Simulation of Regenerative Braking at an Electrical Scooter

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Abstract— **The paper deals with MATLAB simulations of the regenerative braking for an electrical scooter. Various modern possibilities to achieve regenerative braking at light electric vehicles are approached firstly. Afterward one presents aspects of the original simulations related to a scooter equipped with a single-stage bidirectional DC/AC converter based on a general full-bridge inverter in order to implement regenerative braking. The simulator relies on a model from the SIMULINK library, which represents a synchronous motor with permanent magnet and trapezoidal excitation. Other major components of the simulator are: a model of converter with three-phase bridge, realized with MOSFET transistors and anti-parallel diodes; a logical model of the control circuits for the transistors placed on the bridge's arms in order to make the motor to advance, respectively to cause its braking. Two modules were conceived to test the current drawn (or injected) from (or toward) the source during scooter's advance (or brake), respectively to test the consumed (or recovered) energy. The paper includes the simulated waveforms corresponding to various quantities, at the beginning or ending of the braking process, considering a filling factor of 70%. Other simulations were performed with a variable filling factor, in order to evaluate the recovered energy when the speed was reduced from 45 km/h up to 20 km/h. Considering the variation of the recovered energy with the filling factor, the simulations revealed an increase of this energy up to a certain value when the factor is increased at the beginning of the variation range, followed by the recovered energy decrease for higher values of this factor. The phenomena responsible for these variations are discussed. For the studied scooter, the reducing of speed from 45 km/h up to 20 km/h is reflected in a maximum recovered energy of 35% from the total energy stored as kinetic energy by the moving scooter with a maximum weight, respectively 43% from difference between the scooter's initial and final kinetic energies respectively.**

I. INTRODUCTION

From the point of view of power density, output efficiency, control, reliability, and future maintenance, most electric vehicle designers use permanent magnet synchronous machines (PMSM) in their applications [1-3]. The brushless DC (BLDC) machine has a trapezoidal back EMF, in which the armature is usually energized by the rectangular current [4].

Regenerative braking provides an effective way of extending the driving range of battery powered electric vehicles (EVs) [5]. Several types of regenerative braking systems already exist [6-8].

The existing systems differentiate from each other by the concepts and strategies used, and therefore have different potential to increase the driving range of electric driven vehicles. Furthermore, the potential depends on the actual traffic situation and the actual state of the vehicle components [9].

According to the driving conditions, the braking process can be classified as constant speed braking and variable speed braking. The constant speed braking is usually required during the downhill road driving, while the variable speed braking often occurs in the general deceleration process [4].

Ref. [10] provides the following classification of the regenerative braking systems:

1. Category A: an electric regenerative braking system which is not part of the service braking system, and shall only be activated by the accelerator control and/or the gear neutral position
2. Category B: an electric regenerative braking system which is part of the service braking system, and shall have only one actuating unit which in this case is the brake pedal.

In [12] several kinds of regenerative braking systems are briefly described considering their efficiency for light electric vehicles, as follows:

- Electric brake motor: When the accelerator pedal or throttle handle is released, the electric motor becomes an electric generator and brakes the vehicle. Very little electric energy is recovered.
- Collaborating regenerative braking. When the rider hits the brakes, disks or drums operate normally and, in addition, a sensor in the hydraulic circuit (or another system) detects braking force and turns the motor into a generator. This system recovers relatively little electric energy because mechanical braking remains active.
- True regenerative braking. When the rider hits the brakes, disks or drums are replaced by electric motor braking, which generates electricity. In this configuration, a maximum of energy is reclaimed (between 20% and 40% energy savings).

A 100% electrical braking system on the rear wheel (the wheel with the electrical motor) is described in [12]. This system demonstrated a good efficiency for light electric vehicles (LEV). The regenerative braking system is made up of: (a) a hydraulic unit that “hooks into” the hydraulic circuit of the “conventional” brake; (b) the brake lever or pedal; (c) brake lines; (d) a hydraulic (regenerative braking) unit ; (e) a brake caliper.

Interesting studies focusing on solutions relying on ultracapacitors banks were issued recently for LEVs. Their starting point is related to the limit of batteries, related to how fast and how often they can be charged. Regenerative braking produces a lot of current in a short amount of time and therefore batteries have a hard time capturing all of the energy during braking. Being aware that ultracapacitors are able to capture large amounts of current in a short amount of time and can be (re)charged thousands of times, Klefstad and K. Pierson present in [13] their results obtained with and original regenerative braking system placed on an electric scooter using ultracapacitors to store the reclaimed energy. The system was monitored, analyzed, and controlled wirelessly by NI Lab2IEW's cRIO. 2 switches were used to control the operation of the regenerative braking process and a data acquisition system choused which capacitors to charge by controlling the transistors. Also it gathered voltages used to determine when to switch capacitors. A boost converter circuitry was designed to boost the voltage from the capacitor bank to power the motor. At the moment of issuing [13], the research team was under way of developing an appropriate algorithm meant to allow for the boost converter to operate most efficiently for a certain range of speeds.

The back electromotive force (EMF) of a general permanent magnet synchronous machine used in most LEVs is neither perfectly sinusoidal nor perfectly trapezoidal. Rectangular commutation is widely adopted in various LEVs [4].

In order to achieve the dynamic regenerating and charging over a wide speed range, a good technical solution consists in using a bidirectional DC/AC power converter [14]. During the braking period, the switching sequence of the power converter is controlled to inverse the output torque of the three-phase brushless DC motor, so that the braking energy can be returned to the battery [5].

Since the issues concerning cost, volume, maturity of technology and reliability are important when developing a LEV [4],[15],[16], this paper deals with the simulation of a single-stage bidirectional DC/AC converter based on a general full-bridge inverter. This technology can achieve several goals: energy recovery, electric braking, ultra-quiet braking and extending the driving range [5].

II. THE SIMULATOR DESCRIPTION

In order to simulate the operation of a vehicle with electric drive which uses a DC brushless motor, we built a MATLAB-SIMULINK model. It relies on a model from the SIMULINK library, designed to represent a synchronous motor with permanent magnet and trapezoidal excitation. Fig. 1 depicts the block schematic of the model. The equations used by the motor's mathematic model are presented below:

$$\begin{aligned}
\frac{di_a}{dt} &= \frac{1}{3L_s}\left[2u_{ab} + u_{bc} - 3R_s i_a + \ p\omega_r\left(-2e_a + e_b + e_c\right)\right] \\
\frac{di_b}{dt} &= \frac{1}{3L_s}\left[-u_{ab} + u_{bc} - 3R_s i_b + \ p\omega_r\left(e_a - 2e_b + e_c\right)\right] \\
\frac{di_c}{dt} &= -\left(\frac{di_a}{dt} + \frac{di_b}{dt}\right) \\
T_e &= p\ \left(i_a e_a + i_b e_b + i_c e_c\right)
\end{aligned} \tag{1}$$

where:

L_s - inductance of the phase windings [H];

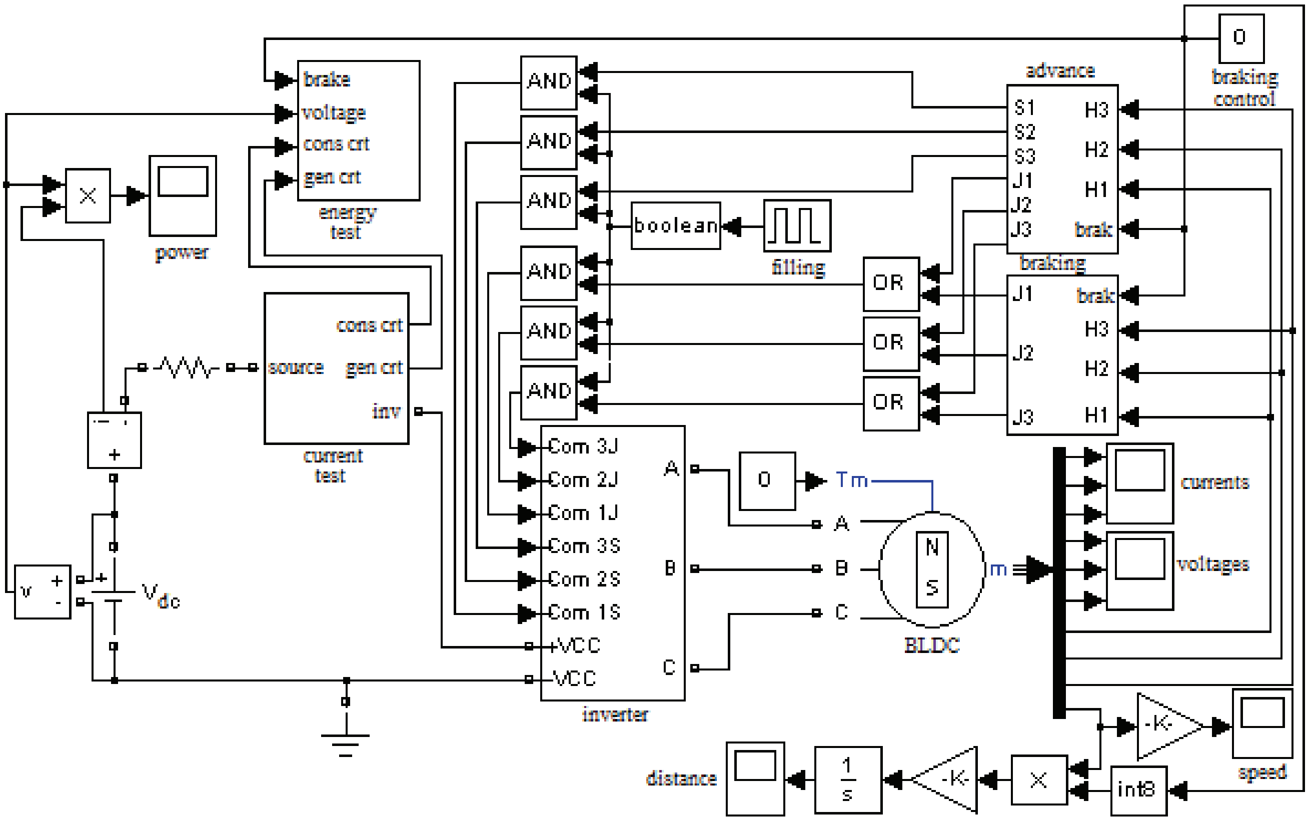

Fig. 1. Block schematic of the simulator

R_s - resistance of the phase windings [Ω];
i_a, i_b, i_c - currents flowing through the phases a, b and c [A];
e_a, e_b, e_c - back electromotive voltage across the phases a, b and c [V];
u_{ab}, u_{bc} - voltages between phases (ab and bc) [V];
ω_r - rotor's angular velocity [rad/s];
ϕ - flow created by the motor's permanent magnet [Wb];
p - number of pairs of poles;
T_e - electromagnetic torque [Nm].

The waveforms corresponding to the back electromotive voltages are characterized by a trapezoidal shape, considered for our simulation as having a perfect shape (Fig. 2).

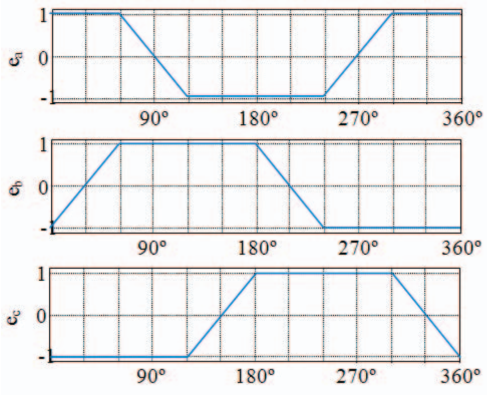

Fig. 2. Back electromotive voltages

The rotor's motion equations are:

$$\frac{d\omega_r}{dt}=\frac{1}{J}\left(T_e-F\omega_r-T_m\right)$$
$$\frac{d\theta}{dt}=\omega_r \qquad (2)$$

where:
J - moment of inertia for motor and load [kg·m^2];
F - viscous friction factor for motor and load [p.u.];
T_m - torque for mechanical load [Nm];
θ - rotor's angle of position [rad].

The kinetic energy equivalence is used as starting point for the representation of the inertia effect of the assembly scooter-load under the form of the motor's inertia moment:

$$E=\frac{mv^2}{2}=\frac{m\left(\frac{\omega d}{2}\right)^2}{2}=\frac{\frac{md^2}{4}\omega^2}{2}=\frac{J_{ech}\,\omega^2}{2} \qquad (3)$$

where:
m - total weight [kg];
v -velocity [m/s];
d - wheel's diameter [m] ;
ω - angular velocity [rad/s];
J_{ech} - equivalent moment of inertia [kg·m^2].

After identification we got:

$$J_{ech}=\frac{md^2}{4} \qquad (4)$$

The vehicle movement on a downhill slope can be represented by a resistant mechanical torque at the motor's shaft T_m.

Assuming a constant velocity $v=\omega d/2$ during a period Δt, the work developed by the torque T_m should compensate the vehicle's potential energy variation:

$$mgv\Delta t\ sin\alpha = T_m\,\omega\Delta t \qquad (5)$$

where:
g - acceleration of gravity [m/s^2];
α - downhill slope [rad].

It results:

$$T_m = mg\frac{d}{2}sin\alpha \qquad (6)$$

The torque T_m will be positive when the vehicle is climbing up and negative when it is moving down.

Other blocks are included by the model, as follows:
- Model of converter with three-phase bridge, realized with MOSFET transistors and anti-parallel diodes;
- Logical model of the control circuit for the transistors placed on the bridge's top and bottom arms in order to make the motor to run forward;
- Logical model of the control circuit for the transistors placed on the bridge's bottom arms in order to get the motor's braking;
- Module used to test the current drawn from the source during the regime for advance, respectively to test the current injected into the source during braking;
- Module used to test the consumed and respectively recovered energy.

III. REGENERATIVE BRAKING

Depending on velocity, the regenerative braking can be achieved in two ways.

A. *Regeneative braking at high speeds*

At high speeds, the voltage between two phases from the motor used as generator is proportional to the speed and overcomes the battery's voltage. In this case the energy is recovered in a natural way: through the anti-parallel diodes the converter turns into a three-phase bridge rectifier and a certain current flows toward the battery. The higher the voltage across the motor's terminals, the higher the braking torque.

B. *Regenerative braking at low velocities*

At low velocities, the voltage is low and the braking effect can be obtained by using 2 different operating regimes alternatively: in short circuit and respectively in regenerative braking.

We will denote by P_+ the phase for which the maximum positive voltage drop is achieved and by P_- the phase for which the maximum negative voltage drop is achieved.

For a period the motor operates in short-circuit, by controlling the switching device (the transistor that we will denote by T_+) placed on the bottom arm of the converter which is connected to P_+. Through T_+ and respectively through the anti-parallel diode corresponding to the transistor (T_-) from the bottom arm which is connected to

P_-, a current continuously increasing in time is flowing, as depicted by Fig. 3 [17].

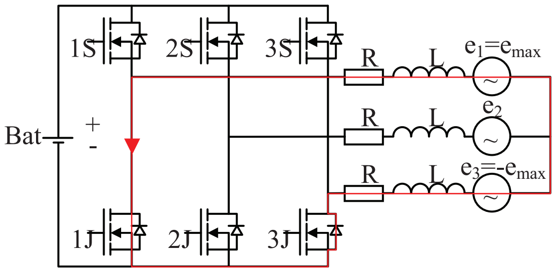

Fig. 3. Current's flowing during the braking process.

In this way, a certain amount of energy is stored in the motor's inductivity. After a while, the transistor from the bottom arm is blocked. From this moment, the energy stored in inductivity results into a voltage increase which in turn forces the current to flow toward the battery through the anti-parallel diodes from the bottom and top arms of the P+ and P-, as depicted by Fig. 4.

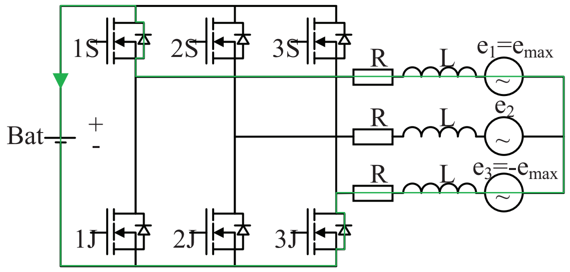

Fig. 4. Current's flowing during the process of energy recovering.

In order to control the braking torque, the PWM filling factor is modified. This makes possible the switching between energy recovering and braking.

IV. SIMULATION RESULTS

We used the simulator described above to perform simulations concerning the regenerative braking at a scooter characterized by the following parameters:

- maximum velocity	45 km/h;
- rated power of motor	1 kW;
- motor speed	600 rot/min;
- motor rated current	25,1 A;
- battery voltage	48 V;
- wheel diameter	400 mm;
- total maximum weight	200 kg.

Figs. 5-11 depict the waveforms corresponding to various quantities which present interest for the studied case, at the beginning or ending of the braking process, considering a filling factor equal to 70%.

Other simulations were performed for various values of the filling factor. Fig. 12 depicts the values of recovered energy when the speed was reduced from 45 km/h up to 20 km/h.

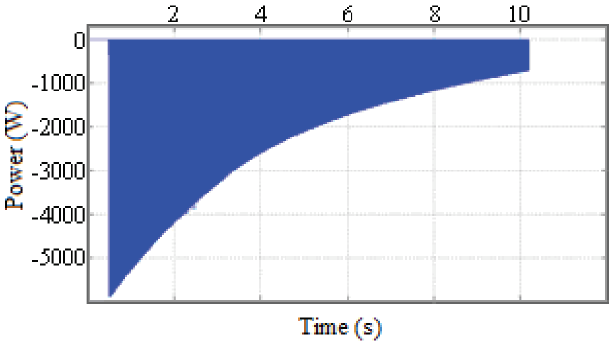

Fig. 5. Power recovered during the braking process.

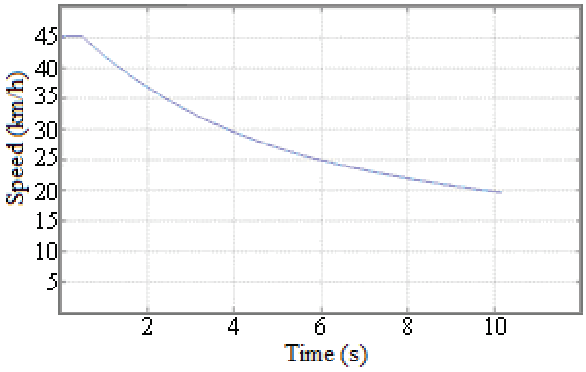

Fig. 6. Speed variation during the braking process.

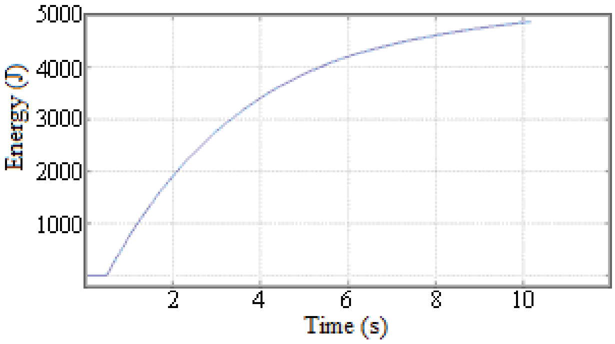

Fig. 7. Variation of recovered energy during the braking process.

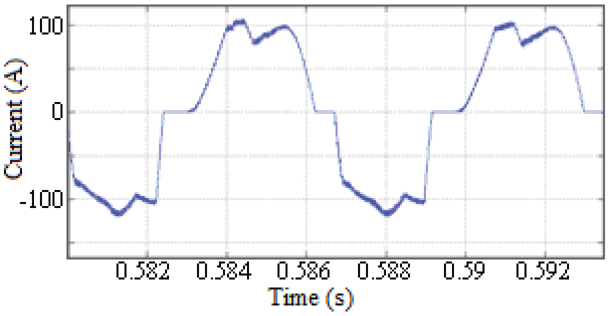

Fig. 8. Motor's phase current at the beginning of the braking process.

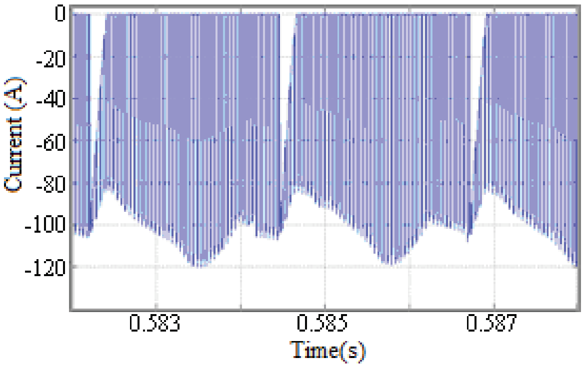

Fig. 9. Current injected into the source at the beginning of the braking process.

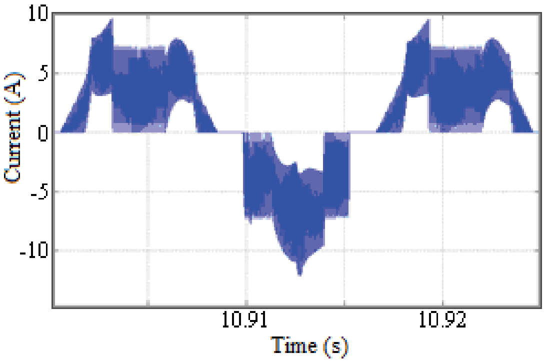

Fig. 10. Motor’s phase current at the end of the braking process

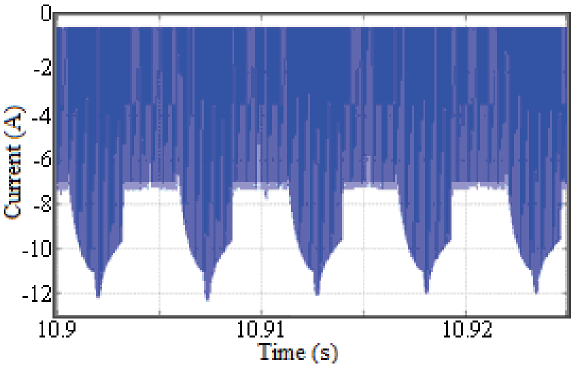

Fig. 11. Current injected into the source at the end of the braking process.

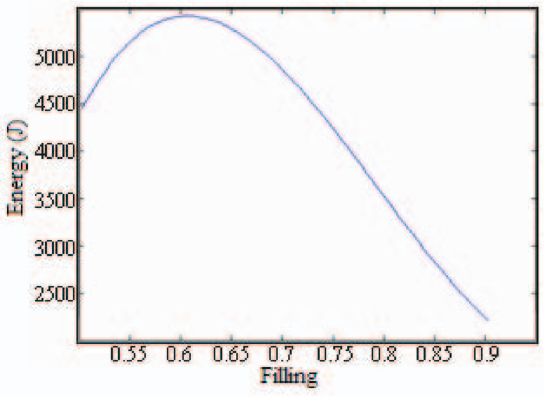

Fig.12. Influence of filling factor over the recovered energy.

V. CONCLUSIONS

Considering the variation of the recovered energy with the filling factor, the simulations revealed an increase of this energy up to a certain value when the factor in increased at the beginning of the variation range, followed by the recovered energy decrease for higher values of this factor. The phenomena responsible for the variation of the recovered energy with the filling factor can be resumed as follows:

- For high filling factors, the switching devices from the bottom arms of the three-phase bridge are forced to remain in conduction for a long time. In this period, the motor operates in short-circuit and dissipates energy along the circuit’s resistances (e.g. along the motor’s windings resistances, along the electronic components' resistances etc.). The dissipated energy is unrecoverable.
- For low filling factors, owing to the small time corresponding to the operation in short-circuit, the current is slightly increasing, resulting in a small increase of the energy stored in the circuit’s inductivities. Accordingly there is obtained a reduced value of the self-induction voltage which appears at the transistor’s blocking and forces the flowing of current toward the battery. In this situation the braking effect is reduced, the brake requires a longer time and consequently a longer distance. The braking effect is mainly caused by the dried and viscous braking from the system.
- There is an optimum value of the filling factor, for which the recovered energy reaches its maximum value.

For the studied scooter, the reducing of speed from 45 km/h (corresponding to a kinetic energy of 15625 J) up to a speed of 20 km/h (corresponding to a kinetic energy of 3086 J) is reflected in a maximum recovered energy of 5430 J (35% from the total energy stored as kinetic energy by the moving scooter with a maximum weight, respectively 43% from difference between the scooter’s initial and final kinetic energies respectively).

In an ideal case, the control should be improved such as to become optimal in the sense of providing a maximization of the recovered energy.

In practice other factors related to the braking process (e.g. its duration or the distance between the braking process's starting and ending points) should be considered as well. In order to consider them, additional restrictions are to be imposed or the type of the approach should be changed (the control's designer should deal with a multi-criteria decision problem).

Moreover, additional measures must be taken in order to prevent the overcoming of certain limits specific to the equipment (e.g. the motor’s overheating because of the current's raising or the battery capacity to take over the corresponding peaks of power).

A parameter influencing the recovered energy is the final speed, but it cannot be known at the moment when the braking is initiated. Estimations can be done (e.g. those relying on the driver’s personality [9]) but the control algorithm’s complexity is increased accordingly.

At small speeds the braking efficiency is low (the deceleration is small) and therefore an additional system with mechanical braking must be used.

ACKNOWLEDGMENT

This work was supported by the grant number P09004/1373/31.03.2014, cod SMIS 50140, entitled: Industrial research and experimental development vehicles driven by brushless electric motors supplied by lithium-ion accumulators for people transport - GENTLE ELECTRIC.

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