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Pioneering Battery-Supercapacitor Hybrid Energy Management for E-Scooters for Sustainable Urban Transportation

***Abstract**. Many modern electric vehicles use hybrid energy storage systems, which combine multiple energy sources. Because of their rapid charge and discharge cycles, high power densities, longer lifespans than batteries, and resistance to stress, supercapacitors (SCs) are the best option for HESS when combined with batteries. In order to improve the independence of electric vehicles, SCs are used as energy storage devices during sudden power changes and to recover braking energy. In this paper, a speed management strategy is implemented to improve the performance of electric scooters by providing the necessary power from load and power recovery during braking or counter-load. This tactic relies on a so-called ON/OFF control technique to measure the SC and battery's power sharing. To evaluate the effectiveness of the electric scooter's control strategy and the system's energy management under varying loads, a MATLAB/Simulink model has been created. The findings demonstrate that using a super capacitor alleviates the electrical strain placed on the battery.*

***Streszczenie.** Wiele nowoczesnych pojazdów elektrycznych używa hybrydowych systemów magazynowania energii, które łączą wiele źródeł energii. Ze względu na szybkie cykle ładowania i rozładowania, wysoką gęstość mocy, dłuższy okres eksploatacji niż baterie oraz odporność na stres, superkondensatory (SC) są najlepszym rozwiązaniem dla HESS w połączeniu z bateriami. Aby poprawić niezależność pojazdów elektrycznych, SC są używane jako urządzenia magazynujące energię podczas nagłych zmian mocy i do odzyskiwania energii hamowania. W tym dokumencie wdrażana jest strategia zarządzania prędkością w celu poprawy wydajności skuterów elektrycznych poprzez zapewnienie niezbędnej mocy z obciążenia i odzyskiwania mocy podczas hamowania lub przeciążenia. Ta taktyka opiera się na tak zwanej technice kontroli ON/OFF do pomiaru podziału mocy SC i baterii. W celu oceny skuteczności strategii sterowania skuterem elektrycznym i zarządzania energią systemu pod różnymi obciążeniami stworzono model MATLAB/Simulink. Wyniki pokazują, że stosowanie super kondensatora łagodzi obciążenie elektryczne umieszczone na baterii. (**Pionierskie zarządzanie energią hybrydową z wykorzystaniem akumulatora i superkondensatora w hulajnogach elektrycznych na rzecz zrównoważonego transportu miejskiego**)*

Keywords: Scooter electric, BLDC motor, Lithium ion battery, Supercapacitor
Słowa kluczowe: Skuter elektryczny, silnik BLDC ,akumulator litowo-jonowy, superkondensator

Introduction

The electric vehicle (EV) is one of the most important solutions for environmental concerns and the depletion of fossil fuels, especially in urban areas with a large number of internal combustion engine (ICE)-powered vehicles [1–2].

In numerous Asian nations, three-wheeled vehicles and scooters are widely favoured and considered the most cost-effective mode of transportation. In urban settings, they are frequently employed as a means of transport over short distances, serving the purpose of circumventing traffic congestion [3]. In the past few years, there has been a significant amount of research conducted in the domain of light electric vehicles, including three-wheeled vehicles and electric scooters. These vehicles have gained attention as compelling subjects for study [4–5]. Nevertheless, electric vehicles (EVs) currently encounter challenges in energy storage systems (ESS) pertaining to issues of security, size, cost, and management control problems [7].

The primary component of electric vehicles (EVs) is the energy storage system (ESS), which commonly utilises batteries such as nickel-metal hydride (NiMH), lead-acid, and lithium-ion. Nevertheless, electric vehicles equipped with a battery (referred to as B-EVs) do possess certain drawbacks, including a restricted driving range, a relatively brief battery cycle life, and a diminished power density. In order to address the aforementioned challenges [6], it is necessary to consider the implementation of hybrid energy storage systems (HESS) in addition to advancements in storage device technology. The HESS relies on a combination of two or more energy sources, each possessing distinct characteristics [8].

The super capacitor is another type of energy storage device used in the hybrid topology. It is used as an extra source of power, mostly because it has a high power density and a long cycle life [8–9]. So, supercapacitors can be used in an electric vehicle's hybrid system for one or more of the following four reasons [10]:

1-The acceleration of the vehicle got better.
2-Increasing the vehicle's driving range and how well it works .
3-Reduce the battery's peak currents to make the battery last longer.
4-lowering the cost of capital by replacing some batteries right away.

In addition, in order to implement and enhance the HESS, it is necessary to develop a power management strategy in order to achieve the highest possible level of performance from both of the energy storage devices [8]. This is an essential step in the process. Energy management is an essential concern for hybrids that use batteries and super capacitors. It means determining the best way to share the flow of power in order to extend the lifespan of the battery; one relevant way to accomplish this goal is to control the current flowing through the battery in order to reduce the amount of strain placed on the battery [11].

The purpose of this study is to propose a method for the distribution of energy between different storage devices that is based on an ON/OFF control method of speed. has been tested and validated in MATLAB using a variety of different scenarios, and the software Simulink has been put into place. The results of the simulation that were obtained show some interesting accomplishments

Modelling and description of the system

At the present time, there are a few different HESS configurations that have been suggested for use in EV applications. Several published studies have suggested that an electric drive train equipped with both a super capacitor and a battery could serve as the ESS.Despite this, there are a wide variety of topologies that can be utilised for this HESS due to the numerous design, control strategy, and system constitution variations [12–13].

Figure 1 illustrates the study's proposed system model for a hybrid energy storage system for electric scooters. The study was carried out by the authors of the aforementioned study.

Batteries serve as the primary source of energy for the proposed system, while a super capacitor serves as an auxiliary source. Additionally, the system includes two dc-dc converters, an inverter, a BLDC motor drive, and gears [14]. This is illustrated in the figure below.

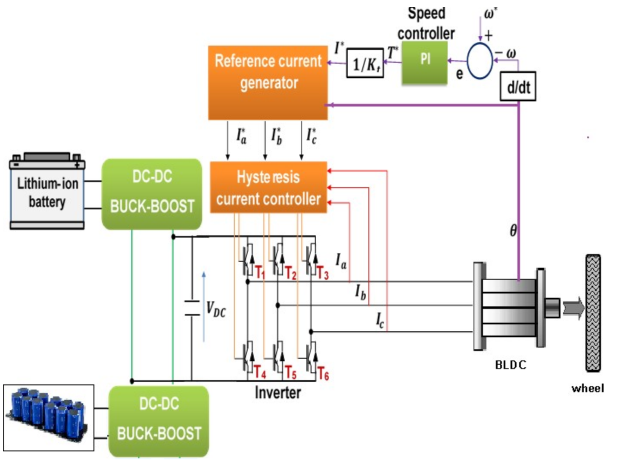

Fig.1. HESS of the studied E-Scooter

The battery-powered model

Li-ion batteries were chosen for this study due to their superior energy density and efficiency when compared to other battery types like NiCd, NiMH, and lead-acid. [15-16] . To characterise and display the dynamic behaviour of batteries, a block electrical model of the batteries is available in the Matlab library. Figure 2 depicts the battery-equivalent circuit [14–17]. In [19], the benefits of lithium are discussed. The following equation describes lithium-ion battery discharge and charging:

Charge Model $(i^* \langle 0)$

$$V_{bat} = E_0 - K\frac{Q}{Q-i_t}i^* - K\frac{Q}{Q-i_t}i_t + A\exp(-Bi_t) \tag{1}$$

Discharge Model $(i^* \rangle 0)$

$$V_{batt} = E_O - K\frac{Q}{i_t - 0.1Q}i^* - K\frac{Q}{Q-i_t}i_t + A\exp(-Bi_t) \tag{2}$$

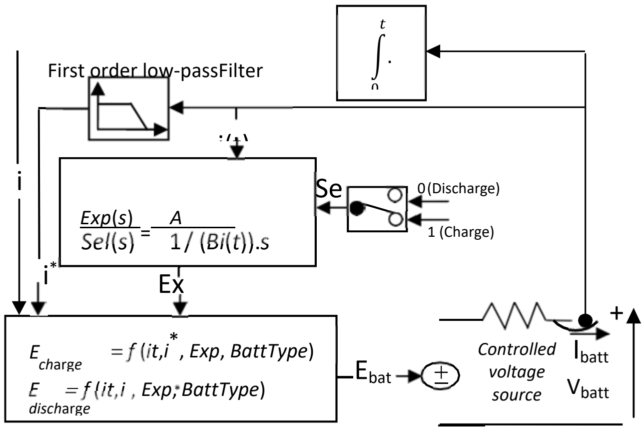

Fig. 2. A Lithium-ion battery's equivalent circuit

Equations (1) and (2) involve the following variables: E_0 constant voltage (V), K steady constant (Ah), i^* low frequency current dynamics (A), i_t extorted capacity (Ah), Q maximum battery capacity (Ah), A exponential voltage (V), B exponential capacity (Ah). The state of charge (SOC) of a fully charged battery is 100%, while a completely discharged battery has a SOC of 0% [2–14].

The model of the supercapacitor

Because of its high power densities as well as its limitless charge and discharge rates in comparison to the battery, the Sc has been chosen to serve as a secondary source of energy. [20]. The practical models that were proposed in [21] consisted of three different RC branches, and the parameters were derived from the terminal measurements of charging and discharging the SC. The term "dynamic model" refers to the other types of models that can represent SC behaviour. The transient behaviour of the supercapacitor can be simulated using these models. Experimental testing, such as supercapacitor discharge and charge at constant current and electrochemical impedance spectroscopy under environmental constraints [22–23], is used to determine the model parameters. This work makes use of the SC model that is accessible through Matlab SimPowerSys.

Dynamic electric scooter model

The EV is affected by numerous forces from various sides, and these forces are considered to be resistive.
Figure 3 illustrates these forces

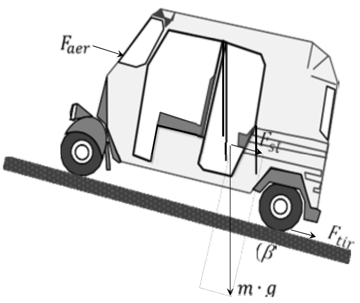

Fig.3. The forces acting on the E-Scooter.

There are three distinct driving resistance forces that affect the traction force the electric scooter exerts: [14]

$$F_{res} = F_{tir} + F_{slp} + F_{aer} \tag{3}$$

$$F_{res} = f_r.m.g + m.g.\sin\alpha + \frac{1}{2}\rho.c_x.A_f.v_h^2 \tag{4}$$

The rolling resistance force is denoted as F_{tir}, the aerodynamic resistance torque is represented by F_{aer} and the slope resistance is indicated by F_{slp}

Table 1. The parameters of the electric scooter used in our study

Parameters	value
Wheel radius r (m)	0.29
Total transmission efficiency n	93%
Scooter mass M (Kg)	230
Scooter frontal area A (m2)	2.09
Scooter friction coefficient f	0.01
Distance between the back and the front wheel L(m)	2.4

Modelling of Brushless DC Traction Motors:

During the traction phase of an electric vehicle's operation, the BLDCs function as motors, and during the braking phase, they function as generators. Hall-effect position and speed sensors are typically included in the package of this type of electric motor. These sensors make it possible for the motors to function properly [24].

The diagram of the basic units of the controller for BLDCM can be found [26–27] and is depicted in Figure 4.

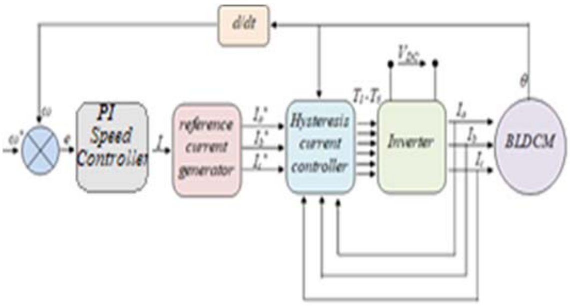

Fig.4. A schematic representation of the BDLC motor control.

The following equation explains the mathematical model of three-phase BLDCM that has been developed [24].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-MM & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

Let v_a, v_b ,and v_c represent the phase voltages; i_a , i_b, and i_c, denote the phase currents; and e_a , e_b, and e_c, symbolise the phase back electromotive forces (BEMF). Additionally, R and L correspond to the stator resistance and inductance, respectively, while M represents the mutual inductance of the motor.

Equations (6) and (7) present the electromagnetic and mechanical formulations of the motor, as documented in references [24–27].

$$T_e = \frac{i_a.e_a + i_b.e_b + i_c.e_c}{\omega} \tag{6}$$

$$J.\frac{d\omega}{dt} = T_e - f.\omega - T_L \tag{7}$$

The scooter motion control strategy :

The mechanism for regulating the scooter's speed must be simulated in order to create motion. Simple guidelines exist for achieving this goal. The scooter's propulsion motor is continuously energised by the voltage source so long as the scooter is accelerating. If the maximum speed is reached, just use a different power source or one with a lower voltage to continue running the motor. The scooter's speed drops significantly when the electricity is either off or reduced. To accelerate once again after going too fast, the complete power supply must be restored, as shown in Fig. 5. This method of controlling speed is an example of the ON/OFF control mechanism utilised in many dynamic control systems [28].

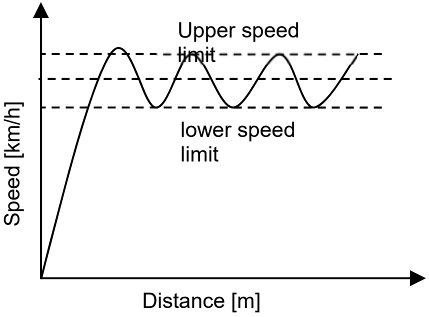

Fig. 5. Strategy for scooter linear speed control: ON/OFF

Results and Discussions

In order to analyse the operational efficiency of a multi-source scooter system, a series of simulation experiments were done utilising the MATLAB/Simulink programme.

Figures 6, 7, 8, and 9 depict the rotor speed, phase current, and electromagnetic torque voltage curves of the DC transformer respectively.

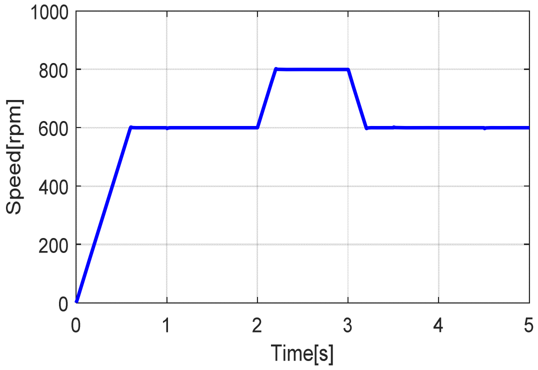

Fig. 6. Rotor motor speed variation

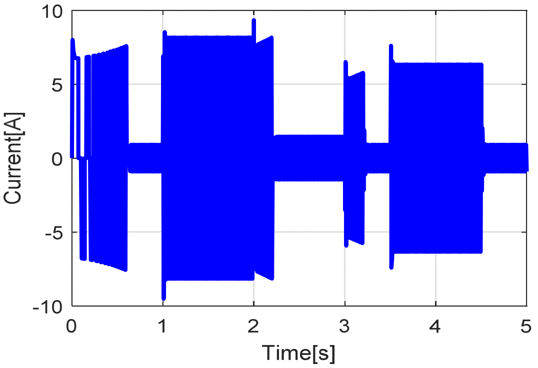

Fig. 7. Phase current of traction motors

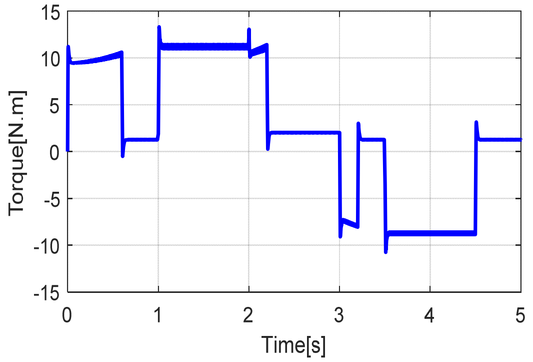

Fig. 8. Fig. 8. Electromagnetic Torques behaviour.

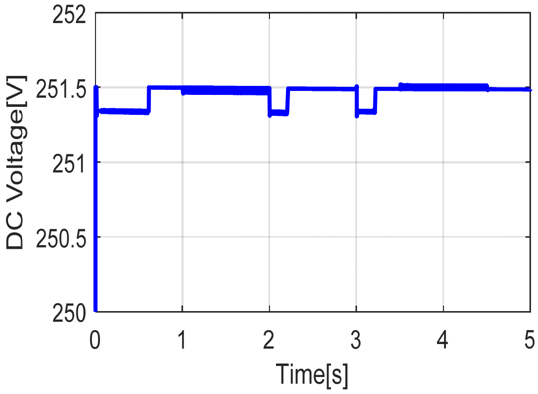

Fig. 9. Boost and Buck boost voltage output enhancement

To turn on the engine, it needs an effort equal to 251.5V. This is what converters do to raise the output voltage of both the battery and the supercapacitor.

In order to activate the engine, an input of 251.5 volts is required. Converters are responsible for increasing the output voltage of both the battery and the supercapacitor.

In order to achieve an acceleration from 0 to 600 revolutions per minute (rpm) within a time frame of 0.6 seconds, the engine necessitates an electromagnetic torque of roughly 12 Newton metres (Nm). In order to achieve an electromagnetic torque of 14 Nm, a current of 9 A is necessary. Similarly, when the speed is stabilised within the range of 1 to 2 S, a current of 10 A is required.

At time t = 2 seconds, the engine is regulated by a variable rotational speed of up to 800 revolutions per minute (rpm), a torque exceeding 15 Newton-metres (Nm), and a current of 11 amperes (A) during the intervals from 2 to 2.3 seconds. Between the time interval of 3 seconds and 5 seconds, a counteracting load is imposed on the motor in order to decrease the electromagnetic torque to a value of -6 Nm.

Figures 10, 11, 12, and 13 depict the variations in current, power, and state of charge (SOC) of the battery and supercapacitor across the several stages of the experiment

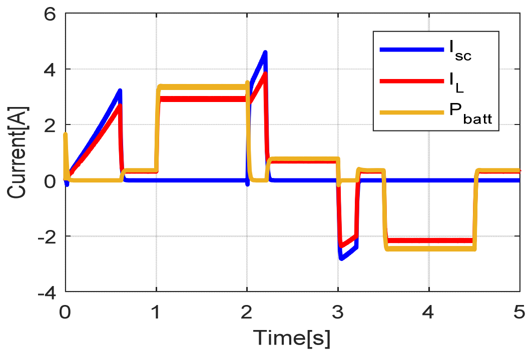

Fig.10. Current in Different stage

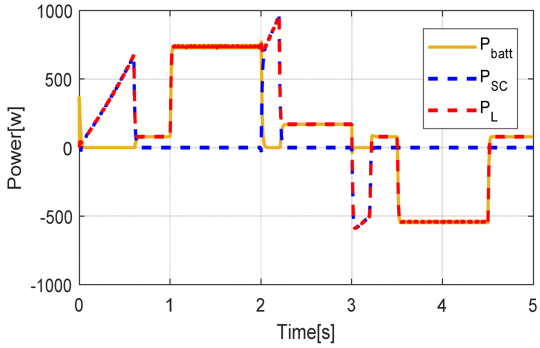

Fig. 11. power at various stages

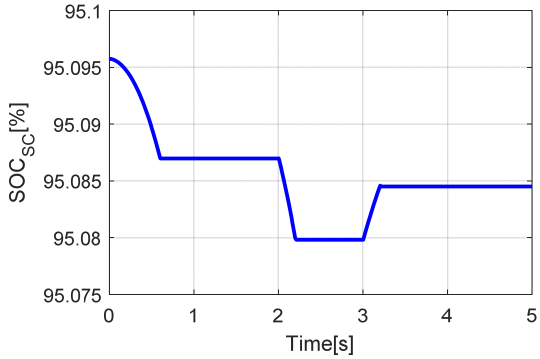

Fig.12. SOC (%) of Supercapacitor enhancement

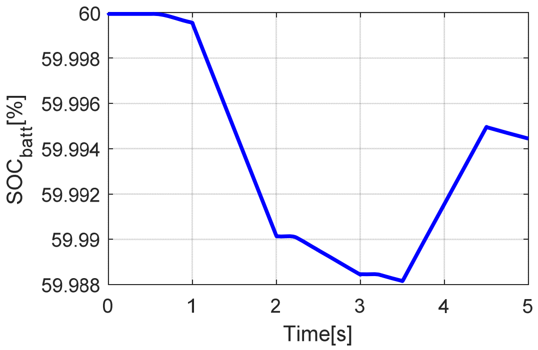

Fig. 13. The battery SOC (%) change.

The acquired simulation results are depicted in figures 12 and 13. It is important to realise how important these findings are, as they show how supercapacitors can help prevent deep discharges of batteries by balancing the current peaks caused by sudden power demands. Moreover, during the process of motor braking, the supercapacitors undergo charging.

Conclusion

The hybrid energy source that we have proposed in this paper incorporates the most beneficial aspects of both existing energy storage technologies, namely the high energy density of batteries and the capability of supercapacitors to rapidly charge and discharge their stored energy.

It is possible to use regenerative braking with this method, which enables the scooter to regain and store energy that it would have otherwise lost while decelerating. This is one of the most significant advantages of this approach.

In addition, the supercapacitors allow the excess energy that is generated by the scooter as it travels downhill to be captured in an effective manner, making it possible to have a readily available source of power for acceleration whenever it is required.

By integrating these two different energy storage technologies in a seamless manner, our goal is to significantly extend the scooter's operational range while simultaneously reducing the number of times it needs to be recharged. This will result in improved user convenience and increased support for environmentally responsible modes of transportation.

The incorporation of supercapacitors not only increases the runtime of the scooter, but it also helps to prolong the lifespan of the batteries. This is accomplished by minimising the depth of discharge, which is an important factor in the longevity of batteries.

This cutting-edge hybrid energy system is not only beneficial to the electric scooter industry, but it also makes a contribution to the overarching objective of achieving sustainable urban mobility. This is accomplished by lessening the carbon footprint and fostering transportation solutions that are cleaner and more energy efficient.

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