Modeling of the Hybrid Electric Drive with an Electric Power Splitter and Simulation of the Fuel Efficiency

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Keywords
Hybrid electric vehicle (HEV), Simulation, Efficiency, Converter control, Power converters for HEV, Test bench, Power transmission, Supercapacitor, Regenerative power, Software for measurements

Abstract
This paper presents the results of the modeling of the HEV with an electric power splitter (EPS) and simulation of the fuel efficiency of this type of vehicle. The new innovative technological approach is presented by using the special type of synchronous machine that splits the mechanical power on two separate power transmission parts and therefore it is called electric power splitter.
EPS is based on a double rotor synchronous permanent magnet generator. It is consisted of two rotating parts, a classic permanent magnet rotor and a rotating stator. The rotor is firmly coupled to the drive shaft of the internal combustion engine of the vehicle (ICE). The rotating stator, which structurally is typical AC machine stator, is firmly coupled to the transmission of the vehicle that leads to the car wheels. This technical solution enables the ICE to operate on the most optimal revolutions during the entire driving schedule.

Two distinguish approaches has been realized in order this new innovative technological solution to be confirmed as eligible. First approach is creation the mathematical model of the entire system, taking into account all the necessary preconditions, environment influences, machine and component characteristics. The results have been obtained by using this precisely determined mathematical model and by simulating the characteristics of all essential values for the entire drive, which gives clear view of the capabilities and potentials of this new HEV system.

The second approach is based on experimental verification. In order to be performed the laboratory tests on this HEV concept, an experimental working stand was set up in the laboratory. ICE and the traction load are simulated with controlled AC induction motors. The entire working stand presents complex machine, measure and control system for realization of this task.

Introduction
Improving the fuel efficiency of the passenger vehicles is the ultimate goal of entire scientific and technical community. The main purpose of the hybrid electric drive is achievement of higher
efficiency in energy transmission from internal combustion engine (ICE) to the traction wheels of the
vehicle. The hybrid electric vehicle (HEV) represents the transient solution from standard internal
combustion engine driven cars to all-electric driven vehicles (EV). Some car manufacture companies
already have successful commercial models (like Toyota Prius and Honda Insight), but all are based
on significant different technological solution.
In the Research Center of Engine and Automotive Engineering Josef Bozek (RCJB) at CTU in Prague,
there is ongoing project for development of hybrid electric drive. For that purpose, the experimental
working stand has been created at the Department of Electric Drives and Traction at Faculty for
Electrical Engineering. Main innovative characteristics of this hybrid drive is using of super-capacitor
(SC) as accumulation unit and electric power splitter (EPS).
Commercial hybrid electric cars, for splitting energy from ICE are using the planetary gear and
separate electrical generator for electrical power supply of the traction motor and charging of the
battery (Toyota Synergy Drive). In the hybrid electric system developed on the CTU in Prague, the
power splitting is performed entirely electrically by using the EPS. Also in this working stand, instead
of chemical battery for accumulation of the recuperative breaking kinetic energy, it is used the super-
capacitor as new technological element for electrical energy storage. That gives opportunity to store
energy without transformation from electrical to chemical and back. It brings higher efficiency in
energy form transformation.

Power splitting by using the electric power splitter in HEV
The technological concept of HEV with EPS and super-capacitor is shown on Fig. 1. The internal
combustion engine is the main and only power source of the vehicle that produces the mechanical
power \( P_{\text{ice}} \). EPS is specially constructed synchronous generator with two rotating parts. The main
rotor is classic permanent magnet rotor and it is firmly coupled to the drive shaft of ICE. The other
rotating part is functionally same as all other AC machines, but with capability of rotation, placed on
bearings. This part of the EPS is firmly coupled to the transmission that leads to the car wheels and
rotates with the speed proportional to the vehicle velocity (speed V). This technical solution enables
the ICE to operate on most optimal revolutions during entire driving schedule.

Fig. 1: HEV drive with electric power splitter
Produced mechanical power $P_{ic}$ from ICE by using EPS is divided into electrical $P_{epe}$ and mechanical power $P_{epm}$. Induction traction motor (TM) is inserted on the shaft of the EPS rotating stator and represents the main electrical propulsion to the vehicle. EPS and TM are electrically connected through two traction AC/DC and DC/AC power converters for HEV with intermediate DC link circuit. On this DC circuit, a SC is connected via charging and discharging DC-DC power converter, which precisely regulates the power flow from DC circuit and SC.

The traction motor is powered by $P_{el}$ that is generated in EPS ($P_{epe}$) and by additional power from SC ($P_{sc}$):

$$P_{el} = P_{epe} + P_{sc} \quad (1)$$

Traction motor TM produces mechanical power $P_{tm}$ which with mechanical $P_{epm}$ added from EPS is transmitted to the car wheels. Total proportion power of the car $P_{car}$ is expressed by formula:

$$P_{car} = P_{epm} + P_{tm} \quad (2)$$

When the car is braking, TM changes the function from motor to generator. By this way, car kinetic energy produces the deceleration power that can be partially converted into electric energy, which is accumulated in the SC and in the future can be used for the next acceleration in following driving cycles.

By precise engine control system, HEVs can significantly avoid the energy losses within the ICE. This is achieved by controlling the engine operation at speed and load (power on the output drive shaft) combinations where the engine is the most efficient. This process is enabled by using the energy storage device (super-capacitor) to either absorb or substitute part of the ICE output, allowing it to operate only at speeds and loads where it is most efficient. As seen on the engine map (Fig. 2), the ICE can provide the most efficiency only on the narrow area highly dependent on specific output power and revolutions of the drive shaft. Driving strategy of the HEVs is based on providing the working conditions to the ICE in order to keep it in this most effective region of work.

![Engine map of the fuel efficiency (1200 [cm$^3$] internal combustion engine)](image)

Fig. 2: Engine map of the fuel efficiency (1200 [cm$^3$] internal combustion engine)
Fuel efficiency calculation of the vehicle

Vehicle efficiency is calculated for standardized driving cycles. Fuel efficiency of the passenger vehicles is defined as demanded amount of fuel ($L_{\text{car}} [\text{l}]$) for driven car trajectory distance ($S_{\text{car}} [\text{km}]$). In Europe, this value is measured according to predetermined working regime defined as NEDC – New European driving cycle:

![Fig. 3: NEDC – New European driving cycle](image)

NEDC is consisted of 1200 sec. driving schedule, which combines 800 seconds urban and 400 seconds of highway driving (Fig. 3). Urban driving is consisted of four repeated cycles (ECE 15), each with three different acceleration, idle and deceleration regime. Highway driving (EUDC) is continuous driving with predetermined changes of the speed $V$. This is standardized European driving schedule (NEDC) for calculating the fuel consumption and vehicle efficiency. The vehicle drives the first 800 sec. (urban driving). Total driven distance is measured or calculated ($S_{\text{car}}$) during this process. This value is divided by consumed amount of fuel ($L_{\text{car}}$) and the consumption $Q_{\text{urb}}$ of the vehicle for urban driving is calculated:

$$Q_{\text{urb}} = \frac{S_{\text{car}}}{L_{\text{car}}}$$

(3)

The same approach is for calculation of consumption $Q_{\text{hgw}}$ for the highway driving (EUDC cycle from 800 to 1200 sec.). For calculating combine consumption $Q_{\text{com}}$ (urban and highway NEDC), for the entire NEDC (1200 sec.) is calculated the car trajectory $S_{\text{car}}$ and fuel consumed $L_{\text{car}}$.

Kinematic model of the vehicle for performance simulation

In vehicle simulations, whether there are for conventional ICE vehicles, EVs, or HEVs, it is necessary to be created the kinematical model (KM) of the vehicle. That presents the mathematical representation of the vehicle and it is core element into the simulation program. The KM is mathematically created for the predetermined car specifications, like car weight $m$, efficiency of transmission $\eta_{\text{tm}}$, ICE fuel consumption and output power, number of super-capacitor accumulative units, efficiency of electrical power converters e.g.

During the motion (drive), the vehicle is affected by different forces, $F_{\text{air}}$ aerodynamic drag forces, $F_{\text{r}}$ rolling resistance forces, $F_{\text{s}}$ resistive gravity forces and $F_{\text{a}}$ acceleration force as shown on Fig. 4.

Aerodynamic drag forces are calculated with equation:

$$F_{\text{air}} = \frac{1}{2} \rho \cdot C_{\text{A}} \cdot A \cdot (v - v_{\text{ref}})^2$$

(4)

Aerodynamic resistance is represented thought a $F_{\text{air}}$ drag force that the vehicle must overcome at a certain speed. This term is proportional to the square of the speed of the vehicle and, therefore, tends to be small at low speeds, but increases rapidly with velocity.
Fig. 4: Acting forces on the vehicle during drive

Rolling resistance forces $F_r$ are depended on weight of the vehicle $m$, road resistance drag $f$ and angle of inclination $\alpha$. This force (5) is constant regardless of the speed of the vehicle and tends to dominate at relatively low speeds.

$$ F_r = m \cdot g \cdot f \cdot \cos \alpha $$ (5)

Resistive gravity forces $F_s$ are the forces that propel (or decelerate) the vehicle on a non-zero angle of inclination $\alpha$:

$$ F_s = m \cdot g \cdot \sin \alpha $$ (6)

This force (6) is positive (is in the same direction as rest of the resistive forces) when the vehicle is on up-hill climbing ($\alpha>0$). If the vehicle is moving downhill ($\alpha<0$), $F_s$ is negative and propels the vehicle. The mass inertia of the vehicle is manifested through the acceleration force $F_a (0)$. It is non-zero only when the vehicle is accelerated ($a>0$) or decelerated ($a<0$) and has no effect under constant-speed cruising conditions ($a=0$).

$$ F_a = m \cdot a $$ (7)

Total required force $F_{car}$ at the wheels of the vehicle, in order to overcome all the resistive forces during the drive, is the sum of all above described forces:

$$ F_{car} = F_s + F_r + F_{air} + F_{a} $$ (8)

The most essential physical value of the vehicle kinematical model is the total demanded power $P_{car}$ on the car wheel. This power is directly depended from drag forces $F_{car}$ and actual vehicle velocity $V$:

$$ P_{car} = F_{car} \cdot V $$ (9)

**Results of the kinematic model simulation**

Using the programming simulation package Matlab, the simulation has been made. The main approach in this simulation is to determine energy fluctuations in the hybrid drive during NEDC driving schedule. For this purpose, function and behavior of each component of the system is determined and taken into account according to previously described kinematical model of the vehicle.
The kinematical model is mathematically created for the predetermined car specifications, like car weight, efficiency of transmission, ICE fuel consumption and output power, number of accumulative units SC and efficiency of electrical power converters. Program calculates all this values according to the NEDC (Fig. 3). Obtained data are presented in characteristics that are functions of time $t$. The power on the drive shaft of the internal combustion engine $P_{\text{ice}}$ follows the needed driving power $P_{\text{car}}$ that is shown on Fig. 5:

![Fig. 5: $P_{\text{car}}$ and power produced on drive-shaft if the ICE $P_{\text{ice}}$](image)

That is the main advantage of hybrid electric drive that cannot be performed in normal cars in which the ICE must instantly and rapidly change the working regime according to the actual power demand. That results with high fuel consumption and low efficiency. Also in HEVs, the ICE is working only when the working regime demands the significant power, which is not the case with conventional cars in which ICE is working all the time even when the car is not moving like in normal urban driving.

![Fig. 6: Fluctuation of the accumulated energy $W_{\text{sc}}$ into SC](image)

ICE provides power to drive the vehicle and for charging the SC and keep the $U_{\text{sc}}$ above the critical minimal level $U_{\text{sc min}}$. Therefore, $P_{\text{ice}}$ depends on actual energy volume $W_{\text{sc}}$ accumulated in the super-capacitor (Fig. 6), which is determined from actual SC voltage $U_{\text{sc}}$:

$$W_{\text{sc}} = \frac{C \cdot U_{\text{sc}}^2}{2}$$  \hspace{1cm} (10)

Fig. 7 presents the actual voltage of SC. According to equation (10), by measuring the $U_{\text{sc}}$, the precise data of accumulated energy $W_{\text{sc}}$ in the super-capacitor can be obtained during the entire working regime.
Working regime is determined in order $U_{sc}$ to be maintained between the two critical values $U_{scmin}$ and $U_{scmax}$. This is important because SC must not be overcharged ($U_{sc} \leq U_{scmax}$) and it must be keep over minimal level ($U_{sc} > U_{scmin}$) to have energy reserve. Low voltage of SC is undesirable because the current level $I_{sc}$ of SC is increased and with that, the efficiency of SC is rapidly decreased.

Fuel consumption is measured in each time interval. By knowing the total fuel consumed on the end drive regime (in EDS $t=800$ [s] for urban and $t=1200$ [s] for combine drive regime) and total driven distance, the consumption of the hybrid-electric drive is calculated. For urban driving it is 25.6 [km/l], for highway 21.4 [km/l] and combine driving is 23.2 [km/l]. In Table I these values are compared with standard driven cars with the similar characteristics:

**Table I: Fuel consumption**

<table>
<thead>
<tr>
<th></th>
<th>urban</th>
<th>highway</th>
<th>combine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid-electric vehicle</td>
<td>25.6</td>
<td>21.4</td>
<td>23.2</td>
</tr>
<tr>
<td>Standard ICE vehicle</td>
<td>13.7</td>
<td>19.2</td>
<td>17.2</td>
</tr>
</tbody>
</table>

**Experimental verification of the HEV technological concept**

In order to be performed laboratory testing of this HEV concept, the experimental working stand has been created in the laboratory at laboratory for electric drives and traction on FEE-CTU in Prague. The scheme of this laboratory stand is shown on Fig. 8:
The main functional units of the stand are the same as the units of the HEV concept shown on Fig. 1. On this HEV laboratory model, ICE and the car wheels have been substituted with two regulated induction motors. Internal combustion engine is simulated by a controlled electric AC induction motor. Traction load is simulated with another controlled AC induction motor. The main working structure of the experimental stand is consisted of four electrical machines, as shown on Fig. 9:

![Fig. 9: Machines of the laboratory working stand of HEV for experimental analysis](image)

Also, as an essential functional part of the stand are five semi-conductor power electronic control units, super-capacitor and all the necessary instrumentation, control, power supply and protection equipment, for precise control of the process and data acquisition. The entire working stand is monitored and regulated by data acquisition system with real-time feedback control. For this realization, it has been used two NI USB6009 data-logging multifunction devices and Spider 8 measurement system. The core of the automatization system is based on measuring and data processing software LabVIEW 8.6. The full operational supervisory control and data acquisition (SCADA) system for the working stand with visual control graphical interface is already realized and it is fully functional (as shown on Fig. 10):

![Fig. 10: Supervisory control and data acquisition (SCADA) system for the HEV working stand](image)

As can be seen from the control panel, all the essential values are measured and controlled in real time. The user interface gives clear view of energy control and provides precise power control of each component. By using this highly dynamic measure and control system on the working stand, the precise substitution of the traction forces \( F_{car} \) can be experimentally generated. That can be achieved with LabVIEW interface for vehicle parameters and traction power control (Fig. 11).
Conclusion

The results show the main specifications of this new model of hybrid electric drive according to the European driving schedule. This mathematical model uses experimentally verified data from laboratory working stand and these simulations provide the results that prove the eligibility of this new technological solution. The results present the operating conditions of all systems during the driving regime. The changes in the values as a function of time give an overview of the energy fluctuations in each component of the system. This technological solution enables standard passenger cars to consume almost 50% less fuel in urban driving (ECE15 cycle) and less then 20% in highway (EUDC cycle). The final numerical results for fuel consumption show the significance of this new technological approach. Enabling vehicles to drive a greater distance using the same amount of fuel is the main task in increasing the efficiency of passenger cars.

References