CONFIGURATIONS OF HYBRID-ELECTRIC CARS PROPULSION SYSTEMS

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Abstract — **Over the last few years, hybrid electric cars have taken significant role in automotive market. 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. In this paper, all implemented systems are described, analyzed and compared.**

***Index terms*—power converters, motor drives, energy efficiency, power control, battery**

1. INTRODUCTION

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 5 million vehicles worldwide are sold and their number is exponentially increasing. All major car production companies already have hybrid-electric models, which are in commercial use or will be soon lunched on the market.

Bu 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 (HEVs) 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**.

2. STANDARD PROPUSION AND NEW ELECTRIC PROPUSION TECHNOLOGIES

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 (Figure 1).

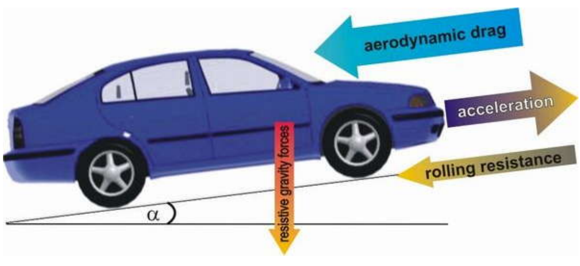

Fig. 1 Power demanded phenomenon during the vehicle driving

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 2 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.

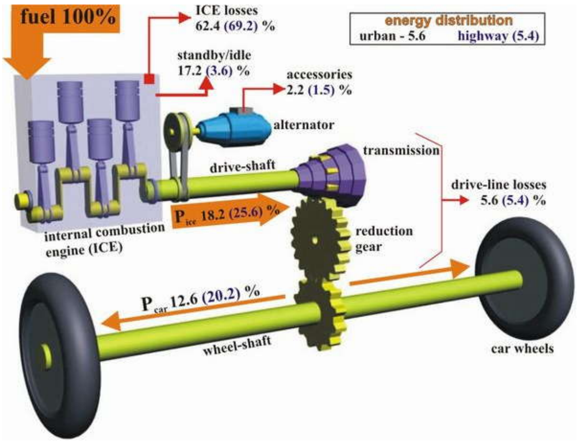

Fig. 2 Energy flow (from fuel energy to power at the wheels) for a midsize automobile

The most significant losses are within the ICE which can reach up to 70% from the fuel chemical energy. ICE moving parts create friction, especially pistons, crankshaft and valves. There are a number of aerodynamic and fluid drag losses (pumping losses) because air must be pumped through air cleaner, intake manifold, valves, and exhaust system. Most importantly, spark-ignition engines reduce their power output by throttling the air flow which causes additional fluid drag losses that are very high even at light loads. Much of the heat generated by combustion cannot be used for work and is wasted. Heat engines have theoretical efficiency limits and attaining even these limits is impossible. Heat is lost through cylinder walls before it can do work which sometimes is even 45% of all fuel losses. Some fuel is burned at less than the highest possible pressure. 25 % fuel energy is lost as heat in exhaust system. Engine itself must be regulated and controlled which means additional energy is lost in engine control.

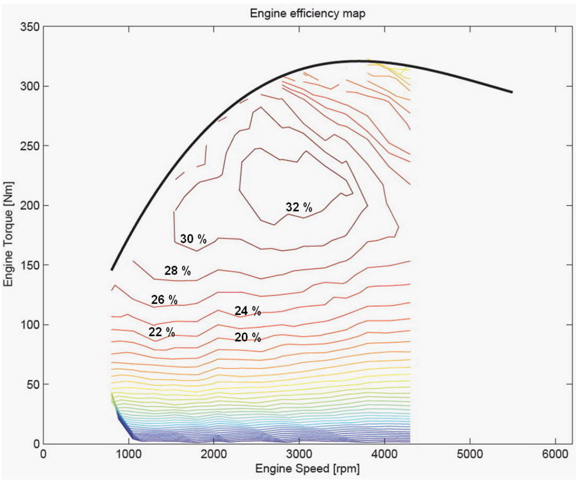

Fig. 3 Fuel efficiency map of typical internal combustion engine

Part of engine losses would occur under any circumstances. That is because four-stroke cycle of ICE is based on laws of thermodynamics for conversion of the heat energy into useful mechanical work. According to these laws it's hardly to achieve high efficiency in energy form transformation from heat to mechanical. Complex modifications of the machine are needed only to be reached efficiencies close to 35%. Average standard car ICE efficiency is 25% as shown on fuel efficiency map on Figure 3.

2.1 Electric vehicles

Electric vehicles (EV) have been developed as a solution for environmental friendly means of transportation. Propulsion (Figure 4) is based on electric traction motor (TM) instead of internal combustion engine. Traction battery (TB) supplies the electrical energy for TM and represents the only energy storage unit for propulsion on the vehicle. During recuperation, TM goes into generator regime of work, generates electricity from kinetic energy of the car, decelerates the vehicle and charges the battery.

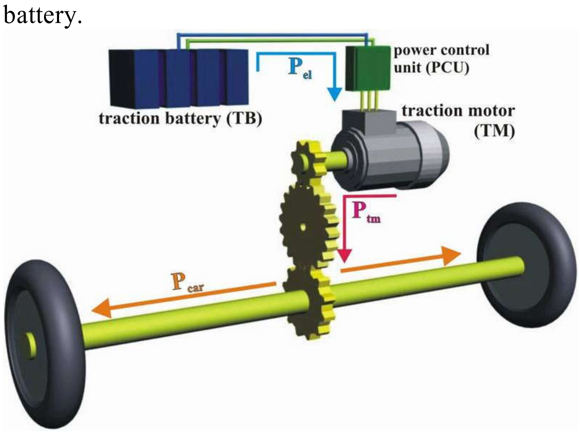

Fig. 4 Fuel efficiency map of typical internal combustion engine

During propulsion of the vehicle, the traction battery is discharged. Produced power P_{tb} from battery is transmitted by power pathway to the traction wheels.

Electricity is cheaper then petroleum and gives economic advantage contrary to the gasoline propelled cars. In addition, the efficiency of the vehicle is improved with the process of recuperation. In standard vehicles, this braking energy is disposed as heat by friction in mechanic brakes.

A strong argument for using electric vehicles is based on its efficient use of energy. Overall efficiency varies from 25[%] up to 80[%]. The energy efficiency will vary greatly with how a battery is used. If the battery is charged and discharged rapidly, energy efficiency decreases considerably.

The most significant role of the EV is environmental impact, because electricity driven vehicle does not dispose any gases. It presents ideal solution as a zero emission vehicle (ZEV), but it has some drawbacks that resulted with commercial failure. Traction batteries have relatively low energy storage capacity, which are significantly lower than the chemical energy of the fossil fuel stored in the fuel tank of the standard vehicle. That results with short driving range of EV with one battery charging. In addition, TB demands long charging time and special non-standard charging units. The use of EV is quite limited because of lack of infrastructure for charging on open roads, which is not the case with the standard cars that have wide range of petroleum pumping stations at their disposal.

2.2 Fuel cell electric vehicles (FCEV)

The range of electrical vehicles can be extended if there is refuelable power source on-board vehicle that produces electricity and charges the traction battery. Electric vehicles that have fuel cells as on-board RPS are classified as FCEV. Fuel cell technology is only RPS which fulfils the ZEV requirements.

Fuel cells are electrochemical devices that convert chemical energy directly into useful electrical energy (Figure 5). In contrast to internal combustion engines, there is no intermediate conversion into thermal energy and from that to mechanical energy and therefore the efficiency is higher. Fuel cells deliver electrical energy without any combustion products. As an on-board energy carrier for fuel cells is used hydrogen H_2.

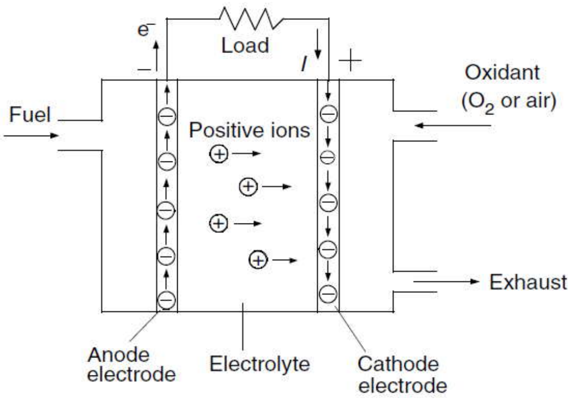

Fig. 5 Fuel cell system of operation

The specific energy of hydrogen as a fuel is substantially better than that of electrochemical batteries and it is competitive with fossil fuels. Therefore, fuel-cell vehicles seem to be able to combine the best features of EVs and of ICE-based vehicles, with zero local emissions, high efficiency and a reasonable range. Like purely electric vehicles, fuel-cell vehicles are classified as zero-emission vehicles, because only product of their work is harmless water vapor H_2O.

The integration of a fuel cell in a propulsion system seems simple in principle and various prototypes have already been developed. The combined problems of on-board hydrogen storage and of the lack of a hydrogen refueling infrastructure so far have represented an impediment to the wide-scale adoption of FCEVs. Also, hydrogen cannot be found in free form in nature like fossil fuels. The most common process in H_2 production is electrolysis of water. It means that electric energy must be spent in production of the hydrogen. Hydrocarbons like methanol, gasoline, diesel and natural gas have been proposed as on-board fuel processors that generate hydrogen as an alternative hydrogen source for FCEVs. Although the energy density is much higher than only-hydrogen storage, these systems are rather complex and introduce additional efficiency losses related to the various stages of fuel preparation, reforming and hydrogen cleaning. Moreover, they produce CO_2 emissions, which diminish their zero emissions label. Also, this technology has a poor dynamic response that makes control and regulation a difficult task.

Charging batteries in EV and producing hydrogen for FCEV raises concerns in outcome of their overall energy efficiency and environmental impact. If electric energy, like in many countries is produced from fossil fuels (coil, oil or natural gas), only environmental benefit is relocation of pollutants from urban to sub-urban surrounding where typically are placed the electrical power plants. Efficiency in power plants is greater than ICE, but produced electrical energy do many conversions (Figure 6) with transfer, distribution, charging batteries or electrolyzes producing hydrogen. At the end, the overall efficiency is lower than ICE. If electricity is produced from clean energy sources like renewable (hydroelectric, wind energy or solar) or from nuclear power plants, the environmental and economical impact of electric and fuel cell vehicles is evident.

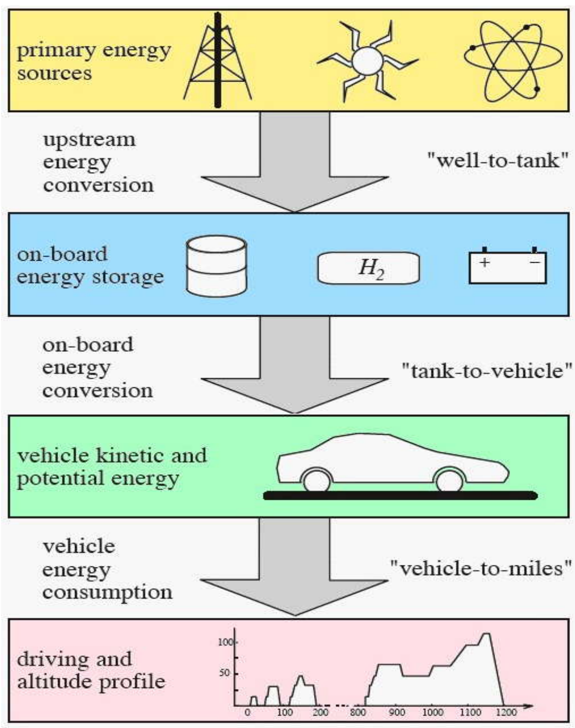

Fig. 6 Stages of energy conversions

3. ENERGY SAVINGS POTENTIAL OF HYBRID-ELECTRIC VEHICLES

All this disadvantages of the EVs compared with standard vehicles resulted with commercial failure. Therefore, hybrid car emerges as a solution for environmentally friendly vehicle that combines both technologies of the standard gasoline ICE driven car and 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 electric vehicles 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. In contrary to fuel cell vehicles, they do not require special produced fuel (like H_2). 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 of a hybrid over a conventional vehicle are: regenerative braking, more efficient operation of the ICE, elimination or reduction of idle, smaller and lighter ICE. Also, there are counterbalancing factors reducing HEVs energy advantage, including: higher weight of the vehicle and electrical losses.

3.1 Series Hybrids

The basic concept for HEV has originated from EV. Limited capacity of TB demanded on-board electric production unit - the electrical generator (EG). This device produces the electricity that charges the battery during vehicle drive. This approach solves the problem with short driving range of EV and eliminates the dependence of special infrastructure for battery charging. Initial categorization of this type of vehicles was Extended Range Electric Vehicle (EREV).

Because the main on-board energy carrier for propulsion is gasoline, not the electricity, this type of vehicle generally is categorized as Serial Hybrid Electric Vehicle (SHEV). It is "serial" because of the energy transformation process during the driving cycle. ICE produces mechanical power P_{ice} that propels the rotor of the electric generator (Figure 7). The generator produces electrical power P_{eg}, which with the additional power from the traction battery P_{tb} powers the TM ($P_{eg}+P_{tb}=P_{el}$). Traction motor produces mechanical power P_{tm} that propels the car. In the process of vehicle deceleration TM changes into generator regime gaining recuperative role same as in EVs. It brakes the car and saves partial kinetic energy of the vehicle by charging the traction battery.

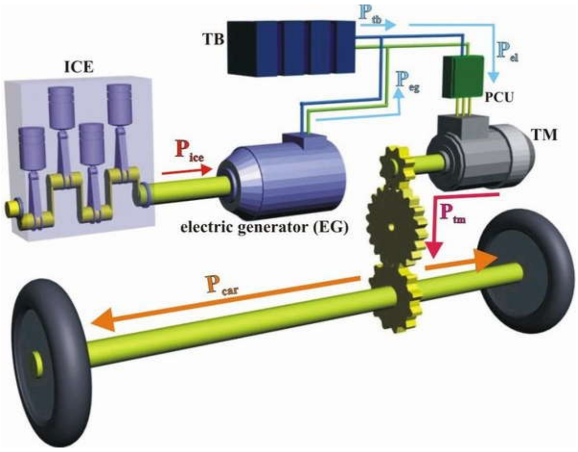

Fig. 7 Configuration of a series HEV

In a series configuration, all of the traction power is provided only by the TM, which obtains electricity directly from the ICE-EG or from the TB. Onboard control system must decide the operating advantages and disadvantages of the various energy pathways available to the system. Crucial segment for achieving better efficiency is creating the power management in choosing the most optimal energy pathway. There are several energy path-ways in serial HEV concept: engine to generator to traction motor energy pathway (ICE→EG→TM), battery to traction motor pathway (TB→TM), battery being recharged from the engine (ICE→TB) and regenerative braking energy pathway (TM→TB).

This concept of propulsion has better energy efficiency characteristics then standard ICE driven vehicles. Basically this is achieved by the process of recuperation braking, which has the significant role especially in city driving regime. Also, the driveshaft of the ICE is connected only to the rotor shaft of the EG. This enables ICE shaft to rotate with desired revolutions, keeping the working regime of the ICE on the most optimal level. Non-direct connection of the ICE to the car wheels also enables optimal load to the engine during rapid changes of the drive, like sudden acceleration and power demand, which are overtaken by TB. This gives opportunity to the ICE to work on the most efficient level during the entire driving regime keeping the engine to work on most efficient revolutions. Series HEV design results in a simpler mechanical connection to the wheels than parallel hybrids, which allows more freedom in component placement. The electric motor can easily be sized such that only a single-speed transmission is required which leads in decreasing the transmission losses. Full power is available at all times, even when operating in ZEV mode. Some car production companies have series production of SHEVs which like automaker Chevrolet with the model Volt.

3.2 Parallel Hybrids

In parallel hybrids, both the ICE and the electric TM can drive the wheels (Figure 8). Both machines are connected to the same drive-shaft and each provides separate drive power P_{ice} and P_{tm}:

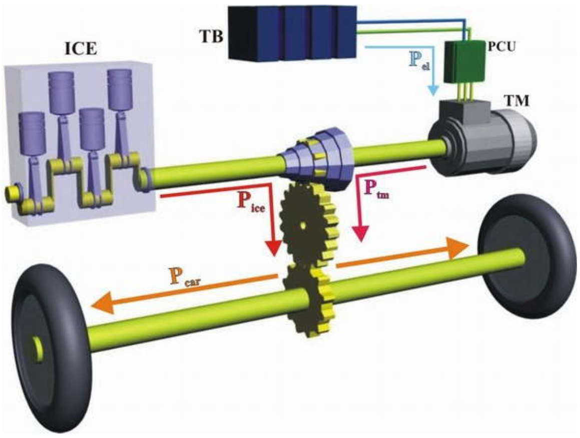

Fig. 8 Configuration of a parallel HEV

This concept is successfully commercially implemented in Honda Civic Hybrid and the new improved model Honda Insight. Commercially this solution is called a mild hybrid system, is to use the motor only as a power booster and for regenerative braking. With no "only-electric" operation, the TM and storage device may be relatively small and thus less expensive. Parallel design offers the advantage of drive system redundancy. If either of the drive systems should fail (ICE or TB-TM), the other system would still be available to move the vehicle for service. A parallel hybrid usually provides better highway fuel economy, due to its efficient ICE loading at steady highway speeds and less mass than its series counterpart. It also provides the ability to withstand long uphill grades.

The most significant advantage is the more efficient direct connection of ICE shaft to the wheels, which enables less power transformations and thus higher efficiency. In other words, the combination of transmission, torque converter and differential is more efficient than the series HEV's ICE-to-wheel path. Another major advantage is that a parallel hybrid's electric traction motor will be significantly smaller than that required on a series hybrid. This is because TM is used only for power boost, since in the series case the TM is the only propulsion drive. This yields a significant cost savings. Also, parallel system's operational complexity has been overcome with good design and the rapid advance in onboard computing. New advanced on-board computer systems are capable entirely to fulfill the requirements for instantaneous power control management of complex hybrid systems with sophisticated control strategy that provides solid car performance and good fuel economy.

3.3 Combined hybrid-electric drive (Toyota Prius)

Combining the pathways of the serial and parallel hybrid propulsion systems creates the combine HEV. In order to obtain the benefits of both parallel and serial concepts of HEV, car manufacturer Toyota have introduced the serial-parallel concept of HEV, which is commercially presented as Toyota Hybrid Synergy Drive (THS drive). This concept is implemented in the first and the most successful commercial hybrid vehicle Toyota Prius (Figure 9). It is complex HEV system with serial and parallel energy pathways synergistically combined in one propulsion system. Besides Toyota's model Prius, this system is also used in Lexus hybrid models.

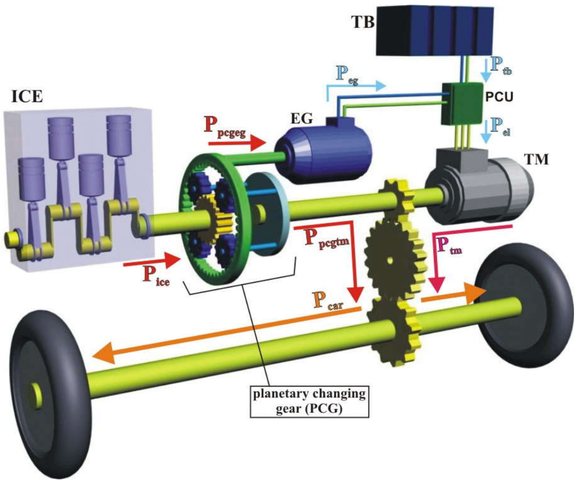

Fig. 9 HEV Configuration of Toyota's parallel/series drive (THS drive)

The technical solution is based on using the planetary changing gear (PCG) as mechanical power splitter. It enables the mechanical power P_{ice} from the shaft of the ICE to be divided into two energy pathways creating two drive powers P_{pcgeg} and P_{pcgtm}. First is parallel pathway, connecting PCG to the TM shaft and the transmission to the wheels. Second is serial pathway connection PCG to the separate electric generator (EG). Same as serial HEV, P_{pcgeg} is transformed into electrical P_{eg}, which with additional power P_{tb} from TB, thought power control unit, powers the TM.

All this characteristics categorize Toyota Prius as the most successful hybrid-electric vehicle. It is on the market for more than ten years and has overcome all the expectations with more than 3 million sold units worldwide. It is the most fuel efficient mid-size petroleum-driven car, with fuel efficiency approximately 4.6 [L/100km] in urban driving. It is widely known as the most ecological and environmentally friendly family passenger car currently on the market.

4. HEV-CVUT CONCEPT OF HYBRID-ELECTRIC PROPULSION SYSTEM

New type of HEV system is developing at Czech Technical University in Prague. Main innovative characteristics of this hybrid drive is using of super-capacitor (SC) as an energy accumulation unit and electric power splitter (EPS).

The schematic representation of the HEV-CVUT working concept with EPS and super-capacitor is shown on Figure 10. 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.

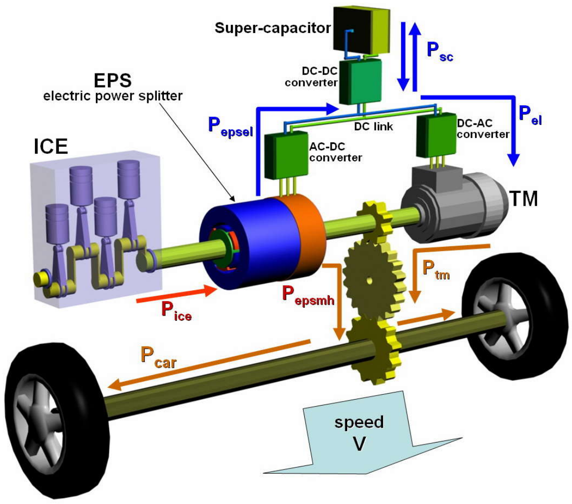

Fig. 10 Configuration of HEV-CVUT concept

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.

Experimental, analytical and 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.

Final results have proven that this system has satisfactory driving characteristics for commercial use. The most important is system's fuel efficiency that provides economical sustainability for possible future commercial implementation of this technology.

5. CONCLUSION

This paper has given overview of all new technologies implemented in automotive industry utilizing electric motor drives, power electronics and control technology. As described in the paper, all this electrical engineering technologies are increasingly involved in automotive technology, which was usually mechanical engineering branch.

The main goal of implementing this relatively new technology is enabling better fuel efficiently of the commercial cars. That means less fuel consumption for more distance covered. In nowadays, this attribute is even more important with everyday rising of the oil-prices. In year 2008 the crude oil price has reached even 147 [US$/barrel]. That has indicated that fossil fuel - oil as a primary transportation fuel is not anymore easy affordable commodity. Efficiency in fuel consumption has become essential issue not just for car manufacture industry but also for consumers.

The most important factor for implementation of the hybrid-electric technology on the market is its economic sustainability. The consumers are assured that by buying hybrid-electric vehicle they will have investment feed-back with less fuel expenses. That has lead to mass purchase of HEVs in services that have extensive urban driving, like taxi companies, police patrol cars and private owners that have substantial everyday driving range.

Besides different concepts of the propulsion systems, near future will give an answer which of this electric, fuel-cell or hybrid technology will be dominant.

6. REFERENCES

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