Controller Design for Induction and Brushless Motors Using Matlab with Digital Signal Processor (DSP)

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Abstract– The automation process is a very important pillar for Industry 4.0. One of the first steps is the control of motors to improve production efficiency and generate energy savings. In mass production industries, techniques such as digital signal processing (DSP) systems are implemented to control motors. These systems are efficient but very expensive for certain applications. From this arises the need for a controller capable of handling AC and DC motors that improves efficiency and maintains low energy consumption.

This project presents the design of an adaptive control system for brushless AC induction and DC motors, which is functional to any type of plant in the industry. The design was possible by implementing Matlab software and tools such as digital signal processor (DSP) and Simulink.

Through an extensive investigation of the state of the art, three models needed to represent the control system have been specified. The first model for the AC motor, the second for the DC motor and the third for the DSP control; this is done in this way so that the probability of failure is lower. Subsequently, these models have been programmed in Simulink, integrating the three main models into one.

In this way, the design of a controller for use in AC induction motors, specifically squirrel cage and brushless DC motors, has been achieved. The final model represents a response time of 0.25 seconds, which is optimal for this type of application, where response times of 2e-3 to 3 seconds are expected.

Keywords— Motor Control, Digital Signal Processor (DSP), Industry 4.0, Inductive Motor, Brushless Motor.

I. Introduction

Motor control is a fundamental part of industrial production, so any professional in the control area must know the characteristics, operation, and parameters for controlling a motor regardless of its type. We are currently in an industrial revolution; therefore, motor control is increasingly automated, different control methods are designed and implemented to make production processes more precise and efficient.

Multiple proposals have been developed to control different electric motors using Matlab and Simulink tools. [9] presents the design of a speed and position control system for a direct current motor, the system uses an interface in MATLAB that communicates with a 32Bits ARM microcontroller programmed on the MBED platform. In this work, the user, through the graphic interface, can carry out the design process of a control system from the acquisition of data to identify the plant to the simulation of the system directly on the engine. This allows the user to quickly view the operation of the newly designed controller and to adjust and tuning the controller.

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[3] use a board with DSP technology and Simulink with RTW to perform real-time control simulations for a DC motor.

[7] present the design, simulation and implementation of a speed controller based on a digital signal processor (DSP). The applied method is known as integral variable structure model following control (IVSMF), which takes the error between the state of the model and the controlled plant, this error must be minimized using the limits defined in the sliding mode plane. The control has been used to drive two types of permanent magnet motors, a PMDC motor and a brushless AC motor, obtaining precise speed regulation in both cases.

The development of the present work allows to provide an alternative to drivers and frequency inverters to use AC induction motors and DC brushless motors from the same controller without affecting the efficiency of the motors and generating considerable energy savings. This proposal presents great operational and economic advantages in current industries.

II. Methodology

A. Parameters to control AC induction and DC brushless motors

Before establishing the mathematical model of the drivers, several parameters of the motors had to be considered, these parameters are detailed in Table I and Table II.

TABLE I
INDUCTION MOTOR PARAMETERS

Parameters	Value
Voltage (line-line)	460 ($Vrms$)
Even poles	2
Rated power	7460 VA
Frequency	60 Hz
Power	10 HP
Speed	1760 RPM
Rotor type	Squirrel cage
Motor inductance (Lm)	0.1486 H
Rotor inductance (Lr')	0.001452 H
Rotor resistance (Rr')	0.451 Ω

TABLE II
BRUSHLESS MOTOR PARAMETERS

Parameters	Value
Rotor angle	120°
Even poles	1
Magnetization of magnets	1 Wb
Speed	1400 RPM
Voltage	150 VDC

Also, important to determine certain parameters of the power system, especially the RMS voltage and V_0 to determine the value of the capacitor and resistors of the DC bus. The three-phase rectifier produces large loads of currents and voltages, in Fig. 1 a three-phase diode bridge rectifier is shown [2].

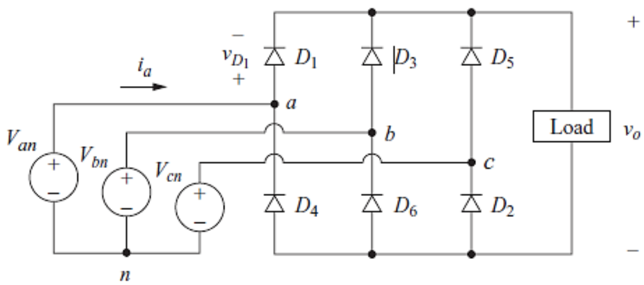


Fig 1. Three phase full wave rectifier [2]

To complete the necessary calculations, the currents of the conducting diodes must be calculated, which is equal to the load current. These calculations are carried out by applying Kirchhoff's law at nodes a, b, and c (see Fig. 1).

$$ia = i_{D1} - i_{D4} \quad (1)$$

$$ib = i_{D3} - i_{D6} \quad (2)$$

$$ic = i_{D2} - i_{D5} \quad (3)$$

To calculate the three-phase apparent power, it is necessary to determine the current I RMS, which is given by:

$$I_{D,RMS} = \frac{1}{\sqrt{3}} I_{o,RMS} \quad (4)$$

Where:

I_o is the average output current, defined as:

$$Io = \frac{3\sqrt{3}}{\pi} * Vm * \frac{\sqrt{2}}{Z} = \frac{3}{\pi} V_{m,L-L} \quad (5)$$

Vm is the average output voltage.

$V_{m,L-L}$ is the line-to-line voltage.

Z is an impedance. For the AC motor the impedance RL is defined:

$$Z = \sqrt{R^2 + (\omega L)^2} \quad (6)$$

For the DC motor the RC impedance is defined:

$$Z = \sqrt{R^2 + (1/\omega C)^2} \quad (7)$$

Inverters are made of IGBTs or MOSFETs, a pseudo-sinusoidal voltage is generally required in the three-phase phases a, b, and c, for this the spectral vector modulation (SVM) technique is used. [4] mention that this technique generates less harmonic distortion in the output voltage and improves the efficiency of the voltage supplied by the filter or DC bus.

The voltages generated between the combinations of the conducting transistors are transformed to the αβ system as observed in Fig. 2.

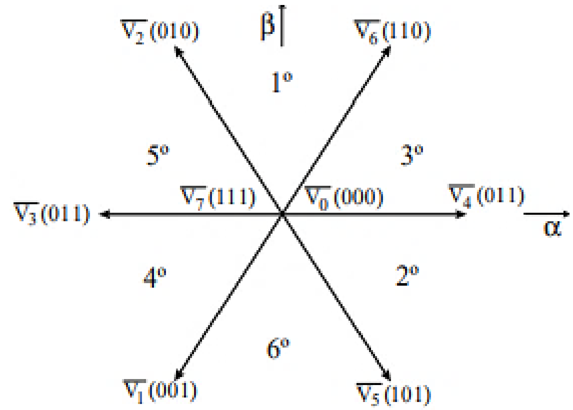


Fig 2. Possible combinations of switched vectors [4]

These transistors have the function of acting as switches when a load is applied. Eight combinations of the different voltages are generated, two voltages whose values are equal to zero are discarded, that is, six voltages are chosen. These voltages are those coming from the state of the transistor (a, b, c) the Clarke transform is applied to it. The SVM technique generates the triphasic voltages that control the on and off times of the transistors, adding the eight vectors [8, 9].

B. Mathematical model for the control systems of AC induction and DC brushless motors

FOC control is a technique that is performed in a synchronous biphasic coordinate system, for this there are two mathematical methods known as Clark and Park transforms. A FOC system is shown in Fig. 3.

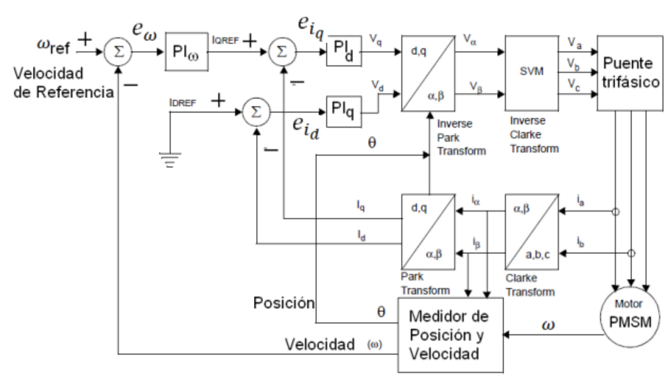


Fig 3. Field oriented control (FOC) block diagram [4]

The FOC controller works by making the electrical flow in the d axis equal to 0, it controls the speed by varying the torque of the current in the q axis. The load angle (it is the angle between the magnetic flux of the stator and the flux of the rotor) must be 90 ° to obtain the maximum torque, that is, they must be orthogonal.

The inverter converts the desired voltage in the time domain, the outputs in the PI controllers work through the inverse Clarke and Park transform generating the equivalent phase voltages since the current required for the motor is measured in two phases in a system balanced and the third is calculated based on the other two currents, to these the Clarke and Park transform is applied to the inputs of the PIs. The Clarke transform uses two static axes α and β (see equation 8), the voltages and currents $v_a, v_b, v_c, i_a, i_b, i_c$ when the Clark transform is applied are obtained $v_\alpha, v_\beta, i_\alpha$ and i_β. On the other hand, the Park transform converts the variables α and β turns them into a movement system that is in sync with the rotor, that is, on orthogonal axes d and q, where the current and voltage variables arev_d, v_q, i_d and i_q (see equation 9) [4].

$$[V_\alpha\ V_\beta\ ] = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \end{bmatrix}[V_a\ V_b\ V_c\ ] \qquad (8)$$

$$[V_d\ V_q\ ] = \frac{2}{3}\begin{bmatrix} cos(\theta)\, sen(\theta) \\ -sen(\theta)\ (\theta) \end{bmatrix}[V_\alpha\ V_\beta\ ] \qquad (9)$$

FOC controllers have a small variant when used with AC or DC motors, which is the type of controller, a PID controller converts current variations to a desired current in q i_{QREF}, while the PI controller returns the current $i_d = 0$. To determine these controls, it is necessary to determine the following parameters:

For the speed error in a FOC control, where the variables involved are ω_{ref} what is the desired speed, ω is the speed and e_ω is the speed error.

$$e_\omega = \omega_{ref} - \omega \qquad (10)$$

For the desired current, where the variables K_{pw}, K_{iw} and K_{dw} are the proportional, integral, and derivative gains, respectively.

$$I_{QREF} = K_{pw}e_\omega + K_{iw}\int_0^t e_\omega\, dt + K_{dw}\frac{de_\omega}{dt} \qquad (11)$$

For the current error in q, where K_{PVq} and K_{IVq} are the gains of the voltage controller at q.

$$e_{iq} = I_{QREF} - i_q \qquad (12)$$

For the voltage at q, where K_{PVq} and K_{IVq} are the gains of the voltage controller at q.

$$V_q = K_{PVq}e_{iq} + K_{IVq}\int_0^t e_{iq}\, dt \qquad (13)$$

The same calculations are repeated for the d axis.

C. Controller simulation for a brushless DC motor

Firths, the motor parameters were chosen (see Table 2). Later, a basic control system was assembled using Simulink, in this case a start and stop for the brushless DC motor (see Fig. 4), where a basic control for said motor is shown.

To create a physical model of a brushless DC motor using Simulink, the BLDC (brushless DC motor) block was used which represents a trapezoidal profile back-EMF (back electromotive force, produced when the motor rotates), then it was configured with the parameters of the Table 2. Then, three neutral phases were connected to the motor terminals and an electrical three-phase reference. For the mechanical connections of the motor, it is necessary to rotate the motor shaft, for this, the *"ideal angular velocity"* programming block is used (this block generates a torque causing the rotor to follow a specific angular trajectory). Both parts must work synchronously, for this; a local function is created with a sample time of 2e^{-3} sec.

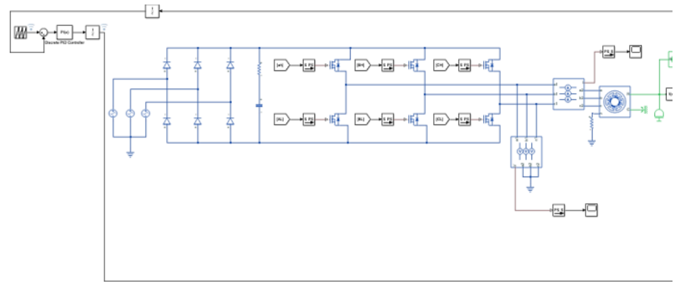


Fig 4. Power control and controller part for a dc brushless motor

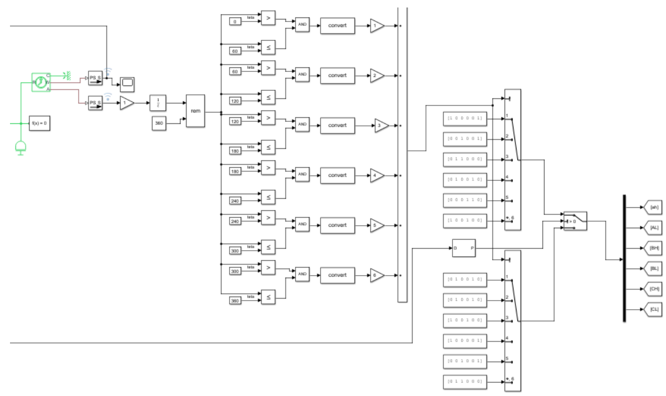


Fig 5. Controller for electric motor, specifically the signal processor

In the diagrams shown in Fig. 4 and 5, to start the motor, the phases must be controlled at the correct time. A control algorithm is needed which decides the direction of the angular position, based on this, the turning on and off the switches (MOSFET) for the phase change is managed.

A Hall effect sensor is also needed to determine the sector the rotor is in, the logic switching works using the current sector to select the corresponding switch pattern, assuming the angular position of the rotor is known (every 60 °, see Fig. 6).

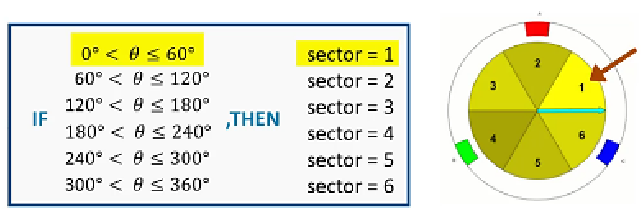


Fig 6. Unmodulated rotor angular position sectors [5]

The logic of this sensor is to define two conditions for each sector, that is, for the first sector the condition is $0° < \theta \leq 60°$, then the logical operators compare the value that is generated by the *Remainder* block with the angles from 0 to 360 °. The

Remainder block stores the resultant between the number of poles (in this case 1) and 360 °.

Finally, the PI controller was made (the parameters of P = 0.01 and I = 5 are used) to control the speed from 0 to 1400 RMP. A gradual sequence repeater of 0.5 seconds was used, with times between 0.0 up to 4.5 seconds, to come up with any algebraic loop that may occur in the modelling of the system, a block called *"Unit delay"* is added. The modulator is connected to this block, two of which were made; a Buck converter and a PWM modulator, the PWM modulator is the one presented in Fig. 5, despite being easier to simulate, it works better with both systems, using a Buck converter implied changing the original design and modifying the system to the AC motor.

D. Controller simulation for an AC induction motor

The motor parameters are set (see Table 1), in the same way a start and stop control is performed by directly connecting the three-phase lines to a three-phase generator block. The following equations are used for the FOC control.

For the transfer function of the Z transform, the following model is used:

$$H(z) = \frac{num(z)}{den(z)} = \frac{numz_{0m} + numz_{1m} - 1 + \cdots + num_m}{denz_{0n} + denz_{1n} - 1 + \ldots + den_n} \quad (14)$$

To determine the electrical angle, where ωr is the frequency of the motor and ωm is the mechanical speed of the rotor.

$$\theta = \int (\omega r + \omega m) dt \quad (15)$$

For the angular velocity of the rotor, where Lm is the inductance, Iq the current in the q axis, Tr is the rotor torque.

$$\omega r = Lm * \frac{Iq}{Tr * \varphi r} = \frac{0.1486 * Iq}{0.3327 * \varphi r} \quad (16)$$

For motor flux, where the rotor torque and inductance.

$$\varphi r = Lm * \frac{Id}{1 + Tr * s} = 0.1486 * \frac{Id}{1 + 0.3327 * s} \quad (17)$$

$$Tr = \frac{Lr\prime}{Rr\prime} = 0.3327 \quad (18)$$

$$Lr = Lr' + Lm = 0.1486 + 0.001452 = 150mH \quad (19)$$

Finally, for the current in the q axis:

$$Iq = \frac{2}{3} * \frac{2}{p} * \frac{Lr}{Lm} * \frac{\vartheta}{\varphi r} = 0.6729 * \frac{\vartheta}{\varphi r} \quad (20)$$

In the same way these equations are repeated for the d axis.

For mechanical displacement or sliding, where ns are the revolutions, p the number of even poles and f the frequency.

$$s = 1 - \frac{ns * 2 * p}{120 * f} \quad (21)$$

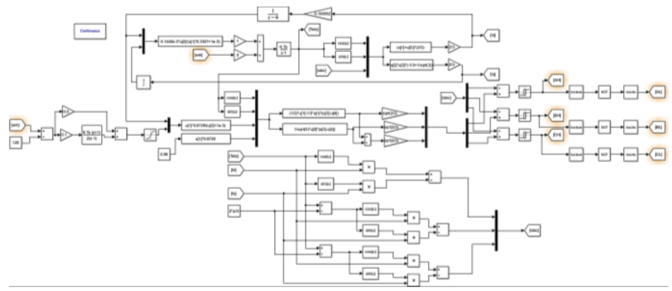


Fig 7. FOC control for induction motor

In induction motors, the three-phase current in the windings in the stator creates a magnetic field that rotates at synchronous speed, causing the rotor to move at a slightly slower speed. This difference in speed is known as slip (s or wm), it is necessary to produce torque. In an FOC control the motor torque and the rotor flux are controlled independently, for this the three sinusoidal currents of the stator must transform into two DC components within a reference frame that rotates synchronously. To achieve this, the Clarke and Park transforms are used. The current in the d-axis allows the rotor flux to be controlled by providing an adjustment in motor efficiency and power factor (PF). The current in the q axis is orthogonal to that of the d axis, allowing control of the motor torque. The stator currents and the rotor speed are measured and fed into the flux to obtain the axis currents (q, d), the rotor magnetization current and the angle of the reference frame, the angle is used in the later stage when performing the inverse Clarke and Park transform.

The FOC block is made up of 5 blocks, the first block (starting from the top) calculates the flow (see Fig, 7), which is used to determine the electrical angle, the second block calculates the electric angle (torque), for this it´s necessary $\varphi r, Iq\ y\ wm$, which is one of the most important since it is part of the Park transform. The penultimate block calculates the Clark transform and the speed control. After applying the inverse Park and Clarke transform, a block generates PWM modulation, uses the required stator voltage to drive the IGBTs.

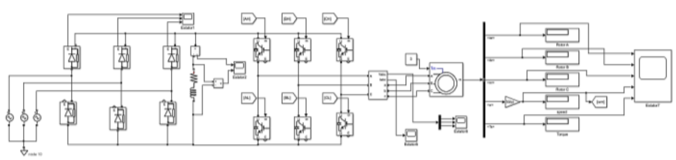


Fig 8. Power control for AC induction motor

E. DSP controller simulation

The signal processing simulates the conditions of a factory, this allows to obtain simulated data in real time. In the simulation, to be able to process the signals of the motors, a spectral analysis must first be carried out to explore the signal based on it. Then digital filters are built which function as unique processing algorithms to later be evaluated.

It is important to consider the size of the memory of the DSP, the internal memory tolerates values between 256 to 32,769 words. It is also considered an external address bus; this depends on the DSP type used.

For the design of the DSP control blocks, a system method called *pipelining* is used, the segmentation improves the performance of the DSP, it is a non-continuous memory allocation technique, and the logical address space of the process is divided into different blocks of different sizes, executing groups of instructions in parallel [1].

When referring to segmentation refers to the division of blocks, a block is created for the analogy output signals and another for the digital input and output signals.

Tension signals and current signals come out of a DSP; this is known as signal adjustment. In Fig. 9 the analogy output block is shown, the phase voltages are received from the inverter and the system voltages and currents from the DSP system. The constants represent the fault settings and are taken arbitrarily since they represent the faults of a real factory (in this case a real factory is not simulated, only the operation of the block is checked), parameter 0 (the first constant) enables or disables the data through the decision making made by the Switch blocks. The function of the *Transfer Fcn First Order* block is to multiply each of the measured signals to obtain a less abrupt response. The gains divide the signals by 10 since in a panel this increases the magnitude of the signal 10 times. After being compared by the second Switches pass through the Saturation blocks, this is a protection measure of the DSP. Finally, they are stored in the DAC blocks.

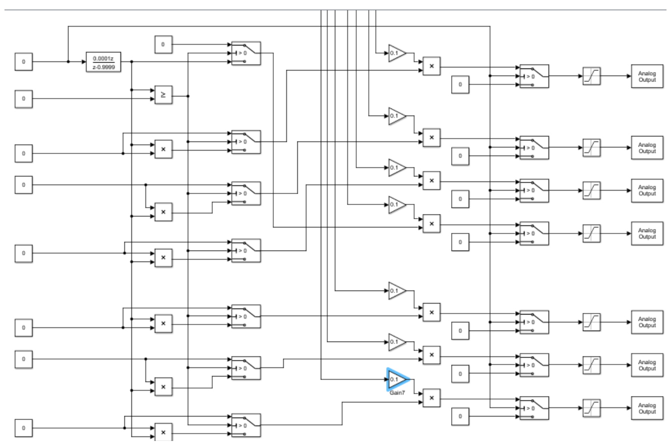


Fig 9. Analog outputs block.

Once the information on voltages and currents is received, the regulator calculates the excitation, this excitation produces a voltage drop that the DSP understands must be incorporated into the system, this corresponds to an analogy output.

Digital signals are the signals sent between the equipment to the factory (in simulation) in short periods of time. In the block of Fig. 9, only one digital input is shown since only the input of the switch that determines whether to open or close is required. The constants 0 correspond to that of two switches, the first is a signal from a breaker and the second is a manual switch. If the manual mode is inactive then the digital input is selected, then the signal is compared with a value like the previous one to keep it closed otherwise it opens. The second part shows the digital outputs, the first represents a high voltage input, the second a low voltage input which is the one coming from the input block and the last one is a general signal.

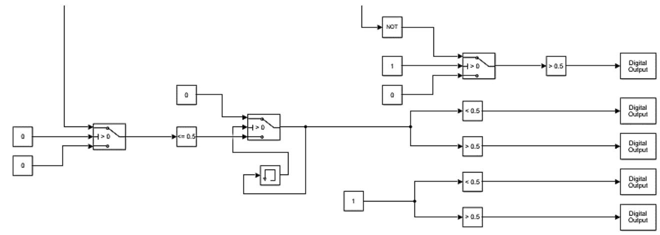


Fig 10. Digital input and output signals

III. COMPUTATIONAL SIMULATIONS

To correctly validate the controller design, several simulations were performed in Matlab's Simulink, the results were compared with various controller simulations. It began with the basic simulations of the start and stop controls of the motors, it continued with the PID controls evaluating the parameters of rise time, establishment time, among others. Finally, ADC and DAC converters were compared by the DSP side, these comparison data were simulated by analysis to extract the data of the constants of the PID controls, of the inductances, resistances, and capacitances of the controllers.

IV. RESULT

A. Control variables

The summary of the critical variables is illustrated in the Table III.

TABLE I.
SUMMARY OF CRITICAL VARIABLES

Variable	Magnitude	Unit	Description
Z_{DC}	1.6667	Ω	DC filter impedance
Z_{AC}	10.6	Ω	DC filter impedance
I_{α}	0.05692	V	Clarke transform current α
I_{β}	0.646	V	Clarke transform current β
θ	0.5	Rad	Electrical angle
wm	962	RPM	Rotor angular velocity
wr	1777	RPM	Electrical angular velocity
φ_r	0.04238	Rad	Electric rotor angle
Tm	0.3327	$N*m$	Mechanical torque
Te	84.41	$N*m$	Torque on the rotor
Lr	150	mH	Inductance in the rotor
Iq	0.2345	A	Current q of the Park transform
Id	0.01743	A	Current $\boldsymbol{d}$ of the Park transform
KI_{DC}	0.01	NA	Integral constant for the PID DC
KP_{DC}	5	NA	Proportional constant for the PID DC
KI_{AC}	0.1	NA	Integral constant for the PID AC
KP_{AC}	15	NA	Proportional Constant for PID AC
t	3	S	Simulation time
s	0.02223	NA	Mechanical slip

B. Development of mathematical models

Due to each model, the next step was to design a mixed model and for this it is based on Fig. 11, where subsystems are made, first the modulation blocks for both engines were joined. The blocks for power control are linked separately by the electrical power factor, which is different, however, the three-phase sources use the same magnitude of 460 Vrms.

The logic control blocks are related to each other by means of the DSP, which sends, analyzes, and receives the signals. For the simulation, the diodes use a resistance value of 0.1 Ohms and 0.8 V, which does not affect the simulations since these blocks work ideally independent of these values, even so, it is not recommended to place values that do not exceed 10mΩ to 150 $k\Omega$.

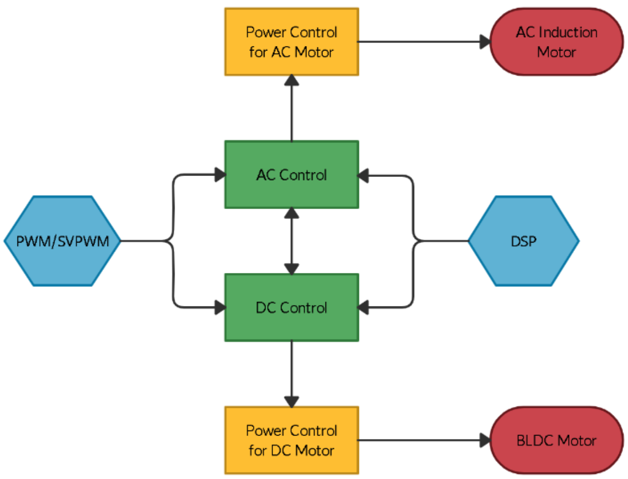


Fig 11. System block scheme

The DSP block is a simplification of physical DSPs since, if it processes and sends the signals, but it does so in an ideal process, that is, there is no physical medium from which to take or receive the signals.

C. Controller simulation for BLDC motor

In Fig. 12 the output of the currents in the MOSFETs is shown, for the simulation a value of 0.1 V is placed in the MOSFET blocks, the sinusoidal waves are in step but are not in phase, in addition to this, a rectangular pattern which should not occur at this stage.

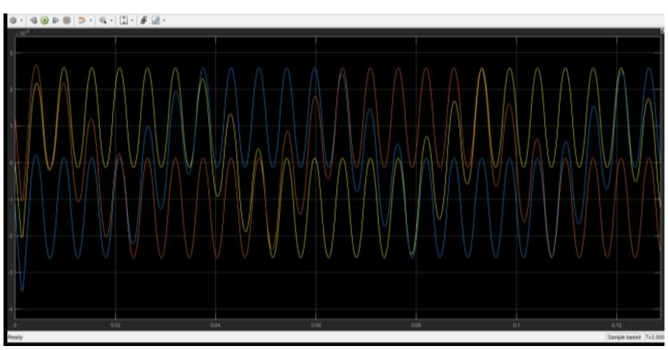


Fig 12. Inverter currents for BLDC motor

As shown in Fig. 13, the voltages at the output of the three-phase inverter with MOSFET, as well as the voltage waves, a discrepancy is found in each of the signals, in this case they are all rectangular with displacement, in addition to this they are synchronous the three signs.

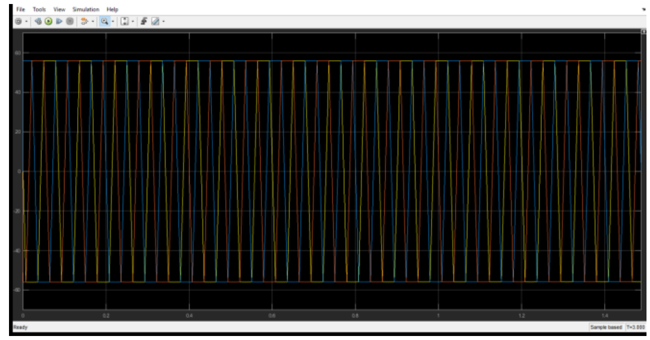


Fig 13. Inverter output voltages

To understand the discrepancies of the inverter output signals, the modulation block was analysed. As can be seen in Fig. 14, the six signals from the PWM modulation block are perfectly modulated.

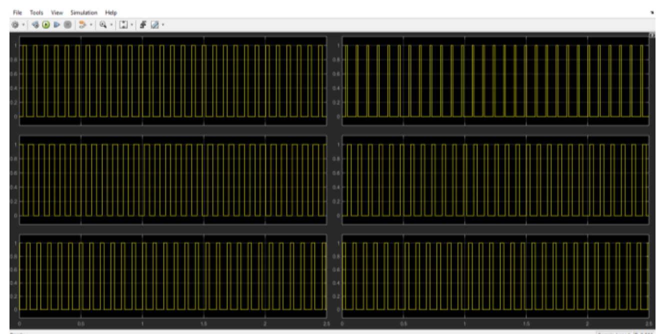


Fig 14. PWM modulation for FOC control of BLDC motor

D. Controller simulation for induction motor

Due to the SVM modulation for the current case, the signal starts with noise which should not happen since it is simulated in an ideal case, even so, due to calculation errors, perhaps they are established at a point for times greater than 1sec. For this block, the larger the time the more stable it becomes, it can be verified by simulating the block separately as illustrated in Fig. 15.

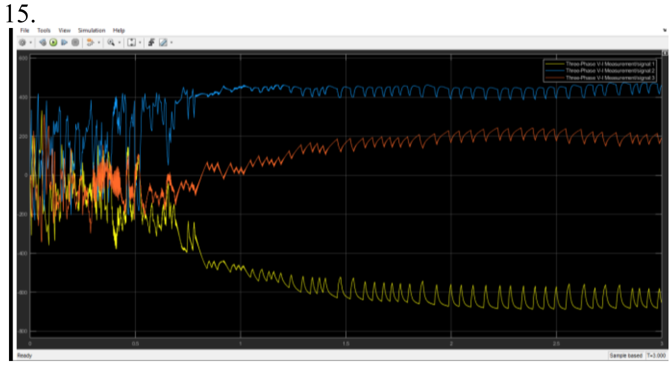


Fig 15. Inverter current output signals with IGBT for the induction motor

In Fig. 16 the voltage outputs corresponding to the inverter are observed, here the SVM modulation is observed without finishing it, each waved peak corresponds to the SVM modulation, but the rectangular pulses are more common in the PWM modulation.

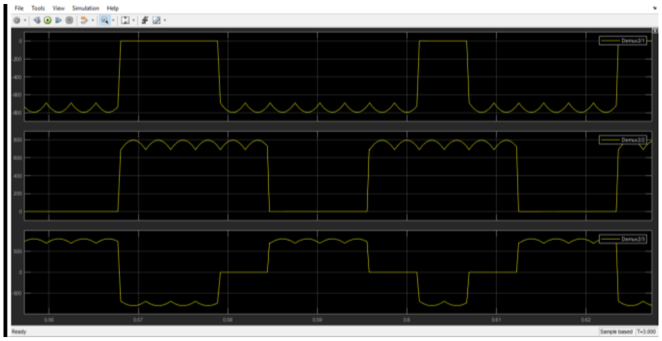


Fig 16. Inverter voltage output signals with IGBT for induction motor

In the same way, the signals of the modulation block for the induction motor were analysed, originally it was proposed to use SVM modulation, and however, a hybrid mixture is proposed. The PWM modulation is created, but when it is mixed with the blocks $Iabc$ and $Iabc°$, a vector space is generated without being fully modulated and this is what is observed in Fig. 17.

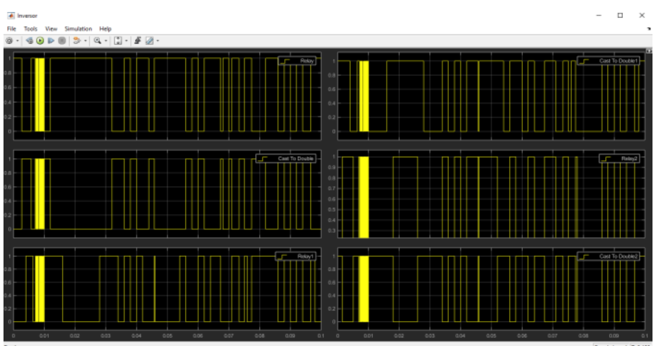


Fig 17. PWM modulator signals for the induction motor

E. DSP Control Simulation

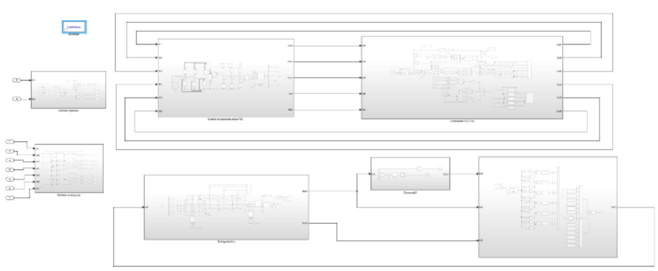
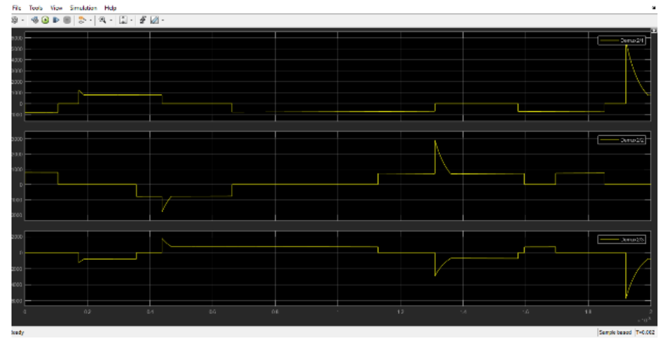
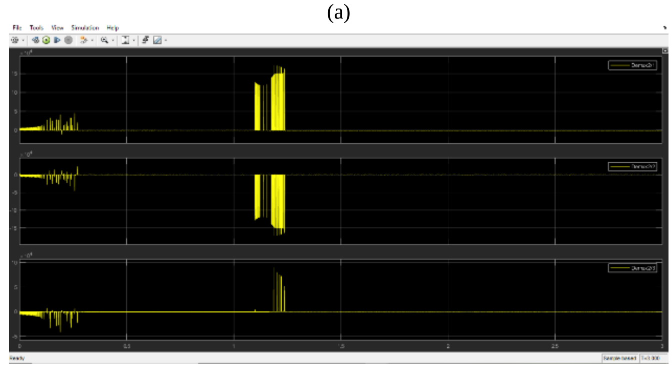


Fig 18. Segmented model DSP controller and FOC

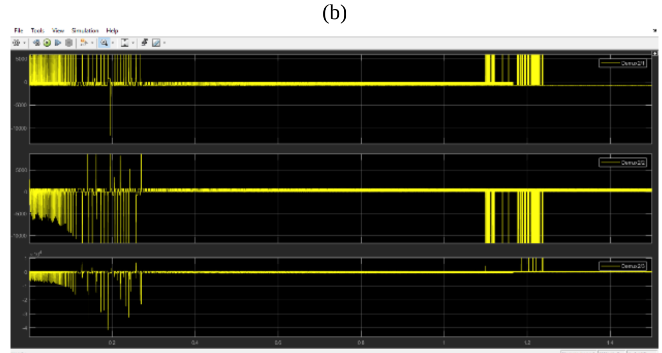
To check the DSP system, the other two controllers are incorporated, the upper one is the power control and the logic control for AC and the lower one is the power control and logic control for DC. The two side blocks represent the DSP control, the highest is for digital signals and the lowest is for analog signals. To check the operation, several simulations were carried out, first with a time of t= $2.5e^{-3}$ sec, nevertheless, the precision for the DC control is lost, while for the AC control it works well. Then for a t = 3sec, for these simulations these times are too long which affects the simulation, and the DSP does not perform correctly in real time, so a last simulation was carried out for a t = 1.5sec.



(a)

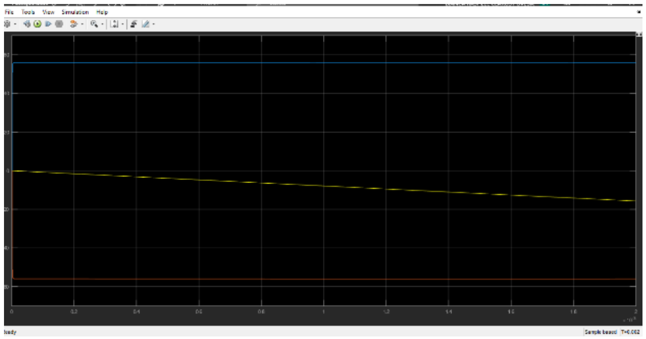


(b)

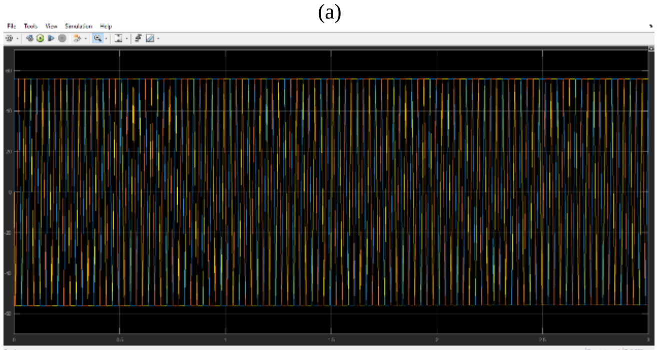


(c)

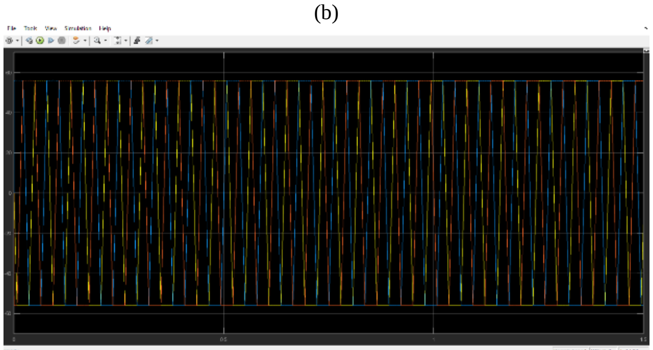
Fig 19. Voltage signals at the inverter output for the AC motor using the DSP control for (a) t = 2e-3 SEC, (b) t = 3.0 sec and (c) t = 1.5 sec



(a)



(b)



(c)

Fig 20. Voltage signals at inverter output for DC motor using DSP control for (a) t =2e-3 sec, (b) t = 3.0 sec and (c) t = 1.5 sec

V. Conclusions

It was possible to design a controller for burning cage induction AC motors and for brushless DC motors using Matlab, Simulink and digital signal processor (DSP). The proposed model presents a response in a simulation time of 0.25sec, which is outstanding for this type of simulation where a response time between $2e^{-3}$ to 3.0sec is used.

A mathematical model for the DC motor controller was developed based on a PWM modulated FOC control. This control conforms to a design for use with any DC motor.

A mathematical model for the AC motor controller was developed based on SVM modulated vector control. This control conforms to a design for use with squirrel cage, double squirrel cage, or permanent magnet AC induction motors.

It was possible to develop a DSP system, the ability to process in real time of the DSP allows a reliable controller capable of operating efficiently regardless of the speed that the motor works, it also offers the possibility of implementing more advanced control schemes by varying the speed in high performance.

The control model proposed in this work presents a new approach for the control of motors implemented in the industry. The advantage of this model is that it will reduce implementation costs and provide energy savings. The objective of future works is to validate the proposed methodology through physical tests, however, the analyzes and simulations presented validate a successful implementation in real applications.

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