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Evaluation strategy of regenerative braking energy for supercapacitor vehicle

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ABSTRACT

In order to improve the efficiency of energy conversion and increase the driving range of electric vehicles, the regenerative energy captured during braking process is stored in the energy storage devices and then will be re-used. Due to the high power density of supercapacitors, they are employed to withstand high current in the short time and essentially capture more regenerative energy. The measuring methods for regenerative energy should be investigated to estimate the energy conversion efficiency and performance of electric vehicles. Based on the analysis of the regenerative braking energy system of a supercapacitor vehicle, an evaluation system for energy recovery in the braking process is established using USB portable data-acquisition devices. Experiments under various braking conditions are carried out. The results verify the higher efficiency of energy regeneration system using supercapacitors and the effectiveness of the proposed measurement method. It is also demonstrated that the maximum regenerative energy conversion efficiency can reach to 88%.

1. Introduction

One of the most important features of electric vehicles is that the kinetic energy of vehicle mass in the braking process can be converted into other forms of energy and stored in the storage devices. Those regenerative braking energy can be converted to the kinetic energy of vehicles by controllers when starting or accelerating again [1]. The energy regeneration system can be classified into three categories: flywheel energy-storage system, hydraulic energy-storage system and electrochemical energy-storage system. Electrochemical energy-storage system was proved to be a promising technical means to realize the energy regeneration in vehicles. If an electric vehicle runs at a high-speed mode, the transient current due to braking feedback in the motor bus will increase up to 200 A or more [2], and this current will cause enormous damage to traditional batteries such as lead acid and lithium batteries. In contrast to the traditional batteries, the supercapacitors have higher power density, and it is more reasonable for the large amount of braking energy to be quickly charged into supercapacitors by proper transformation from kinetic energy to electrical energy. Therefore, the supercapacitors can greatly enhance energy savings and consequently extend the driving range. On the other hand, supercapacitors could output huge current instantaneously, and then reduce the power output of the batteries. Moreover, the accelerating capability of electric vehicles and battery life will also be improved accordingly.

As such, installing a supercapacitor as an auxiliary power source for electric vehicles has become the latest research focus [3–13]. Different energy system architectures with supercapacitors for electric vehicles were proposed by Faggioli et al. in [3], and their research shows that application of supercapacitors to electric traction systems can lead to substantial benefits in terms of electric vehicle performances, battery life and energy economy. Thounthonga et al. [4] demonstrated the application of the fuel cell and supercapacitors in electric vehicles to form a hybrid power source. In their research work, a small-scale test bench was set up to verify the excellent performances of the proposed energy management, and the experimental results show that during the motor starts/stops or other significant steps, the designed hybrid energy system could provide the balance of energy and also absorb excess energy from regenerative braking. Ortuzar et al. [5] adopted an auxiliary energy system based on supercapacitors and evaluated the cost of different power support systems, and the results showed that when the proposed auxiliary energy-system configurations were included, the cost could be reduced significantly compared with the system powered only by fuel cells. Moreover, the cost reduction was more when the supercapacitors were employed for this purpose. Guidi et al. [6] investigated the impact of the addition of a power buffer using supercapacitors to a pure electric city vehicle equipped with an energy dense

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Sodium–Nickel Chloride (ZEBRA) battery. Reference [6] also showed remarkable loss reduction in the battery during normal city driving was believed to result in a longer battery life. Dixon et al. [7] introduced the combination of a ZEBRA battery (high specific energy but low specific power) with UCAPs (low specific energy but high specific power), and this arrangement could increase driving range, efficiency, acceleration, and regenerative braking capability in electric vehicles. Paladini et al. [8] arranged the supercapacitors as secondary energy buffers to capture a significant portion of the braking energy and thus to improve the fuel economy for all cycles. Takahara et al. [9] proposed an alternative way of applying supercapacitors with serial and parallel configuration mode to a pure electric vehicle equipped with traditional batteries. The implementation of a hybrid energy system using supercapacitors was demonstrated by Cao and Emadi [10], Carter et al. [11], Hochgraf et al. [12], and Blanes et al. [13] to protect the batteries on an electric vehicle from high-peak currents and therefore their lifetime will be extended. Based on the above analysis, it is concluded that the supercapacitors, as part of hybrid energy sources in electric vehicles, can greatly improve vehicle performance in terms of efficiency, acceleration, driving range, and regenerative braking.

However, hybrid energy system with supercapacitors is always complex and its corresponding control strategy is difficult to be designed in applications. With the development of supercapacitor technologies, it is possible to use them as vehicle's independent energy sources, especially for short-distance vehicles such as city buses, tunnel trucks and terminal trucks in wharf. The main reason is that those vehicles with supercapacitors could qualify with fast-recharging capability, the frequent start–stop and regenerative braking [14–19]. Hori [14] produced a supercapacitor vehicle, which could complete charging in five seconds and could reach to the maximum speed of 50 km h^{-1}.

The literature has shown the feasibility to replace the original storage devices by supercapacitors in electric vehicles. However, none of them discussed the assessment of energy regeneration efficiency in details. Moreover, there are no effective methods and equipment to achieve an accurate measurement of the regenerative braking energy in supercapacitor vehicles. In present research, the detection algorithm for evaluating the regenerative braking recovery efficiency for a supercapacitor load trucks with a regenerative braking strategy is proposed. Meanwhile, a measurement system for testing the regenerative braking efficiency in various conditions is also investigated.

2. Supercapacitor vehicles and assessment equipment

2.1. Characteristics of supercapacitor vehicle

Supercapacitor vehicles can be divided into two types: pure supercapacitor electric vehicles and hybrid supercapacitor vehicles. A hybrid supercapacitor vehicle is composed of supercapacitors and batteries or fuel cells. It is obvious that hybrid electric vehicles with supercapacitors have a complex energy management system. A pure electric vehicle with supercapacitors as the only energy source will have a simpler energy management system, faster recharging speed and lower cost compared with hybrid electric vehicles. Therefore, pure supercapacitor electric vehicles have more advantages in the condition of short distance and frequent start–stop. Energy regeneration technology has been widely used in electric vehicles or electric motorcycles; however, the regenerative braking energy is not well utilized because the power density of batteries like lead–acid, Ni-MH and Lithium is lower than that of supercapacitors so that it is difficult to increase the overall energy efficiency of vehicles. Furthermore, the optimal design of control strategy over regenerative braking is also required. Electric vehicles powered only by supercapacitors have become a recent focus of research due to their potentially high performance. The issue is that there are no experimental evaluations for regenerative energy in supercapacitor vehicles at present. The accurate evaluation becomes a critical work to push the supercapacitor vehicle technologies forward. Thus, developing an easily implemented measurement system is necessary to achieve the regenerative-braking energy evaluation.

The supercapacitor vehicle to be used in current research is showed in Fig. 1. The major parameters of the tested vehicle are listed in Table 1. The electric truck powered by supercapacitors is developed to freight the heavy goods in the wharf. They have the fast charging capability and high energy efficiency. Various parameters, such as current and voltage of the supercapacitors and motor, vehicle speed, acceleration, and brake pedal signals are measured to evaluate the regenerative braking efficiency.

This supercapacitor electric vehicle has an energy regenerative system, consisting of a general braking system, a power transmission system, a motor and its control system, and an accumulator and energy management system. When the driver steps on the brake pedal, the brake controller will judge which conventional braking strategy should be applied according to the motor's working condition, the charging state of supercapacitors, wheel's sliding rate and other parameters. When braking system runs in regenerative braking mode or composite braking mode, the kinetic energy of the vehicle can be transformed to electric energy by the motor, and this process is considered as the regenerative braking energy that will be stored into the supercapacitors. When the truck starts rapidly or speeds up, the regenerative braking energy stored earlier will be released to increase the energy efficiency and extend the driving range on a single charge.

Fig. 1. The supercapacitor truck.

Table 1
Specification of the supercapacitor vehicle.

Parameters	Value
Vehicle weight	10,000 kg
Maximum speed (no-load)	40 kmh^{-1}
Electric power rating	140 kW
Maximum speed of motor	4000 rpm
Driving range (no load)	20 km
Supercapacitor	UCE15V80000A
Maximum discharge current	600 A
Maximum regenerative current	300–400 A
Voltage	350–590 V
Driving range(load)	4 km