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POSSIBILITIES OF ENERGY RECOVERY IN ELECTRIC VEHICLES USING ULTRACAPACITORS

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Abstract

The concept of double secondary energy source with batteries and ultracapacitors (UCAP's) for golf cart based small size electric vehicle is presented in the paper. For short distance (neighbourhood) person transport in cultural, historical and natural heritage location such as places of tourist interest electrically driven vehicles, equipped with advanced energy storage and management devices could be used. The achievement of higher efficiency of energy conversion and energy exchange between different kinds of secondary energy sources is a very important way of hybrid and electric propulsion systems development. Each vehicle in order to move must produce tractive power on its wheels to counteract against the aerodynamic drag force, rolling resistance force and gravity forces during ascent. Moreover, during accelerating the vehicle must overcome inertia forces. Most of energy delivered to the system during accelerating is consequently lost irrecoverably during braking. Wherever the tractive power is produced by electric machines (in cases of FC vehicles, HEVs as well as EV), energy losses during braking can be reduced due to effective regeneration. Capabilities of secondary energy sources to store energy depend on important vehicle parameters: maximum range, grade ability and acceleration ability. These parameters affect life cycles of traditional secondary energy sources (electrochemical batteries). Use of UCAP's enables improvement of battery life cycle and simultaneously a decrease in electric (EV) or hybrid electric vehicles (HEV) exploitation costs. The stack of UCAP's is an ideal energy store for braking energy recuperation because of possibility to receive large portion of energy in short time without decreasing the operate parameters. Too high current in short time causes shortening of battery life cycle. The microcomputer controllers and power electronics devices are necessary for a proper battery and stack of UCAP's cooperation and energy exchange management.

Keywords: *ultracapacitor, energy recovery, DC/DC boost-buck converter, battery, energy source*

1.Introduction

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 drivetrain solution is high and achieves up to 34% HC and CO of total quantity of emission of all cars. The congestion of the city centres by cars, high emission, low traffic efficiency, high conventional city transport costs and high energy consumption were the reason for the search for a small-size vehicle which would guarantee the comfort of individual short-distance travel, especially in the cities. Moreover, the nature of city vehicle movement causes frequent stopping while the car idles. 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, shortening of average distances the cars cover appears. Different kinds of energy storage devices exist: classic batteries, advanced technology batteries, flywheels and ultracapacitors. The storage devices, called secondary energy sources, can transform energy from one kind into another in a reversible mode and is able to store energy. Primary energy source convert energy 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. Both ICEs and FCs are unable to store energy. EV equipped with high-efficiency electric motors (EM), controllers and power electronics devices provide environmentally friendly and highly efficient urban transport. 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. Small-size electrical vehicles based on golf cart, suitable for tourist traffic service during warm season are Zero Emission Vehicles (ZEV), moving with limited velocity (25 km/hr) and equipped with necessary systems such as: braking devices, seat belts, lighting, etc. Electrochemical batteries, used as secondary energy sources, have relatively short life cycle. Tourist traffic is characterized by frequent stop and brake. It causes unfavorable 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 (differently than batteries) could be deeply charged/discharged in short time due to low value of internal resistance without life cycle decreasing. Wherever the tractive power is produced by electric machines (in cases 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 against the aerodynamic drag force, rolling resistance force and gravity forces during ascent. Moreover, during accelerating the vehicle must overcome inertia forces. Most of energy delivered to the system during accelerating is consequently lost irrecoverably during braking. Additionally some energy is needed for lighting, air-conditioning or support systems.

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 in 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 emitted. The size of an electric propulsion motor is defined for each vehicle from the point of view of 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. Oversize of propulsion motor 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 3000 F for a single cell at the voltage of 2.5 V. Large capacity is achieved thanks 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. In its construction UCAP is similar to electrochemical battery. UCAP 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 (active carbon) with micropores’ diameters reaching nanometer. The active surface of each electrode reaches 2300 m^2/g. In UCAP, the energy is stored as an electric charge, which accumulates in micropores and at the border between the electrodes' solid material and the electrolyte. The micropores in the active carbon are irregular in size and shape, which reduces efficiency. Newly developed ultracapacitors have ability to overcome energy limitation by using vertically aligned, single-wall carbon nanotubes. Nanotubes have a regular shape, and a size that is only several atomic diameters in width. The effective surface area is much greater, and this significantly increased single cell capacitance. The separator, which is built of a material that enables ions transfer, separates electrodes with opposite electric charges. Two types of electrolyte are currently used: organic (propylene carbonate) and aqueous (potassium hydroxide, sulphuric acid). They differ substantially as far as the parameters called Equivalent Series Resistance (ESR) is concerned. The organic electrolyte is characterised by a higher value of ESR and greater energy density. In connection with large capacity, UCAP is characterised by very high specific power (power density) measured in W/kg. The power density of UCAP is higher than in any battery type. Main advantages of ultracapacitors:

- high efficiency (>99% even at high load currents),
- high power density,
- high current capability due to low ESR (UCAP's can deliver or absorb very high current),
- quickly charging/discharging (to 30 s),
- wide voltage range (only limit – cell max voltage),
- wide operation temperature range (-40 - +65 ^oC),
- long Life Cycle (more than 500 000 cycles; reversible process of energy exchange – only ions and electrons move, no chemical reaction),
- battery exploitation life extension (combining UCAP's and battery to complex energy source protect battery from peak current loads),
- UCAP's are nearly maintenance free,
- easy series or parallel integration (when UCAP's are series integrated, common current flows trough all cells, and due to possible different cell capacity, the cell voltage can vary; active or passive voltage balancing circuit could avoid cell overvoltage),

4. Golf cart based electric vehicle with energy recovery

Power flows on rear driven EV with double secondary energy source are shown at the Fig.1.

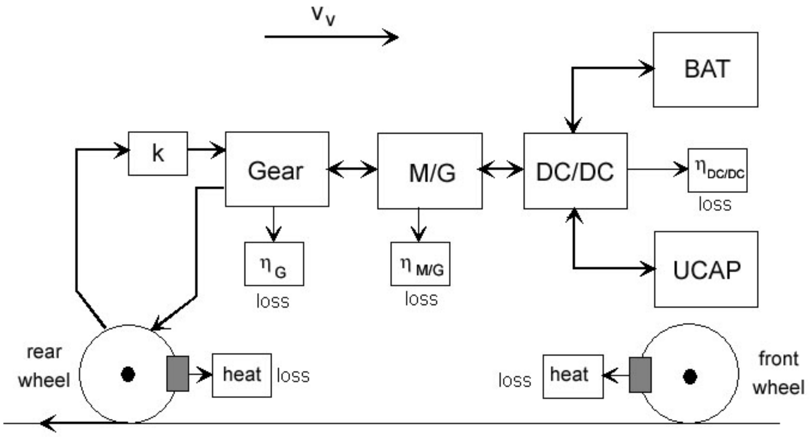


Fig.1. Energy flows in rear wheels driven, EV with energy recovery

Energy recovery occurs during vehicle deceleration. It is possible then use of the electric machine as a generator propelled by vehicle wheels. Due to obligatory convention of positive and negative power, the positive power is delivered by energy source and negative power is absorbed by energy source. Thus, tractive power should be negative during energy recovery. Sometimes, when vehicle is moving, its tractive power could be positive while acceleration is negative. It means, that vehicle propulsion unit delivers insufficient energy to overcome total resistances (movement, aerodynamic, gravity). In such case energy recovery is impossible. Power on wheels, during vehicle movement, could be determined as:

$$\begin{aligned} P_W &= v_v(\Sigma F) \\ \Sigma F &= F_A + F_R + m_v a \\ F_R &= m_v g C_R \\ F_A &= \frac{1}{2}\rho A C_X v^2 \end{aligned} \tag{1}$$

P_W - tractive power on wheels [W],
v_v - vehicle velocity [km/h],
F_A - aerodynamic drag resistance [N],
F_R - rolling resistance [N],
a - acceleration $\left[\frac{m}{s^2}\right]$,
g - gravity $\left[\frac{m}{s^2}\right]$,
C_R - rolling resistance coefficient,
C_X - air drag coefficient,
A - vehicle frontal area [m^2],
ρ - air density $\left[\frac{kg}{m^3}\right]$.

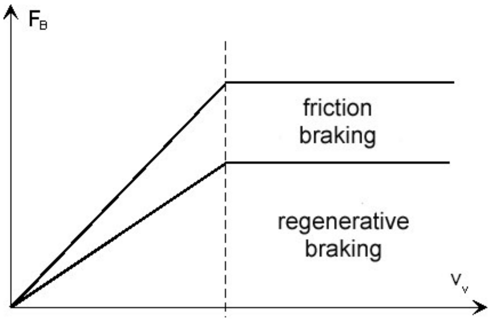


Fig. 2.Friction and regeneration braking share

After taking into account fraction of braking force at propelled axle c and regenerative braking coefficient k, tractive power on wheels could be expressed as:

$$P_W = ckv_v(F_A + F_R + m_v a) \tag{2}$$

c - fraction of braking force at propelled axle; $0 < c \leq 1$,
k - regenerative braking coefficient.

Moreover, energy accumulated in rotating inertias of vehicle wheels, motor/generator and driveline should be taken into account. Then final total power on energy source terminals, after efficiency losses reduction is expressed as [1]:

$$P_{ES} = \eta_{M/G}\eta_G v_v \left\{ ck\left[F_A + F_R + \left(m_v + 4\frac{J_W}{r_R^2} \right) a \right] + \frac{J_{M/G}G^2}{r_R^2} a \right\} \tag{3}$$

P_{ES} - power on energy source terminals [W],
η_G - gearbox efficiency,
$\eta_{M/G}$ - motor/generator efficiency,
J_w - wheel ant tyre moment of inertia [kgm^2],
$J_{M/G}$ - motor/generator moment of inertia [kgm^2],
G - total gear ratio,
r_R - wheel rolling radius [m].

Particular kind of energy can be obtained from formula (3) by integrating over time or passed distance,

$$E_R = m_v g \int_0^s C_R ds \tag{4}$$

$$E_A = \frac{1}{2}\rho C_X A \int_0^s v_v^2 ds \tag{5}$$

$$E_K = m_v \int_o^s a ds \tag{6}$$

E_R - energy for rolling resistance overcome [J],
E_A - energy for aerodynamic resistance overcome [J],
E_K - kinetic energy [J],
s - passed distance [m].

or, for regenerative braking consideration E_K could be expressed simplified in time domain as:

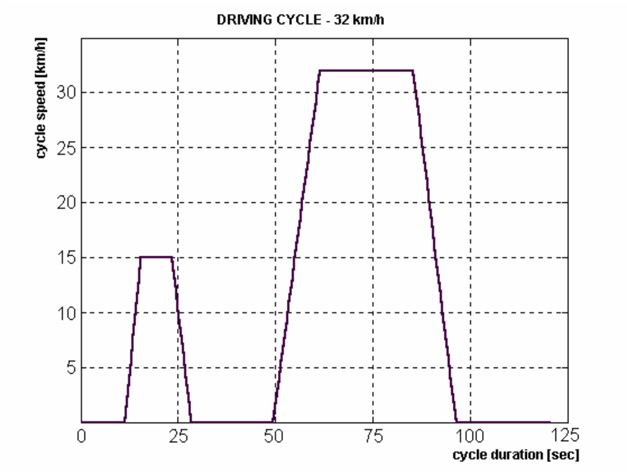
$$E_K = \frac{1}{2} m_v \left(v_P^2 - v_K^2 \right) \tag{7}$$

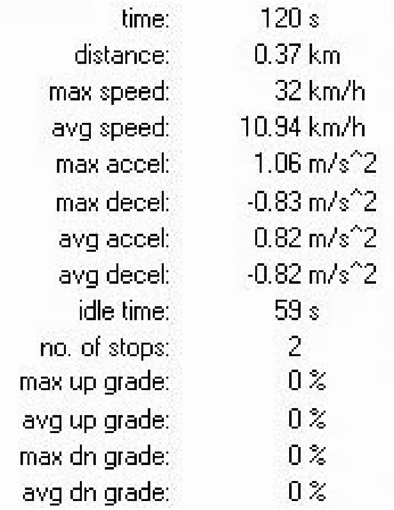
A substantial part of kinetic energy (usually dispersed and lost during braking) may be saved in the system if the vehicle is equipped with regeneration device. during accepted drive cycle simulation.

$$E_{REG} = \frac{1}{2} m_v \eta_{M/G} \eta_G \eta_{DC/DC} ck \left(v_P^2 - v_K^2 \right) \tag{8}$$

E_{REG} - recovered energy [J],
$\eta_{DC/DC}$ - DC/DC converter energy transfer efficiency,
v_P, v_K - initial and final vehicle velocity respectively [km/h].

Difference between possible recovery energy and real absorbed energy is a consequence of limited driveline, motor/generator and DC/DC converter efficiency. Use of golf cart as an electric vehicle requires application of special driving cycle with limited speed and particular schedule of stopping the vehicle. For this reasons, a new driving cycle was prepared. Duration of the cycle is 120s and for time extension this duration is multiplicated. Maximum vehicle speed in this cycle achieve 32 km/h and average vehicle speed is about 11 km/h. Driving cycle is performed on a chassis dynamometer; in our case it was simulated. In order for two DC sources (battery and UCAP) with different and changing levels of voltage, UCAP voltage depends on its State of Charge (SOC). To cooperate, a power electronic DC/DC converter is needed, as it enables energy transfer from the lower voltage source to the higher voltage source and the other way round.





time:	120 s
distance:	0.37 km
max speed:	32 km/h
avg speed:	10.94 km/h
max accel:	1.06 m/s^2
max decel:	-0.83 m/s^2
avg accel:	0.82 m/s^2
avg decel:	-0.82 m/s^2
idle time:	59 s
no. of stops:	2
max up grade:	0 %
avg up grade:	0 %
max dn grade:	0 %
avg dn grade:	0 %

Fig. 3. Driving cycle layout and description

Fig. 4 shows a basic structure of such 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 (V_{OUT}) and input voltage (V_{IN}) of the DC/DC converter depends on the PWM duty ratio (D). 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 situation often occurs during buffer assembly of battery and UCAP.

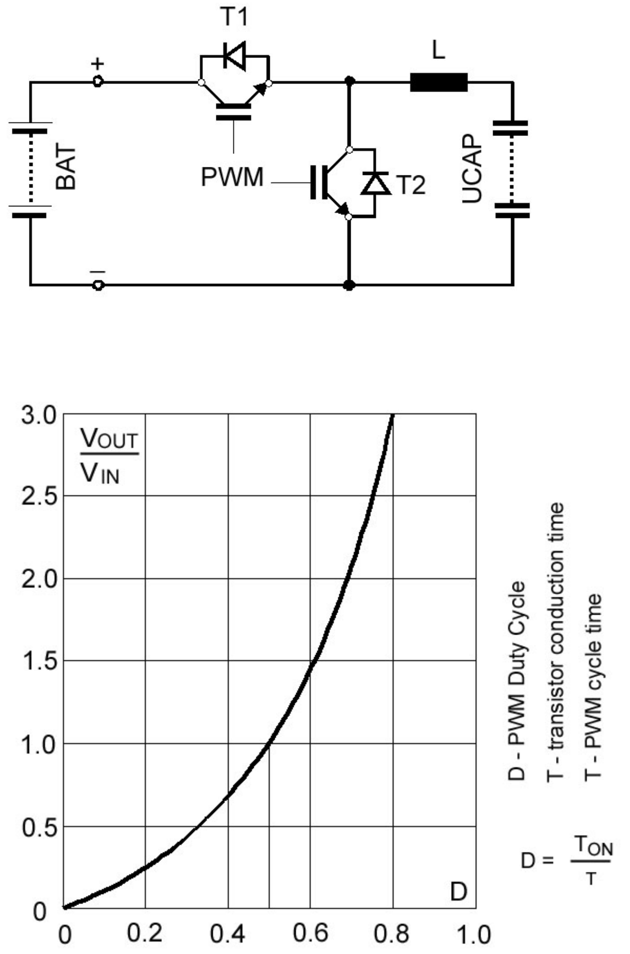


Fig.4. Boost-Buck DC/DC converter operation vs. PWM Duty Cycle

The control system decides to which of the two sources energy will be transferred [7]. In the case of regenerative braking, the system will select UCAP taking into account the ability to accept large amounts of energy in 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 impact their premature degradation caused by conditions of exploitation. Cycle Life (CL) is defined as the maximum number of deep discharges that does not yet cause irreversible damage of the source. Thus CL is strongly related to the Depth of Discharge (DoD) parameter. CL 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) [2]. It is the relation of the current electric capacity to the so-called useful electric capacity. An important limitation of the electrochemical batteries is the derogation of parameters in low temperatures. Much lower CL means the necessity to exchange the expensive batteries a few times during EV or HEV usage cycle. CL for lead-acid batteries reaches 1000 while for UCAP it reaches over 500 000.

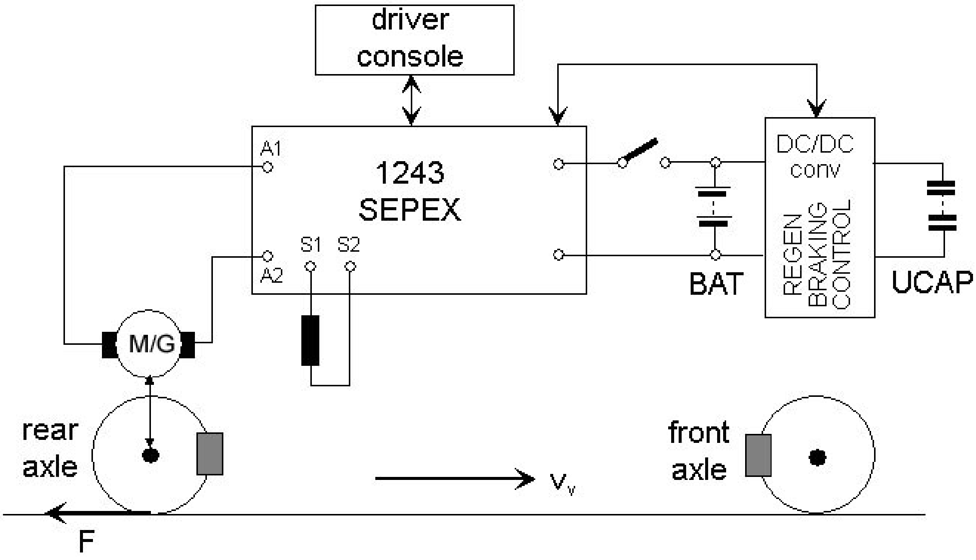


Fig. 5. Golf cart based Electric Vehicle configuration

Vehicle parameters:

- total mass about 500 kg,
- power of electric motor $P_N = 2.8$ kW ($U_N = 48$V),
- vehicle velocity 25 km/h,
- max amount of kinetic energy that could be recovered 12.5 kJ
- average braking time 10 s.

For obtaining proper size and number of UCAP cells in series, Maxwell procedure [4] was applicated. Obtained number of UCAP (for chosen kind Maxwell BCAP0013-450 F) is 22, and total series capacity – 15 F. UCAP meets capacity requirements, but simulation of single cell voltage distribution is not satisfied – thus final cell number is 23. Corrected total capacity is 19.6 F, and series resistance 0.552 Ω. Minimum voltage is 37.61 V, and average UCAP stack power 1.38 kW, which means capabilities of 13.8 kJ energy recovery during 10 s. Such kind of ultracapacitors is produced for vehicle energy systems, and is characterized by 10 years life cycle, very low internal resistance and the high number of charge/discharge cycles – 500 000. Total mass of selected UCAP is 4.37 kg.

5. Conclusions

Practically unlimited number of charging/discharging cycles enables energy management for all loads (acceleration, braking), which decreases vehicle exploitation cost due to prolonged battery life. Double secondary energy source could protect main battery against peak current loads, thus life of traction batteries is also prolonged. Regenerative braking decreases exploitation costs and prolongs battery recharging period and vehicle range. Additional quick energy from UCAP makes start and acceleration of the vehicle easier.

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