COMBINED REGENERATIVE AND MECHANICAL BRAKING IN ELECTRIC VEHICLE

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***Abstract*—Regenerative braking in electric vehicles involves a storage element, such as supercapacitor, which can store energy peaks generated by braking. This article describes the development of an experimental prototype of a system that simulates an electric vehicle induction motor using a supercapacitor bank for supplying and storing energy. The system allows carrying out the study of power supplied to the vehicle, causing acceleration, and recovered from it during the deceleration. Tests were performed to find best ways to recover the kinetic energy in regenerative braking, aiming more efficiency. The proposed system can work together with mechanical braking for low speeds, high deceleration or emergencies, keeping the braking performance.**

Keywords—Regenerative Braking, Supercapacitors, Energy Recovery, Simulation

I. INTRODUCTION

One of the problems associated with electric vehicles (EV) is their relatively low autonomy when powered only by batteries. Furthermore, especially in urban routes, the number of procedures of acceleration and braking is very large, which leads to peaks of power in both processes. It is known that a better battery performance, regarding the yield and the lifetime, requires that such peaks are limited [1].

In order to do not compromise the expected performance of EVs, one can use other stored energy devices, such as supercapacitors (SC) [2], which can be applied to minimize power peaks on batteries, becoming them responsible only for the average demand. As well known, the capacity of batteries to absorb the high energy recovered is limited, so the SC bank plays a key role in the kinetic energy recovery available for the EV [3,4].

As part of the study, we modeled and simulated an EV of our experimental system, focusing on aspects of electrical and mechanical braking.

Regenerative braking is a system that utilizes the mechanical energy from the motor by converting kinetic energy into electrical energy and fed back to the sources of energy.

For that, we study the behavior of regenerative braking (RB) power, based on an EV with three-phase induction motor driven by a variable frequency inverter. The combined action of mechanical and electric brake is proposed as a means of minimizing the inefficiency and poor controllability of RB at low speeds, ensuring the expected behavior for the slowdown.

Our study employs an experimental prototype that simulates an electric vehicle powered only by supercapacitors. We measured the regenerative energy during regenerative braking stage. This experimental system can be used in a real vehicle for decelerations at low speed (or motor frequencies), where the vehicle cannot be completely controlled.

II. REGENERATIVE BRAKING SYSTEM

The use of regenerative braking aims recovering the kinetic energy lost during braking and reducing the mechanical brake wear. In an electric vehicle, when the speed is reduced, the electric machine can operate as a generator. Such process depends on the topology and on the control applied to power electronic converter that drives the electric machine.

Figure 1 shows one possible configuration of sources and converters. The DC/DC converters are bidirectional in current and keep up an adequate voltage sources level (batteries and SC) to feed the DC link converter that drives the motor. Therefore, during the braking stage the power flow is from the electric machine to the sources. The management system must ensure that power flow will be directed to the SC, since the recovery process of charging the batteries is slow and has higher losses [5].

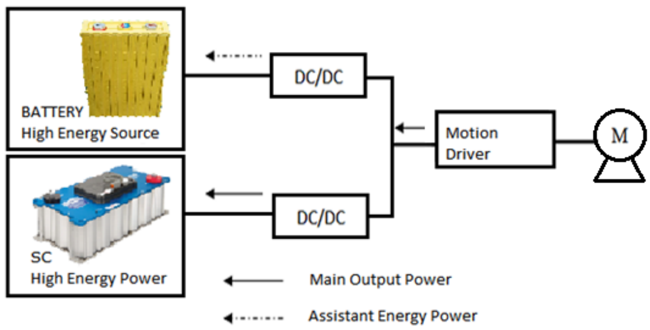

Fig. 1. Power flow in the vehicle in the RB stage.

Supercapacitors are characterized by the capacity to supply high peak power, which is to say, to support high currents. In that apparatus, the accumulated energy is low in comparison with what is possible with batteries [6,7]. The use of both sources is necessary to get a high range performance in a EV.

Figure 2 presents the main components of the experimental bench that emulates a EV, allowing us to perform experimental tests to study the braking system both in the stages of electric regenerative braking and the mechanical brake along the decelerations. Block A shows a brake disk and caliper for front brake that it is applied by a hydro-pneumatic control valve, to simulate a braking pedal force; Block B shows a SC bank that is connected in DC link the inverter; Block C shows an induction motor and a speed reducer, being connected its axis a front wheel that represent the inertia of quarter of a vehicle. The vehicle chosen is a four passengers, 1000 cc, and common in Brazilian market.

Fig. 2. Workbench, (A) Caliper front brake, (B) SC bank and (C) font wheel prototype of the vehicle.

Figure 3 shows the scheme of the braking system based in our experimental prototype of a EV. As can be seen, it is powered by an inverter and supplied SC bank. The system integrates the electric brake with the mechanical brake. After receiving the brake command, the inverter reduces the synthesized frequency so that the slip of the motor becomes negative to act as a generator. The energy removed from the vehicle refers to the reduction of kinetic energy, and thus velocity, once the mass is fixed.

The power required for acceleration of a vehicle is lower than for braking. The vehicle project presupposes a certain speed variation in a given time interval, which, in first approximation, determines the torque and maximum power requirement. The braking process lasts usually much less time than for acceleration, which implies a higher peak power.

When braking is purely mechanical, the energy removed from the mass in motion is converted into heat. Using RB the energy flows back into the converters and sources. In the case of a EV, the engine is also dimensioned to the process of acceleration and cruising (constant speed operation) [8].

During braking, the convertors can possibly operate in overload. Depending on the need of the driver for braking, this is an acceptable procedure, provided there are protection devices that prevent an exaggerated elevation of temperature. But beyond a determined limit of power, the motor has to be connected to electronic converters that handle that power. Typically the ability to support overloading of an electronic circuit is less than of an electromagnetic device, such as the motor. The overload capacity of short-term (a few seconds) of electronic converters have to be respected at risk of destruction.

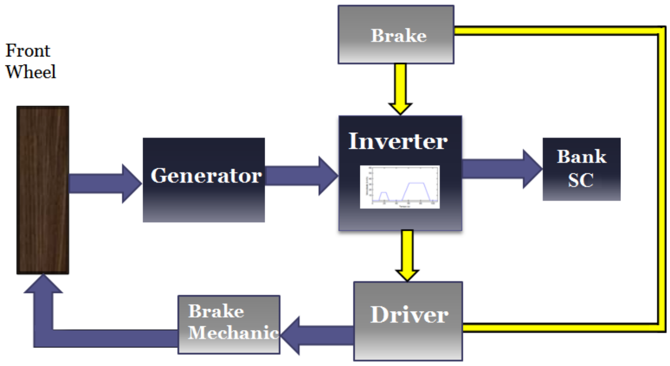

Fig. 3. Regenerative Brake System with SC Bank.

Whenever the demanded deceleration by the driver produces a current value that is not supportable by the converters, it is necessary concomitant use of mechanical brake. There is also the issue about the passenger safety, if the electrical system does not work properly in braking, the deceleration will not be the expected [3].

Figure 4 shows the flow diagram and the regenerative braking strategy that will act at low speeds for our system. From the defined deceleration applied by the driver (brake pedal), a command to reduce the frequency of the inverter is generated, which causes the motor to operate as a generator. If the power or the resulting current is excessive for the converters, a braking torque additional is provided by the mechanical brake.

As will be seen in sequence, at low speed (which is to say at low frequency inverter output), the electromagnetic torque resulting in electrical machine begins to show strong oscillations, which affect the braking procedure, besides causing discomfort to the user. Therefore, in such condition regenerative braking is disabled and the vehicle speed reduction happens exclusively by mechanical braking.

III. STUDY OF BRAKING

The parameters are based on a small vehicle, driven by a three-phase induction motor of 60 cv, 4 poles, and a gearbox 1:2.5. The total inertia on the motor shaft is 6.83 kg.m^2.

Computational modeling allows better understanding of the process applied to regenerative braking for electric vehicles with induction motors. We performed simulations of an electric vehicle using Matlab/Simulink, aiming at studying the braking process, as shown in Figure 5.

The Block A shows the generation of the reference speed to be applied to the inverter. Block B is related to the mechanical braking to be applied at the decelerations: the mechanical torque will act in accordance to the strategies of control showed in Figure 4. Block C shows the vehicle dynamic behavior, with measurements of torque and motor speed. It also includes parameters related to the friction between tire and ground.

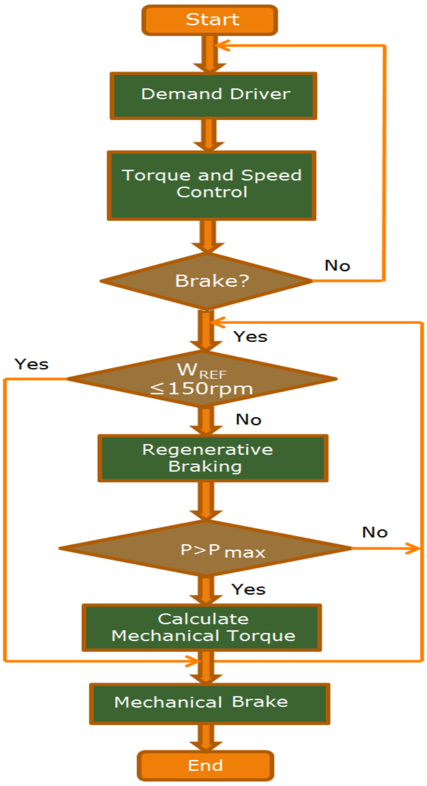

Fig. 4. Flow diagram of the algorithm for braking

The friction coefficient (μ) is given by equation (1). It is defined from the normal force (F_N), generated by a proportional valve which relates the control voltage to the pressure of the pads on the brake disc , and from the friction force (F_F), measured using a torquimeter, that generates a voltage proportional to the torque caused by braking [9,10].

$$\mu = \frac{F_F}{F_N} \tag{1}$$

Figure 5 explains the Block A of Figure 6. It shows the generation of the frequency reference (speed reference) to be sent to the inverter. V_{REF} is the desired speed, while ω_m is the motor measured speed. The torque required to equalize the speeds is determined through a PI compensator. From that torque, considering the moment of inertia of the system and the electromagnetic torque of the motor, it is determined the reference to the inverter [11].

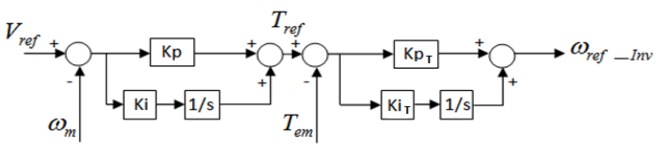

Fig. 5. Generation of the inverter reference speed (frequency)

$$T_{ref} = K_i \int (V_{ref} - \omega_m)dt + K_p(V_{ref} - \omega_m) \tag{2}$$

$$J\ \dot{\omega}_{ref\_Inv} + B.\omega_{ref\_Inv} = T_{ref} - T_{em} \tag{3}$$

A. Definition of Speeds

The following values are representative of the urban application of a conventional vehicle. Situations are studied with the following velocities in the wheels:

- Level 1: 35 km/h or 323 rpm
- Level 2: 50 km/h or 461 rpm
- Level 3: 65 km/h or 600 rpm

Taken a small vehicle, the decelerations do not exceed $5m/s^2$. The usual deceleration rate for passenger vehicles using mechanical brakes are:

- Level 1: $1.5\ m/s^2$ or low
- Level 2: $2.5\ m/s^2$ or medium
- Level 3: $3.5\ m/s^2$ or high

The above values where considered in the simulations and experimental tests of this work.

As the objective is to combine the use of electric and mechanical braking, it is necessary to characterize the mechanical braking system. The equation 4 shows the relationship between the necessary normal force applied to the caliper and the deceleration rate.

$$F_N = \frac{J_W * Deceleration}{2 * D_R * T_R * \mu} \tag{4}$$

In above equations, K_{pT} is proportional to the friction coefficient for the pads and disk and K_{iT} is proportional (inversely) to the moment of inertia.

TABLE I
Wheel Parameters

Tire Radio (T_R)	0.2876	m
Wheel Inertia (J_W)	38.3	kg/m²
µ	0.35	adm.
Disk Radio (D_R)	0.095	m
EV Mass	1317	kg

The following values of supercapacitors were used in workbench.

TABLE II
Supercapacitors Details

MODULES	MAXWELL	EPCOS
Nominal Capacitance	165 F	150 F
Rated Voltage	48 VDC	42 VDC

Figure 7 shows the normal force applied by the mechanical brake and the respective deceleration values.

As the mechanical brake is commanded by a voltage controlled proportional hydraulic valve, it is necessary to know the relationship between the input voltage and the applied force.

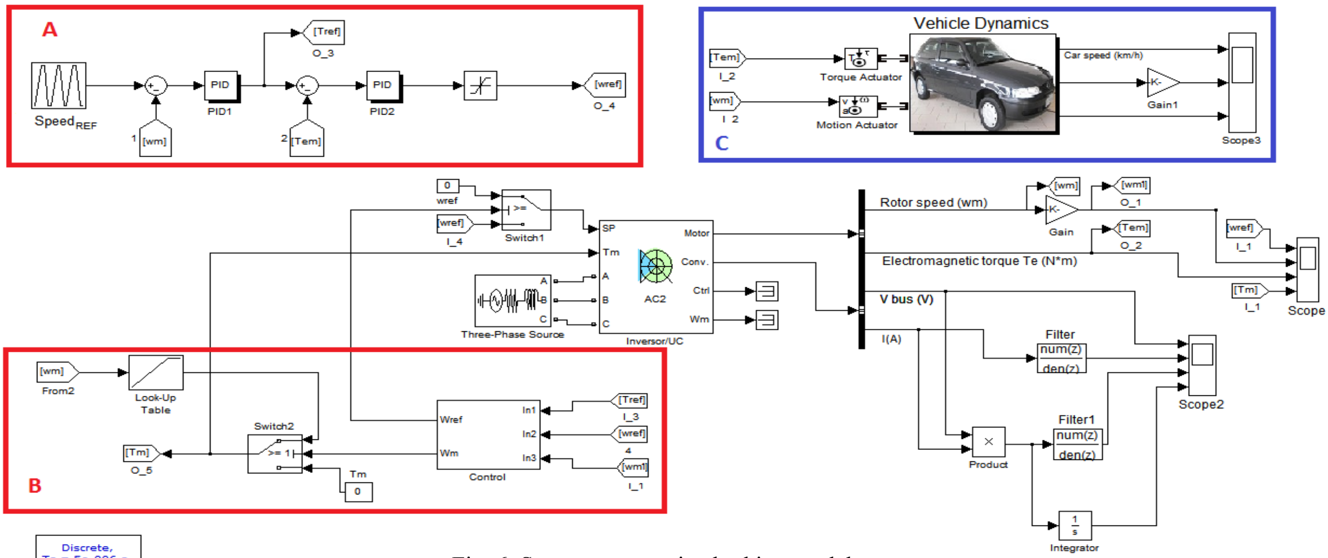

Fig. 6. Stages regenerative braking model

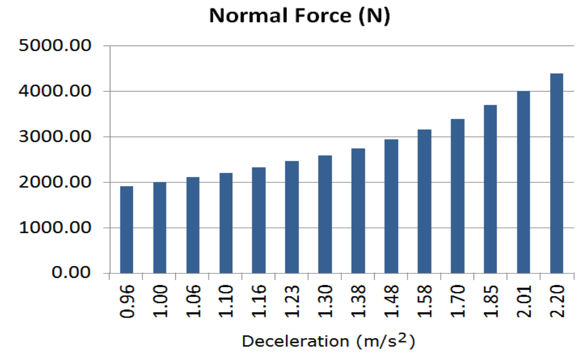

Fig.7. Normal Force applied to the Brake Caliper

IV. RESULTS

A. Simulaion: study without mechanical brake

Defining a deceleration ramp for the inverter results a constant electromagnetic torque in the generator. Using only the electrical brake the kinetic energy will be converted in electricity and absorbed by the motor drive and dissipated according to the circuit losses.

As shown in Figure 8 in circle 1, the torque produces oscillations in the started. However, in the circle 2 the torque produced by the induction machine presents high oscillations in the low speed range during both, starting and stopping. This behavior is due to the voltage/frequency control of the inverter, without current control. The slow acceleration minimizes the effect on the start, but not in the braking.

For these simulations the only power source is the 17 F SC bank, previously charged to its nominal voltage (320 V).

B. Simulation: study with the use of mechanical brake

According to the procedure described in Figure 4, when the speed reaches a low value during braking, the kinetic energy is very small and, in practice, the available energy is very low. So, disabling the electrical braking and substituting it by the mechanical one allows conducting the EV until the complete stop, maintaining constant torque. Figure 9 shows these results.

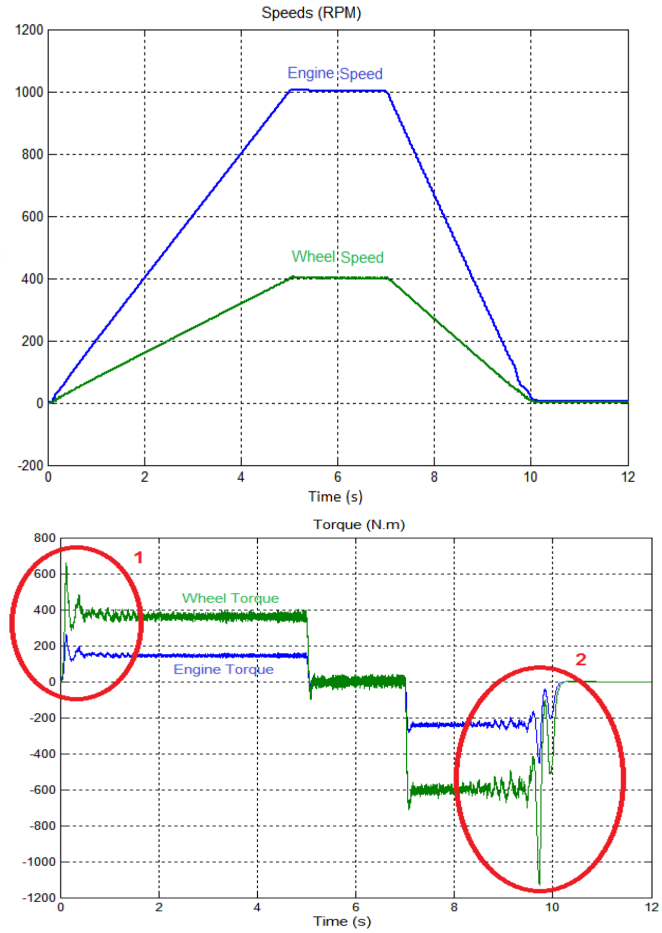

Fig. 8. Driving simulation without mechanical brake.

Figure 10 shows the power in the bank of supercapacitors. This power is calculated multiplying the average current in the SC bank by its voltage. Due to the system losses (electrical, friction and aerodynamic), the recoverable energy is always lower than the consumed power. Note that when the electric brake system is disconnected, power recovered already is practically zero. During cruise, the consumed power is low, the necessary for compensating the losses (friction and aerodynamic).

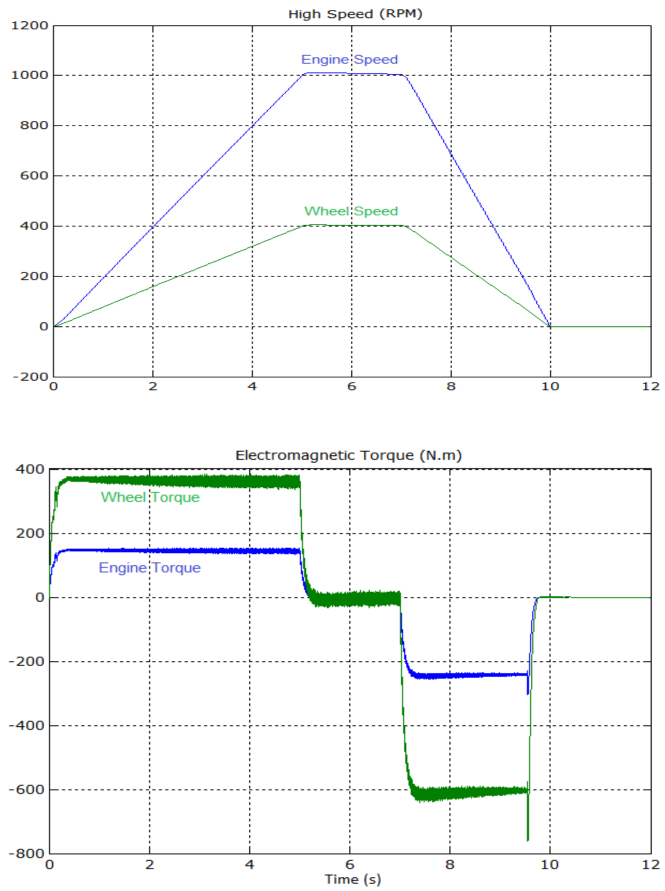

Fig. 9. Driving simulation with complementary mechanical brake at low speed.

Table III summarizes the data regarding this simulation. As the driving cycle is short and the cruise speed is high, the corresponding kinetic energy is high, allowing a 50% energy recovering.

TABLE III

Electrical quantities for driving cycle for 1000 rpm

Peak Power	18 kW
Peak Current	55 A
SC Initial Voltage	320 V
SC Final Voltage	315 V
Supplied Energy	50 kJ
Recovered Energy	25 kJ

C. Experimental results

These tests were carried out in the workbench shown in Figure 2 (Railway Laboratory), with the parameters indicated in section II [14].

Figure 11 shows driving cycles with two deceleration times, 10s and 12s. The deceleration time is a parameter that can be programmable in the inverter available in the laboratory.

In these tests the motor cruise is 900 rpm. Using only electrical brake, at low speed, as the power regeneration doesn't occur, the deceleration changes and the final stop depends on the system friction losses.

Figure 12 shows different cruise situations, thus changing the initial kinetic energy, maintaining the deceleration.

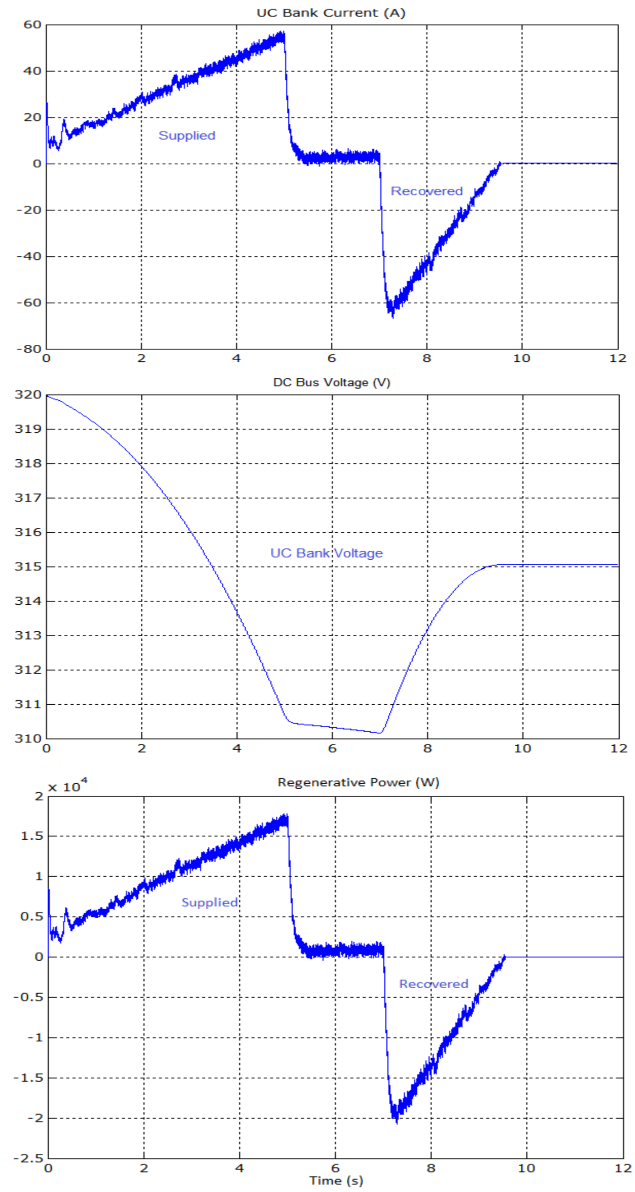

Fig. 10. Current, Voltage and Power during the driving cycle

Figure 13 shows the power in the SC bank. During acceleration and cruise the power is positive and, in the braking period, it becomes negative, recovering energy to the SC. The final part of the braking procedure is made by the mechanical brake. Note that the regenerative effect stops before the effective stop of the EV. The applied force to the caliper is regulated to permit the same torque and the same deceleration. The results obtained are in the Table IV. Even with lower cruise speed, the consumed energy is high due to the longer cycle.

TABLE IV

Electrical quantities for driving cycle for 400 rpm

Peak Power	18 kW
Peak Current	65 A
Initial Voltage SC	320 V
Final Voltage SC	314 V
Supplied Energy	70 kJ
Recovered Energy	20 kJ

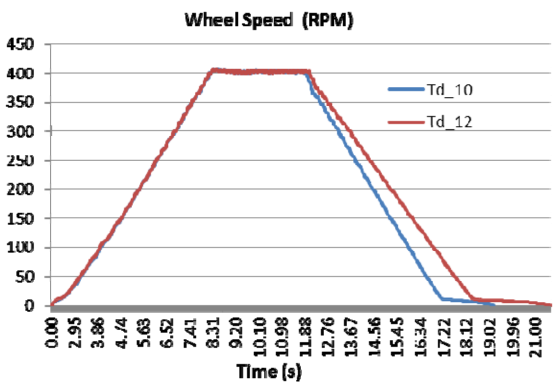

Fig. 11. Experimental tests without mechanical brake.

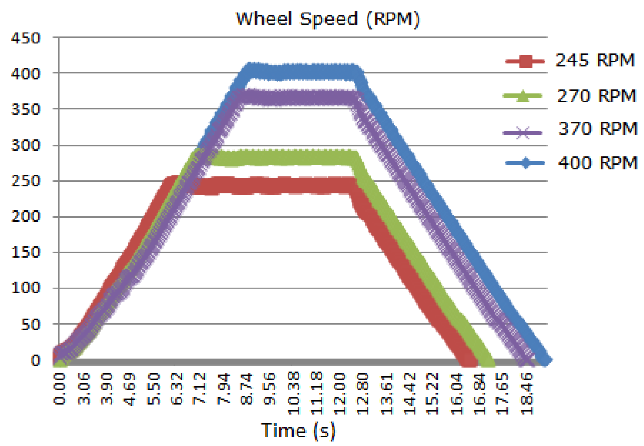

Fig. 12. Driving cycles with different cruise and same deceleration.

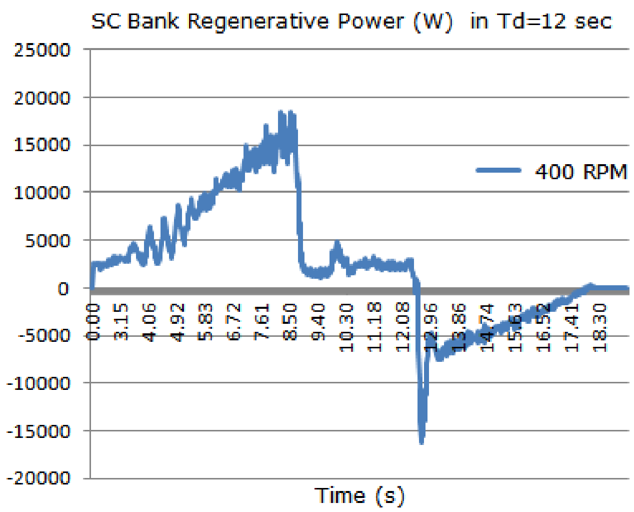

Fig. 13. Power in the SC bank during driving cycle.

D. *Simulation: Combined electrical and mechanical braking*

The next simulation combines, simultaneously, electrical and mechanical brakes. In this case, the braking command determines a deceleration that results 200 N.m torque. While the regenerative brake produces such value, the mechanical system doesn't operate. As the electrical torque decreases, a complementary torque is provided by the mechanical part, thus maintaining the desired behavior. Figure 14 shows the simulation results.

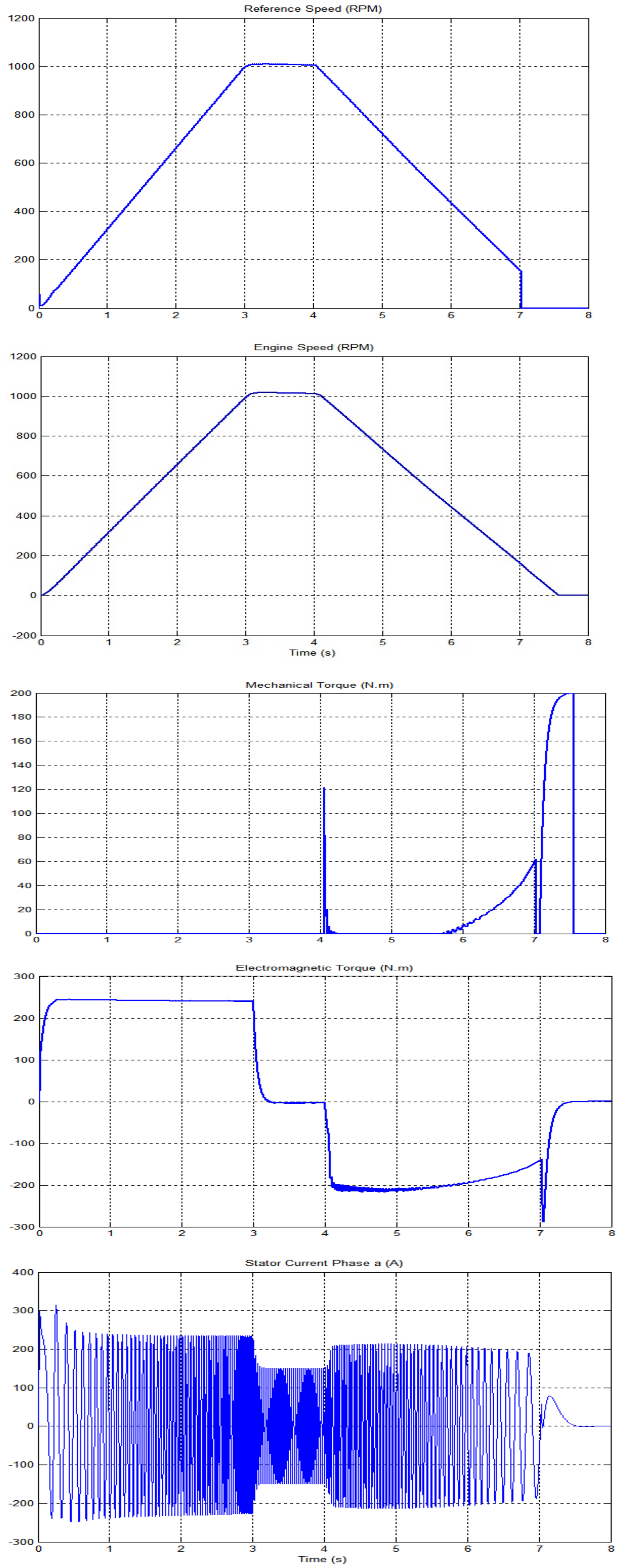

Fig. 14. Combined electrical and mechanical brakes. From the top: Reference signal for the motor; motor speed; machanical brake torque; electromagnetic torque; induction motor current.

TABLE V
Electrical Quantities for Driving Cycle

Peak Power	28 kW
Peak Current	96 A
SC Initial Voltage	320 V
SC Final Voltage	315 V
Supplied Energy	45 kJ
Recovered Energy	27 kJ

V. CONCLUSIONS

This paper has discussed the procedure of regenerative braking of electric vehicles. The EV studied is a light, passenger, urban use vehicle, driven by an induction motor. The recovered energy is absorbed by a supercapacitor bank.

The results point out the necessary combined use of electrical and mechanical braking. The reasons are the electromagnetic torque oscillation in low speed, the requested braking torque higher than the power absorption capacity of the electric source (including the converters) and emergency situations. Below a certain speed limit, when the kinetic energy is already very low, it is proposed to use mechanical braking, ensuring the desired braking torque.

The combination of electrical and mechanical brakes must result a deceleration that complies with the input command given by the driver through the brake pedal.

Simulations and experimental results confirm the expectations and indicate the feasibility of such combined action of both brake systems.

Energy recovery is directly related to the kinetic energy in the beginning of braking and therefore depends on the driving cycle considered. Energy consumption related to aerodynamic losses, friction in general and electrical losses in the system starter, obviously, cannot be recovered.

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REFERENCES

[1] Battery University, Basics about Discharging [Available in http://batteryuniversity.com/learn/article/discharge_methods] 2012.

[2] S. Pay; Y. Baghzouz, "Effectiveness of battery-supercapacitor combination in electric vehicles", *IEEE Power Tech Conference Proceedings*, Bologna 23-26 June 2003

[3] A. A. Ferreira, J. A. Pomilio, G. Spiazzi e L. de Araujo Silva,: "Energy Management Fuzzy Logic Supervisory for Electric Vehicle Power Supplies System*", IEEE Transactions on Power Electronics*, Volume 23, Issue 1, Jan. 2008 pp. 107 – 115

[4] G. Giuseppe; "*Energy Management Systems on Board of Electric Vehicle, based on Power Electronics*". 2009. Ph.D. Dissertation, – Faculty of Information Technology, Mathematics and Electrical Engineering, Norwegian University of Science and Technology – Trondheim, Norway.

[5] L. Solero; A. Lidozzi; J.A Pomilio: "Design of multiple-input power converter for hybrid vehicles", *IEEE Transactions on Power Electronics*, Vol. 20, No. 5, Sept. 2005 Page(s):1007 – 1016

[6] M.K Yoong; Y.H Gan; G.D Gan; C.K Leong; Z.Y Phuan; B.K Cheah; K.W Chew, "Studies of Regenerative Braking in Electric Vehicle", *Proc. of IEEE Conference on Sustainable Utilization and Development in Engineering and Technology*, 2010.

[7] F. S. Garcia, A. A. Ferreira, J. A. Pomilio, "Control Strategy for Battery-Ultracapacitor Hybrid Energy Storage System", *Proc. of 24th IEEE Applied Power Electronics Conference – APEC 2009*, Washington – DC, USA, Feb. 2009, pp. 826-832.

[8] A. Burke, "Ultracapacitors: why, how, and where is the technology,", *Journal of Power Sources*, Vol. 91, Issue 1, November 2000, Page(s): 37 – 50

[9] A. H. C. Santos, "*A contribution to the study of friction brakes for application in regenerative braking*" (in Portuguese). Ph.D. Dissertation, – School of Mechanical Engineering, University of Campinas – Brazil, 2009.

[10] M. Ehsani, et AL., *Modern electric, Hybrid Electric, and Fuel Cell Vehicles*, second edition, USA: CRC Press, 2008.

[11] Yu Xiangpeng; Shen Tielong; Li Gangyan; K.Hikiri, "Regenerative Braking Torque Estimation and Control Approaches for a Hybrid Electric Truck ", *Proc. of American Control Conference (ACC)*, 2010.

[12] Yang Jung Do; Ho Kim Young; Wook Kim Sun; Lee Suck-Hyun, "Development of ultracapacitor modules for 42-V automotive electrical systems", *Journal of Power Sources*, Vol. 114, Issue 2, 12 March 2003, Page(s): 366 – 373.

[13] W. Lhomme; P.Delarue; P.Barrade; A.Bouscayrol; A.Rufer, "Design and Control of a Supercapacitor Storage System for Traction Applications*", Proc. of IEEE Industry Applications Society (IAS) Annual Meeting*, 2005.

[14] M. G. S. Perez Paredes, "*Braking Regenerative in Electric Vehicle driven an Induction Motor: Study, Simulation and Implementation*", (in Portuguese) Master Dissertation, FEEC – Unicamp – Brazil, 2013.