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ULTRACAPACITORS AS AN ADVANCED ENERGY SOURCE FOR BRAKING ENERGY RECOVERY IN ELECTRIC VEHICLES

For short distance (neighbourhood) transport of people in locations of cultural, historical and natural heritage such as places of tourist interest, electrically driven vehicles, equipped with advanced energy storage and management devices could be used. Increasing the efficiency of energy conversion and energy exchange between different kinds of secondary energy sources is very important for the development of hybrid and electric propulsion systems. The capabilities of secondary energy sources to store energy depend on important vehicle parameters: maximum range, gradability and acceleration ability. These parameters affect life cycles of traditional secondary energy sources (electrochemical batteries). Using ultracapacitors (UCAP) as an additional secondary energy source makes it possible to improve the life cycle of a battery and simultaneously to decrease the exploitation costs of electric (EV) or hybrid electric vehicles (HEV). Such electrochemical elements are called: ultracapacitor, supercapacitor, pseudocapacitor or Electric Double Layer Capacitor (EDLC).

1. ELECTRIC CITY VEHICLE BACKGROUND

City cars are those that cover daily up to 25 km. Total mileage of this type of vehicles makes up 9% of daily course of all vehicles. However, emission of this group of vehicles with conventional powertrain solution is high and reaches up to 34% HC and CO of the total amount of emission of all cars [1]. The congestion of the city centres by cars, high emission, low traffic capacity, high conventional city transport costs and high energy consumption were the reason for searching for a small-sized vehicle which would guarantee comfort of individual short-distance travel, especially in the cities. Moreover, the nature of city vehicle movement causes frequent stopping while the engine is idling. This causes increased emission with lack of transport effect while energy loss ensuing from idling reaches 11%. In the case of the second or third vehicle in the household, there is a shortening of average distances the cars cover. Different kinds of energy storage devices are available, such as classic batteries, advanced technology batteries, fly-

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wheels and ultracapacitors. The storage devices, called secondary energy sources, can transform energy from one kind into another in a reversible mode and are able to store energy. The primary energy sources convert energy in one way: the Internal Combustion Engine (ICE) converts the chemical energy of the fuel into mechanical energy of rotational torque and the Fuel Cells (FC) convert the chemical energy of the fuel directly into electric energy. Neither ICEs nor FCs are able to store energy.

Electric vehicles equipped with high-efficiency electric motors (EM), controllers and power electronic devices provide environmentally friendly and highly efficient urban transport. EVs use secondary energy sources only. They 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 historical part of Kraków constitutes precious heritage of the world famous material culture – listed on UNESCO ranks. Thanks to this fact, about 7 million tourists visit Kraków each year. There arises a need to organize a specific kind of transport within the enclave of historical monuments for some of them (e.g., handicapped persons). Currently electrical vehicles based on golf cart are used, which are suitable for tourist traffic service during warm seasons. These are Zero Emission Vehicles (ZEV), moving with limited velocity (25 km/h) and equipped with necessary systems such as braking devices, seat belts, lighting, etc. Electrochemical batteries, used as secondary energy sources, have relatively short life cycles. Tourist traffic is characterized by frequent stops and brakes. This causes unfavourable mode of operation. Frequent states of deep charge/discharge of a battery cause premature use-up.

A new concept of secondary energy source with UCAPs leads to new possibilities of taking over peak loads. Moreover, the regenerative braking efficiency could be increased which will be very important in this case. UCAPs (unlike batteries) could be deeply charged/discharged in a short time due to the low internal resistance without life cycle decreasing.

Wherever the tractive power is produced by electric machines (in the case of FC vehicles, HEVs as well as EV), energy losses during braking can be reduced due to effective regeneration. Each vehicle in order to move must produce tractive power on its wheels to counteract the aerodynamic drag force, rolling resistance force and gravity forces during ascent. Moreover, upon acceleration a vehicle must overcome inertia forces. Most of the energy delivered to the system when accelerating is consequently irrecoverably lost during braking. Additionally, some energy is needed for lighting, air-conditioning or support systems. In conventional vehicles, their power on wheels is won from fuel via an ICE with low efficiency. Figure 1 shows a proportion of energy flow in a medium-sized conventional vehicle for two driving cycles: city and motorway ones [2]. Evidently, most of the fuel energy is lost and only 12.6% of the total energy in city cycle is delivered to vehicle wheels. In motorway cycle the loss increases to about 20%.

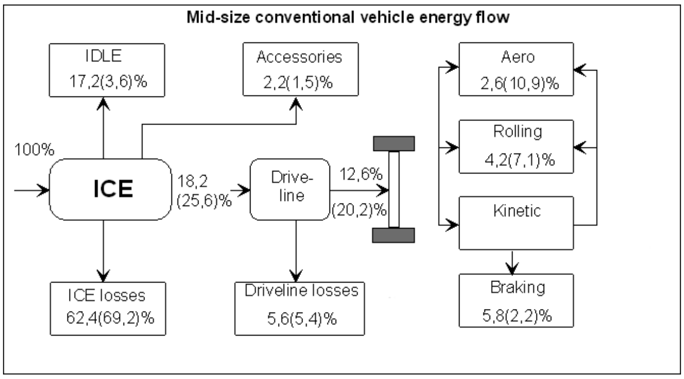

Fig. 1. Use of energy in a conventional vehicle [2]

2. REGENERATIVE BRAKING

Energy freed during braking by a conventional vehicle is lost entirely, whereas in the HEV or EV it can be retained in the system, namely in the secondary energy source. Energy regeneration is possible because an electric machine can work in a reversible mode, i.e., as a propulsion electric motor or as a generator in regenerative mode during braking. It is estimated that for intensive urban traffic up to 15% of energy could be saved as a result of regenerative braking. The amount of savable energy is limited because the braking process takes place in a short time with a large amount of energy being emitted. The size of an electric propulsion motor is defined for each vehicle taking into account traction parameters of the vehicle and the potentially recovered energy during braking would require
a much larger (and heavier) machine, able to convert a large amount of mechanical energy into electrical energy in a short time. Making a propulsion motor oversized is technically and economically unjustified. 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.

3. ULTRACAPACITORS

Ultracapacitors are characterised by very big capacities reaching 2700 F for a single module at a voltage of 2.5 V. Large capacity is achieved owing to the capacitor's special construction. In a conventional capacitor, energy is stored as an electric charge on two metal plates separated by a thin layer of dielectric. In a typical electrochemical battery, energy is stored in a chemical form as an active material filling wafer plates constituting the electrodes. In its construction UCAP is similar to electrochemical battery. UCAP consists of two electrodes saturated with electrolyte and a separator

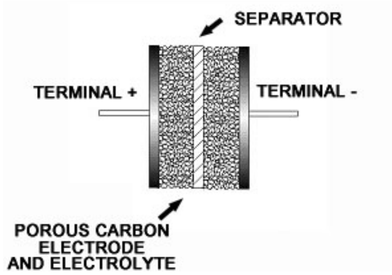

Fig. 2. Ultracapacitor structure

placed between them. In order to get very large active surface, electrodes are made of porous material (active carbon) with pore diameters measured even in nanometers (figure 2). The active surface of each electrode can be as large as 2300 m^2/g. In UCAP, the energy is stored as an electric charge, which accumulates in micropores and at the border between the solid material of electrodes and the electrolyte. The separator, which is built of a material that enables transfer of ions, separates electrodes with opposite electric charges. Two types of electrolyte are currently used: organic and aqueous ones [3]. They differ substantially as far as the parameters called Equivalent Series Resistance (ESR) are concerned. The organic electrolyte is characterized by a higher value of ESR. In connection with large capacity, UCAP is characterized by a very high specific power (power density) measured in W/kg. The power density of UCAP is higher than in any other battery type.

4. ENERGY REGENERATION SYSTEMS

For two DC sources (battery and UCAP) with different and changing levels of voltage, UCAP voltage depends on the State of Charge (SOC). In order to cooperate, a power electronic DC/DC converter is needed, as it enables the energy transfer from the lower voltage source to the higher voltage source and the other way round. Figure 3 shows a basic structure of such a system without the necessary Pulse Width Modulation (PWM) controller, which determines duty ratios for T_1 and T_2 transistors. The interdependence of the output voltage (U_{OUT}) and input voltage (U_{IN}) of the DC/DC converter depends on the PWM duty ratio (D) (figure 4). For 0–0.5 values of D, the boost-buck converter allows the energy to be transferred from the higher voltage source to the lower voltage source. On the other hand, for 0.5–1 values of D, energy transfer to the higher voltage source is possible. Such a situation often occurs during buffer assembly of battery and UCAP. The control system also decides to which of the two sources energy will be transferred [4]. In the case of regenerative braking, the system will select UCAP taking into account the ability to accept large amounts of energy in a short time. Batteries are not accommodated to a very quick charging by high current. Golf carts and derivative EV used as tourist transport vehicles in historical city centres have, as a basic energy source, lead-acid batteries. Certain battery parameters have an impact on their premature degradation caused by conditions of exploitation. Cycle Life (CL) is defined as the maximum number of deep discharges, which still does not cause irreversible damage to the source. Thus CL is strongly related to the Depth of Discharge (DoD) parameter. Cycle life is listed jointly with the percentage of the discharge (e.g., 50% DoD). Consequently, the same battery may be characterized by, e.g., 1000 cycles at 50% DoD or just 400 cycles at 100% DoD. The battery cannot be completely discharged, as this would risk irreversible damage. Another parameter describing the state of energy source is State of Charge (SoC) [5]. It is the relation of the current electric capacity to the so-called useful electric capacity. An important limitation to the electrochemical batteries is the derogation of parameters at low temperatures. A much shorter CL means the necessity of exchanging expensive batteries several times during EV or HEV usage cycle. The cycle life for lead-acid batteries reaches 1000 while for UCAP it reaches over 500 000. The energy required by the vehicle may be presented as a function of time:

$$E = mg\, f_t \int_0^t v dt + K \int_0^t v^3 dt + \frac{m}{2}(v_p^2 - v_k^2),$$

where:

- m – mass of the vehicle [kg],
- g – acceleration due to gravity [m/s^2],
- f_t – rolling resistance (here, $f_t = 0.014$),
- v – vehicle speed [m/s],
- K – $K = \frac{1}{2}\rho \cdot C_x \cdot A$; ρ – air density [kg/m^3], C_x – aerodynamic drag coefficient, A – vehicle frontal area [m^2],
- v_p, v_k – initial and final vehicle speed during braking [m/s].

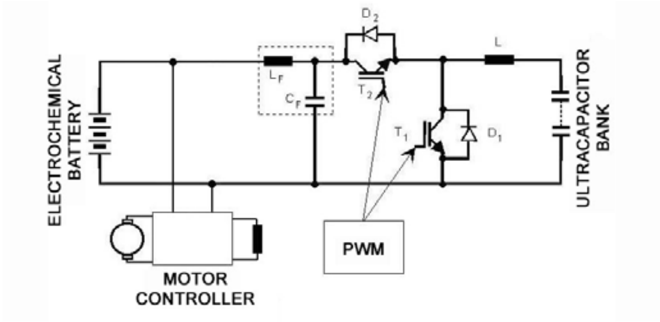

Fig. 3. General diagram of battery/ultracapacitor cooperation

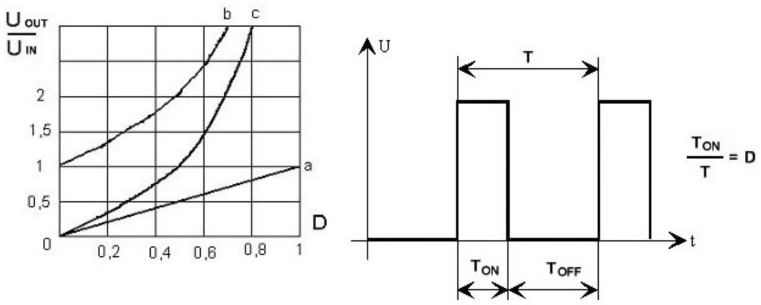

Fig. 4. DC/DC conversion depending on coefficient D

The successive terms in the equation stand for the energy to overcome the rolling resistance, energy to overcome aerodynamic drag and kinetic energy of the vehicle achieved during acceleration. A substantial part of kinetic energy (usually dispersed and lost during braking) may be saved in the system if the vehicle is equipped with regeneration device. For estimating the level of possible kinetic energy recovery, simulation in Matlab/Simulink environment has been performed applying special low speed vehicle drive cycles. Vehicle parameters:

– total mass about 500 kg,
– power of electric motor P = 2.8 kW (U = 48V),
– vehicle speed 25 km/h,
– maximum amount of kinetic energy that could be recovered 12.5 kJ,
– average braking time 10 sec.

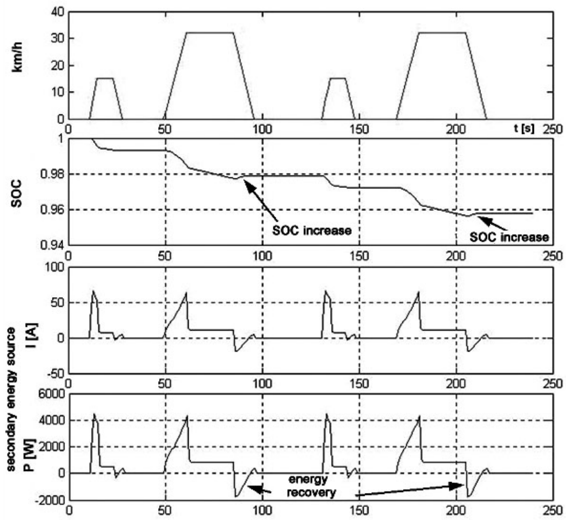

Fig. 5. Results of simulation of EV concept

The obtained number of UCAP (for the chosen kind of Maxwell BCAP0013-450 F) is 22, and the total series capacity is 15 F. UCAP meets capacity requirements, but simulation of single cell voltage distribution is not satisfied; thus final cell number is 23. The corrected total capacity is 19.6 F, and series resistance 0.552 Ω. The minimum voltage is 37.61 V, and average UCAP stack power is 1.38 kW, which indicates the capability of recovering the energy of 13.8 kJ during 10 sec (figure 5). Such a type of ultracapacitor is produced for vehicle energetic systems, and is characterized by 10 years' life cycle, very low internal resistance and the high number of charge/discharge cycles amounting to 500 000. The total mass of selected UCAP is 4.37 kg.

5. CONCLUSION

The main advantages of ultracapacitors in electric vehicles include:

– prolonging the life of traction batteries,
– regenerative braking (saving energy),
– protecting the battery against peak current loads,
– full energy capabilities at low temperatures,
– short charging and discharging times (0.3–30 s),
– obtaining additional quick energy to make the start and acceleration of the vehicle easier.

The number of charging/discharging cycles being practically unlimited enables energy management for all loads (acceleration, braking), which decreases vehicle exploitation cost due to prolonged battery life.

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ULTRAKONDENSATORY JAKO ZAAWANSOWANE ŹRÓDŁA ENERGII W UKŁADACH ODZYSKU ENERGII W POJAZDACH O NAPĘDZIE ELEKTRYCZNYM

Do transportu osób na krótkich odległościach w miejscach stanowiących historyczne, kulturowe lub naturalne dziedzictwo mogą być stosowane pojazdy elektryczne wyposażone w zaawansowane technologicznie źródła energii i systemy zarządzania. Uzyskanie wyższej sprawności przetwarzania energii, a także transfer energii pomiędzy wtórnymi źródłami energii różnych typów jest ważnym kierunkiem rozwojowym w dziedzinie pojazdów elektrycznych i hybrydowych. Możliwość magazynowania energii przez wtórne źródła zależy od ważnych parametrów pojazdu: maksymalnego zasięgu, zdolności do pokonywania wzniesień i przyspieszania. Te parametry wpływają na żywotność tradycyjnych wtórnych źródeł energii (baterii). Zastosowanie ultrakondensatorów jako dodatkowego wtórnego źródła energii umożliwia wydłużenie żywotności baterii i jednoczesne zmniejszenie kosztów eksploatacyjnych pojazdu elektrycznego.