An Overview of Electrical Vehicle and Hybrid Electrical Vehicle Drives

Anton Rassõlkin
Tallinn University of Technology (Estonia)
Anton.Rassolkin@ttu.ee

Abstract— An overview of electrical vehicles and hybrid electrical vehicles is presented. Main features of traction system are presented with their benefits and drawbacks. The traction system architectures, propulsion systems and used power electronic converters areas are covered. The main areas of future researches are squared.

I. INTRODUCTION

World population reached seven billion people in 2011 and the number of vehicles in operation surpassed the 1 billion units already in 2010. According to OICA (International Organization of Motor Vehicle Manufacturers) statistic about 80 million vehicles were produced in 2011 and the number is increasing each year. With further urbanization, industrialization and globalization, the trend of rapid increase in the number of vehicles worldwide is inevitable. The main issues due to increasing of vehicle number are limited volume of oil and the emissions from burning oil products. The world consumes approximately 85 million barrels of oil every day but there are only 1300 billion barrels of proven reserves of oil. At the current rate of consumption, the world will run out of oil in 42 years [1]. The emissions from burning fossil fuels increase the carbon dioxide (CO2) in the Earth’s atmosphere [1]. Increasing of CO2 is a cause of greenhouse effect and climate change. As result in long-term consequences it will lead to rising sea levels and instability of ecosystems. Cutting fossil fuel usage and reducing carbon emissions are the main goals of humanity. Using of Hybrid Electrical Vehicles (HEV) instead of Internal Combusting Engine Vehicle (ICEV) could notably decrease the atmosphere pollution. Effect of using of Electrical Vehicle (EV) could be even better.

Well-to-wheel studies show that, even if the electricity is generated from petroleum, the equivalent kilometres that can be driven by 1 litre of petrol is 46 km in an electric car, compared to 14 km in an ICEV [1]. Moreover, a size of petrol-to-electrical transmission is more compact, while with a pure mechanical transmission from engine to wheels a large number of gears are required and with a generator-motor traction system wide range of operating speeds are available. Sure, the producing of electricity is complicating process and not always friendly to environment and often connected with burning of fossil fuels as well. In the same way, currently used electrical grids have a list of disadvantages. But on the other hand, today is available quite big range of renewable energy sources and energy storage systems that are combined into the smart electrical grids. EV’s have many advantages and challenges. Nowadays, EV is widely used as public electrical transport. It’s difficult to imagine the modern megalopolis without underground railways or land electrical transport like tramway car or trolley bus. In that case research in the field of HEVs and EVs seems to be very interesting and necessary.

II. HEV AND EV TOPOLOGIES

There are many different ways to combine internal combusting engine (ICE) with an electrical machine. The electrical machine is designed to handle transient power variations and helps the engine to operate more constantly so that higher efficiency and lower tailpipe emissions can be achieved [6]. The variety of electrical machine / combustion engine designs can be differentiated by how the electric and combustion portions of the power train connect, at what times each portion is operation and what percent of the power is provided by each hybrid component [7].

Nowadays used topologies are presented in this paper. Available nowadays energy storage systems that could be used in HEV and EV were presented in previous studies [3] and needed to be taken into account during the vehicle topologies analyse.

A. Assist HEV

The electric motor is essentially a very large motor which operates not only when the engine needs to be turned over, but also when the driver presses the throttle pedal and requires extra power [7]. Because of the small range of the electric drive assist hybrid could not operate in pure electrical mode, but it can be used as assist motor in wide range of controlled torques and speeds. As well the part of kinetic energy could be converted into electrical energy during regenerative braking while vehicle decelerates. The size of electrical battery used in assist hybrids is reduced that reduce the total weight of the vehicle.

B. Mild HEV

The mild hybrid has a small electric motor that mostly used as starter and generator sometimes it does operate as traction motor as well. Usually, the power rating of the electric motor may be in the range of about 10% of the engine power rating [8]. Mild hybrid could operate as pure electrical vehicle (the combustion engine is switched off in that mode) only in small speed range, up to 10 km/h. The design of the traction part of mild hybrid is similar to combustion engine vehicle traction system, because booths are very close.

C. Full HEV

Full hybrids are type of the vehicles that can use pure electrical traction mode, that notably reduce CO2 emission. The hybrid-drive concept appears in many forms depending on the mix of energy sources and propulsion systems used on the vehicle [9]. The traction energy could be taken from two
separate energy sources there are several combination of these available.

D. Parallel HEV

Parallel HEV is only hybrid vehicle that can switch between two types of drives and could be used separately or simultaneously, depends on traction mode. The electric drive also can be used as a generator to recharge the batteries when the engine produces more power than is needed to propel the vehicle [10]. Combustion engine and electric drive are coupled mechanically by special gear construction and could be unplugged by reswitching of a clutch. Parallel hybrid use mostly electrical drive in urban areas, because of urban driving particular qualities, fast acceleration/deceleration and short-time duty cycles. In highway traction mode, the vehicle runs with a high constant speed and ICE is used. Combustion engine shows its better performance only in a small working range with high speed and torque that means the speed variation is unwished. Parallel hybrid could recharge its batteries not only during regenerative braking, but also during ICE traction mode. However, ICE is used not on its better performance mode and that is one of parallel hybrid drawbacks. Double traction system increases the price of the vehicle as well.

E. Series HEV

Series HEV use only electrical drive for traction. ICE is decoupled from mechanical transmission and used to produce kinetic energy for the generator that converts it into electrical. That means traction system requires double energy conversion: mechanical-electrical-mechanical. A weakness of a series hybrid system is that series hybrids require separate motor and generator portions which can be combined in some parallel hybrid engines; the combined efficiency of the motor and generator will be lower than that of a conventional transmission thereby offsetting the efficiency gains that might otherwise be realized [7]. Because of the high controllability performance of electrical motor that topology reduces the size of gearbox and mechanical transmission. That’s why series hybrid widely used in heavy industrial vehicles like excavators and diesel-electrical locomotives also for urban vehicles that required often stop duties like buses and delivery cars.

F. In-Wheel Motor HEV

Some variation of series hybrids have separate small electric in-wheel motors (sometimes called hub motors) installed independently at each wheel. That allows separately control of the power delivery to each wheel, and therefore simplifies traction control of the vehicle [7]. Such system allows regulating the acceleration/deceleration torque values independently for each wheel. The mechanical part could be reduced even more than in series hybrids. It means additional batteries can be installed on the free space that has been occupied by the transmission, which helps to increase the driving range per charge [20]. Most conventional electrical machines (such as ac excited or brushed dc motors) are not suitable for application in in-wheel motor drive because of their poor torque density and overload capability [11]. For that reason in-wheel hybrids required special designed motors like axial-flux ironless permanent magnet motors or synchronous permanent magnet outer rotor motors.

G. Series–Parallel HEV

Series–parallel HEV has two couplings mechanical and electrical. That allows overcoming of the drawbacks of booth technologies and using their benefits with best performance. The main aim of such system is the reduction of the fuel consumption [12]. As well, drivability can be optimized based on the vehicle’s operating condition [2]. The main drawback of series-parallel hybrid is increased vehicle price in compare with other hybrids.

H. Plug-In Hybrid Electric Vehicles (PHEV)

The only difference of plug-in hybrid from the hybrid vehicle is presence of the cable that allows connecting vehicle to electrical grid. Depends from the energy flow direction plug-in systems divides could be divided on two parts: vehicle-to-grid (V2G), if the energy flow goes to the grid from the vehicle; grid-to-vehicle (G2V) if the batteries are charged from the grid. G2V allows recharging the batteries without using ICE that makes daily used light PHEV more environmentally friendly. The basic concept of V2G power is used in electric drive vehicles to provide electric power to the grid while the vehicle is parked [13]. It means that the batteries on parked and plugged-in vehicle could be recharged during the lean hours and discharged during the peak hours if it’s necessary. To allow such bi-directional energy flow (G2V and V2G) the charging systems should be specifically designed and optimized. In that case the vehicle is used as a smart consumer, so-called prosumer (combined producer and consumer) and can be used as a part of smart electrical grid. Connected to the smart grid PHEV could bring new features into the grid like STATCOM, active filter or even portable power plant [2].

I. Fuel Cell Electric Vehicle (FCEV)

A fuel cell (FC) is a galvanic cell in which the chemical energy of a fuel is converted directly into electrical energy by means of electrochemical processes [14]. There are some tanks required to store the fuel, usually hydrogen. It makes the FCEV more similar to series hybrid but with a less energy conversion stages. The main benefits of FC are – zero emission, as the sole product of reaction is water; high electric efficiency of single device up to 60 %; very simple construction. The mainly drawback of a fuel cell for today is its high price and limited technologies [3]. Vehicles powered solely by fuel cells have some other drawbacks, such as a heavy and bulky power unit caused by the low power density of the fuel cell system, long start-up time, and slow power response [14]. To overcome this drawbacks some hybrid solution are presented, where the FCEV are combined with some other vehicle technologies [15]-[17].

J. All Electrical Vehicles (EV)

EV use chemical battery as a primary energy storage and only electric motor for traction. It means that they have zero tailpipe emission and more friendly to environment than other vehicles.

The EV has many advantages over the conventional ICEV, such as zero emissions, high efficiency, independence from
fossil fuels, and quiet and smooth operation [8]. Usually EV simplified mechanical motor to wheel transmission that is similar to series hybrid and in-wheel series hybrid vehicles. The design and parameters of the traction system of EV depends mostly on speed-torque and speed-power characteristics.

All of the major automotive manufacturers have production EVs, many of which are available for sale or lease to the general public [5]. While EV is novel technology a lot of challenges on its development and research areas exist. New standards and requirements should be prepared. Moreover, public recharging infrastructure is required and used nowadays, electrical grids need to be renewed or rebuilt to withstand the increasing load. Due to European Union directives the governments support the idea of HEV and EV with taxes braking and other benefits for HEV/EV owners. Though, it seems that the main problem is the driver habits on vehicle use and refuelling.

III. ELECTRIC MOTORS FOR HEV AND EV PROPULSION

Electric motor has relative benefits and drawbacks in compare with traditional ICE. Sure electrical motor is more efficient and has a zero emission. A major advantage of electric motor is that torque generation is very quick and accurate [4]. That makes EV and HEV more controllable and manoeuvrable in urban areas. The main drawbacks are electrical energy sources that are usually short-term storages.

There are several types of direct current (DC) and alternating current (AC) electric motors that can be used as traction motors in HEVs and EVs drives.

A. DC Motors

The DC motors were used in last century in electrical transportation due to their developed status and suppleness of speed control. Speed-torque diagram of the series excite DC motor is very close to load speed-torque diagram of the vehicle that’s why it was widely used in public transport area: tramway cars, trolleybuses, electric trains and diesel-electrical locomotives. A number of prototype EVs in the 1980s and prior were built based on DC series motors as well. However, the size and maintenance requirements of DC motors are making their use obsolete, not just in the automotive industry, but in all motor drive applications [5].

The main drawbacks of DC motor is a collector brushed that are required to change the direction of the current inside the rotating part of the motor (armature). A result of high friction between brush-contacts and collector: high friction losses, increasing of the temperature of the machine, low reliability, decreasing of the lifecycle and low efficiency.

B. Permanent Magnet Motors (PM Motor)

PM DC motor is a brushed DC motor with an independent excited magnet. Because of the limited technologies of PM their power range is small and the speed-torque diagram is close to parallel excited DC motor. All these drawbacks make PM DC motor not suitable for high power traction applications.

PM AC motor also known as brushless direct current motor (BLDC), is a three phase windings and permanent magnet excite rotor. For EV and HEV applications, motor size is relatively large compared to the other smaller power applications of PM motors, which amplifies the cost problem [5]. However, the PM AC motors could be used in assist and mild hybrids. The benefit of this motor is that currents do not need to be induced in the rotor (like in induction motor), making them somewhat more efficient and giving slightly greater specific power in the same time the drawback is that it is costlier due to the presence of PM [7].

C. Switched Reluctance Motors (SRM)

SRM is also known as doubly salient machine, has a simple construction and excellent fault tolerance characteristics. The stator and the rotor of the SRM are made of iron which are magnetized by the current through the stator winding. These motors have no windings, magnets, or cages on the rotor, which helps to increase the torque and inertia rating. The motor speed-torque characteristics are an excellent match with the road load characteristics, and performance of switched reluctance motors for EV/HEV applications have been found to be excellent [5].

The main drawback of SRM is that the timing of the turning on and off of the stator currents must be much more carefully controlled [7], the more complex control device is required. The main challenges of switched reluctance motors are acoustic noise and torque ripple.

D. Induction Motors

Quite mature technology of AC induction motor got a hard development push in last 30 years together with power electronics progress. Field-oriented control (FOC) of induction motor can decouple its torque control from filed control. This allows the motor to behave in the same manner as a separately excited DC motor [18].

Because of low stability and overheating on low speed, induction motors mostly found an application in high speed vehicles, otherwise some additional mechanical transmission required for speed reduction. Moreover, the efficiency of the induction motor in no-load or light-load operation modes is very small ca 20..30%, but it increases gradually with the rated load and reaches ca 75..92% [19]. The main benefits of induction motor are high reliability and low manufacturing cost.

E. Synchronous Permanent Magnet Outer Rotor (In-Wheel) Motors

Usually as in-wheel motor the permanent magnet synchronous machine (PMSM) is used, it has high torque density, excellent efficiency and overload capability [21]. However, there may be risks of demagnetization and mechanical damage of the rotor’s magnets in extreme driving conditions [22]. The assembly configuration of in-wheel motor system consists usually not only of the motor itself, but also from reduction gear, mechanical brake and wheel.

IV. POWER ELECTRONICS USED IN HEV AND EV

Power electronics are required to provide the electrical energy conversion between electrical parts of the HEV and EV drive. The inverters required to provide connection between AC traction motors and the batteries. Rectifiers are used in case of applying AC generators as a kinetic-to-electrical energy converter. DC/DC converters equal the DC link voltage from all energy sources, if more than one is used.
Special attention should be pointed on the charging systems, while they have a specific requirements and standards.

A. Inverters

While the most of energy storage devices are voltage sources, the voltage source inverter (VSI) got the most common in HEV and EV applications, but it presents difficulty hurdles for the automakers to address the important issues on system cost, weight, volume, and reliability [23]. VSI is used to control the speed of induction motors and PM AC motors. The switches are usually IGBTs for high voltage, high-power hybrid configurations or MOSFETs for low voltage designs [2]. Voltage surges caused by rapid voltage transitions, made by pulse-width modulation (PWM) control technique, can cause motor insulation degradation, bearing failure due to the resulted shaft leakage current, and unacceptable electromagnetic interference effects upon the control circuits, as well as acoustic noises in the motor [23].

The current source inverter (CSI) uses an inductor for energy boosting in distinction from VSI that uses capacitor. It has several inherent advantages that includes its voltage boosting capabilities, its natural shoot-through and short-circuit protection capability, and a sinusoidal output voltage due to the effect of the output ac filter capacitors, which are much smaller than the VSI’s dc capacitor [23].

B. Rectifiers

In series HEV and series-parallel HEV a synchronous generator is frequently used to convert mechanical energy produced by ICE into electrical one. Rectifiers are required to convert output AC of synchronous generator into DC for battery. There are four common rectifier circuits in series HEV: uncontrolled full-bridge diode rectifier, controlled full-bridge thyristor rectifier, uncontrolled full-bridge diode rectifier with dc/dc boost converter and PWM voltage-source current controlled rectifier [24]. Uncontrolled rectifiers do not allow the bidirectional energy flow that means same generators could not be used as starter machine to soft ICE start.

In regenerative braking mode the motor is controlled to achieve stored in the rotating part of traction motor kinetic energy, in that case the VSI, that controls the speed of the AC motor, is operated as a PWM rectifier.

C. DC/DC Converters

The typical application of a buck converter in a HEV and EV is to step down the high voltage (HV) battery voltage (typically 200 – 400 V) to charge the auxiliary battery (14 V) [2]. With such high step-down voltage rate the duty cycle of the buck converter is small as well that affects the design of the inductor, capacitor, current ripple and voltage ripple. Moreover, control and regulation of the buck converter output voltage becomes more difficult.

Boost converter or non-isolated bidirectional DC/DC converter is used to step up the HV battery up to HV DC bus. The best operating voltage for VSI that controls traction motor is around 600 V. As well that converter allows the backward energy flow, from the DC link back to battery during the regenerative braking.

Some application are required: a non-galvanic isolation between battery and DC link. In that case the best solution is isolated bidirectional DC–DC converter with a high frequency AC link.

D. Charging Systems for PHEV and EV

The charging system of the PHEVs and EVs is one of the most important parts of the whole system. Charging current, speed and efficiency are the main topics that need to be discussed and standardized. Available today charging systems with a charging time and energy needs are presented in Table 1. There is couple of charging system topologies used nowadays.

Typical on-board chargers limit the power because of weight, space, and cost constraints and are dedicated to charge the battery for a long period of time; an off-board battery charger is less constrained by size and weight [25].

Uncontrollable charging systems are based on diodes and mostly bridges schemes cascade with DC/DC converters are used. Diode rectifier bridges have the following drawbacks: the input current harmonic content is high and absorbs reactive power from the grid [27]. The power factor could be improved by using the controllable PWM rectifiers. Moreover, PWM rectifier has sinusoidal grid current, low THD and allows bidirectional energy flow (both G2V and V2G working modes are possible).

<table>
<thead>
<tr>
<th>Charging level</th>
<th>Charging time</th>
<th>Power supply</th>
<th>Voltagge</th>
<th>Max current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>6-8 h</td>
<td>1ph</td>
<td>3.3 kW</td>
<td>230 V</td>
</tr>
<tr>
<td>Primary</td>
<td>3-4 h</td>
<td>3ph</td>
<td>7 kW</td>
<td>230 V</td>
</tr>
<tr>
<td>Fast</td>
<td>0,3-0,5 h</td>
<td>3ph</td>
<td>10 kW</td>
<td>400 V</td>
</tr>
<tr>
<td>0,3-0,5 h</td>
<td>1-2 h</td>
<td>24 kW</td>
<td>400 V</td>
<td>32 A</td>
</tr>
<tr>
<td>Off-board</td>
<td>DC</td>
<td>43 kW</td>
<td>400 V</td>
<td>63 A</td>
</tr>
<tr>
<td></td>
<td>100 - 125 A</td>
<td>400 - 500 V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are several drawbacks of plug-in charging systems: the cable and connector typically delivers 2-3 times more power than standard plugs at home and this increases risk of electrical shock especially in wet environments; the long wire poses a trip hazard and gives to poor aesthetics for such systems; in harsh climates that commonly have snow and ice, the plug-in charge point may become frozen onto the vehicle [27]. To overcome this drawbacks and inexistence of physical contact between the source and the load wireless inductive charging systems could be used. The main benefits of wireless charging systems are: the galvanic isolation requires less maintenance, high output power and possible usage in harsh environments (that is important for north regions as Estonia). The main drawbacks that can be pointed out are: resonant circuits hard to tune, electromagnetic interference, magnetic field does not penetrate metals (if there is any metallic object in the middle of the magnetic connection the losses increase and the system may not work), magnetic radiation [28].

V. CONCLUSIONS

The HEV and EV technology, including system, electric propulsion, power electronics, and charging systems, has
been reviewed. Together with previous studies [3] there are some drawbacks of today’s HEV and EV drives which could be detected. The capacity of energy storage systems needs to be extended in that case improving of total drive efficiency is very important. One of the possible solutions is to join together different energy storage systems and advanced power electronic schemes are required. Similarly some new power electronic solutions are required for improving the charging systems of future vehicles, to make charging of EV more costumers friendly. There is no exactly solution for propulsion system for HEV and EV that means electrical motors and their control methods need to be studied more carefully.

There are a quantity of HEVs and EVs already available on the market. However, an on-road test there is not always possible to test each subsystem separately. In that case the test benches of some standard parts of the vehicles seem as a good solution to concentrate on improving of the whole system.

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REFERENCES

[26] Lei Shi; Haiping Xu; Dongxu Li; Zengquan Yuan; “A novel high power factor PWM rectifier inverter for electric vehicle charging station,” Electrical Machines and Systems (ICEM0S), 2011 International Conference on , vol., no., pp.1-6, 20-23 Aug. 2011