WROCLAW UNIVERSITY OF SCIENCE AND TECHNOLOGY

DESIGN OF AN AUTOMATION CONTROL SYSTEM FOR THE PULTRUSION PROCESS

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Resumen:

El sistema de pultrusión es un proceso de fabricación utilizado para producir perfiles de fibra de vidrio reforzados con resina de alta resistencia y durabilidad. Es un proceso continuo que se realiza mediante la extrusión de la mezcla de resina y fibra de vidrio a través de una matriz que le da la forma deseada.

Los productos fabricados con el proceso de pultrusión son conocidos por su alta resistencia y durabilidad. La fibra de vidrio utilizada en el proceso es conocida por su resistencia a la tracción, mientras que la resina termoestable se cura para formar un material duro y resistente. Los perfiles de fibra de vidrio reforzados con resina son también ligeros y resistentes a la corrosión, lo que los hace adecuados para una amplia variedad de aplicaciones.

En este TFG se pretende mejorar dicho proceso, implementando el control de este. En el diseño del control se deberá investigar cuáles son las opciones disponibles y valorar la mejor según las especificaciones requeridas durante el proceso de pultrusión

Para conseguir este objetivo, se automatizará el movimiento de un motor trifásico a través del inversor E500-4T, el cual se conectará mediante el conversor a USB RS-485 al PC, donde se escribirá un programa en LabVIEW con las instrucciones para conseguir el objetivo.

Además, se pretende diseñar un sistema para la medición de la velocidad de la fibra durante el proceso. Este dato, será de utilidad ya que queremos hacer girar el motor trifásico a la misma velocidad que la fibra.

DESIGN OF AN AUTOMATION AND CONTROL SYSTEM IN THE PULTRUSION PROCESS

Abstract:

The pultrusion system is a manufacturing process that produces high-strength and durable resin-reinforced fibreglass profiles. It is a continuous process that is carried out by extruding the resin and fibreglass mixture through a die to give it the desired shape.

Products manufactured using the pultrusion process are known for their high strength and durability. The glass fibre used in the process is known for its tensile strength, while the thermosetting resin cures to form a tough, resilient material. The resin-reinforced fibreglass profiles are also lightweight and corrosion-resistant, making them suitable for a wide variety of applications.

The aim of this work is to improve this process by implementing the control of this activity. In the control design, the available options will be investigated, and the best one will be evaluated according to the specifications required during the pultrusion process.

To achieve this objective, the movement of a three-phase motor will be automated through the E500-4T inverter, which will be connected via the RS-485 USB converter to the PC, where a LabVIEW program will be written with the instructions to achieve the objective.

In addition, we intend to design a system for measuring the speed of the fibre during the process. This data will be useful since we want to rotate the three-phase motor at the same speed as the fibre.

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REPORT

DESIGN OF AN AUTOMATION AND CONTROL SYSTEM IN THE PULTRUSION PROCESS

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DESIGN OF AN AUTOMATION AND CONTROL SYSTEM IN THE PULTRUSION PROCESS

1. Introduction

1.1 Description of the pultrusion process

The pultrusion system is a manufacturing process used to produce high-strength and durable resin-reinforced fibreglass profiles. It is a continuous process carried out by extruding the resin and fibreglass mixture through a die to give it the desired shape.

Products manufactured using the pultrusion process are known for their high strength and durability. The glass fibre used in the process is known for its tensile strength, while the thermosetting resin cures to form a tough, resilient material. The resin-reinforced fibreglass profiles are also lightweight and corrosion-resistant, making them suitable for a wide variety of applications.

The pultrusion process involves using a mixture of thermosetting resin and glass fibre, which is fed into a resin bath. The mixture is then passed through a die, which gives the desired shape to the profile. The matrix is heated to aid the curing of the resin, which is done by heat or ultraviolet light. Once the profile has been formed and cured, it is cut to the desired length and packaged for shipping.

The following figure (*Fig. 1*) shows an example of a schematic diagram of the pultrusion process.

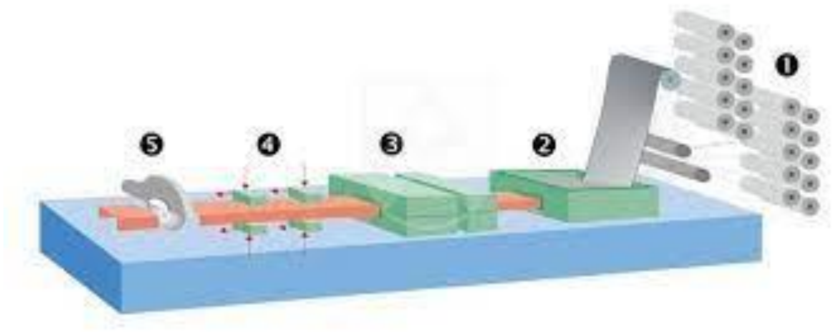

Figure 1. Schematic diagram of pultrusion process

1.2. Description of the automation of the pultrusion process.

This project deals with the automation of the pultrusion process, using an inverter in charge of the control of the three-phase motor, by means of communication via Modbus through the RS-485 communication interface to a PC where the desired control instructions are programmed using the LabVIEW programme.

Therefore, the system is composed of:

- Inverter
- Three-phase Motor
- Communication via Modbus protocol
- Hardware required for monitoring and data collection
- Design of the process speed measurement system
- Software application LabVIEW

1.3. Applications

Common applications for pultrusion products include construction, marine, sports and consumer products.

In construction, fibreglass profiles are used to reinforce structures, providing increased strength and durability. *(Fig. 2)*

In the marine industry, pultrusion products are used to manufacture boat hulls, providing strength and durability in harsh marine conditions. *(Fig. 2)*

In sports, pultrusion products are used to manufacture sports equipment such as golf clubs and fishing rods. *(Fig. 2)*

In consumer products, pultrusion products are used to manufacture automotive parts, appliance parts and a variety of other products. *(Fig. 2)*

Figure 2. Applications of the pultrusion process

1.4. Motivation

There are several reasons why controlling and automating the pultrusion system can be beneficial:

1. Improved product quality: Automating the pultrusion system can help improve the quality of the final product. By automating the resin mixing, extrusion and curing process, greater accuracy in material dosing and production speed can be ensured, reducing the variability of the final product, and improving its quality.

2. Increased process efficiency: Automation of the pultrusion system can help increase the efficiency of the production process by reducing downtime and improving resource utilisation. Automation can also help reduce material waste, which can be beneficial to the profitability of the business.

3. Operator safety: The use of automated systems can help improve the safety of pultrusion system operators. By eliminating the need for operators to be in direct contact with materials and production processes, the risk of accidents and injuries is reduced.

4. Quality control: Automation of the pultrusion system can also provide greater quality control in the production process. By using automated sensors and monitoring systems, material quality can be controlled, and problems can be detected in real-time, allowing corrective action to be taken quickly and effectively.

5. Production flexibility: Automating the pultrusion system can provide greater flexibility in production by allowing for quick changes in the process. Automated systems can accommodate different profile sizes and shapes, as well as different material mixes, allowing for greater customization and adaptability in production.

1.5. Project developments

The pultrusion system is a manufacturing process used to obtain solid or hollow parts with a constant section, thus replacing traditional materials such as steel, concrete or wood.

The novelty of this project means that a great deal of time has been invested in the search for the optimum components and materials to carry out the implementation of this project. In addition to the various tests that have been carried out on a smaller scale, trying to prove the viability of the work carried out in the laboratory in a real future implementation.

2. Elements of the system

As mentioned above, extensive research has been carried out in which various components have been tested to find the optimal device for each part of the system.
In this section, the different components investigated are explained, as well as the reasons for choosing or discarding them and the various assemblies carried out.
The project can be divided into the research part of the materials that in the future will be implemented in the pultrusion process itself and the tests and experiments carried out in the laboratory.

2.1 Inverter

The primary function of the inverter is to convert direct current (DC) to three-phase alternating current (AC) to produce the AC signal with the desired amplitude, frequency and waveform.
Two different inverters have been tested in the choice of inverter.
The first of these is a single-phase inverter, the GD10-0R7G-S2-B model from Shenzhen INVT Electric Co., Ltd., shown in (*Fig. 3*) with which the PC communication via Modbus was tested, and for the first time, it was possible to control the movement of the motor.

Figure 3. GD10-0R7G-S2-B single-phase inverter

The other inverter tested was the E500-4T0022(B) model from Shenzhen Simphoenix Electric Technology Co., Ltd., shown in (*Fig. 4*) a three-phase inverter.

A three-phase inverter consists of three AC circuits, each of which is 120 degrees out of phase with the other. This allows for a more efficient and balanced power distribution compared to single-phase AC, which consists of a single AC circuit.

In addition, a three-phase inverter can offer a higher load capacity than a single-phase inverter, making it especially useful in high-power applications. They can also provide higher energy efficiency compared to other types of inverters.

For all these reasons, it was finally decided that the inverter to be used for this project was the E500-4T0022(B).

Figure 4. E500-4T0022(B) Three-phase inverter

2.2 Three-phase Motor

The three-phase motor, shown in (*Fig. 5*), is used to execute the mould movement. The LabVIEW program will control it through an inverter communicating via Modbus protocol.

This motor must move according to the linear velocity of the bar; it will be seen later that to achieve this, we will use a closed loop.

Figure 5. Three-phase motor

2.3 Modbus Protocol

Modbus is a communication protocol widely used in industrial automation and process control systems.

The Modbus protocol is based on a master-slave architecture, where a master device controls one or more slave devices via a communication network, as shown in *(Fig. 6)*. This project has a master, the PC, and a slave, the inverter.

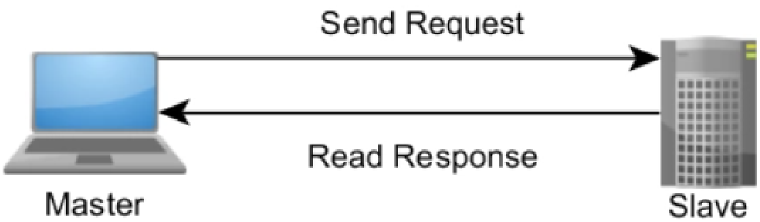

Figure 6. Schematic of Modbus protocol

In Modbus, this command is a set of data layers. The first layer is the application data unit (ADU), the type of Modbus being used.

There are three types of application data:

1. ASCII
2. TCP/IP
3. Remote terminal unit (RTU)

In this project, it has been decided to use RTU, which uses a compact binary representation.

For most applications, the ADU to choose depends on the desired physical network (Ethernet, serial...), the number of devices on the network and the ADU supported by the master and slave devices on the network.

Within each ADU, there is a protocol data unit (PDU) which is the core of the Modbus protocol. Each PDU contains a function code and associated data. Each function code has a well-defined response, which can be thought of as the command sent to the slave.

Modbus defines a message structure that is used to exchange data between devices on the network. Messages are made up of bytes of data and are sent via a communication medium, such as an RS-485 or Ethernet cable. RS-485 has been used for this project.

For communication between the inverter and the PC. The master sends a command including:

- Slave machine address (generally 1 to 30)
- Function code
- Initial register address
- Data register

An example can be seen in (*Fig. 7)*.

(2). Set inverter running frequency as 50.0Hz

Main machine request:

Slave machine address	Function code	Register initial address		Register data		CRC CHECK	
		High	Low	High	Low	Low	High
01	06	10	02	01	F4	2C	DD

Slave machine response: inverter in 50.0Hz running condition responds the same data with main machine request.

Figure 7. Example protocol format

To which the inverter responds by executing the master's command (*Fig. 8*).

(3). Read current running frequency, output current, inverter response frequency 50.0Hz and output current 1.1A of inverter.

Main machine request:

Slave machine address	Function code	Register initial address		Number of registers		CRC CHECK	
		High	Low	High	Low	Low	High
01	03	D0	00	00	02	FC	CB

Slave machine response:

Slave machine address	Function code	Number of reading bytes	1st register data		2nd register data		CRC CHECK	
			High	Low	High	Low	Low	High
01	03	04	01	F4	00	0B	FB	FA

Figure 8. Example protocol format

Modbus is a simple and easy-to-implement protocol, making it ideal for process control and industrial automation systems. In addition, its wide adoption and the large number of supported devices make it a popular choice for system integration in industrial environments.

Due to all the above, it was decided to use this protocol with the named configuration and components for the system's communication.

2.4 RS-485 Communication interface

The RS-485 communication interface is a serial communication standard that is commonly used for data transmission in industrial networks.

RS-485 uses a bus topology to connect multiple devices to a single communication line. Each device is connected to the communication line via an RS-485 transceiver, which enables data transmission and reception.

One of the advantages of RS-485 is its ability to transmit data over distances of up to 1.2km, making it ideal for industrial applications where long-distance networking is required. In addition, RS-485 is also noise resistant and can withstand harsh industrial environments.

Another advantage is that RS-485 allows bi-directional communication, which means that devices connected to the communication line can transmit and receive data. This enables the implementation of complex real-time monitoring and control systems.

It was therefore decided to use the RS-485 communication interface in this project.

During the laboratory tests, two RS-485s were used, we can see them in (*Fig. 9)* and (*Fig. 10)*. The second one was finally selected.

Figure 9. First RS-485 used.

Figure 10. Chosen RS-485.

To use the RS-485, it is necessary to install a driver to enable the COM port.

After trying several drivers without the expected result, the one developed by national instruments was used.

In the connection process, we must make sure that when the RS-485 is connected to the PC, the power led (PWR) is turned on, and we know that we are transmitting content when the TXD and RXD are also turned on.

2.5 Software LabVIEW

LabVIEW software was used to develop the application on the PC.

In LabVIEW, the Modbus library allows users to create data acquisition and control applications based on the Modbus protocol. This library also includes a set of VIs (Virtual Instruments) that are used to send and receive data using the Modbus protocol. The VIs in the Modbus library includes VIs to connect to a Modbus device, send and receive data, and configure communication parameters with which we can interact with the inverter and read or write data from Modbus registers.

In summary, the Modbus library in LabVIEW is a useful tool for interfacing with electronic devices using the Modbus protocol in data acquisition and control applications.

Commands will be sent to the slave while reading the responses to them.

1. Engine start-up
2. Desired rotational frequency
3. Request for motor parameters
    - 3.1 Frequency, F [Hz]
    - 3.2 Voltage, V [V]
    - 3.3 Current, I [A]
    - 3.4 Revolutions per minute, rpm [rpm]
4. Analogue port measurement request

The following figures (*Fig. 11)* and (*Fig. 12*) show the LabVIEW blocks from the Modbus library.

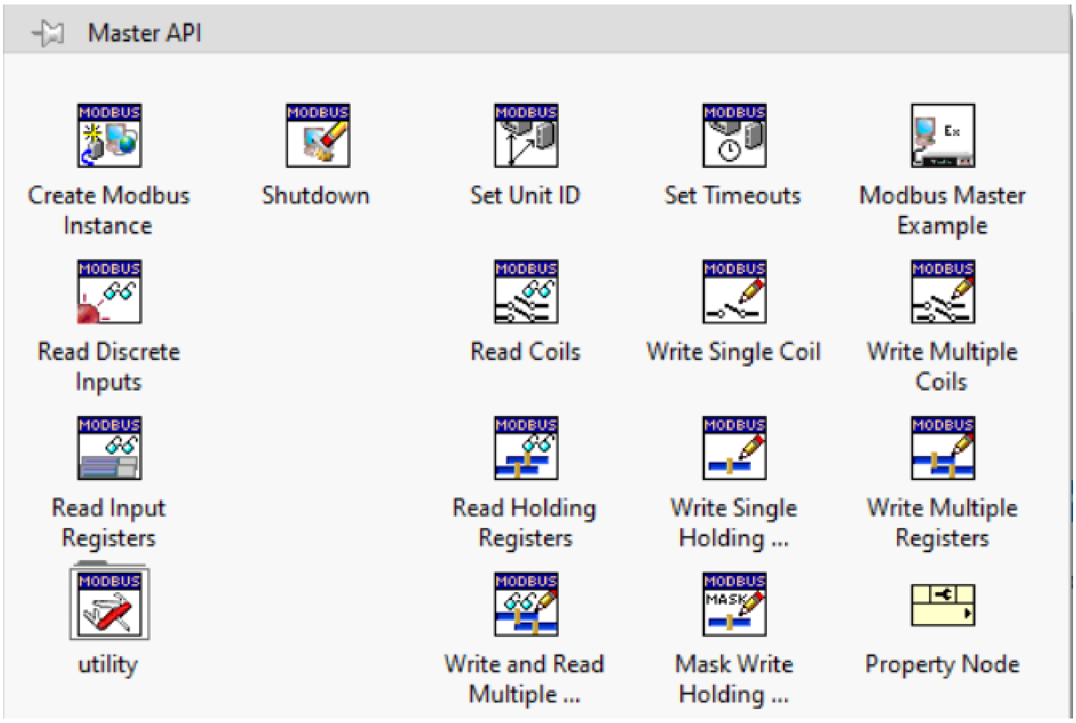

Figure 11. API Master Block

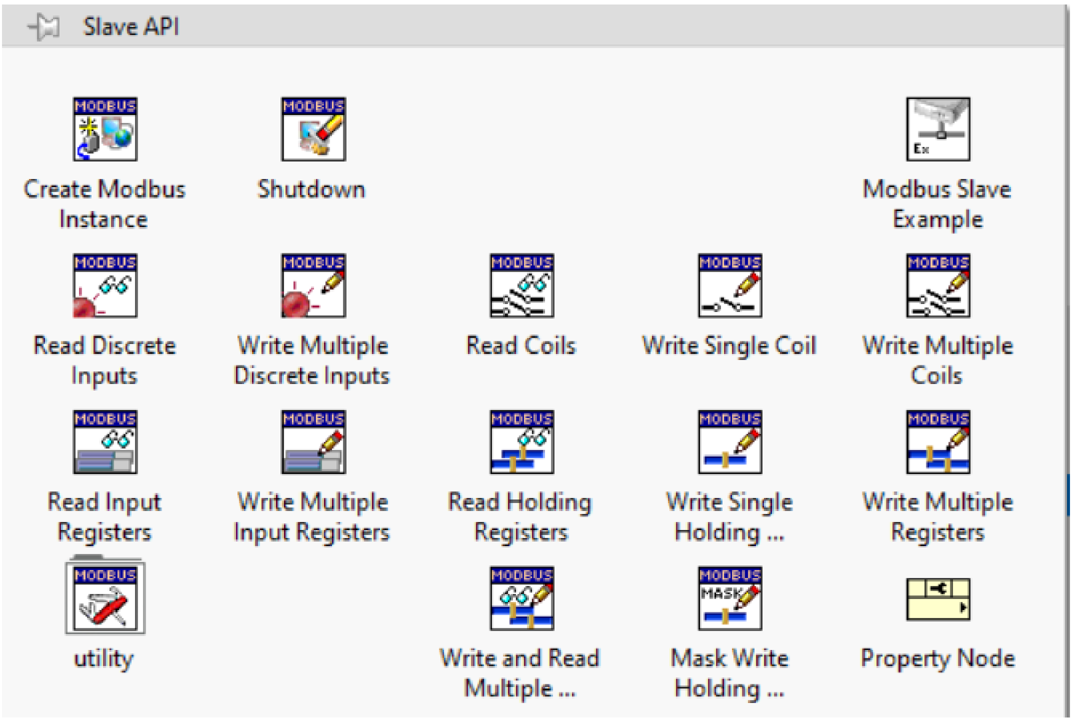

Figure 12. Slave API Blocks

2.6 Bar speed measurement system.

A system has been designed in order to measure the speed of the fibres during the pultrusion process.

In the laboratory, a setup has been made simulating the movement to be measured in the real pultrusion process.

The following devices have been used for this purpose:

1. DC Motor
2. Encoder
3. Power supply (DC Motor and Frequency converter)
4. Frequency converter
5. Potentiometer

The encoder records the movement of the bar during the pultrusion, which for our work is the movement of a DC motor, as we can see in *(Fig. 13)* and generates a signal such that the value of the revolutions per minute at which the bar rotates corresponds to a number of pulses per second. The movement of the motor is controlled by a potentiometer circuit, which allows to regulate the speed of the system. This motor is powered by the power supply in *(Fig. 14)*. In order to be able to appreciate the speed at which the process works; this signal has been adapted.

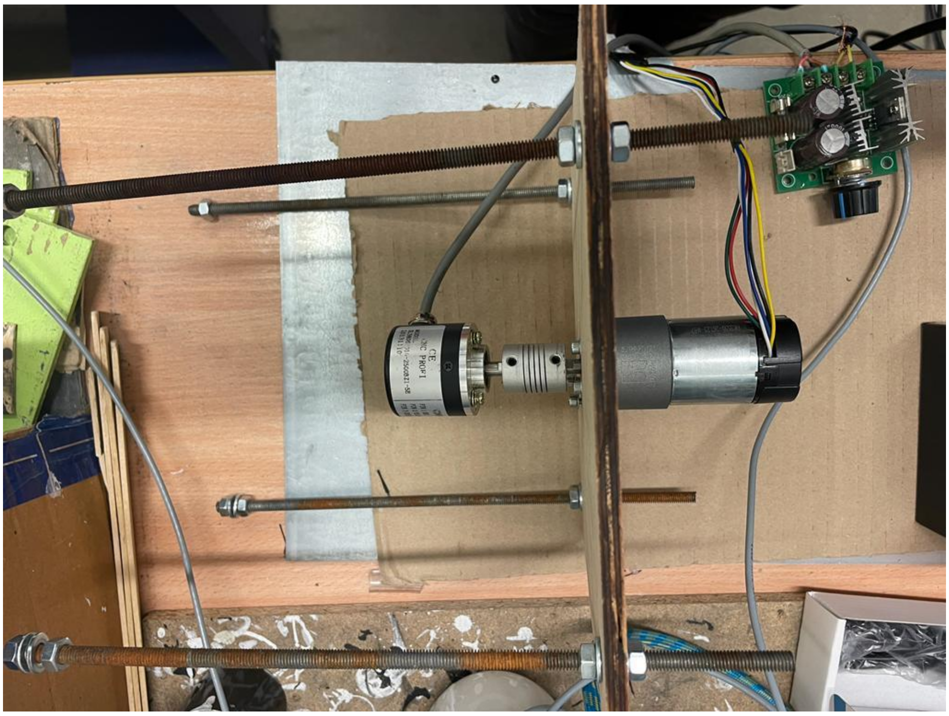

Figure 13. Encoder, DC Motor and Potentiometer Circuit.

Figure 14. DC Motor Power Supply

The signal generated by the encoder is sent to the frequency converter, where each pulse corresponds to a specific frequency. The converter used is a programmable frequency converter, as seen in *(Fig. 15)*. The program developed by the company has been used to adjust the frequency multiplier range and thus obtain the appropriate resolution.

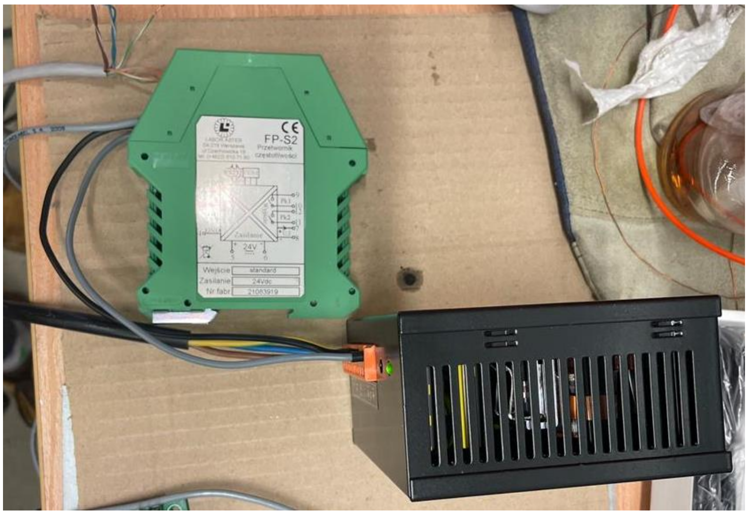

Figure 15. Frequency converter and Power supply.

The frequency converter was connected to the inverter, which was simultaneously attached to the PC using Modbus via the RS-485 communication interface. In the LabVIEW program, the inverter was given the command to read the analogue input, thus obtaining the signal corresponding to the movement of the bar.

3. Calculations

In order to make the measurement system of the speed of the bar during the process, we must make the following calculations:

When making the calculations, a desired final value was set, with which the bar speed was set back step by step at each assembly stage.

DATA:

Range of frequency converter: $0 - 3000$ peaks/sec

Analog output of the frequency converter: $0 - 10V$

The equivalence between the analog input and the range of the frequency converter, stands as the maximum value of the analog output ($10V$) corresponds with the maximum value of the range of the frequency converter ($3000\ peaks/sec$).

Resolution of the frequency converter: $1\ rev - 2500\ peaks/sec$

Radius of the rebour: $30\ cm$

Pitch: $1\ cm$

In the real implementation, we will have to consider the ratio of power transferred to the motor. For this experiment, we are going to establish this ratio as: $R = 4$

The maximum velocity of the motor is, $1380rpm$, which corresponds with the maximum output that the inverter can give ($50Hz$).

To make a clear example, we will calculate the value for the medium value. That is 5V in, the analog input.

First, we have the establish the equivalence between the analog input and the frequency converter:

As we know, the maximum output is $10V$, corresponding to $3000\ peaks/sec$. We can easily say that for $5V$, we will have $1500\ peaks/sec$.

$$X = \frac{(1500\frac{peaks}{sec} * 1rev)}{2500\frac{peaks}{sec}} = 0.6\ rev$$

As the radius of the rebour is $30cm$, we can say that every turn or revolution of it, is equal to this $30cm$.

With that said, we can calculate the linear velocity:

$$Vl = 0.6\ rev * 30\ cm = 18\ \frac{cm}{s}$$

As we made the close loop of the system. It will be interesting to know the angular velocity of the engine as well as the frequency of it.

Considering the $Pitch = 1cm\ R = 4$ we calculate the angular velocity of the engine.

$$Vl = Pitch * W_m$$

$$W_m = \frac{Vl}{p} = \frac{18}{1}$$

$$W_{engine} = W_m * R = 180 * 4 = 720\ rpm$$

With the engine's angular velocity, we can easily calculate the frequency of work from it.

$$Freq_{engine} = \frac{720\ rpm * 50\ Hz}{1380\ rpm} = 26.09\ Hz$$

Now, to implement these in LabVIEW calculations, we must make a formula that works for every value entered. The previous calculation will help us with this.

Saying that the analog output volts is N, and making all the transformations as we previously did for the medium analog output value. We have:

$$W_{engine} = N(V)\frac{3000(\frac{peaks}{sec}) * 30(cm) * R}{10(V) * 2500(\frac{peaks}{sec}) * 1(cm)}$$

$$W_{engine} = N(V) * 14{,}4$$

$$F_{engine} = W_{engine} * \frac{50(Hz)}{1380(rpm)}$$

$$F_{engine} = N * 5{,}2$$

With that, in LabVIEW, we can connect the measurement of the analog input multiplied by the calculated factor to the input of the motor. Achieving the mentioned closed loop, moving the motor with relation to the speed of the rebour during the process.

4. LabVIEW software simulation

Using LabVIEW software, a programme has been designed with which we can control the movement of the motor while measuring the desired parameters.

As previously mentioned, the Modbus library has been used for programming in LabVIEW.

To write the program, we must do the following steps:

First, a Modbus instance must be created (*Fig.16*), and the following parameters shown in *(Table 1)* need to be configured. In our case, it was decided to work with:

Baud rate	9600 bauds/seg
Parity	None
Serial type	RTU
Unit ID	1
VISA resource name	COM3 port
Error in & error out	Error in & error out
Flow control	None

In the first program (*Fig. 17*), the three-phase motor was started, only by entering a fixed frequency, without sending any measurement command.

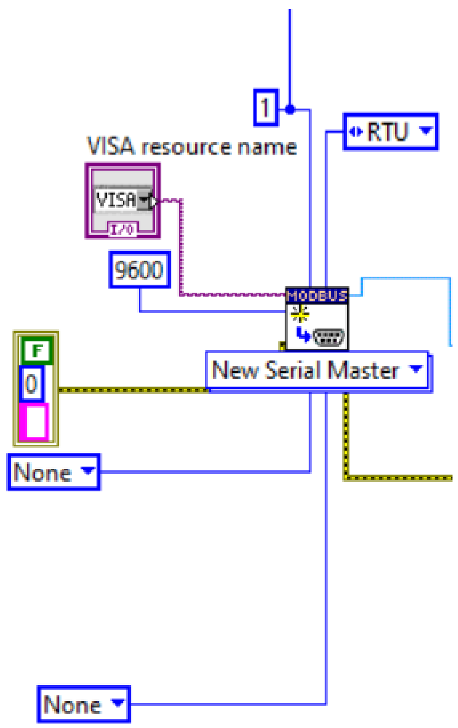

Figure 16. Serial Master Block

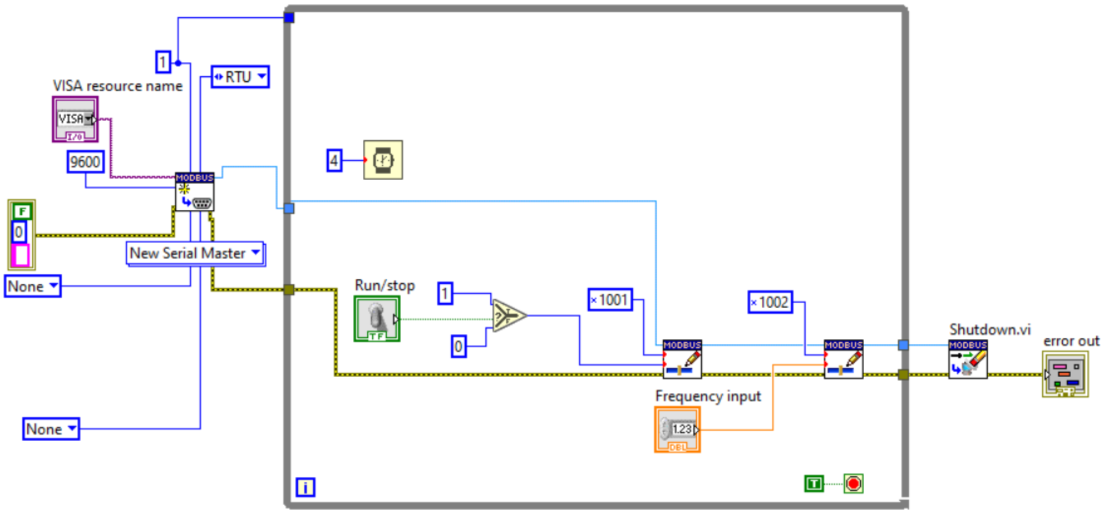

Figure 17. First LabVIEW program

In order to be able to carry out the process repeatedly, a while loop is used, in which the following has been implemented:

For additional security, an emergency button has been created to stop the programme in case of any inconvenience during the process.

Moreover, it can be seen in (*Fig. 21*) that the program checks if an error is going on every time, it starts the simulation. This is done by sending the operation command codes *(0x0020)* and *(0x0003)* seen in *(Fig. 18)*.

(2) Operation command corresponding to operation command code:

Operation command code	Operation command
0x0000	Invalid command
0x0001	FWD running start
0x0002	REV running start
0x0003	Stop
0x0004	FWD inching of slave machine
0x0005	REV inching of slave machine
0x0006	Inching running stops
0x0020	Fault reset of slave machine

Figure 18. Operation command error checking

Once this has been checked, the Write Single Holding Registering Register.vi block is used (*Fig. 21*); in it we send the start-up address (*Fig. 19*) of the inverter.

(1). Start 1＃ inverter in FWD running condition

Main machine request:

Slave machine address	Function code	Register initial address		Register data		CRC CHECK	
		High	Low	High	Low	Low	High
01	06	10	01	00	01	1D	0A

Figure 19. Address FWD running condition.

The command to set the inverter operating frequency is then sent (*Fig. 20*).

(2). Set inverter running frequency as 50.0Hz

Main machine request:

Slave machine address	Function code	Register initial address		Register data		CRC CHECK	
		High	Low	High	Low	Low	High
01	06	10	02	01	F4	2C	DD

Figure 20. Address Frequency Setting

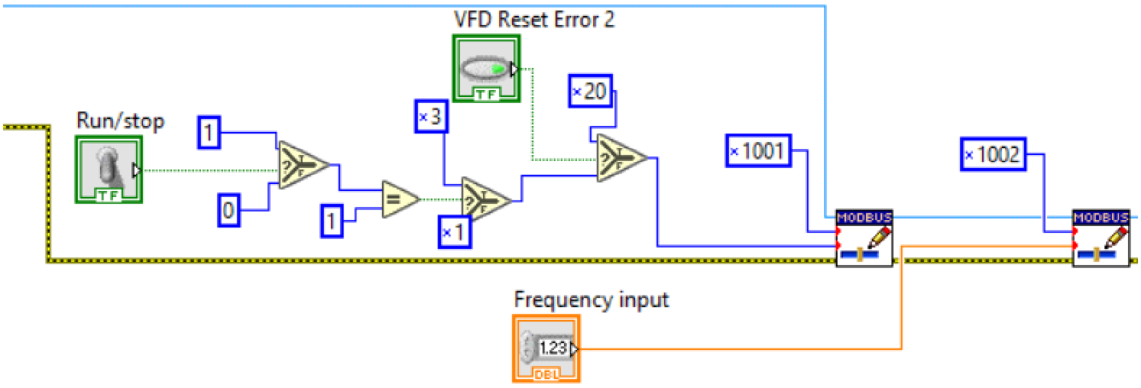

Figure 21. Block orders

Through the Modbus Read Holding Registers.vi block (*Fig. 23*) and entering the addresses of the desired parameters and the number of registers (*Fig. 22*) depending on the parameters to be measured.

4.3 List of status monitoring parameters

Monitoring code	Content	Unit
d-00	Inverter's current output frequency	Hz
d-01	Inverter's current output current (effective value)	A
d-02	Inverter's current output voltage (effective value)	V
d-03	Motor revolution	rpm
d-04	Voltage at the DC terminal in the inverter	V
d-05	Inverter's input AC voltage (effective value)	V
d-06	Set frequency	Hz
d-07	Analog input AI	V
d-08	Running liner speed	
d-09	Set liner speed	

Figure 22. Status list of monitoring parameters

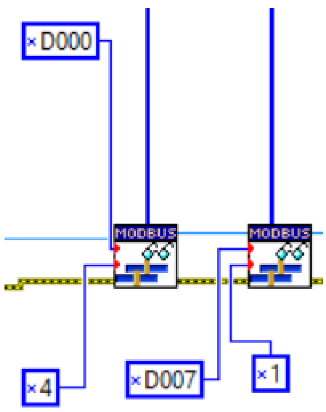

Figure 23. Modbus Read Holding Registers.vi block.

We managed to measure the following parameters (*Fig. 24)* and *(Fig. 25)*:

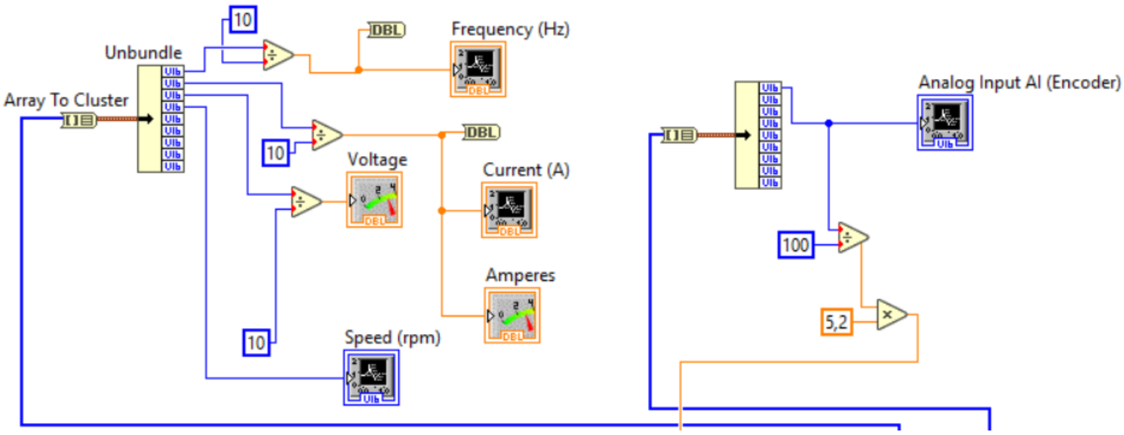

Figure 24. Measurements of parameters LabVIEW

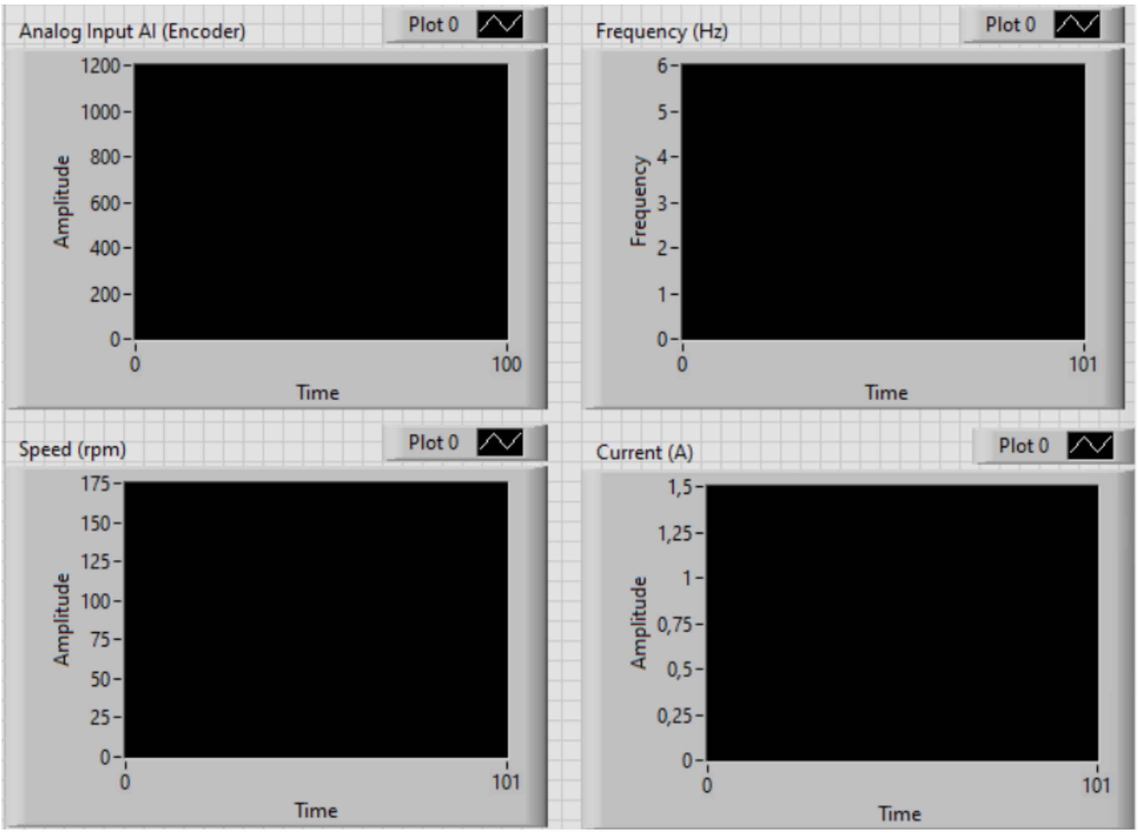

Figure 25. Measurements of parameters graphs.

With these graphs, we can visualise the analogue input coming from the movement of the pultrusion process, the frequency and current at which the inverter is working, and the revolutions per minute of the three-phase motor.

5. Graphs from the simulation

The final simulation of the whole system showed the following graphs (Fig. 26) and (Fig. 27).

The work was simulated at maximum speed (Fig.26) and half speed (Fig. 27).

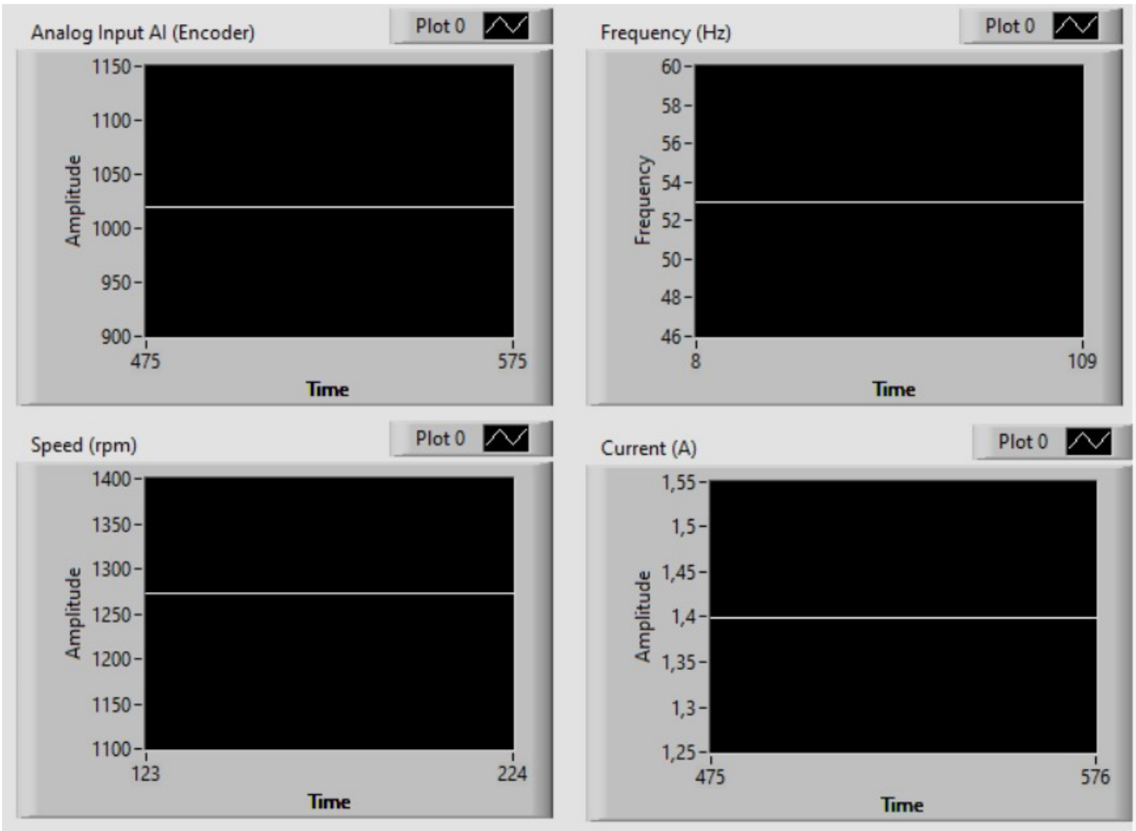

Figure 26. Results working at max speed.

Analysing the figure above, we can see how the three-phase motor is working at its maximum speed, the same as the DC motor. It can also be seen that the current and frequency measured are maximum for this setting.

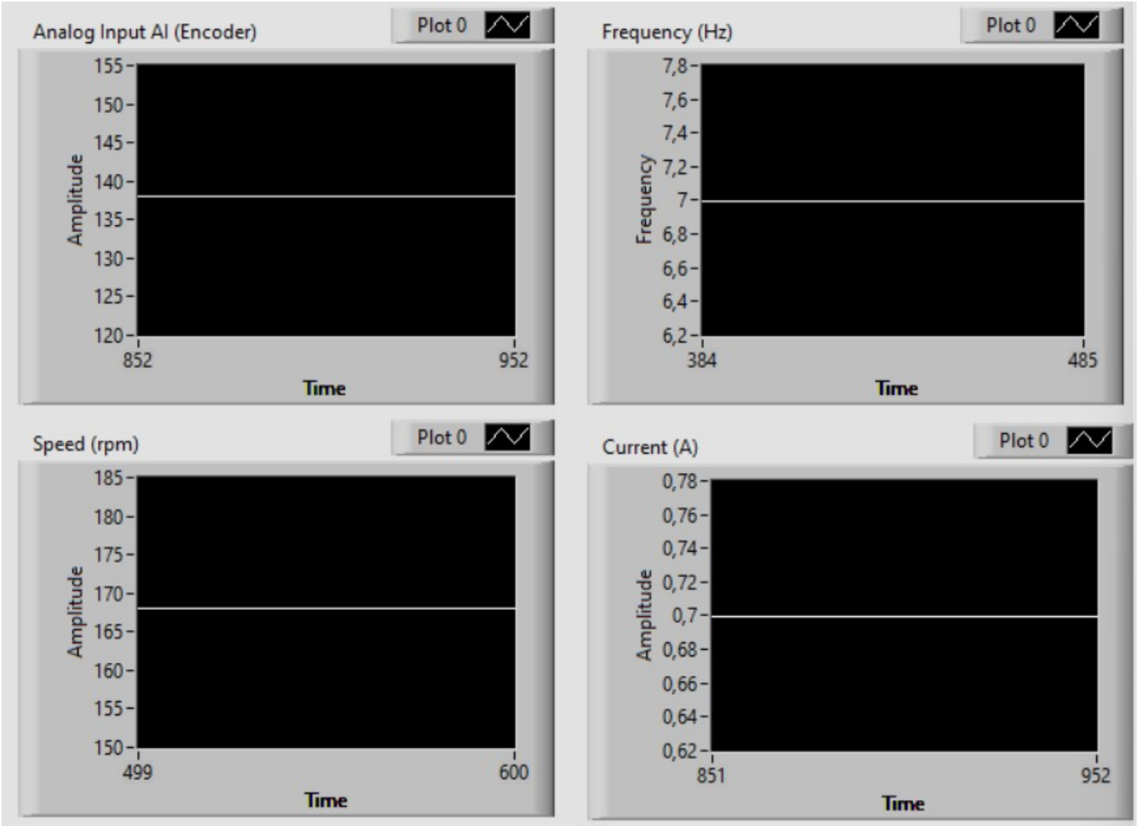

Figure 27. Results working at half of the max speed.

Analysing the figure above, we can see how the three-phase motor is working at half of its maximum speed, the same as the DC motor. It can also be seen that the current and frequency measured is half what was for the previous setting.

With that, it can be said that the system is working as it was designed.

6. Results and Conclusion

6.1 Software

The LabVIEW software sends the commands and receives the information from the inverter satisfactorily. It also displays the information of the different parameters requested on the screen.

6.2 Hardware

The inverter executes the commands received by the PC and sends back information from the peripherals.

The three-phase motor moves at the desired speed in relation to the bar speed of the pultrusion system. This results in a closed loop.

The bar speed measurement system is able to give an accurate, real-time value of the speed at which the system is moving.

6.3 Global

With all of the above and in view of the results shown in the previous point, it is possible to affirm that the system designed for the control of the pultrusion system performs what was planned at the beginning. Therefore, it can be established that the project is finished and works correctly.

7. Future work

Based on what has been concluded, a number of improvements and extensions can be made to the project.

PID controller implementation: the addition of a PID controller in the control of the pultrusion system will help to improve accuracy, stability, and responsiveness, leading to better control of the process or system being regulated.

Real implementation: It would be interesting to implement the work carried out in the laboratory, in order to verify the conclusions drawn in the previous point, as well as to study the possible industrialisation of the system proposed in this document.

8. Bibliography

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