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A CASE-STUDY VISION

Brushless DC motor control system for active myoelectric prostheses

Sistema de control de motores de corriente directa sin escobillas para prótesis activas mioeléctricas

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ABSTRACT

A prosthesis is an artificial substitute for a missing part of the body that makes it possible to recover some degree of function of the lost limb. Prosthetics are classified as passive and active. These last ones require a driver system and a control system which are indispensable to determine if the motion a person is doing is executing effectively. In this sense, the driver system and the control system play a fundamental role in the functioning of active prosthetics when myoelectric sensors are used for their activation. The following paper presents the development of a Field Oriented Control of position for brushless direct current Motor equipped with Hall effect sensors. The system is built for a 5W EC-max 16 Ø16 mm brushless motor coupled to a GP 16 A Ø16 mm planetary reducer, together with an Arduino Uno board and a simple Field Oriented Control module. An open-loop position control system and a closed-loop position proportional-integral control system were implemented. The results indicate that closed-loop control shows a stability time, rise time, peak time and a steady state error less than the open-loop system. Also, that there is not notable hysteresis in the motor. These results will allow a more precise position control on a myoelectric prosthesis for transhumeral amputees.

RESUMEN

Una prótesis en un sustituto artificial para una parte faltante del cuerpo que permite recuperar en cierto grado la función del miembro perdido. Las prótesis se clasifican en pasivas y activas, estas últimas requieren un sistema de actuadores y sistemas de control los cuales son indispensables para determinar si el movimiento que la persona realiza es ejecutado efectivamente. En este sentido, el sistema de accionamiento y de control juegan un papel fundamental en el funcionamiento de

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las prótesis activas cuando se usan señales mioeléctricas para su activación. Así, en este documento se presenta el desarrollo de un sistema de control de campo orientado de posición para motores de corriente directa sin escobillas equipados con sensores de efecto Hall. El sistema está constituido por un motor de corriente directa sin escobillas EC-max 16 Ø16 mm de 5W acoplado a un reductor planetario GP 16 A Ø16 mm, una placa Arduino Uno y el módulo para el controlador de campo orientado. Se implementó un sistema de control de posición en lazo abierto y un sistema de control proporcional-integral de posición en lazo cerrado. Los resultados indican que el sistema de lazo cerrado presenta un tiempo de estabilidad, tiempo de subida, tiempo pico y error de estado estacionario menor que el sistema de lazo abierto. También se ha demostrado que no hay histéresis notable en el motor. Estos resultados permitirán realizar un control de posición más preciso sobre una prótesis mioeléctricas para personas con amputación transhumeral.

1. Introduction

A prosthesis is an artificial substitute for a missing body part that allows the function of the missing limb to be restored to some degree. Upper limb prostheses can be classified as passive or active. Passive prostheses are those that do not have the ability to perform complex actions and are limited to raising and lowering the arm. They are also known as cosmetic prostheses, since they only have the function of hiding the amputation. Active prostheses are motorized devices and sensors that mimic the movements of a human arm. These prostheses generally work through the activation of voluntary movement or intention of the movement where the device will respond to the function that the person is performing, this is called functionality, other types of active prostheses are used for rehabilitation processes, i.e., devices with pre-programmed routines for the person.

Currently, the market offers low-cost technologies and open source systems that can be used for the development of active prostheses. [1]. Myoelectric active prostheses that use myoelectric sensors to capture electrical signals from muscles when they contract or relax, replicate to some degree the movements of the upper limb with some limitations [2]. These prostheses take into account factors such as speed, strength, and accuracy in their performance [3]. However, the process of adapting a prosthesis for a person who has suffered an amputation can become complex, since initially there may be a rejection to the use of the prosthesis due to the discomfort that this can generate when it is installed in the amputee, this due to factors such as weight, or the generation in some cases unnatural movements to be performed.

One of the world's leading companies in the development of prostheses is Ottobock, a company that offers solutions that allow a great performance in the use of a prosthesis. However, the prices of their solutions are not affordable for a large percentage of people who have suffered amputations. One of the fundamental aspects in the development of active prosthesis is the actuator system, leading companies in the market use brushless DC motors (BLDC), with which they manage to improve the performance in the use of the prosthesis. BLDC motors have a reduced size compared to DC motors that provide the same torque and speed, in addition they can present efficiency levels of almost 100% [4]. [4], being thus the actuators that currently offer better performance levels in the use of active prostheses to position their axis at a required angle. [5], with an appropriate response time according to the generated control signal. However, one of the disadvantages when using a BLDC motor is the implementation of a control system that allows positioning the motor shaft at a required angle [6].

Thus, this paper presents the development of a position control system by means of field oriented control (FOC) for BLDC motors equipped with Hall effect sensors. The development includes the comparison of the system behavior under two position control strategies, (i) in open loop, (ii) in closed loop by means of a PI controller and (iii) a hysteresis test.

2. Theoretical Framework and State of the Art

2.1. BLDC motor

A BLDC motor is an electric motor that lacks brushes in its stator for commutation. A BLDC motor has windings that emit magnetic fields. The windings are located in the motor stator and a permanent magnet is used as the rotor. When there are more than two magnetic fields, the torque of the motor is going to align with these magnetic fields, if a rotating magnetic field is produced around the rotor, this causes the torque to chase the rotating magnetic field, spinning the rotor [7]. If the motor is equipped with Hall effect sensors, then these can detect these magnetic fields.

Figure 2 shows a BLDC motor, which consists of a permanent magnet (rotor) and stator windings. These windings are commutated with three-phase voltage. Hall-effect sensors detect the rotor positioning, allowing control of the motor by providing rotor positioning feedback to determine which voltage to apply to the windings, either positive, negative or zero, for a required rotor position. [8].

The advantages of BLDC motors are (i) no carbon brushes for commutation, lower maintenance costs, (ii) high efficiency, (iii) adequate torque, and (iv) adequate and controllable speeds. [9]. Among their disadvantages are that (i) they have higher costs, (ii) they require complex control systems [10](iii) suffer from vibrations and (iv) have audible noise [11] [11] . [11].

BLDC motors are applied in various areas, e.g. (i) automobiles, (ii) industrial automation, (iii) aerospace technology, (iv) washing machines, and (v) air conditioning. [12]. Ottobock Company uses BLDC motors for the drive systems of its upper limb prostheses. [13].

2.2. Oriented Field Control

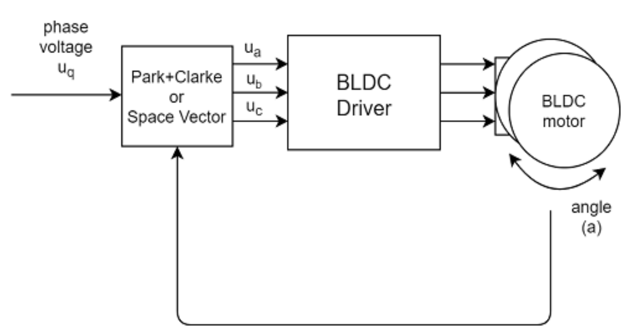
Field Oriented Control (FOC), also called vector control, calculates the three-phase voltage phases entering the motor to create a magnetic field that forms a 90° angle with the magnetic field of the BLDC motor rotor. The electric force of a motor is represented by Eq. (1).

$$F = B * I * L * \sin\alpha \quad (1)$$

where F is the electric force of the motor, B is the magnetic field strength, L is the length of the winding cable, I is the maximum motor current, and a is the angle between B and I. It must be kept at 90° to obtain the maximum motor torque.

Figure 1 shows the block diagram of a FOC system, where the input of the system is observed. which is a voltage with phase and magnitude. This phase must be equal to the angle at which the motor rotor is to be positioned. The block called "Park + Clarke" or "Space Vector" is used to perform the FOC.

Figure 1. Diagram of the Closed Loop FOC System. [14].



There are two ways to perform FOC, sinusoidal modulation, using the Park+Clarke transform, or vector space control, using vector space modulation. The Park transform receives a vector and its angle and represents it in another coordinate system as described in Eqs. (2-3).

$$U_\alpha = -U_q \sin\theta \tag{2}$$

$$U_\beta = U_q \cos\theta \tag{3}$$

The Clarke transform converts the system into the three-phase system as described in Eqs. (4-6).

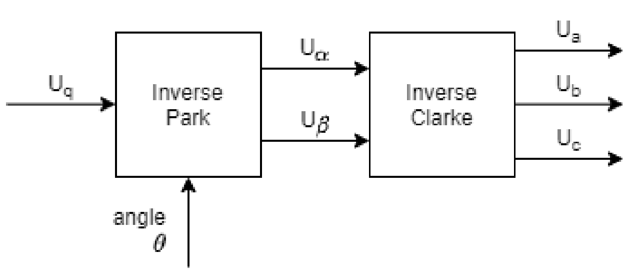
$$U_a = U_\alpha \tag{4}$$

$$U_b = \frac{-U_\alpha + \sqrt{3}U_\beta}{2} \tag{5}$$

$$U_c = \frac{-U_\alpha - \sqrt{3}U_\beta}{2} \tag{6}$$

When using this type of sinusoidal modulation for the FOC, the system appears as shown in Figure 2 where is the desired voltage for the system. Depending on the position of the rotor detected by the Hall-effect sensor and the phases of the input voltages, the value of . The final result is the PWM signals of y which will allow the rotor to be positioned at the angle of the incoming voltage. incoming voltage [14]. This system can be used in conjunction with PI/PID controllers to ensure better performance levels [15-18].

Figure 2. Sinusoidal Modulation [14].



3. State of the Art

At [19] they present a FOC control system for hysteresis motors using magnetic fields for commutation, as well as BLDC motors. The authors have modeled a hysteresis motor and control its angle with the FOC control system. The results show that the system can control the positioning of the motor.

At [20] perform FOC control to a BLDC motor based on vector space modulation, this type of modulation consists of transforming the voltage and current vectors of the motor to three-phase waves. The voltage and current vectors control the angle of the motor, by controlling these vectors, the angle can be controlled. The three-phase waves enter the system controller to drive the motor. The purpose of this study was to reduce the ripple in the motor response when controlled without FOC.

At [21] present the results of driving a permanent magnet machine with FOC and low frequency trapezoidal control. The results show that the FOC has better transient response under load, but the trapezoidal control offers better torque.

At [5] they implemented an optimized FOC control algorithm on an FPGA with Hall effect sensors. The results show that the system can position the motor rotor at a required angle with an error of 0.935°.

At [22] they implemented two types of control systems to a BLDC motor, (i) PI and (ii) FOC. After an analysis of the performance of these two systems, the authors concluded that the FOC control system maintains its speed constant, has lower ripple in its torque response and has lower harmonics in its currents than the PI control. An SMO (Sliding Mode Observer) scheme was implemented to the FOC system, which minimized the speed error and oscillations that the PI-controlled motor had.

At [23] present a review article containing several ways to control the positioning of permanent magnet motors, induction motors and reluctance motors without using sensors, some of the control strategies reviewed, use state observers controlling the position of the motor rotor with respect to a set value.

4. Materials and Methods

The following are the materials and methods for the development of the BLDC motor control system.

4.1. Materials

The main materials for the development of the control system are (i) an Arduino one board which requires the PCImanager library, (ii) a SimpleFOC module which requires the Simplefoc library and, (iii) a Maxon EC-max 16 Motor.

4.1.1. SimpleFOC Library

The SimpleFOC library is an open source library used to implement the FOC System for BLDC motors. The library contains functions that perform the complex operations of the FOC, it also has the functionality to initialize three different types of sensors, such as: Hall effect sensors, Encoders and magnetic sensors. Additionally, it is possible to integrate properly developed source code for a specific sensor if the library does not have a function for that sensor, or if its way of handling that sensor is not satisfactory enough for the user. This library allows to control BLDC motors regardless of the number of poles of the motor, with open-loop or closed-loop control systems. [24].

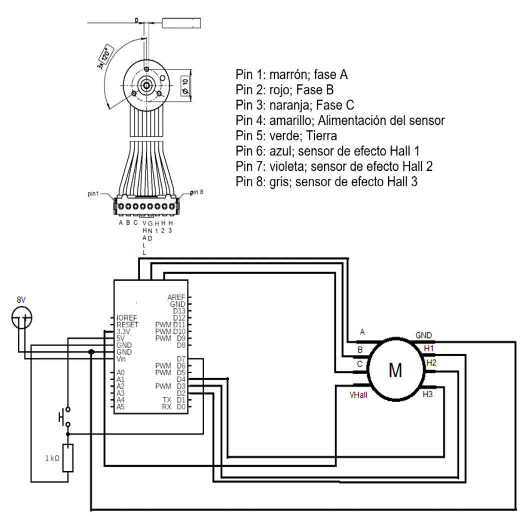
4.1.2. *PciManager* Library

The PciManager library allows the Arduino to perform pin interrupts at the software level. This is implemented for the Hall effect sensors to detect which of the three sensors is detecting a magnetic field. The three Hall effect sensors are passed as a parameter during the initialization of the three interrupts so that the pin of each individual sensor can be taken into account.

4.2. Methods

To implement the system, the simpleFOC module is connected to the Arduino Uno. The module requires an 8V voltage source and a push button to 5V supply from the Arduino Uno in series with a 1kΩ resistor connected to ground, making it a pull-down resistor. The motor has a total of 8 wires, each of a unique color. The module has 3 pins on its top corresponding to phases a, b, and c. The brown wire (A) connects to phase a, the red wire (B) connects to phase b and the orange wire (C) connects to phase c. The yellow wire (VHall) connects to the 3 V pin and the green wire (GND) connects to ground. The motor has three wires with each wire corresponding to a Hall sensor. The blue wire (Hall1) connects to pin 2, the purple wire (Hall2) connects to pin 3 and the gray wire (Hall3) connects to pin 4. The push button output signal connects to pin 7. Figure 3 depicts the connection diagram where the pin layout of the Arduino Uno and the module are the same. These two boards are connected one above the other, where the Arduino Uno is below the simpleFOC module.

Figure 3. ***SimpleFOC*** **Module and Maxon Motor Connection Diagram [19].**



4.2.1. Control System Programming

For the programming of the control system, the Arduino IDE and the SimpleFOC library documentation were used to develop the codes. Figure 4 shows the flow diagram of the code structure.

In the first block, the SimpleFOC, PciManager and PciListenerImp libraries are imported. The first library is used to perform the FOC and the last two are for interrupts that allow detecting which of the three Hall sensors is active, then, the instance of the BLDC motor is created, inserting as parameter the number of poles the motor has, in this case 8. The controller is instantiated, inserting as parameter the pins for phases a, b and c, which are 9, 5 and 6, and the enable pin, pin 8. The Hall sensors are also instantiated, passing as parameter the pins of each individual sensor, which are 2, 3 and 4, and the 8 poles of the motor.

Subsequently, the interrupts are initialized, using the Hall effect sensors and the serial monitor command line as parameters. The variables that will be used by the algorithm are declared: (i) target_angle, which stores the angle entered in the command line, (ii) val, the binary value of the push button, (iii) i, a variable that will always be equal to 6.28 rad (360°), (iv) flag, which detects if the push button was pressed, (v) rad, which stores the angle detected by the Hall sensors, and (vi) poles, the number of poles that the motor has.

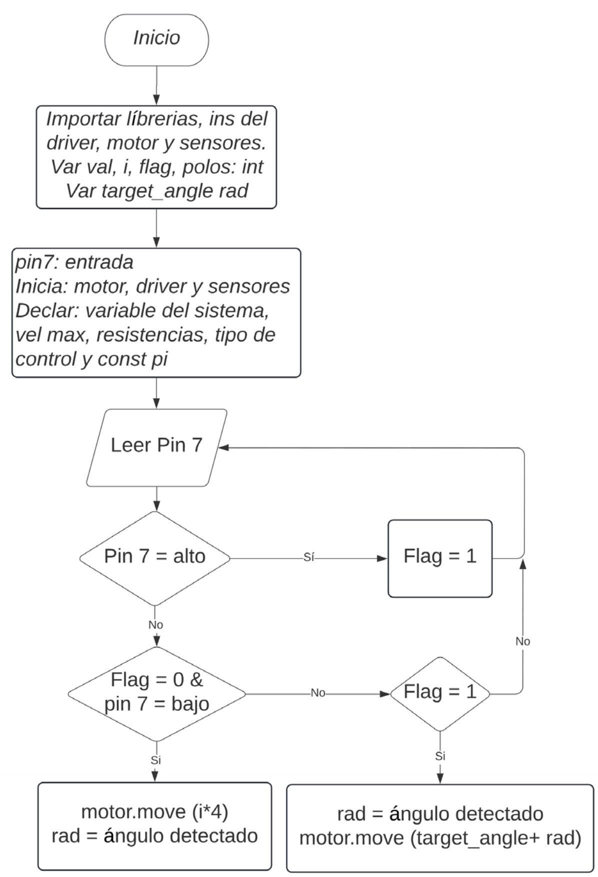
For the setup block, pin 7 has been declared as an input for the push button and the controller, sensors and motor were initialized. We declared the system supply voltage of 8 V, pull-up resistors for the 3.3kΩ Hall effect sensors already built into the Arduino, the motor speed and maximum motor voltage equivalent to 3 V, declared the control type either open or closed, and declared the PI counters if the control type is closed-loop.

For the loop section, the voltage level of pin 7, the push button, must be read. If the level is low, the motor will start to make a 360° turn. As the motor turns, the rad variable stores the current angle the motor is at. When the button is pressed, the flag variable will be equal to 1. If flag is equal to one, the motor will position itself at the current motor angle, using the rad variable, summed with the target_angle variable, which is entered on the serial monitor command line.

For closed-loop control, the constants for the PI controller are declared and that the type of control is to be closed-loop.

It is important to mention that the radians entered must enter the system being multiplied by 4. This is due to the distribution of the Hall effect sensors in the motor. These sensors are spaced 90° apart, causing the rotor to be segmented into 4 parts. The entire range from 0° to 360° is limited to one of these segments.

Figure 4. General Flow Diagram



4.2.2. System Evaluation

In the evaluation of the system, the Arduino millis function was used to count the passage of time. When a certain amount of time has passed the desired angle changes. When the push button is pressed, the angle will be equal to 90°. After 1000 ms the angle changes to 180°. Finally, after 6000 ms the angle changes to 360°. This process is performed to change the incoming angle without using the serial monitor so that the program does not restart and waste a lot of time, a sampling time of 1 ms is used for the process.

The code was run for both open loop and closed loop control. Adjustments were made to the code to ensure proper operation of the system. The PI counters were calculated by means of the tuning technique. To verify that the two control systems can control the motor angle, a total of 30 tests were performed on the motor, 10 for the open-loop angle control, 10 for the closed-loop angle control and 10 for the motor hysteresis test.

The characteristics evaluated for the angle control without considering the load weight on the motor were the stability time, rise time, peak time, maximum overrun percentage and steady state error. Additionally, the hysteresis test characteristic is determined, which is defined by the difference between the input angle and the output angle. The angles tested for the control were 90°, 180° and 360° and the angles used for the hysteresis test were 20° and 40°. The average and standard deviation are calculated from the total number of tests.

5. Results and Discussion

5.1 System Evaluation

Figure 5 shows the output of the open loop system for three different angles. It is observed that its output does not show oscillations. Table 1 presents the evaluation characteristics of the system.

Figure 5. Open Loop Control.

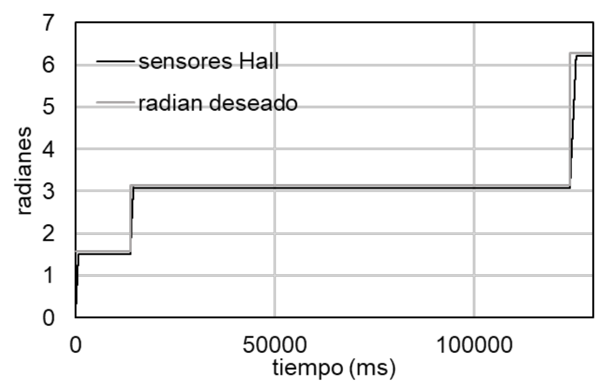


Figure 6 shows the block diagram of the PI control system where the proportional constant P = 0.2 and the integral constant I = 25. The system receives the reference angle, then the system executes the control action, where the Hall effect sensor serves as feedback for the error signal and for the Park and Clarke transform.

Figure 7 shows the output of the closed loop system for three different angles. Note that the system presents oscillations in its dynamics until the steady state is reached. The characteristics presented in Tables 1 and 2 show that the closed-loop system has on average a lower stability time than the open-loop system for each angle. Also the closed-loop system has lower rise time, peak time and steady state error.

For each average obtained, the standard deviation was calculated, which is considered adequate for almost all the characteristics, except for the maximum exceedance, which has a high standard deviation, indicating that there is a great deal of variability in the results of the 10 tests (Table 2).

Table 1. Open loop system characteristics.

Position	1.57 rad		3.14 rad		6.28 rad	
Characteristics [s]	average	standard deviation	average	standard deviation	average	standard deviation
Stability time	0,82999	0,09012	0,83953	0,29492	1,19137	0,62278
Rise time	0,60872	0,03744	0,46814	0,20533	1,03022	0,34511
Peak time	1,13655	0,14214	1,47843	0,69160	2,67956	1,01698
Percentage of maximum overrun [%].	1,62301	0,18989	1,76326	3,12118	1,21097	1,14565
Steady state error	0,03822	0,00033	0,01982	0,00038	0,01490	0,00538

Source: Own.

Table 2. Closed Loop System Characteristics.

Position	1.57 rad		3.14 rad		6.28 rad	
Characteristics [s]	average	standard deviation	average	standard deviation	average	standard deviation
Stability time	0,70736	0,23438	0,58576	0,38090	0,75542	0,52444
Rise time	0,47843	0,02743	0,31110	0,21734	0,41779	0,37195
Peak time	1,01234	0,52071	1,16402	0,39129	2,24844	1,04853
Percentage of maximum overrun [%].	1,54433	0,50311	0,42800	0,64325	0,30415	0,59839
Steady state error	0,00490	0,00569	0,00000	0,00000	0,00102	0,02128

Source: Own.

Figure 6. Closed Loop Control System.

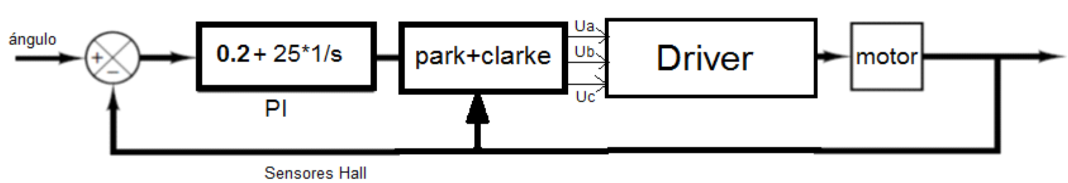
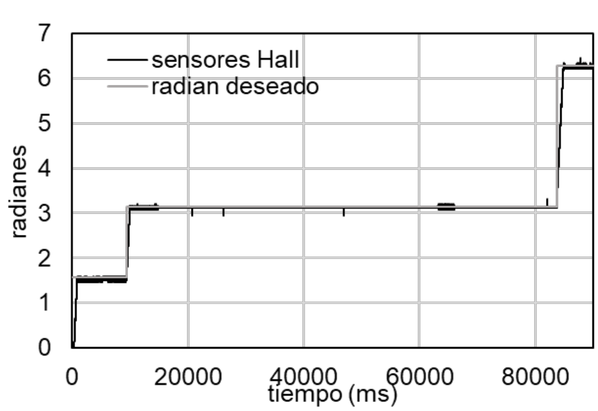


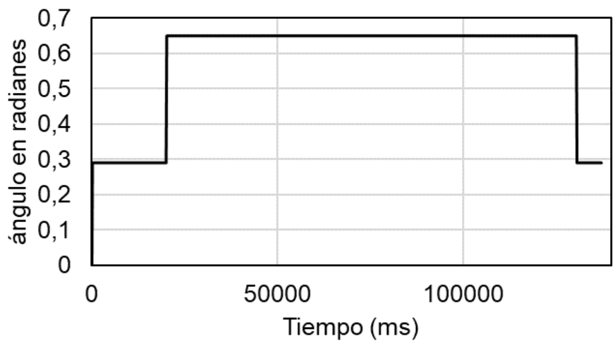
Figure 7. Closed Loop Control



From the 10 hysteresis tests it is obtained that there are no differences in the remarkable hysteresis of the motor. Figure 8 shows the hysteresis characteristic of the motor. Note that the changes in the ascending step present the same characteristics as the descending step.

Hysteresis in a motor represents energy losses that can be caused by the core windings of the motor. These losses are caused by the inability of the ferromagnetic core to allow the same magnetic flux when there is a change of polarity. [7], this causes error in the positioning of the motors, causing the magnetic flux not to be equal with each stator commutation. The present motor has no noticeable hysteresis, which means that the motor can assume angles with minimal uncertainty.

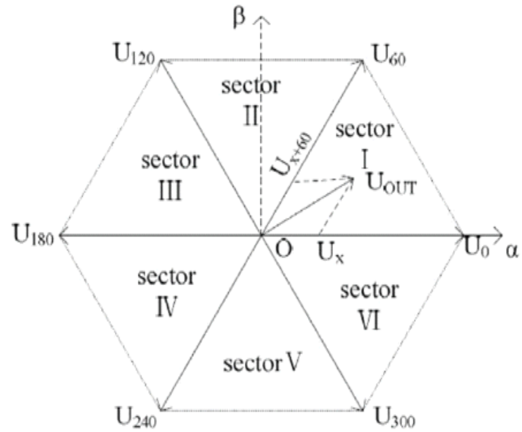
Figure 8. Hysteresis



Regarding the study presented in [19] which shows an overrun, the one presented in this paper has no overrun, which is important for motor protection. In the study presented in [21] they used FOC for its sensorless control, that is without feedback, unlike the present article, which not only performs control without feedback, but also performs control with feedback presenting better results. In the studies presented in [5, 20, 22] they used vector space modulation for the FOC.

This is a more complex control method compared to the Park and Clarke control implemented here. The vector space modulation takes into account 6 segments as presented in Figure 9 of the reference frame. . These segments are taken into account and Hall effect sensors are used to detect in which segment is the motor rotor. According to this type of modulation, 6 specific formulas are required for each segment and apply a specific modulation percentage, while the system applied in this project only requires three formulas explained in the theoretical framework.

Figure 9. Vector Space Segments [22]



The studies presented in [23] use vector space modulation, making them more complex than the study presented here. It is important to mention that these studies do not use sensors, which are cheaper compared to control systems that use sensors, but use state observers to control the rotor positioning, this includes the current entering the motor, the electromotive force present in the motor and the magnetic fields produced in the motor windings.

Additionally, the possibility of implementing more accurate Hall effect sensors can be considered. The Hall effect sensors used in this project are included internally in the motor itself. Using more accurate sensors will help to reduce the uncertainty obtained in the results.

6. Conclusions

In this paper, the angular control of a brushless direct current (BLDC) motor was performed, performing satisfactory tests with three different angles with little uncertainty, i.e., absolute errors in the order of 10^{-3}, indicating that the methodology and development is suitable for position control in upper limb prostheses.

In the control system design, the simpleFOC module together with the SimpleFOC and PciManager libraries proved to be suitable for controlling the angular position of the EC-max 16 motor. The Maxon motor did not present significant differences in the hysteresis test, this means that it has equal behavior to reach the position, either upward, i.e., starting from a position lower than the desired position, or downward which is to reach the position starting from a position higher than the desired position. The system also allows to execute the movement with times relatively adequate and coherent to the movement of the typical arm without generating abrupt movements in a prosthesis.

The library and the simpleFOC module are adequate tools for the implementation of an open-loop or closed-loop control system. For future research, it is recommended to model the BLDC motor to perform simulations of the whole system to allow a more accurate tuning of the proportional and integral constants of the PI controller in order to reduce the oscillations present in the closed-loop control. Finally, the derivative action component can be added to the system controller to have the possibility of improving the time response.

Acknowledgments

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