National University of Science and Technology
POLITEHNICA Bucharest
Faculty of Mechanical and Mechatronics Engineering
Doctoral School of Mechanical and Mechatronics Engineering

DOCTORAL THESIS
SUMMARY

CERCETĂRI TEORETICE ȘI APLICATIVE PRIVIND TRANSFORMAREA ȘI TRANSMITEREA ENERGIEI EOLIENE PRIN INTERMEDIUL SISTEMELOR CU MEDIU FLUID DE LUCRU / THEORETICAL AND APPLIED RESEARCH ON THE TRANSFORMATION AND TRANSMISSION OF WIND ENERGY USING FLUID-BASED SYSTEMS

SCIENTIFIC COORDINATOR
Prof.dr.ing. MIHAI AVRAM

DOCTORAL STUDENT
Ing. BACIU IONELA MIHAELA

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Abstract

The thesis *"Theoretical and Applied Research on the Transformation and Transmission of Wind Energy Using Fluid-Based Systems"* proposes a broader approach to integrating fluid working medium systems into the structure of wind energy generation systems.

These systems are discussed and analyzed by addressing both existing achievements in the specialized literature and invention patents that attempt to resolve certain shortcomings of wind energy generation systems. The literature review led to a series of possible solutions and development directions. The systematic analysis of specialized works resulted in the outlining of several technical solution concepts, as well as the selection of the three most promising ones.

Based on these, conceptual schemes of possible hydraulic transmissions were developed for integration into wind energy systems. The proposed solutions aim to transform wind energy, by means of hydraulic transmission, into other forms of energy such as electrical, hydraulic, and thermal energy.

The three proposed solutions are distinct hydraulic circuits that can be integrated into wind systems but serve different applications:

- supplying hydraulic energy for a vehicle lifting platform,
- generating electrical energy for the grid,
- transforming wind energy into thermal energy.

Based on the conceptual schemes, functional verifications were carried out, leading to the selection of the most suitable solution for physical implementation. After outlining the general concept for the experimental model, a conceptual hydraulic circuit scheme of the transmission was developed, including the most important parameters as well as other relevant variables.

Based on this scheme, fundamental laws of fluid mechanics, and the associated physical phenomena, the behavior of the system equipment was mathematically described.

The development of the mathematical model of the equipment enabled numerical simulations to be carried out, providing further insight into the system's behavior and the associated phenomena. As with any numerical simulation, certain simplifying assumptions were introduced, which may have affected the results to some extent. The results obtained from the simulation of the simplified circuit indicated that the proposed hydraulic transmission model, intended for implementation on a wind turbine, could be used for its intended purpose.

To verify the validity of the results, the research progressed to the stage of developing the experimental model, considering the previously obtained results and selecting equipment with specifications as close as possible to those derived from the theoretical analysis. In developing the experimental model, consideration was given to each piece of equipment's requirements regarding occupied space, communication type, mounting method, and other relevant aspects.

By correlating information from the equipment datasheets with the theoretical data, the control architecture was designed. This architecture included the type of communication protocols used, equipment power supply methods, data acquisition procedures, data management, programming languages used to develop the control software, and the particularities of each component. Due to the large number of devices and sensors, multiple microcontrollers were employed to manage the flow of data and commands.

In constructing the experimental model, new techniques were used to manufacture custom-made components, allowing optimization of certain circuit equipment and ensuring specific mounting solutions for the test bench. The experimental model was developed in stages to allow testing of its critical subassemblies, particularly the electric motor control system. Each stage of test bench assembly involved checks of mechanical mounting, electrical connections, and related aspects.

After assembling the experimental model and pre-testing its subassemblies, the hydraulic transmission was tested. This test followed a specific methodology, which involved establishing criteria related to the number of tests performed, the duration of each test set, reference thresholds for flow rate, pressure, and temperature, as well as equipment operating states.

The experimental tests confirmed the initial hypothesis, namely that the hydraulic transmission can transmit and transform wind energy into thermal energy. The results were validated both through data acquisition from sensors and through thermal images captured with a thermal camera during testing. During the tests, several phenomena associated with temperature increases in a hydraulic circuit were observed, such as pressure and flow rate drops, but these did not significantly affect the results.

Insufficient insulation of electronic equipment from the external environment introduced noise into the obtained results. This noise was eliminated by filtering the signals.

The analysis of the obtained results and of the entire process—from the review of the specialized literature to the development and testing of the experimental model to the identification of several possible future developments of the experimental model, including:

- improving the command-and-control architecture for better coordination of data and control signals, as well as for noise prevention.
- replacing the hydraulic regulation and control equipment with high-performance models to increase the system's response speed to control signals.
- developing an auxiliary energy recovery system for conditions in which wind speeds exceed the wind turbine's design values. This system could have multiple configurations, either storing energy in accumulators or directing the excess flow to a hydraulic motor that drives a generator or another piece of equipment.

The solution proposed in this work provides promising premises for the further development of fluid working medium systems in the field of wind energy, particularly to produce thermal energy from a sustainable resource.

Organization of the Thesis

The doctoral thesis comprises 217 pages. From the perspective of its scientific content, the thesis is structured as follows: an introduction presenting the motivation for choosing the topic; a chapter dedicated to the general presentation of the work; three chapters addressing the fundamental issues of the study; and a final section of conclusions, which includes the main scientific contributions of the research, organized as follows:

Chapter 1, entitled "Introduction," analyzes the current energy context, highlighting the need to improve the method of wind energy capture by replacing the classical method of energy transmission—from the rotor to the generator—with a method that offers more possibilities for transmitting the captured energy in a faster and more flexible manner [20]. Improving existing solutions for energy transformation and transmission has become an increasingly pressing requirement, given the growing demand for energy [1, 2, 20]. Replacing the conventional transmission system brings advantages such as reduced wear, extended transmission service life, reduced overall size, simplified maintenance processes, improved controllability, and faster intervention capability on the turbine [3, 4, 20].

Hydraulic transmissions are already present in certain wind turbine subsystems, being used for nacelle orientation, blade pitch adjustment, and turbine braking [5, 20].

This chapter also provides several suggestions regarding the steps necessary to achieve maximum potential, namely: selecting a suitable site; properly designing the turbine in accordance with the characteristics of the area where it is to be installed; selecting the systems responsible for energy transformation and transmission, as well as those used for positioning—particularly when a hydraulic transmission is employed for one or more subsystems. Special attention must be paid to the functional characteristics of the equipment [5,6, 20]. As with any technical installation located near natural habitats or residential areas, it is necessary to comply with current standards and regulations, which impose specific noise limits to avoid affecting both wildlife and human populations. Another important aspect is the continuous monitoring of the wind installation to prevent and detect potential operational issues [7, 8, 20].

The chapter concludes by presenting the objectives of the thesis, which are centered around a main research theme: the study and analysis of fluid working medium systems, with applicability in the field of renewable energy.

Chapter 2 is dedicated to presenting the general concepts of the thesis, with particular emphasis on highlighting the original elements that are further developed in Chapter 5 of the work.

Chapter 3 presents an analysis of the current stage of development of wind energy systems. This chapter examines studies conducted by specialists in the field, with the aim of identifying elements that can be improved. At the same time, it seeks to determine the main research directions. Several sectors dependent on energy supply were identified, namely: the food industry, the automotive industry, and household consumption [9, 20].

A range of technical solutions, both simple and complex, were identified. The simplest solutions consist of one or more wind turbines serving one or more consumers. Regarding complex solutions, hybrid energy supply systems stood out due to the advantages they offer,

such as energy compensation and the provision of a support system to ensure stable energy production regardless of weather conditions [10, 20].

Fields were identified in which wind energy is used to obtain potable water through desalination processes, to pump drinking water for irrigation systems, and to power transmission-reception installations located in isolated areas [11,12, 20].

With regard to obtaining thermal energy from wind resources, several applications were identified that use this energy source indirectly. In practice, the electrical energy generated from wind is used to heat water in a boiler. [13,17, 20]

This chapter also highlights the structural elements of a classical wind turbine, as well as its technical and functional characteristics. Based on an analysis of the largest wind turbine manufacturers, several turbine models from each major producer were selected and their technical specifications analyzed. The analysis revealed general development trends, showing that all manufacturers tend to increase turbine dimensions to obtain greater amounts of energy [10, 13, 20].

Although the advantages of large-scale turbines are evident—such as higher energy production and greater stability—there are also disadvantages related to the logistical effort required for special oversized transport operations. Transporting structural elements and turbine components is difficult, may disrupt road traffic, creates maneuvering challenges on certain road segments, and may require considerable time for transport and installation [11,12, 20].

The areas where turbines are installed may undergo changes in their overall visual appearance, particularly for residents of nearby settlements, as well as for local wildlife, which may be disturbed by the noise and rotational movement of the turbine blades [8,13,14, 20].

Another aspect analyzed in Chapter 3 concerns small-scale wind turbines, especially those intended for domestic use. It was found that, at the European level, there is no general standardization regarding their dimensions, nor a strict classification of small-scale turbines. For these turbines, the main constructive variants and their functional particularities were presented. Factors influencing turbine functionality were discussed, particularly those related to geographical location and meteorological conditions [15, 16, 20].

Considering the theme and objectives of the thesis, the hydraulic subsystems used within wind energy systems were analyzed in greater detail. Systems responsible for damping vibrations caused by wind speed variations were examined [17, 20].

Among the elements discussed were wind energy systems used in the domestic environment, whose utilization is continuously increasing [18]. Several wind turbine models were identified, and their technical specifications were analyzed [19, 20].

Chapter 4, "Proposed Solutions for the Developed Models", focuses on the analysis of three hydraulic transmission models developed both from a theoretical perspective and from the standpoint of hydraulic circuit design. The proposed models are [20]:

- a drive system for an automotive lifting platform used in vehicle service operations.
- a system for converting wind energy into electrical energy.
- a hydraulic system capable of converting wind energy into thermal energy.

For each solution, conceptual schemes of the proposed systems were developed. Based on these schemes, the components of each system were analyzed from both constructive and functional perspectives. Following the constructive analysis, the system with the greatest

potential for physical implementation and the highest degree of innovation was selected for functional testing [20].

The system chosen for functional testing was the one designed to transform wind energy into thermal energy. For this purpose, specialized software was used to simulate and visualize the operation of the equipment (*FluidSim developed by Festo*) [20, 21]. Functional testing provides an overall view of the phenomena that may occur during the operation of hydraulic system components, allows verification of equipment compatibility, and enables dynamic system optimization before physical implementation [20].

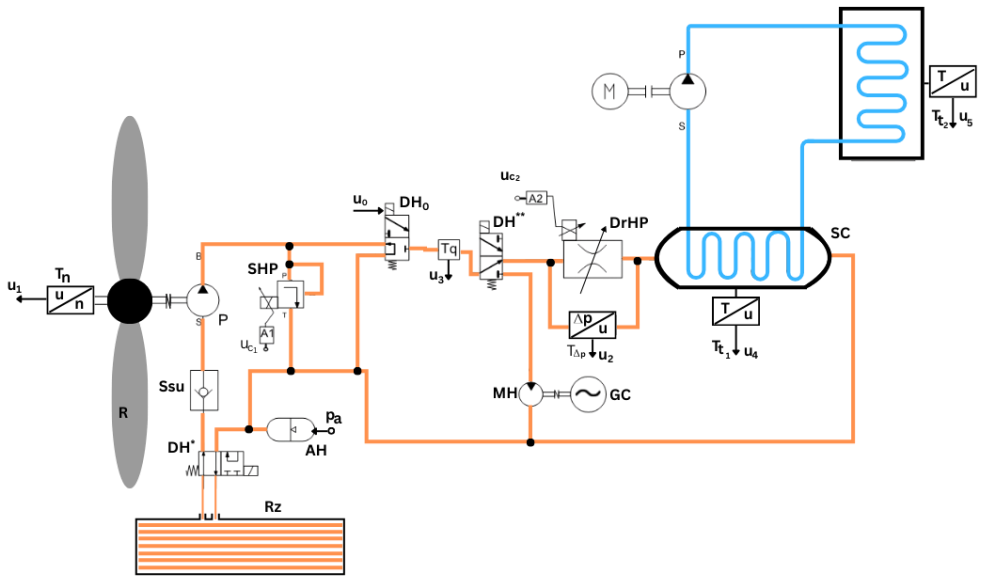


Figure 1. The schematic diagram of a hydraulic energy transmission system and its conversion into thermal energy [20]

The chapter concludes with the selection of the hydraulic transmission model that will be analyzed both theoretically and experimentally. The chosen solution is presented in Figure 1.

Chapter 5, "Theoretical and Experimental Analysis of the Proposed Model," is organized into subchapters that address different aspects of the research methodology used for the theoretical and experimental analysis [20].

The first subchapter, "General Considerations," briefly presents the main steps required for the theoretical and experimental analysis of the proposed hydraulic transmission model. The steps of the theoretical analysis are [20, 21, 22, 23, 24, 25]:

- Constructive and functional analysis of the hydraulic transmission model, resulting in a conceptual scheme that highlights the system's key parameters.
- Identification of important parameters and relevant variables.
- Adoption of simplifying assumptions to reduce computational effort.
- Determination of the mathematical model based on the operating equations and fundamental laws of mechanics, particularly fluid mechanics.
- Geometric or structural optimization is aimed at improving the performance of the proposed model.

- Verification and validation of the proposed model through numerical simulation.

The theoretical analysis allows for the determination of the performance of the hydraulic transmission model [20, 24, 25, 26].

The second subchapter follows the steps outlined above. It begins with the system's conceptual scheme, which illustrates the main components and their relevant parameters (Figure 2). The role and specific characteristics of each piece of equipment are highlighted. For each component, constructive and functional parameters were determined through consultation of specialized literature and datasheets [20, 26].

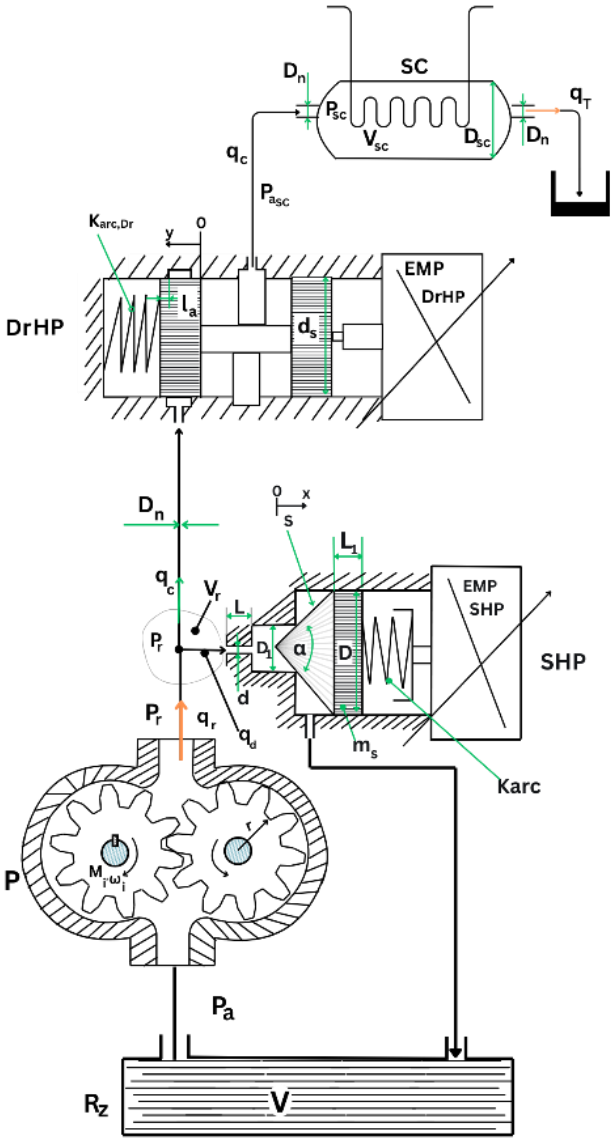


Figure 2. Basic diagram of the hydraulic transmission [20]

By correlating the fundamental laws of fluid mechanics with the equations of motion of the movable elements of the equipment, the mathematical model of the proposed hydraulic transmission was determined [20, 23]. The mathematical model also accounts for losses occurring in the system, which are highly relevant for the application in which the hydraulic transmission is integrated [24, 25, 26].

The validation of the mathematical model of the proposed transmission was carried out using two different simulation environments: Simcenter Amesim (student version) and Matlab-Simulink. Both environments allow for the numerical simulation of mathematical models and the creation of multiple operating scenarios, facilitating the determination of the characteristics of the analyzed model or models. The numerical simulation of the hydraulic transmission model focused on monitoring relevant parameters for assessing energy potential, providing opportunities for improvement while simultaneously validating the mathematical model [20].

The numerical simulation involved modeling a hydraulic pump with a displacement of 6 cm^3, a nominal speed of 1500 rpm, and a maximum delivered flow of 9 l/min. Control and regulation elements, such as the throttle and pressure valve, were also modeled, the latter having a maximum pressure limit of 60 bar. The input signal to the mathematical model was the variation in wind speed, which was converted into angular velocity and rotational speed. This signal was selected for a period during the year 2022 [20].

The mathematical model of hydraulic transmission was validated by comparing the results obtained. Although small differences exist between the outcomes, they are due to the different configurations of the simulation software used. It was observed that in both models, the fluid temperature tends to rise and exhibits slight thermal inertia when wind speed decreases [20].

The third subchapter addresses the experimental analysis of the proposed hydraulic transmission model. It begins by reiterating the primary goal of the transmission model: transforming wind energy into thermal energy and transferring it to other systems. The proposed transmission model was designed as a laboratory test stand, accommodating multiple constructive variants of wind turbines by varying the functional parameters of the electric motor acting as the wind rotor [20].

The creation of the physical hydraulic transmission model starts with the schematic representation of the proposed system. The proposed installation is presented in contrast with the conventional variant to highlight the fundamental differences. In the classical wind turbine variant, the nacelle houses both the transmission and the generator, resulting in large overall dimensions. The proposed variant reduces the size and mass of the nacelle, leaving only the hydraulic pump within it [20].

The proposed solution also brings additional advantages, such as flexibility, modularity of the transmission, and high efficiency, with the main disadvantage being the need for a complex electronic control system. The electronic control system manages all operational, monitoring, and self-regulation processes [20].

Before physically implementing the proposed hydraulic transmission model, the main tasks it must perform were outlined. A simplified architecture of the energy conversion installation was developed, allowing the establishment of characteristics to be implemented in the control program. Considering the need for remote access to the installation for safety reasons (during testing) and limited accessibility to the locations of such wind turbines, the system was designed to also operate on site [20].

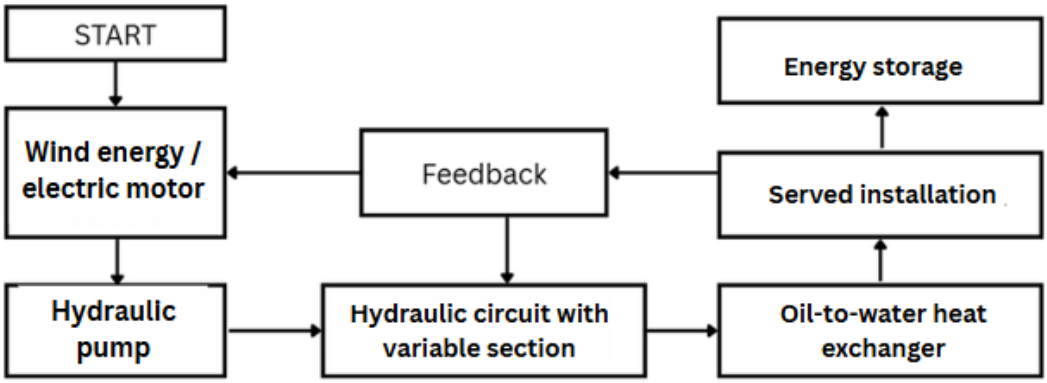


Figure 3. Simplified architecture of the energy conversion installation [20]

Figure 3 presents the simplified architecture of the installation for converting wind energy into hydraulic energy and subsequently into thermal energy. The installation operates as follows: the drive motor of the hydraulic pump is started, either directly driven by a wind rotor; the rotational movement at the pump shaft generates forces that allow the hydraulic fluid to be drawn from the reservoir into the pump body and discharged through the outlet. The fluid discharged by the pump is then directed into a hydraulic circuit with a variable section, which allows both manual and automatic adjustment of the flow section, and subsequently passes through an air-to-water heat exchanger [20].

By varying the flow section, friction forces are generated, which have the secondary effect of increasing the temperature of the working fluid. The energy lost as heat (the elevated oil temperature) is recovered via the heat exchanger, which transfers this energy to a water recirculation circuit. In this way, the hydraulic circuit is protected from overheating, and the recovered heat is used to warm specific spaces instead of being wasted. Both the water installation, which absorbs the thermal energy, and the system generating thermal energy from wind operate in a closed loop, with the possibility of adjusting parameters even during operation [20].

The selection of components for the hydraulic circuit was based on both the results obtained during functional testing and the theoretical analysis of the mathematical model. Equipment from catalogs was chosen to have values closely matching those determined through theoretical analysis. The electronic command and control system was selected based on the specifications and requirements of the circuit equipment and sensors. Some sensors and components required electronic signal adaptation circuits, which were developed in the laboratory [20].

To determine the position of each component within the system and to validate the operating principle, a conceptual diagram of the experimental stand was created, encompassing the entire installation (Figure 4) [20].

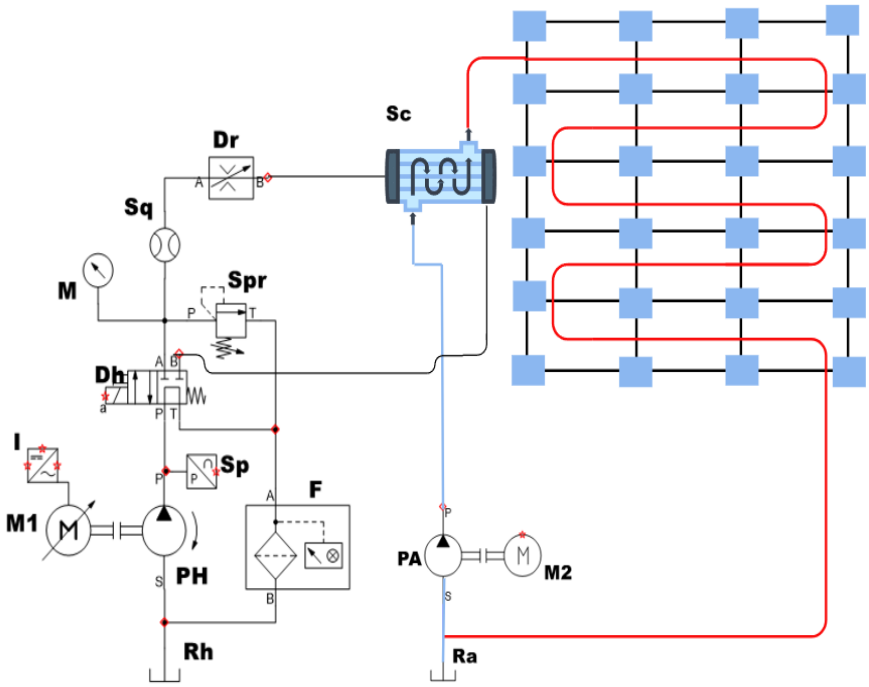


Figure 4. Conceptual diagram of the experimental stand [20]

The hydraulic transmission model consists of [20]: Rh – oil reservoir; PH – hydraulic pump; M1 – electric motor; I – frequency converter; Sp – pressure sensor; Dh – 4/2 electrically controlled hydraulic directional control valve; M – manometer; Spr – pressure control valve; Sq – flow meter; Dr – hydraulic throttle; F – return filter.

The water recirculation system is composed of the following equipment [20]: Ra – water tank; PA – hydraulic water pump; M2 – electric motor; SC – oil-to-water heat exchanger; Ci – heating circuit.

To monitor the temperature at the level of the experimental model, a series of temperature sensors were integrated at critical points and on equipment. The selection of equipment for the hydraulic transmission, as well as for the recirculation circuit, was based on the prior selection of the maximum power that the wind turbine can generate, namely 2.2 kW. Considering the imposed limit for the generated power, an electric motor with a maximum power close to this value was chosen. Following the technical specifications of the electric motor, a compatible hydraulic pump was selected, both in terms of drive speed and the elements that connect these two pieces of equipment. A gear-type hydraulic pump was identified, whose complete specifications can be found in ANNEX X. The chosen pump came as a kit that included both the connecting elements between the flange of the electric motor and the pump, as well as the coupling that connects the shafts of the two pieces of equipment [20].

The selected hydraulic pump has the following main technical specifications: a displacement of 6 cm^3; a maximum working pressure of 250 bar; a rotational speed of 1500 rpm [20, 26].

To be able to modify the speed of the electric motor so that the introduced variations reproduce the changes in wind speed, a frequency converter was chosen, whose specifications are found in ANNEX XI. In choosing this converter, the following were considered: compatibility with the electric motor, the control methods it allows (open loop or closed loop),

as well as the communication protocols it uses to communicate with other devices or equipment (e.g., MODBUS; HTTP; RS485) [20].

The directional control valve used to direct the fluid flow generated by the hydraulic pump was chosen in a configuration that allows the pump to run unloaded and to return the discharged fluid back to the reservoir. This configuration offers several advantages: protection of the hydraulic circuit against overpressure; disconnection of the pump circuit for replacing equipment, as well as testing the operation of the assembly formed by the electric motor and hydraulic pump. In addition to the configuration of the directional control valve chambers and ports, the following were also considered: the type of control, which for this application required at least electrical control; the maximum flow that can pass through it, as well as the maximum pressure. The complete specifications of this equipment are detailed in the catalog sheet, ANNEX IV [20].

Connecting the directional control valve in the circuit involved mounting it on a CETOP-type distribution plate, whose specifications are found in ANNEX III. This distribution plate integrates a pressure valve designed to protect the circuit under high loads. The distribution plate has a special port where a manometer or a pressure sensor can be installed [20].

For varying the flow section, a simple-design throttle was chosen, capable of withstanding the maximum pressure in the hydraulic transmission circuit. Complete specifications for this equipment can be found in ANNEX V [20].

Additionally, to extend the adjustment range of the circuit pressure, a pressure valve was selected that offers a wider regulation interval. Along with this valve, a compression spring was chosen to replace the factory spring in the pressure valve, allowing the pressure adjustment range to reach lower values than those typically used in hydraulic circuits. Correct pressure adjustment at this valve is ensured by a Bourdon tube manometer, mounted in the block where the valve is integrated [20].

The hydraulic oil reservoir was chosen to comply with the minimum volume required to ensure continuous fluid supply to the hydraulic circuit. It is equipped with the following accessories: vent, return filter, and hydraulic oil level indicator [20].

Regarding the hydraulic fluid used, a high-quality oil with excellent physico-chemical properties was selected. It maintains its viscosity at high temperatures at levels that do not generate losses. Considering the maximum power generated by the system, a heat exchanger capable of dissipating up to 6 kW of heat was chosen. Details regarding its connection elements in both circuits are described extensively in ANNEX IX [20].

To determine the flow rate of the fluid passing through the circuit, a turbine flowmeter with quadrature output was selected, and to monitor pressure variations in the hydraulic transmission circuit, a pressure transducer was chosen [20].

After selecting all the equipment for the transmission circuit, command-and-control architecture was developed. This includes the control electronics involved both in transmitting control signals to the hydraulic equipment and in acquiring signals from sensors. In Figure 8, the command-and-control architecture is shown, highlighting that the connection between the electronic control devices (e.g., Raspberry Pi) is bidirectional, based on feedback [20].

The central element of the electronic control system is a mini-computer with an ARM Cortex-A72 processor, 8 GB of memory, and SD support for the operating system (the

Raspberry Pi model). Its role is to manage communications and tasks between and among the microcontrollers in the system [20].

Due to the complexity of the experimental stand, many microcontrollers were necessary to implement all specific functions, including signal reading, communication via different protocols, and sending control signals. The microcontrollers used are: ESP32, Arduino Uno, and Arduino Mega [20].

To measure temperature values in the system, 16 thermistor-type temperature sensors were installed. Their main characteristic is a decrease in resistance as temperature increases. The voltage drops measured by these sensors are converted by the control program into temperature values, based on the technical characteristics described in the catalog sheet [20].

Pressure regulation in the hydraulic transmission circuit was carried out using two different approaches. The first approach involved manual adjustment of the circuit throttle, which indirectly regulated pressure by narrowing the flow section. The second approach involved automating the throttle operation, controlling it remotely with a stepper motor [20].

The automation process of the throttle involved creating connecting elements between the stepper motor and the throttle. These elements were designed using Autodesk Inventor and physically produced through 3D printing additive technologies. In Figure 5, the 3D model of the throttle actuation assembly is shown [20].

This assembly consists of the hydraulic throttle; the coupling that connects the throttle gear to the shaft of the stepper motor; and the support system, which provides rigidity to the entire assembly. The support piece is composed of two parts, allowing the attachment of the motor flange and the throttle body. In Figure 6, the resulting physical model can be observed [20, 38].



Figure 5. The 3D model of the hydraulic throttle actuation assembly [20, 26, 38]

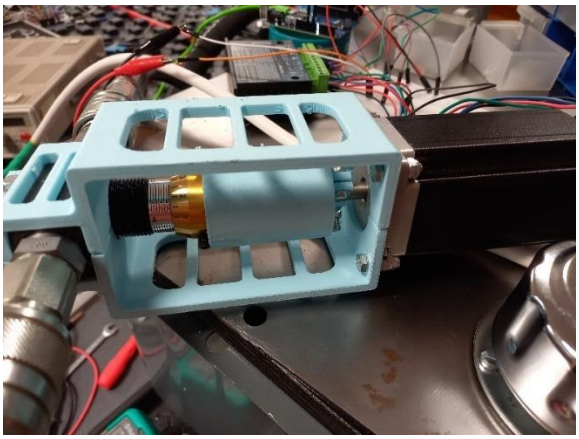


Figure 6. The physical model of the remote actuation assembly of the hydraulic throttle [20, 26, 38]

The assembly and installation of the tested system involved securing the electric motor, acting as the wind turbine rotor, to the base of the experimental stand. Due to the constructive particularities of the motor, it was necessary to find a mounting solution that would not affect either the stand base or the motor. The solution identified consisted of raising the electric motor

on two U-shaped aluminum profiles and fastening them to the base with two pairs of identical parts, specifically designed to the required dimensions and manufactured using additive 3D printing technologies (Figure 7) [20].

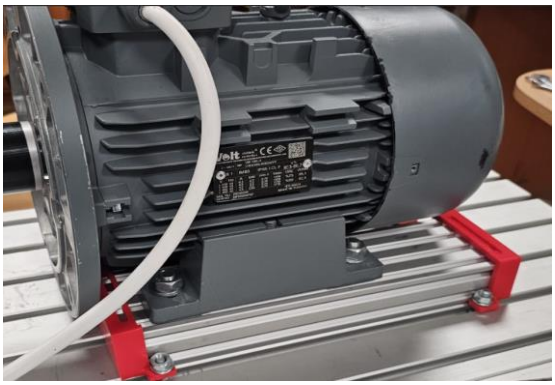


Figure 7. The mounting system of the electric motor to the test bench frame [20]

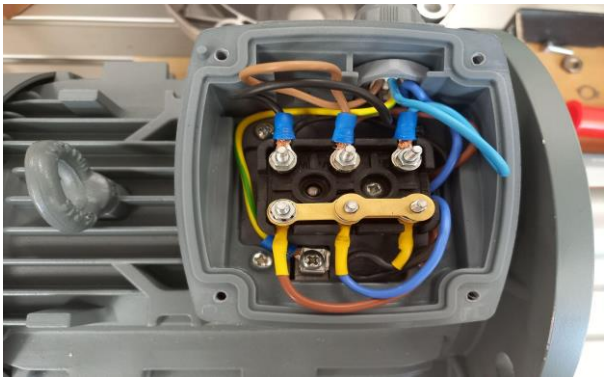


Figure 8. The electrical connections of the motor phases [20]

The electrical connections for the phases of the electric motor were completed (Figure 8). Subsequently, the motor was connected to the terminals of the frequency converter. In addition to connecting the motor, several other electrical connections were made on the frequency converter, allowing activation or deactivation of the motor windings, as well as communication through MODBUS protocols via the installation of the Ethernet module [20].

After establishing the connections between the motor and the frequency converter, the coupling required to transmit rotational motion from the motor to the hydraulic pump was installed, along with the flange connecting the hydraulic pump body to the motor flange [20].

To verify the operation of the motor and its controller, an intermediate test of this subassembly was carried out. This test involved varying the motor speed via the frequency converter and checking it with a tachometer, as well as verifying the physical connection between the motor and pump and visually confirming that the pump was not blocked [20].

Validating this connection between the components allowed the assembly of the remaining parts of the experimental stand to proceed. In Figure 9, the hydraulic path of the transmission can be seen, consisting of hoses, hydraulic equipment along the path, and sensors in the circuit [20].

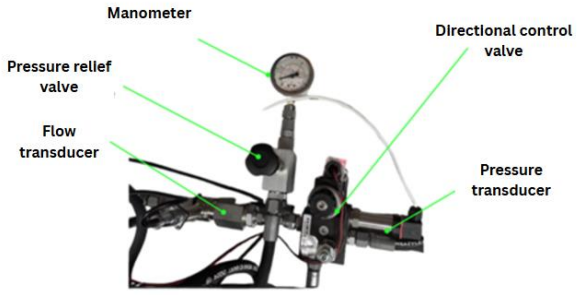


Figure 9. The hydraulic circuit consisting of hoses and connected equipment [20]

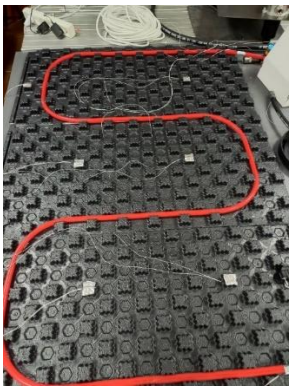


Figure 10. The water recirculation circuit [20]

To complete the entire installation, the water recirculation circuit was implemented (Figure 10). This circuit consists of an electric motor; a hydraulic water pump; a flow meter; piping route; connecting elements between the components; a plate with grooves for pipe mounting and thermal insulation; the electronic control system for command and data acquisition from the sensors in the circuit; and temperature sensors [20].

Validation of the temperature sensor readings was carried out by comparing them with data captured by the thermal camera used [20].

The design of the control algorithms considered all the elements of the installation. The algorithms were created to allow sending electrical commands to the equipment, acquiring and storing data from the sensors, enabling emergency system shutdown, and integrating communication protocols such as TCP/IP, RS232, and MODBUS [20].

In Figure 11, the command-and-control architecture is shown. For the protection of both the system and the operator in case of operational anomalies, equipment failures, or cyberattacks, a redundant protection system was implemented [20].

The control program was developed in two programming languages, Python and C++, to optimize data acquisition and system control. To facilitate monitoring of system changes and parameter variations, a graphical user interface was designed [20].

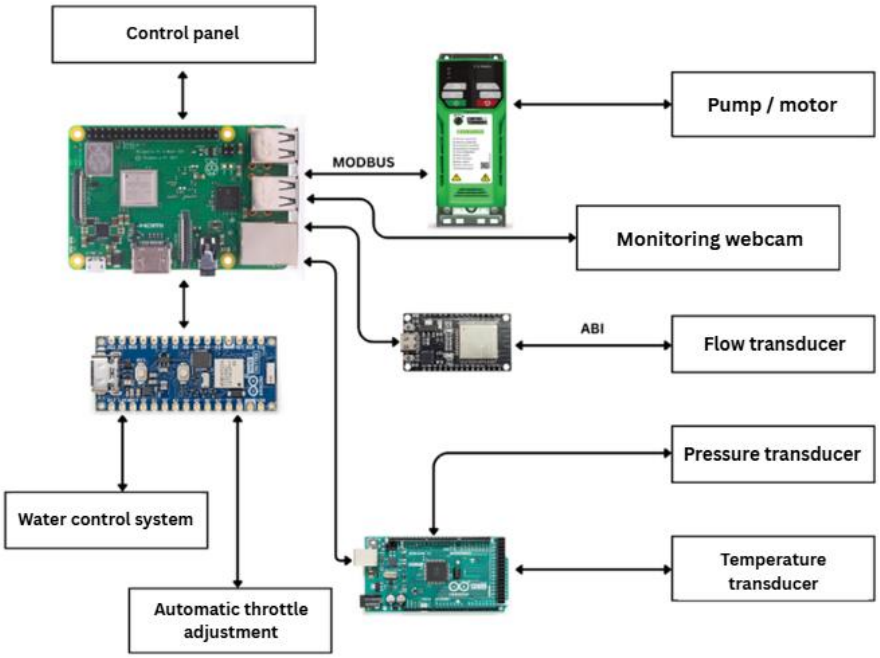


Figure 11. Electronic command and control architecture [20]

By going through all the steps mentioned above, the experimental testing of the stand was carried out (Figure 12 and Figure 13) [20, 26].

In the end, the experimental stand is composed of the following elements: 1 – electric-controlled hydraulic directional control valve, distribution plate, and pressure transducer; 2 – flow transducer; 3 – hydraulic fluid reservoir; 4 – throttle; 5 – frequency converter; 6 – router; 7 – AC-DC power supply; 8 – control circuit; 9 – webcam; 10 – hydraulic pump; 11 – electric motor; 12 – water pump, electric motor (not shown); 13 – water recirculation circuit (not

shown); 14 – flow meter (not shown); 15 – temperature sensors (not shown); 16 – water tank (not shown) [20, 26].

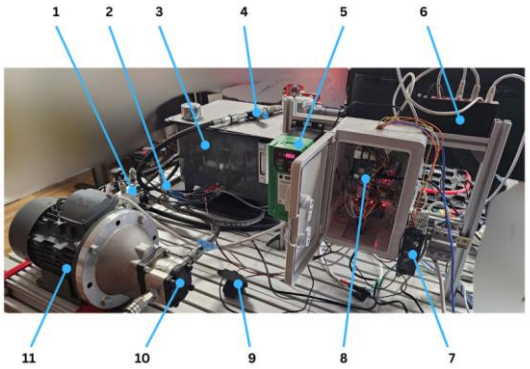


Figure 12. Hydraulic transmission within the experimental stand [20, 26]

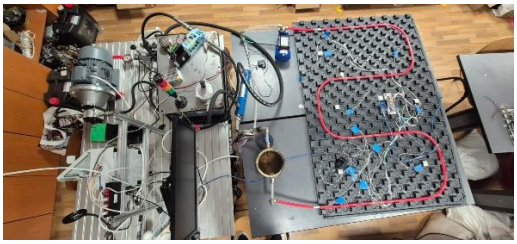


Figure 13. Top view of the experimental stand [20]

To reduce acquisition costs for some of the components used to secure the equipment, parts were manufactured using additive technologies. Even though the equipment temperature may increase, these materials have a high melting point, making them suitable for such applications. Additionally, through temperature control, the equipment will never reach a temperature high enough to endanger the mounting components. From the very first tests, an increase in the working fluid temperature was observed both with the thermal camera and through direct inspection of the hydraulic line and equipment [20, 26].

The testing of the hydraulic transmission followed the methodology below [20, 26]:

- Selection of the number of test series for each configuration.
- Establishment of the time interval for each test series, with the chosen duration being 30 minutes.
- Selection of reference pressures for testing, in this case: 0 bar, 10 bar, 20 bar and 50 bar.
- Selection of reference rotational speeds, in this case: 500 rpm, 1000 rpm and 1500 rpm.
- Selection of the opening pressures for the safety valve.
- Selection of switching positions for the hydraulic directional control valve (closed or open).
- Determination of the initial temperature of the hydraulic fluid for each test series.
- Continuous monitoring of the working fluid temperature and determination of the final temperature reached at the end of the 30-minute test.
- Determination of the actual pressure in the hydraulic circuit of the transmission.
- Determination of the fluid flow rate circulating through the hydraulic circuit.

A series of tests were conducted at pressures of 10 bar, 20 bar and 50 bar, with hydraulic pump speeds of 500 rpm, 1000 rpm and 1500 rpm. The primary objective of these tests was to evaluate and fully characterize the system, as well as its thermal response under varying operating parameters. A secondary objective was to observe transient phenomena that typically occur during testing under dynamic load conditions [20, 26].

Testing the hydraulic transmission at a pressure of 10 bar and a pump speed of 500 rpm resulted in a constant hydraulic fluid flow rate of approximately 4.5 l/min (Figure 14) [20, 26]. Achieving the desired pressure in the circuit required opening the directional control valve and

progressively adjusting the flow section. Regarding the working fluid temperature, an increase of 8 °C was observed during the 30 minutes of testing [20, 26].

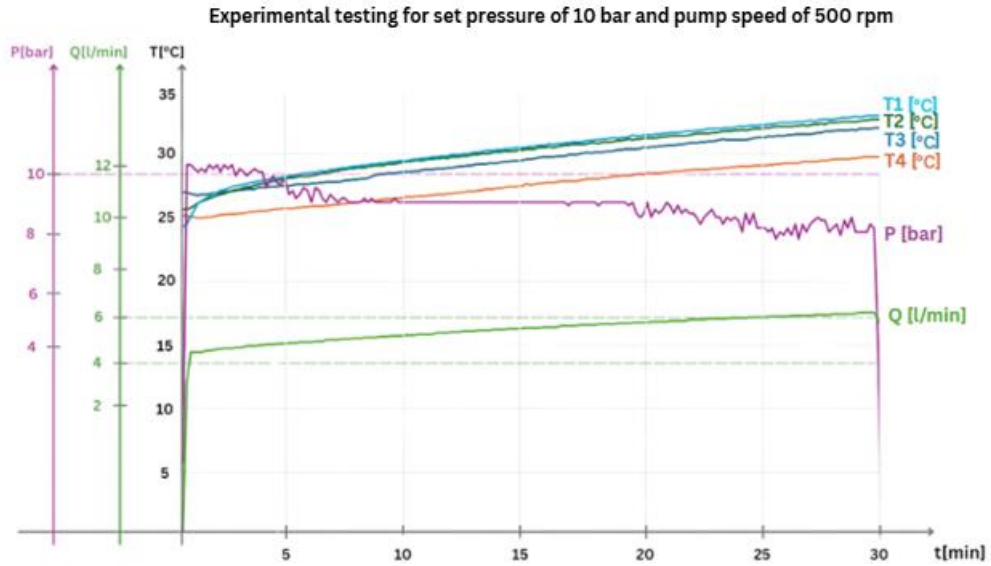


Figure 14. Experimental testing of the hydraulic transmission for reference values of 10 bar pressure and pump speed of 500 rpm [20, 26]

The next series of tests involved maintaining the same working pressure of 10 bar while increasing the rotational speed of the electric motor to 1500 rpm. The increase in speed had a direct and immediate impact on the volume of working fluid circulating through the system, with the flow rate reaching approximately 6 l/min (Figure 15). This test series involved the same adjustment maneuvers of the hydraulic equipment. At the end of the test series, it was observed that the hydraulic fluid approached a temperature of 15 °C [20, 26].

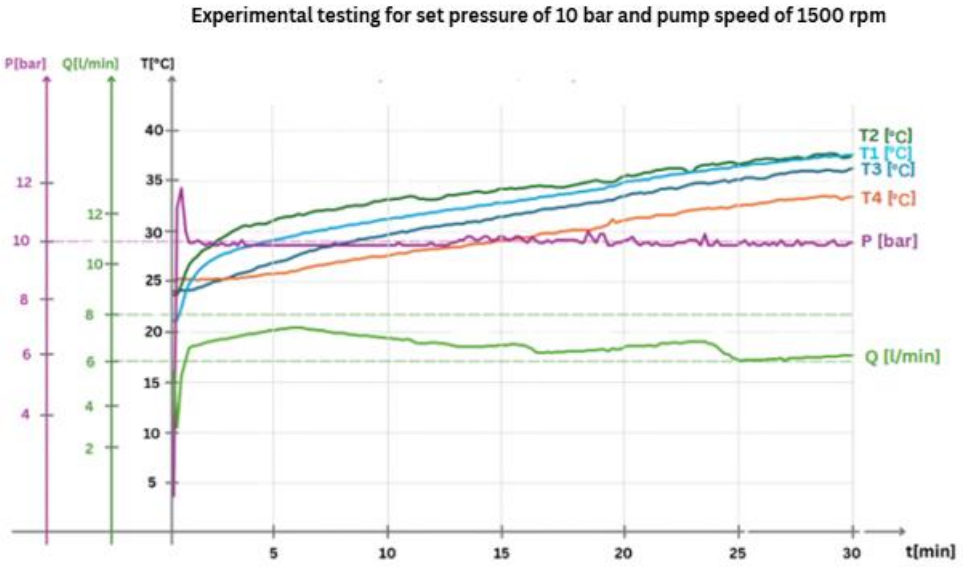


Figure 15. Experimental testing of the hydraulic transmission for reference values of 10 bar pressure and pump speed of 1500 rpm [20, 26]

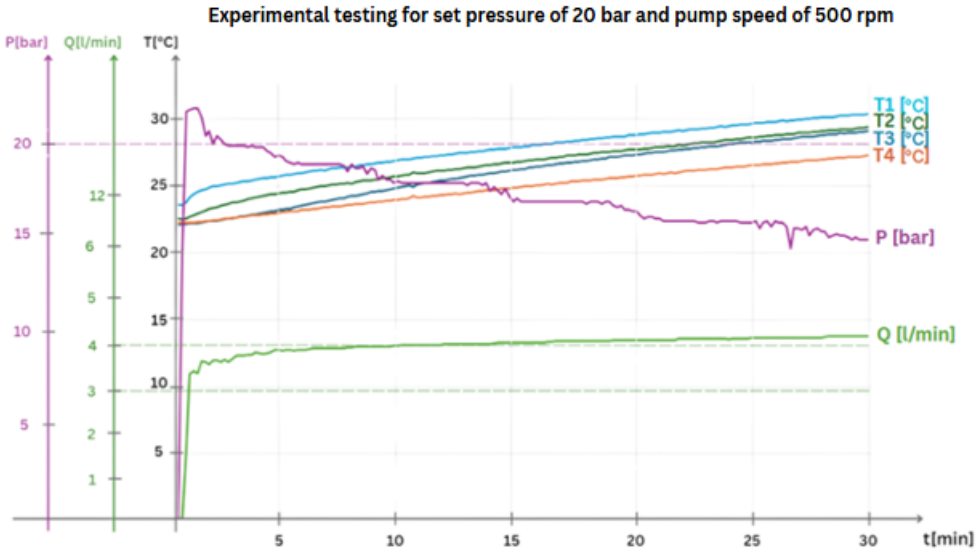


Figure 16. Experimental testing of the hydraulic transmission for reference values of 20 bar pressure and pump speed of 500 rpm [20, 26]

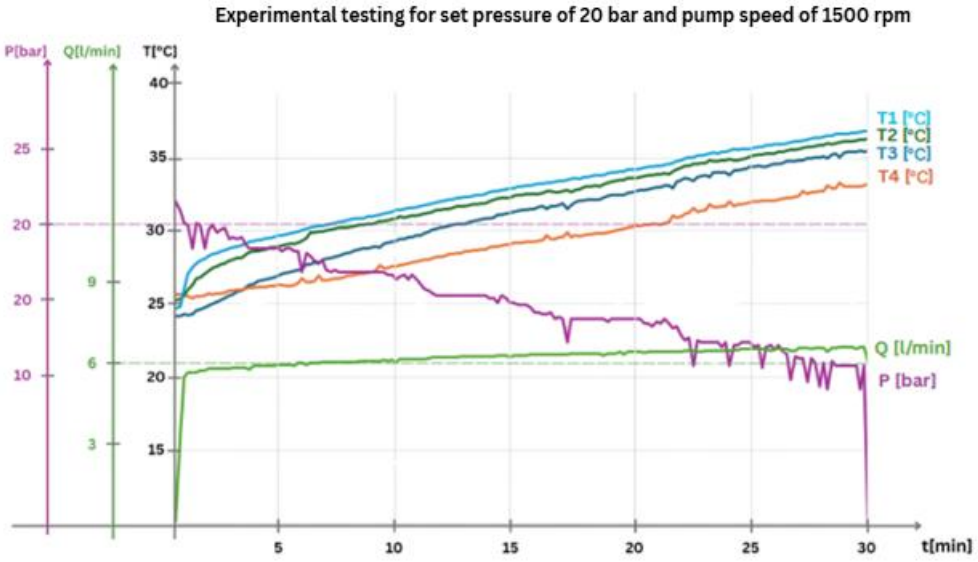


Figure 17. Experimental testing of the hydraulic transmission for reference values of 20 bar pressure and 1500 rpm [20, 26]

During the execution of these test series, a tendency for pressure to decrease was observed, accompanied by a negligible decrease in flow rate. This phenomenon is characteristic under conditions of elevated working fluid temperature. Tests conducted at a pressure of 20 bar and rotational speeds of 500 rpm and 1500 rpm led to similar results (Figures 16 and 17). The intrinsic characteristics of the hydraulic pump also contributed to the observed outcomes [20, 26].

Finally, a series of tests were carried out on the hydraulic transmission at a working pressure of 50 bar and rotational speeds of 500 rpm and 1500 rpm (Figures 18 and 19). For the first set of tests in this configuration, an increase in the fluid temperature of approximately 15 °C was recorded, while for the second set of tests at the higher speed, the temperature rise was much more significant, around 43 °C. Regarding the testing of the circuit at a pump speed of 1000 rpm, no significant variations were recorded, making it unnecessary to continue with these test series, as the results would have been redundant [20, 26].

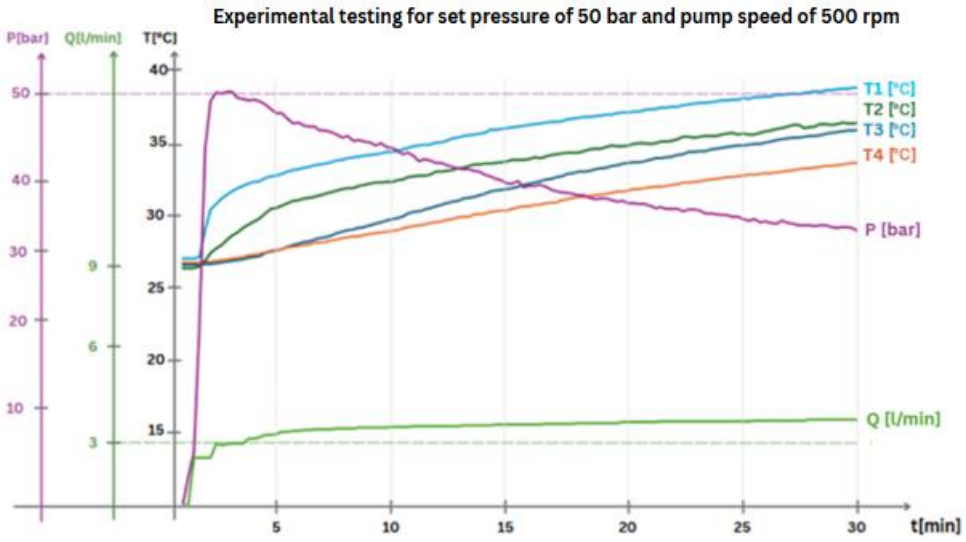


Figure 18. Experimental testing of the hydraulic transmission for reference values of 50 bar pressure and pump speed of 500 rpm [20, 26]

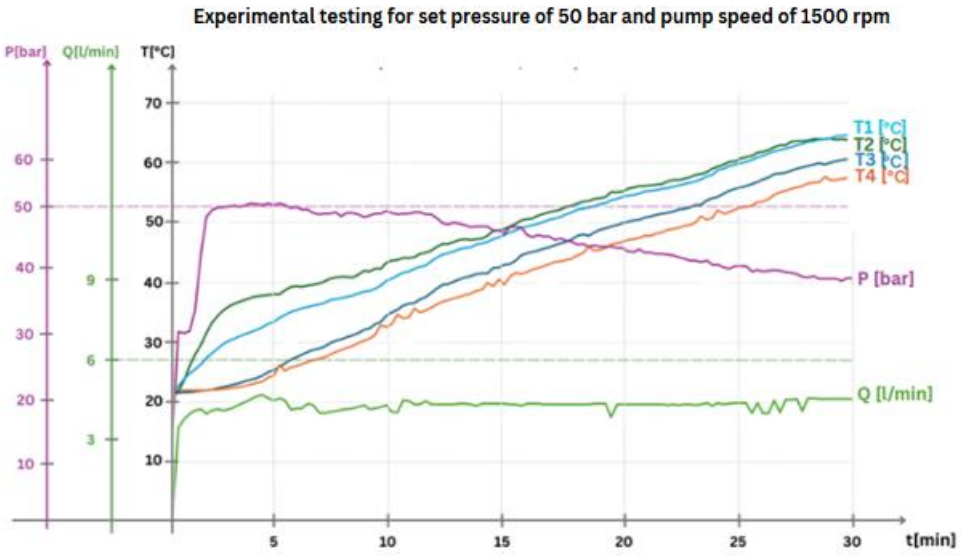


Figure 19. Experimental testing of the hydraulic transmission for reference values of 50 bar pressure and pump speed of 1500 rpm [20, 26]

During the testing period, the hydraulic circuit of the transmission was monitored both through the control software and with a thermal camera, which allowed capturing the maximum

and minimum temperature values for each component in the system, as well as along the hydraulic line [20, 26].

Below are some of the captures taken with the thermal camera (Figures 20–21), showing the temperatures reached by the hydraulic transmission during the tests [20, 26].

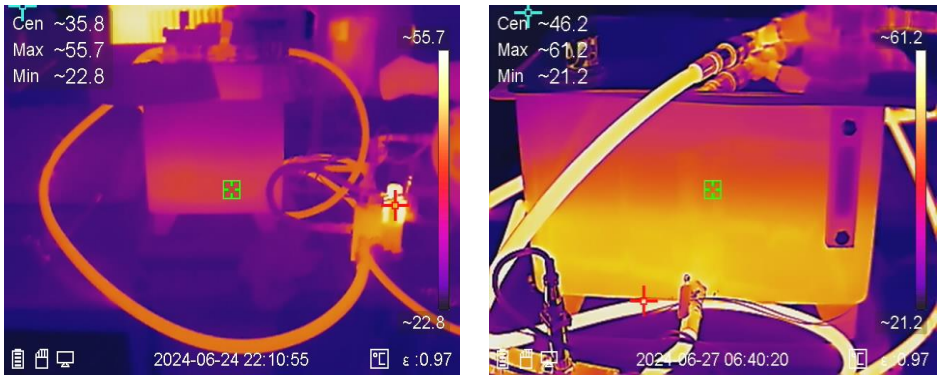


Figure 20. Hydraulic tank temperature [20, 26]

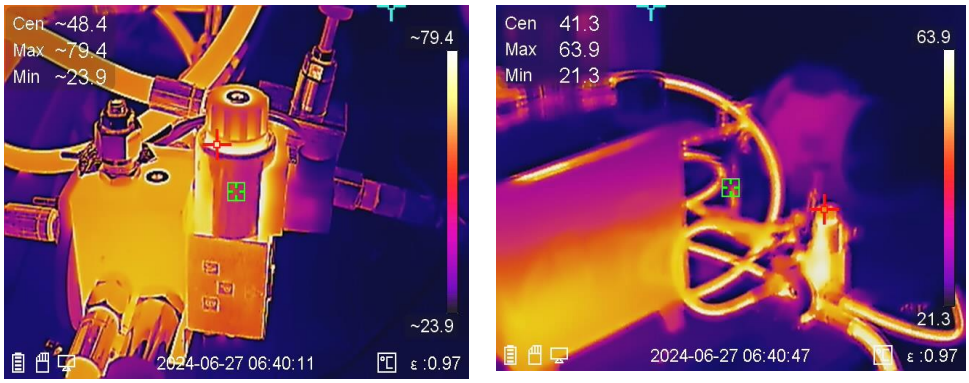


Figure 21. Temperature of the directional control solenoid and the hydraulic line [20, 26]

The general conclusions drawn from experimental testing highlighted the following points [20, 26]:

- Although the laboratory results are encouraging, testing under real operating conditions is necessary to obtain a complete understanding of the phenomena occurring during system operation, as well as to optimize and improve the transmission both in hardware and software.
- Special attention must be paid to the control architecture to synchronize communication types, data acquisition, and the transmission of control signals.
- It was also found that insufficient insulation of electronic components can introduce noise into the measured values. Signal filtering was therefore required to eliminate this noise.
- Conducting experimental tests on hydraulic transmission was hindered in some cases using manual adjustment instead of automated control for certain hydraulic equipment.

The comparative analysis of the results aimed to contrast the theoretical outcomes with the experimental findings, as follows [20]:

- The theoretical analysis cannot capture phenomena that appear during the operation of the experimental model (e.g., noise or other disturbances independent of the transmission itself). These phenomena can be determined experimentally and subsequently incorporated into the simulation model.
- The theoretical analysis cannot combine, in a single numerical model, information regarding the system's static or dynamic behavior and structural changes in the materials of which the equipment is made.
- Experimental testing provides a clear picture of the phenomena and behaviors of the system's equipment.
- The experimental model contradicts the numerical model in terms of the system's thermal inertia, which is significantly higher than the values obtained theoretically.

The optimization of the proposed system focuses on future development directions and the anticipated outcomes. Possible future enhancements for the overall installation could aim at recovering transmission energy losses during periods when wind speeds exceed the wind turbine's design values. The surplus energy generated could be stored in an accumulator battery and released during periods of low wind speeds. Another potential development direction could involve replacing manually or electrically controlled hydraulic equipment with proportionally controlled devices. A third possible improvement is the recovery of lost energy and its conversion into electrical energy through an auxiliary hydraulic motor, using a three-way flow regulator to direct the hydraulic fluid toward the auxiliary motor [20, 26].

Considering the results already obtained from testing the experimental model, these developments could be implemented together to ensure the optimal operation of the system, particularly in the case of the underfloor heating system, where heat transfer testing was specifically conducted [20, 26].

The anticipated outcomes of the proposed system optimization are based on the suggested improvements and on automating the regulation of certain parameters of the experimental model. Improvements are expected in system response times due to the replacement of conventional control equipment with proportional control devices. Thanks to the proportional control equipment and the working fluid temperature, the thermal energy transferred to the serviced system will be more precisely regulated. Enhancing the control architecture can further increase the performance of the experimental hydraulic transmission model by improving the data processing capacity and the responsiveness of commands sent to the equipment [20, 26].

Chapter 6, "Final Considerations," briefly summarizes the elements studied and the results obtained, based on a methodology defined through the specific objectives of the thesis.

This chapter also highlights the original contributions of the author. The author's originality is reflected in the experimental results obtained from testing the experimental stand of the proposed hydraulic transmission model. Another element of originality lies in the testing methodology followed by the author, as well as the design of the hydraulic transmission circuit and the selection of its components [20].

An additional significant contribution is provided by the control architecture of the entire system, which enables its integration into IoT systems. It is important to emphasize the author's intention to leverage this research for the development of new technologies and systems in the field of renewable energy. The doctoral thesis can also contribute to increasing the level of knowledge in relevant disciplines for future generations of students, who may continue research in this area [20].

Regarding future research directions, the author aims to further develop the experimental model of the hydraulic transmission so that it can be tested under real operational conditions on a wind turbine. Additionally, the author intends to develop a more user-friendly interface with greater accessibility for individuals with sensory impairments, as well as for users who are less familiar with this type of system [20].

Dissemination of doctoral research

The research conducted during the doctoral internship was disseminated at international scientific conferences, specialized journals, and invention salons. The main disseminated works are:

1. Constantin, V.; **Popescu, I**.; **Avram**, M., „Mechatronic Test Bench Used to Simulate Wind Power Conversion to Thermal Power by Means of a Hydraulic Transmission", *Technologies*, vol. 13, nr. 6, art. 236, 2025, indexat **SCOPUS**, **Web of Science (Q1)**, Open Access,DOI:10.3390/technologies13060236. **WOS:001514647700001**
2. **Popescu, I.-M.; Avram, M.**; Kadirova, S.; Stănescu, V.-A.; Vasilescu, A.-G.; Baboianu, G., „Mechatronic System and Method of Determining Internal Volume of Hydraulic Geared Pumps", în: Machado, J.; Trojanowska, J.; Soares, F.; Rea, P.; Butdee, S.; Grămescu, B. (eds.), *Innovations in Mechatronics Engineering IV*, *Lecture Notes in Mechanical Engineering*, Springer, Cham, pp. 470–480, 2025, indexat **SCOPUS**, DOI: 10.1007/978-3-031-94223-5_40.
3. **Popescu, I.-M**.; Popescu, V.-Ș.; Vasilescu, A.-G.; Constantin, V.; **Avram, M**., „STATE OF THE ART OF CONVENTIONAL WIND TURBINES DEVELOPMENT", *International Journal of Mechatronics and Applied Mechanics*, vol. 1, nr. 19, 2025, indexată Google Scholar, **SCOPUS**, DOI: 10.17683/ijomam/issue19.
4. **Baciu, I.-M**.; Vasilescu, A.-G.; **Avram, M.;** Grămescu, B.; Constantin, V.; Moraru, E., „A Review of Additive Technologies Applied to Gear Transmission", în: *Innovations in Mechanical Engineering III*, *Lecture Notes in Mechanical Engineering*, Springer, Cham, pp. 44–55, 2024, indexat **SCOPUS**, DOI: 10.1007/978-3-031-62684-5_5.
5. **Popescu, I.-M.;** Constantin, V.; Moraru, E.; Stănescu, V.-A.; Nica, I.-C.; Baboianu, G., „Design and Simulation of a Smart Hydraulic Throttle", în: *Proceedings of the IEEE International Conference on Electrical Engineering and Automatic Control (EEAE)*, pp. 1–6, 2025, indexat **IEEE Xplore**, DOI: 10.1109/EEAE65901.2025.11273700.
6. **Popescu, Ionela Mihaela**; Victor Constantin; Daniel Nanca. "Aspects Regarding Methods for Hydraulic Cylinders Synchronization." Hidraulica (Magazin de Hidraulică, Pneumatică, Tribologie, Ecologie, Sensorică, Mecatronică), nr. 3 (2025): 66-72.
7. **Popescu, I.-M**.; **Avram, M.**; Constantin, V.; Vasilescu, A.-G.; Grămescu, B., „Theoretical aspects regarding the development of a method for internal volume determination of externally geared pumps", *Proceedings of 2024 International Conference on Hydraulics and Pneumatics – HERVEX*, pp. 68–75, 2024, neindexat.

8. Chiriță, A.-P.; Șefu, Ș.-M.; **Baciu, I.-M**.; Rădoi, R.-I.; Popescu, A.-M., „Power control of a wind turbine using an electrohydraulically controlled active pitch control mechanism”, *IOP Conference Series: Materials Science and Engineering*, vol. 1262, nr. 1, 2022, neindexat, DOI: 10.1088/1757-899X/1262/1/012078.
9. **Baciu, I.-M**.; **Avram, M**.; Grămescu, B.; Constantin, V., „Experimental Analysis of an Open/Closed Hydraulic System”, *Proceedings of 2023 International Conference on Hydraulics and Pneumatics – HERVEX*, pp. 31–36, 2023, indexată Google Scholar, EBSCO.
10. Șefu, Ș.-M.; Tudor, B. A.; Dumitrescu, L.; **Baciu, I.-M**., „Recycling and Reuse of Hydraulic Components and Materials, Component Principles of the Circular Economy”, *Proceedings of the 22nd International Multidisciplinary Scientific GeoConference – SGEM 2022: Energy and Clean Technologies*, vol. 22, nr. 4.1, pp. 225–230, 2022, DOI: 10.5593/sgem2022/4.1/s18.29, neindexat.
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12. **Baciu, I.-M**.; Chiriță, Al.-P.; Rădoi, R.-I.; Drumea, P.; Voicea, I., „Improving the energy efficiency of wind turbines using hydraulic drive”, *Proceedings of the International Symposium ISB-INMA TEH' – Agricultural and Mechanical Engineering*, București, România, pp. 592–601, 2021, neindexat.

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