ENERGY SAVING AND ENVIRONMENT FRIENDLY TECHNOLOGY OF HYBRID-ELECTRIC VEHICLE WITH NEW POWER TRANSMISSION AND ENERGY RECUPERATION APPROACH

Cundev Dobri[1], Mindl Pavel[2]
Faculty of Electrical Engineering, University "Goce Delcev" - Stip, Republic of Macedonia [1]
Department of Electric Drives and Traction, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic [2]

Abstract: *The main purpose of the hybrid-electric vehicle (HEV) is reaching of higher efficiency in energy transmission from internal combustion engine (ICE) to the traction wheels of the vehicle and saving the kinetic energy of the vehicle, which usually is wasted as heat during braking. Commercial hybrid car model (Toyota Prius), for splitting energy from ICE uses the planetary gear and separate electrical generator for electrical power supply of the electrical traction motor and charging of the chemical battery. In the HEV system developed on the Czech Technical University (CTU) the power splitting is performed entirely electrically by using the electric power splitter (EPS), which presents a special type of synchronous generator with two rotating parts (a classic permanent magnet rotor and a rotating stator). The rotor is firmly coupled to the drive-shaft of ICE, and the stator is firmly coupled to the transmission that leads to the car wheels. Vehicles that utilises this hybrid propulsion system will consume 35% less fuel on highway drive and even 60% less fuel in urban drive.*

Keywords: ENERGY EFFICIENCY, AUTOMOBILE TECHNOLOGY, HYBRID-ELECTRIC VEHICLE, POWER MANAGEMENT, FUEL EFFICIENCY, COMMERCIAL IMPLEMENTATION

1. Introduction

The propulsion system of the commercial vehicles hasn't had significant changes since first cars have started driving the roads. Internal combustion engine (ICE) is basic propulsion unit based on four-stroke Otto's or Diesel's cycle and consumes petroleum or diesel fossil fuel.

More energy efficient system is electrical propulsion. The main propulsion unit is electrical motor, which can be DC, AC induction or synchronous motor. It has successful implementation in railway vehicles like trains and in modern city public transportation lake metros, trams and trolleybuses. These vehicles have successful commercial use because of the continuous electric power supply from the over-line wire that is directly connected to the electric power grid. Electric passenger vehicles do not have this quality. Their power sources are chemical batteries, which are heavy, with low energy density and quite expensive. Therefore, electric vehicles (EV) never had successful commercial implementation despite their high-energy efficiency.

There are successful technological solutions of hybrid-electric propulsion systems implemented in commercial passenger cars. Every automobile manufacturer of hybrid vehicles has unique hybrid propulsion system (HPS). Motivational reasons for successful implantation of hybrid-electric technology in automotive industry originate from various causes. In recent years, hybrid electric vehicles (HEV) have taken significant role in automotive market. Since the first serial produced hybrid car in 1997 (Toyota Prius) their presence on the roads is rapidly increasing. More than a million vehicles worldwide are sold and their number is exponentially growing. All major car production companies already have hybrid-electric models, which are in commercial use or will be soon lunched on the market.

By definition, a hybrid vehicle is a vehicle with two distinct sources of potential energy that can be separately converted into useful motive kinetic energy. This potential energy may be stored in a number of forms including super-capacitors (electrical), batteries (electro-chemical), pressurized fluids (mechanical), rotating flywheel (mechanical) and fuel (chemical).

Hybrid electric vehicles represent a technological cross between conventional automobiles and electric vehicles. They combine an electric drivetrain, including battery or other energy storage device, with a quickly refuelable power source (RPS). RPS can be internal combustion engine (gasoline or diesel), fuel cell or gas turbine. In present commercial HEVs as RPS is used internal combustion engine, which is proved technology. This RPS recharges the electrical storage device (battery or super-capacitor) and may drive the wheels directly together with the electric motor. That can be achieved, either through a direct mechanical drivetrain or indirectly by providing electric power to the motor. If ICE can drive the wheels directly (in parallel with the electric motor), this is a parallel hybrid. If ICEs function is to produce electricity to the motor and to recharge the storage device, with only the traction motor driving the wheels, this is a series hybrid. Combination of parallel and serial hybrid energy patterns in one HEV concept defines parallel/serial hybrid system or also called combine hybrid.

Recuperative systems are used in vehicles that have capabilities to recuperate (recover or save) kinetic energy of the vehicle. This energy is accumulated in energy storage unit. This process is used during the deceleration of the vehicle and it is called recuperative braking or just recuperation. This process can be achieved by mechanical or electrical means of recuperation. In practice, the electrical means proved to be more effective and therefore have successful commercial use. It is based on precisely controlled electrical machines, motors and generators connected to the drivetrain of the vehicle. During the recuperation, the vehicle is decelerated by electrical generator, which is connected, directly to the shaft of the wheels or with the reduction gear and transmission. The generator is propelled by the kinetic energy of the vehicle - it converts that energy from mechanical to electrical, breaks (decelerates) the vehicle and produces electrical energy. This energy is stored in accumulative device - chemical battery or super-capacitor. In this thesis, the focus is aimed at recuperative systems with super-capacitors for hybrid-electric vehicles.

Besides hybrid-electric vehicles and electric vehicles, recuperation of kinetic energy is also used in Formula 1 racing cars, starting with season 2009. This system is known as KERS – Kinetic Energy Recovery System, which in essence presents hybrid propulsion system.

2. Energy savings potential of hybrid-electric drivetrain vehicles

In order to maintain movement, vehicles must produce power at the wheels to overcome aerodynamic drag (air friction on the body surfaces of the vehicle, coupled with pressure forces caused by the airflow), rolling resistance (the resistive forces between tires and the road surface), and any resistive gravity forces associated with climbing a grade. Further, to accelerate, the vehicle must overcome the natural resistance of its mass for acceleration, called inertia. Most of the energy expended in acceleration is then lost as heat in the brakes when the vehicle is brought to a stop. In addition, the vehicle must provide power for accessories such as heating fan, lights, power steering, and air conditioning. Also, a vehicle will need to be capable of delivering power for acceleration with very little delay when the driver depresses the accelerator, which may necessitate keeping the ICE in a standby mode.

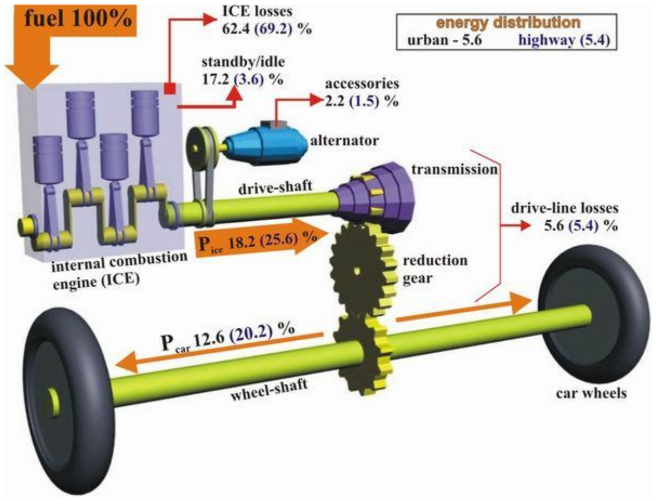

Fig. 1 Energy flow (from fuel energy to the wheels) for a midsize automobile

A conventional ICE-driven vehicle uses its engine to convert fuel energy into shaft power, directing most of this power through the drivetrain to turn the wheels. Substantial amounts of energy are lost along the way. Figure 1 represents how fuel energy is converting into work at the car wheels for a typical midsize vehicle. This figure shows average percentage losses from total chemical energy of the fuel for urban and for sub-urban (highway) drive.

Hybrid car emerges as a solution for environmentally friendly vehicle that combines both technologies of the standard gasoline ICE driven car and all-electric vehicle (EV). Because is hybrid of two different propulsion systems, internal combustion engine and electrical motor, it is called Hybrid Electric Vehicle - HEV. They provide the benefits of both EVs and traditional internal combustion vehicles, while minimizing the limitations of each. HEVs utilize the high efficiencies and low emissions of pure electric vehicles and the range and refueling capabilities of only ICE driven vehicles. HEVs use gasoline as fuel, so they have the advantages of easy and quick refueling and affordable on-board energy carrier.

In terms of overall energy efficiency, the conceptual advantages and counterbalancing factors (disadvantages) of a hybrid over a conventional vehicle are shown in Table 1:

***Table 1:** Advantages and disadvantages of HEVs*

Advantages	disadvantages
Regenerative braking	Higher weight of the vehicle
More efficient operation of the ICE	More complex drivetrain
Elimination or reduction of idle	Necessity of on-board computer control system
Smaller and lighter ICE	Electrical losses

3. New concept of hybrid-electric car propulsion system (HEV-CVUT)

Commercial hybrid electric cars (Toyota Prius), for splitting energy from ICE are using the planetary changing gear (PCG) and separate electrical generator (EG) for electrical power supply of the TM and charging the TB (Figure 2).

In the hybrid electric system developed on the CTU Prague (named as HEV-CVUT), the power splitting is performed entirely electrically by using the EPS. Theoretically, it is expected by reducing one weigh component, overall mass of the vehicle to be reduced. That directly will influence the reduction of the fuel consumption. Elimination of one energy transformation means that significant energy transformation losses will be avoided. Also, instead of chemical battery for accumulation of the breaking kinetic energy, in this drive concept, 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.

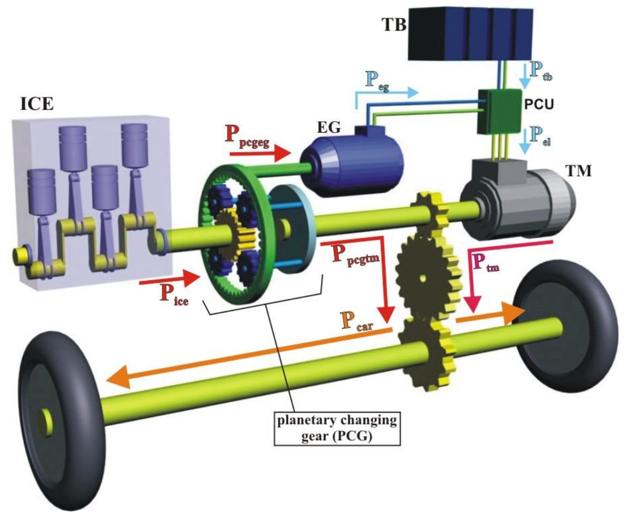

***Fig. 2** Configuration of Toyota's parallel/series drive (THS drive)*

The schematic representation of the HEV-CVUT working concept with EPS and super-capacitor is shown on Figure 3. Internal combustion engine is main and only power source of the vehicle that produces the mechanical power P_{ice}. EPS is special type of synchronous generator with two rotating parts: classic permanent magnet rotor and rotating stator. The rotor is firmly coupled to the drive-shaft of ICE. The stator of the EPS is firmly coupled to the TM and to the transmission that leads to the car wheels and rotates with the speed proportional to the vehicle velocity. This technical solution enables engine to operate on most optimal revolutions during entire driving schedule, same as serial HEVs.

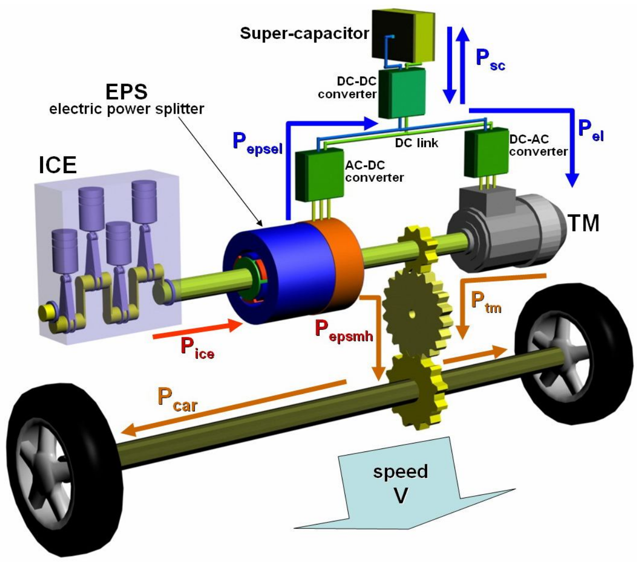

***Fig. 3** Configuration of HEV-CVUT concept of HEV drive*

In this HEV system are defined seven distinguished powers:

- P_{ice} – mechanical ICE output power on drive-shaft,
- P_{epsmh} – mechanical output power on the EPS stator shaft,
- P_{epsel} – electrical EPS output power to the DC circuit,
- P_{sc} – electrical charging (discharging) power to the SC,
- P_{el} – electrical power from DC circuit that powers the TM,
- P_{tm} – mechanical output power produced by TM,
- P_{car} – traction power of the car wheels that propels the vehicle.

Mechanical power P_{ice} is divided into electrical P_{epsel} and mechanical power P_{epsmh} by EPS. Electrical power splitting concept is based on controlling of AC/DC power converter, which regulates the current flow into the EPS stator windings. By regulating the stator current, it is regulated the magnetic field within the machine. Regulated magnetic field enables direct regulation of the torque on stator shaft and by this means the mechanical power P_{epsmh}.

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 with intermediate DC link. On DC link a SC is connected via charging and discharging DC-DC converter. TM is powered by P_{el} which is generated in EPS (P_{epsel}) and by additional power from SC (P_{sc}):

$$P_{el} = P_{epsel} + P_{sc} \cdot \eta_{dcdc} = P_{epsel} + P_{scdc} \tag{1}$$

Traction motor TM produces mechanical power Ptm which with mechanical P_{epsmh} added from EPS is transmitted to the car wheels. Total power P_{car} that propels the car is sum of these two powers:

$$P_{car} = (P_{epsmh} + P_{tm}) \cdot \eta_{trans} = (P_{epsmh} + P_{el} \cdot \eta_{tm} \cdot \eta_{dc-ac}) \cdot \eta_{trans} \tag{2}$$

When the car is braking, TM changes the function from motor to generator. By this way car decelerating kinetic energy can be partially converted into electric energy that is accumulated into the SC. In the following drive cycle this energy can be used for the next acceleration and overcoming the resistive forces.

HEV-CVUT is enormously complex concept of hybrid-electric drive. It has numerous power transformations and energy pathways. Power control, regulation of the energy pathways, detailed description of each components, its function and efficiency is described in following sections of this thesis.

This concept of hybrid-electric drive have the same advantages as Toyota Prius concept as a parallel/serial HEV. By using the one device for power splitting (electric power splitter) instead of two separate devices (mechanical planetary changing gear and separate electric generator), enables more fuel efficient process, because there are less energy transformations and less component weight. EPS enables more flexibility between ICE drive-shaft and propulsion drivetrain because the only connection between those two shafts is the magnetic field between the stator and the rotor of the EPS. Also implementing the super-capacitor, which has more power density then chemical battery, as energy storage unit gives more power boost and recuperation power absorbance.

All this characteristics of the HEV-CVUT car hybrid system gives promises that this solution has significant technical potential for even more fuel efficient vehicle with possibilities for more flexible and competitive driving performance. Unfortunately, direct component and partial segment comparison of Prius THS drive and HEV-CVUT concept is not possible. THS drive is commercial technology, protected with intellectual property rights and most of the components properties are industrial secret.

4. Experimental testing of the new HEV concept

Experimental working stand has been created in the laboratory in order to be performed laboratory testing of this HEV concept. The scheme of this laboratory stand is shown on Figure 4. The main functional units of the stand are the same as the units of the HEV concept shown on Figure 3.

On this HEV laboratory model, ICE and the car wheels has 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.

Entire working stand is consisted of four electrical machines (shown on Figure 4), five semiconductor power control units, super-capacitor and all the necessary instrumentation, control, power supply and protection equipment.

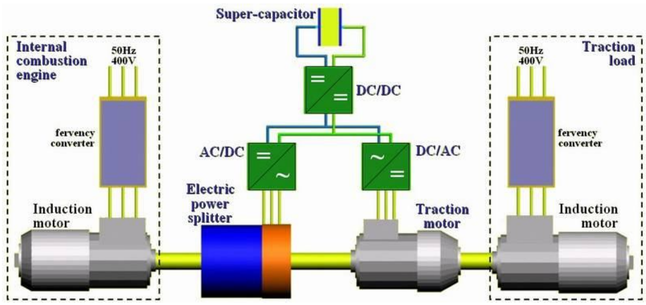

Fig. 3 Laboratory experimental working stand of HEV-CVUT

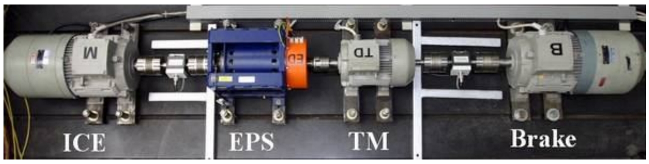

Fig. 4 Electrical machines of the laboratory working stand

Numerous results have been obtained during testing. The essential test results are the overall efficiency of entire HEV energy transformation system (Figure 5) and measured efficiency of electric power splitter EPS (Figure 6) for defined inclinations of the vehicle.

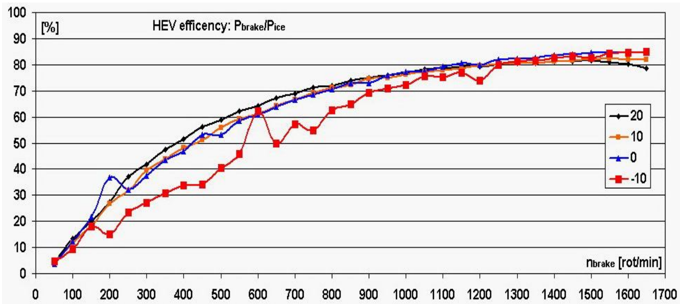

Fig. 5 Experimental characteristics of HEV system efficiency

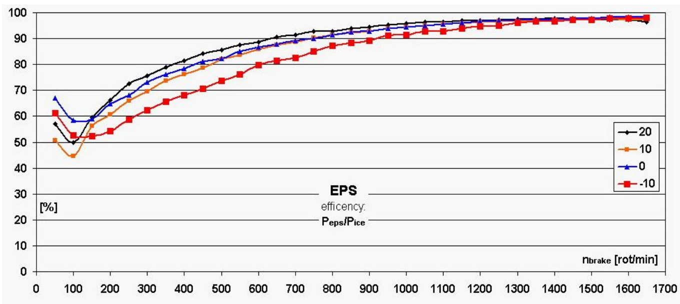

Fig. 6 Experimental characteristics of EPS efficiency

The results are showing the main specifications of this new concept of hybrid electric drive during the predetermined driving schedule. Final results have proven that this system has satisfactory driving characteristics for commercial use.

5. Simulation of the system performance using experimental results

Experimental results are interpolated into mathematical model that is used as concept for simulation of the vehicle performance. Simulation has been made by means of Matlab programming interface. The main approach in this simulation is to determine energy fluctuations in the hybrid drive during driving schedule. For this purpose, function and behavior of each component of the system is determined and taken into account like aero- dynamical resistance, rolling resistance between the tires and the road surface, density of the ambient air, cross-sectional area of the vehicle, coefficient of drag, etc.

Results of the simulation are shown in graphs that represent the calculated values in function of the time *t* during entire driving regime. The essential part for simulation of power drive system is precise calculation of the efficiency of each component where there is energy transformation. It has been calculated the efficiencies of ICE (fuel consumption according to the power demand P_{ice} and revolution of the drive-shaft), efficiency of EPS (the electrical P_{epsel} and mechanical P_{epsmh} power transformation), efficiency of TM, efficiency of transmission and SC as shown on Figure 7:

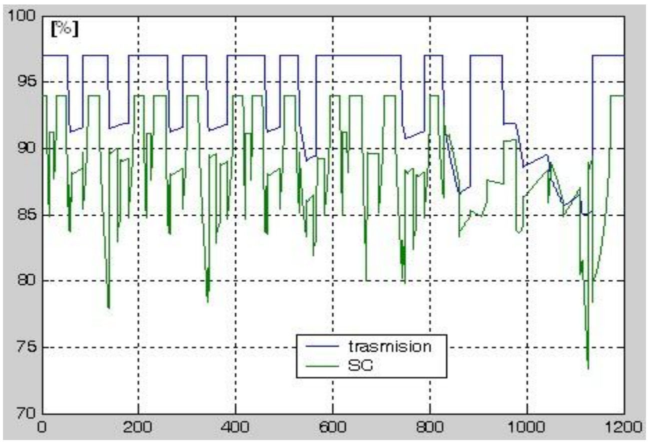

Fig. 7 *Efficiency of transmission and super-capacitor*

Fuel consumption is measured in each time interval. By knowing the total fuel consumed on the end 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 2 this values are compared with standard driven cars with the similar characteristics:

Table 2: Fuel consumption

[km/l]	urban	highway	combine
Hybrid-electric vehicle	**25.6**	**21.4**	**23.2**
Standard ICE vehicle	**13.7**	**19.2**	**17.2**

6. Conclusions

Simulation results confirmed that vehicles that utilize this hybrid propulsion system will consume 35% less fuel on highway drive and even 60% less fuel in urban drive. The most important characteristic is system's fuel efficiency that gives economical sustainability for possible future commercial implementation of this technology.

This research has provided numerical verification of the eligibility for HEV-CVUT car hybrid system. Final results have proven that this system has satisfactory driving characteristics for commercial use.

The development of HEV-CVUT car hybrid system is continuous process that will continue. Control strategy simulation program will be adopted for possible commercial use. Also, as research continues new computational options will be added and the program structure will be continuously improved with new options. Working parameters and characteristics from experimental results provides directions for further development of HEV-CVUT.

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