Interactive Simulation for Teaching the Influence of Power Management on Hybrid Electric Cars Overall Energy Consumption

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***Abstract* — Usage of sustainable energy is a key factor for solving future environmental issues. The purpose of the project SustEner is to modernize sustainable electrical energy vocational training by enhancing existing or establishing new training methods in enterprises and education. This paper presents the SustEner module power management techniques in hybrid electrical cars. Increasing market demand for hybrid electric vehicle (HEV) leads to a higher effort on training and education of high qualified engineers in this field. Beside the development and design of different HEV components also the interaction and efficiency of the entire system is a key factor. Understanding the power flow from one component to the other improves the ability of developing high efficiency HEV. Online teaching tools provide the possibility of teaching complex technical problem in an easy way and with high approval. Thus an interactive simulation tool was developed teaching power management techniques for HEV. In the following an interactive online tool is presented based on a MATLAB/Simulink HEV model enabling configuration of a HEV and efficiency analysis for a specific drive cycle.**

***Keywords* — electric car, hybrid, simulation, power flow, efficiency, teaching.**

I. INTRODUCTION

Transportation sector is strongly influenced by the availability of a primary energy source like oil. Predictions show that the oil and reserves will run out within the next decades. The transportation network based on oil production and derived fuel products will no longer be affordable [1]-[2]. Furthermore, beside the waste of resources also the environmental pollution must be taken into account [3]. So, reduction of fuel consumption and increasing efficiency is enforced from two sides. Improvement of existing technologies and development of new technologies is absolute necessary to solve this issue. Due to these facts solutions must be found reducing/replacing the oil based transportation. On the other side the existing power distribution network of fossil fuels cannot be neglected. Thus the transition from oil based to non-oil based transportation must be gradual and not suddenly. In this way new vehicle power train technologies must meet the demands of several points. Nowadays such technologies can be found in Hybrid Electric Vehicles (HEV). HEVs form a bridge technology meeting the effort of both, fast and comfortable individual mobility and saving resources [4].

It is obvious that the research efforts must be increased in this area. Engineers and students in the field of electrical drive systems must be motivated and well trained for the topic. To raise the interest and quality of teaching the support of modern information and communication technology can be helpful [5]-[6]. Complex technical problems can be explained in an easy and simple to understand way [7]-[10]. In this paper an interactive simulation tool is presented which covers the mentioned issues. In a first step a MATLAB/Simulink based model is devolved to enhance the investigations on Power management techniques of a HEV. After that the model was transformed into the Programming language ‘Processing’ enabling the usage on an e-Learning platform provided within the project SustEner.

II. TEACHING OBJECTIVES AND DEMANDS

The learning module is addressed to a specific group of active engineers and upcoming ones. This target group consists of engineers and students involved in the field of e-mobility and design of power train applications in HEV. The tool is presented as a web browser based program and application, respectively.

The user is guided through different steps of presetting different boundary conditions and finally testing the configuration by a simulation. The simulation is performed through a longitudinal simulation of the vehicle by a preset driving cycle. The focus of this tool is given on the overall efficiency and power consumption due to the preset driving cycle and the parameters of the configured vehicle.

The key factors that can be preset by the operator within this tool can be described as follows:

- Vehicle configuration: power rating of internal combustion engine and electric machine (EM);

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Configuration of battery storage size and vehicle mass. Predefining of energy distribution strategy, covering the full range from an all-electric vehicle to a conventional car powered by a combustion engine only.

- Driving cycle: Choose of predefined driving cycles, e.g. the New European Driving Cycle (NEDC), Manipulation of driving cycle. Define own driving cycle with various percentages of highway and inner city, as well as up and downhill passages.
- Ambient conditions: Enable and disable different auxiliary systems as air conditioning, lights, entertainment, etc. representing driver demands and/or ambient conditions.

The focus of the learning module is laid on the presentation of the energy distribution between different vehicle components rather than the function of each individual component. With these possibilities the student should be able to understand the interaction of all components through the entire system. So, the teaching goals can be defined as:

- Improvement of knowledge regarding the hybridization level influence on entire system efficiency. The peak efficiency is often communicated as the dominant parameter of a drive train technology. However, the achieved range of operation is mostly defined by the energy consumed at partial load conditions. In such cases the auxiliary power consumption can exceed demanded drive power of the vehicle. By comparing the configured HEV with a conventional driven vehicle the understanding of maximum efficiency and low fuel consumption should be enhanced.
- According to the additional components in the drive train of a HEV (e.g. EM, battery storage) also the vehicle mass is increasing. Thus an arbitrary power rating of electrical machine and/or battery capacity is not rational. The student should be able to configure a reasonable HEV regarding power rating and desired drive range demands with available components.
- Consideration of the ecological impact of personal mobility. By comparing the consumed overall energy and the total CO_2 emission to cover the driving cycle based on different boundary conditions.

III. Simulation of a Hybrid Electric Vehicle

A. Hybrid electric Vehicle Basics

In hybrid electric cars the needed force for driving is generated by the internal combustion engine (ICE) and the EM in combination. A general overview of the main HEV components is given in Fig. 1.

The main purpose of the EM in parallel configuration is to keep the ICE working near its optimum combustion efficiency. The goal is to reduce the fuel consumption and the pollutant emissions as well as to improve the efficiency of the entire system.

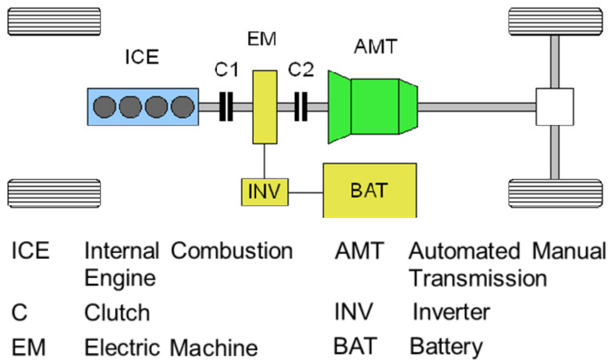

Fig. 1: Example of a hybrid drive train.

Conventional vehicles and their power train with an ICE are usually ten times overdesigned to meet the demands of desired driving performance [11]. This leads to the disadvantage that the ICE is usually operated in partial load conditions and not at its optimum operating point. As a result, the power consumed by auxiliary systems of the vehicle like heating, air conditioning, power steering, audio or lighting may even be higher than that consumed for actually driving. In addition the efficiency of the drive train dramatically decreases in partial load conditions. However in public discussion usually only the peak efficiency numbers are communicated sometimes leading to expectations that cannot be met in practical operation. In this way the key point of an HEV is to distribute the power in a way to keep the overall efficiency as high as possible.

Considering an urban traffic situation, the average speed is about 20 km/h. Thus it is clear that the necessary traction power is only a fraction of the conventional installed vehicle power (maximum vehicle speed). By operating point adjustment of the ICE through an EM in the drive train this disadvantage can be reduced. The optimum level of hybridization as well as load sharing strategy and electrical energy storage management for highest overall efficiency will thus depend on the driving cycle and vehicle parameters. This power distribution is controlled by the control strategy and power management unit of a HEV. The goal of the power management unit is to distribute the demanded torque for actually driving performance between the different power sources and to keep the efficiency on the maximum level. Knowledge of these procedures provides the possibility of further improvements in this area.

B. Mode of Operation

A HEV can be operated in different modes. Beside the hybrid mode with ICE and EM working in combination, also the pure electric mode and the conventional mode are possible. In the present module the mode of operation can be preset as follows. In a first step the vehicle can be configured as a conventional car where only the ICE is used for propulsion. The so obtained results of fuel consumption and emissions can be used as baseline for comparison. Another possibility given by the model is the configuration of the vehicle as pure electric car. Thus the vehicle parameters must be adapted to achieve real world scenario. For example, the vehicle gross weight must be increased compared to the conventional vehicle for same installed power. Finally, the vehicle can be configured as an HEV. Two different static strategies can be preset, the high efficiency and the low ICE fuel consumption strategy, respectively. The operation of an HEV is distinguished by the working of ICE and EM in combination. However, there might be some operating points where only pure electric or pure conventional mode is reasonable. Two typically operating points are given in the low and high speed area. In the low speed region it is sufficient to use only the EM (adequate EM power provided). On the other end in high speed areas often single ICE operation is more efficient than hybrid or even pure electric operation. At the end the student should be able to put these decision criteria in the way of optimal overall efficiency and fuel consumption.

C. *Simulation of Vehicle Components*

In the following, the presented simulation model is based on a parallel hybrid system. The EM with the power electronics and battery storage can be switched on or off from the power train. The ICE and the EM are ideally uncoupled - the vehicle can then be operated conventionally (ICE only), purely electrically or mixed (hybrid operation). The output power of the ICE and EM can be superposed mechanically by a planetary gear (speed addition), direct coupling (torque addition) or traction addition by separation of ICE and EM working on different axes. The main advantage of the parallel configuration is that both devices can be designed smaller than the needed maximum power due to power and torque addition. So, the drive components can be designed more efficiently. Furthermore the EM can be operated either as motor and generator. Basically, the energy flow of the electric system can be considered to transfer between battery storage, inverter and the electrical motor/generator. So, the complex system is much easier to understand for users not widely familiar with hybrid systems.

In the following a brief description of the main components is presented. As aforementioned, the focus of this module is based on the power distribution. Thus the description and component models are presented in a global point of view.

Internal combustion engine

The ICE is one of the main components of an HEV. It serves as an energy converter unit. Stored energy in a fuel (gasoline, diesel, natural gas) is converted through combustion to kinetic (rotational) energy.

The input parameters needed are the angular speed n and the torque M. As output the power P is provided to the power train. On the other side the fuel consumption and emissions are the main parameters for efficiency investigations. These parameters are provided by fuel consumption and emission maps depending on the engines angular speed and torque. Maximum engine speed is given as single parameter while the maximum torque curve depends on engine speed. In Fig. 2 the ICE is presented with the main parameters as a block diagram.

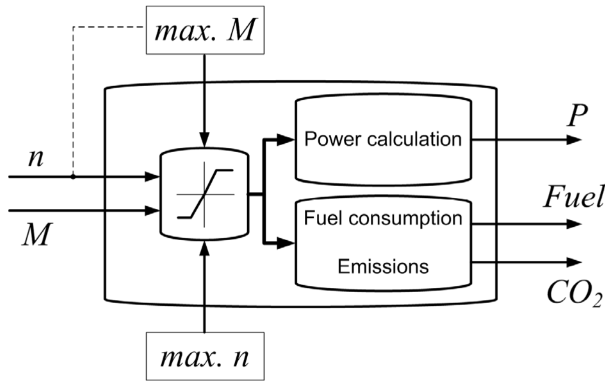

Fig. 2: Block diagram of ICE model

Electric machine

The electric motor is also an energy converter from electric energy into kinetic (rotational) energy. The operating regimes of an EM can be given as follows:

* Converting electric energy stored in the battery into mechanical power to drive the vehicle.
* Converting mechanical power from the internal combustion engine into electric power in order to charge the battery.
* Recovering mechanical power from braking to recharge the battery.

The input parameters of the EM are defined equal to the ICE ones as angular speed and torque. On the other side the machine power together with the machine efficiency are the output parameters. The efficiency depends on machine speed and torque. Here the EM is not specified either as a DC machine, synchronous or induction machine type due to the global point of view. The inverter in the configuration presented is included in the EM efficiency.

Battery storage

The battery serves as the storage for the electric energy. In HEV the demands for a battery storage system are: high power and energy density, low mass, long life cycle and low costs.

According to the driving cycle and performance of the vehicle the power is generated or demanded by the EM. This serves as the input parameter of the battery storage. The state of the battery is represented by its state of charge *SOC*. Furthermore the nominal voltage *V*, the battery capacity *Cap* and the range of usage *RoU* in percentage of *SOC* are the determining parameters. In Fig. 3 the block diagram scheme is presented for a battery storage system.

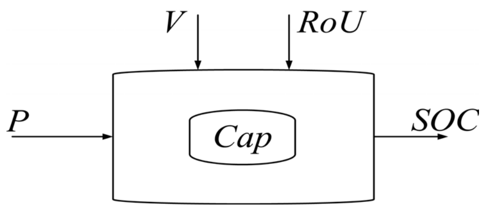

Fig. 3: Block diagram of battery storage

Gearbox

A gearbox is composed of a collection of gears that are arranged so as to multiply the torque of the engine. The main purpose of the gearbox is the adaption of speed and torque characteristics of engine and vehicle.
The input and output parameters are provided as input speed/torque and output speed/torque, respectively. The gear ratio γ_{gear} is a preset value for a specific gear number and can be chosen manually or automatically (automatic transmission). The input and output relation can be given as:

$$n_{output} = {}^{1}\!/_{\gamma_{gear}} \cdot n_{input} \qquad (1)$$
$$M_{output} = \gamma_{gear} \cdot M_{input}$$

Entire system

In Fig. 4 the power flow diagram of the entire system is presented as a block diagram. Model input variables are the acceleration and speed currently needed for the actual drive cycle point. Through the slope of the road, rolling resistances and different parameters (vehicle weight, aerodynamic, etc.) leading to the acting force on the wheels are calculated and considered constant for a short time period. According to the power train parameters (wheel radius, gearbox losses, gear ratio) the demanded torque is obtained and a decision is made which operating mode best suits in this case as described above.

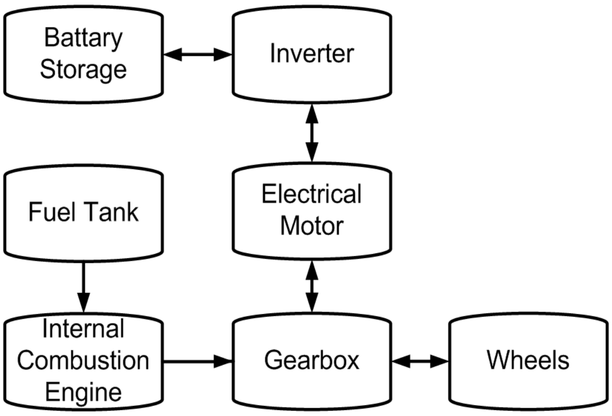

Fig. 4: Power flow diagram of a parallel hybrid system

IV. INTERACTIVE SIMULATION TOOL FOR ONLINE APPLICATIONS

A. Software Implementation

The parallel hybrid system's first implementation was realized using the powerful analysis and testing tools of Matlab/Simulink.
In order to guarantee a user friendly and smooth interactive operation that facilitates the student's learning efforts, the model equations and control loops have then been reprogrammed with the programming language 'Processing.js,' which is a JavaScript language especially suited for the presentation of interactive content. It is based on Java and ports the code to JavaScript. Therefore it is possible to render the application in an HTML canvas element, which consequently enables the software's execution in all new versions of Firefox, Opera, IE9, Safari and Chrome, without the need of certain plug-ins. If a Java runtime is already installed even older browsers are supported, since a Java applet is generated when using 'Processing.'
At the end of the design process a target application was established that models internal HEV interactions and simulates driving cycles with the possibility to configure a wide range of system parameters. In using this software the student will develop a feeling for the influence of these parameters on the vehicle's energy balance as well as its overall performance and can compare multiple vehicle configurations.

B. Practical Use and Educational Goals

This section illustrates the application's approach in interacting with the user with respect to specific educational goals. In addition, examples of possible analysis topics show the software capabilities.

a) Basic Component Selection

The central idea is to offer the users a high grade of interactivity by giving them the possibility to adjust basic model parameters to individual interests. For the drive train these are: ICE, EM power and size of energy storages (fuel tank, battery). These components give the variable vehicle weight (derived from typical values of actual cars), which is added to the user defined base weight.

Educational objectives:

Arouse user curiosity and keep them focused by:

- Accessible web based presentation
- 'Easy to learn' experience
- Numerous adjustment options

Consideration of these basic principles gives the student a smooth learning experience and facilitates vocational adjustment.

Possible analysis topics:

- What is good component scaling?
- How does it affect the maximum driving range?
- Are certain combinations more viable then others, with regard to a specific field of application (e.g. highway or city operation)?

b) Driving cycle specification

The field of operation, mentioned in the previous section, corresponds to a specific driving cycle, which is characterized by the three diagrams shown in Fig. 5. Those are time dependent courses of vehicle speed, altitude (height) and acceleration. The user may select from predefined driving cycles (e.g. the NEDC) or define own ones. Additional ways to adjust the duty cycle simulation include modifications of auxiliary equipment usage, load sharing strategy and simulation speed/duration (slow, real time, fast forward).

Educational objectives:

Lowering gateway hurdle, though allowing adaptability for experienced users by:

- Quick start possibility (predefined driving cycles or load sharing strategies)
- Intuitive graphical adjustment (shifting/inserting dots in Fig. 5)
- Teaching the importance of a holistic view on the drive system (overall vs. peak efficiency).

Possible Analysis Topics:

- Influence of auxiliary power consumption (ambient conditions) on HEV efficiency.
- Analysis of partial load operation with arbitrary power flow from ICE and EM alone or both (hybrid operation).
- Test feasibility of chosen component scaling with respect to different load requirements.
- Investigate design philosophies (‘fun to drive’, maximum power, high efficiency, etc.) and their influence on hybridization level.

c) Simulation output

Fig. 6 depicts a typical output window shown during a simulation run, which is constantly updated with the following information (Numbers correspond to Fig. 6):

Target (blue) and actual (red) traces of

(1) Altitude (height) over time

(2) Speed over time

From altitude and speed traces already driven remaining distance can be derived.

Cockpit elements

(3) Current value of HEV speed

(4) Current value of ICE rotational speed

(5) Temperature display (climate data, ambient data)

Note: Ambient temperature is adjustable; cockpit temperature is set to a fixed value of 20°C.

(6) Heating/air conditioning

(7) Headlights

(8) Hybrid drive train with energy sources (charge/fuel level) and energy flow schematic

Educational objectives:

- Clearly structured overview of simulation progress.
- Showing state variables ‘in action.’
- Giving a responsive and intuitive feedback through imitation of real car dashboard view.
- Developing sense for share of auxiliary power in total power consumption.

Possible Analysis Topics:

- Driver demands vs. HEV performance
- Comparison of actual and target altitude/speed values (deviations characterize the HEV limits).
- Pushing a concept to its limits (causing breakdown).
- Relationship between HEV performance and security issues.
- Analyze influence of changing ambient conditions on drive system.
- Monitoring of energy distribution and load sharing to analyze total energy efficiency (as opposed to peak values), also considering the loss of efficiency for partial load conditions.

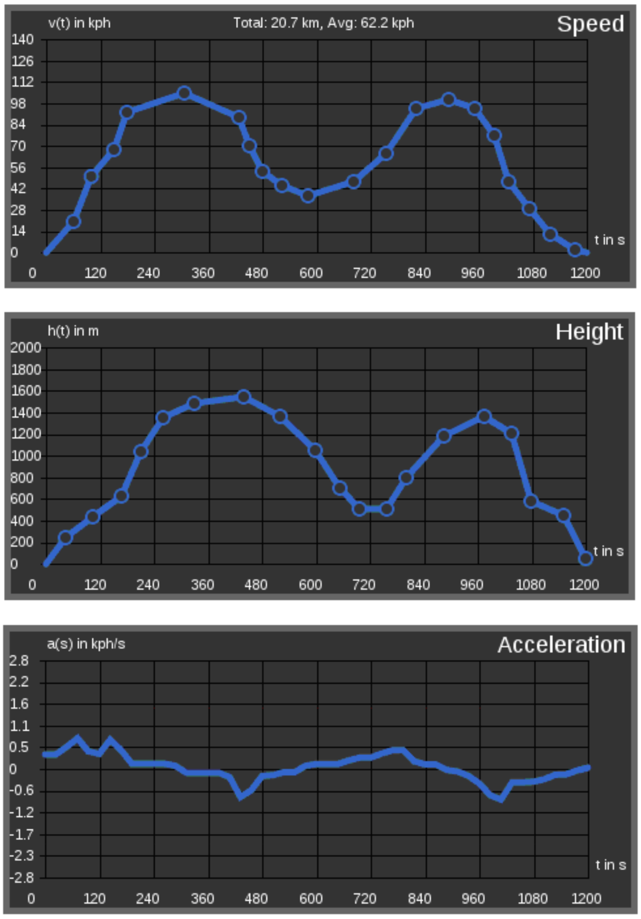

Fig. 5: Vehicle speed, altitude (height) and acceleration profile over the course of time are used to define a specific driving cycle.

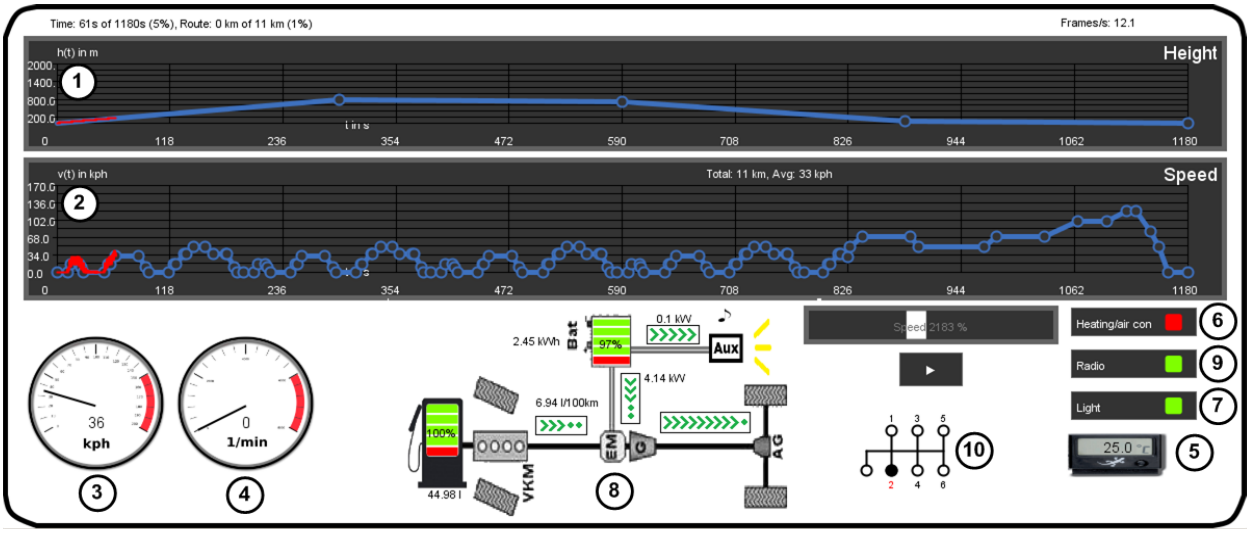

Fig. 6: Output window during typical simulation run of predefined driving cycle (blue traces). Red traces show actual values. **(1)** Altitude (height) over time, **(2)** Speed over time, **(3)** Current value of HEV speed, **(4)** Current value of ICE rotational speed, **(5)** Temperature display, **(6)** Heating/air conditioning (on/off = green/red), **(7)** Headlights (on/off = green/red), **(8)** Hybrid drive train with energy sources (charge/fuel level) and energy flow schematic (green arrows), **(9)** Radio (on/off = green/red), **(10)** Gearshift position.

At the end of the simulation process a summary is given, which shows accumulated CO_2 output and energy usage curves and compares total energy efficiency to the one of a predefined standard HEV.

Educational objectives:

- Teaching ecological impact (greenhouse gas production/energy consumption).
- Demonstrate that energy efficiency and CO_2 emission of different types of vehicles vary with route type/driver demands.

Possible Analysis Topics:

- Analyze the HEV's 'ecological footprint.'
- Find suitable hybridization levels for different route types.

VI. Conclusion

The presented web based simulation and learning module is aimed at teaching HEV power management and load sharing strategies. Based on a parallel hybrid drive system it is designed to test various drive/strategy configurations on typical driving cycles, with respect to total energy consumption and the energy flow between the different components. In using the program, students can improve their knowledge about internal and external (e.g. ambient conditions) HEV interactions, allowing them a comprehensive view of total vehicle power consumption and efficiency and stressing the importance of partial load conditions instead of peak values.

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Lifelong Learning Programme

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