ECORFAN-Journal Taiwan 8[15]1-9: e1815109

Article

Reconstruction of motor voltage control signal in industrial applications using IoT

Reconstrucción de la señal del control de voltaje de un motor en aplicaciones industriales mediante IoT

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CONAHCYT classification:

Area: Engineering
Field: Engineering
Discipline: Electronic Engineer
Subdiscipline: Electronics devices

https://doi.org/10.35429/EJT.2024.8.15.1.9

History of the article:
Received: February 02, 2024
Accepted: December 15, 2024

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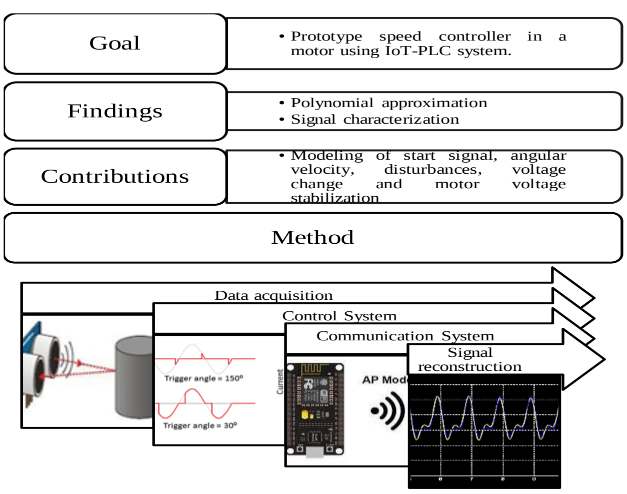
Abstract

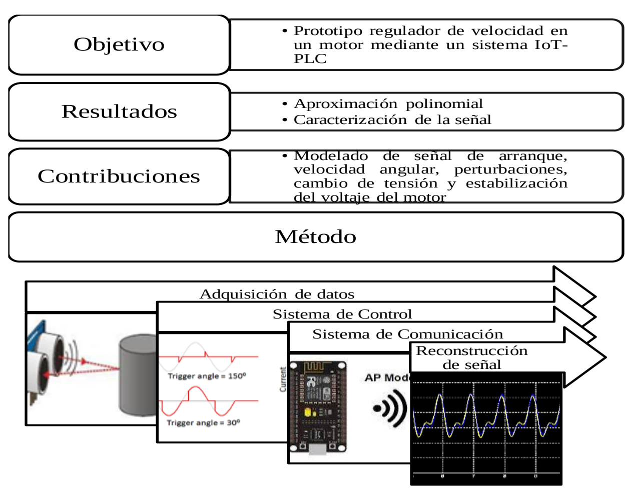
The IIoT allows to have an efficient automation system that monitors specific parts of a system in real time. This paper implements a prototype of speed control and monitoring in a motor belonging to an industrial process with PLC, where the current regulation is related to the data acquisition system and the proposed control algorithm in an IIoT architecture. Finally, the characterization of the starting signal is modeled by means of the angular velocity, the disturbances present in the voltage change and stabilization will be processed using the numerical integration theory and the Matlab tool, to obtain a polynomial approximation of order n.



IIoT, Numerical Integration, Polynomial Approximation

Resumen

El IIoT permite tener un sistema de automatización eficaz que monitoree partes específicas de un sistema en tiempo real. Este artículo implementa un prototipo de control y monitorización de velocidad en un motor perteneciente a un proceso industrial con PLC, donde la regulación de corriente está relacionada con el sistema de adquisición de datos y el algoritmo de control propuesto en una arquitectura IIoT. Finalmente se modela la caracterización de la señal de arranque mediante la velocidad angular, las perturbaciones presentes en el cambio de tensión y estabilización serán procesadas usando la teoría de integración numérica y la herramienta de Matlab, para obtener una aproximación polinomial de orden n.



Aproximación polinomial, Integración numérica, IIoT

Citation: Camacho-Altamirano, Ulices, Martínez-Carrillo, Irma, Juárez-Toledo, Carlos and Hernández-Epigmenio, Miguel Ángel. [2024]. Reconstruction of motor voltage control signal in industrial applications using IoT. ECORFAN-Journal Taiwan. 8 [15]1-9: e1815109.

Introduction

The growing trend of the Internet of Things (IoT) is exemplified in new technologies in society, from communication or being able to control home devices remotely, to knowing in real time the location of an online order. According to (Chen et al., 2014) the different applications proposed through the IoT, generate a positive impact for human communication, practically today all the necessary areas are covered in services for businesses and society.

Technological progress through the IoT is reflected in the numerous and diverse applications that have generated an impact since the appearance of the first devices connected to the Internet, today the diversity of applications is the daily life of businesses and society (Hassan et al., 2023).

The recurrent improvement of devices and technology in products and services will have a greater impact on the use of IoT for daily coexistence, (Sarathkumar et al., 2024), mention that Therefore, we use IOT-based techniques to solve issues.

Although the communication paradigm through IoT creates new trends with more technology, where the advancement of applications include, (M2M) Machine to Machine communication, autonomous vehicles, 3D printing, smaller and more efficient sensors, (RFID) radio frequency monitoring, security systems, smart cities, smart grids, smart homes, cyber-medicine, asset management and logistics, agriculture, industrial control and monitoring among others, are some applications that correspond to the rise of IoT (Camacho et al., 2020).

The smart factory is the result of the fusion of the virtual and physical world, where the objective is based on real-time operations, integrated supply chain, virtualization of physical systems for remote monitoring of industrial processes, autonomous and decentralized decision making, prediction of maintenance in equipment connected to the network system, timely response to new demands and changes in the production process according to (El-Gendy,2020).

The importance of IoT applied to industrial processes, especially in Industry 4.0, has allowed companies to be more competitive with the latest advances through the Industrial Internet of Things (IIoT), where industrial processes have been technified worldwide, (Abdullin et al., 2020) defines IIoT as the set of sensors, instruments and autonomous devices connected through the Internet focused on industrial applications, which allows to collect data, perform analysis and optimize production, increase efficiency, reduce costs in the manufacturing process and provide services. For (Milić & Babić, 2020) the IIoT is a fundamental part of Industry 4.0, where the connection between physical and virtual systems allows, to collect data, increase efficiency, optimize production, perform analysis and reduce costs in the manufacturing process and provide services.

Figure 1 shows some applications where IIoT connects machines and devices in industries such as oil, gas, utilities, manufacturing, robotics applications, autonomous vehicles, integration of sensors in machines and tools described by (Jaidka et al., 2020).

Box 1

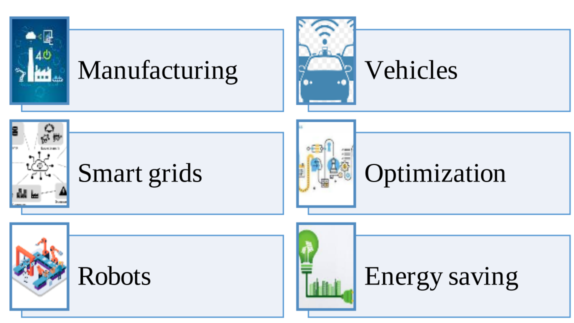


Figure 1

Applications of IIoT systems

Source: (Jaidka et al., 2020)

According to (Tintelecan et al.,2020), electric motors are used to convert electrical energy into mechanical energy, however, they are vulnerable to operating problems generated by long times of use, their commercial, residential and industrial applications require the design of devices to control the improvement in energy consumption (Verma et al.,2024).

The development and improvement systems in more efficient electric motors in the industrial sector driven by strict regulations on electrical energy consumption and reduction of operating costs in production processes set the basis for the improvement of low-cost devices (Awais et al., 2019).

ISSN: 2524-2121.
RENIECYT-CONAHCYT: 1702902

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In (Ramirez et al.,2018), states that the main use of motors in the manufacturing industry corresponds to process control, where some variables controlled in industrial processes are temperature, current, voltage, torque, speed and position.

The objective of this work is to reconstruct the starting signal, voltage change and voltage stabilization of the AC motor coupled to the conveyor belt belonging to the industrial process of a PLC, where the travel speed will be determined by varying the speed of the system through a coupling monitored through the IoT platform.

The methodology to be used is described in Figure 2.

Box 2

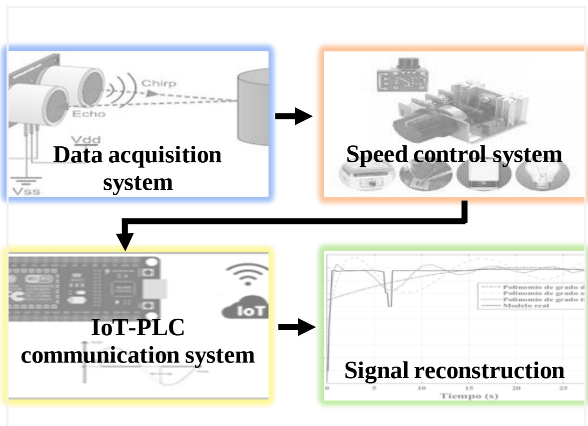

Figure 2
Proposed methodology
Source: Own elaboration

Phase control circuit

(Sharma et al., 2018) refers that regulating devices are used in applications that require control of power, temperature, speed or motor starting, therefore, the control or regulation of power delivered to the load through the thyristor or silicon-controlled rectifier (SCR), is controlled by the trigger potential applied to the gate and the direction of the electric current.

The Triode for Alternating Current or (TRIAC) defined by (Alvarez et al., 2017) is a three-terminal AC semiconductor switch, it is activated in conduction by applying a power signal to the gate electrode, which conducts current in either direction when turned on. The operation of the TRIAC in its conducting state is controlled by the trigger potential applied to the gate and the direction of the electric current is determined by the polarity of the potential it receives according to (Cabrera et al.,2019).

A widely used method for power control is phase control, it consists of a thyristor circuit (DIAC and TRIAC) activated by alternating current, different firing angles generate certain waves of the rectified voltage (Camargo et al., 2017). The voltage wave, the firing and conduction angles are shown in Figure 3, where the electronic switch on high blocks the current flow through controlled intervals, resulting to current supply for the alpha conduction interval (α).

Box 3

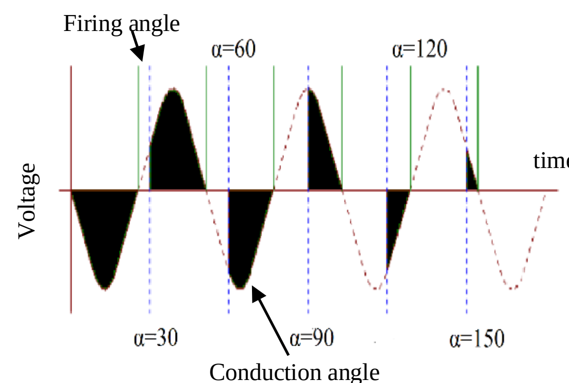

Figure 3
Phase control
Source: (Cabrera et al., 2019)

IIoT system proposed

The combination of architectures, mechanisms and algorithms used in the industrial factory for monitoring and control activities of industrial processes, is established as the pillar of the Industrial Internet of Things (IIoT), to achieve the goal of industrial monitoring and control in motors, machines and devices used in industry facilities (Kolisnyk et al., 2022). The correct operation of the system in industrial processes is based on the continuous monitoring of sensors that collect the relevant data of the process through the Industrial IoT system according to (Duarte dos Santos et al., 2022). As IIoT systems are used more frequently in production processes, the system becomes more secure by monitoring real-time data from the PLC (Ali et al., 2020).

In this work, the procedure to regulate the motor speed is proposed, using the ARDUINO family microcontroller shown in Figure 4. The device conformed by the phase angle control TRIAC circuit is used to feed a single-phase induction motor; where the TRIAC control has a range of variation from a minimum value to the maximum.

The electrical coupling is the control structure where the obtained data is processed by the algorithm that relates the input and output values, the data obtained by the ESP8266 NodeMCU Wi-Fi card provides the necessary information for speed monitoring.

Box 4

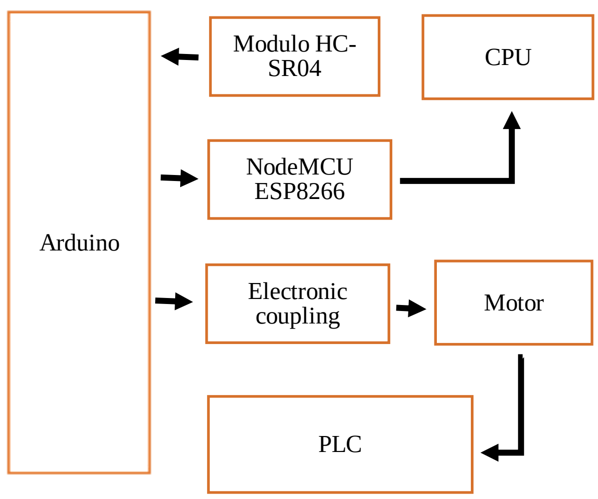

Figure 4
Proposed IIoT system
Source: Own elaboration

Figure 5 (a) corresponds to the elements of the electrical coupling of the IIoT system where, Data acquisition system (1), Speed control system (2) and, IIoT-PLC communication system (3). While Figure 5 (b) shows the elements of the SIMATIC S7-200 PLC proposed for the study where, Pneumatic system for piston actuator (1), Three-phase motor (2), Material feed tower (3), Solenoid valve system (4) and, S7-200 CPU (5).

Box 5

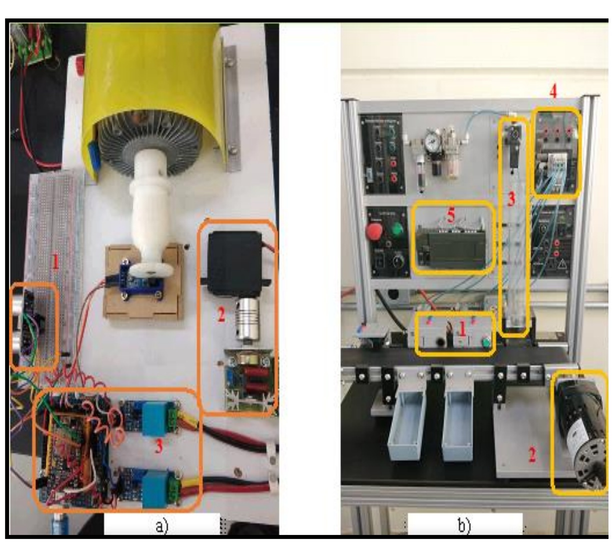

Figure 5
IIoT electronic coupling
Source: Own elaboration

Lab tests

The technique of speed regulation in motors using the voltage-frequency relationship is the proposed control by supplying alternating current through the periodic cut of the sinusoidal signal. The development of the algorithm that establishes the information exchange between the data acquisition system and the proposed control system relates the input and output variables, namely, the distance measured by the ultrasonic sensor is directly proportional to the firing angle.

Figure 5(a) represents the proposed power regulation and motor speed variation system that is activated when the TRIAC controls the passage of alternating current to the load by switching between conduction and firing angles. The conduction angle response for 180°, corresponds to a firing angle $\alpha=0°$, such that it represents 100% of the motor speed when the material supply of the IIoT system is at maximum capacity.

Figure 6 shows the laboratory tests of the proposed control, where the current supply is modified by periodic cuts in the sinusoidal signal. To obtain an approximate 20% reduction of the initial speed, the firing angle calculated by the algorithm is $\alpha=30°$, and $\alpha=60°$ if a 50% speed reduction is desired.

The firing angle $\alpha=120°$ represents the minimum voltage at which the motor can operate without affecting its performance, corresponding to the torque-speed characteristic, $\alpha>120°$ would imply total motor shutdown.

Box 6

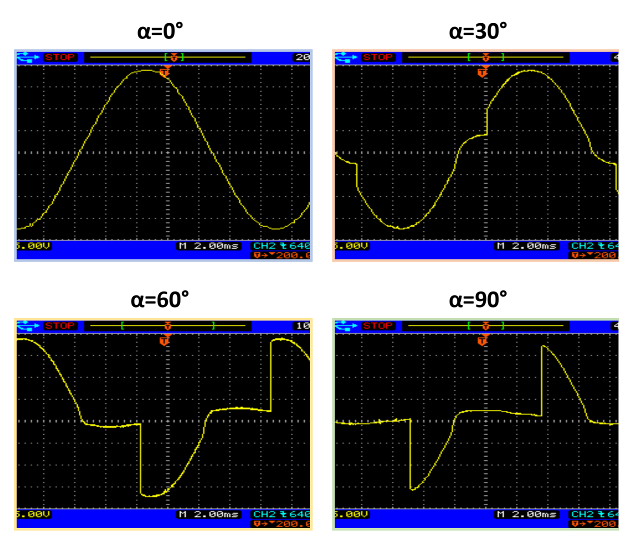

Figure 6
Speed control by firing angle α
Source: Own elaboration

ISSN: 2524-2121.
RENIECYT-CONAHCYT: 1702902

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Polynomial Approximation

Constructing a mathematical function generated by series of data obtained from measurements made by experiments relating two or more variables is the definition of interpolation by (Jorquera & Gelmi, 2014), whose objective is to determine a function that verifies the data and facilitates manipulation due to its simplicity and operability in the area of experimental sciences and engineering.

In (Quezada et al., 2004) the system of equations (1) is used to obtain a polynomial of degree n satisfying the points $y_0, \dots, y_n$, generated by $y_0 = f(x_0),\ y_1 = f(x_1), \dots y_n = f(x_n)$.

$$\begin{cases} a_0 + a_1 x_0 + \cdots + a_n x_0^n = y_0 \\ \vdots \\ a_0 + a_1 x_n + \cdots + a_n x_n^n = y_n \end{cases} \quad [1]$$

Newton's binomial theorem described in (Hernandez et al., 2015) is an arrangement, where equation (2) describes the development of positive powers of a binomial from the k combinations of a group of j elements

$$y_{k+1} = \binom{k}{0} y_{i+1} + \binom{k}{1} \Delta^1 y_1 + \binom{k}{2} \Delta^2 y_1 + \binom{k}{3} \Delta^3 y_1 + \cdots + \binom{k}{k} \Delta^k y_1 \quad [2]$$

as reported in (Cheng-I & Yeong-Chin, 2016) y_k can be expressed as a polynomial of k combinations and degree j.

$$y_{k+1} = a_0 + a_1 k + a_2 k^2 + \cdots + a_j k^j \quad [3]$$

Considering the continuous function at $a \le x \le b$, determine a polynomial $P_n(x_i)$, of degree n shown in equation (4).

$$P_n(x_i) = a_0 + a_1(x) + a_2(x^2) + \cdots + a_n(x^n) \quad [4]$$

Equation (5) expresses the resulting n-order polynomial generated by a system of n defined points

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \cdots + a_n x^n \quad [5]$$

where $(a_0, a_1, \dots, a_n)$ correspond to the unknowns required to approximate the polynomial function of equation (5), with this method it is easy to calculate the derivatives and integrals described in (Qui et al., 2016).

Results

The main objective of the polynomial approximation is to find appropriate coefficients to approximate the exact solution. (Zhou et al., 2017) states the idea is to use polynomials up to a certain degree as candidate solutions to find the solution satisfying the given equations at some specific points.

The objective of this work is to obtain a polynomial whose precise, concise and approximate description corresponds to the real behavior of the system generated by the different stages, in order to validate the proposed method where equation (6) takes into account the variability by voltage change.

$$\boldsymbol{x} \in [\boldsymbol{a}, \boldsymbol{b}] \rightarrow \mathbb{R}\ \boldsymbol{y}\ \{\boldsymbol{n_0}, \boldsymbol{n_1}, \dots, \boldsymbol{n_m}\} \quad [6]$$

where m is the total number of elements of the angular velocity ω .

Equation (7) corresponds to the number of times that the behavior of the real model described in (Camacho et al., 2023) will be divided.

$$\begin{aligned} \boldsymbol{x_1} &= [\boldsymbol{n_1}, \boldsymbol{n_2}, \dots, \boldsymbol{n_k}] \\ \boldsymbol{x_2} &= [\boldsymbol{n_{k+1}}, \boldsymbol{n_{k+2}}, \dots, \boldsymbol{n_p}] \\ &\vdots \\ \boldsymbol{x_l} &= [\boldsymbol{n_{q+1}}, \boldsymbol{n_{q+2}},, \dots, \boldsymbol{n_m}] \end{aligned} \quad [7]$$

The relationship between the input and output variables obtained from the laboratory tests corresponds to the firing angle (α) and the angular velocity (ω). Table 1 shows the average measurements of the corresponding to ω over a time interval.

Box 7

Table 1

Parameters of the control and the data system

Firing angle (α) in degrees	Angular velocity (ω) in RPM
0°	3631.79
30°	3024.09
60°	1934.04
90°	492.81

Source: Own elaboration

ISSN: 2524-2121.
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Figure 7 shows the signal related between the firing angle and the angular velocity, for the purpose of the study the transformation from revolutions per minute (RPM) to radians per second (rad/s) is performed.

Box 8

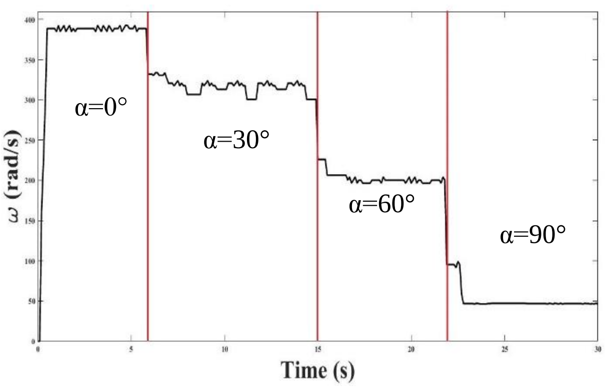

Figure 7

Real model according to firing angle α

Source: Own elaboration

Different stages that the system contemplates during the study period are observed, the first one being the start-up, followed by the voltage changes. The points in Table 2 corresponding to the data collection that satisfy the coefficients of equation (5).

Box 9

Table 2

Coefficients of Equation 5

Coefficient	Result
a_0	-57.22
a_1	1555.34
a_2	-2333.95
a_3	2099.0
a_4	-1279.41
a_5	554.04
a_6	-174.38
a_7	40.63
a_8	-7.13
a_9	0.96
a_{10}	-0.10
a_{11}	0.01
a_{12}	$-5.18x10^{-4}$
a_{13}	$2.59x10^{-5}$
a_{14}	$-1.01x10^{-6}$
a_{15}	$3.07x10^{-8}$
a_{16}	$-7.03x10^{-10}$
a_{17}	$1.17x10^{-11}$
a_{18}	$-1.35x10^{-13}$
a_{19}	$9.65x10^{-16}$
a_{20}	$-3.18x10^{-18}$

Source: Own elaboration

The following shows the resulting polynomial generated in the reconstruction of the angular velocity ω. The polynomial closest to the real behavior of the system is represented in equation (8).

$$f(x) = -57.22 + 1555.34t - 2333.95t^2 + 2099t^3 - 1279.41t^4 + 554.04t^5 - 174.38t^6 + 40.63t^7 - 7.13t^8 + 0.96t^9 - 0.1t^{10} + \cdots - 3.18x10^{-18}t^{20} \quad [8]$$

Figure 8 compares the curve of the real model at different voltage changes with different polynomials, of degrees ten, thirteen and twenty respectively.

Box 10

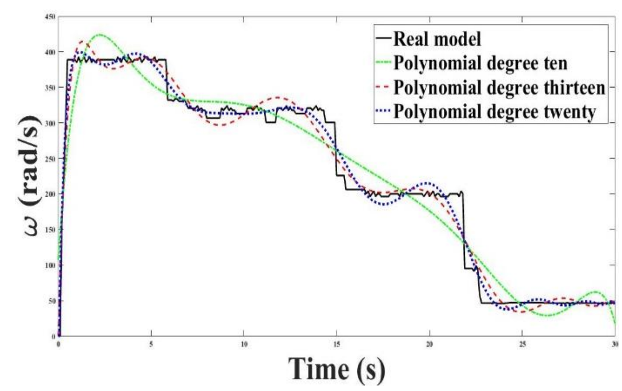

Figure 8

Real model, Polynomial degrees ten, thirteen and twenty

Source: Own elaboration

The polynomial generated by equation (8) represents the curve closest to the real model, the comparison between both is shown in Figure 9.

Box 11

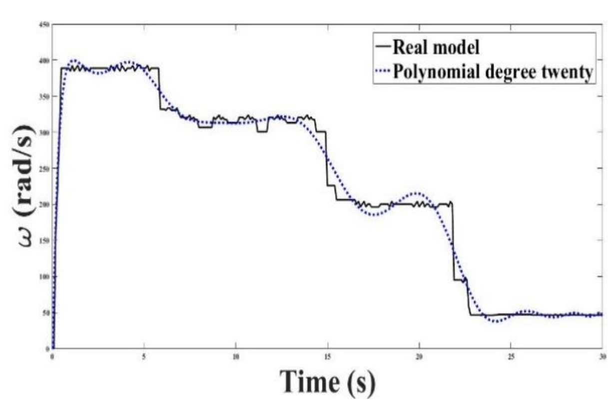

Figure 9

Comparison between the real model and the polynomial model of degree twenty

Source: Own elaboration

ISSN: 2524-2121.
RENIECYT-CONAHCYT: 1702902

Finally, an additional feature of the proposed method is the possibility to approximate the trajectory in the phase plane, which allows to obtain the stress change behavior of the study model. Equation (9) represents the relation (position θ, velocity ω) belonging to the phase plane.

$$\frac{d\theta/_{dt}}{d\omega/_{dt}} = \frac{\omega(t)}{\alpha(t)} \quad [9]$$

where $\alpha(t)$ is the acceleration in (rad/seg^2) represents a polynomial function of order n corresponding to the numerical approximation obtained from the angular velocity ω.

Figure 10 shows the phase diagram, which clearly indicates the stages of the system behavior.

Box 12

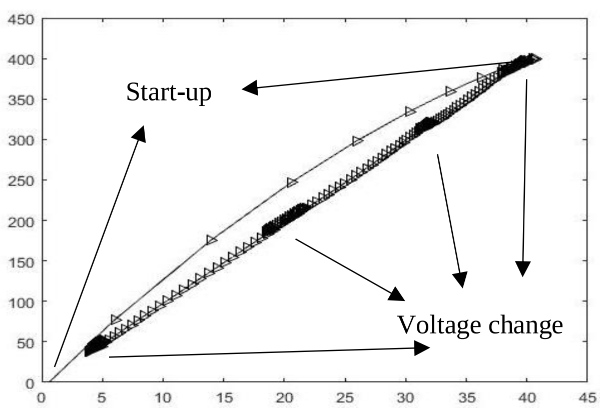

Figure 10
Phase plane of velocity change
Source: Own elaboration

Conclusions

The proposed system uses a single-phase motor, referring to the electrical coupling for control, the implementation allows to work properly with motors of similar characteristics, also meets the objective allowing to control the motor through the configuration provided by the algorithm and the control device interconnected to the IoT network shown in Figure 5.

Polynomials of different degrees are exposed in the work, in order to verify:

- The numerical method based on polynomial equivalents can approximate the physical model represented in Figure 9 where the higher the degree of a polynomial the better approximation to the real model curve is obtained.
- If a better appreciation of the dynamics of the system is desired, it can be represented by sectioning the phenomenon in time windows for each voltage variation and obtain a polynomial approximation of lower degree.

Finally, future work will focus on working on the control of the three-phase motor, this will allow to keep the PLC module without costly and irreversible modifications.

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Authors' Contribution

Camacho-Altamirano, Ulices: Contributed to the project idea, method and research technique. Developed the data acquisition system, the speed control algorithm and the writing of the article.

Martínez-Carrillo, Irma: Developed the numerical model for the processing of the data obtained through laboratory tests. Supported the electronic coupling design and the writing of the article.

Juárez-Toledo, Carlos: Contributed in the design of the electronic coupling, the communication protocol of the IIoT system, the method and laboratory tests.

Hernández-Epigmenio, Miguel Ángel: Worked on data acquisition through laboratory tests, numerical model for data processing and debugging of the results.

Availability of data and materials

The electronic coupling and laboratory tests were developed in the automation laboratory of the UAP Tianguistenco of the Universidad Autonoma del Estado de Mexico. The control algorithm and images were obtained from Matlab software.

Funding

The authors are grateful to the Consejo Mexiquense de Ciencia y Tecnología with grant ESYCA2023-144929.

Abbreviations

3D	Three-Dimensional
AC	Alternating Current
CPU	Central Processing Unit
DIAC	Diode Alternative Current
IIoT	Industrial Internet of Things
IoT	Internet of Things
M2M	Machine to Machine
PLC	Programmable Logic Controller
RFID	Radio Frequency Monitoring
RPM	Revolutions Per Minute
SCR	Silicon-Controlled Rectifier
TRIAC	Triode for Alternating Current
Wi-fi	Wireless Fidelity

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Basics

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