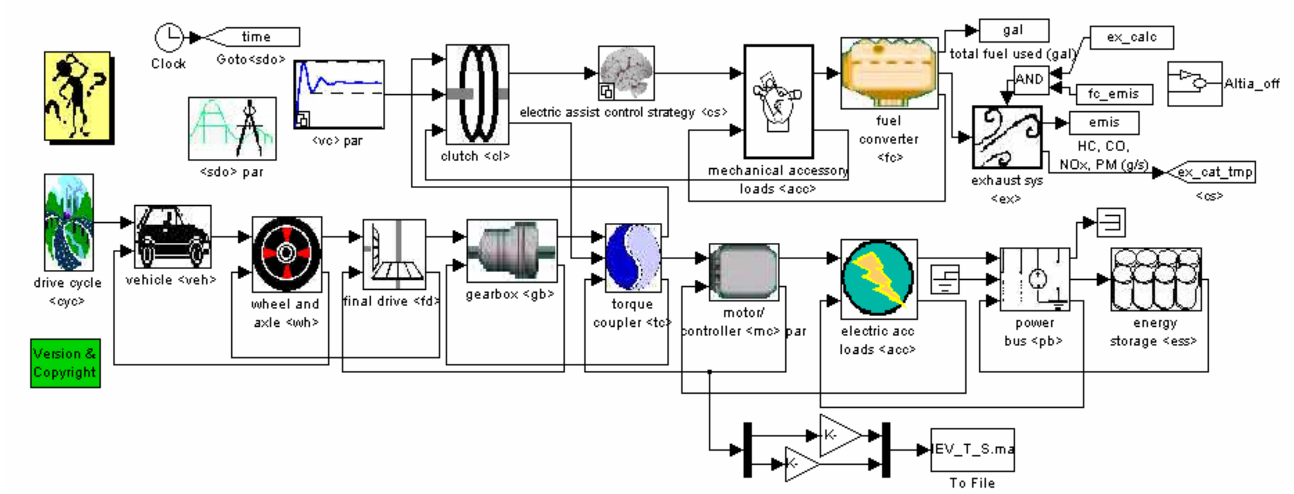

Fig.3. ADVISOR vehicle setup

ADVISOR (Advanced Vehicle Simulator) is a very useful computer simulation tool for the analysis of energy use and emission in both conventional and hybrid or electric vehicles [2]. With a modular environment within Matlab and Simulink, ADVISOR allows the user to interchange a variety of components, vehicle configurations, and control strategies.

The complete powertrain can be simulated by implementing its dynamic models in ADVISOR. This enables the use of a large number of currently available EV, HEV and powertrain models. Fig. 3 presents the modality of study by simulation of the dynamical behavior of a parallel hybrid electric vehicle.

One known speed profile, used by test laboratories to certify automobiles production in USA, is the Federal Urban Driving Schedule (FUDS). The FUDS, presented in Fig.4, is 1369 seconds long, covering a distance of 12 km at an average speed of 31.6 km/h.

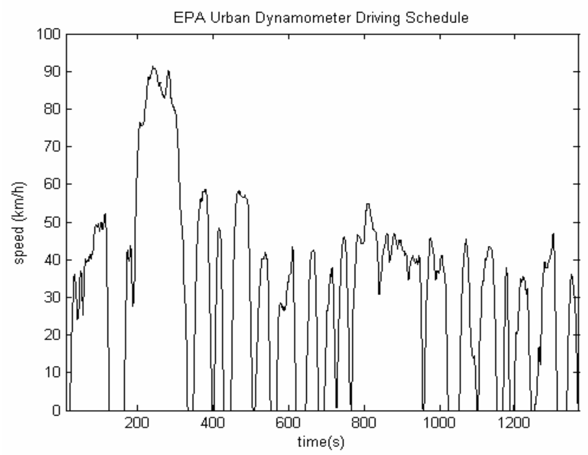

Fig.4. FUDS speed profile

4 Hardware and Software Resources of the Prototyping Station

Off-line simulation is very useful for choosing and adapting the control structure and the algorithms for machine-converter association. Realistic simulation is a fundamental step in the design of advanced nonlinear controllers. The actual implementation for certain interesting solutions poses a lot of additional constraints that often compromises the use of some interesting solutions [3]. A researcher in this field would greatly consider the availability of prototyping tools permitting a fast experimental verification of controller performance and an easy comparison of different solutions as far as robustness, dynamical performance, feasibility are concerned. Important specifications of the prototyping tool are related to peripheral interface capability, computational power, availability of standard high-level programming language and user interface, real-time handling trace capability of the most relevant I/O or state variables. Besides, an open system is required for upgrading to new functions. Simulation must be available too, strongly interconnected with software development environment. From the functional point of view, the prototyping station should permit ideal as well as realistic simulation of plant and controller, real-time implementation of the controller using a simulated plant and, at last, final controller verification on the actual plant.

The prototyping station is mainly intended for simplifying experimental validation of nonlinear algorithms for HEVs electric drives (Fig.5). The main part of the test stand consists of a standard cage induction motor (4kW, 1430 rpm) supplied by a voltage source PWM inverter.

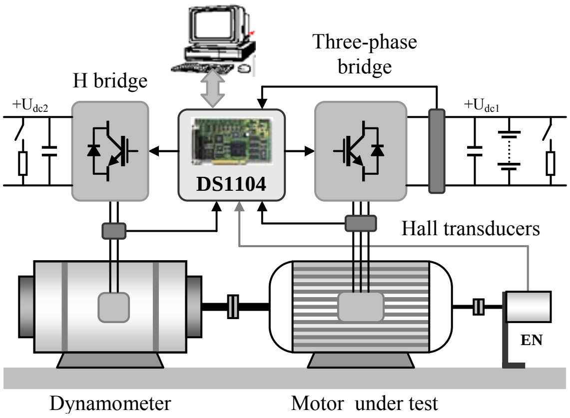

Fig.5. Hardware resources of prototyping station

In the power stage IGBT transistors are used. Phase voltages and currents of the induction motor are acquired through an acquisition system that contains Hall transducers. The speed is measured with an encoder. The second part of the test stand is the mechanical loading system that is conceived with dc motor. The armature current of the dc motor is also measured with Hall transducer.

The chosen control system to cover all the needs for peripheral interface is a dSPACE DS1104 system based on Motorola PPC microprocessor and a TMS320F240 digital signal processor. The associated software is ControlDesk, a tool that provide all capabilities including hardware management, data acquisition and graphical user interface [4]. Moreover, a graphical environment of Simulink is used to build a true development system for motion control algorithms. The results are prepared for immediate code generation using Real-Time Workshop of Simulink. In this way these tools facilitate the rapid design.

In order to investigate adaptive, robust, or intelligent control techniques is desirable to have a programmable dynamometer, which can emulate linear or nonlinear load models. This allows realistic testing of electric drives and also provides desired linear or nonlinear loads for experimental validation of the advanced control algorithms in the laboratory. The general approach is to use inverse mechanical dynamics, in which the shaft speed is measured and used to derive the desired torque for the dynamometer [5].

For the test bench, two main factors must be studied carefully to accurately reproduce the vehicle road load seen by the propulsion drive. First, the dynamometer must be capable to follow the imposed torque profiles with minimum error and delay. This allows the test bench to accurately describe the dynamic changes of the vehicle following a driving schedule. Second, the dynamometer must be capable of changing from negative mechanical power (i.e. generator mode) to positive mechanical power (i.e. motoring mode) in order to simulate deceleration, downhill etc. This enables the study of power flow, regenerative breaking, and power stability of the dc bus.

To evaluate “motor-controller” unit (see Fig.3) in a system context, DS1104 controls induction motor-inverter assembly as an “automatic driver” and the dc motor–chopper in that a way to emulate the interaction among the components, vehicle, and on-road environment. “The automatic driver manipulates the brake and throttle” to keep vehicle in targeted speed. This was realized by means of a PI-speed controller added to FOC structure of induction motor (Fig.6),[6].

For specific test runs, ControlDesk also provides mechanisms to assist in the generation of test stimuli (data streams). It has the capability to playback recorded data streams, captured during either simulations or actual test runs. Any data waveform

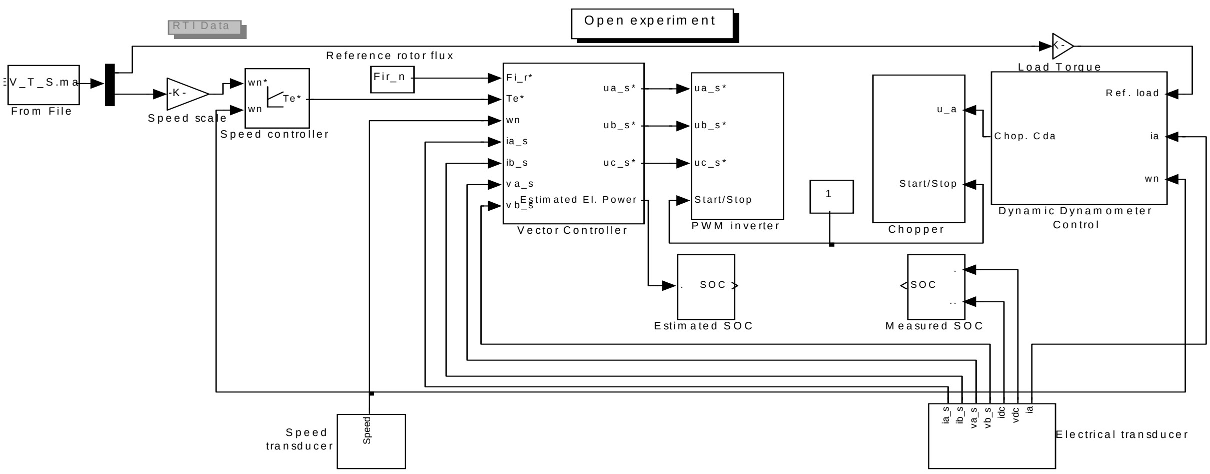

Fig.6. Simulink model for real time control of prototyping station

stored in a predesigned mat-file format can be used for this purpose. The dSPACE hardware and software systems provide the automatic buffering and interpolation processes that allow for real-time data playback during evaluation tests. This capability has been used very effectively to control "the automatic driver" and the dynamometer. The last one is torque-controlled to replicate the torque, obtained from the simulated vehicle.

5 Experimental Results

It was shown that a user can simulate off-line any combination of the drive train components obtaining the time traces of the mechanical quantities for a chosen drive cycle. These values are saved into a mat-file and used as references inputs for the control system of the prototyping station. Note that the dynamometer simulates not only the vehicle torque (i.e. the road load) but also the heat engine contribution to the total torque. Thus, the dynamometer simulates the difference between these two torque requirements.

Even in case of the vehicles with little dimensions (1268 kg mass) the necessary power can to overtake the installed power of prototyping station. In this case, the torque and speed commands were scaled down from those of the actual HEV.

The speed command was divided by 5, while the torque command was divided by 10. Thus, the mechanical power is scaled down by 50. The scaled speed is the reference for the "automatic driver", and the scaled torque is the reference for the dynamometer. Once that the entire system is setup in Matlab/Simulink (see Fig.6), the dSPACE automated code generation feature produces the required DSP code. Fig. 7 presents the user interface in ControlDesk.

In the first window the automatic driver's control performances are presented (reference and measured speed). The second window presents the behavior of the emulated motor/controller unit. The control algorithm used (indirect FOC) provides the rated magnetizing state (i_d^*-i_d), and also the active components (i_q^*-i_q) requested to develop the torque that moves with the imposed speed on the selected drive cycle. The last window shows the reference torque obtained from the off-line simulation of the vehicle and the estimated shaft torque of the controlled dynamometer. All presented traces were recorded for the FUDS drive cycle.

The SOC is an important parameter that offers precise information on the charging / discharging level of the battery pack. This permits to calculate the residual capacity (in Ah) or the residual energy (in kWh) that remains available in the battery pack. The SOC can be calculated by using the following relation:

$$SOC = \frac{Q}{Q_{max}} = \frac{Q_{max} - Q_{used}}{Q_{max}} \qquad (5)$$

where Q is the instantaneous battery capacity or the battery charge level, Q_{max} is the maximum battery capacity (nominal level) and Q_{used} is the charge delivered by the battery pack or the difference

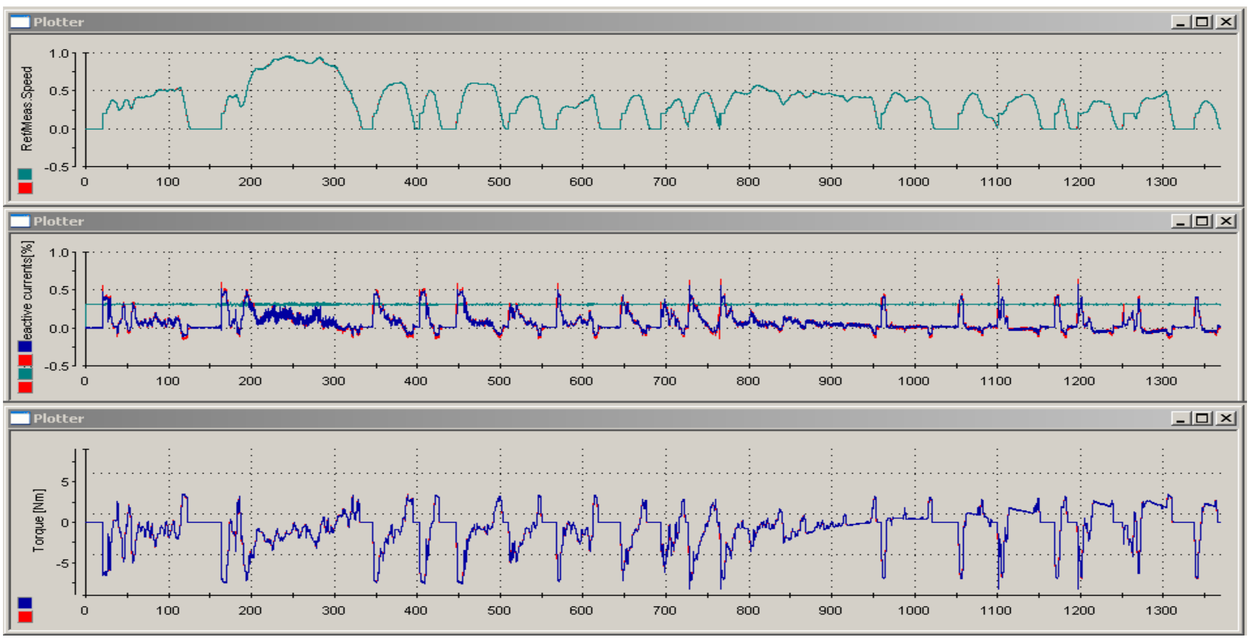

Fig.7. ControlDesk user interface for real-time of prototyping station

between the maximum and instantaneous capacity. The size of the battery pack is determined by the power and the energy demand. The power must be greater than the one of the electrical motor. Also, during the vehicle operating cycle, the energy stored in the battery pack must be sufficient to maintain the SOC between two limits. The literature [7] indicate the following SOC limits for optimal operating range: SOC_{top}=0.6, SOC_{bottom}=0.4. Once these limits were chosen, the energy capacity (C_b) of the battery pack can be calculated [7]:

$$C_b = \frac{\Delta E_b}{SOC_{top} - SOC_{bottom}} = \frac{\Delta E_b}{\Delta SOC} \; [kWh] \qquad (6)$$

where ΔE_b is the maximum change in the battery storage energy during a vehicle operating cycle. For an usual lead/acid battery the specific energy capacity is around 40Wh/kg and the energy density is around 68 Wh/dm^3. Knowing C_b for a certain battery pack and the energy that charge/discharge the batteries, and using (6) the variation ΔSOC can be calculated.

The power of electrical drive can be calculated based on voltage and current measurements of dc link. On the other hand, using the orthogonal components of currents (i_{sd} and i_{sq}) and the reference voltages (u_{sd}^*, u_{sq}^*) from the synchronous reference frame the instantaneous electrical power can be estimated with:

$$p = u_{sd}^* \cdot i_d + u_{sq}^* \cdot i_q \qquad (7)$$

The traces of these powers (measured and estimated) are presented in the first diagram of Fig.8.

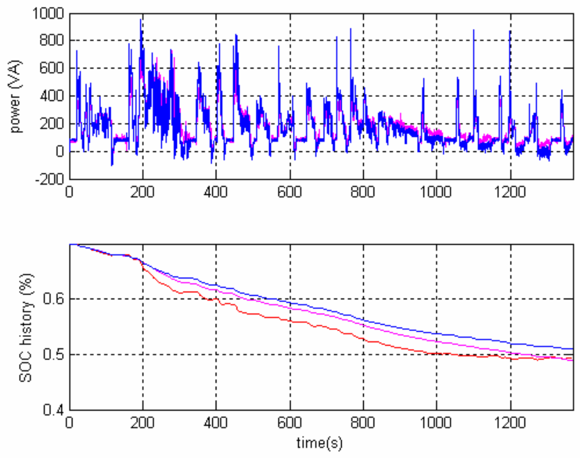

Fig.8. Time history of motor power and change in the battery storage energy

Based on the above mentioned powers the SOC was calculated with (6). The second diagram of Fig.8 shows three traces of the history of SOC. From top to bottom, the first is the measured SOC, the second is the estimated SOC and the third is the simulated SOC with the ADVISOR. It can be seen that all the traces have quite the same variation. Thus, using the current transducers needed in vector control technique one can estimate the SOC evolution based on the power calculated with (7).

6 Conclusions

HEVs are currently receiving the greatest attention. Our final goals are to find hybridization emission benefits and optimize a control strategy based on emission reduction. Application development requires a complex, very long testing and developing procedure for testing a number of configurations and control algorithms. Although a final algorithm can only be placed into some marketable hardware, their development is the most comfortable on PC's.

We have created a development environment. This integrated methodology of development and testing makes the longest part of the development process easier, faster and more suitable for documentation. By analyzing the recorded data for an emulated drive cycle one can be determined both the energetic and economic requirements, and the performances of motor-inverter assembly and also the validation of certain models of the virtual or emulated component parts (battery, mechanical transmission etc.).

References:

[1]D.Hermance, S.Sasaki, "Hybrid Electric Vehicles Take to the Streets", *IEEE Spectrum*, 1998, pp.48-52

[2] http//www.ctts.nrel.gov/analysis/

[3] R.Morici, C.Rossi, A.Tonielli, "Fast Prototyping of Nonlinear Controllers for Electric Motor Drives", *Proc. of the 12th IFAC World Congress*, Sydney, Australia, 1993, pp.445-450

[4] ***, ControlDesk.Experiment Guide, dSPACE GmbH, Paderborn, Germany, March, 2005

[5] V.Horga, M.Rățoi, M.Albu, I.Graur, "Emulator Control of Dynamic Characteristics of Mechanical Loads", *The 2nd Int. Conf. on Electrical and Power Engineering EPE'02*, Romania, 2002, pp. 227-234

[6] V.Horga,A.Onea, M.Rățoi, C.Boțan, "Induction Motor Control Based on Minimum Number Parameters Model", *The Bulletin of the Polytechnic Institute of Jassy*, Tome XLVII (LII), 1-4, 2002, pp.77-85

[7] M.Ehsani, Y.Gao, K.L.Butler, "Application of the Electrically Peaking Hybrid Propulsion System to a Full-Size Passenger Car with Simulated Design Verification", *IEEE Trans. on Vehicular Technology*, vol.48, no.6, November 1999, pp.1779-1787.