ADVANCED BATTERIES AND SUPERCAPACITORS FOR ELECTRIC VEHICLE PROPULSION SYSTEMS WITH KINETIC ENERGY RECOVERY

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Abstract

For city and neighbourhood people transport, electric driven vehicle with advanced energy storage and electronic control system could be competitive for conventional transportation means. Advanced energy storage and full utilization of regenerative braking system leads to significant energy saving. Regenerative braking is particularly important in city traffic, where a lot of acceleration/braking cycles occur. Replacement of internal combustion engines driven cars with electric vehicles give various benefits: decrease of transport sector impact on climate warming by CO_2 emission reduction and general human health condition increase by elimination of toxic exhaust gases components emission by passenger cars. Particular interest of EV research is focused on lithium based batteries and supercapacitors. Nano-Lithium-Titanate battery could be fully recharged in a very short time and current peaks have no damage impact on the battery. Such batteries have high Cycle Life value (25000) and long life calendar (20 years).Fast charging systems should be equipped with energy converter built inside charging station. The converter has to be based on intelligent control system, for charging parameters setting (stable voltage, charging current, charging time) for different electric vehicles. To estimating charge/discharge characteristic and regenerative braking effectiveness, a simulation in MATLAB environment has been performed based on factory parameters. Graphical simulations results are presented in the paper.

***Keywords**: Lithium-Titan ate Battery, Regenerative braking, Supercapacitor, Electric Vehicle*

1. The potential of electric vehicles performances increase due to advanced battery use

The process of energy conversion from crude oil reservoir or coal deposit to the vehicle wheels during necessary processing phases with energy losses on each step could be characterized by an efficiency chain. For ICE vehicles, the chain consists of following efficiency values: crude oil refinement, liquid fuel distribution, ICE and engine and transmission. For EV efficiency chain includes: refinement to fuel oil or coal processing, electric energy production, battery charging device, energy conversion within the battery, electric engine and transmission. The efficiency chain for an electric vehicle is much longer than for ICE vehicles, but the total energy conversion efficiency is similar in both cases: 15–19% for ICE vehicles and 14–20% for EV [1]. Significant differences are observed from the CO_2 emissions point of view. Estimations made by the US Department of Energy show that if 10% of the total number of vehicles had an electric drive, the CO_2 emission would decrease by 60 million tons per year and if all vehicles had an electric drive CO_2 emission would decrease by half [1].

Transport sector is responsible for 21% of greenhouse gases emission in whole European Union [2]. Average CO_2 emission 130 g/km for whole fleet of passenger's car in European Union have to be achieved in year 2015. Next steps – 95 g/km is the target for year 2020 and 80 g/km for year 2030. This could be achieved only by introduction of new technologies, mainly by vehicle electric propulsion systems generalization [3].

The EVs history is along one - the first electric vehicle (tricycle) was built in 1881. In 1900, between a total of 4200 sold cars in the USA was 38% of electric vehicles. Around 1920 the first EV era finished for such reasons: invention of electric starter for ICE and mass production of FORD T with easy access to fuel distribution points. Nowadays EVs take the advantage of the latest achievements of technology, such as: advanced battery and other electrochemical energy storages, modern electric machines constructions, efficient up-to-date power electronic energy converters and sophisticated control algorithms and techniques. All these devices enable to build new generation vehicle which is: environment friendly, energetic efficient and comfortable. Predicted EVs popularity growth should provoke prices decrease. Electric vehicles, propelled by high-efficiency electric motors, controlled by computers and power electronics devices provide environmental friendly and highly efficient urban transport means. EV use secondary energy sources only. EV do not emit harmful substances and additionally have the ability to regenerate energy during braking, thus reducing the negative impact of the developing economy on the natural environment and cultural and historical heritage. The feature of EVs - kinetic energy recovery possibility – is very important in the city or neighbourhood personal transport, increasing vehicle range between battery recharging processes.

2. Electrochemical energy storages for electric vehicles

As a secondary energy source, suitable for regenerative braking applications, following devices are used:
- Lead-Acid batteries,
- NiMH batteries,
- Li-Ion batteries,
- Li-Poly batteries,
- Supercapacitors.

Nowadays, particular interest is connected with batteries based on lithium and supercapacitors. Important characteristics of energy storages are specific power in [W/kg] and specific energy in [Wh/kg]. In the case of electric driven vehicles, specific power is critical from the point of view of traction properties such as ability to accelerate or to ascend elevation, while specific energy is decisive for the maximum range of the vehicle.

Advanced lithium batteries

First cycle capacity loss is strongly associated with typical lithium-ion batteries with carbon-based anodes. This causes irreversible capacity loss of the battery during the first charging process. Range of such losses could be (depending on battery size and construction) from 5% to 15% of nominal capacity. During first charging process the thin solid electrolyte layer is developed on the graphite structure. This layer is called 'solid electrolyte interface' (SEI) made from $Li+(CO_3^-,OH^-)$. In fact this is additional internal resistor which causes total internal resistance increase. In the consequence – the input and output current limits are lower. Moreover, heat losses increase. This drawback could be reduced by using new anode material (Fig. 1), e.g. nano-titanate (nLTO). Active surface of this material is about 100 m^2/g while for carbon graphite is about 3 m^2/g. SEI layer is not developed and internal resistance is low. Lithium-Titanate battery could be fully recharged in a very short time (depend on charger power) and current peaks have no damage impact on the battery. Thus, nano Lithium-Titanate batteries have high Cycle Life value (25000) and long life calendar (20 years). Lithium-Titanate batteries could be characterized by high values of specific energy and often they are considering as combination battery-supercapacitor. This means, that such kind of battery could accept high currents (charging) as well as deliver high currents (discharging).

Altairnano nano-Lithium Titanate Battery

For negative electrode in Altairnano lithium-titanate batteries nano-porous $Li_4Ti_5O_{12}$ (lithium-titananium-oxide), made by Du Pont, called nLTO is used. Due to lack of SEI battery have extremely fast charging and discharging rates without any damages in battery structure. This feature and low internal resistance enables long cycle life (up to 25000 deep cycles, 80% of initial capacity remain) and declared calendar life 25 years. Depends on charger device power, EV battery could be fully recharged in few minutes. Battery has higher thermal stability than other lithium batteries and due to use nonreactive negative electrode material battery is chemically save. Operating temperature range is wide (-40^{o}C to +55^{o}C) – proper for EV application. Maximum charge and discharge currents reach 6C (360A for 50 Ah battery).

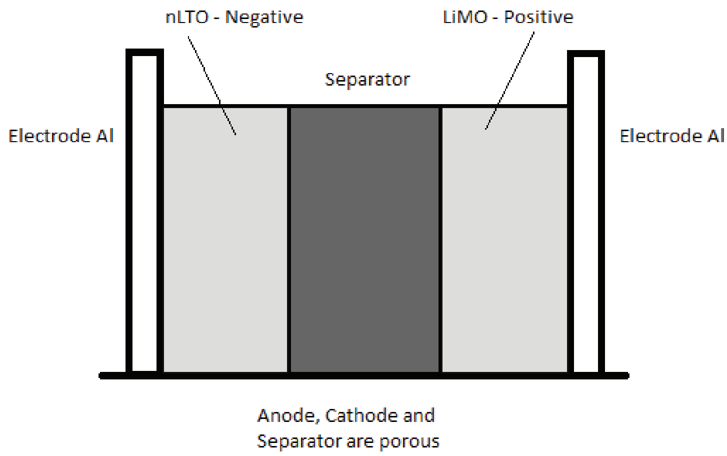

Fig. 1. NanoLithium-Titanate scheme

Toshiba SCiB battery

By use of similar materials than Altairnano, Toshiba developed new battery marked Super Charge Ion Battery (SCiB). The battery has similar advantages – thermal safety, fast charging (up to 10C), 80% capacity remaining after 6000 deep charge/discharge cycles, high values of specific power, wide range of operate temperatures (-30^{o}C to +50^{o}C). Technology is nearly mature – such batteries are produced for market available Mitsubishi EV (i-MEiV).

Supercapacitors

Supercapacitors are characterized by extremely high capacities reaching 3000 F for a single module at the voltage of 2.5 V or 2.7 V [6]. Large capacity is achieved due to the capacitor's special construction. In a conventional capacitor, energy is stored as an electric charge on two metal plates separated with a thin layer of dielectric. In a typical electrochemical battery energy is stored in the chemical form as an active material filling wafer plates constituting electrodes. The supercapacitor structure is similar to the electrochemical battery. The supercapacitor consists of two electrodes saturated with electrolyte and a separator placed between them. In order to achieve very large active surface, electrodes are made of porous material (activate carbon) with pores diameters about 5 nanometres. The active surface of each electrode reaches 2300 m^2/g. The supercapacitor stores energy as an electric charge accumulated in nanopores and at the border between the electrodes solid material and the electrolyte. The separator, which is built of a material that enables ions transfer, separates electrodes with opposite electric charges. In connection with large capacity, supercapacitor is characterized by very high specific power measured in [W/kg]. The power density of supercapacitors is higher than in any battery type. Sometimes such devices are called ultracapacitor or Electric Double Layer Capacitor (EDLC). Supercapacitors are used in vehicle electric drives in combination with classic electrochemical battery. Both energy storages are complementary due to high value of supercapacitor specific power (acceleration, gradeability) and battery specific energy (range). Because off different charge/discharge characteristics, energy storage build from battery and supecapacitors have to be equipped with power electronics DC/DC converter buck-boost type.

Tab. 1. NanoLithium-Titanate Batteries Parameters

Parameter	Altairnano 24V, 60Ah	Toshiba 24V, 4.2 Ah
Nominal Voltage	24 V	24 V
Nominal Capacity	60 Ah	4.2 Ah
Max Charge Current Cont.	360A (6C)	50A (10C)
Max Discharge Current Cont.	360A	15A
Pack Weight	27.4 kg	2 kg
Specific Power [W/kg]	Up to 4000 W/kg	Up to 3900 W/kg
Specific Energy [Wh/kg]	52 Wh/kg	100 Wh/kg

Tab. 2. Different Energy Storage Comparison

Energy Storage	Specific Energy [Wh/kg]	Specific Power [W/kg]	Efficiency [%]	Life Cycle	Charging Time
Lead - Acid	35-50	150-400	80	500-1000	6-12 [h]
Nickel - Hydride	60-80	200-300	70	1000-2000	6 [h]
Lithium - Polymer	150-200	350	90	5000	6 [h]
Lithium – Ion (classic)	80-130	200-300	95	5000	1-6 [h]
Nano Lithium - Titanate	50-100	1000-4000	95	25000	0.2-6 [h]
Zinc - Air	100-220	30-80	60	500	5 [s]
Supercapacitor	1-10	<10000	85-98	>500000	0.3-30 [s]

3. Modelling and simulation of electrochemical batteries

The Nano-Lithium-Titanate battery, built from 40 cells of 2.3 V and 50 Ah capacity, was chosen for charge/discharge and regenerative braking simulation. Electric parameters of battery are: 46 V nominal voltage and 100 Ah nominal capacity. Single cells were connected as series and parallel. Total mass of battery is 64 kg. Based on cell specifications and factory published discharge characteristic, parameters for battery modelling and performance simulations were completed. Fig. 2 shows battery discharge characteristic for 1C; 3C and 5C discharge current (100A, 300A and 500A respectively).

For regenerative braking performance simulations (Fig. 3.), the 50 A constant current load was applied to the electric motor. The electric motor operate mode change from propulsion to regenerative braking was achieved by changing sign of current load from positive to negative. When the angular velocity and load have the same signs – electric machine operates as propulsion motor and in other case – electric machine operates as generator. During simulation, change of load sign depends on battery State of Charge (SOC) level – here 30% and 90% of full SOC. Recharging from 30% of SOC to 90% of SOC in this simulation takes 21.6 min.

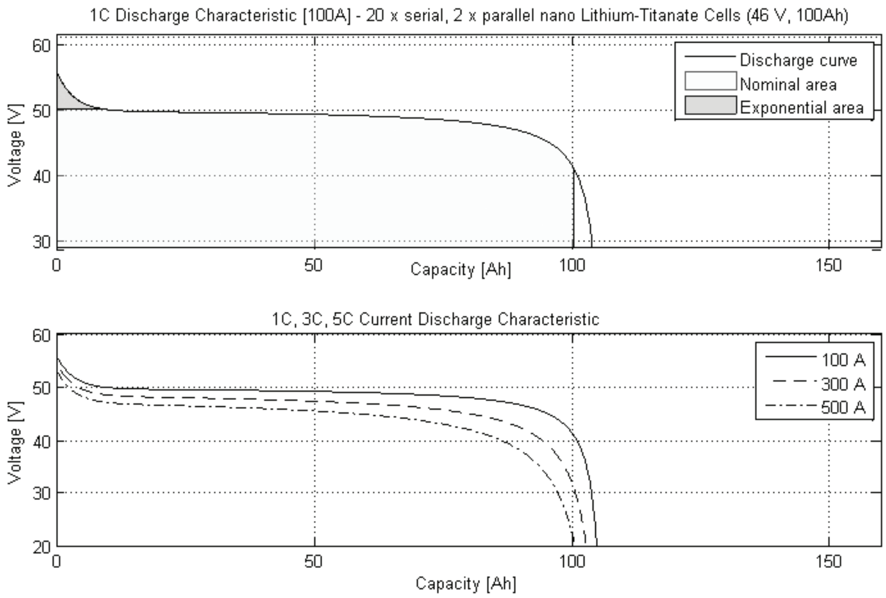

Fig. 2. Battery Discharge Characteristic for 1C, 3C and 5C Current

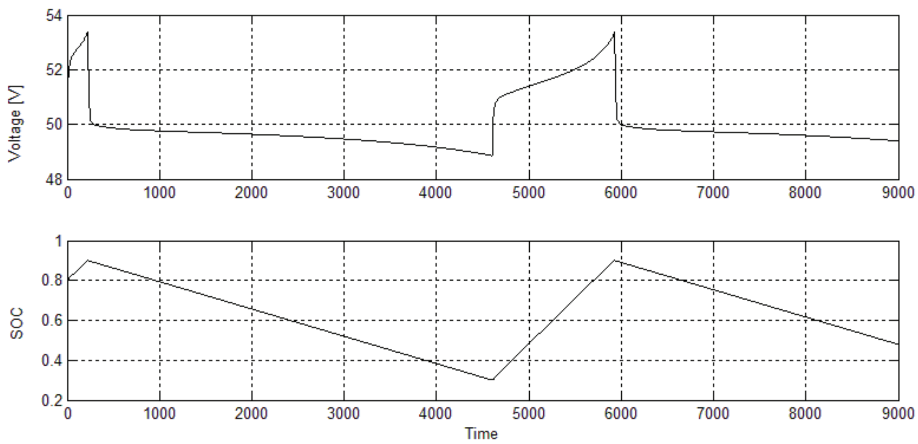

Fig. 3. Simulation of Charge and Discharge battery 50 A Current.

Dynamic model of Lithium–Ion rechargeable battery [4, 5] was applied. Model can be modified for particular battery by using of discharge characteristic parameters.

$$E_d = E_0 - K\,\frac{Q}{Q-it}\,i^* - K\,\frac{Q}{Q-it}\,it + A\,exp\,(-B\,it),$$

$$E_c = E_0 - K\,\frac{Q}{it+0.1Q}\,i^* - K\,\frac{Q}{Q-it}\,it + A\,exp\,(-B\,it), \quad (1)$$

E_0 - Constant voltage [V],
K - Polarization constant [Ah^{-1}],
I^* - Low frequency current dynamics [A],
I - Battery current [A],
it - Extracted capacity [Ah],
Q - Max battery capacity [Ah],

A - Exponential voltage [V],
B - Exponential capacity [Ah-1].

4. Regenerative braking

Regenerative braking has such long history as EVs. In the first application of regenerative braking, kinetic energy during braking was transferred into battery, and the vehicle range was extended significantly. Energy freed during braking by a conventional vehicle is irrecoverable and is completely converted to heat [8]. By using electric propulsion system, kinetic energy can be retained in the system, namely in the secondary energy source (battery, supercapacitor, flywheel). It is possible because an electric machine can work in a reversible mode. During acceleration or cruising it works as an electric motor while during braking or downhill coasting its operates as generator, converting kinetic energy to electric energy to store in secondary source. It is estimated that in intensive urban traffic up to 25% of energy could be saved as a result of regenerative braking.

The amount of saveable energy is limited because the braking process takes place in a short time with a large amount of energy emitted. The size of an electric propulsion motor is defined for each vehicle from the point of view of traction parameters of the vehicle. The total kinetic energy, which could be potentially recovered during braking would require larger, heavier and more expensive machine, able to convert a large amount of mechanical energy into electrical energy in a short time. Such oversizing of propulsion motor is technically and economically unjustified [9].

A controller decides about the amount of regained energy on the basis of the control strategy. A certain amount of energy may be used if a mechanical braking system is needed for quick braking. Based on sensors signals (angular throttle position and brake pedal angular position) and signals speed of changes, controller software makes a decision. Achieve a high efficiency of energy conversion and transfer between different kinds of secondary energy sources is a very important way to develop electric propulsion systems. Important exploitation parameters such as maximum vehicle range, gradeability, acceleration ability have decisive influence on choice of appropriate kind or combination of secondary energy sources in electric vehicle. Exploitation circumstances impact in significant way on conventional secondary energy sources, such as electrochemical batteries. In the case of classical batteries (Lead-Acid), number of deep charging/discharging cycles decreases battery Life Cycle. This impact, different in particular cases (for conventional Lead-Acid batteries this impact is very essential, in the case of advanced lithium batteries it have lower significance). Uses of supercapacitors, which during regenerative braking can intercept energy accumulation from generator, extend battery Life Cycle. Moreover, they can cover pulse high power demands from drive. Such difficult conditions for battery occur in the city traffic: frequently stopping and frequently vehicle accelerating.

5. Charging systems

Electric vehicle battery charging systems can be divided into two groups taking into consideration a place of charging: home charging systems and network charging systems. The first group applications use typical home electric socket. Current output home sockets is 16 A for single phase installation and 32 A for tree phase installation. Full home charging takes 5 to 6 hours typically. Electric vehicles producers have to install on-board energy conversion AC/DC system. Such device should convert alternative electric current with 230 or 400 V voltage to direct current with stable voltage, which is suitable for vehicle traction battery. AC/DC energy converter increase mass of vehicle in the degree depended of charging power and increase costs. Network charging systems, especially designed for fast charging, should be equipped with energy converter built inside a charging station. The converter have to be equipped with intelligent control system, for charging parameters setting (stable voltage, charging current, charging time) for different electric vehicles. Power of fast charging stations depends of required full recharge time. Typical energy of small EV is about 10 kWh. For 1 hour recharging time, power of charger has to be minimum 10 kW, for 15 min recharging time – 40 kW. With charging power growing and charging time shortening, mass and costs increase. Market prices for charging stations are high and reach about 20 000–40 000 Euro per station.

6. Conclusions

Small size electric vehicles for city and neighbourhood purposes, equipped with advanced energy storage and modern propulsion system with kinetic energy recovery will be more and more competitive for conventional cars. On the areas with expected expansion of short range electric transport has to be built infrastructure of public or commercial fast charging stations. Interest for buying EV significantly grows up after construction of network fast charging stations. EVs users prefer to recharge batteries at home, but awareness that they have possibility to use charging station have psychological impact and causes interest of buying electric vehicles. Advanced batteries can be frequently deeply recharged without memory effect and significant capacity decrease. Home recharge process requires few hours but fast charging is possible in few minutes. Supercapacitors use in EVs applications is reasonable with conventional batteries (lower efficiency connected with DC/DC converter necessity and lower reliability). Total mass of advanced batteries is significantly lower than conventional ones.

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