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EMBEDDED

SOLAR ANGULAR CONTROL SYSTEM TO MAXIMIZE POWER AND PROMOTE SOCIAL AND ENVIRONMENTAL INCLUSION IN MEXICO

SISTEMA EMBEBIDO DE CONTROL ANGULAR SOLAR PARA MAXIMIZAR POTENCIA Y FOMENTAR INCLUSIÓN SOCIAL Y AMBIENTAL MÉXICO

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ABSTRACT

In recent decades, wind energy has been the fastest growing and most developed renewable energy source worldwide. Since wind turbines are directly connected to the electrical grid, it is essential to maximize the power extracted from the wind and convert it into the greatest possible amount of electrical energy. To achieve this, monitoring key variables such as turbine current, voltage, and wind speed is critical. This work presents the design and implementation of an embedded system to control the blade pitch angle through wireless communication with a master controller that determines and sends the optimal angle to reach the maximum power point. A subordinate subsystem is responsible for adjusting the blades according to the received signal. The master controller uses an algorithm that analyzes input readings to optimize energy generation. This system identifies the optimal wind speed and blade angle for maximum output, maintaining continuous movement to ensure efficient and stable turbine operation. From a social perspective, this research represents a key tool to promote the integration of clean energy in Mexican communities, especially in rural areas where reliable energy access is limited. This contribution improves quality of life, fosters sustainable development, and reduces dependence on polluting fossil fuels. Additionally, the system encourages the adoption of smart technologies, generates local employment opportunities, and provides technical training in the energy sector, aligning with Mexico's social and environmental objectives.

Keywords: Renewable energy, Wind loading and aerodynamics, Pitch angle embedded system, Communications and

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control systems, Maximum power point.

RESUMEN

En las últimas décadas, la energía eólica ha sido la fuente renovable con mayor crecimiento y desarrollo a nivel mundial. Dado que las turbinas eólicas están conectadas directamente a la red eléctrica, es fundamental maximizar la extracción de potencia del viento y convertirla en la mayor cantidad posible de energía eléctrica. Para ello, es imprescindible monitorear variables clave como la corriente, el voltaje de la turbina y la velocidad del viento. Este trabajo presenta el diseño e implementación de un sistema embebido para controlar el ángulo de las palas mediante comunicación inalámbrica con un controlador maestro que determina y envía el ángulo óptimo para alcanzar el punto de máxima potencia. Un subsistema subordinado se encarga de ajustar las palas según la señal recibida. El controlador maestro utiliza un algoritmo que analiza las lecturas para optimizar la generación energética. Este sistema permite identificar la velocidad del viento y el ángulo óptimos para la máxima producción, manteniendo un movimiento continuo que asegura una operación eficiente y estable de la turbina. Desde una perspectiva social, esta investigación representa una herramienta clave para promover la integración de energías limpias en comunidades mexicanas, especialmente en zonas rurales donde el acceso a energía confiable es limitado. Esto contribuye a mejorar la calidad de vida, fomentar el desarrollo sostenible y reducir la dependencia de combustibles fósiles contaminantes. Asimismo, el sistema impulsa la adopción de tecnologías inteligentes, generando oportunidades de empleo y capacitación técnica en el sector energético local, alineándose con los objetivos sociales y ambientales de México.

Palabras clave: Energía renovable, Carga eólica y aerodinámica, Sistema integrado de ángulo de paso, Sistemas de comunicación y control, Punto de máxima potencia.

INTRODUCTION

A study by the World Energy Council (WEC) reveals that the demand for energy worldwide by 2020 will be between 50–80% greater than in 1990; additionally, annual energy consumption for 2007 of 22 billion kWh/year was projected to become 53 billion kWh by 2020. According to the World Bank, world energy consumption per capita increased from 2,127,313 kWh in 1990 to 3,132,148 kWh in 2014 (Banco Mundial, 2024). Similarly, energy consumption in Mexico went from 1,185.04 kWh in 1990 to 2,157,324 kWh in 2014, implying increases of 47.23% worldwide and 82.04% for Mexico in per capita consumption (Enerdata, 2024).

Research has led to the development of various control methods, including algorithms to identify the maximum power point in wind turbines (Chen et al., 2022; Honarbari et al., 2021; La Tona et al., 2020; Liu et al., 2023; Majout et al., 2022; Wang et al., 2023; Yang et al., 2023; Zhang et al., 2023; Zou et al., 2023). The peak speed ratio (TSR) control method maintains a constant optimal tip speed ratio for a specific wind turbine regardless of wind speed (Yang et al., 2023). The Perturbation and Observation (P&O) control method, also known as the hill-climbing technique, is a mathematical optimization strategy used to identify the local maximum of a specific function: if the operating point is left of the peak, the controller moves it right to approach the maximum power point (MPPT), and vice versa (Lee & Chun, 2019).

Several studies have addressed control methods for wind turbines aimed at optimizing energy production. Among them, Chen et al. (2022) applied variable frequency modulation compensation techniques to improve performance in hydraulic turbines. Majout et al. (2022) demonstrated the stability of sliding mode control using Lyapunov functions, while Honarbari et al. (2021) implemented extended Kalman filters and fuzzy control to minimize unpredictable effects in PMSG systems. La Tona et al. (2020) applied growing neural gas artificial neural networks to improve reliability and reduce costs. More recently, research such as that by Yang et al. (2023) and Zhang et al. (2023) employed CFD simulations and advanced control strategies to optimize the aerodynamics and operation of turbine blades.

Furthermore, Zammit et al. (2017) developed an incremental current-based MPPT algorithm for a PMSG micro wind turbine connected to a DC microgrid, adjusting reference current based on DC link voltage for optimal power transfer across wind speeds.

Standards such as IEC 61400-12-1 have been recommended to improve testing and energy yield calculations. Nonlinear model predictive control has shown reductions in fatigue and gust loads (Schlipf et al., 2013; Raach et al., 2014). Yaw control strategies optimize turbine loading and structural parameters (Fleming et al., 2016). Incorporating wake modeling into individual pitch control (IPC) strategies also better reduces loads compared to generic methods.

Sliding mode control methods have been validated with offline and real-time simulations achieving successful control objectives (Munteanu et al., 2008). The robust stability of closed-loop systems combining MPPT and sliding mode current control was demonstrated using Lyapunov theory (Lee & Chun, 2019).

To achieve maximum efficiency in generating electrical energy from wind turbines, accurate measurement of airflow passing through the blades is essential. Blade positioning plays a critical role, as blades adjust their angle based on wind direction to better capture kinetic energy (Obando et al., 2020). A subordinate subsystem handling blade position control enhances this energy capture.

The purpose of having the maximum power point tracking algorithm is primarily to generate maximum power at different wind speeds. Therefore, monitoring the variables and having a position controller, also controlling the movement of the blades in the wind generator, seeks to obtain maximum efficiency in the production of electrical energy. The objective of this study is to develop and implement an embedded pitch angle control system for a wind turbine, with a focus on achieving Maximum Power Point Tracking (MPPT) through blade pitch angle adjustment. A slave subsystem will be responsible for controlling the blade positions, while the master controller will feature an algorithm to determine the maximum power point based on input readings and remotely adjust the blade angle accordingly. The system will monitor and record variables such as wind speed, power generated, and blade angle in the slave subsystem, plotting results to identify optimal angles and speeds for maximum power generation.

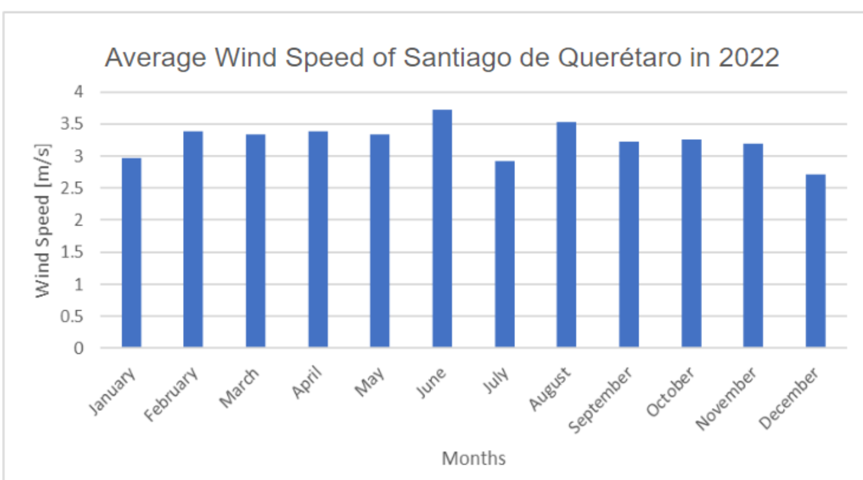
This work aims to develop an embedded system to control the pitch angle of wind turbine blades, maximizing power output while supporting Mexico's sustainable energy agenda. By combining technological innovation with environmental responsibility and social progress, the proposed system aspires to propel the adoption of wind energy as a driver for both ecological preservation and community empowerment.

MATERIALS AND METHODS

Location Description

The location where the system was installed is in a house located in the metropolitan area of the state of Queretaro. Figure. 1 shows the average annual speed in Santiago de Querétaro is 2.85 m/s with an average maximum gust of 13.24 m/s. The development of the research for the development and implementation of the embedded system to find the maximum power point is in the Santa Rosa Jáuregui delegation of Querétaro on Ignacio Zaragoza Street in the Pedregal neighborhood, whose coordinates are 20.741376 N, -100.454207 W.

Fig. 1. Weather in Santiago de Querétaro in 2022 (average Speed).



Source: developed by the authors.

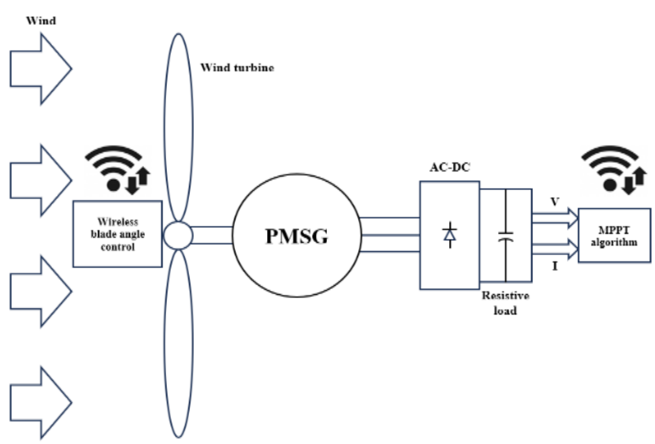
Controller Description

To realize the embedded system of the slave subsystem for the command of the pitch angle, the programming of the motors for the movement of the wind generator blades was implemented, so the master control of the system was used instrumentation to analyze its performance and control the process, considering the electrical power of the wind generator.

Basic Topology

The proposed structure of the Wind Energy Conversion System based on a PMSG with wireless slave blade angle control is shown in Figure. 2. This structure makes it possible to establish wireless slave blade angle control (pitch angle control) mounted at the center of turbine while the desired blade angle is computed on ground side using the MPPT algorithm stage, which requires current and voltage of the load to calculate instantaneous power necessary for iterative power increments calculations.

Fig. 2. Proposed Wind Energy Conversion System on a PMSG topology.

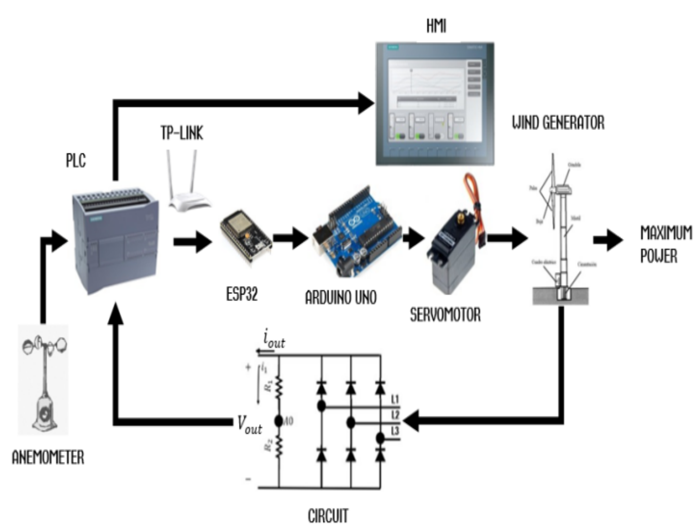


Source: developed by the authors.

Schematic Diagram of Wind Generator Control Operation

The control is performed by means of a closed loop system applied to a process, thus obtaining the maximum power point by means of the generation of energy passing through the wind generator and obtained by the analog inputs. The process has as main variable the voltage thrown from the generator terminals that passes through the diode rectifier bridge controlled by the movement of the servomotors that make the blades move to better capture the wind gusts that are present. The main control is in the Programmable Logic Controller (PLC) Siemens with Central Processing Unit (CPU) is 1214C DC/DC/DC which sends by Transmission Control Protocol and Internet Protocol (TCP/IP) protocol the angle to determine which is the most suitable for obtaining the wind gusts to the integrated card by Espressif Systems (ESP32) with Wireless Fidelity Alliance Inc (Wi-Fi) which in turn passes through the integrated circuit for the conversion of voltage levels so the information is received by the Arduino UNO card to move the servomotors according to the value of the angle received by the master controller. To monitor the wind speed, the voltage from the anemometer to the second analog channel of the PLC was used. The controller is the most important element because it receives the signal given by the analog reading inputs and sends the data so that the operator can visualize them in the Human Machine Interface (HMI) Siemens KTP700 Basic, besides overseeing performing the control algorithm to obtain maximum power. Therefore, the system can react autonomously and oversees collecting the highest power generation by the wind generator. The master controller is responsible for receiving the voltage to perform the power calculation and thus, with the algorithm shown in Figure. 3, determine the angle to be sent to the slave controller. The master controller is also responsible for receiving the reading of the wind speed present in the anemometer built, display the results such as voltage, current, power and wind speed read on the HMI and perform the logic to make the data storage of the test measurements.

Fig. 3. Schematic diagram of the general operation of the embedded system for the maximum power point.



Source: developed by the authors.

Instrumentation

The instrumentation used in the embedded pitch angle system are shown in Table 1 with the specifications of each one of them.

Table 1. Instruments used in the embedded pitch angle system.

Device	Model	Specifications
PLC	Siemens 1214C DC/DC/DC	SIMATIC S7-1200, CPU 1214C, compact CPU, DC/DC/DC, onboard I/O: 14 digital inputs (DI) DC; 10 digital outputs (DO) DC; 2 analog inputs (AI) to DC, Power supply: to DC, Program/data memory
HMI	Siemens KTP700 Basic	Key/touch panel, TFT display, 65536 colors.
Arduino UNO	Arduino	ATmega328P microcontroller, 14 DI and 14 DO, 6 AI.
ESP32	DEVKIT V1	Microcontroller Tensilica 32-bit Single-/Dual-core CPU Xtensa LX6, Input Voltage to 25 DI and 25 DO, 6 AI, analog outputs (AO) 2.
PROFINET Switch	Siemens SCALANCE XB005	AC/DC power supply, with 5x 10/100 twisted pair ports with RJ45 socket.
TP-Link	TL-WR480N	, LAN Ports 4 .
24V Power Supply	MDR-60-24	Power supply to , power output and Current output
5V Battery	Adata Pv120	Voltage output with 2 outputs at .
Servomotor	MG995	RPM: degrees (), degrees () Voltage: Torque: .
Wind Generator	NE-400R	Voltage , Power , Weight .

Source: developed by the authors.

RESULTS AND DISCUSSION

The wind generator was placed at a strategic point on the top floor to be able to capture the wind gusts and near the device was placed the master controller with the HMI and TP-Link so that they could connect via TCP/IP protocol with the slave sub-system to control the blade angle.

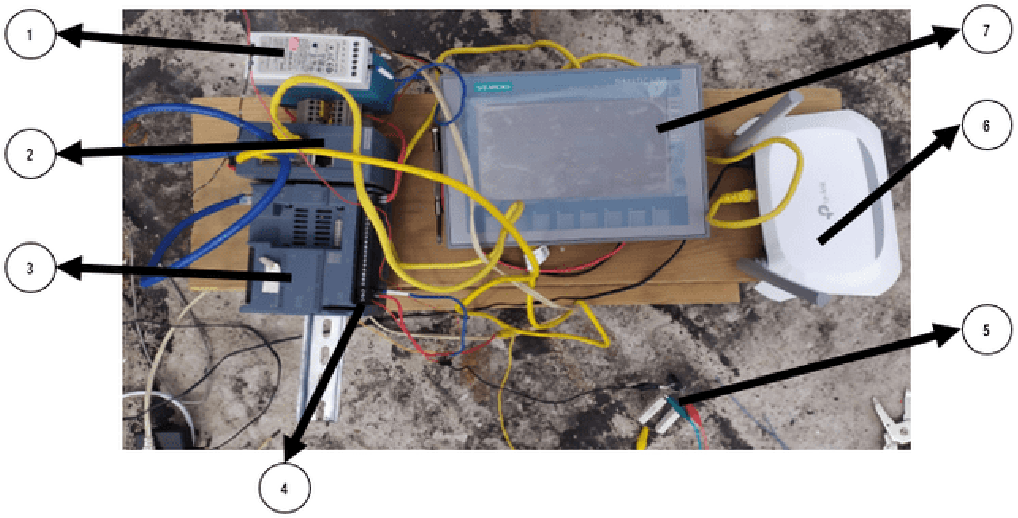
As shown in Figure. 4, the wind generator with the embedded system was placed to control the pitch angle mounted in position for readings while the yellow arrows indicate the direction in which the wind strikes the blades.

Fig. 4. Devices of the wind generator with embedded system for pitch angle control where 1. Wind generator and 2. Embedded system for positioning the pitch angle.

Source: developed by the authors.

The final and functional prototype was the master controller to send the pitch angle calculated by the algorithm to obtain the maximum power point to the embedded system for pitch angle control. As elements the PLC, the HMI and the TP-Link, the connections for the analog and PROFFINET channels Figure. 5. Where 1. Power supply of 1.24 V, 2. Switch for PROFINET ports, 3. PLC, 4. Connections for reading analog channels of the wind generator and the constructed anemometer, 5. Circuit for wind generator voltage reading, 6. TP-Link and 7. HMI.

Fig. 5. Devices of the master controller.



Source: developed by the authors.

Weather changes were a fundamental part of the measurements taken, since September had cloudy and rainy days, which did not allow the embedded system to find the point of maximum power. When the weather was favorable and speeds were higher than 1.11 m/s, the measurements could be taken correctly.

The first functional tests were carried out on August with an average wind speed of 3.61 m/s, considering that the average speed was higher than the minimum allowed to work correctly, it was possible to work with the embedded system to obtain the maximum power point and obtain the data.

The data shown in Table 2 are “Record” is to the number of the stored data, “Date” is to the date in month/day/year format extracted from the PLC, “UTC Time” is to the PLC time that between each record is increased by one second, “Voltage” is to the voltage reading in V units from the wind generator, “Current” is to the current reading in unit of A of the wind generator and “Angle” is to the angle present in the embedded system for pitch angle control in unit of sexagesimal angle.

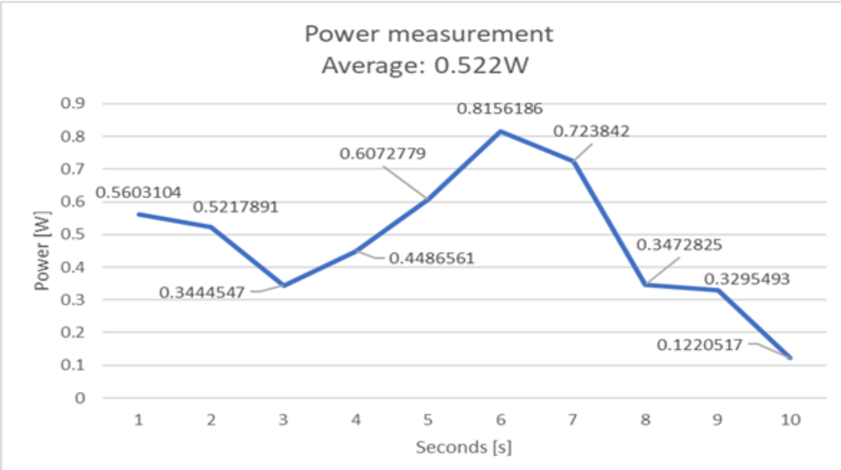
Table 2. Data displayed on the PLC data logger.

Record	Date	UTC Time	Voltage	Current	Power	Angle
1	08/14/2022	0:29:43	9.927	0.049	0.492	50
2	08/14/2022	0:29:44	11.750	0.058	0.690	55
3	08/14/2022	0:29:45	11.426	0.056	0.647	55
4	08/14/2022	0:29:46	11.598	0.057	0.652	60

Source: developed by the authors.

By taking the first 10 measurements of the day to observe the behavior, the following power measurements were obtained from the wind generator and the angle on the embedded system requested by the MPPT algorithm. The first measurements taken on the system were without the wind measurements and had power measurements shown in the graph in Figure. 6 were such that the average power was 0.522W with a maximum point at measurement 6 with 0.815W.

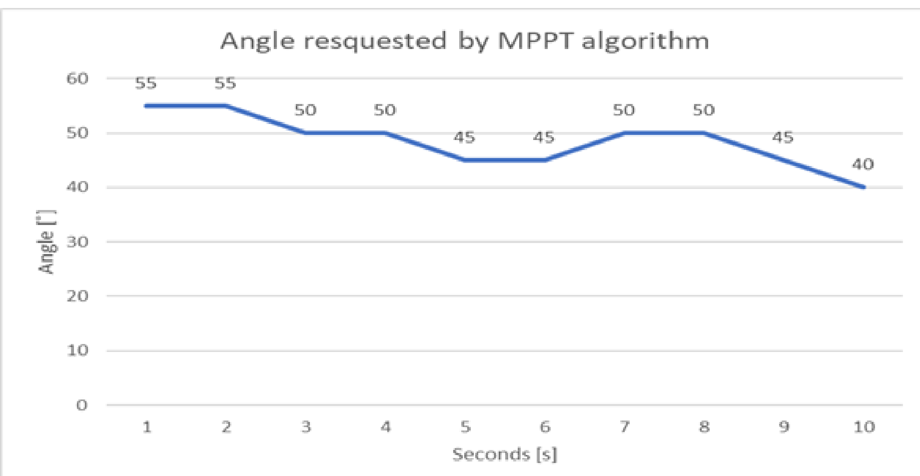
Fig. 6. Plot of the power measurement in the wind generator for 10 seconds.



Source: developed by the authors.

For the present reading that had the embedded system requested by the MPPT algorithm were such that for the measurement of the highest power in measurement 6 had a value of 45˚ and in the measurement of the point with the highest speed in measurement 2 was 55˚shown in Figure. 7.

Fig. 7. Plot of the angle requested by the MPPT algorithm for 10 seconds.



Source: developed by the authors.

As shown in Figure. 6 and 7 the different measurements of the power in the wind generator and the angle requested by the MPPT algorithm, it could be determined that depending on the angle a certain power value is obtained, the first measurements indicate that a maximum power point was had with the angle of 45˚ with 0.815.

Prototype Improvements

The improvements that were made to the prototype wind generator and the controller to obtain the maximum power point were initially to the blades. The first measurements were with an average below the minimum operable limit, so the solution was to place an extra element to the blades. Acetate blades were proposed to force the blades to capture more airflow in the measurements and not increase the weight of the blades.

The modifications were made to the pitch angle control with the acetate sheets to try to cover most of the PVC surface. The other improvement that was made was to place the anemometer for the velocity readings present in the wind generator. So, the data logger was adapted to add the velocity measurement and display it in the file to visualize the data as shown in Table 3.

Table 3. The caption must be followed by the table.

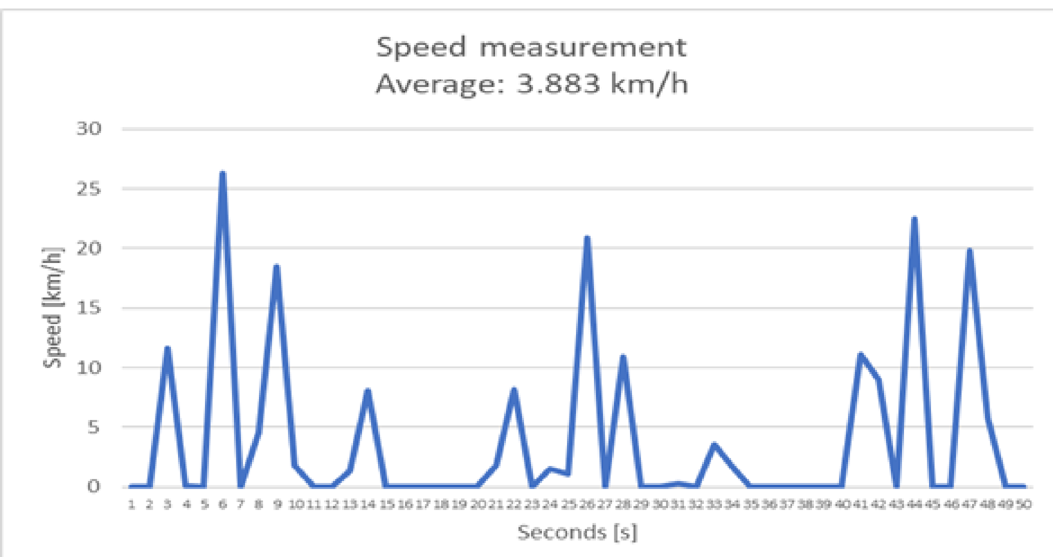
Record	Date	UTC Time	Voltage	Current	Power	Speed	Angle
1	08/26/2022	17:49:19	3.730	0.018	0.069	0.000	50
2	08/26/2022	17:49:20	2.740	0.013	0.037	0.004	50
3	08/26/2022	17:49:21	4.120	0.021	0.085	11.610	45
4	08/26/2022	17:49:22	6.600	0.033	0.217	0.1220	45

Source: developed by the authors.

Once the velocity measurement was added to the datalogger, measurements were taken. The plot shown in Figure. 8 shows 50 measurements, which means 50 seconds of the velocity present in the constructed anemometer.

In the measurements there were peaks of speed up to 26.306 km/h in measurement 6, readings with 0 km/h which means that the wind was not able to move the blades of the anemometer and finally an average speed of 3.883 km/h which was still below the required speed to operate the system.

Fig. 8. Plot of the speed measurement in the anemometer with speed average 3.883 km/h.

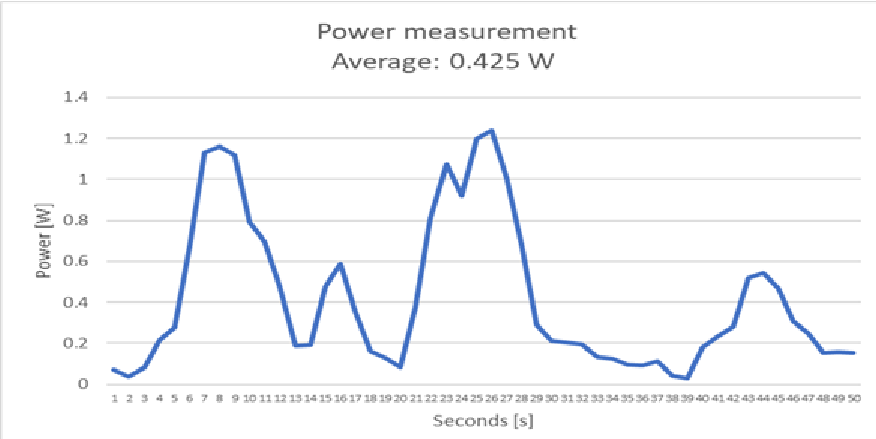


Source: developed by the authors.

For measurement of the wind generator power, there was an average of 0.425 W and two power peaks, the first one was at measurement 8 with a power of 1.161 W and the next power peak was at point 26 with 1.24 W.

In the speed measurement of the constructed anemometer there were measurements, which as mentioned, were not able to move the blades to measure the speed, which in comparison to the power measurement are close to 0, which means that the wind generator with the embedded system to move the pitch angle had no movement (Figure. 9).

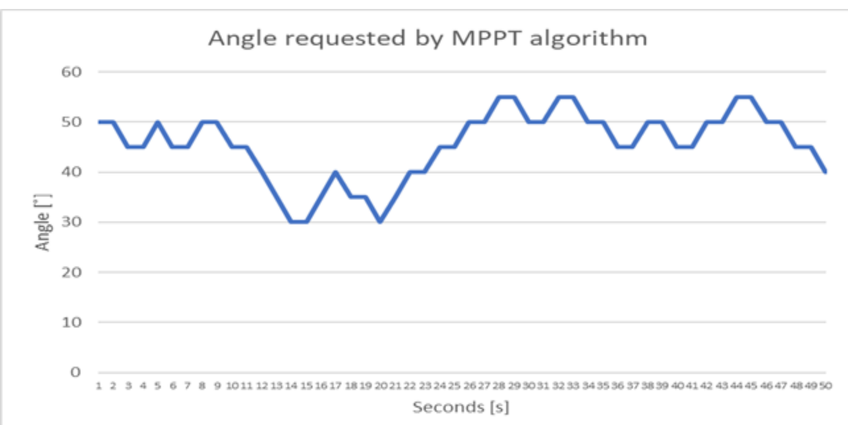
Fig. 9. Plot of the power measurement in the wind generator with power average 0.425 W.



Source: developed by the authors.

Figure. 10 shows the plot of the angle requested by the MPPT algorithm it was had that in the current peaks that were presented in the power measurement were such that a value of 50°and 50˚respectively, this means that one of the points in which it was possible to obtain points of maximum power hover between 50˚ with the present speed this does not mean that with this you can determine a point to the measurements that were presented initially so it is necessary to do more tests to determine it.

Fig. 10. Plot of the angle requested by MPPT algorithm.



Source: developed by the authors.

What could be noticed when making the measurement in the month of October, were that the angle requested by the MPPT algorithm in the values close to 0 to 20˚, and from 70 and 90˚ the power in the wind generator is almost 0 so it can be defined that in those angles there is an air flow capture, even if there is the presence of wind.

For the lower range of the angle, in the tests it could be seen that the wind speeds did not make the embedded system move for the positioning of the pitch angle due to the shape of the blades with the acetate and in the higher range what happened was that the position of close to 90˚ made it stop completely despite the presence of wind, this means that it was a brake on the system. Angles between 25 to 65˚ were the best angles to be able to capture the wind flow and have power generation in the system. In consideration with the information obtained, the adjustment that was made was in the algorithm to find the point of maximum power. It was adjusted in programming so that the system would allow the angle to be calculated according to the proposed range 25 to 65˚.

The following measurements were taken on October 15, that day was a very windy day, with gusts of up to 30km/h according to the forecast of that day, so it was a good day to make measurements and capture the power generation. The measurements were taken in 100 seconds intervals.

With the range defined in programming, we had powers of up to 2.042 and 1.9178 W which were the highest points and an average of 0.506 W being the highest obtained until these measurements, with a speed of up to 48.343 km/h captured by the anemometer built.

The angle that was present in the embedded system requested by the MPPT algorithm remained in the established range and maintaining a power generation always above 0, this means that the system never stopped completely and never had a value such as to stop the system and stop generating power.

The velocity signal present in the constructed anemometer varied a lot between measurement lapses. The data are shown graphically in Fig. 11, 12 and 13 respectively.

Fig. 11. Measurements plots (Power).

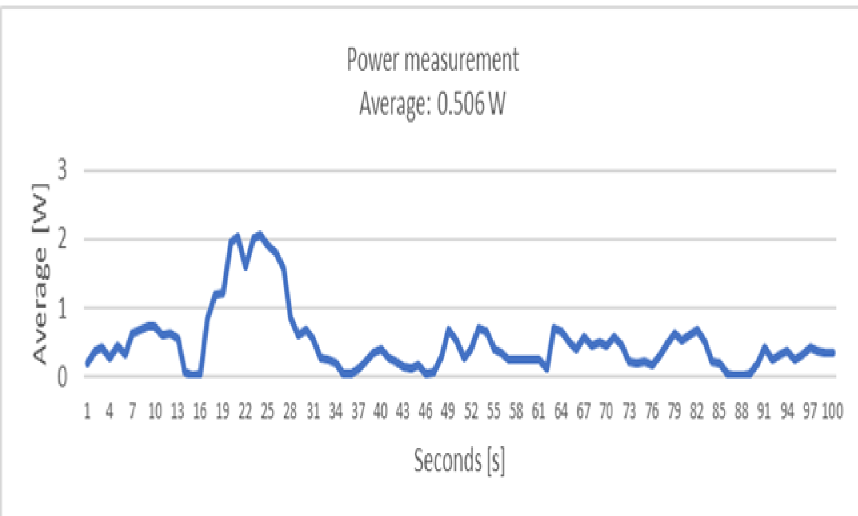


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Fig. 12. Measurements plots (Speed).

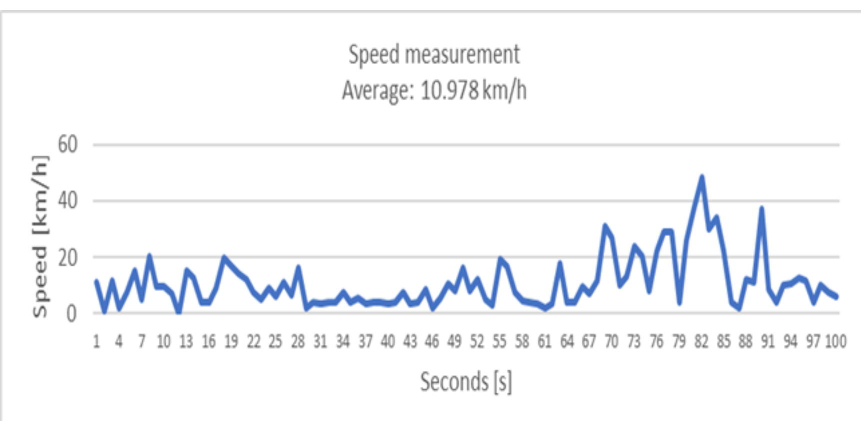

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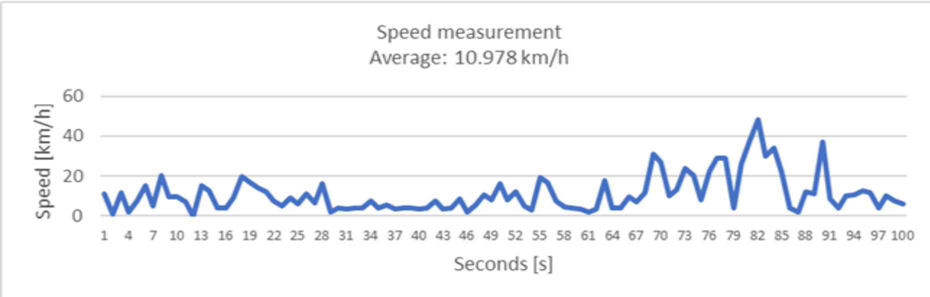
Fig. 13. Measurements plots (Angle requested by MPPT algorithm).



Source: developed by the authors.

Social Impact of the Research

The development and implementation of an embedded system for pitch angle control in wind turbines significantly contributes to social well-being and sustainable development in Mexico. Firstly, by optimizing wind energy generation and increasing conversion efficiency, this technology can promote access to clean and reliable energy in rural or marginalized areas where the conventional power grid is limited or unstable. This directly improves the quality of life in communities by facilitating education, access to basic services, and fostering sustainable productive activities.

Moreover, the adoption of renewable technologies like this has a positive impact on public health by reducing dependence on polluting sources and lowering greenhouse gas emissions, which are essential factors for mitigating climate change and improving local air quality. Employment generation is also favored, both in the manufacturing, installation, and maintenance of these systems and in the creation of new productive chains related to renewable energies.

Additionally, the transfer of knowledge and technological capabilities at the local level through projects like this promotes the training of specialized human capital, increasing scientific and technological development and fostering technological independence. In summary, the project not only provides technical solutions for energy efficiency but is positioned as a driver of comprehensive social development, environmental sustainability, and energy justice for Mexican society.

Alignment with the Sustainable Development Goals (SDGs)

The development and implementation of the embedded system for pitch angle control in wind turbines directly contributes to several United Nations Sustainable Development Goals (SDGs), promoting comprehensive, sustainable, and equitable development in Mexico.

SDG 7: Affordable and Clean Energy. This project drives the optimization of wind power generation, a renewable and clean energy source, facilitating access to sustainable electricity in rural and marginalized areas. By maximizing efficiency and energy output, it helps diversify the energy matrix and reduces dependence on fossil fuels.

SDG 11: Sustainable Cities and Communities. By fostering the use of clean and decentralized technologies, the system supports the development of more resilient communities that are less vulnerable to power outages or lack of energy access, improving quality of life and promoting social inclusion.

SDG 9: Industry, Innovation, and Infrastructure. The project strengthens energy infrastructure through the integration of intelligent embedded systems, boosting local technological innovation, knowledge transfer, and the training of specialized human resources in renewable energy and advanced control systems.

SDG 13: Climate Action. Reducing greenhouse gas emissions through the promotion of renewable energies contributes to combating climate change. This system optimizes the use of wind energy, helping mitigate environmental impact and protect ecosystems.

SDG 8: Decent Work and Economic Growth. The implementation and maintenance of renewable technologies generate qualified local jobs, promoting sustainable production chains and fostering inclusive economic development.

CONCLUSION

An embedded system was designed and implemented to control the pitch angle of wind turbine blades using wireless communication with a master controller capable of sending the optimal angle to maximize generated power. The system includes a subordinate subsystem responsible for the physical positioning of the blades. The use of a robust PLC allows remote connection, real-time visualization via HMI, and storage of essential electrical data (voltage, current, power, and wind speed).

Results demonstrate that generated power depends both on wind speed and blade angle. The system maintains the maximum power point during intervals, although the limited average wind speed (4.676 km/h) at the test site reduces the duration of these periods.

It was identified that angles close to 0° generate insufficient movement due to blade shape, while angles near 90° completely stop the system, eliminating generation. Additionally, adverse weather and low wind limit system effectiveness, especially given the blade mass (151 g).

The use of industrial-grade equipment provides standardized signals, expandability (more generators connected to the same controller), remote monitoring, and adjustment. The main disadvantage is high cost, suggesting future research focused on low-cost digital systems.

Proposed improvements for future work include exclusively using the secondary subsystem with Wi-Fi and PWM sensors, optimizing system placement to better capture airflow, adjustments to increase power using voltage dividers, and developing applications for real-time monitoring and remote pitch angle range adjustment.

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