

Design of an Electronic Power System for Energy Losses in DC motor using Regenerative Braking

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I. ABSTRACT

This work approaches the saving energy for electric propulsion system through a regenerative braking, which associates the concept of kinetic energy conversion into electricity that can be stored in batteries. Four DC motors and a mechanical system, which is used to simulate the inertia of a vehicle, compose the system. The main issue is to design, prove and evaluate the driver and respective control in different states of the mechanical system.

Keywords—*regenerative braking; current peak; energy loss; battery; DC motor; mechanical system.*

II. INTRODUCTION

For many years, conventional vehicles with internal combustion engines were the cars greatest demand worldwide, but the shortage of conventional fuels and increasing environmental pollution are driving the development of new trends in the design of vehicles. Hybrid and electric vehicles (EVs) have had a growing acceptance because of their quiet operation and zero greenhouse gas emissions therefore are chosen for conversion to autonomous system [2].

EVs can use DC or AC motors, but most manufacturers prefer AC motors for efficiency, low maintenance cost yet. Although, the current work in relation to the regenerative braking demonstrate that efficiency of DC motors can be increased. Regenerative Braking (RB) is an energy recovery mechanism, which converts the kinetic energy of the vehicle into electrical energy which is stored during braking and can occur at different times:

- When the accelerator pedal is released, the regenerative braking reduces vehicle speed and simultaneously accumulates electricity.
- During a downward slope, the regenerative braking allows recovery energy while the speed is stabilized.
- During braking, the regenerative braking works when pedal brake is pressed during vehicle movement.

This paper presents a comparative study between the configurations of power electronics system with regenerative braking and without regenerative brake applied to DC motors in a vehicle of Ackerman architecture scaled, in which the engine will run as a passive element during operation and generator during the transition state (deceleration). Furthermore the design of both configurations and bidirectional DC-DC converter, which will be designed for this vehicle Ackerman scale architecture is presented.

III. OBJECTIVES

A. GENERAL OBJECTIVE

Design an electronic power system that reduces energy losses in the DC motor using regenerative braking.

B. SPECIFIC OBJECTIVES

1. Design a mechanical structure based on an Ackerman architecture conditioned for the installation of motors, sensors and processor.
2. Design a power electronic system which improves the efficiency of the system by using regenerative braking.
3. Design a control system, which optimizes the operation of the engines.

IV. HYPOTHESIS

A. GENERAL HYPOTHESIS

H1. The regenerative braking applied optimally to DC motors in the power electronics system will reduce energy losses occurring during the current peaks.

B. SPECIFIC HYPOTHESIS

H2. The application of regenerative braking in DC motors with the power electronics system will reduce energy losses occurring by increasing the speed with respect to the speed desired.

H3. The power electronic system will increase the autonomy of the vehicle reducing energy losses.

H4. The controller will allow a good coordination of parameters of each mobile vehicle engine.

V. PROPOSED SYSTEM

The project was divided into three parts to better cover the development in each of their fields, these being:

1. Mechanical Structure
2. Power Electronics Design
3. PID Control

1. MECHANICAL STRUCTURE

The mechanical structure is based on the architecture Ackerman and scale of 1:10, an approximate average vehicle. In this project we have focused in the direction of a conventional vehicle given its importance for control over it.

1.1. Ackerman Condition

Considering a front wheel drive vehicle, shown in Figure 1, and moving to the left, it has a kinematic condition between the inner wheels and the outer wheels to avoid slipping. That condition is called Ackerman condition and is expressed by:

$$\cot\delta_o - \cot\delta_i = \frac{w}{l} \dots (1)$$

Where δ_i is the angle of the inner wheel and δ_o is the angle of the outer wheel. The inner and outer wheels are defined based on the rotational center O.

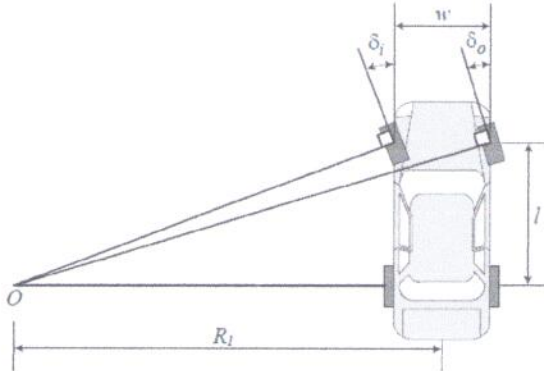


Figure 1. Front-wheel drive and Ackerman condition

The distance between the front wheels is expressed by w , and the distance between the axis of the front wheels and the rear wheel shaft is expressed by l . Where w and l , which are considered as the width and length of the vehicle.

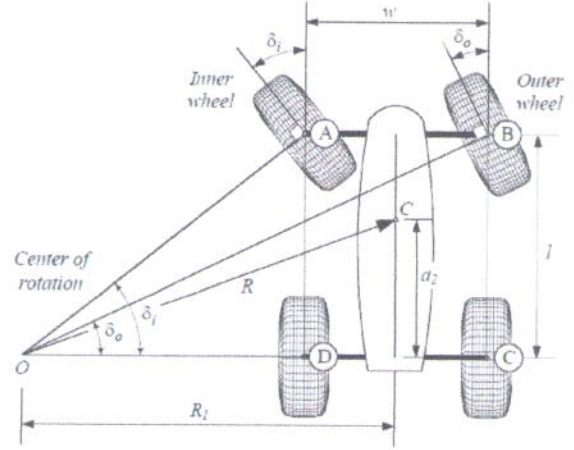


Figure 2. Front wheel drive and external and internal angles of the front wheels.

In Figure 2, the geometry with Ackerman condition is shown where R is the radius of gyration (under the center of mass of the vehicle) and can be calculated considering the triangle OAD and triangle OBC, so that:

$$\tan\delta_i = \frac{l}{R_1 - \frac{w}{2}} \dots (2)$$

$$\tan\delta_o = \frac{l}{R_1 + \frac{w}{2}} \dots (3)$$

Equating and solving R_1 , we have:

$$R_1 = \frac{1}{2}w + \frac{l}{\tan\delta_i} \dots (4)$$

$$R_1 = \frac{1}{2}w + \frac{l}{\tan\delta_o} \dots (5)$$

Then, equation (1) is obtained.

Since equation (1) the kinematic Ackerman condition. Similarly, we can calculate the vehicle turning radius such that:

$$R^2 = a_2^2 + R_1^2 \dots (6)$$

$$\cot\delta = \frac{R_1}{l} \dots (7)$$

Replacing and clearing R , we have the equation that represents the turning radius of the vehicle.

$$R = \sqrt{a_2^2 + l^2 \cot^2 \delta} \dots (8)$$

This is a geometric condition, which seeks the implementation of different angles on the outer and inner wheels; however, there is no four-bar mechanism that fully meets this requirement. Likewise, there have been various multi-bars approximate the desired solutions mechanisms. All these mechanisms seek to satisfy this condition are called Ackerman mechanism (Jazar R, 2008).

An important observation is that decreasing parameter $\frac{w}{l}$, the external and internal angle approach in their values, as shown in Figure 3[4].

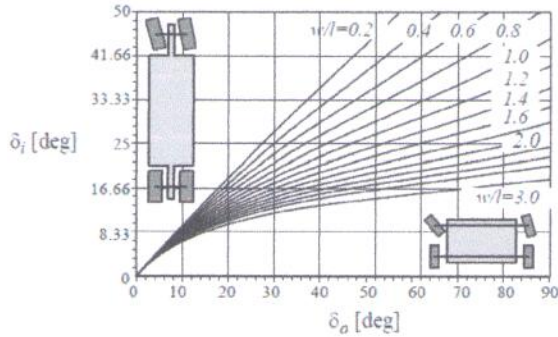


Figure 3. Relationship between external and internal angle of a vehicle.

1.2. Address trapezoidal mechanism

The steering mechanism is a trapezoidal four-bar system has been used for several decades [4]. This mechanism has two characteristic parameters, the β angle and trailing arm d , as it is shown in Figure 4.

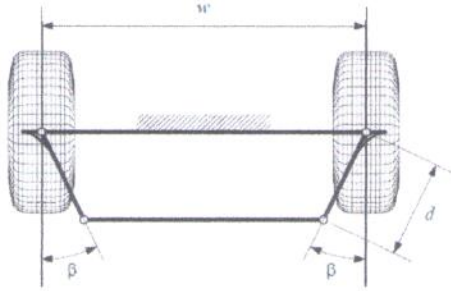


Figure 4. Trapezoidal steering mechanism.

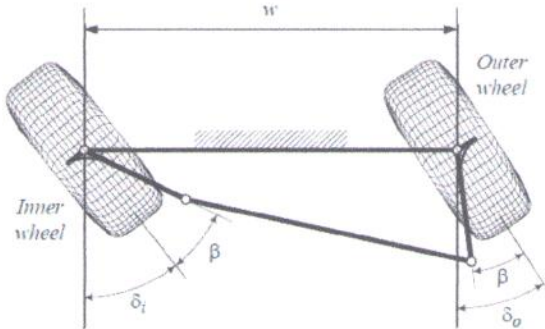


Figure 5. Trapezoidal steering mechanism turning clockwise.

Figure 5 shows the mechanism by turning to the left is shown, showing the angles of the outer wheel and the inner wheel. In [4], the proposal is the following equation:

$$\sin(\beta + \delta_i) + \sin(\beta + \delta_o) = \frac{w}{d} + \sqrt{\left(\frac{w}{d} - 2\sin\beta\right)^2 - (\cos(\beta - \delta_o) - \cos(\beta - \delta_i))^2} \dots (9)$$

Figure 6 approximation parameters for a specific model, where various values of β compared with respect to the ideal line tested Ackerman observed. It

is the approximate value of the approximately ten degrees in that range.

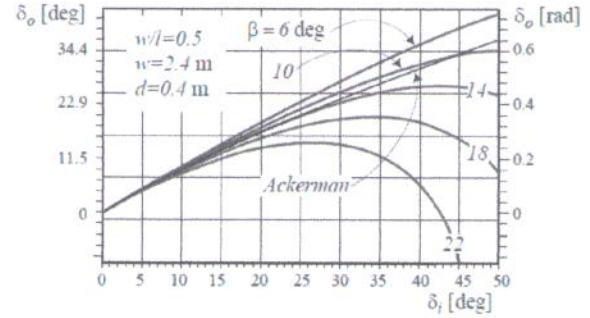


Figure 6. Approach trapezoidal direction

2. POWER ELECTRONICS DESIGN

2.1 H-BRIDGE

A bridge H is an electronic power circuit which controls the direction and speed of the engine. Often, the engines are controlled from a "brain" or microcontroller to achieve a mechanical purpose. The microcontroller provides instructions to the motors, but cannot provide the necessary power to drive the motors. H bridge microcontroller receives instructions and amplified to drive a motor mechanic. This process is similar to how the human body generates mechanical movements; the brain can provide the electrical impulses that are directed, muscle required for mechanical strength. Muscle represents both the H bridge [7].

2.1.1 Control Directorate – H-bridge-topology

Most DC motors can rotate in two directions depending on how the battery is connected to the motor. Both the DC motor and battery are two devices that have positive and negative terminals. To run the motor in the forward direction, the motor positive cable to the positive battery cable and connect negative to negative.

However, to operate the engine backward connections is changed; connecting the positive battery cable to the negative motor cable and the negative battery cable to the positive motor cable. An H-bridge circuit allows a large DC motor, run in both directions with a logic input signal low.

The electronic structure of the H-Bridge is explicit reference to the name of the circuit - H. Power electronics actually form a configuration of the letter H, as shown in Figure 7. The switches are a symbol of the MOSFET, electronic power components which are used for switching.

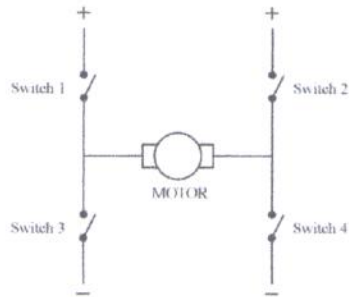


Figure 7. Bridge topology H.

If you want to rotate the motor in the forward direction, the switches 1 and 4 must be closed to power the motor. Figure 8 below is the H Bridge, who drives the motor in the forward direction.

If you want to rotate the engine in the reverse direction, the switches 2 and 3 must be closed to power the motor. Figure 9 below is the H Bridge, who drives the motor in reverse direction [7].

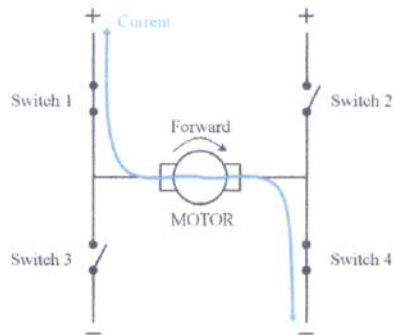


Figure 8. Topology, Bridge H - Forward direction.

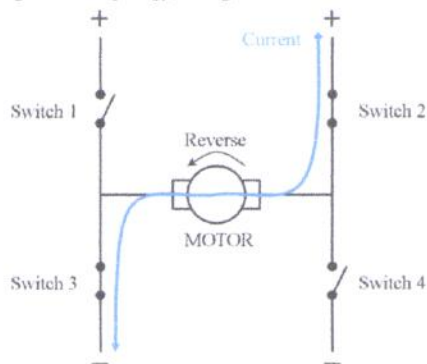


Figure 9. Topology, Bridge H - Reverse direction.

2.1.2 Speed control - PWM Technique

The motor is controlled by 4 switches, above. For explanation of the speed control, only the switches 1 and 4 will be considered that the speed control is identical in the forward and backward direction. That is, when the switches 1 to 4 are activated, the engine will eventually be at full speed. Similarly, if only the switch 4 is turned on while the switch 1 is off, then the motor stops. Using this system, run the engine for a 1/2 of full speed, switch 1 should light up in half the time and off for the other half. In order to implement this system in reality, it must take into account two main factors, the frequency and duty cycle.

3. REGENERATIVE BRAKING

In the regenerative braking, as discussed above, the goal is not to dissipate energy into heat, in either a mechanical brake or strength, but rather take advantage of it to recharge the battery that powers the engine, improving efficiency system. This creates the need to involve a block in the system, powering the engine and to provide a discharge path to power when the engine speed is reduced. This block is usually implemented with a bidirectional converter, which there is various configurations, each with advantages and disadvantages.

3.1 Bidirectional DC-DC converters

Focusing on the project in the reference [3], where the study of an electric car is shown, powered by DC motors, using the concept of regenerative braking. The general diagram used as circuit of battery charger is shown in Figure 10, for a topology of an active switch and Figure 11, for a topology of two active switches.

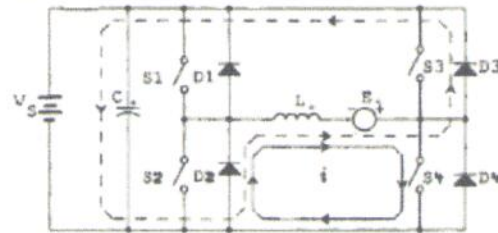


Figure 10. Switching power 1

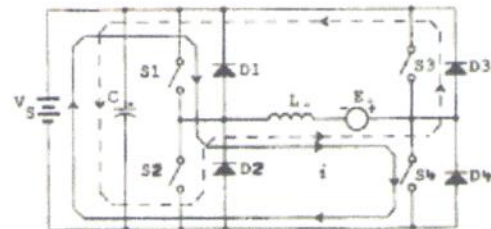


Figure 11. Source switching 2

In both circuits the inductance referred to as "Lab" represents the winding of the DC motor and the "Eab" source EMF induced return. In Figure 4, the continuous line as the current path in the initial state of the current path is displayed when the switch 4 is on, and the dotted line, when the switch 4 is off, in the second state. The switch 4 is turned off when the current reaches a defined threshold, charging the battery. When the current flowing to the battery is reduced, the switch S4 is turned on again, repeating the process when you are braking. For the second topology, in Figure 5. In the first state are turned on switches S1 and S4, creating a current path followed by the continuous line generated by the EMF induced in the windings. When you reach the limit (threshold), the switches S1 and S4 are turned off, creating a current path followed by the dotted line. Another type of DC-DC converter is further developed in reference [6], which employs two "half-bridges" interconnected by a transformer as shown in Figure 12. This

converter reduces the switching elements improving efficiency. The stray transformer coil is used as a resonant elements and capacitors "snubber" include switch parasitic capacitors to achieve zero voltage switching. The circuit operates in boost mode when the vehicle is in motion, fueling the bus voltage required for the engine. Regenerative braking is required when the battery charging circuit, acting in buck mode.

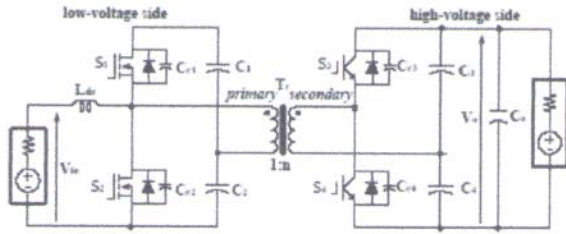


Figure 12. 3 switching source

4. PID CONTROL

For the PID control design of the DC motor, we must first carry out a mathematical model of the DC motor, to establish it as a plant (through its technical data sheet or experimentally determining plant). To control the speed of the DC motor, we consider as a variable, the PWM (Pulse Width Modulation). The PWM is to vary the ignition timing of a square wave (keeping period) varying the percentage of the period for the signal being given a voltage pulse (Duty Cycle). This varies the average voltage (Average Voltage); it is shown in Figure 13. Thus noticing the change in DC motor speed.

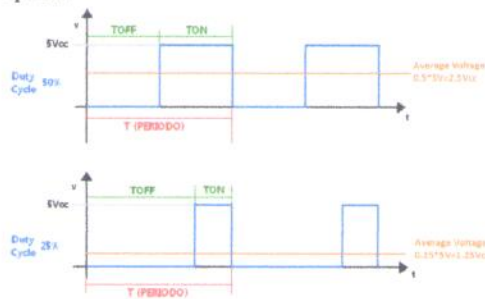


Figure 13. PWM variation

The measure of the speed (RPM), it's performed by an encoder that is built in the DC motor. The modeling of the engine is done experimentally, because they don't have technical data of the motor. This modeling is done through a DAQ (Data Acquisition) and use of software (Labview). For this, a series of measurements of the engine speed vs. Duty cycle applied, the system transfer function is obtained (Determination of the engine plant).

The PID control is a digital control (discrete) by the following equations for discrete PID control speed.

$$\begin{aligned} e(k) &= (\text{Valor set point} - \text{valor medido}) \rightarrow \text{Error} \\ CP(k) &= Kp * e(k) \rightarrow \text{PROPORTIONAL CONTROL} \\ CI(k) &= e(k) * Ki + CI(k-1) \rightarrow \text{INTEGRAL CONTROL} \\ CD(k) &= Kd(e(k) - e(k-1)) \rightarrow \text{DERIVATIVE CONTROL} \\ PID(k) &= P(k) + I(k) + D(k) \rightarrow \text{PID Control} \end{aligned}$$

Where:

$$\begin{aligned} Kp &= \text{Constant Proportional} \\ Ki &= \text{Constant Integral} \\ Kd &= \text{Constant Derivative} \\ e(k) &= \text{current error} \\ e(k-1) &= \text{prior period error} \\ CP(k) &= \text{proportional control} \\ CI(k) &= \text{integral control} \\ CI(k-1) &= \text{integral control of previous period} \\ CD(k) &= \text{derivative control} \end{aligned}$$

The theoretical equation for the PID control of a DC motor, begins in error identification of the system and application of constants and operations that compensate this error, these constants are based on each individual controls. All this is the PID control.

The PID controller eliminates steady state error and minimizes the transient time achieving good stability in the system, and a small overshoot.

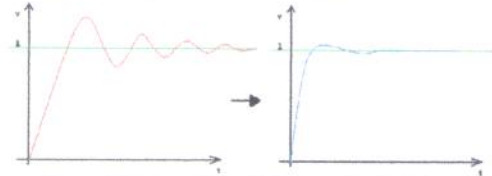


Figure 14 Action of the PID control in the DC motor

Thus the system is structured according to Figure 9

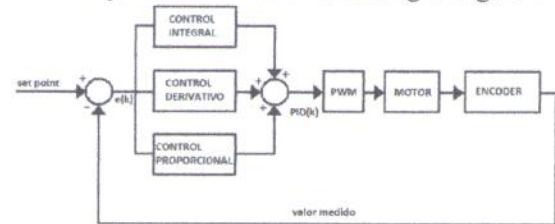


Figure 15 System Structure

VI. STATE OF THE ART

A. REGENERATIVE BRAKING

Some applications of regenerative braking on electric and hybrid vehicles, reports related to the subject give only a general idea of its operating principle. Similarly, the items related to the subject give us a theoretical basis for understanding the regenerative braking. In the article, "Regenerative braking system for a hybrid electric vehicle" by SR Cikánek and KE Bailey [8], is analyzed, the regenerative braking system (RB) for a parallel hybrid electric vehicle (PHEV), which performs the energy recovery vehicle. There is a description of the regenerative braking algorithm and the simulation results of a PHEV's dynamic model using regenerative braking. In the article, "Modeling and simulation for hybrid electric vehicles. II. Simulation" He Xiaoling and Hodgson, J.W [9], is used, the model of a hybrid electric vehicle

(HEV) based on the model developed for a parallel HEV, built at the University of Tennessee, Knoxville (UT-HEV). The simulation results for the UT-HEV predict vehicle performance and provide improved of the vehicle control. The simulation model provides the ability to recover energy through the regenerative braking, depending on the speed and acceleration. In the article, "Regenerative Braking for an Electric Vehicle Using Ultracapacitors and Buck-Boost Converter" John W. Dixon, Micah Ortuzar and Eduardo Wiechmann[9], shown, a control system for an electric vehicle batteries and ultracapacitors. The purpose of this device is to allow acceleration and deceleration of the electric vehicle with minimal energy loss, and minimal use of the battery bank. In times of slowdown regenerative brake converts kinetic energy into electrical energy which is stored in the ultracapacitor.

B. CONTROL SCHEMES

Another important aspect from the standpoint of research, control methodology is to be used for the controller design. Some research modeling of electrical systems are shown:

- The thesis of Gerardo Vicente Guerrero Ramirez, with the theme "Modeling and Simulation of Drive Systems Three Phase Induction Motors"[10] show, models based on the theory framework, simulating different operating conditions of each of the electronic converters that make up the proposed drive system and the induction motor used. Knowledge of its characteristics and its proper interpretation depends on making the right decisions for the selection of equipment supply, protection, control and engine load of squirrel cage induction.

Neural networks and fuzzy logic as universal approximates multivariate functions, [12, 13, 14, 15, 16, 17, and 18].

With the help of fuzzy logic, it is to gain entrance relationship - desired output from the training data. Desired output - For the relationship ANFIS® use of architecture (Adaptive Neuro Fuzzy Inference System-based), which is achieved by constructing a set of if-then rules, with functions of membership functions for the relation input-desired output [13].

VII. ADVANTAGES AND DISADVANTAGES

7.1. ADVANTAGES

- During the conventional braking, part of the kinetic energy is absorbed by the brakes and turned into heat. Thus with the use of regenerative braking, the increased range of an electric vehicle reaches between 5% and 10%. Along with this, the brake wear is reduced and therefore the maintenance costs are reduced, too.
- Increase the autonomy of electric and hybrid vehicles as well as improving their performance and zero emission of polluting gases.

7.2. DISADVANTAGES

- The complexity of the regenerative braking system has made it difficult introduction massively in the various markets of electric vehicles.
- A regenerative braking system is not able to meet all the requirements of braking a car.

VIII. METHOD

The electric-electronic media is important for the project, because without the necessary components and sensors, the system would be incomplete and exposed to multiple errors.

For this project, a series of components used in the Table 1 describes the most relevant.

Sensor or Device	Serial
Motor DC with encoder	100:1 Metal Gearmotor 37Dx57L mm with 64 CPR Encoder
MOSFETs	IRF540 y IRF9540
Bidirectional current sensor	ACS759ECB-200B-PFF-T
Microcontroller	mbed npx lpc1768
Battery	PowerStar 12V 100AH SLA

To meet the objectives 4 units of the engine shown in Figure 16 were used.

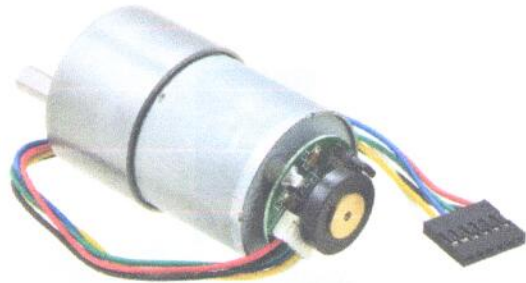


Figure 16. Motor 100:1 Metal Gearmotor 37Dx57L mm with 64 CPR Encoder

These motors must be able to start the vehicle with their respective weight necessary to generate a considerable kinetic energy in flat stretches, downhill slopes and have the ability to climb certain slopes you consider in the study. Also the vehicle must have the autonomy to keep moving for a considerable time that allows for the measurements that are studied in the project.

IRF540 MOSFET (n-channel) and IRF9540 (p-channel) are shown in Figure 17, it was chosen because it can withstand the voltage and current used by the motor, 3 amps and 12 volts respectively.



Figure 17. The field effect transistor metal-oxide-semiconductor or MOSFET

The current sensor is an electronic device that allows us to evaluate in real time the current is being conducted in a given circuit. This sensor is able to measure the goodness of the current in both directions of current flow.

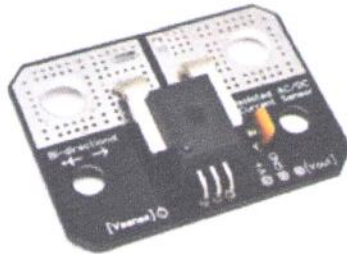


Figure 18. Bidirectional current sensor

The microcontroller is an embedded system considered as a computer at the micro level, the mbed NXP LPC1768 is a microcontroller, which is designed for prototyping of all types of devices, especially those that include Ethernet, USB, and the flexibility of a plenty of peripheral interfaces and FLASH memory.

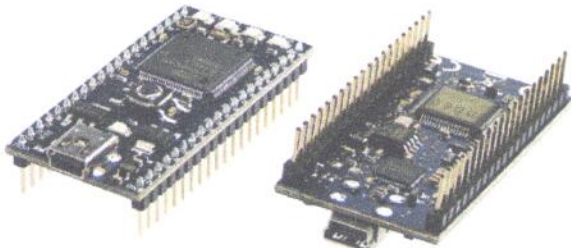


Figure 19. Mbed npx lpc1768

The block diagram is shown in Figure 19. It shows the development of the project, where each function determines the vehicle specifications.

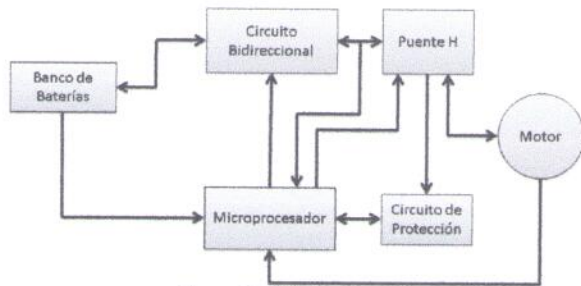


Figure 20. Blocks diagram

In addition to the block diagram, it is essential to have a means to implement the objectives specified, and this can be done by establishing more specific functions that are not covered by the block diagram, so the conceptual diagram is described in Figure 20.

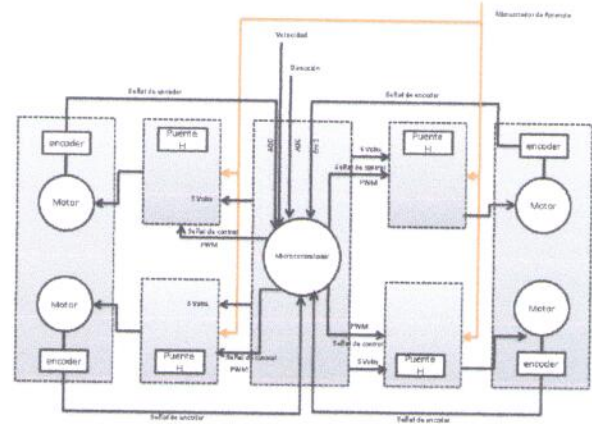


Figure 21. Conceptual diagram

It should also have the configuration and arrangement of space in the vehicle, as shown in Figure 21.

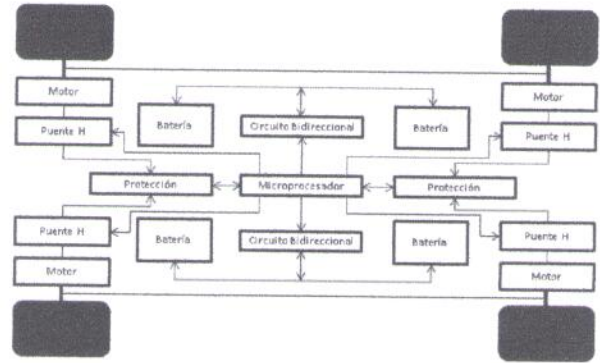


Figure 22. Settings for the vehicle architecture ackerman

KINEMATIC MODEL OF THE VEHICLE

The vehicle develops an Ackerman architecture, a description of this architecture is shown in Figure 12, which is applicable to the calculation.

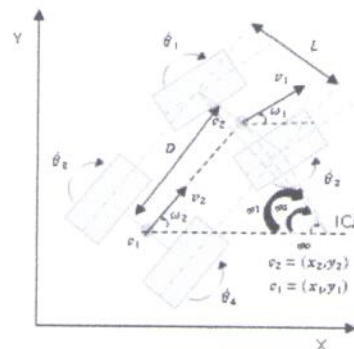


Figure 23. Ackerman Architecture

L = lateral spacing between the wheels.
 D = longitudinal spacing between the wheels.
 ω = It is the angular velocity of the vehicle.
 v = linear vehicle speed
 θ = rotation angle of the vehicle.
 R = ICC radio
 x_c = position on the axis X of the C_1
 y_c = position on the axis Y of the C_1

Calculating the speed (v):

$$v_i = \dot{\theta}_i * r \dots (10)$$

r , the radius of the wheels.

$$\rightarrow = \frac{v_1 + v_2}{2} \dots (11)$$

$$\rightarrow = \frac{v_3 + v_4}{2} \dots (12)$$

According to the figure representing the kinematic model for the ackerman architecture, Equation 15 that relates the direction of the front wheels is obtained.

$$\cot(\theta_i(t)) = \frac{(R - \frac{L}{2})}{d} \dots (13)$$

$$\cot(\theta_o(t)) = \frac{(R + \frac{L}{2})}{d} \dots (14)$$

By matching the instantaneous curvature radius R in equation 13 and 14, it is:

$$\cot(\theta_o(t)) - \cot(\theta_i(t)) = \frac{L}{d} \dots (15)$$

In the figure, it has placed an imaginary additional wheel, between the two front wheels. If we leave aside the two actual front wheels, we can see a tricycle architecture. Then, to calculate the angle of rotation of the additional wheel, matching R in the equation 16 with equations 13 and 14, the equation 17 is obtained.

$$\cot(\theta_s(t)) = \frac{R}{d} \dots (16)$$

$$\cot(\theta_s(t)) = \cot(\theta_i(t)) + \frac{L}{2d}$$

$$\cot(\theta_s(t)) = \cot(\theta_o(t)) - \frac{L}{2d} \dots (17)$$

$\theta_s(t)$, It is equivalent to the angle α_s , in equations calculated for architecture tricycle.

The vehicle speed v is the speed that possess the drive wheels, which are the rear wheels of the Ackerman architecture.

Then, V_s , that is the imaginary wheel speed is calculated as shown in Equation 18.

$$V_s = \frac{v}{\cos(\theta_s(t))} \dots (18)$$

Now to get the position of the vehicle equation 18 is replaced by:

$$\omega_1(t) = \frac{V_s(t) \sin(\alpha(t))}{d} = \dot{\theta} \dots (19)$$

Again you can get the vehicle speed by the equation 20:

$$v(t) = V_s * \cos(\alpha(t)) \dots (20)$$

The equations for \dot{x}_c and \dot{y}_c which are the final equations indicating the vehicle location, they are written as Equations 21 and 22.

$$\dot{x}_c = v(t) \cos(\theta(t)) = V_s(t) \cos(\alpha(t)) \cos(\theta(t)) \dots (21)$$

$$\dot{y}_c = v(t) \sin(\theta(t)) = V_s(t) \cos(\alpha(t)) \sin(\theta(t)) \dots (22)$$

The matrix representation of equations 19,21 and 22 is:

$$\begin{bmatrix} \dot{x}_c(t) \\ \dot{y}_c(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} \cos(\theta(t)) & 0 \\ \sin(\theta(t)) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v(t) \\ \omega_1(t) \end{bmatrix} \dots (23)$$

Then, for the position of the vehicle. We integrate Equation 23, as shown in equations 24,25 and 26.

$$x_c = \int_0^t v(T) \cos(\theta(T)) dT \dots (24)$$

$$y_c = \int_0^t v(T) \sin(\theta(T)) dT \dots (25)$$

$$\theta_c = \int_0^t \omega(T) dT \dots (26)$$

VEHICLE DESIGN

Taking into account the kinematic equations and constraints of these, we proceeded to make the vehicle design in the Software Solidworks 2014, remaining as shown in Figure 23.

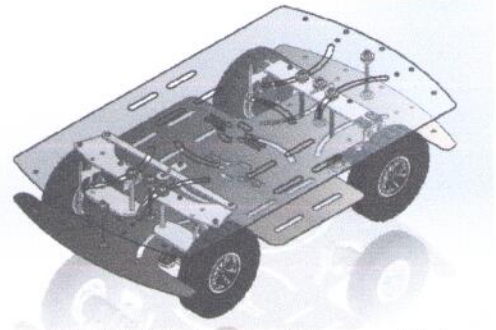


Figure 24 Vehicle design based on Ackerman architecture

CALCULATION H-BRIDGE

To perform our bridge plate H, Eagle use the software, leaving the schematic as shown in Figure 24:

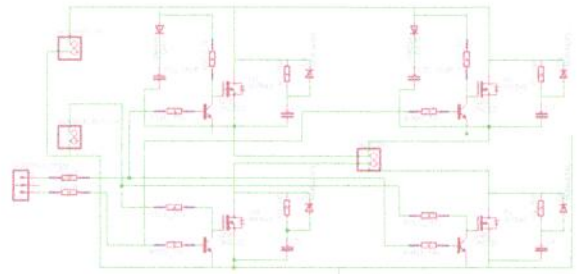


Figure 25 H bridge scheme

In our case, we had to use the MOSFET IRF540 as it supports up to 28 amps of current drain-source, which suits our purpose. To modify the PWM motor speed used in the gate of the MOSFET, which is to control the duty cycle by programming. In applying the PWM, the working frequencies are about 10 kHz. So we noticed peak current in the MOSFET, to solve this problem had to design a Snubber, this circuit cannot be simulated in this software because it does not contain all the details of certain components such as power MOSFET, which is why their design was performed experimentally using the signals on an oscilloscope.

PID CONTROL DESIGN

We know the PID control algorithm in continuous time is as follows:

$$u(t) = K \left[e(t) + \frac{1}{Ti} \int_0^t e(t) dt + Td \frac{de(t)}{dt} \right] \dots (27)$$

When we pass the domain of S, PID control can be written as follows:

$$U(S) = K \left[1 + \frac{1}{TiS} + TdS \right] E(S) \dots (28)$$

To perform this digital level control must be discretized control law, in our case should discretize the PID control law. For this we will use the Z transform, which we have:

$$\frac{U(z)}{E(z)} = Kp + \frac{Kp \cdot T}{Ti(1-z^{-1})} + Kp \cdot Td \cdot \frac{(1-z^{-1})}{T} \dots (29)$$

This equation represents the discretization of a position PID control, but our focus is on a digital PID control of speed, for which we have:

$$\frac{U(z)}{E(z)} = Kp + \frac{Kp \cdot T}{Ti(1-z^{-1})} + \frac{N \cdot T(1-z^{-1})}{Td + NT - Td \cdot z^{-1}} \dots (30)$$

Where T is chosen our period, now the next step is to transform the equations are transformed Z difference equations so that we can implement the control law in the mbed.

For this we perform the inverse Z transform, from which we get:

$$Uk = Uk1 + a \cdot Ek + b \cdot Ek1 + c \cdot Ek2 \dots (31)$$

Where:

Ek = Reference value – Sensed value.

$$a = Kp + \frac{Kp \cdot T}{Ti} + \frac{Kp \cdot Td}{T} \dots (32)$$

$$b = Kp + \frac{2 \cdot Kp \cdot Td}{T} \dots (33)$$

$$c = \frac{Kp \cdot Td}{T} \dots (34)$$

Now, you have the control law in difference equations, all that remains is to implement them in the equation Uk with Kp , Ti and Td engine parameters, choosing a sampling time T with which they will work.

IX. RESULTS

Taking as reference the project's objectives it is demonstrated by testing the behavior of the speed at different slopes and speeds.

We use mbed microcontroller to be small and have a high throughput for system control and memory requirements necessary. In the pictures below you can see the voltage at the motor applying different "duty cycle":

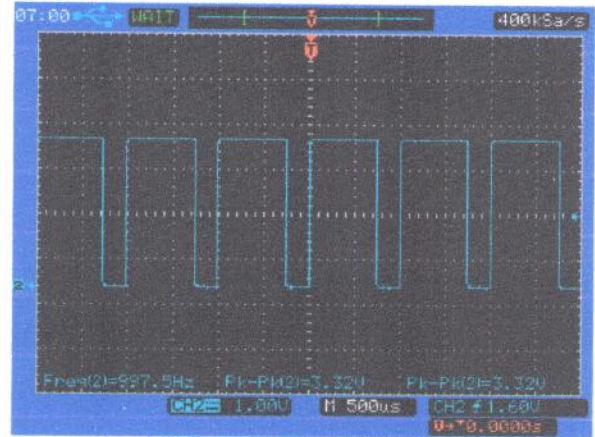


Figure 26 Signal of mbed with 75% Duty Cycle.

In the picture below, we can see that the deformation of the wave in the engine is low and has managed to avoid current peaks achieving a nearly square wave:

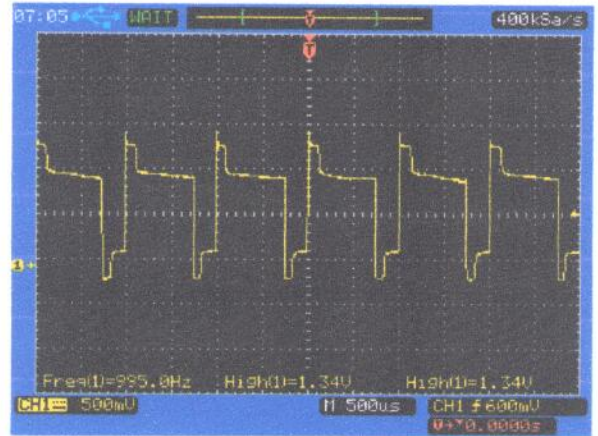


Figure 27 Voltage at the motor with a duty cycle of 75%.

In this image we can see the classic 50% duty cycle, which serves to reduce the motor speed to half, with the mbed we achieve a nearly perfect square wave 1KHz:

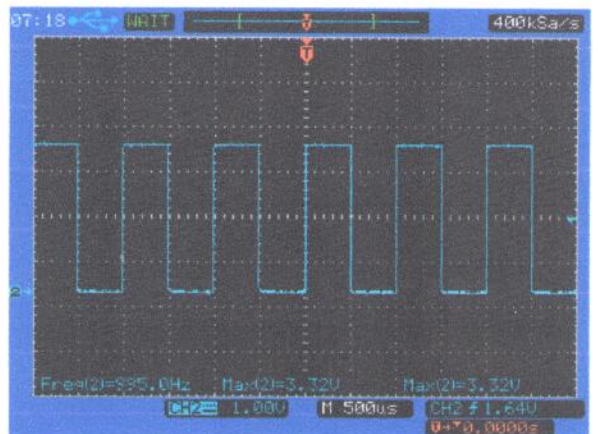


Figure 28 Signal of mbed with a 50% Duty Cycle.

With the above we get the following signal waveform in the motor:

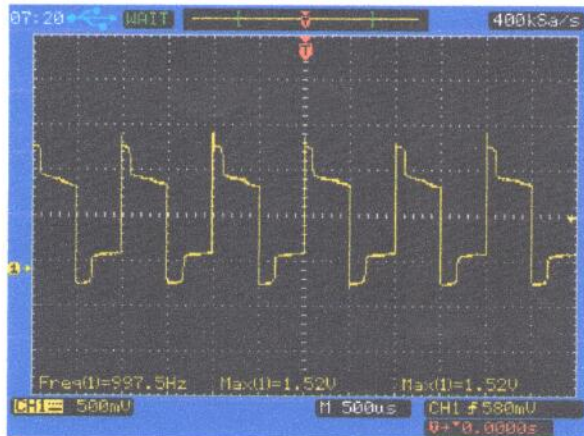


Figure 29 Voltage at the motor with a duty cycle of 50%.

For lower speeds use a PWM duty cycle of 25%, so we reduce the engine speed to the quarter:

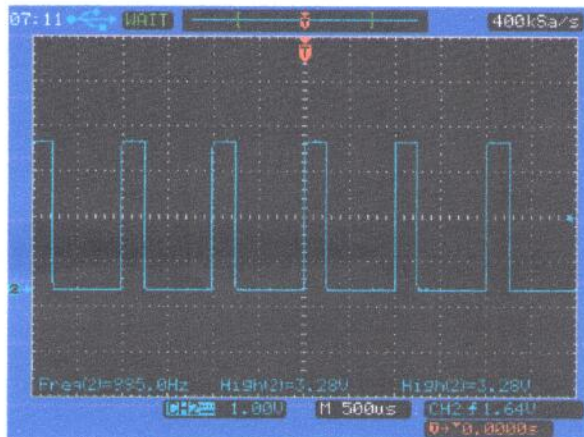


Figure 30 Signal of mbed with a 25% Duty Cycle.

In applying the PWM duty cycle mbed with 25%, as seen in the picture above we obtain the following waveform:

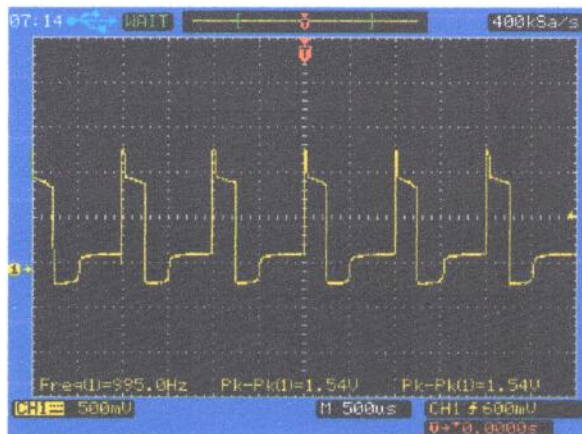


Figure 31 Voltage at the motor with a duty cycle of 25%.

X. DISCUSSION

At first the project application, it showed it was not feasible due to the high cost of electronic devices, why certain thus achieving the project feasible devices designed. This regenerative braking technology already exists but it's not applied to all subject areas mainly due to economic and adaptation to current systems issues. With this project, we disclose more energy saving topic-showing results showing the effectiveness of this system.

XI. FEASIBILITY

The feasibility of this system is reflected in the energy saving in the various systems have to be applied; these energy savings will be able to compensate for the initial financial expenditure on the implementation of this system also soon be profitable for users. A cost estimate for the implementation of full-scale project was conducted, shown below in Table 1.

Cost Estimation, USD	
Development	150
Components	543.58
Devices	250
Software	200
Total	\$1,143.58

Table 1. Estimated cost for the project implementation.

XII. RECOMMENDATIONS

For the use of regenerative braking it is necessary to have prefaced sections on the slopes, no matter the pitch. Additionally, it is recommended to use electric motors that incorporate a gearbox to prevent the incorporation of mechanical linkages that affect system efficiency.

The steering system of the vehicle is not accurate and therefore it is possible to use a simpler geometry to establish an optimal motion control.

XIII. CONCLUSIONS

The efficiency of the bidirectional circuit functioning as a power supply for charging 600 mA is consumed within the ranges established and known functionality of switching sources of Boost and Buck configurations, which have a linear transfer function.

As the motors are coupled directly to the wheels, for tuning motion control and engine brake it is based on the response speed of the electrical system. Because of this, times are less than or equal to the second order.

According to the data obtained in the tests could prove braking to recharge the battery using the

concept of regenerative braking on steep sloping longer necessary to generate an inertia in the vehicle capable of increasing the BEMF generated by the motor.

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