FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 27, N° 2, June 2014, pp. 299 - 316
DOI: 10.2298/FUEE1402299K

ELECTRIFICATION OF THE VEHICLE PROPULSION SYSTEM – AN OVERVIEW

Vladimir A. Katić, Boris Dumnić, Zoltan Čorba, Dragan Milićević

University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Abstract. *To achieve EU targets for 2020, internal combustion engine cars need to be gradually replaced with hybrid or electric ones, which have low or zero GHG emission. The paper presents a short overview of dynamic history of the electric vehicles, which led to nowadays modern solutions. Different possibilities for the electric power system realizations are described. Electric vehicle (EV) operation is analyzed in more details. Market future of EVs is discussed and plans for 2020, up to 2030 are presented. Other effects of electrification of the vehicles are also analyzed.*

Key words: *EV Short history, Electric Vehicles, EV Power System*

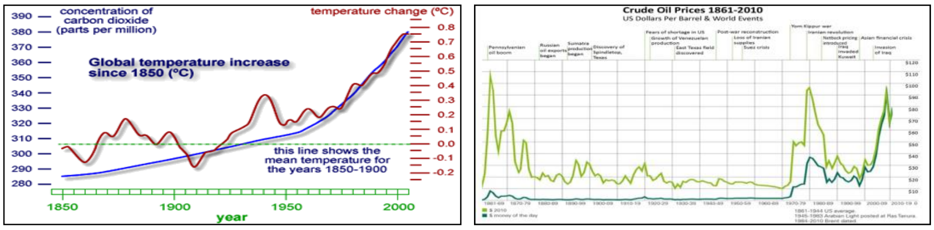
1. INTRODUCTION

Transportation sector is the major energy consumer. As statistical data from 2009 and 2010 show, the transportation is spending as much as 19% (2009) of global total energy use [1]. In the EU its share in 2010 goes up to 31.7% or 365.2 million toe [2]. It is also contributing to 23% of the energy related green-house-gasses (CO_2) emission (2012), which is significant increase from 6.5% in 1990 [2], [3]. If current trend continues, transportation energy use and CO_2 emission are projected to increase by nearly 50% by 2030 [1]. Although EU 2020 policy target is to decrease green-house-gasses (GHG) emission by 20% in 2020, the above data shows that transportation sector will not contribute much to it. This future is not sustainable, as the effects of climate change resulting from global temperature increase and fast rise of CO_2 concentration (Fig.1, left) are evident. Such a negative trend needs to be addressed and some possible solution should be pointed out.

Replacement internal combustion engine (ICE) with electric propulsion in passenger cars is seen as a way for decreasing GHG emission and to mitigate the climate change problems [4]. Electric propulsion is not new, and it dated back to mid 19th century, when the first electric vehicles (EV) were presented [5]. However, the market destiny was not favorable to EVs and in 1930s they were totally abounded. The revival started in late 1980s when environmental awareness of the population increased due to fast rise of the GHG and especially CO_2 emission (Fig.1, left). At the same time, fast depletion of fossil fuels raised oil prices and put forward questions of energy future of the mankind (Fig.1,

Received February 12, 2014
Corresponding author: Vladimir Katić
University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
(e-mail: katav@uns.ac.rs)

right). Intensive research efforts and new improved power conversion technology enable rapid development and cost-effective solutions.



(Source: http://philebersole.wordpress.com/2012/03/19/the-epic-history-of-oil/) *(Source: http://www.climatechoices.org.uk)*

Fig. 1 Concentration of the CO2 and temperature change since 1850 (left) and Crude oil prices history 1861 – 2010 (right)

Different structures of electric drive trains are possible: hybrid, as a combination of the ICE and electric motor, or fully electric one [4]. The propulsion using fuel-cells or hydrogen energy is also offered, but in this paper it will not be discussed in more details. Nowadays, all major car makers companies are offering some models with hybrid or electric propulsion. Still, the motor type (induction, synchronous, reluctant, brushless DC or other) and battery packaging are not standardized and there are a lot of room for innovations and improvements.

In this paper, an overview of current status in this field, regarding above presented problems is presented. Additionally, market prospects and trends up to 2030 are considered, showing that ill destiny of early electric cars will not be repeated.

2. Short History

End of the 19th century brought great discoveries in the field of electrical engineering and raised enormous hopes on its rapid development and application. One of the fascinating presentations of that time was at the World Exhibition in Chicago in 1893, where a new product for the transportation, the electric car was shown. This was result of more than 100 years of discoveries and innovations in the field of electricity, which yielded to creation of simple electric carriage powered by non-rechargeable primary battery cells by Scottish inventor Robert Anderson in 1838, invention of rechargeable lead-acid battery by French physicist Gaston Plante in 1859 and its basic improvement for use in vehicles by another Frenchman Camille Faure in 1881 [5].

The first electric car was made by French engineer Gustav Trouve in 1881. It was a three-wheel vehicle with a 70W DC motor powered by lead-acid battery. At the same time Englishmen William Ayrton and John Perry develop their solution, an electric tricycle with a motor power of 350W and a maximum speed of about 15 km/h. Vehicle was supplied from lead-acid batteries, and speed control was achieved by changing battery connections [5].

The sudden development of electric traction using a DC drive and its commercialization in the urban regions of (electric trams, trains, ships, etc.) led several companies to start EV manufacturing in 1896. The first produced cars found application as New York City taxis (Fig. 2). They had a maximum speed of 32 km/h and radius of up to 40 km [5].


(Source http://en.kllproject.lv/new-york-yellow-taxi-photo.html)

Fig. 2 Electric (Yellow) Taxi in New York around 1901

At the beginning of the 20th century motorized transport customers could choose between a steam-powered vehicles, gasoline or electric ones. The market was divided, without any indication as to which drive will be dominant in the future. Steam-powered vehicles had speed and they were cheaper, but they suffer from long start-up time (to warm up they needed about 45 minutes), and need to make frequent stops for water. Vehicles with internal combustion engines had vibration, noise and smell due to exhausted gases. They needed manual operation to start, changing gears presented a special problem during a drive, but the price was moderate and they could be used for longer trips at a reasonable speed without stopping. The popularity of electric vehicles was due to some advantages they had over their competitors. They were convenient for short distances, around the city limits, easy to start and to drive (no difficulties with gear shifting), reaching high speeds. The first man to break 100 km/h speed barrier was Camille Jenatzy's, a Belgian race driver with his electric car named *Jamais Contente* in 1899. Electric vehicles were clean and quiet, also, but expensive, as they were built for upper class in form of massive carriages, with fancy interiors and from expensive materials. During this period, nearly fifty companies manufactured electric cars covering 38% of the U.S. market. The electric vehicles were prosperous until 1920s with the peak of production in 1912 [5].

Electric drive technology has not kept pace with the needs of population for traveling on long distances nor in terms of speed or a suitable infrastructure for energy supply (battery charging stations). Already in 1913 the general observation was that electric vehicles are losing competition with gasoline cars. The Great Depression '20s in the United States and in the World has drastically limited the resources for innovation in this area, so it gradually decreased production in the U.S. and other companies in Europe. The final blow was when the Ford Motor Company developed a system of mass production and launched the famous model Ford T4 for price 50% lower than the corresponding electric cars. Up to the 1930s electric vehicles have disappeared from the car market in the USA.

However, a series of circumstances brought electric cars, again, in the focus of researchers and the general public attention. Developments in power electronics and wide application of semiconductors (solid-state) power converters in late 1950s have reduced losses, improved operation of electric drives and increased energy efficiency to over 90%. New algorithms of analogue and latter digital control using microprocessors, enables high-quality and reliable motor speed control occupying small space. In sixties the production was limited to small experimental types. Models P50 and Peel Trident of the Peer Electric Mini Car company were suitable for city rides and parking introducing three-wheeler structure with fiberglass bodywork (Fig. 3, left). Similarly, model Enfield 8000 (Fig. 3, right) was produced as small city car in London and had two doors and four seats. DC electric motor of 6 kW and 220Ah lead-acid batteries enabled the radius of up to 90 km and a maximum speed of 60 km/h. It was manufactured in only 106 copies, so the price was not competitive and was no treat to dominant gasoline powered cars.

(Source: http://www.trendhunter.com) (Source: www.veicolielettricinews.it)

Fig. 3 Peel electric cars (1962) and Model 8000 Enfield (1969)

One of the turning points in the automakers industry happened in mid-1970s, when oil supply was restricted due to political instabilities in the Middle East, resulting in serious energy crises and sharp oil prices jump (Fig.1). Additionally, news that the oil reserves are limited and that they will be soon exhausted brought new concerns. At the same time, concerns for the environment and high air pollution in the big cities, due to exhaust gasses from the gasoline cars and threat to population health, started “green” movement in many countries. With increased environmental awareness and with GHG (especially CO_2) emission effects on climate changes (Fig.1), the movement became a worldwide. It encouraged the search for alternatives in transportation power train and lead to re-considering of electric cars or proposing hybrid solutions.

During the 1980s the research efforts continued, but besides the various models of mini cars, no serious commercial attempts were made. A key problem has been the batteries, their great weight and relatively small energy capacity leading to short driving range. Additional challenge has been improvements at the heat engine competition, i.e. significant reduction of exhausting gasses and fuel consumption of the ICE.

Still, the nineties brought the first models of electric car to the market, the EV1, which General Motors produced from 1996 to 2003 (Fig. 4, left). EV1 was accelerating from 0-100 km in 8 s, the maximum speed was 160 km/h and it had a radius of 193 km. The first models in 1996 use 53 Ah lead-acid batteries, with internal voltage of 312 V, which enabled the range of 100 km. Later models (2nd generation 99-2003), switched to the NiMH (nickel metal hydride) batteries, which reduced weight and increased range of up to 240 km. The batteries have been in the form of a package with capacity of 26.4 kWh, which consisted of

26 pieces of 13.2 Ah 77 V batteries, and with a bus voltage of 343 V. However, the basic model price was high and it needed complete replacement of the batteries after only 40,000 km, so it did not withstand competition and was removed from the market.

Another significant market attempt was launch of the Honda's EV Plus model in 1997, which uses DC brushless 49 kW motor and NiMH batteries (Fig. 4, right). EV Plus had a maximum speed of 130 km/h and radius of up to 160 km. It was produced in 340 copies, only, and they were sold exclusively leased, as their price was high. In the end, Honda pulled all the cars from the market and dismantled most of them in 1999.

(Source: http://www.telegraph.co.uk/motoring/picturegalleries/5423182/A-history-of-General-Motors-in-pictures.html) (Source: http://www.barthworks.com)

Fig. 4 General Motors EV1 (1996) and Honda model EV Plus with NiMH batteries

Frequent increases in prices and uncertainty of the oil market, as well as mature environmental awareness, especially in economically developed countries, have contributed that the beginning of the 21st century is marked by the decision of the majority of the world's great car manufacturers to start the production of hybrid and electric vehicles. The landmark is clearly marked by two models: a hybrid car Toyota’s *Prius* and an electric car Teslamotors’s *Roadster*.

Toyota Prius is result of careful thinking and evaluative strategy of passenger car development from the ICE, over hybrid to electric propulsion. It is the first successful hybrid model, produced for more than 15 years. It has appeared in three generations (Prius, Prius + and Prius Plug -in) and was sold over 3,000,000 units (Fig. 5). The details of these models are widely known, but it is worth mentioning that it is a hybrid solution, in which the 500 V electric motor (27kW, 37KS) directly powered from an electric generator, which powered internal combustion engine (like, drive the alternator on standard vehicles with ICE) [6]. Internal combustion engine has a capacity of 1.8 l, 100 hp with an average fuel consumption of 4 l/100km, and the excess energy is stored in batteries. NiMH battery has a capacity of 6.5 Ah, and consists of 28 modules of 7.2 V, of total weight of 30 kg, with an output voltage of 202 V. Specific battery power is 1300 W/kg, and the durability of 300.000 km. Last generation include larger battery packs and charging ability of the public distribution network, Plug-in Prius.

Other similar models hybrids, especially plug-in solutions, include Chevrolet Volt (or Voxal Ampera or Opel Ampera), Ford Fusion Energi PHEV, Ford C-max Energi PHEV, etc.

(Source: http://www.automagazin.rs)

Fig. 5 Three generations of Toyota Prius, the top selling hybrid in the World

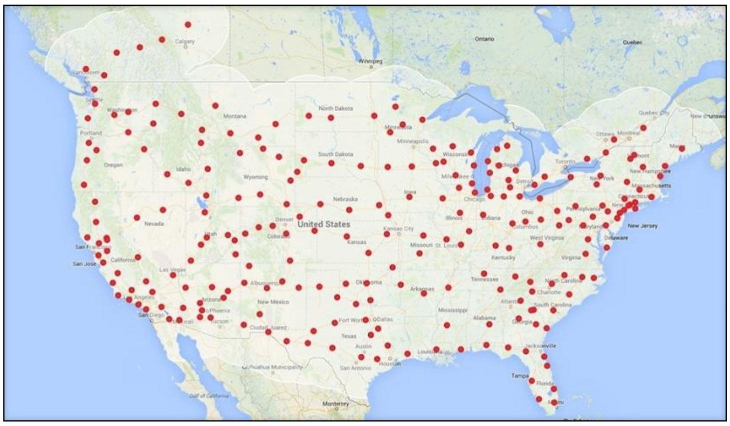
Tesla Roadster appeared in 2008 and presents an innovation in the field of electric cars. Electric propulsion is based on a three-phase, four-pole, AC electric motor, which is controlled by the microprocessor-controlled three-phase inverter and powered from the lithium-ion (Li-ion) battery capacity of 60 kWh and 200,000 km of guaranteed operation (there is option of 85 kWh batteries and with unlimited duration of warranty). His driving performances are impressive - it needs only 3.7 s to accelerate to 100 km/h, and with single battery charge may drive up to 400 km (Fig. 6). For charging it may use the garage battery charger, which can fill the battery in 4h or mobile charger, with which charging takes 6 h. The new model (2014) Tesla S offers some improved options like fast battery swap and better charging.

(Source: http://www.teslamotors.com/roadster)

Fig. 6 Tesla Roadster model 2008

The Teslamotors Company is also making significant investment to develop network of charging stations for energy supply of electric vehicles across the country. In 2014 there are feeder cells in most metropolitan areas in the U.S. with fast chargers of 120 kW, where charging takes only 30 min. The company is planning for 2015 to cover with fast chargers the most important cities and routes in USA enabling easy coast-to-coast ride (Fig. 7).

In recent years, more and more models of electric cars of serial production are available in the market, some of which are already well-known: aforementioned Tesla Roadster, then the Mitsubishi i-MiEV, Nissan Leaf, Reva (manufacturer REVA Electric Car Comp. from the UK), Peugeot iOn, Citroen C-ZERO, Renault Zoe, BMW i3 and others. Leaf and i-MiEV, with total sales of over 15,000 units each, are now the best-selling full electric cars.



(Source: http://www.teslamotors.com/supercharger)

Fig. 7 The charging station infrastructure in USA – Teslamotors plan for 2015

3. Electric Vehicular Power System

A passenger vehicle or a motor car has four power systems: mechanical, hydraulic, pneumatic and electrical one to operate a large number of different loads and to perform assistance to the propulsion system main power train – internal combustion engine (ICE). However, all systems are actually powered from the ICE, except batteries, which could be charged off-board (this option is rarely used, i.e. only when batteries are depleted and needs to be re-charged). To improve efficiency and reduce oil consumption and gasses emission of an ICE, involvement of electrically powered drive train is needed. For example, efficiency of an ICE reaches 30-33%, but of an electric motor (machine) it could go between 80-90%, even beyond.

The motor car electrification or process of application of electric energy for powering some apparatus or equipment in an ICE powered vehicles started way back in 1908, when the first electric device was implemented. It was electric horn, or Klaxon, which was powered directly from dry battery cells. Problem with non-rechargeable dry cells and a need for better lighting was solved by introduction of rechargeable batteries and dynamo generator in 1912. The main goal of that time was to simplify driving, especially starting, than to increase safety, to improve convenience and passenger comfort. Therefore, many other electrical apparatus and electronic devices were introduced (electric starter, wind screen wipers, air-conditioning, modern entertainment systems, on-board computers, information system, sensors, radars, parking assistance, and many others) later on, demanding more electrical power and secure and reliable supply.

However, previous electrification goals have not included the main power train, i.e. the ICE, which is actually the trend of recent decade. Nowadays, the motor car electrification has wider goal, the one which has been mentioned at the beginning of this paper, i.e. to improve efficiency, reduce emission and improve performance. In addition, the need for smarter, more reliable, safer vehicle, integrated in modern communication (Internet) and social networks, but also connected with other vehicles on the road, requires more electric, electronics, communication and computer systems on board.

The level of electrification is defined as ratio of peak electric power to peak power of all power generating systems (electric and ICE) [7]. Regarding this feature of a motor vehicle, several levels of electrification may be distinguished:

1. ICE with non-propulsion electric systems
2. More electric vehicle (MEV)
3. Hybrid electric vehicle (HEV)
4. Plug-in hybrid electric vehicle (PHEV)
5. Full electric vehicle or battery electric vehicle (EV or BEV)
6. Future EVs – Fuel-cell powered EVs, Solar assisted EVs, etc.

3.1. ICE with non-propulsion electric systems

ICE with non-propulsion electric systems uses electric power for operation of a number of electrical loads (previously mentioned), but not for the drive train. All those loads are supplied from an alternator (12V, 0.8 – 1.7 kWp), an AC electrical generator with AC/DC conversion and with backup from lead-acid battery (12V, 45Ah-110Ah). As number of loads is increasing, energy management and increase of efficiency became essential. The long debated proposal for increasing the battery voltage to 42V, have been abounded due to significant additional costs and lower reliability, although many advantages have been pointed out [8].

3.2. More electric vehicle (MEV)

More electric vehicle (MEV) is a car that keeps its ICE propulsion system, but optimizes other systems (non-propulsion), especially electrical one. The main characteristic of such vehicles is integration of the starter and alternator (integrated starter/alternator – ISA), which enables easy implementation of start-stop function and regenerative braking. The start-stop function ceases motor operation during short stops in front of traffic lights and similar situation with idling engine, resulting in lower fuel consumption and CO_2 emission per km. The regenerative braking function uses the kinetic energy of the vehicle during braking or down-hill riding to convert it to electrical and charge the batteries. That function improves energy management and better utilization of different electrical loads.

3.3. Hybrid electric vehicles (HEV)

Hybrid electric vehicles (HEV) are step in evolution towards full electric ones. They are compromise between huge investments needed for developing completely new vehicle model and requirements of modern society to decrease CO_2 gasses emission and fuel consumption. They may be also classified as low emission vehicles in compliance with new legislation, especially in the state of California (USA) [9]. The main idea of HEV is to apply electric energy for propulsion in addition to the ICE. Depending on the level of electric propulsion implementation, different levels of hybridization are defined. These levels are expressed with vehicle's hybridization factor or with ratio between its peak electrical power and its peak total electrical and mechanical power. In that sense, the hybrid vehicles can be divided into micro hybrids, mild hybrids, power (full) hybrids and energy hybrids [7]. Micro hybrids usually have a hybridization factor of 5-10%, mild hybrids between 10-25%, while power and energy hybrids between 30-50%.

The main advantages of hybridization or of having a dual power train are that combining electrical motor and ICE higher efficiencies may be reached, better flexibility of drive, improved riding autonomy, while fuel consumption and gasses emission are decreased. There are several possibilities of organization of such a dual power train, so HEVs may be additionally classified into series, parallel and series-parallel [10]-[14].

The series hybrid architecture consists of three machines connected in series (Fig. 8). The ICE drives an AC electric generator that produces power for charging batteries (DC) and driving the AC electric motor, which is attached to the transmission or directly to the differential or the wheels. To connect different power systems and voltage levels, an AC/DC and a DC/AC converter are needed. In such a way, the DC link decouples two electrical machines, while the electrical system mechanically decouples ICE from the wheels. Problem is that overall efficiency gain is not significant due to multiple power conversion.

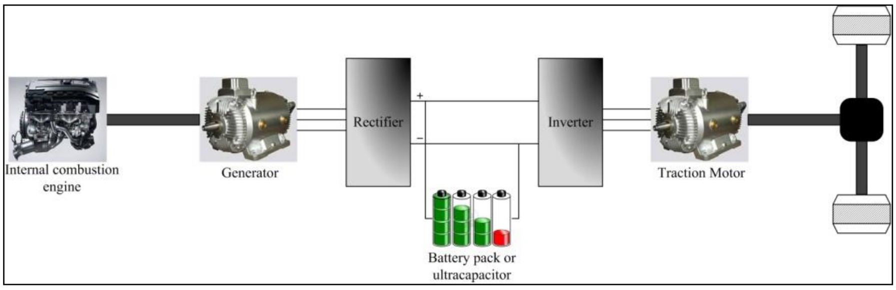


Fig. 8 Series hybrid electric vehicle architecture

In a parallel hybrid vehicle both electrical machine and ICE are contributing to the propulsion as they are mechanically coupled to the transmission or the wheels (Fig. 9). The electrical machine is assisting the ICE in order to reduce the fuel consumption, so it is used mainly during start-up and speed acceleration. On the other hand, it enables regenerative function and battery charging through power electronics converter. The battery, i.e. energy storage system is relatively small providing enough power for short operation, but not enough to energize all-electric mode, especially at high speeds. For such an application supercapacitor or ultracapacitors are recently proposed [15].

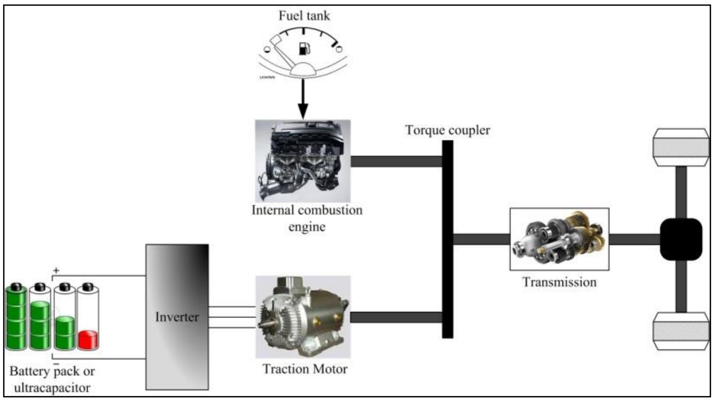


Fig. 9 Parallel hybrid electric vehicle architecture

In a serial-parallel hybrid two electrical machines are combined with ICE to provide both series and parallel paths for power (Fig. 10). Electrical motor and ICE are mechanically coupled for delivering power to the wheels. ICE is also coupled with electrical generator to generate electricity for charging batteries. Batteries are providing power to electric motor. Regenerative function for charging batteries is possible, also.

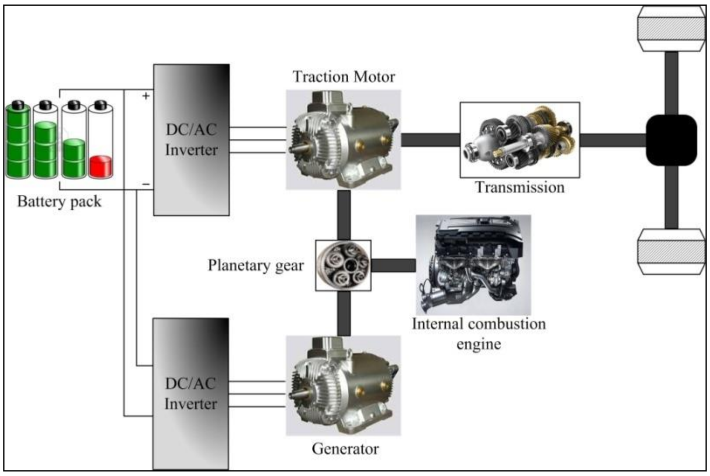
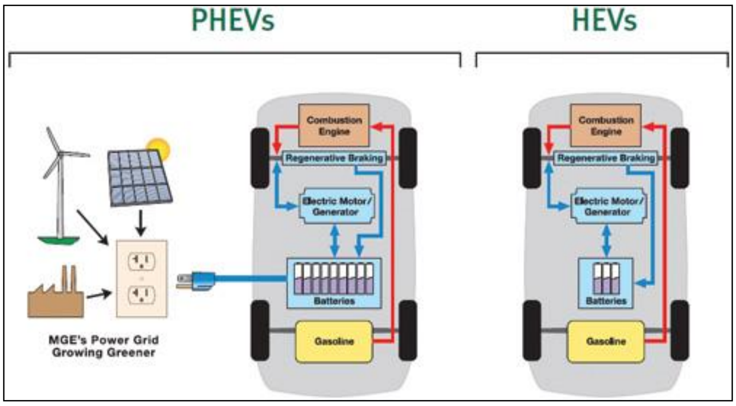


Fig. 10 Series-parallel hybrid electric vehicle architecture

3.4. Plug-in hybrid vehicles (PHEV)

While the HEVs have electric assistance to ICE, the PHEVs have a high-energy-density energy storage system that can be externally charged (Fig. 11). This enables that the vehicle can run in full electric mode or electric assisted mode. Again, series, parallel or series-parallel hybrid power trains are possible. As the batteries are of higher energy capacity than in HEVs, such vehicles are also called range-extended HEVs.



(Source: http://www.mge.com/environment/innovative/hybrid-vehicles.htm)

Fig. 11 PHEV in comparison to HEV

PHEVs may have on-board charger which could be bidirectional and enable smart-charging capacity, which is recognized as vehicle-to-grid (V2G) charging mode. Also, off-board or public chargers in V2G mode may be used, together with home chargers (vehicle-to-home V2H charging mode).

This gives PHEVs more flexibility and possibility in running in two operating modes: charge-depleting and charge-sustaining mode. In the first mode, electrical energy from the batteries is used to provide power until it is consumed, i.e. the state of charge of the batteries reaches predefined minimal value. After that the ICE is turned on and the vehicle runs in a hybrid mode. If the state of charge of the batteries is sustained in predefined range, this operation mode is called charge-sustaining mode.

3.5. Full electric vehicle or battery electric vehicle (EV or BEV)

Full electric vehicles or electric vehicles (EVs) or battery electric vehicles (BEV) has all-electric propulsion system. There is no other engine, then electric motor. The electric power system has the same concept as at the beginning at the end of 19th century, when the energy was supplied from rechargeable batteries, and then energy conversion block make adaptation to the needs of the DC electric motor, which was powering the car. However, the technology and the efficiency of the whole system have been improved through intensive research and innovation using computer modeling, simulation, emulation and laboratory and prototype testing [4], [7], [11], [13], [14], [16]- [19]. Nowadays power train components include improved high voltage batteries of high energy density, supercapacitors (or ultracapacitors) of high power density, battery (energy) management system, high voltage DC grid (130V – 400V), power conversion system (DC/DC converters and DC/AC inverter), on board battery charger (AC/DC converter), AC motor/generator, low voltage battery, low voltage (12V) DC power grid for non-propulsion loads. Off-board chargers and plug-in features are also included in the system. Complete EV's electric power system is shown in Fig. 12.

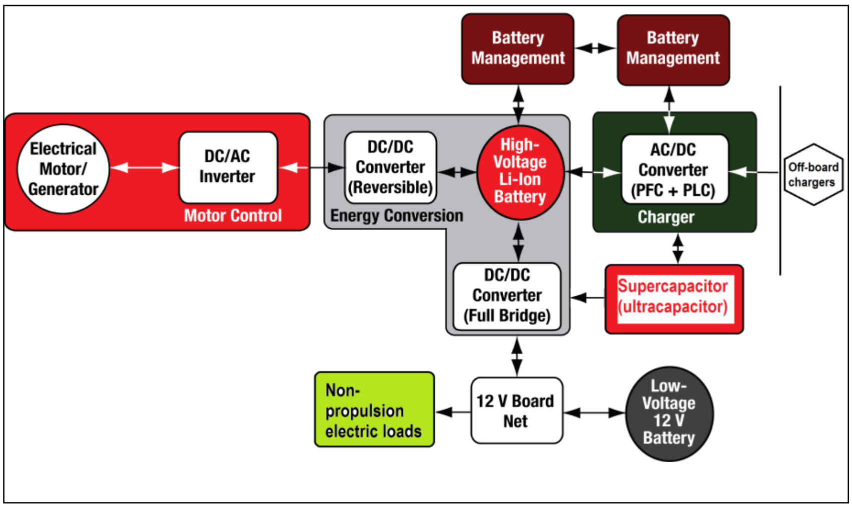


Fig. 12 Typical power system architecture in an EV

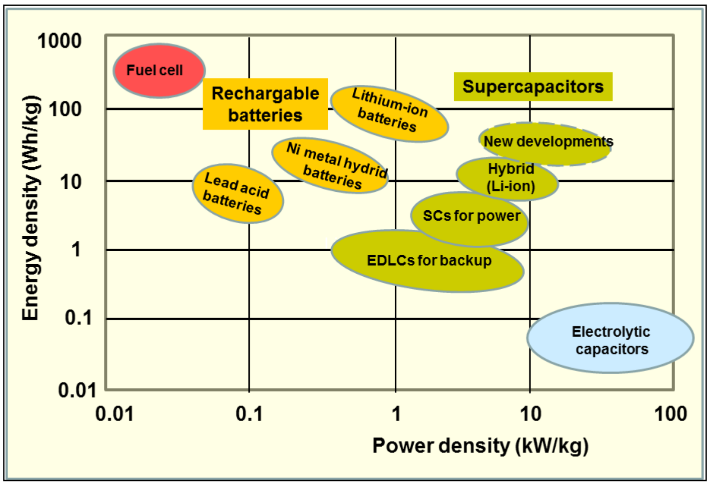
3.5.1. Batteries and supercapacitors

The batteries and supercapacitor perform an energy supply and storage system of an EV, enabling high energy and power supply. Normally, batteries (packed to produce high voltage output) are the main energy source of the propulsion system, determining the operation of the vehicle and its driving range. Besides this one, the EV has a separate low voltage battery (12V) for supplying non-propulsion loads. To improve the performance, especially in high power demanding driving moments, like starting the car, speed increase or fast acceleration, a superconductor is considered as additional power source in the power train, parallel to the batteries [16], [20]-[22].

The batteries have evolved from the lead-acid ones, which are reliable, low price, and standardized, but heavy (9-15 kg), short-lived (500-800 cycles) and of lower specific energy (33-42 Wh/kg) and power (0.18 kW/kg) density. Today's Li-ion batteries are more convenient for EV and PHEV applications, having 3,500 cycles in a life time, a specific energy density of 130-140 Wh/kg, and a power density of 2.4 kW/kg (Fig. 13). Increase production and innovations will lead to further improvements, so in 2015 it is expected that Li-ion batteries will reach a specific energy of 250-300 Wh/kg and a specific power density of 3.5 kW/kg, while the costs will decrease from 0.5-0.6 €/Wh in 2011 to 0.15-0.25 €/Wh in 2015 [16].

However, the main problem of long battery charging time is still remaining to be solved. Improving AC/DC converters to convert AC power from the public grid to DC, either as off-board (public or home) or as on-board charger resulted in four charging modes – from the fast one (20-30 min) to slow one (6-8 h) [23]. However, this is still not satisfactory, as people are used to short refuelling time with the ICE.

One possible solution is offered with flow batteries, which are kind of rechargeable fuel cells [4], [24]. There are several types (like redox, hybrid and membrane-less), but the most promising are the vanadium redox batteries, which have a life time of 10,000 cycles, quick and easy recharging similar like refuelling an ICE, as it is done simply by replacing the electrolyte. The main disadvantages are a relatively poor specific energy density 10-20 Wh/kg and the system complexity and size.



(Source: http://en.wikipedia.org/wiki/File:Supercapacitors-vs-batteries-chart.png#file)

Fig. 13 Energy storage devices: energy vs power density

Fast charging are achieved with supercapacitors or ultracapacitors (or electrical double layer capacitors) for power applications, which are energy storage devices like electrolytic capacitors, but of capacitance values up to several thousand farads (Fig. 13) [15], [21]. Their main advantage is very high specific power density (from 2 kW/kg to 15 kW/kg in 2013, with expectation of further rise - up to 30 kW/kg), long life time (10^5 – 10^6 charge/discharge cycles) and very fast charging time (several seconds). On the other hand, the specific energy density is relatively low (10-15 Wh/kg), so they are not suitable to be use as solely energy storage units.

3.5.2. Energy conversion

Standard electric power system of an ICE powered cars has 12V DC bus, which is appropriate for powering all loads. Due to increased power demand in modern vehicles, 42V DC bus was considered, but this idea has been abounded due to economical reasons.

However, in a HEVs and EVs besides conventional vehicular loads, there is an AC electric motor, as the main propulsion for a car motion, which needs higher operating voltage. Therefore, a separate high voltage DC bus, which is supplied from high voltage battery, is needed [13]. The battery output voltage depends on state of charge i.e. on depletion level and may vary between 125V to 200 V. A regenerative DC/DC convertor is used to boost the voltage up to DC bus system level of 400 V. If battery voltage is below nominal 200 V, than the DC bus voltage is also decreased to minimum 267 V.

The on-board or off-board charger is a three-phase AC/DC converter in H Bridge or back-to-back topology connected to high voltage DC bus. The DC/DC converter operating in buck mode is transferring the energy to high voltage battery and through 12V DC/DC converter to low voltage battery, also.

The traction inverter, which function is to provide AC power to the main, traction AC motor, has input voltage range between 190 V and 400 V. The inverter is H bridge topology, composed of IGBT switches with free-wheeling diodes and controlled with space vector modulated PWM or different other control algorithms. All these converters are operating in switch-mode resulting in high efficiency and low losses. Still, sophisticated energy management is needed to coordinate energy flow and enable high efficiency. Further improvements in these directions are expected in the future.

3.5.3. Traction electric motor

Although DC motor seems logical choice for EV's propulsion, as it is powered from DC batteries, today's solutions are based on AC motors. Induction or synchronous AC motors are used as traction motors, due to their lower weight and costs, higher reliability and lower maintenance needs. For high power propulsion, induction motor is used. For example, Tesla Roadster is using a 3-phase 4-pole induction motor of 185 kW power and with maximum speed of 6,000 rpm.

For four wheel drive, four permanent magnet synchronous motors (PMSM) are mounted as a part of a wheel structure. The advantages of such realization are elimination of mechanical gears and differential, which are used in single radial machine drive system. This gives higher efficiency, less weight, and improved reliability, but has usual size and weight restriction, so they are convenient for small vehicles.

3.6. Future EVs

Nowadays electric vehicles are powered from electric batteries, which are charged from the public electric grid. However, such electric energy is generated partially (30% - 70%) from fossil fuels powered plants (coal, oil or similar) and therefore such EVs are not contributing to reduction of the CO_2 emission and improving the environment in full sense. In fact, the emission area is only moved from the big cities to the area where the coal or oil plant is located. It may be estimated that a coal plant CO_2 emission for a 1km of a 40kW (52HP) EV drive is around 200 gCO_2/km [16]. Therefore, additional efforts and technical innovations are needed to achieve full green effect of EVs operation. There are several ideas, but for the moment only applications with solar energy and hydrogen energy using fuel cells have been manufactured as prototype in some EV models.

Solar energy is converted to electrical one using photo-voltaic effect in photo-cells. There are two ways of using this renewable energy source. One is for charging batteries during park time and the other is powering the vehicle from photo-cells integrated in the cover of the vehicle. The first solution is very popular enabling different parking shades design. The second possibility is practical only for non-propulsion apparatus/loads in the vehicle, like air-conditioning, or in case of very light vehicles [25].

Fuel-cell (FC) is using H_2 gas as the fuel, and combines it with oxygen to produce electricity and H_2O as output. Therefore it is environmentally friendly and does not emmit any GHG. The complete scheme of a FC EV is shown in Fig. 14. The cell is producing electricity and store it to the batteries, from which it is consumed by electric motor. The process is of low dynamics, so additional power using supercapacitors are considered [26].

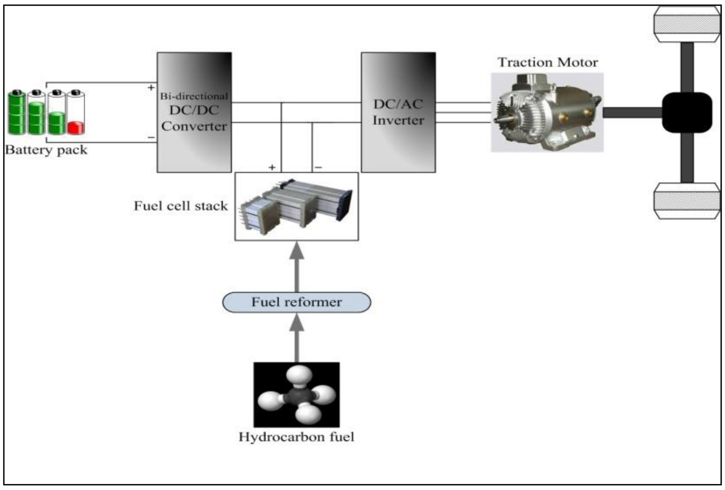


Fig. 14 Fuel cell electric vehicle architecture

4. EFFECTS OF VEHICLES ELECTRIFICATION

Electrification of the vehicle propulsion system and development of plug-in EV (PEV) industry is the final step toward achievement of low or even zero emission passenger cars. The process started as individual effort of some innovators in 1960s up today’s determination of all major car makers companies to include at least one hybrid or electrical model in their portfolio. At the moment the number of sold HEVs, PHEVs and EVs is rapidly rising, spreading form a group of countries called EV Initiative (EVI).

Market success and high public acceptance of hybrid models in USA, especially Toyota Prius and Chevrolet Volt, which was sold in more 3,000,000 cars, made breakthrough in application of electric energy in the power propulsion of modern vehicles. PHEVs are dominating in USA market, with 70% of share, followed by Japan with 12% and The Netherlands with 8% in 2012 [16]. The data show that there was around 180,000 PEVs on the road in 2012 [27]. As of December 2013, this number has been risen up to 380,000 PEVs (passenger cars and utility vans) worldwide, and almost 2,000,000 EVs (PEVs+HEVs). Fig. 15 (left) shows annual EV sales by drive-train (HEV, PHEV, BEV) in 2013 and further prospects up to 2022 [27]. It can be seen that there is huge EV market prospective and that the annual sales of several million units are envisages. Other sources forecast that in 2020 the EV industry (HEV+PHEV+BEV) will produce between 5,000,000 units [27] up to 7,500,000 units [28], [29], reaching 15% [7] up to 20% [28] (Fig.15, right) of all vehicles sales.

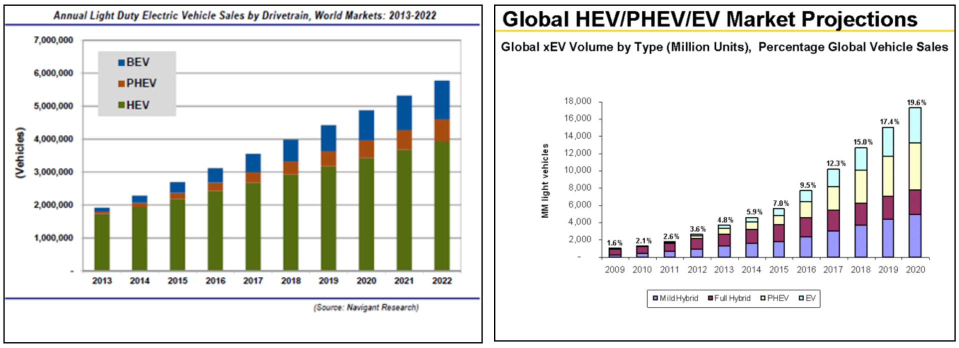


Fig. 15 Left: Annual EVs worldwide sales forecast 2013–2022 [27];
Right: Cumulative EVs sales 2009-2020 [28].

Still the most of the sales will be in range of mild and full hybrid EVs, which are in class of low emission vehicles (LEV). Therefore, the goal of decreasing the overall level of CO_2 by 20% in EU will not be achievable, with electrification, only. However, in long run, up to 2050, the effects will be more significant. Fig. 16 shows cumulative GHG emission savings of a fleet of 11.2 million EVs that will be sold between 2010 and 2020 under three scenarios. Maximum savings is reaching almost 45 million metric tons of GHG (For comparison purpose, in 2009 U.S. emitted 7000 million metric tons) [29].

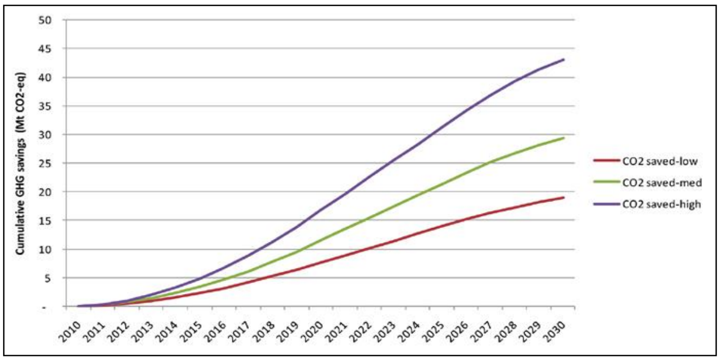


Fig. 16 Cumulative GHG savings due to use of EVs 2010-2030 [29]

Another effect of fast growth of the EVs may be increase of electricity demand and influence on stability of electrical grid. An estimation with similar three scenarios shows that in 2020 additional 7 TWh is needed, while 40 TWh in 2030 (Fig. 17). This is not a significant demand for a large country capacity like USA, so it may be concluded that there will be not major problem in providing electricity supply for the EVs. Another research shows that in the California, no additional capacities will be needed to charge 10 million EVs between 11 p.m. and 8 a.m., but a 30% of new capacities will be required if these vehicles are charged between 5 p.m. to 12 a.m. [30].

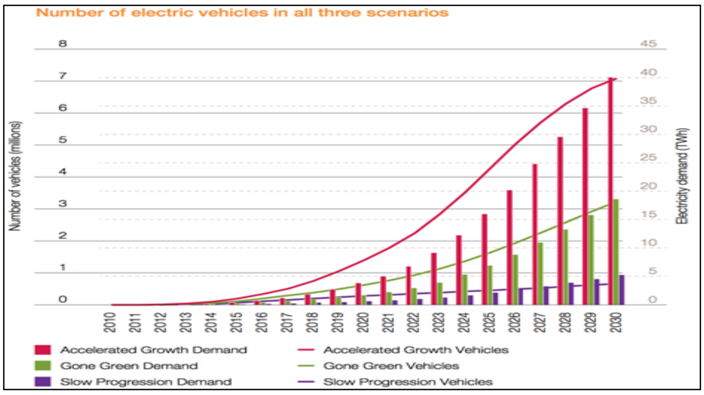


Fig. 17 Number of EVs and their electricity demand forecast (2010-2030).

5. CONCLUSION

Electrification of vehicles is entering in the final stage where the remaining ICE propulsion is gradually replaced with electric one. Different solutions are possible for the drive train – hybrid, plug-in hybrid or full electric. The EVs power system is characterized with dominant DC bus, AC electric motor and multiple voltage levels. The main power source is battery, but additional power may be supplied from supercapacitors, also. To operate such a system, several power electronics converters with sophisticated control methods and energy management are needed. Also, special on-board and/or off-board electricity chargers are integrated in the system.

The market perspectives for the EV industry are very promising. A huge rise in production is expected in coming years. This will have effects on decreasing the GHG emission, but in long run. On the other hand, no significant influence on existing public power system is expecting, especially if battery charging is performed during night hours. Still, to become competitive with ICE cars, further improvements and innovative development is needed and expected in the future.

Acknowledgement: *The paper is a part of the research done within the project No. 114-451-3508/2013-04 co-financed by the Provincial Secretariat for Science and Technological Development of A.P. Vojvodina.*

References

[1] International Energy Agency, "Transport, Energy and CO_2 – Moving Toward Sustainability", Report, Paris, 2009, http://www.iea.org/publications/freepublications/publication/transport2009.pdf

[2] European Commission – Eurostat, "Consumption of Energy", Data from August 2012, On-line only: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Consumption_of_energy

[3] International Energy Agency, "Technology Roadmap: Electric and Plug-in Hybrid Electric Vehicles (EV/PHEV)", Report, Paris, Released 2009, Updated June 2011, http://www.iea.org/publications/freepublications/publication/name,3851,en.html

[4] B.K. Bose, "Global Energy Scenario and Impact of Power Electronics in 21st Century", *IEEE Transaction on Industrial Electronics*, Vol.60, No.7, pp.2638-2651, July 2013, DOI: 10.1109/TIE.2012.2203771

[5] ***, "The History of Electric Vehicles", Electric Vehicles News, Available On-line (Feb. 2014), http://www.electricvehiclesnews.com/History/historyearly.htm

[6] R.H. Staunton, C.W. Ayers, L.D. Marlino, J.N. Chiasson, T.A. Burress, "Evaluation of 2004 Toyota Prius Hybrid Electric Drive System", Report for the U.S. Department of Energy, May 2006, http://k0bg.com/images/pdf/890029.pdf

[7] A. Emadi, "Transportation 2.0", *IEEE Power & Energy Magazine*, Vol.9, No.4, pp.18-29, July/Aug. 2011, DOI: http://dx.doi.org/10.1109/MPE.2011.941320

[8] J.G. Kassakian, H.C. Wolf, J.M. Miller, C.J. Hurton, "Automotive Electrical Systems circa 2005", *IEEE Spectru*m, Vol.33, No.8, pp.22-27, Aug. 1996, DOI: http://dx.doi.org/10.1109/6.511737

[9] U.S. Department of Energy, Alternative Fuels Data Center, "California Laws and Incentives for Air Quality / Emissions", 2013, http://www.afdc.energy.gov/laws/laws/CA/reg/3843

[10] A. Emadi, S.S. Williamson, A. Khaligh, "Power Electronics Intensive Solutions for Advanced Electric, Hybrid Electric, and Fuel cell vehicular Power Systems", *IEEE Transaction on Power Electronics*, Vol.21, No.3, pp.567-577, May 2006, DOI: http://dx.doi.org/10.1109/TPEL.2006.872378

[11] K. Rajashekara, "Present Status and Future Trends in Electric Vehicle Propulsion Technologies", IEEE *Journal of Emerging and Selected Topics in Power Electronics*, Vol.1, No.1, pp.3-10, March 2013.

[12] C. Shen, P. Shan, T. Gao, "A Comprehensive Overview of Hybrid Electric Vehicles*", International Journal of Vehicular Technology*, Vol.2011, Article ID 571683, pages 7, 2011, On line available: http://dx.doi.org/10.1155/2011/571683

[13] H. van Hoek, M. Boesing, D. van Treek, T. Schoenen, R.W. De Doncker, "Power Electronics Architectures for Electric Vehicles", *Int. Conf. on Emobility - Electrical Power Train*, 8-9 Nov. 2010, Leipzig, DOI: 10.1109/EMOBILITY.2010.5668048

[14] A. Emadi, Y.J. Lee, K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles", *IEEE Transaction on Industrial Electronics*, Vol.55, No.6, pp.2237-2245, June 2008, DOI: http://dx.doi.org/10.1109/TIE.2008.922768

[15] J.W. Dixon, M. Ortúza, E. Wiechmann, "Regenerative Braking for an Electric Vehicle Using Ultracapacitors and a Buck-Boost Converter", *17th Electric Vehicle Symposium (EVS17)*, Montreal (Canada), Oct.15-18, 2000, http://web.ing.puc.cl/~power/paperspdf/dixon/42a.pdf

[16] N.C. Kar, K.L.V. Iyer, A. Labak, X. Lu, Ch. Lai, A. Balamurali, B. Esteban, M. Sid-Ahmed, "Courting and Sparking: Wooing consumers' interest in the EV market", *IEEE Electrification Magazine*, Vol.1, No.1, pp.21-31, Sep.2013, DOI: http://dx.doi.org/10.1109/MELE.2013.2272481
[17] E.M. Adzic, M.S. Adzic, V.A. Katic, D.P. Marcetic, N.L. Celanovic, "Development of High-Reliability EV and HEV AC Propulsion Drive with Ultra-Low Latency HIL Environment", *IEEE Transactions on Industrial Informatics*, Vol. 9, No.2, pp.630-639, May 2013, DOI: 10.1109/TII.2012.2222649
[18] N. Janiaud, F.-X. Vallet, M. Petit, G. Sandou, "Electric Vehicle Powertrain Simulation to Optimize Battery and Vehicle Performances", IEEE Vehicle Power and Propulsion Conference (VPPC), Lille, 1-3 Sep. 2010, DOI: http://dx.doi.org/10.1109/VPPC.2010.5729141
[19] Seref Soylu (Editor), "Electric Vehicles – Modelling and Simulations", InTech Europe, Rijeka, Croatia, 2011, http://www.intechopen.com/books/electric-vehicles-modelling-and-simulations
[20] L. Sun, C. C. Chan, R. Liang, Q. Wang, "State-of-art of Energy System for New Energy Vehicles", *IEEE Vehicle Power and Propulsion Conference (VPPC)*, September 3-5, 2008, Harbin, China, DOI: http://dx.doi.org/10.1109/VPPC.2008.4677574
[21] M. Halper, J. Ellenbogen, "Supercapacitors: A Brief Overview", Mitre, Mc Lean, Virginia, USA, March 2006, http://www.mitre.org/sites/default/files/pdf/06_0667.pdf
[22] C.C. Chan, L. Sun, R. Liang, Q. Wang, "Current Status and Future of Energy Storage System for EV", 23rd Int. Battery, Hybrid and Fuel Cell Electric Vehicle Sym. & Exh. (EVS-23), Anaheim, 2-5 Dec. 2007, http://www.lifepo4.info/Battery_study/Batteries/Current_Status_and_Future_of_Energy_Storage_System_for_EV.pdf
[23] IEC 62196-1 standard: "Plugs, socket-outlets, vehicle couplers and vehicle inlets–Conductive charging of electric vehicles", Genève, 2003.
[24] T. Nguyen, R. Savinell, "Flow Batteries", *Interface*, The Electrochemical Society, Vol. 19, No.3, pp.54-56, Fall 2010, http://www.electrochem.org/dl/interface/fal/fal10/fal10_p054-056.pdf
[25] R. Sims, P. Mercado, W. Krewitt, et al., "Integration of Renewable Energy into Present and Future Energy Systems", Chapter 8 of the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, U.K. and New York, USA, 2011, http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch08.pdf.
[26] K. Rajashekara, "Propulsion System Strategies for Fuel Cell Vehicles", SAE 2000 World Congress, Detroit, USA, March 6-9, 2000, http://am.delphi.com/pdf/techpapers/2000-01-0369.pdf
[27] S.Shepard, J.Gartner, "Electric Vehicle Market Forecasts", Navigant Research, Report, 4Q 2013, http://www.navigantresearch.com/research/electric-vehicle-market-forecasts
[28] R. Lache, D. Galves, P.Nolan, "Electric Cars: Plugged In 2", Deutsche Bank, FITT Research Report, Nov.2009, http://gold-estate.com/content/Lithium/ElectricCarsPluggedIn2.pdf
[29] L. Schewel, D.M. Kammen, "Smart Transportation: Synergizing Electrified Vehicles and Mobile Information Systems", Environment – Science and Policy for Sustainable Development, Vol. 4, Sep.-Oct. 2010, On line available: http://www.environmentmagazine.org/Archives/Back%20Issues/September-October%202010/smart-transportation-full.html
[30] Federal Communication Commission, "Connecting America: National Broadband Plan" March 2010, http://download.broadband.gov/plan/national-broadband-plan.pdf