ESTADO ACTUAL DE ESTRATEGIAS DE CONTROL EN SISTEMAS DE RECUPERACIÓN DE ENERGÍA EN VEHÍCULOS ELÉCTRICOS.

CURRENT STATUS OF CONTROL STRATEGIES IN ENERGY RECOVERY SYSTEMS IN ELECTRIC VEHICLES.

Juan Carlos Núñez, Albino Martínez, José Pastor Rodríguez, Oscar Sandoval, Rubén Posada y Manuel Adam

Oriente 9 No 852, Colonia Emiliano Zapata, CP. 94320 Orizaba, Veracruz México. Departamento de Estudios de Posgrado e Investigación.
Manuel Adam. Int. Internado Palmira S/N. Col. Palmira. CP 62490, Cuernavaca Morelos México. Adscrito al Departamento de Ingeniería Electrónica TecNM/CENIDET

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ABSTRACT:

There is currently an increasing demand for electric vehicles that require greater autonomy and energy efficiency when driving them. Control strategies in energy recovery systems are crucial to optimize the amount of energy returned to the battery and to ensure safety and stability for the user.

In this paper, active fault tolerant control systems (AFTC) and passive fault tolerant control systems (PFTC) with other specialized control strategies (Fuzzy Logic, Neural Networks and Perturbation Rejection Controllers) are compared with classical PID controllers.

The results of the simulations show that, keeping the battery voltage constant, returns of about 12% of the battery charge capacity are achieved while the braking time of the vehicles is reduced.

Keywords: Braking controllers, electric vehicle, electric motor, energy recovery system, fault tolerant control.

RESUMEN:

Actualmente se está produciendo un aumento en la demanda de vehículos eléctricos que requieren una mayor autonomía al conducirlos. Las estrategias de control en sistemas de recuperación de energía son cruciales para optimizar cantidad de energía que regresa a la batería y garantizar seguridad y estabilidad al usuario.

En este trabajo se comparan sistemas de control tolerantes a fallos activos (AFTC) y pasivos (PFTC) con otras estrategias de control especializadas (Lógica Difusa, Redes Neuronales y Controladores de Rechazo de Perturbaciones) son comparadas con controladores PID clásicos.

Los resultados de las simulaciones muestran que, manteniendo constante el voltaje de la batería se logran retornos alrededor del 12% de la capacidad de carga de la batería y mientras que el tiempo de frenado de los vehículos es reducido.

Palabras clave: Controladores de frenado, vehículo eléctrico, motor eléctrico, sistema de recuperación de energía, control tolerante a fallos.

1.- INTRODUCTION

Electric vehicles have gained more attention in recent years because they can reduce or eliminate emissions of gas burned by vehicles and dependence on oil [2]. However, the driving distance for electric vehicles (EVs) is limited by battery power [3]. One of the most important features of EVs is the ability to capture energy from the brake when the EV is in a braking situation [4]. The electric motor can be controlled to produce an appropriate amount of braking force to recover energy from the braking system as much as possible, and that this is stored in the battery and re-used to increase driving distance and energy efficiency [4].

In order to improve the energy efficiency and performance of regenerative braking dynamics, some control strategies for EVs based on modern control theory have been developed and applied to regenerative braking [5,6]. Mathematical models of driving and regenerative braking have been designed by applying neural networks with sliding mode controllers to improve and recover more energy [7]. There are cooperative control algorithms for regenerative braking for a 6-speed transmission based on a parallel hybrid EV [8]. A fuzzy logic control has been designed to adjust the regenerative brake torque dynamically and improve the energy coming from the regenerative brake [9,10]. Adaptive regenerative braking is a control strategy used to determine braking commands that guarantee maneuverability. [11]

In different sources, the use of Super Capacitors (SC) is proposed to help the battery with better energy management. Since SCs have a high power density, but low energy density, they can be used as an auxiliary when starting the vehicle or on uphill slopes, generating power peaks that can be harnessed by the engine, thus allowing the battery to work with less stress. However, these SCs are expensive, so they cannot be used indiscriminately [25].

This paper shows an analysis of the state of the art of control strategies applied to energy recovery systems in electric vehicles and provides a brief discussion about the benefits that each of them provides, ensuring greater vehicle stability and better autonomy.
The results showed that FTCs achieve better stability, but fuzzy controls provide greater energy recovery. A balance between these parameters is crucial to achieve user comfort and safety, while achieving greater vehicle autonomy.
This paper is divided into 4 sections. Section two covers the materials and methods most frequently mentioned in this work. Section three makes mention of control strategies applied to energy recovery systems with the objective of optimizing the amount of energy recovered. Section four concludes and provides some ideas for future work.

2.- MATERIALS AND METHODS

2.1 ELECTRICAL SYSTEMS.

Electric vehicles are motor-driven machines that operate on the basis of electrical energy. They can use one or several motors to carry out their operation. Electric motors provide a clean and safe alternative to internal combustion engines [26]. There are electric vehicles that use external power sources; however, vehicles with autonomous propulsion (battery bank and super capacitors) are currently gaining momentum. It is considered that electric vehicles are more efficient than gasoline or diesel internal combustion vehicles, since the cost per battery recharge tends to be lower than the cost per gasoline tank recharge, however, the recharge time is longer, and although currently in the literature we find studies where strategies are analyzed to increase the speed of battery charging [25], it is still slow compared to the aforementioned vehicles.

Regenerative braking is a braking strategy that recharges the battery of the electric vehicle when it is under braking [4]. When the motor is in traction, the battery energy decreases over time. The higher the speed, the more power the motor consumes and therefore the energy transfer between the battery and the motor is higher. When the motor is in a braking situation (either by releasing the accelerator pedal or pressing the brake pedal) there is a return energy (generated by magnetic induction) that recharges the battery. Some authors [12,13,14] use super capacitors to store the energy in them and release it in a single stroke to the motor when it needs a sudden increase of energy, for example, when it is uphill or tries to break the inertia when starting with an initial speed of 0 m/s. It is also used as an interface between the power system and the battery to capture current peaks and discharge them to the battery.

2.2 Types of motors commonly used in electric vehicles.

Brushless motors (BLDC). This type of motors are widely used in EVs due to their excellent torque, higher speed range, high power density and low maintenance [16]. They are composed of a moving part which is the rotor, which is where the permanent magnets are located, and a fixed part, called stator, on which the windings are arranged. They are mainly used in *scooters* or electric scooters due to their low cost, high speed-torque ratio, longer life, low weight and low maintenance requirements.

Permanent magnet synchronous motors (PMSM). Its rotational speed is directly proportional to the frequency of the alternating current network that feeds it. It is used in electric vehicles due to its high torque-current ratio, power-to-weight ratio, high efficiency, high power factor and robustness [27]. However, the accuracy in speed control is difficult due to the nonlinear coupling between winding currents and rotor speed [17].

Asynchronous motors. These are alternating current (AC) motors in which the electric current is caused by electromagnetic induction of the magnetic field of the stator coil in order to produce the rotor torque. Therefore, they do not require mechanical commutation as in the case of synchronous motors. They are basically composed of the rotor, which can be squirrel cage or wound, and a stator, where the inductor coils are housed, which are three-phase and 120 degrees out of phase with each other [14].

2.3. SUPER CAPACITORS (SC)

They are electrical charge storage devices used as an interface between the power stage that controls the motor (inverter) and the battery [25]. Because batteries cannot recover energy peaks, they are used to capture those peaks and slowly discharge them to the batteries. They are commonly connected via a diode to assist the battery in acceleration and deceleration [25].

2.4. FAULT TOLERANT CONTROL.

Due to the demand for reliability required today in safety-critical systems such as aircraft, spacecraft, nuclear plants and chemical plants processing hazardous materials, it is necessary to design systems capable of tolerating potential failures in order to improve reliability while providing desirable performance. These control systems, are often referred to as Fault Tolerant Control Systems (FTCS). [20]

An FTCS is a system that has the ability to accommodate component failures automatically. They are capable of maintaining overall system stability and acceptable performance despite being subjected to faults. [20].

Fault tolerant controllers are divided into two types: Passive (PFTCS) and Active (AFTCS). In passive controllers, the controllers are mixed and are designed to withstand a predetermined class of faults. This approach does not require Fault Detection and Diagnostics (FDD) schemes or controller reconfiguration, however, it is limited by its fault tolerant capabilities [20].

On the other hand, the AFTCS reacts to system component failures by reconfiguring the control action in order to stabilize and provide acceptable system performance, with the advantage that, under certain circumstances, it is allowed to work under degraded conditions [20].

AFTCSs are divided into four sub-systems: (1) a reconfigurable controller, (2) an FDD scheme, (3) a controller reconfiguration mechanism, and (4) a command/reference governor. [20].

Figure 1 shows the general structure of an AFTC. In the FDD module any faults in the system should be detected and isolated as fast as possible. Faults, system input/output variables and post-fault system models need to be estimated online in real time [20]. Based on the information provided by the post-fault system model, the reconfigurable controller should maintain stability in addition to ensuring that the closed loop of the system follows the input command path in the face of faults, which generates that a compensating controller should be synthesized [20].

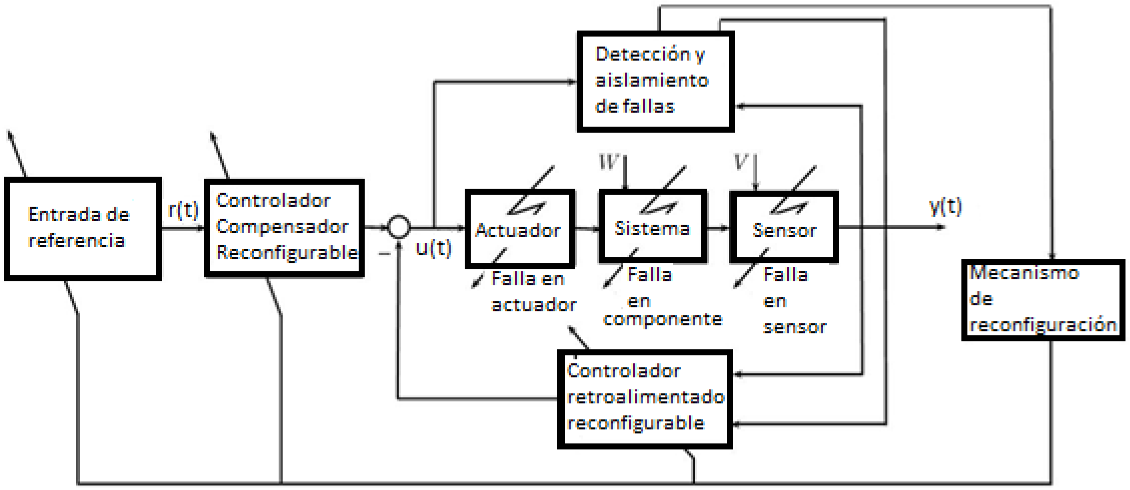


Figure 1. General scheme of the AFTCS [20].

To prevent a potential saturation of the actuator and to take into account the performance under degradation conditions after the failure happens it is necessary to design a command that automatically adjusts the input or reference trajectory [20].

3.- CONTROL STRATEGIES.

This section addresses studies related to fault diagnosis, tolerant control and fuzzy control systems applied to energy recovery systems that provide greater stability and safety to the electric vehicle (EV) driver.

3.1. MODELING AND DIAGNOSTIC STRATEGIES FOR PMSM STATOR FAULT DIAGNOSIS

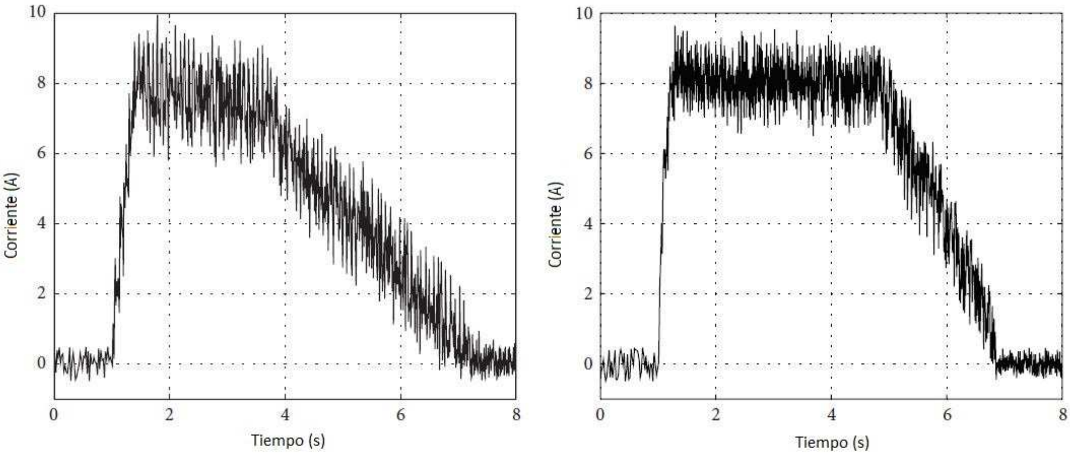
An undetected fault in a Permanent Magnet Synchronous Motor (PMSM) can lead to high repair costs or even cause catastrophic failures [22]. Among the number of faults that exist in PMSMs, the most serious are short-circuit faults, slewing faults, and phase-neutral faults. If not detected in time, swing faults can lead to phase-neutral faults. In [22], a mathematical model of phase-neutral fault and a mathematical model of a PMSM motor in abc coordinates were proposed using Matlab/Simulink™. The Zero Sequence Voltage Component (ZSVC) in the swing fault was analyzed which provides the basis for PMSM fault diagnosis.

The main contribution was the new approach to diagnose rotating faults and phase-neutral faults based on the mathematical model of the stator. This model included a flux equation (based on the stator winding flux), a voltage equation, a motion equation, a short-circuit voltage equation. The mathematical model of the PMSM under abc coordinates presented better phase-neutral fault results. Through ZCVS components it was also possible to detect swing faults. Using Matlab/Simulink™, the mathematical models of pass-neutral and swing faults were established and through simulation the three-phase stator current, voltage, torque output and speed characteristics were analyzed, which provides theoretical basis for the diagnosis of stator winding faults [22].

3.2 MODELING AND CONTROL OF REGENERATIVE BRAKING FOR A BLDC MOTOR

To observe the current brake current and unknown regenerative brake system disturbances, an automatic disturbance rejection control (ADRC) is proposed in [12] to control the regenerative brake current. A typical ADRC consists of a nonlinear tracking differentiator (TD), an Extended State Observer (ESO) and a Nonlinear State Feedback Control Law (NLSEF) [12]. The ESO is responsible for observing the regenerative brake current.

The battery voltage change is small in the regenerative braking recovery process. If the battery voltage is considered constant, the amount of energy recovery is proportional to the braking current within a given period. Faster response and smaller steady state error of braking current mean that energy recovery is increased and recovery efficiency is improved. Simulation results show that the performance of the ADRC controller is superior to that of the PI controller (see Fig. 2) as it keeps the regeneration current constant for a longer time. [12].



(a) Controlador PI (b) Controlador ADRC

Fig.2. Braking current response at 35 km/h. [12]

Experimental results show improved energy recovery efficiency and robustness to disturbances in a motorcycle with two electric motors (BLDC) with a 48V power supply and a constant braking current of 8A as the results are compared with a PI controller at speeds of 20 to 35 km/h [12].

3.2 FAULT-TOLERANT CONTROL FOR A REGENERATIVE ABS BRAKING SYSTEM

The braking strategy is crucial to ensure the safety of the driver at the time of the braking situation. A failure in this system can lead to fatal accidents [13]. It is considered [13] important to model an Anti-lock Braking System (ABS) to obtain the behavior parameters of the system in a failure situation because in the literature it is suggested that the impact of failure in braking situation (sensors and actuators) hinders the ability of the vehicle to slow down [13]. Due to the above, a regenerative ABS (a combination of regenerative braking and friction braking)) equipped with an FTC was designed in [13] to generate a failure-free braking response in sensor components, considering error detection and load calculation [13].

A Sliding Mode Controller (SMC) was used and the parameters ε , k, Fbi, respectively, at 3, 10 and 3900 showed a good response to the slip ratio, with a maximum overshoot of 19% and a settling time of 0.1s and a steady state error and braking time of 0.87 seconds.

These results were compared to a PID with Kp, and τ_i τ_d , respectively of 250, 138 and 8.8. The response generated by the system with the given times had a maximum over impulse of 9.8%, a settling time of 0.4s with a steady state error and braking time of 1.19 seconds [13]. The performance of the system using an AFTC is better than the system without it. It was shown that the sensitivity and error results remain stable using the ATFC, while the system with a PID made the system unstable when sensor faults occur [13]. When the brake is applied, the system will reduce the battery state of charge due to the timing of the regenerative braking system. The motors in electric vehicles will produce torque and give load to the wheel. Reverse torque in electric motors is used to generate energy, so that the state of charge of the battery is prevented from being lost, at most 0.53%. The system shows the ability to recover energy when braking force is applied.

In [15] a case similar to [13] is analyzed: an ACTF ABS system with regenerative braking with actuator failures based on an SMC. The ABS system with regenerative braking allows energy recovery when there is a sudden and strong braking situation. Figure 3 shows that, when sudden braking happens, the battery state of charge (SOC) value is 80% and when the EV stops, the state of charge becomes 79.47%. This provides a regenerative ABS that can recharge the battery by 0.53% [15].

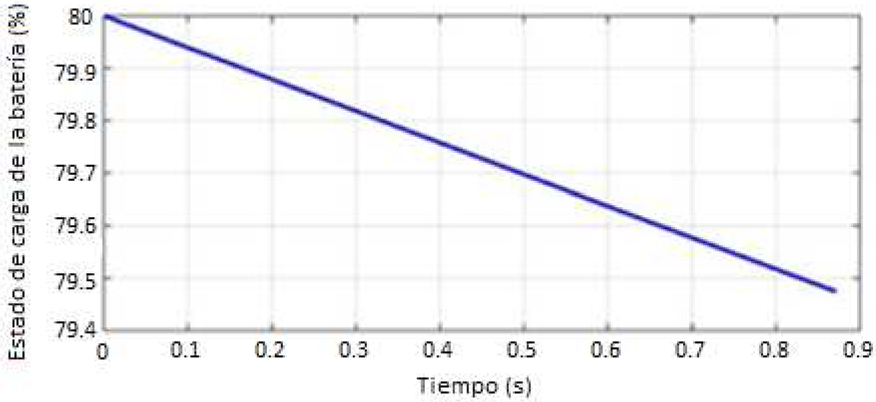


Fig.3. Battery state-of-charge response. [15]

The control strategy is the same as that proposed in [13]. The AFTC can compensate the errors in the hydraulic actuators in regenerative ABS with a bias error of 9%, 12% and 16% and an effectiveness loss of 6% with performance parameters of maximum overshoot, settling time and steady-state error without AFTC respectively of 19.4%, 0.0808s and 0.9% [15]. While with ATFC running, maximum over-pulse, settling time and steady-state error of 18.3%, 0.801s and 0.9% were achieved. With an effectiveness loss of 6%, the displacement ratio becomes 0 without the AFTC at 0.87s, while with the AFTC this ratio remains stable at 0.87s until the vehicle stops [15].

3.3 NEW FAULT-TOLERANT INDUCTION MOTOR CONTROL ARCHITECTURE FOR ELECTRIC VEHICLE CURRENT SENSOR FAILURES

An active CTF was developed for an induction motor (IM) in automotive applications in the presence of three current sensors biased for arbitrary faults [23]. A differential algebraic approach was applied to act as a fault detector and isolator (FDI) and estimate residual dynamic currents in the stationary reference frame. The results are sent to a decision unit that detects the fault and identifies the failing sensor based on a boundary scheme [23]. An online reconfiguration is presented to calculate the appropriate current signal to be used by a Rise-Backstepping controller to handle fault tolerance and keep the system performance unchanged, even if sensor faults exist. This architecture demonstrated that all current sensor faults depend only on the input and output measurements and their derivatives with a 1-D fault estimation model. Because of this, it is valid for any MI control scheme and allows to reset the sensor fault condition. Furthermore, the residual limits used are well defined and suitable for the entire operating range. The robustness of the generated residuals in disturbance of torque applications was also demonstrated [23].

The main contribution of this paper is the active CTF based on differential algebraic estimation of dynamic current faults in the stationary reference frame. The solution using the CTF is cost-effective regardless of the speed control strategy involved in the IM drive and robust to load torque variation with a 1-D model that uses available measurements to detect different types of faults, such as DC offset, gain errors, and disconnection [23].

First, the MI model was provided considering a control with three current sensors prone to arbitrary faults and in the presence of load disturbances. Then, a differential algebraic approach for the FDI was proposed to estimate residual currents in the stationary reference frame. This algebraic estimator was designed in terms of residual currents being the solution of some polynomial equations whose coefficients are just functions of the measured terminal voltages and currents and their derivatives. After the fault occurred, the isolation task was performed using a boundary-based scheme, followed by reconfiguration of the existing hardware redundancy-based control scheme to keep the system performance unchanged even under fault conditions [23].

Simulation results revealed the efficiency of the CTF considering the detection of different types of faults in current sensors and also the ability to recover from the fault [23].

3.4 ADAPTIVE SLIDING MODE CONTROLLER FOR ELECTRIC VEHICLE WITH 4 INDEPENDENT WHEELS

Vehicles controlled by four independent motors, are gaining acceptance as objects of study thanks to their performance [18] however, the complex control coordination for the 4 motors and their reliability present themselves as major challenges. The contribution of this work was the design of a fault tolerant control by adaptive sliding modes, aiming to cope with the operation of multi-motor coordinates against actuator failures.

The results showed acceptable performance as stability was maintained. Adaptive sliding mode control was designed to take care of uncertainties and disturbances [18]. In the multi-motor system, faults were accommodated using tolerant control allocation. The limitations of the motors and the friction of the tire with the asphalt were also considered. Simulation and experimental results show that this strategy improves vehicle performance [18]. A failure of one motor in the drive system (4 independent motors) did not significantly affect the skid speed dynamics in driving situations such as a small change in steering angle and low vehicle speed, however, the vehicle trajectory deviated from the desired trajectory, which obviously increased the driver's load [18].

In the case of high speeds, the friction coefficient of the vehicle is lower, so a serious traffic accident may be caused if an actuator failure occurs, therefore, it was proposed to design a CTF to improve the maneuverability and reliability of cars with 4 independent motors [18].

3.6 FUZZY LOGIC APPLIED TO A REGENERATIVE BRAKING SYSTEM WITH BLDC MOTOR.

In [16] a robust control for regenerative braking is proposed using a combination of fuzzy logic control and a classical PID to a non-carbon motor (BLDC Motor). Fuzzy logic control is slower than PID, since the braking torque needs to be in real time, which is why PID is used. The main drawback of using fuzzy logic, is to ensure the stability of the VE so the author proposed a nonlinear model of a fuzzy system to ensure stability and it was observed that the input applied to the system was controlled by two parameters: Braking force and battery voltage. The results were shown in 3 parts: the brake, the speed and the battery state of charge when the pedal is pressed. It was shown by simulation in MATLAB™ that, when the brake was applied, the speed decreased and the battery state of charge increased. With a maximum torque of 1000 Nm applied for 200ms, the battery state of charge increased 100mV as shown in Figure 4.

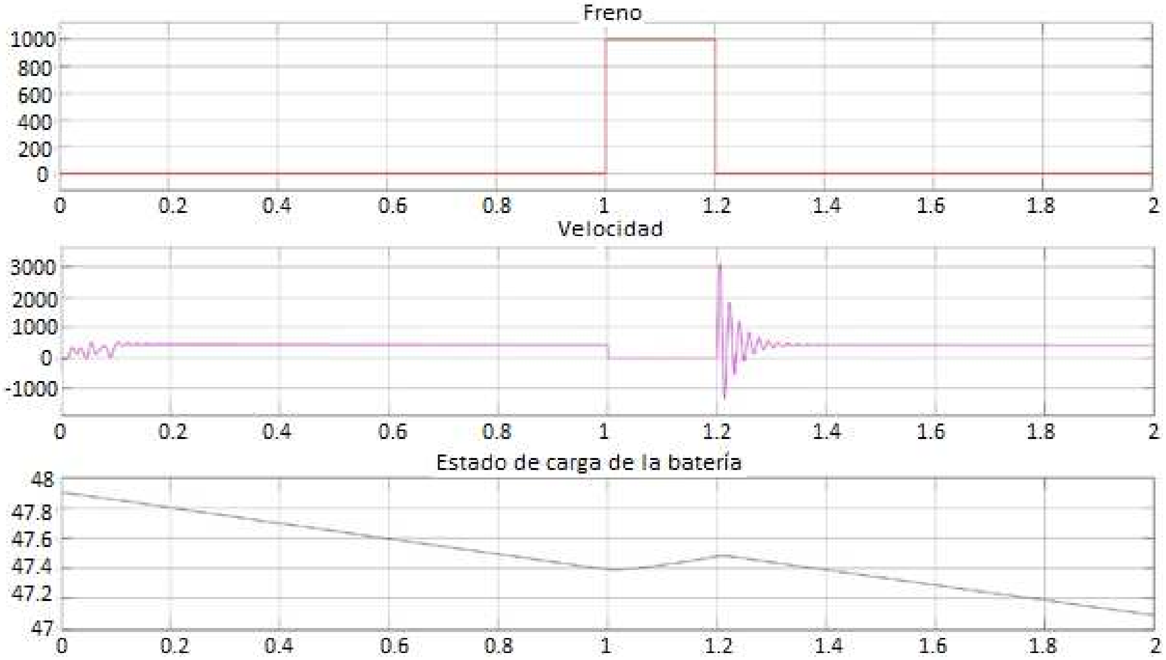


Figure 4. Simulation results of the implemented system for three parameters: brake, speed and battery state of charge.

3.7 REGENERATIVE BRAKING CONTROL STRATEGY FOR HYBRID VEHICLE WITH REAR-AXLE DRIVE

Regenerative braking has been shown to be an effective method for hybrid electric vehicles to extend the driving range of the unit. In [19], a method to recover more energy generated by the braking process using a control for a rear motor is proposed. First, a control strategy for the braking force distribution for front and rear tires is proposed. Subsequently, a fuzzy control (based on the Mamdani strategy) was designed to determine the distribution between the hydraulic braking force and the regenerative braking force for braking the rear tires. This Mamdani fuzzy logic controller has 3 inputs: brake force, vehicle speed and battery state of charge, and the regenerative braking force coefficient as the only output. This strategy was verified by the New York City Transit Department under MATLAB/Simulink simulations. The results show that this control strategy can achieve an energy recovery of 28.29% as shown in Figure 5 and Table 1[19].

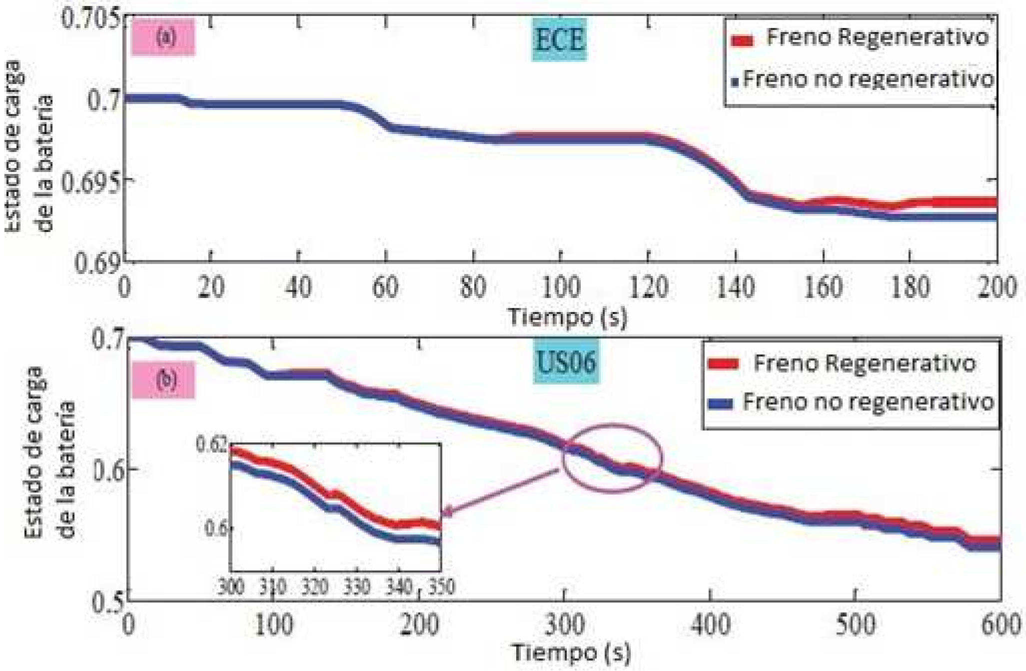


Figure 5. Battery state of charge: (a) European Economic Commission ECE, (b) US06 emission test cycles. [19]

	US06	ECE	NYCC
Total brake energy (kJ)	2026	158.2	628.1
Regenerative braking energy (kJ)	314.2	45.23	114.1
Braking recovery energy (%)	15.51%	28.29%	18.17%

Table 1. Braking recovery energy from typical driving cycles.

3.8 FUZZY CONTROL FOR A REGENERATIVE BRAKING SYSTEM IN AN ELECTRIC VEHICLE WITH FOUR WHEEL MOTORS.

A fuzzy control for a regenerative braking system is proposed in [21]. This control strategy selects as inputs: vehicle speed, brake pedal and battery state of charge (SOC) and its output is the proportion of regenerative brake force of the total braking force. Fuzzy control has advantages such as high robustness and convenient design since its simulation time is short, which brings it closer to practical applications. The problem is that it does not ensure vehicle stability and its response time is slow [16]. The braking force is distributed between the front and rear axles in linear proportion. The design of the regenerative braking system was achieved and a series of simulation results were obtained using Matlab/Simulink™ and AMESim™.

In this case, only the situation in straight line driving using a permanent magnet motor (PMSM) was studied. The simulation result allows us to opine that the total energy consumed during one driving cycle is 1.99x105 J and the total energy recovered is 0.35x105 J. [21] The energy recovered efficiency is defined as the ratio of the recovery energy to the consumption energy. The results showed that the recovered energy efficiency changes with vehicle speed. In the end, 17.6% was recovered.

4.- CONSLUSIONES

Studies on these types of strategies that help to improve the autonomy of electric vehicles by supporting energy recovery systems were briefly shown. Some approaches with fault diagnostic systems and reconfigurable controls as well as fuzzy logic were summarized. It was shown that a well-implemented control strategy can optimize energy recovery once regenerative braking is applied, improving the stability, driver safety and reliability of the electric vehicle.

A fault diagnosis analysis was performed for an electric vehicle with a PMSM motor where the rotational faults are diagnosed based on the mathematical model of the stator. This diagnostic strategy allows its implementation in FTC systems for energy recovery. An ADRC control was also analyzed that managed to keep the current constant for a longer time, the battery voltage was proposed constant, so that the energy recovery remains constant during the braking period.

Classic PID controllers are completely discarded because they are slow to respond and compromise the stability of the electric vehicle.

Fault-tolerant controls in both sensors and actuators improved braking time and vehicle stability with an energy recovery of 0.53% in short braking periods compared to a classical PID, which seriously compromised vehicle stability and, therefore, user safety.

With the above we can deduce that, when it comes to energy recovery, we must ensure the greatest amount of it to improve the EV's autonomy, but the vehicle's stability must also be guaranteed, which will be reflected in the user's safety. According to the information presented, we can indicate that FTCs achieve better stability and, therefore, safety in EVs, but fuzzy controls provide a greater amount of energy recovery, although they do not focus on vehicle stability. A balance between these parameters is crucial to achieve user comfort and safety, while achieving greater vehicle autonomy.

A transfer of knowledge about regenerative braking behavior is necessary for scientists, manufacturers and other interested parties to improve regenerative braking systems in terms of energy efficiency and greenhouse gas reduction. As future work, it is recommended to study the behavior of the regenerative braking system under failure situations that allow to continue recovering energy even though the system is working under degraded conditions.

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