ELECTRIC VEHICLE EMULATION BASED ON INERTIAL FLYWHEEL AND A DC MACHINE

EMULACIÓN DE UN VEHÍCULO ELÉCTRICO BASADA EN VOLANTE DE INERCIA Y MÁQUINA DE CD

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ABSTRACT: This paper describes the analysis, modeling, and simulation of an electric vehicle (EV) focused on developing a test bench for reproducing EV dynamics. The EV test bench is composed of an induction motor (IM) drive, which is directly coupled to a dc machine and to an inertial flywheel through a transmission system with bands. The inertial flywheel and the DC machine reproduce the dynamic and forces acting on the EV. A methodology is proposed to design EV test bench to study the EV behavior close to the real test conditions. The EV forces and DC machine analysis can define the different conditions of the EV operation. The modeling and simulation are developed in MATLAB/Simulink, the test bench implemented is controlled by a DSP. Finally, simulation and experimental obtained results can validate the operation of the test bench emulator.

Key words: Electric vehicle, flywheel, model, emulator, DSP, DC machine, induction motor.

RESUMEN: Este artículo describe el análisis, modelado y simulación de un vehículo eléctrico (EV) enfocado al desarrollo de un banco de pruebas para reproducir la dinámica del EV. El banco está formado por un drive de motor de inducción (IM) acoplado directamente a una máquina de DC y a un volante de inercia a través de una transmisión. El volante de inercia y la máquina de DC reproducen la dinámica y las fuerzas que actúan en el vehículo. Se propone una metodología para diseñar un banco de pruebas de EV para estudiar el comportamiento de vehículos eléctricos cercano a las condiciones de operación reales. El análisis de las fuerzas en el EV en conjunto con la máquina DC define las condiciones de operación del EV. El modelado y la simulación son desarrollados en MATLAB/Simulink, el banco de pruebas implementado es controlado por un DSP. Finalmente, los resultados de simulación y experimentales obtenidos validan el funcionamiento del banco de prueba.

Palabras clave: Vehículo Eléctrico (EV), volante, modelo, emulador, DSP, máquina de CD, motor de inducción.

1. INTRODUCTION

Nowadays, worldwide environment contamination due to industrial applications, to transportation and to the strong oil dependence for electrical energy generation, has become a big ecological and health problem [1,2]. Additionally, related to the dependence on oil as a main source of energy, it is important to consider the fact that oil is a non renewable source, which is becoming exhausted worldwide. However, very interesting renewable alternative and clean energy sources are being considered for different applications. A solution for transportation, to solve the oil dependence, is to use electric energy for electric vehicles based on different energy sources such as biodiesel, ethanol, solar, fuel cells, among others, which are replacing the traditional non renewable energies [3-6]. Thus, electric vehicles (EVs) have had a strong development for different required applications, such as cars, scooters, bicycles, hoist, and electrical wheelchairs, among others. These

types of EVs are typically driven by stored electric energy (battery, fuel cell, and ultra-capacitor); however, one of the main EV problems is the short driving range due to the energy storage capacity. So, the way to use storage energy efficiently is an important issue for designing EVs. Recently, researches about the design and implementation of EVs have been developed; some of them have been focused on the efficient way to process energy in order to increase the EV autonomy [7-11]. From the point of view of EV energy management design, a whole analysis of the system, considering the different energy processing elements, it is essential to know how to manage the energy in order to improve the EV performance [8,9,11,12]. Several control techniques are proposed in the literature for adjustable speed drives, trying to improve the dynamic response of speed, torque, and slip ratio output regulation [12-14]. However, studies related to the energy management are not always taken into account. Energy management analysis is an important issue in the development of electric vehicles; it is necessary to understand the relations and interactions of the energy process during acceleration/braking in the different parts of the system. In the above mentioned research some are based on two interesting approaches: simulation by models [13] and experimentation using a test bench of the system [7] in order to correctly describe the operation of the different EV parts. Different approaches have been reported to study the EV behavior; some are based on models of the system and others on test to emulate the behavior of EV by using dynamic loads [15-19]. EV simulation is an interesting method to analyze the behavior, this method is feasible and cheap, but the results obtained depend on the model accuracy to represent the real system; so it is related to the number of parameters considered and consequently the simulation can take a relative long time. The EV test bench can reproduce dynamic conditions close to the real operation behavior of the automobile, but this representation has to be scaled to the real system and the cost is more expensive than the model. These two approaches allow us to propose improvements to the EV system design, from the point of view of energy management by using alternative energy sources associated with efficient energy storage technology, such as batteries, fuel cells, ultracapacitors, flywheel, among others.

The most interesting contributions of this work, with regard to other works from the literature, are: a)

the study of EV systems is based on modeling and experimentation approaches; and b) the test bench includes an inertial flywheel that allows the EV dynamic behavior to be emulated. In this sense, this paper presents the analysis, modeling and Matlab/ Simulink implementation of an EV. Furthermore, the design and experimental implementation of a test bench to emulate a scaled EV. The simulation and experimental obtained results are analyzed based on the energy balance approach.

2. ELECTRIC VEHICLE ANALYSIS

The EV analyzed considers the EV dynamics, the transmission, the source voltage, the control and the induction motor drive, Figure 1. The EV dynamics takes into account all the forces on the EV, and it is possible to observe the behavior under linear or angular acceleration, this behavior is important to compare the EV performance and the rated characteristics of the motor drive. The transmission is represented by a gain relation in order to simplify the system. And finally, the induction motor drive is modeled taking into account the inverter and the induction motor.

2.1. Vehicle Dynamics

The EV model is based on the mechanical and aerodynamical theoretical bases [13]. Figure 2 shows the different forces acting on the EV [4]. The equation (1) describes the EV dynamic, which is defined by the total traction force minus the road load forces acting on the EV.

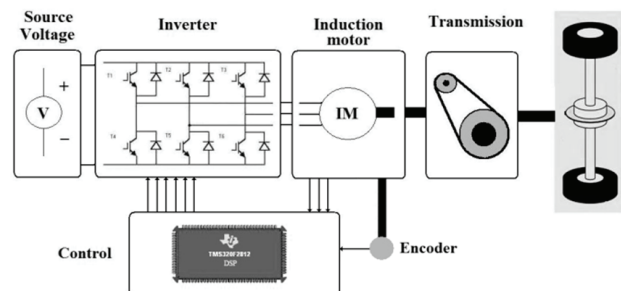$$m\frac{dv}{dt} = F_t - F_g - F_a - F_r \qquad (1)$$

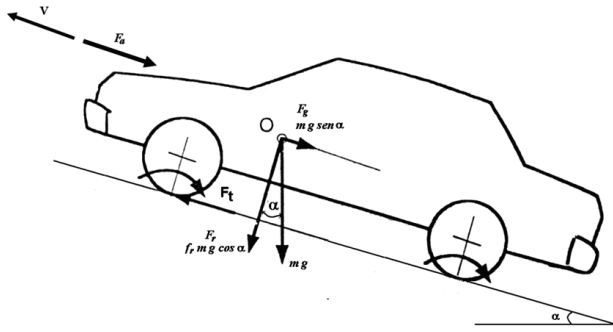**Figure 1**. Block diagram of the EV drive system

Figure 2. Forces acting on the vehicle.

Equations (2) to (4) describe the opposed forces to the movement and the parameters considered for each one.

$$F_r = f_r \, mg \cos \alpha \tag{2}$$

$$F_a = \frac{1}{2} \rho A C v^2 \tag{3}$$

$$F_g = mg \, sen\alpha \tag{4}$$

Therefore, the EV dynamic equation is given by:

$$m \frac{dv}{dt} = F_t - mg \, sen\alpha - \frac{1}{2} \rho A C v^2 - f_r \, mg \cos \alpha \tag{5}$$

2.2. Transmission system

One of the most important issues is the torque imposed to the electric motor. The EV total force (F_t) of equation (5) for linear speed, can be converted to the equivalent motor torque and the angular speed by means of a transmission system (G), Figure 3 shows simplified transmission.

Angular speed (ω) in the electric motor can be related to linear speed (v) of the electric vehicle by (7) through the tire radius (r) and the transmission ratio.

$$\omega = \frac{v}{r} G \tag{6}$$

In the same way, motor torque (τ_t) in the electric motor can be related to the total force (Ft) applied to the electric vehicle by (9) through the tire radius (r) and the transmission ratio (G).

$$\tau_t = \frac{F_t \, r}{G} \tag{7}$$

From (5), the EV dynamic equation (8) can be obtained by introducing the equivalences given in (6) and (7),

which is referred to the shaft of the electric motor. Equation (8) is given in terms of torque and angular speed.

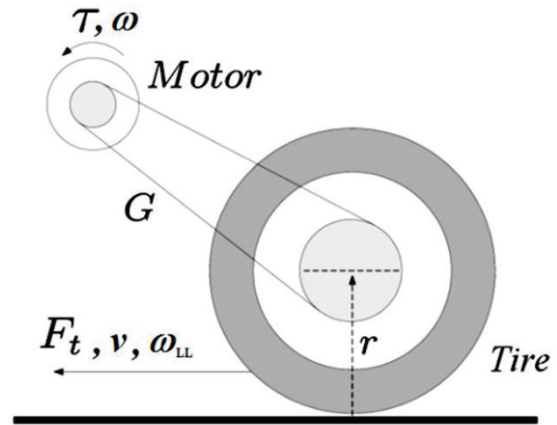$$J \frac{d\omega}{dt} = \tau_t - \tau_g - \tau_a - \tau_r \tag{8}$$

Figure 3. Transmission system of an EV

Hence, the equivalent inertial moment (J) of the total mass of the electric vehicle can be given by (9), also based on the tire radius (r) and the transmission ratio (G).

$$J = \frac{m r^2}{G^2} \tag{9}$$

Also, equivalent expressions of forces acting on the vehicle can be deduced by multiplying by r and divided by G.

2.3. Induction motor drive

Important researches about electric motors have been reported in literature [20,21]; however, the induction motor remains an interesting alternative with a lot of control strategies as proposed in [17]. So, an induction motor drive is developed in this work. The motor drive system consists of an induction motor (IM) and a source voltage inverter with space vector modulation- SVPWM.

The inverter circuit consists of three legs with two current bidirectional switches (IGBT-diode); Figure 4, which is connected to the induction motor by the ABC terminals.
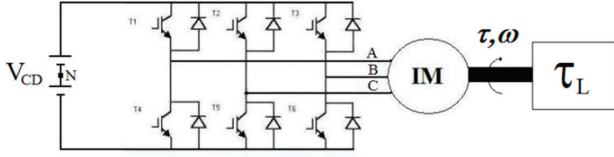
Figure 4. EV drive system.

V_{CD} represents the dc link voltage of the inverter. The three phase voltages needed to supply the induction motor is obtained from ABC output terminals of the inverter and by SVPWM gate signals of the switches (IGBT). A mathematical representation of the inverter is given by (10) [22]. The phase voltages V_{AN}, V_{BN} and V_{CN} are dependent of dc link voltage (V_{CD}) and the modulation signals m_a, m_b and m_c. The modulation signals m_a, m_b and m_c can be only values of 0 or 1, which indicate 0 the switch is opened and for 1 the switch is closed.

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \frac{V_{CD}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} m_a \\ m_b \\ m_c \end{bmatrix} \tag{10}$$

Figure 5 shows the equivalent circuit of a squirrel cage induction motor (IM). The equivalent circuit of the IM is composed of three phases represented by three L-R circuits, for stator and rotor, connected in a Y arrangement.
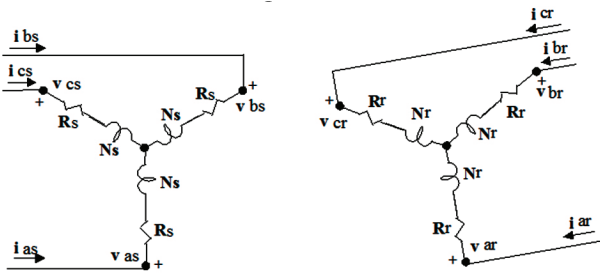

Figure 5. Electric diagram of IM

Each winding produces a magnetic flux, voltages and currents are represented by *as, bs, cs* (stator)*, ar, br* and *cr* (rotor). The angle of the magnetic axes of rotor and stator of the same phase represents the angular position of rotor θ and the angular speed by ω. Figure 5 shows electric diagram of the IM, this diagram is used in order to obtain the mathematical representation of the IM.

Based on the analysis of the electric diagram of IM,

the stator and rotor behavior can be represented by (11) and (12):

$$v_{abcs} = i_{abcs} R_s + \frac{d\lambda_{abcs}}{dt} \tag{11}$$

$$v_{abcr} = i_{abcr} R_r + \frac{d\lambda_{abcr}}{dt} \tag{12}$$

Where the flux linkage λ for a linear magnetic system is defined by (13)

$$\lambda = \mathbf{L}\mathbf{i}, \tag{13}$$

Hence, the relation between the position and angular speed of the rotor is given by expression (14).

$$\frac{d\theta_r}{dt} = n_P \omega_r \tag{14}$$

And the equation (15) represents the electromagnetic torque, which is dependent in the number of poles (P), the stator currents (i_{abcs}).

$$\tau_e = \left(\frac{P}{2}\right)(i_{abcs})^T \frac{\partial}{\partial \theta_r}[L'_{sr}] i'_{abcr} \tag{15}$$

Where:

$$L'_{sr} = L_{ms} \cdot M \tag{16a}$$

$$M = \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r \end{bmatrix} \tag{16b}$$

$$L_{ms} = \frac{N_s^2}{2} \cdot \frac{\pi\mu_0 rl}{g} \tag{16c}$$

The electromagnetic torque is an important parameter to define the power specification of the electric motor in order to achieve the dynamic imposed by the vehicle. If no other torque is considered then $\tau_t = \tau_e$.

The modeling process developed is carried out for each subsystem with the equations (2-4) and (7-16c),

which represent the electric vehicle. The subsystems of the EV are the induction motor, inverter, powertrain of the vehicle, controller strategy, among others, which are implemented in Matlab/simulink in blocks [23-24]. The developed models are implemented with Simulink tools or "S" functions according to the particular requirements of the model. This allows the subsystem models to be used in other applications. The inter connection of the model subsystems is possible by defining the input and output variables for each subsystem; for example the model of the electric vehicle and the induction motor (IM) is connected by the electromagnetic torque ($\tau_t = \tau_e$). The three phase power supply of the IM is generated by a mathematical function given by (10), which consider voltage level V_{CD} that represents the storage system, such as batteries.

3. TEST BENCH OF EV EMULATOR

The design methodology of the test bench has been focused on the reproduction of the EV dynamics close to the real application. Two approaches of analysis have been taken into account in this methodology: a) the simulation of an EV by the implementation of a mathematical model and b) an experimental way using a test bench implementation, which is controlled by a Digital Signal Processor (DSP). The EV model developed is close to the real application with a great flexibility to modify all the parameters of the EV. However, in spite of having a test bench close to the real application, the parameters to be changed are limited by the natural configuration of the test bench. However, flexibility of variation is possible in the moment of inertia (J), variation of the equivalent forces acting on the EV (represented by torques) and also the flexibility to investigate different types of control strategies. Once the analysis of the dynamic movement of the electric vehicle has been defined, the EV test bench can be designed from the mathematical representation obtained, Figure 6.

Based on the equation (8) the dynamic of movement of the EV can be emulated by the proposed test bench, which is composed of an inertial flywheel and a DC machine. The flywheel can emulate the dynamic behavior of the EV through the moment of inertia (J), which represents the equivalence of the mass of the EV. The forces acting on the EV (F_g, F_a and F_r) are represented by the equivalent torques referred to the motor shaft (τ_g, τ_a and τ_r)

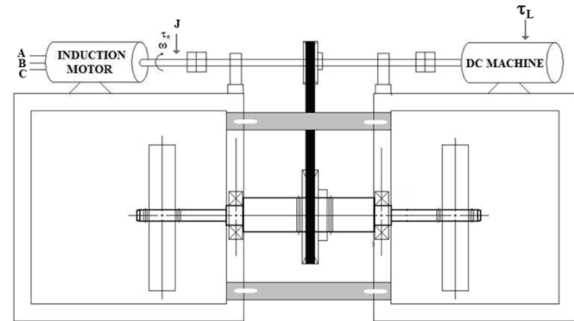$$J\frac{d\omega}{dt} = \tau_t - \tau_g - \tau_a - \tau_r \qquad (17)$$

Figure 6. EV test bench

In order to achieve the emulation of the EV by the proposed test bench, some considerations have to be taken into account:

a) A transmission ratio (G) has to be included to have a relation of angular speed-torque in the IM to the EV tires. It is possible with two pulleys in the IM shaft and the tires shaft, which are interconnected by a transmission band.

b) The moment of inertia and the torques have to be affected by a scaling factor (Rt) in order to reproduce the dynamic of a particular EV of interest. This can be defined by the rates of the motor power, the EV of interest and the motor of the test bench.

$$\frac{P_{m2}}{P_m} = Rt \qquad (18)$$

The torque emulation is possible using the DC machine. Firstly, it is necessary to identify the different terms from the dynamic equation (8) of the EV. Secondly, the dc machine model is analyzed to define the parameters to be controlled in order to match torques defining the forces acting on the EV. The torques can be emulated with the dc machine operating as a generator with a separate dc power supply to the field windings. A load has to be designed in order to emulate the different torques desired.

1) Torque due to the road resistance force (τ_g)

This torque can be emulated by the dc machine, as it can be seen, this kind of torque is a constant value depending only of constant coefficients.

Vehicule	Test bench
$\dfrac{JGg\sin\alpha}{r}$	$\dfrac{JGg\sin\alpha}{r}(Rt)$

2) Torque due to the aerodynamic resistance force (τa)

This kind of torque is dependent on the angular speed (ω) or linear speed and also can be emulated by the dc machine.

Vehicle	Test bench
$\dfrac{\rho A Cr^3\omega^3}{2G^3}$	$\dfrac{\rho A Cr^3\omega^3}{2G^3}(Rt)$

3) Torque due to the rolling resistance force (τr).

This torque is defined by constant parameters and is easily emulated by a dc machine, it depends on the angle (α), if α is constant, this torque remain constant too.

Vehicle	Test bench
$\dfrac{JGgf_r\cos\alpha}{r}$	$\dfrac{JGgf_r\cos\alpha}{r}(Rt)$

Analysis and design of torques

In order to correctly emulate the above mentioned torques, it is important to consider the DC machine model. So the torque of the dc machine (τ_L) has to be equal to the torques due to the forces acting on the EV (τ_g, τ_a and τ_r). Therefore:

$$\tau_L = \left[\frac{JGg\sin\alpha}{r} + \frac{\rho A Cr^3\omega^2}{2G^3} + \frac{JGgf_r\cos\alpha}{r}\right](Rt) \quad (19)$$

In order to simplify (19) a substitution can be made. Hence,

$$\tau_L = Y\sin\alpha + Z\cos\alpha + X\omega^2 \quad (20)$$

where:
$$\frac{JGg(Rt)}{r} = Y \;,\; \frac{\rho A Cr^3}{2G^3}(Rt) = X \;,\; \frac{JGgf_r}{r}(Rt) = Z \;.$$

The DC machine torque (τ_L) is given by (21),

$$\tau_L = L_{af}I_F I_{ar} \quad (21)$$

But considering L_{af} and I_F as constants, then (21) can be simplified replaced by (22),

$$\tau_L = KI_{ar} \quad (22)$$

Equations (20) and (22) are equaled and I_{ar} is given by,

$$I_{ar} = \frac{Y\sin a + Z\cos a + X\omega^2}{K} \quad (23)$$

In equation (23), the current I_{ar} is the parameter that can be adjusted for defining the three terms of the left side of the expression (23). However, (23) has two constant terms that can be reduced to one constant term and the other term depends on the angular speed (ω).

The term I_{ar} can be adjusted using a commutation (converter with current input). Figure 7 shows the proposed circuit configuration. According to the circuit of Figure 7, the following analysis can be done in order to define I_{ar}. Two parameters are introduce R_{load} and duty cycle D

$$I_{load} = I_{ar}(1-D) \quad (24)$$

$$V_a = R_{load}\,I_{ar}(1-D) \quad (25)$$

$$I_{ar} = \frac{V_a}{R_{load}(1-D)} \quad (26)$$

The armature voltage can be given by (27), under constant excitation and considering the armature resistance r_a to be negligible.

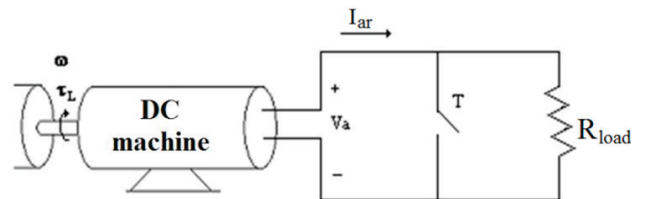$$V_a = K\,\omega \quad (27)$$

Figure 7. Circuit proposed to emulate the EV forces.

By substituting (27) in (23), the expression (28) can

be obtained. It is interesting to carry out an analysis in order to optimize the R_{load} value and the modulation of duty cycle D by defining a signal reference for D.

$$I_{ar} = \frac{K\,\omega}{R_{load}\,(1-D)} = \frac{Ysen\alpha + Z\cos\alpha + X\,\omega^2}{K} \quad (28)$$

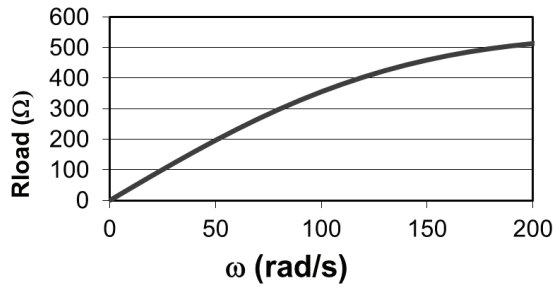$$\therefore R_{load} = \frac{K^2\,\omega}{\left(Ysen\alpha + Z\cos\alpha + X\,\omega^2\right)(1-D)} \quad (29)$$

Figure 8. Simulation result for R_{load} behavior versus angular speed (ω) for $D=0$

Figure 8 shows a simulation varying R_{load} with $D=0$. This situation is a limiting condition and the current only depends on the R_{load} and the angular speed with constant parameters of the EV. The R_{load} value is selected to be a value within the rated characteristics of the dc machine (voltage and power). In a practical implementation, R_{load} cannot vary continuously. For this reason R_{load} is defined to be 500 Ω. This value allows the angular speed to be varied from zero beyond the nominal speed (Figure 9). This R_{load} only depends on angular speed and the electric vehicle parameters. Equation (30) gives the duty cycle (D) as a function of the forces acting on the EV. Equation (30) is obtained from (28) for a given I_{ar}, it is possible to follow the dynamic behavior of the EV.
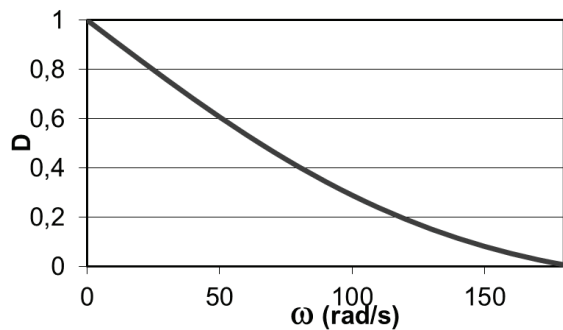

Figure 9. Simulation result for duty cycle behavior versus angular speed (ω) for $R_{load} = 500$ Ω

Figure 9 shows the evolution of duty cycle D when angular speed (ω) varies from zero to the rated speed.

$$\therefore D = 1 - \frac{K^2\,\omega}{\left(Ysen\alpha + Z\cos\alpha + X\,\omega^2\right)R_{load}} \quad (30)$$

Finally, the EV test bench has been implemented according to the design considerations taken into account; Figure 10 shows the test bench implementation.
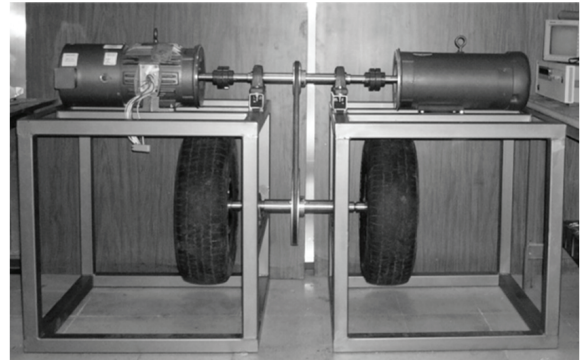

Figure 10. Test bench implementation

4. SIMULATION RESULTS

Now, some simulations are presented for three different drive cycles: 1) City, 2) Road, and 3) under extreme conditions. The results obtained, about instant power and energy, allow the test bench characteristics to be designed and defined.
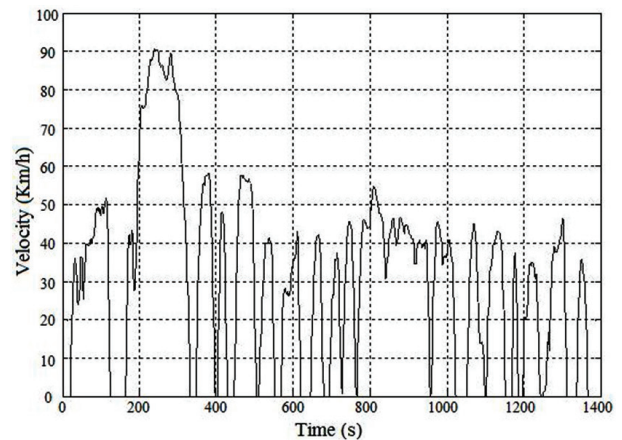

Figure 11. EV city drive cycle

1) City drive cycle

The energy calculated for a city drive cycle is 0.78 MJ at 1400s, this energy allows to design the minimal capacity of battery bank.
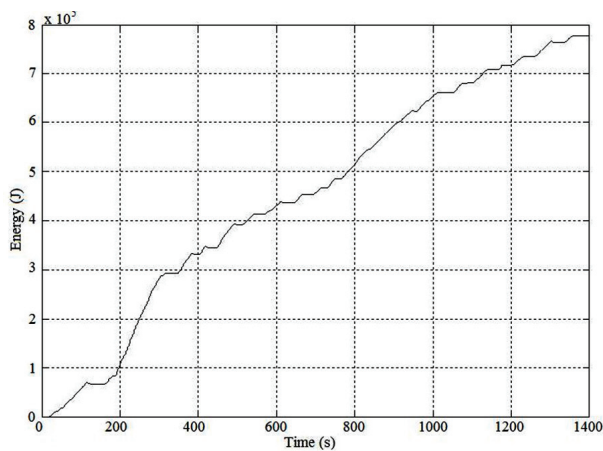
2) Road drive cycle

The energy consumption for this type of drive cycle is 1.2 MJ at 800s. Proportionally, this result shows that the energy consumed is greater than in the city drive cycle. This is due to the different driving conditions imposed on the EV, the recovered energy during regenerative braking for road driving conditions is lower than the city drive cycle.

3) Simulation under extreme conditions

The energy consumed for a single cycle defined in Figure 15 is of 34 KJ. In order to compare the energy consumed in this case with the two cases presented before is necessary to consider the same time of driving.
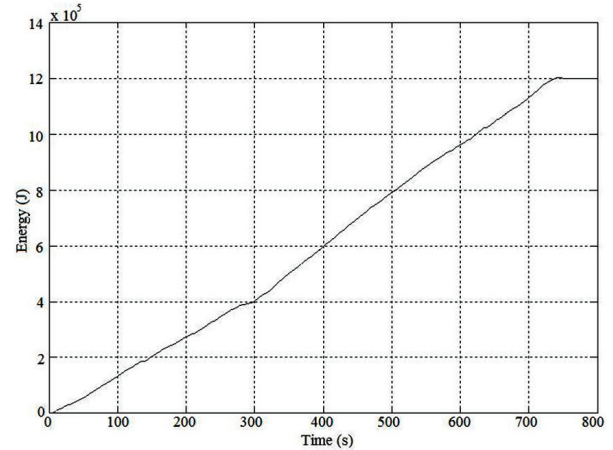
For a case of 800s, the cycle mentioned before has to be repeated 20 times, so the total energy consumed is 0.680MJ. The recovered energy is 15 KJ by cycle, so the total recovered energy during the drive cycle is 0.3MJ.
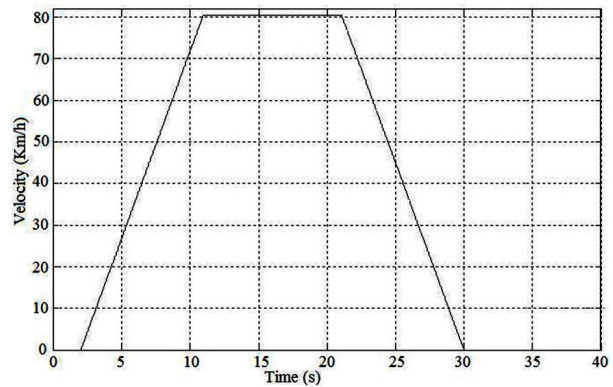

Figure 12. Energy for a city drive cycle
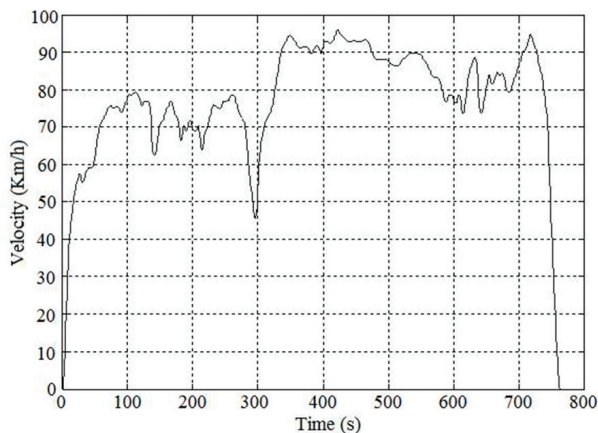
Figure 13. Road drive cycle of EV

Figure 14. Energy of road drive cycle

Figure 15. Linear speed of EV for cycle

- During a road drive cycle the power imposed by the EV remains almost constant and its value depends on the speed reached. Under these drive conditions, due to the few regenerative brakes, the consumed energy depends mainly on the speed of the EV.

- The city drive cycle imposes to the EV several repeated accelerations-decelerations (1.5m/s2), which allows to recover additional energy. During this drive cycle is important to impose an adequate control of the braking in order to maximize the available energy to be recovered.

- The proposed drive cycle is designed in order to be used under different driving conditions. The way to design this drive cycle is possible from an analysis of the EV dynamics based on the instant power, the average power, and the energy. From the above information, it is possible to define a hard or soft drive cycle in order to select the rated power of the motor.
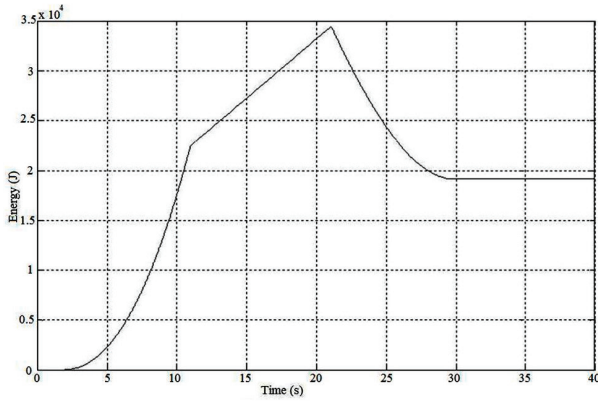
Figure 16. Energy consumed for the cycle proposed

5. EXERIMENTAL RESULTS

The experimental results have been obtained for the parameters given in Table 1; these parameters represent a typical EV of 1600Kg. An interesting test bench characteristic is the possibility of changing the parameters to correctly reproduce the behavior of the EV. Experimental results show the emulation of EV dynamics for different conditions. The phase current before a deceleration is shown in Figure 17. Figure 18 shows the phase current before and during EV acceleration. An increase of current can be observed due to the inertial mass of the vehicle (), which demands additional power during the acceleration or deceleration period. This requires an increase of the instant power, as a consequence the torque demanded from the induction motor (τ_L) is increased. During the deceleration period regenerative braking is possible, so an amount of energy can be recovered and stored to be used during the acceleration period. This can increase the autonomy of the EV.

Table 1. Parameter values of EV and Test bench

Parameters/Coefficient	Value
Electric vehicle (EV)	
m: EV mass	1600 Kg
C: Aerodynamic drag coefficient	0.42
R: Tire radius	0.32 m
f_r: Rolling resistance force	0.008
G: Transmission ratio	12.8
A: Area	2.2 m/s^2
J : EV equivalent inertia (or J_e)	0.2467 kg m^2
Motor	
P_m: Rated power of motor	3 hp (2.24 kW)
τ_e: Rated torque	12 N-m

Parameters/Coefficient	Value
ω: Rated angular speed	1800 rpm
V_s: Stator rated Voltage	230 V
I_s: Rated current	8 A
η_m: Efficiency	89.5 %
Drive	
η_I: Inverter efficiency	90 %
IGBT: Module CM100DU-24HB	1200 V/100 A
V_{dc}: dc voltage (26 batteries)	312 V
• Battery voltage	12 V
• Battery capacity	12 Ah
• Total Energy	13.48 MJ

Figures 17 and 18 show the correct dynamic emulation of the EV by the test bench. In Figure 19, it can be observed that the mechanical speed of the motor correctly follows the dynamic of the speed imposed by the reference control signal.

5. CONCLUSIONS

A methodology to analyze the EV dynamic based on simulation and experimentation has been proposed in this paper. The mathematical analysis allows a model to be developed and a test bench to be designed based on typical EV parameters. The test bench implemented can emulate a scaled EV. The equivalences between a real and the scaled EV, can be from the EV dimensions or from the capacity of the motor. The acceleration curves of the EV and the test bench motor have been presented; these curves show the demands of power, torque and energy to be taken into account to define the EV design considerations, such as specifications of the motor, converters, and others elements. Also, the necessary energy to handle the EV during a drive cycle can be used to design the battery bank.

The results obtained with the test bench and by simulation give a more complete and detailed information for the design. The tool proposed allows the EV dynamic to be studied by simulation varying the parameters and conditions with wide flexibility. These results can be validated with the experimental test bench tool. The EV has been correctly emulated by the test bench under different operating conditions (starting, cruising speed and braking). It is important to mention that the proposed test bench considered improves the EV behavior, which is close to real EV applications.
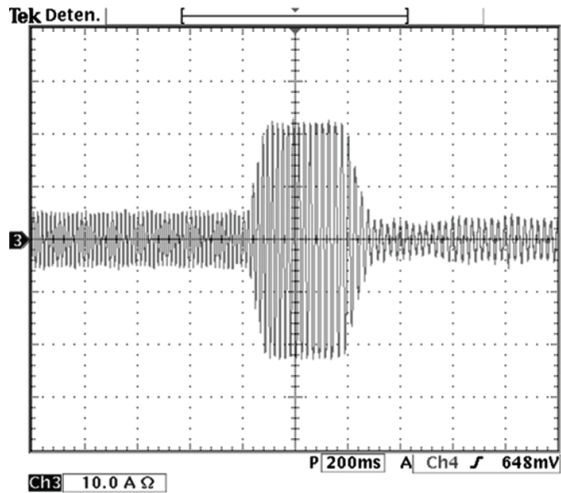
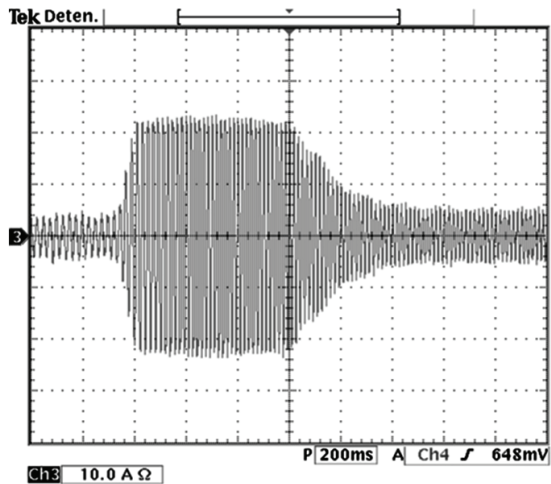**Figure 17.** Phase Current during deceleration (1800 to 1200 RPM)

Figure 18. Phase Current during acceleration (1200 to 1800 RPM)
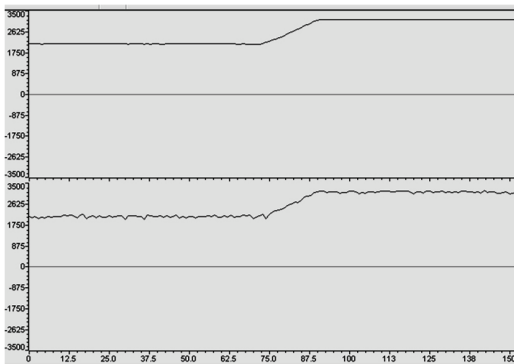

Figure 19. Motor speed and reference speed in acceleration

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