DIGITAL MOTOR CONTROL FOR ELECTRIC VEHICLE POWERTRAIN IMPULSE

CONTROL DIGITAL DE MOTOR PARA IMPULSO DE TREN MOTRIZ DE VEHÍCULO ELÉCTRICO

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Reception: 8/november/2024 **Acceptance**: 27/december/2024

Abstract

This paper presents the modeling, design, and development for a digital motor control (DMC) based in the phase-angle control (PAC), to impulse the powertrain of an electric vehicle (EV). Looking to generate an easy, adaptive, and economical process for electric conversion of internal combustion vehicles, where the original traction system based on an internal combustion motor is replaced by four electric traction systems, one each wheel. The simulations, the development, the results, advantages, and disadvantages of this method are presented in this paper.
Keywords: Electric Vehicle, Digital motor control, Phase-Angle Control, Powertrain Impulse.

Resumen

Este trabajo presenta el modelado, diseño y desarrollo de un control digital de motor eléctrico (DMC) basado en el control angular de fase (PAC), para impulso de *tren motriz de un vehículo eléctrico (EV). Con el objetivo de generar un proceso sencillo, económico y adaptable para la conversión de vehículos de combustión interna, donde el sistema original basado en un motor de combustión es remplazado por cuatro sistemas de tracción eléctricos, uno por cada llanta. Las simulaciones, el desarrollo, los resultados, ventajas y desventajas de este método son presentados en este documento.*

Palabras Clave: *Control digital de motor, Control angular de fase, Impulso de tren motriz, Vehículo Eléctrico.*

1. Introduction

To reduce the emission of polluting gases into the atmosphere, the EU has forbidden registering any new car with an internal combustion motor after 2035 [Lecon, 2023]. This will be very good for the environment and improve the society's life. But this change will also bring another problem, what to do with all the billions of vehicles that will be obsolete, not to mention the high cost for people to change their vehicles. Because it's well known that electric cars today are very expensive.

Indirect field-oriented control (IFOC) and direct torque control (DTC) are often used as torque converters [Bazzi, 2009]. Both use an inverter to directly control the torque of the motor, using space vector pulse width modulation (SVPWM) to calculate the variations of the commutations in the MOSFETs. IFOC and DTC drives are often used to control 3-phase AC motors but can also be used in monophasic applications.

These schemes achieve fast dynamic response, low switching frequency, and harmonic reduction [Durán, 2014]. The disadvantage of this schemes is that the robust control strategy requires so much computational cost, requiring expensive control units. The same thing in [Sallem, 2009] and in [Zerzeri, 2019], where an inverter is used to feed a doubly fed electric machine (DFIM) with a robust nonlinear control strategy based on the classical power distribution.

In [Castro, 2017] a PAC method is used to design a speed control of a universal motor. PAC is a method of power control applied to AC voltages. It works by modulating a TRIAC, SCR, thyristor or thyratron at a predetermined phase angle of the applied waveform. When properly activated, their power dissipation is minimal due to the low resistance path between the anode and cathode, and the external components are also minimal and less complex, making them the perfect device for low-cost applications and an easy implementation [Castro, 2017].

For these reasons, PAC was selected as the more appropriate technology to use in this project, carrying out some improvements to the system proposed, the first one is that this project will use an inverter, but only as an AC source. Leaving the control task to another module call DMC. The second improvement is that this design will include a digital controller with a zero-crossing detector to synchronize firings and obtain better resolution. In this work the closed-loop control for the project is not yet ready, but the motor can be controlled in open loop, leaving the closed-loop control strategy for the next project update.

The objective of this work is to contribute to the development of new systems for converting internal combustion vehicles into electric vehicles, with the aim of achieving social benefits and improving the climate. Also, with the goal of developing an economical system, it is proposed to use a motor that is widely available in the world, the same one that uses a modern washing machine, with a cost of only $50USD. This motor is not that powerful, but it's not that weak either. The proposed motor is shown in Figure 1 and its technical characteristics are given in Table 1.

Source: own photo

Figure 1 Motor proposed: Model: C68XGKC-4566.

The proposed system is simple, the batteries feed an inverter converting direct current (DC) into alternant current (AC), then the DMC controls the motor torque, sending the power traction to the gearmotor, and finally to the wheel. The simplicity of this design ensures an easy implementation and a modular design of EV components, allowing easy updates to the system.

Table 1 Technical characteristics of the proposed motor.

Parameter	Description	Value
ω	Angular velocity	$1800\ rpm$
P	Nominal power	$560\ W$
I	Nominal Current	$9.8\ A$
Topology	Monophasic	$120\ V$

Source: own elaboration

The main difference with other works is that the drive control is separated from the switching scheme (inverter). This is trying to reach 3 goals:

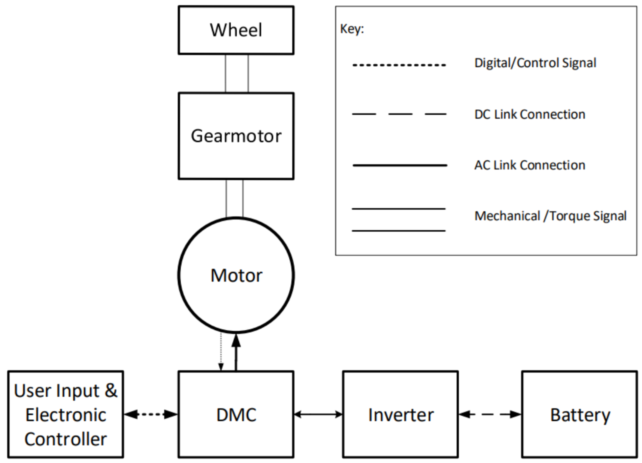
- Make a modular design, where its components are easier to replace.
- Simplify the design of the controller and its calculations.
- Investigate new combinations of drive controllers and switching schemes [Bazzi, 2009].

2. Methods

The first method is a calculation of the torque required by the traction system. Then, the inverter is modeled, calculating the losses generated by the harmonic components to reduce them. Finally, the modeling and design of the powertrain control system, which will allow the user to choose between acceleration, deceleration and reverse.

Diagram of the electric drive system

To understand more this proposed system, a block diagram is presented, with all the modules planned for the traction system. Let´s remember that this traction system is applied directly on wheel. This work is presenting mainly the design of the Inverter, the DMC and the User Input & Electronic Controller. Figure 2 shows the diagram of the electric drive system.



Source: own elaboration

Figure 2 Block diagram electric drive system.

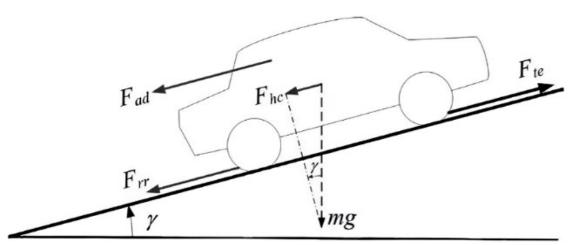
Calculus of the required torque

The Figure 3 shown the forces acting on EV moving on a slope with angle (γ). The friction force F_{rr} between the tires and the surface on which the vehicle moves is given by Equation 1.

$$F_{rr} = \mu_{rr} m g \tag{1}$$

Where:

- μ_{rr} : Static coefficient of friction given by the relationship between the wheels (rubber) and the road (concrete), and its value is 0.01.
- m : Vehicle mass $[kg]$.
- g : Gravity acceleration$[m/s^2]$.



Source: Durán M., Universidad de Antioquia, Colombia

Figure 3 Forces acting on EV.

The aerodynamic drag F_{ad} is the force that opposes the motion of a vehicle due to air resistance, it is defined in Equation 2.

$$F_{ad} = \frac{1}{2}\rho A C_d \vartheta^2 \quad (2)$$

Where:

ρ : The air density [kq/m3].

A : The vehicle front area [m^2].

C_d : The drag coefficient, and its value is 0.19.

ϑ^2 : Vehicle's speed [m/s].

The hill climbing force F_{hc} (with positive operational sign) and the downgrade force (with negative operational sign) are given by Equation 3. Where γ is slope angle.

$$F_{hc} = mgsin(\gamma) \quad (3)$$

The traction force F_{te} is given by Equation 4.

$$F_{te} = \frac{1}{2}\rho A C_d \vartheta^2 + \mu_{rr} mg + mgsin(\gamma) \quad (4)$$

The traction torque T_{te} is given by Equation 5. Where r is the wheel radius.

$$T_{te} = [\frac{1}{2}\rho A C_d \vartheta^2 + \mu_{rr} mg + mgsin(\gamma)] \cdot r \quad (5)$$

And the traction torque in each wheel T_w is given by the Equation 6.

$$T_w = \frac{r}{4}[\frac{1}{2}\rho A C_d \vartheta^2 + \mu_{rr} mg + mgsin(\gamma)] \quad (6)$$

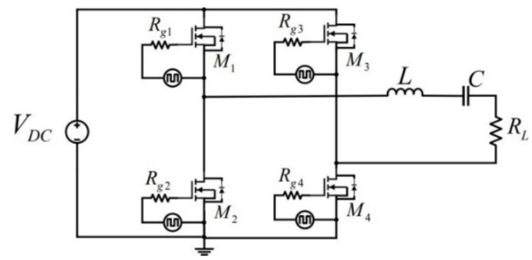
Design of the inverter

An inverter uses transistors to convert DC to AC voltage. Approaching the commutation generated by signals from the computer or generator device. A PWM signal at 60 [Hz] and its reverse signal are used to activate and deactivate four MOSFET transistors to obtain a square wave. A resonant network is then used to convert the square wave into a sinusoidal signal.

Topology

For this work, the classic topology of monophasic full bridge has been chosen, because it is considered the more efficient and used for power applications

[Khan, 2020], furthermore we consider it easier to implement, leaving then the control of the motor to the DMC. Also, with this topology we can generate an AC wave using only a PWM with its inverter to commutate the MOSFETs. Figure 4 shows this topology with a series RLC resonant circuit [Lara, 2022].



Source: Lara, J., ESIME Culhuacán, México

Figure 4 DC-AC Inverter with resonant circuit.

Design Parameters

The next step on the design process is to define the desired values at the output of the inverter, to get what we need at the output. Table 2 shows the required design parameters.

Table 2 Inverter design parameters.

Parameter	Description	Value
P_{RMS}	Power Out	$2.2\ kW$
V_{RMS}	RMS voltage	$120\ V$
F	Frequency	$60\ Hz$
D	Duty cycle	50%

Source: own elaboration

THD and DF

A major drawback of this inverter topology is that in low or medium power applications, the output voltage contains harmonics that cause overheating of the equipment and malfunctions such as vibration in the motors. The calculation of the total harmonic distortion (THD) and the distortion factor (DF) are needed to analyze the efficiency of the inverter and then try to eliminate the maximum values of the harmonic components in the output signal of the inverter using a second order filter [Shahina, 2016]. In this topology, the RMS voltage obtained in the load resistor is calculated using Equation 9.

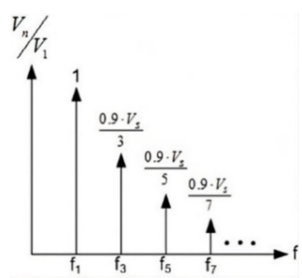
$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^{\frac{T}{2}} (\frac{V_s}{2})^2 dt + \frac{1}{T}\int_{\frac{T}{2}}^{T} (\frac{V_s}{2})^2 dt} = V_s \tag{9}$$

And then the analysis of THD with the Fourier series in Equation 10. Where $n = 1$, is presented as the fundamental component of the signal and $n = 3, n = 5, n = 7$..., etc. are known as the harmonics of the signal. These components are calculated using the Equation 10, resulting the equations 11 and 12. In Figure 5 it's shown the harmonic components until f7.

$$V_{R(t)} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4 \cdot V_s}{n \cdot \pi} \cdot \sin(n \cdot \omega \cdot t) \tag{10}$$

$$V_{1RMS} = \frac{4V_s}{\sqrt{2}\,\pi} = 0.9\ V_s \tag{11}$$

$$V_{3RMS} = \frac{4V_s}{3\sqrt{2}\,\pi} = \frac{0.9}{3}\ V_s \tag{12}$$



Source: Hernández, J., ESIME Culhuacán, México

Figure 5 Harmonic components of the signal.

Then the THD parameter is calculated with the Equation 13. And the DF parameter is calculated with the Equation 14.

$$THD = \frac{\sqrt{(V_{RMS})^2 - (V_{1RMS})^2}}{V_{1RMS}} \tag{13}$$

$$DF = \frac{\sqrt{\sum_n^{\infty}\left(\frac{V_{nRMS}}{n^2}\right)^2}}{V_{1RMS}} = \frac{\sqrt{\left(\frac{V_{3RMS}}{3^2}\right)^2 + \left(\frac{V_{5RMS}}{5^2}\right)^2 + \cdots + \left(\frac{V_{nRMS}}{n^2}\right)^2}}{V_{1RMS}} \tag{14}$$

Then a resonant network is used to reach 2 goals:

- Convert the squared AC wave into a sinusoidal AC waveform.

- Decrease the THD and the DF parameters, to avoid the maximum number of harmonic components.

Resonant network

To calculate the resonant circuit, it is necessary to calculate the desired fundamental component using Equation 15, the inductance and capacitance using the design parameters and equations 16 and 17. A value of Q=10 it´s been considered. And finally, using Equation 18 to calculate the V_s equal to the DC bus that ensures the required V_m.

$$V_m = \sqrt{2PR} \tag{15}$$

$$L = \frac{Q\ R}{\omega} \tag{16}$$

$$C = \frac{1}{L\ \omega^2} \tag{17}$$

$$V_s = \frac{\pi\ V_{1peak}}{4} \tag{18}$$

To simplify the calculation of the resonance network parameters and to perform various simulations before designing the inverter, the LTspice software is used. Figure 6 shows the circuit of the calculated inverter, and Figures 7 and 8 show the RMS voltage and RMS power as simulated by LTspice.

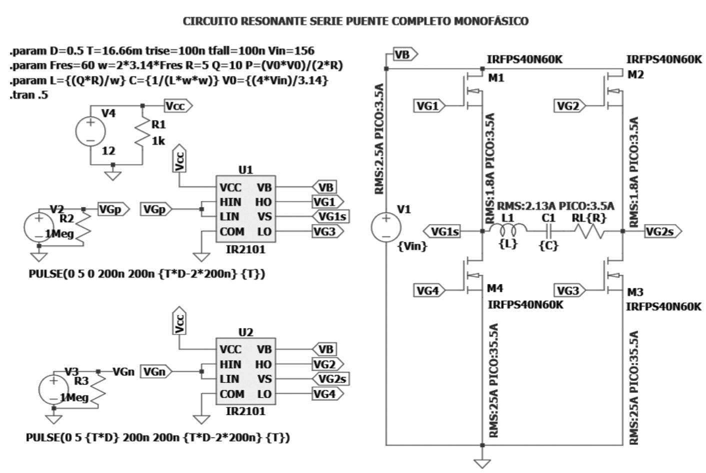


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Figure 6 Calculated inverter with resonant network.

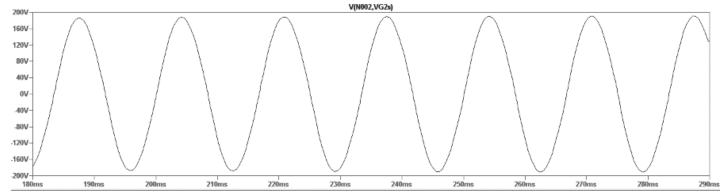

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Figure 7 AC Voltage $120\ V$ RMS.

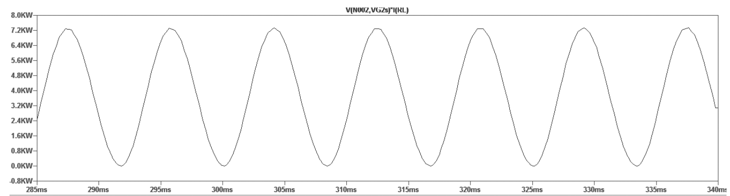

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Figure 8 AC Power $3\ kW$ RMS.

PCB Design with Proteus

Once the calculation and simulation from LTspice is done, the Proteus program is used to print and manufacture the printed circuit board (PCB). Proteus is another great tool for simulating circuits, but with the advantage that it can design and print the PCB. Figure 9 shows the inverter circuit designed in Proteus.

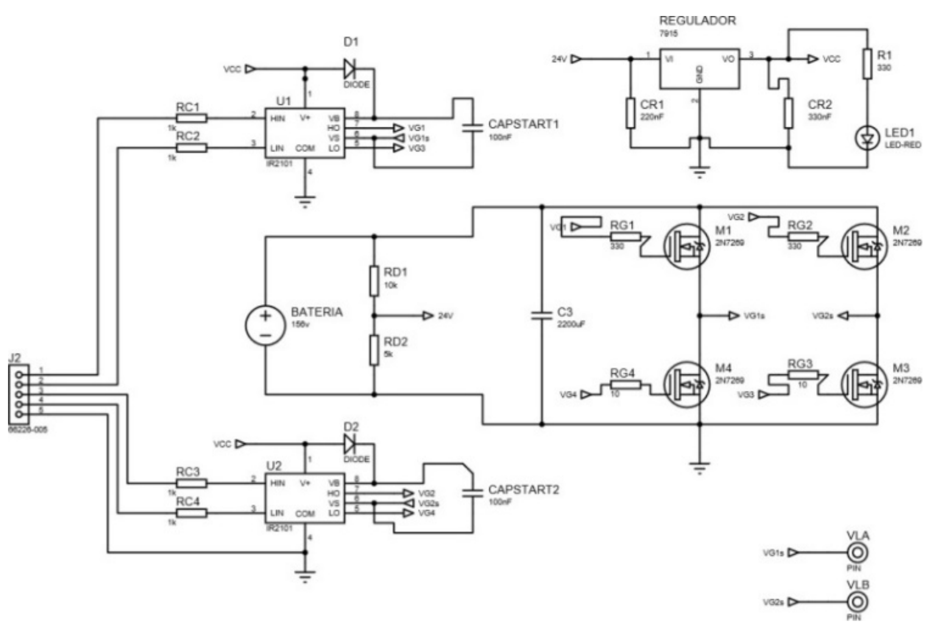

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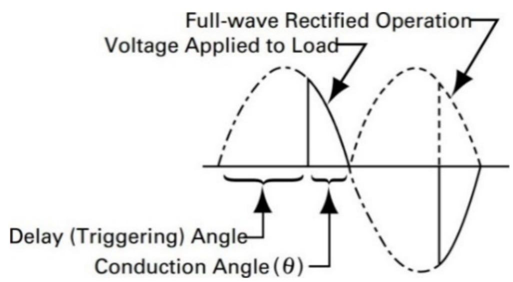
Figure 9 Circuit of the inverter designed in Proteus.

Designing the PAC

This device is a combination of an optocoupler and a TRIAC. The optocoupler is a device that is controlled by a digital signal that comes from the microcontroller and when it receives the 1 logic, activates a TRIAC in the out, this process it's known as "TRIAC trigger". The TRIAC is a bidirectional semiconductor that can control the flow of voltage and current from an AC source (like the one fed by the inverter) using a gate to activate or deactivate the signal. It's like a transistor but used with AC voltage. It can handle high current and high voltage, making it the ideal device for controlling high power. The method involves cutting the AC waveform at exactly the desired angle (or wave period) to control the RMS voltage at the output. In Figure 10 shows the operation of PAC method.



Source: Littlefuse, Chicago, United States

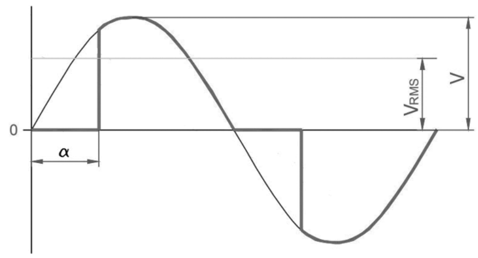
Figure 10 Cutting the wave with a PAC method.

Cutting angle calculation

The RMS voltage at the output of the circuit is related to the angle α, so as the angle increases the VRMS decreases and vice versa. Figure 11 shows the relationship between the angle of the cut and the VRMS. Equation 19 relates two variables. And the Table 3 shows the translation of the angle in milliseconds as a variable that can be managed by the microcontroller as a control delay for the TRIAC trigger.

$$V_{RMS} = \sqrt{\pi - \alpha + \frac{1}{2}\sin 2\alpha} \qquad (19)$$

The maximum cut-off angle for the motor to operate correctly was determined to be $95\ degrees$, or $4.4\ ms$ of TRIAC activation delay.



Source: own elaboration

Figure 11 The relation between the angle of cut and VRMS.

Table 3 Milliseconds according to the angle's cut.

Angle	Milliseconds
0°	0
45°	2.08
90°	4.16
135°	6.24
180°	8.33

Source: own elaboration

Flux diagram of the control program

This part shows the flux diagram that follows the program and allows the user to control the angular velocity and direction of rotation of the motor, Figure 12.

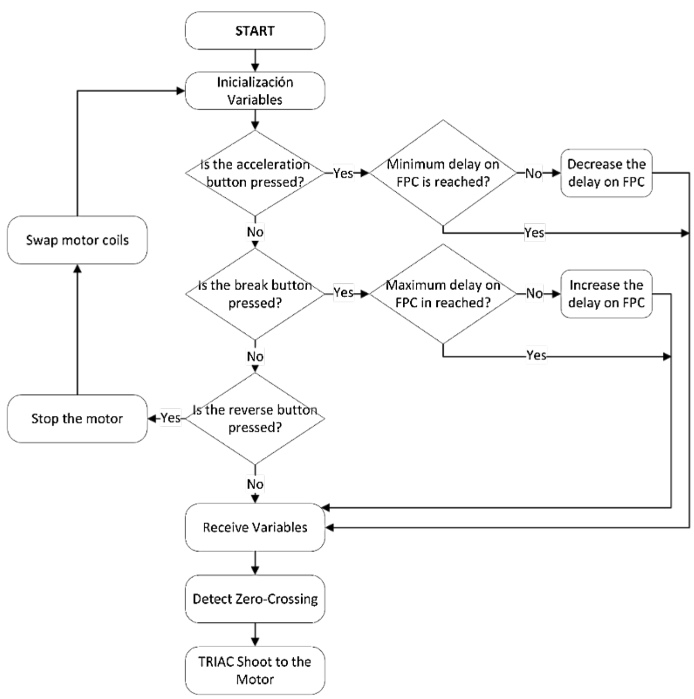


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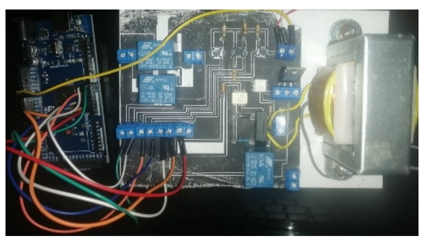
Figure 12 Flux diagram of programming in the microcontroller.

The program was made with language C, using an Arduino, to receive the signal of sensors, make calculations and send a response to the actuator. At first glance it might seem that a microcontroller like the Arduino Uno would not be able to perform all the calculations for this speed controller, but the structured and simple programming allows almost any controller on the market to work for this project.

3. Results

After all the methods used to generate pure sinusoidal alternating current through the inverter and control the RMS voltage at the output of the device through the PAC method, the main objective has been achieved, which is the control of the motor's angular speed and direction of rotation by the user, through only 3 buttons. In this section, the final forms of motor control and the final circuit with the inverter and the PAC are related. Figure 13 shows the third functional prototype of the device. At the time of writing this article, the fourth prototype is being built, whose circuit is shown in Figure 14, and which is also completely usable by the reader.



Source: own photo

Figure 13 Third functional prototype of the device.

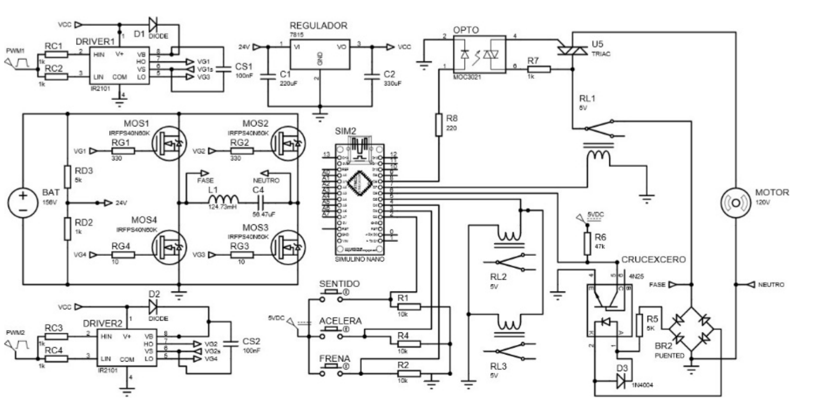


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Figure 14 Full circuit of this work.

Acceleration and Deceleration

For acceleration and deceleration, there are 2 buttons for the user to select. These buttons decrease and increase (respectively) the delay for the TRIAC trigger to cut the AC waveform at the desired angle, allowing the system to increase and decrease the angular speed of the motor by controlling the RMS voltage. It is important to note that another button or system is required to stop the vehicle. This part is not considered in this paper. Figure 15 shows the AC waveform chopped by PAC method in an ideal situation (controlling a resistive load).

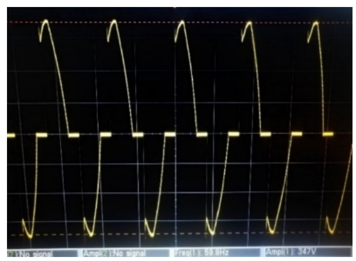

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Figure 15 AC waveform chopped by PAC seen on oscilloscope.

Zero-Crossing

Once the angle is parameterized, it is necessary to detect the zero crossing of the waveform, to send the trigger to the TRIAC at the required time, otherwise the waveform will be cut off in an incorrect shape and the motor will run poorly. To do this job, another optocoupler is needed to sense the waveform and send a logic 1 when it receives zero volts at the gate. It is important to note that the AC signal must be rectified and conditioned to enter the microcontroller. Figure 16 shows the zero-crossing detection on the proteus digital oscilloscope.

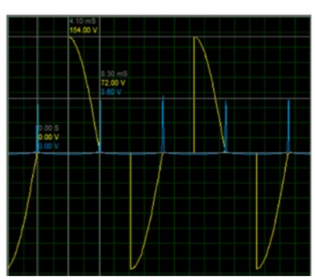

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Figure 16 Zero-crossing detection for the correct cut of AC waveform.

Reverse

To reverse, two relays are used to change the order of the coils in the motor. When the user pushes the reverse button, a deceleration sequence is started and then the motor stop relay is activated to stop the motor completely. Then two relays are activated (or deactivated, depending on the actual state) to exchange the cables of the coils in the motor, this changes the direction of rotation. Then motor activation relay is activated again, and a pre-defined sequence is executed to wait again for the user´s commands.

TRIAC Trigger

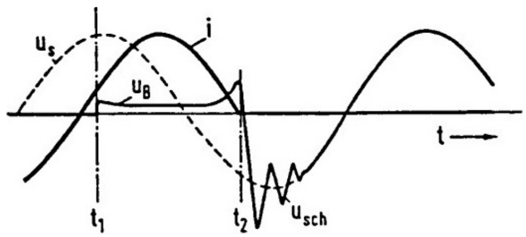
Finally, the last part of the circuit is designed. After all the calculations, the TRIAC receives the order to trigger and allow the alternating current wave to pass to the motor, only for the time indicated by the control, to deliver the RMS voltage necessary to accelerate ($\pm$). Figure 14 shows the complete circuit of this work.

4. Discussion

The device designed can be very light and small, making it ideal to save weight and cost in the manufacturing and the implementation in the vehicles. The use of the four traction systems seems very possible and a simple microcontroller can successfully control all the traction systems, due to the simplicity of the design. However, a disadvantage of this control method is that the energy losses due to the harmonic components are high. The nature of the charge in the motor is inductive so it deforms the waveform cut and generate vibrations in the motor and losses in heat, this represents a waste of energy and discomfort to the driver. Figure 17 shows the effect of breaking a resistive-inductive load, according to the AC principle.

One way to improve the system and avoid the high harmonic components is to implement a snubber circuit before the load to reduce the peaks generated in the AC wave. A snubber circuit is a device used to suppress the voltage transients in electrical systems generated by the sudden interruption of current flow to a large electromotive force (EMF). A properly designed RC snubber can be used with DC or AC loads.

This type of snubber is typically used with inductive loads such as electric motors. The voltage across a capacitor cannot change instantaneously, so a decreasing transient current flows through it for a fraction of a second, allowing the voltage across the switch to rise more slowly when the switch is opened.



Source: Schroder, K., Bochum University, Germany

Figure 17 Breaking a resistive-inductive load.

5. Conclusions

The digital motor control of the monophase motor is successful. Acceleration, deceleration, and reversal can be controlled by the user to increase and decrease the angular velocity of the motor. The RMS voltage can be controlled from $50\ [V]$ to $120\ [V]$ in a uniform way and the cost of the project was so much cheaper than other projects, due to the few devices that were used. In the future of the project this work can be easily replicated to the other wheels of the electric vehicle. It will be possible to control each wheel independently or synchronously, depending on the needs of the design or the function to be development, allowing new forms of vehicle movement, such as horizontal movement for easier parking. This device is not only capable of transforming an internal combustion motor vehicle into an electric vehicle, but it can also help to make it autonomous, to eliminate the need for a human driver to control the vehicle, since it can be easily adapted to vision, radar and GPS systems.

The future of this project is to control four wheels and synchronize them by closing the loop and measuring the speed of each wheel with encoders to properly control the speed of the vehicle. To control all the traction systems in the vehicle, a central computer or central command control is required, but due to the simplicity of the design of the device designed in this work, an FPGA or a microcontroller could be good enough to do the job, allowing the manufacturers to build a very economical conversion kit adaptable to any vehicle. Another thing to do is to avoid the harmonic component generated in the output of the DMC, the first thing to try is to calculate, design and implement an RC snubber circuit, to improve the efficiency of the system and make the user experience more comfortable, avoiding the vibrations and energy losses.

Also it's important to mention that the goal of this work is to help in the transition from the use of fossil fuels to the use of clean energies in vehicles, then this work can be used as a tutorial, since all the circuits and calculations have been tested to serve as a basis for more advanced projects, feel free and confident to use them to improve the world, clean the environment and promote technology for the benefit of society, nature and all living beings.

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