MODELLING, SIMULATION AND CONTROL OF AN ISOLATED PUMPING SYSTEM POWERED BY RENEWABLE ENERGY SOURCES

PhD Thesis – Summary

for obtaining the Scientific Title of PhD in Engineering from Politehnica University Timișoara in the Field of SYSTEMS ENGINEERING

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Pumping systems (PS) have evolved significantly in recent decades through progressive modernization to reach greater efficiency of water exploitation and use. This has been achieved by integrating various modern solutions that have replaced the traditional ones, for example, gravity irrigation has been replaced by sprinkler or drip irrigation systems. The payback of those methods consists of a drastic increase in energy consumption. For this reason, currently the energy consumption of a pumping unit represents the highest cost in operating a PS (water supply system or irrigation system). The PhD thesis proposes, as the main objective, the investigation of ***pumping systems powered by renewable energy sources*** (PSPRES) targeting lower operating expenses of the PS. The PhD thesis contributes to the 2030 target of the European Union, in terms of reduction of greenhouse gas emissions, increasing the share of renewable energy consumption, and increasing the energy efficiency [4]. Therefore, by achieving the proposed objectives and through the research topic of the thesis, which consists of the modeling, control and simulation of the operation of a complex and isolated PS powered by ***renewable energy sources*** (RES), reside the contributions brought in the context of the current energy crisis and global warming.

Chapter 1 - INTRODUCTION - presents the motivations and the objectives of the thesis, as well as the state-of-the-art of the research.

Currently, PS, especially those used in agricultural irrigation, are powered by the national power grid or by diesel or gasoline generators (where the national power grid is lacking, such as in remote areas). Because most of these systems are used during the summer, with maximum demand on the hottest and sunniest days of the year, the solution for powering an irrigation PS may consist of ***photovoltaic generators*** (PVG) due to their excellent integration into such systems. Another solution to power the PS is the ***wind electrical generator*** (WEG) for windy areas and periods. This solution, depending on the characteristics of the wind, can ensure, at the pumping site, the availability of energy also during the night and on cloudy days, when the efficiency of the PVG is very low.

However, despite the economic profitability offered by pumping installations powered by photovoltaic, wind or by photovoltaic-wind hybrid generators and the fact that their market demand is constantly increasing, those types of systems still require a technological maturation to become more robust, durable, reliable and efficient (especially the high-power ones).

A high-performance PS powered by RES has a particular complexity as it requires perfect integration in a single integrated system of 4 subsystems from different technical fields: the renewable energy conversion system (photovoltaic energy, wind energy or hybrid photovoltaic-wind energy); the electrical system; the hydraulic system and the control system.

Due to the continuous decrease in the price of ***photovoltaic*** (PV) panels in recent years, the irrigation with PV energy has become highly tempting and represents the type of system that draws the greatest research effort among PS powered by RES. The only drawback for potential customers remains the lack of the technology necessary for robust and reliable installations. The return on investment in integrating a ***photovoltaic energy conversion system*** (PECS) into an existing irrigation installation is approximately 6 or 7 years, assuming a reliable system (with a lifetime of more than 20 years) [54].

Pumping systems powered by photovoltaic energy conversion systems (PSPPECS) become particularly complex when the installed power increases (>> 25KW), when the PS is directly connected to the irrigation system (without any water storage leading to an operation at constant pressure), when they are isolated (without support from a power grid) or when the hydraulic network is very complex (pumps connected in series and/or parallel).

A system is complex from a technological point of view when the effects of fluctuations and intermittency of the power supply cannot be reduced through the system typology and when the pressure of the pumping fluid must be constant. Examples of such systems are the high-power PSPPECS isolated from the grid, for which oversizing the PECS is not economically feasible and the problems caused by PECS powers intermittency and fluctuations must be overcome by technological means (high-performance control system). Another complex system from a technological point of view is direct sprinkler irrigation because pumping into the hydraulic network is done at high and constant pressure and can be correlated to the variation (fluctuations and intermittency) of the energy available in the PECS only through high-performance technological means.

Some of the technological problems of the PSPPECS highlighted previously, were tried to be solved by the implementation of a European research project called ***Market uptake of an innovative irrigation Solution based on LOW WATer-Energy consumption*** (MASLOWATEN) coordinated by the Polytechnic University of Madrid [21]. The project was supported by the 2020 European Horizon program with a budget of 5 million euros [21]. Through this project, some of the problems presented were researched, by implementing five high-power PSPPECS and by developing a simulation tool called **Sisifo** [22] used to design pumping systems powered by a PVG. The limitations of this tool consist of the fact that only relatively simple PS (a single pump that can pump water into water storage at variable flow and pressure, or directly into an irrigation network at constant pressure and flow) and only systems powered by a PECS (no ***wind energy conversion systems*** - WECS) can be simulated.

Pumping systems powered by wind energy conversion systems (PSPWECS) have been left behind the PSPPECS, even though, as the price of PV energy, the price of wind energy has dropped substantially in recent years, without mentioning that there are irrigation sites where wind energy resources are superior to photovoltaic ones.

One of the problems, that requires research and solution, on which depends the usage of the energy produced by WECS for powering a PS, is the absence of a reliable technology giving efficiency and robustness.

The weak development of PSPWECS can also be due to the small availability on the market for small and medium power WECS (powers between 5kW and 1 MW) and the difficulty raised by the impossibility of offering a wide range of powers, compared to the modularity offered by photovoltaic generators.

The main reason behind conducting PS powering research, especially for the one used in irrigation, is given by the fact that in those systems powered only by PECS, the shadow of the clouds passing represents a serious problem. The PECS can be covered by the shadow of a cloud in a few seconds and its power will suddenly drop (for example, from 700 W/m^2 to 150 W/m^2). This sudden drop in power can cause electrical shocks (which also affect the power semiconductors, because of the large voltage variation during the drop) and hydraulic shocks (cavitation and water hammer in the hydraulic system). Also, in many areas, a PSPPECS can operate for about 1700 hours per year, while a PSPWECS can operate for 3500 ... 4000 hours. The operating period limitation offered by the PSPPECS can be overcome at specific sites by those powered (or hybridized) by WECS.

Although the wind exhibits turbulence and varies more frequently, due to the inertia of the ***wind turbine*** (WT) rotor and generator, those drops cannot be as sudden, avoiding most of the hydraulic and electrical shocks.

Considering the current state of the research, almost non-existent in the area of PSPRES and because the few installations executed internationally are not reliable, in this PhD thesis are developed and implemented a reliable and robust solution for powering high-power PS by a PECS or WECS.

The main objectives addressed and solved in this PhD thesis are:

- modelling and control of a high-power PS;
- modelling and control of a PECS and WECS adapted for powering a high-power PS;
- analysis, synthesis and implementation of some control structures for operating a high-power PS powered by a PECS or WECS.

Chapter 2 - PUMPING SYSTEMS - begins with the description of a high-power PS and its main components: induction motor drives, induction motor, centrifugal pump and the hydraulic network. In subchapter ***2.2 Pumping system modelling***, it is proposed a general and adequate dynamic ***mathematical model*** (MM) for a high-power PS, that can be used for both dimensioning and simulation. The personal contribution to PS modelling consists of developing a model capable of simulating also transitory regimes, not only nominal regimes as the ones presented in the specialized literature [45, 49, 50, 52]. Part of the proposed model has been published by the author in ISI journal - Q1 [54].

In section ***2.3 Pumping system control strategy***, five control strategies are developed, one for driving the pump induction motor at fixed (nominal) speed using a soft starter driver, and four for driving it at variable speed, variable flow rate, variable pressure (pump head), or variable power absorption using a ***variable frequency drive*** (VFD). As can be seen in Figures 2.27 and Figure 2.30, both motor drive types (the soft starter and the VFD) contain, in addition to the control structures, also the execution elements. The soft driver contains the converter and the VFD contains the rectifier and the inverter.

The most common solution to drive high-power centrifugal pumps at a fixed (nominal) speed is to use a soft starter that controls only acceleration at nominal speed (equivalent frequencies from 0 to 50 Hz) and deceleration from nominal speed (equivalent frequencies from 50 to 0 Hz) of the pump induction motor. Figure 2.27 presents the structure of the fixed-speed pump motor powered by a soft starter at nominal frequency.

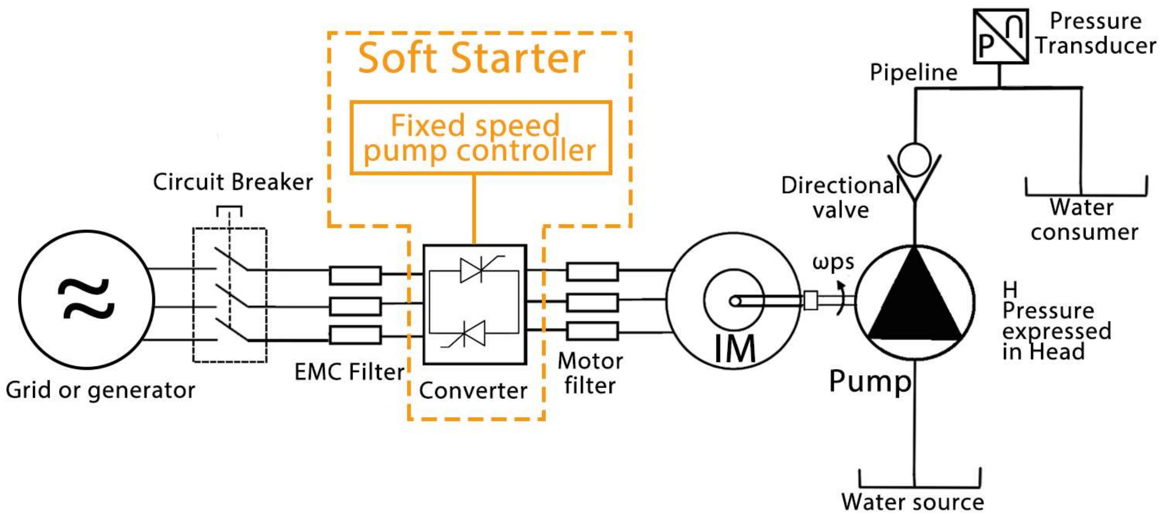

Figure 2.27. Pump-induction motor system driven by a soft starter at nominal frequency

As can be seen in Figures 2.27 and 2.28, the pump induction motor at a fixed speed is controlled using a classical solution for current regulation in vector-controlled AC drives, called the current regulator (represented by the dotted green line in Figure 2.28). This solution considers two equally tuned ***proportional integral*** (PI) regulators, one for the "*d*"-axis (real components) currents and one for the "*q*"-axis (imaginary components) currents. These current regulators are tuned using a second-order equivalent system of induction motor currents [40].

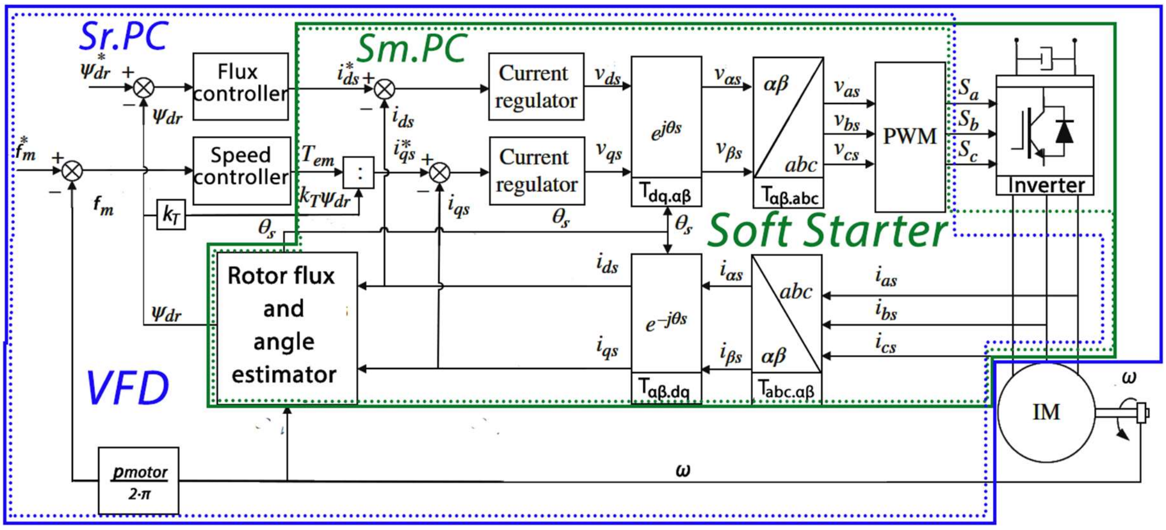

Figure 2.28. Induction motor pump control loops [35]

The most common solution for driving high-power centrifugal pumps at a variable speed is using a VFD (Figure 2.30), which besides controlling the acceleration and deceleration of the induction motor also controls the operating speed, which can differ from the nominal one. Due to this reason, the variable speed (flow rate, pressure or power absorption) pump controller (represented by the dotted blue line in Figure 2.28) uses the same closed-loop systems as the fixed speed controller (represented by the dotted green line), to which a speed controller is added in cascade (Figure 2.28). Parallel to the speed controller loop, a flux controller loop is developed similarly [35].

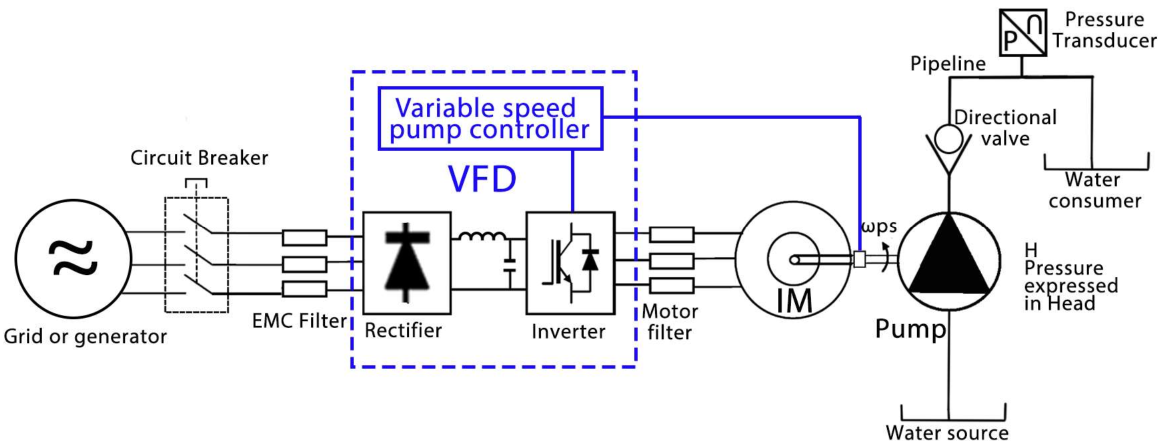

Figure 2.30. Pump-induction motor system driven by a VFD at variable frequency

Personal contributions to the PS control strategy consist of developing several mathematical equations, in order to obtain the electrical frequency ***error*** *Δf=(fm*-fm)* (the deviation of the current value from the reference value) expressed as a function of pump discharge (flow) error $\Delta Q=(Q^*-Q)$, head (pressure) error $\Delta H=(H^*-H)$, or absorbed power error $\Delta P_{pump}=(P_{pump}^*-P_{pump})$ necessary for driving a pump through a VFD to desired flow or head or for tracking a fluctuating and intermittent power source:

$$\Delta Q=\frac{2\cdot\pi}{p_{motor}}\cdot\Delta f\cdot\left(\dot{Q}\right)_{fm^*}=\frac{2\cdot\pi\cdot Q^*}{p_{motor}\cdot fm^*}\cdot\Delta f \quad\text{and}\quad \Delta f=\frac{p_{motor}\cdot fm^*}{2\cdot\pi\cdot H^*}\cdot\Delta Q \tag{2.70}$$

$$\Delta H=\frac{2\cdot\pi}{p_{motor}}\cdot\Delta f\cdot\left(\dot{H}\right)_{fm^*}=\frac{4\cdot\pi\cdot H^*}{p_{motor}\cdot fm^*}\cdot\Delta f \quad\text{and}\quad \Delta f=\frac{p_{motor}\cdot fm^*}{4\cdot\pi\cdot H^*}\cdot\Delta H \tag{2.72}$$

$$\Delta P_{pump}=\frac{2\cdot\pi}{p_{motor}}\cdot\Delta f\cdot\left(\dot{P_{pump}}\right)_{fm^*}=\frac{4\cdot\pi\cdot H^*}{p_{motor}\cdot fm^*}\cdot\Delta f \quad\text{and}\quad \Delta f=\frac{p_{motor}\cdot fm^*}{6\cdot\pi\cdot\left(P_{pump}\right)^*}\cdot\Delta P_{pump} \tag{2.74}$$

where:

$\dot{Q}$, $\dot{H}$ and $\dot{P_{pump}}$ are obtained deriving the affinity laws, *fm* the current electrical frequency, *Q** the reference pump discharge (flow), *H** the reference head (pressure) and P_{pump}^* the reference absorbed power by the pump.

In the last subchapter, ***2.4. Pumping system simulations***, the PS model and the proposed control strategy are validated through five simulations, where the pump is driven at a fixed speed, variable speed, variable flow, variable pressure and variable available power. The performance of the proposed control strategy is determined by analyzing several performance indicators such as: the speed and torque of the induction motor and the pump, the power absorbed by the induction motor from the power grid, including the 3 phases of voltages and currents, and the pumping head and discharge.

Chapter 3 – PHOTOVOLTAIC ENERGY CONVERSION SYSTEM (PECS) starts with a short description of an existing PECS powering a PS in Aragon, Spain [94], a system used further in validating the proposed MM and control structures. The power of the installed PECS is 56,95 kW and its main components are: an array made of 170 PV panels of 335 W, combined in 10 strings connected in parallel, with each of 17 PV panels connected in series (5.695 kW) and distributed on 3 decentralized self-operated horizontal single-axis trackers (57 on each tracker). The trackers have an N-S (north-south) orientation and a 110º range of motion around their axis.

In subchapter, ***3.2 PECS modelling***, a steady state model is developed for dimensioning and simulating the PECS nominal operation during an entire year and a dynamic model is used in the development of the control strategy and for simulating the PECS partial operation and transitional regimes.

In the third section, ***3.3 PECS controller***, is considered a ***maximum power point tracking*** (MPPT) control method based on the ***perturb and observed*** (P&O) algorithm [41, 55, 71], to which were made the necessary changes for further integration into a high-power PS. The flow chart of the P&O algorithm is presented in Figure 3.12.

As personal contributions brought by the current chapter, I would like to mention the PECS dynamic MM and controller (implemented in Simulink), which uses as inputs the solar irradiation and PV cell temperature measured on the mentioned existing PVG. The experimental validation of the simulations has been made for four different scenarios: a clear sky day, a day with a big cloud covering the sky during a period of the day, a day with many small clouds and a fully cloudy day.

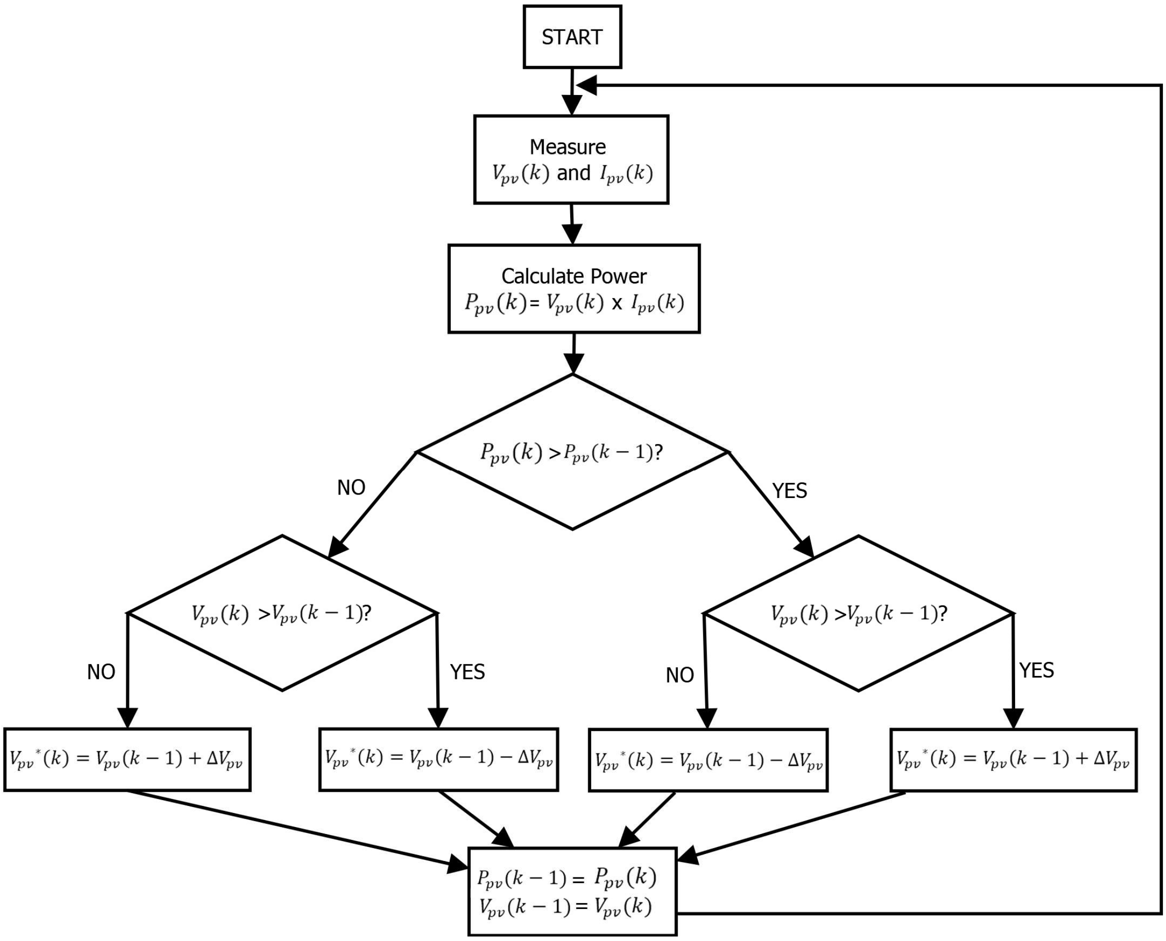

Figure 3.12. P&O algorithm flow chart

The first part of **chapter 4 – WIND ENERGY CONVERSION SYSTEM (WECS)** begins with a description of a general WECS and its main components (rotor, nacelle and tower). In section, ***4.2. WECS modelling***, it is developed a dynamic MM resulted from the combination of the nonlinear models of the WECS components presented in [84] (aerodynamics, tower and blade) with the ones presented in [88] (drive train, ***doubly fed induction generator*** - DFIG and blade pitch actuator). The obtained dynamical MM is capable to simulate the dynamic operation of a WECS (transitional regimes), including the cut-off of the WT.

In ***4.3 WECS control strategy,*** it is developed a control system that combines a first control level (DFIG rotor and grid side controllers, [87]) with a second control level (generator-torque and blade-pitch controllers [88]). The first control level (called the DFIG controller) controls two pulse modulation bandwidths (the DFIG rotor and grid side) that regulate the convertors switch pulses. The second control level, called the ***wind turbine*** (WT) controller, consists of two controllers (the generator-torque controller and the blade-pitch controller) that regulate the rotor and generator torque and speed. A torque controller has been developed, based on the one from [86], which has been improved through its ability to adapt power production to power demand (derating the WECS power when the power demand is lower than the rated power). Through the proposed solution, the generator torque is reduced when the wind reaches the cut-off speed or when the generated power reaches demanded power. Simultaneously, the blade pitching actuator is enabled.

For the synthesis of the PI regulator used to control the blade-pitch angle, an improved version is proposed in which the ***proportional gain*** (K_p) and the ***integral time*** (K_i) are scheduled using the GK(β) function:

$$K_p(\beta) = K_{prated} \cdot GK(\beta) \tag{4.146}$$
$$K_i(\beta) = K_{irated} \cdot GK(\beta) \tag{4.147}$$

where: $\boldsymbol{K_{prated}}$ and $\boldsymbol{K_{irated}}$ are the nominal values of the PI regulator gains; ***GK(β)*** is the scheduling function of the $\boldsymbol{K_p}$ and $\boldsymbol{K_i}$ gains, obtained based on the ***current value of the WT blade-pitch angle (β)*** and the ***value of the blade-pitch angle where the WT rotor torque has doubled (β_k)***:

$$GK(\beta) = \frac{1}{1 + \frac{\beta}{\beta_k}} \tag{4.148}$$

For determining the β_k the sensitivity of the rotor torque from the WECS nonlinear model has been linearized using Tylor series approximation according to Equation 4.26 [89]:

$$\Delta M_{rot} = \left.\frac{\partial M_{rot}}{\partial v_{rot}}\right|_{(v_{roto},\Omega_0,\beta_0)} \cdot \Delta v_{rot} + \left.\frac{\partial M_{rot}}{\partial \Omega}\right|_{(v_{roto},\Omega_0,\beta_0)} \cdot \Delta\Omega + \left.\frac{\partial M_{rot}}{\partial \beta}\right|_{(v_{roto},\Omega_0,\beta_0)} \cdot \Delta\beta \tag{4.26}$$

where:
v_{rot0} [m/s] is the wind speed at the linearization point;
Ω_0 [rad/s] is the rotor angular velocity at the linearization point;
v_{rot0} [m/s] is the wind speed at the linearization point;
β_0 [˚] is the pitch angle at the linearization point;
M_{rot0} [Nm] is the rotor torque at the linearization point;
$\Delta\Omega$ is the change in rotor angular velocity;
Δv_{rot} is the change in wind speed;
$\Delta\beta$ is the change in pitch angle
and ΔM_{rot} is the change in rotor torque.

To determine the pitch angle that doubles the WT rotor, Equation 4.26 is considered, in which the wind speed variation is ignored and the angular velocity is considered to be held constant at the rated point [89]:

$$2 \cdot M_{roto} = M_{roto} + \left.\frac{\partial M_{rot}}{\partial \beta}\right|_{(v_{roto},\Omega_0,\beta_0)} \cdot (\beta_0 - \beta_k) \tag{4.149}$$

where:
M_{rot0} [Nm] is the rotor torque at the linearization point;
β_0 [rad/s] is the rated pitch angle;
βk [rad/s] is the pitch angle where the pitch sensitivity has doubled;
$\left.\frac{\partial M_{rot}}{\partial \beta}\right|_{(v_{roto},\Omega_0,\beta_0)}$ [Nm/°] is the blade-pitch sensitivity.

Resulting, that the blade pitch angle that doubles the WT rotor torque is [89]:

$$\beta_k = \beta_0 - \frac{M_{rot0}}{\left.\frac{\partial M_{rot}}{\partial \beta}\right|_{(v_{roto},\Omega_0,\beta_0)}} \text{ [rad/s]} \tag{4.150}$$

The improvements brought by scheduling K_p and K_i were confirmed by the simulation results presented in section ***4.4. WECS simulations***, where it can be seen that the response of the WT blade-pitch actuator is faster, leading to a faster settling of the produced energy with fewer fluctuations and losses during operation at full load in a high turbulent wind.

Chapter 5 – **PUMPING SYSTEMS POWERED BY PHOTOVOLTAIC ENERGY CONVERSION SYSTEMS (PSPPECS)** starts with the description of a PSPPECS and its main components (PECS, PS, Hydraulic network, Induction motor, variable frequency drive and a PLC- ***programmable logic controller***).

In sub-chapter ***5.2 PSPPECS modelling***, based on the PS and PECS models developed and validated in chapters ***2*** and ***3***, it has been obtained a PSPPECS dynamic MM capable of simulating nominal and transitory operating regimes.

In ***5.3 PSPPECS control strategy,*** it has been developed a strategy for controlling a PSPPECS made of 3 control structures in cascade, as presented in Figure 5.3. To the variable speed pump controller (developed in section ***2.3***), a PSPPECS controller has been added, to which the PECS Controller (developed in section ***3.3***) has been added.

The variable speed pump controller is necessary to drive the pump induction motor through a VFD at different reference speeds. It contains two PI regulators, one for the speed and one for the flux connected in cascade with two equally tuned PI current regulators, one to control the "*d*"-axis (real components) currents and one for the "*q*"-axis (imaginary components) currents. The electrical frequency error $\Delta f=(fm^*-fm)$ (the difference between the reference and current pump frequency) is provided by the PSPPECS controller (Equation 5.1) to the PI speed controller from the variable speed pump controller:

$$\Delta f = \begin{cases} \dfrac{-p_{motor} \cdot \omega_{pss}}{2 \cdot \pi} & P_{PECS} < P_{psmin} \\ \dfrac{p_{motor} \cdot fm^*}{6 \cdot \pi \cdot \left(P_{pump}\right)^*} \cdot \left(P_{PECS} - P_{pump}\right) & P_{PECS} \geq P_{psmin} \end{cases} H < H^* \\ \quad \dfrac{p_{motor} \cdot fm^*}{4 \cdot \pi \cdot H^*} \cdot \Delta H \qquad H \geq H^* \tag{5.1}$$

where:

P_{psmin} represents the minimum power required by the pump motor (to ensure the pumping of the minimum flow required for the pump motor cooling);

P_{PECS} is the power generated by the PECS, P_{pump} is the current power of the pump;

fm and fm^* are the electrical frequencies of the induction motor (current and reference values);

p_{motor} is the induction motor's pairs of poles;

ω_{pss} is the current speed of the pump;

and $\Delta H=(H^*-H)$ the head (pressure) error (the difference between the reference and current pump head).

The PSPPECS controller ensures the control in 3 specific cases:

1. when the pumping head is higher than its reference ($H \geq H^*$), the PSPPECS controller executes a pumping head control;
2. when the pumping head is lower than its reference ($H<H^*$), and the power produced by the PECS it is lower than the minimum power required to operate the pump ($P_{PECS}<P_{psmin}$), the PSPPECS controller decelerates the PS;
3. when the pumping head is lower than its reference ($H<H^*$), and the power produced by the PECS it is higher than the minimum power required for the pump operation ($P_{PECS} \geq P_{psmin}$), the PSPPECS controller drives the PS so that its absorbed power tracks the PECS produced power;

The PECS controller is necessary for operating the PECS at its ***maximum power point*** (MPP) and passing it as a reference to the PSPPEC controller.

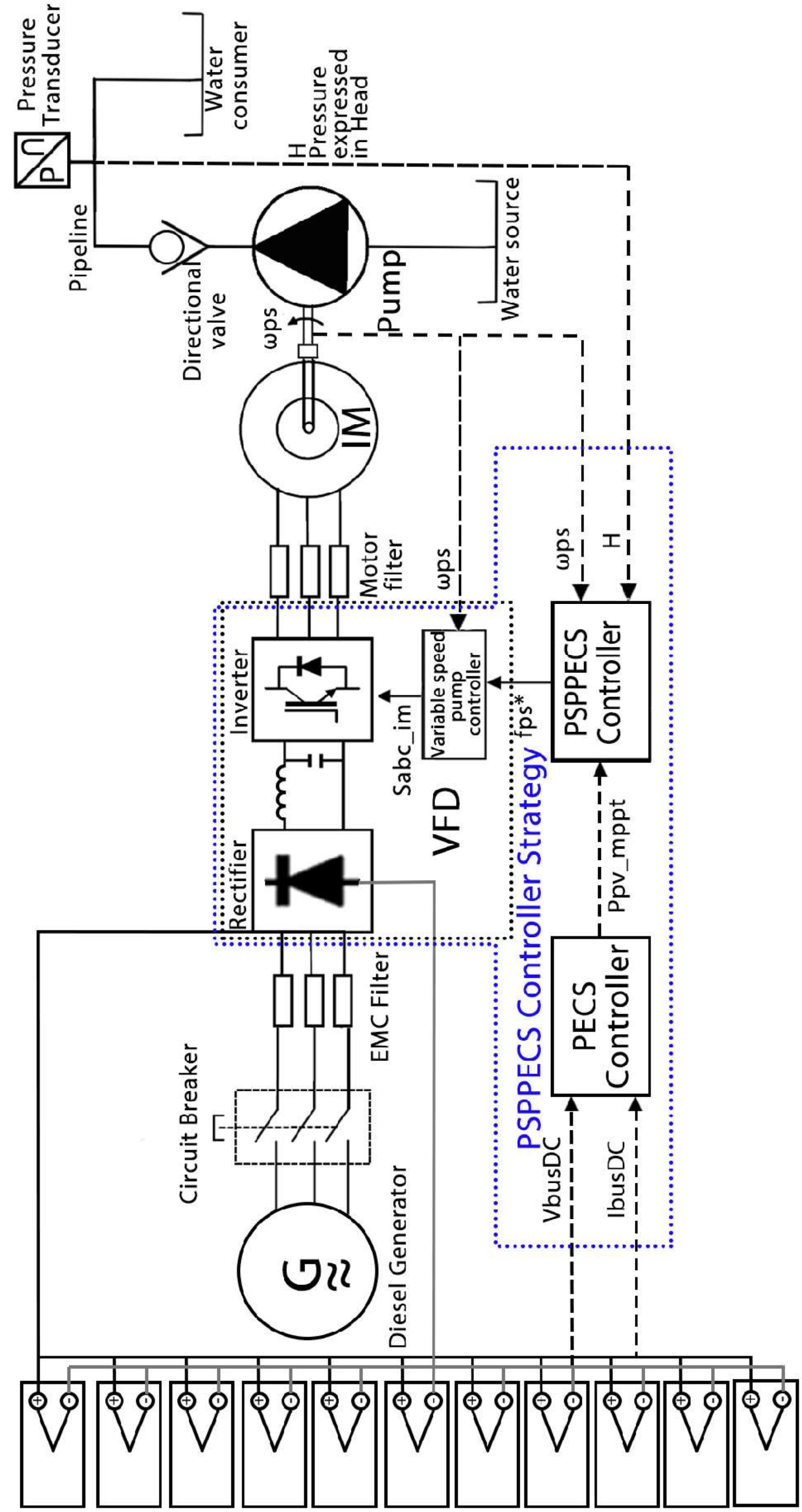

Figure 5.3. Structure of the PSPPECS control system

In section ***5.4. Monitoring system***, a monitoring system has been developed and implemented to determine the performance of the photovoltaic pumping system, a system more precise than the current ones (using the methodology proposed by IEC 62253 [96]), due to its ability to evaluate transitory regimes and detect electric and hydraulic shocks. The proposed monitoring system uses a non-intrusive monitoring data logging and acquisition (whose layout is presented in Figure 5.4) that measures and stores the transducers values each second. The transducers used by the monitoring system are: a calibrated photovoltaic cell (used for measuring the irradiance temperature), a ***direct current*** (DC) voltage transducer (necessary for measuring the DC bus voltage, capable of detecting electric shocks), a pressure transducer (for measuring the hydraulic network pressure, capable of detecting hydraulic shocks), a volume flow transducer (for measuring the discharged flow rate by the pump into the hydraulic network), and a temperature transducer (for measuring the pumping liquid temperature).

In sub-chapter ***5.5. PSPPECS simulations***, the accuracy of the PSPPECS model and the performance of the proposed control strategy are validated by a comparison between the simulated results in Matlab/Simulink (PECS produced power, power absorbed by the VFD, induction motor and pump, the speed and torque of the induction motor and pump, and the pumping head and flow) with those obtained using the proposed monitoring system, on the existing PSPPECS in Aragon, Spain (Figure 5.1) for five representative days (a clear sky day, a day with a big cloud covering the sky during a period of the day, a day with many small clouds and a fully cloudy day).

Figure 5.1. Existing PSPPECS in Aragon, Spain

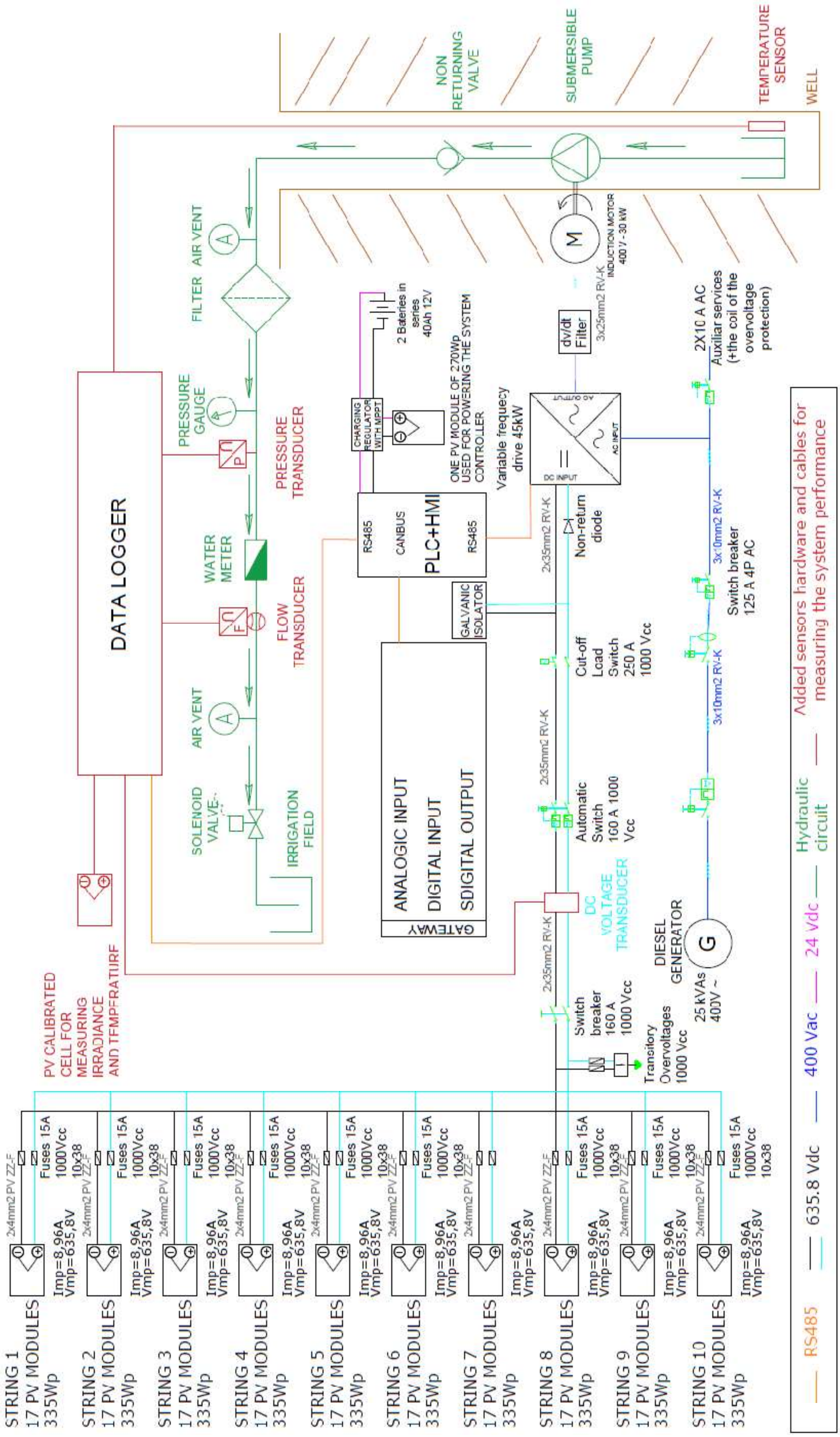

Figure 5.4. The monitoring system proposed for determining the PSPPECS performance

Chapter 6, entitled – **PUMPING SYSTEMS POWERED BY WIND ENERGY CONVERSION SYSTEMS (PSPWECS)** - presents the modelling, simulation and control of a ***pumping system powered by a wind energy conversion system*** (PSPWECS) by developing a dynamic MM and an efficient, robust and reliable control strategy. At the end of the chapter are analyzed the obtained simulation results.

The PSPWECS dynamic MM, developed in section ***6.2 PSPWECS modelling***, considers the connection of a WECS (a WT with pitching blades, its blade pitching actuator, its drive train, its tower, and a DFIG together with its power converters) with an irrigation PS (a centrifugal pump, an induction motor with its power converter, and an irrigation network with a pressure transducer).

The PSPWECS control strategy developed and proposed in ***6.3 PSPWECS control strategy*** (Figure 6.1) contains three levels of controllers: three first-level controllers (two necessary for the power converters of the WECS generator stator and rotor, and one for the pump motor), three second-level controllers (two necessary for the WECS and the one for the PS) and one third-level controller (necessary for the control of the entire PSPWECS system).

The first-level controllers regulate the voltage and current wave forms produced by the WECS (the DFIG stator and rotor controllers proposed in sections ***4.3.4*** and ***4.3.5***), respectively, the ones absorbed by the induction motor of the pump (the controller proposed in section ***2.3.1***).

The second-level controllers contain two controllers that regulate both the torque and speed of the WT rotor and WECS generator (the generator-torque controller and the blade-pitch controller, from sections ***4.3.2*** and ***4.3.3***), respectively, the speed controller of the pump's induction motor (the flux and variable speed pump controller, from section ***2.3.2***).

The third level contains the PSPWECS controller (Figure 6.1), which generates the reference of the WECS power ($P_{WECSdem}$*) according to the pumping pressure reference (expressed in the pump head H) and its reference, as in Equation 6.1 [48]:

$$P_{wecsdem} = \begin{cases} P_{ps0} \cdot \eta_0 & H < H^* \\ \left(\dfrac{3 \cdot P_{ps0}}{2 \cdot H_0} \cdot \Delta H + P_{ps0}\right) \cdot \eta_s & H \geq H^* \end{cases} \tag{6.1}$$

and calculates frequency error $\Delta f=(fm^*-fm)$ (the difference between the reference and current frequency of the motor) of the variable speed pump controller according to power produced by the WECS (P_{WECS}) as in Equation (6.2) [48]:

$$\Delta f = \begin{cases} \dfrac{-p_{motor} \cdot \omega_{pss}}{2 \cdot \pi} & P_{wecs} < P_{psmin} \\ \dfrac{p_{motor} \cdot fm^*}{6 \cdot \pi \cdot \left(P_{pump}\right)^*} \cdot \left(P_{wecs} - P_{pump}\right) & P_{wecs} \geq P_{psmin} \end{cases} \tag{6.2}$$

where P_{psmin} represents the minimum power required by the pump motor (to ensure the pumping of the minimum flow required for the pump motor cooling).

The PSPWECS controller ensures the control in 4 specific cases:

1. when the power produced by the WECS is lower than the minimum power required to operate the pump ($P_{WECS}<P_{psmin}$), the PSPWECS controller decelerates the PS;
2. when the power produced by the WECS is greater than the minimum power required for operating the pump ($P_{WECS}\geq P_{psmin}$), the PSPWECS controller drives the PS, so that its absorbed power tracks the PECS produced power;
3. when the pumping head is lower than its reference ($H<H^*$), the PSPWECS controller demands the WECS to produce only the necessary power for the nominal operation of the PS;
4. when the pumping head is higher than its reference ($H\geq H^*$), the PSPWECS controller regulates the power produced by the WECS according to the PS power demand so that the pressure it is equal to its reference.

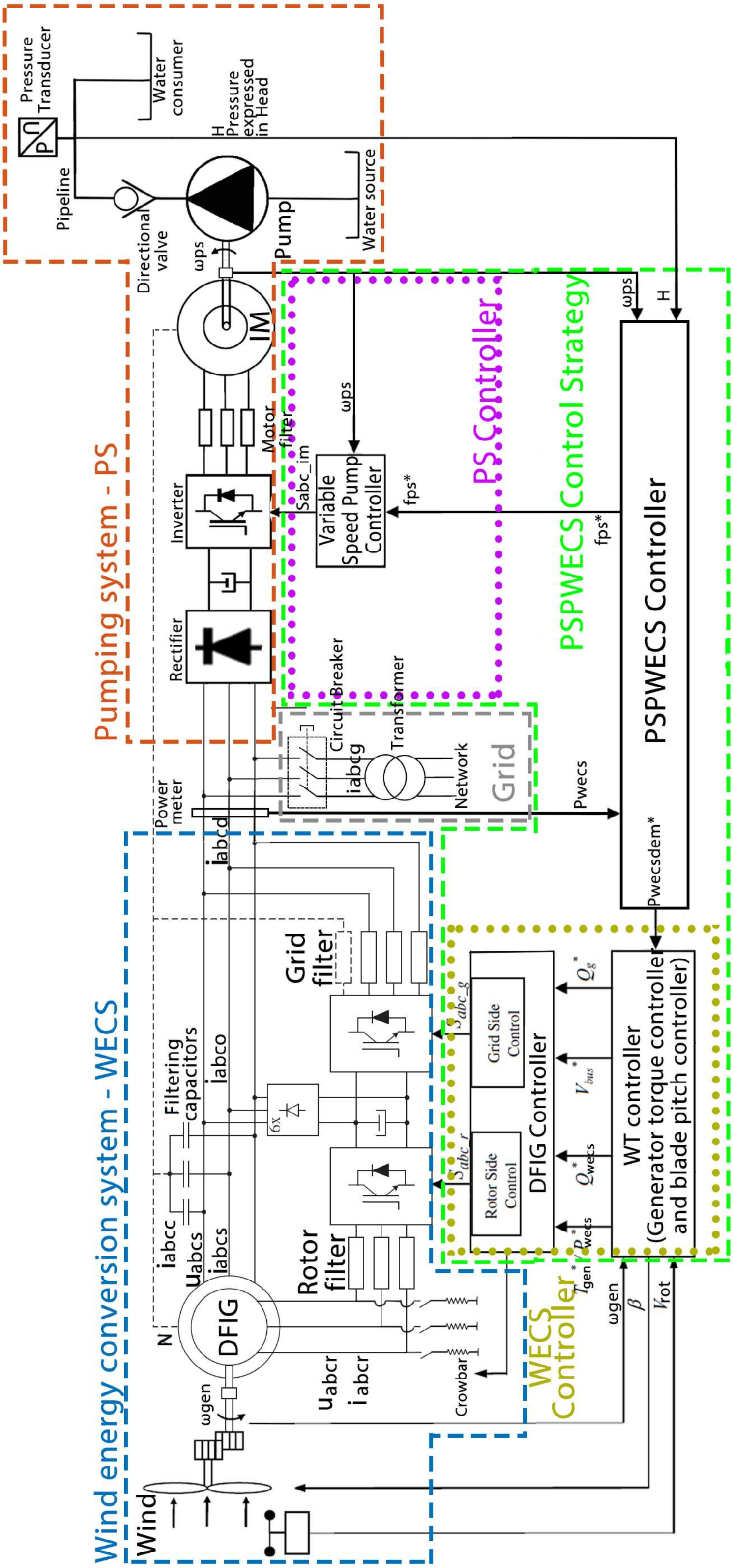

Figure 6.1. Structure of the PSPWECS control system [48]

The simulation results depicted in section ***6.4 PSPWECS simulations***, cover the transition through the entire operation range considered representative for the PWPWECS. The simulation results validate the correctness, performance and effectiveness of the proposed control strategy.

One of the main contributions of the proposed PSPWECS compared to other related work [118, 119], consists of integrating a commercial WECS into an existing PS, without altering its structure or control strategy and that it can be implemented without additional costs.

Chapter 7, **FINAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH** contains the final conclusions correlated with the PhD thesis's main objectives and the author's contributions along with possible directions for further research developments. The overall research contribution brought by this PhD thesis consists of proposing advanced models and control strategies for operating a complex and isolated PS powered by RES (PECS or WECS).

Final conclusions

Solving the problems raised in the PhD thesis, the following main conclusions can be drawn.

The analysis through simulation of a PS operating in various specific regimes (fixed speed, variable speed, variable flow, variable pressure and variable available power) requires the development of MM for the main components (subsystems) of these types of system: the motor driver, the induction motor, the centrifugal pump and the hydraulic network. The developed and proposed dynamic MM of the PS has been implemented and validated both using Matlab/Simulink simulation software and experimentally on an existing PS. The proposed MM can be used for dimensioning and simulation or in the synthesis and development of various PS control strategies.

The PS control strategy has been addressed for two types of induction motor drivers of high-power pumps (commercially available): the soft starter for driving the induction motor at a fixed speed and the VFD with at least one PI controller integrated for driving the induction motor at variable speed, variable flow, variable pressure or variable available power.

The case studies carried out through simulation and experimentally on an industrial high-power PS led to the conclusion that by using the MM developed for the PS components, the proposed control strategies ensure good performance, being recommended for PS configurations with induction motors driven by soft starters or by VFD with at least one integrated PI controller.

A static model was developed for the dimensioning and simulation of the nominal operation of the SCEF, and a single-diode dynamic model was considered for simulating transitory regimes and the synthesis and development of control strategies.

To control the PECS, a control structure was developed for the MPPT of a PECS based on the P&O algorithm and adapted for its further integration into the control strategy of a PS.

The case studies, performed by simulation and experiment, on an existing PECS, confirm that by using the developed MM of the conversion system subsystems, the control strategy provides good performance, and it is recommended for PECS configurations powering high-power PS.

In the current work, a nonlinear dynamic MM was developed, used in the simulation of the transient regimes of a WECS and its linearized version, used in the synthesis of the control strategy.

The variable pitch and speed WECS control strategy was developed on two control levels: the controllers of the DFIG rotor and stator converters on the first level, and the controller of the generator-torque and blade-pitch angle on the second level. To adapt the produced power to a variable reference power by enabling the WT blade-pitch actuator and to decouple the WT rotor when the wind reaches the cut-off speed, changes in the generator-torque controller were required. In addition, significant improvements were made by scheduling the proportionality constant (K_p) and integration time (K_i) of the PI blade-pitch controller; the scheduled K_p and K_i values were obtained based on the linearization of the WECS model, by using the Taylor series approximation and by determining a mathematical equation that allows the calculation of the gains scheduling according to the current value of the WT blade-pitch angle (β) and the value of the WT blade-pitch angle for which the WT rotor torque has doubled (βk).

The case studies, carried out by simulation in Matlab/Simulink, confirm that, using the WECS nonlinear dynamic model, the developed and proposed control strategy provides good performance, being recommended for WECS configurations powering high-power PS.

The PSPPECS dynamic MM developed and proposed in the current work has been implemented and validated both in Matlab/Simulink software and experimentally and it can be used for dimensioning, simulation and in the synthesis and development of various control strategies.

The PSPPECS control strategy was addressed for 3 distinct cases: when the control system executes a pressure control (the case when the pumping head is higher than its reference), when the control system decelerates the operation of the PS (the case when the pumping head is lower than its reference and the power produced by the PECS is lower than the minimum power required for operating the pump) and when the control system drives the PS so that its absorbed power tracks the PECS produced power (the case when the pumping head is lower than its reference and the power produced by the PECS is higher than the minimum power required for operating the pump).

The case studies, carried out by simulation in Matlab/Simulink and experimentally on the existing PSPPECS, confirm that the MM developed for the PSPPECS components, as well as the proposed control strategy ensures good performance and an increase in robustness and reliability (by reducing the number of electric and hydraulic shocks in a PSPPECS).

The PSPWECS controller was addressed for 4 distinct cases: (i) the control system decelerates the PS (when the power produced by the WECS is lower than the minimum power required for operating the pump); (ii) the control system drives the PS so that its absorbed power tracks the WECS produced power (when the power produced by the WECS is higher than the minimum power required for operating the pump); (iii) the control system demands the WECS to produce only the necessary power for the nominal operation of the PS (when the pumping head is lower than its reference); (iv) the control system regulates the power produced by the WECS according to the PS power demand so that the pressure it is equal to its reference (when the pumping head is higher than its reference).

The case studies, carried out by simulation, confirm that by using the MM developed for the PSPWECS components, the proposed control strategy ensures good performance and reduces the load on the mechanical components of the SCEE, as well as the number of hydraulic and electrical shocks in a PSPWECS.

To elaborate the presented PhD thesis, it has been undertaken a bibliography containing **123** references from specialized literature, most of them very recent. Furthermore, the bibliography includes **13** references whose main author or coauthor is the author of the thesis: **1** scientific article published in a journal indexed ISI Web of Science (WoS) with **Q1** quartile and an ***impact factor*** (IF) equal to **2.592**; **1** scientific article published in a journal indexed ISI WoS with **Q3** quartile and an IF equal to **3.252**; **2** scientific articles published in journals indexed ISI WoS with **Q4** quartile, one with an IF equal to **0.782**, and one without an impact factor; **6** scientific papers published in international conference volumes indexed ISI WoS; **2** published in specialized journals indexed in ***international data bases*** (BDI) and **1** book as coauthor.

Personal contributions

The current thesis includes, from the author's point of view, the following significant contributions:

- development and experimental validation (on an existing PSPPECS from Aragon, Spain section ***3.5***, ***5.1*** and ***5.5***) of a PS mathematical model that can be used for both dimensioning and simulation of a pumping systems (section ***2.2***);
- development of the mathematical equations expressing: the electrical frequency ***error*** (the deviation of the current value from its reference) according to pump discharge (flow) error (***Equation 2.70***), the pumping head (pressure) error (***Equation 2.72***), respectively, the error of the power absorbed by the induction motor of the pump (***Equation 2.74***) The relations have been further used to develop the control strategy of the centrifugal pump via a VFD at the reference flow/pressure or to track the power produced by a fluctuating and intermittent power source (section ***2.3.2***);
- design and implementation of control strategies for operating a PS (based on the vector control of an induction machine, whose references for the current regulation are provided by two PI regulators in cascade, one for speed and one for flux) at: variable speed, variable flow rate, variable pressure or variable absorbed power (section ***2.3***);
- carrying out a scenario consisting of five simulations in Matlab/Simulink that served to determine the performance of the dynamic MM proposed for the PS, respectively, the performance of the control strategies developed for fixed speed, variable speed, variable flow rate, variable pressure and variable available power (section ***2.4***);
- the development of a static model, respectively, a dynamic model usable for the simulation of the permanent regime and the transitory regimes in a PECS (section ***3.2***);
- development of a control structure for the MPPT of a PECS based on the P&O algorithm that has been adapted for its further integration into a PS control strategy (section ***3.3***);
- implementing the proposed PECS model and control strategy, and validating them experimentally during four different scenarios: a day with a clear sky, a day with a single large and dense cloud covering the sky during a specific period of the day, a day with many small and fast clouds and a completely cloudy day (section ***3.4***);
- development of a nonlinear dynamic model used in the simulation of the transient regimes of a WECS, and a linearized version, used in the synthesis of the control strategy (section ***4.2***);
- analysis, synthesis and implementation of a WECS generator-torque controller capable of adapting the power production to a variable reference power by enabling the WT blade-pitch actuator and decupling the rotor when the wind reaches the cut-off speed (section ***4.3***);
- analysis and synthesis of a gain scheduling PI controller. The values of the gains scheduling (K_p and K_i) were obtained based on the linearization of the WECS nonlinear model using Tylor series approximation, and by developing the mathematical equations for calculating the gains scheduling based on the current value of the blade pitch angle (β) and the value of the blade pitch angle for which the WT rotor torque has doubled (βk) (***Equations 4.149*** and ***4.150***);
- implementing the nonlinear MM and the control strategy of a WECS and validating them by simulating four different scenarios: the operation at nominal and partial regime (the reference power being ⅓, ½ and ⅔ of the nominal power) to a wind speed covering the entire operating range (a ramp variation from 0 to 30 m/s) and to a time series of a very turbulent wind speed (section ***4.4***);
- development and validation of a PSPPECS model capable of simulating transitory regimes through all the subsystems (centrifugal pump, induction motor, motor drive and PECS) in section ***5.2***;

- development, implementation and validation of a PSPPECS control strategy capable of ensuring the control in 3 distinct cases (section ***5.3***):
  1. when the pumping head is higher than the reference, the control strategy regulates the pumping head;
  2. when the pumping head is lower than the reference and the power produced by the PECS is lower than the minimum power required for the PS operation, the control strategy decelerates the PS;
  3. when the pumping head is lower than the reference and the power produced by the PECS is higher than the minimum power required by the PS operation, the control strategy operates the PS so that the power absorbed by it tracks the power produced by the PECS.
- developing and implementing a more accurate monitoring system than the existing ones (which uses the methodology proposed by IEC 62253 [96]), by using a non-intrusive data acquisition and logging system that measures and records the values of the transducers each second (section ***5.4***);
- implementation, simulation and experimental validation of the proposed PSPPECS model and control strategy (section ***5.5***);
- development of a PSPWECS model capable of simulating transitory regimes through all the subsystems (centrifugal pump, induction motor, motor drive and WECS) in section ***6.2***;
- analysis, synthesis and implementation of a PSPWECS control strategy capable of ensuring the control in 4 distinct cases (section ***6.3***):
  1. when the power produced by a WECS is lower than the minimum power required by the PS operation, the control strategy decelerates the PS;
  2. when the power produced by a WECS is higher than the minimum power required by the PS operation, the control strategy operates the PS so that its power absorbed tracks the power produced by the WECS;
  3. when the pumping head is lower than the reference, the control strategy demands the WECS, through a reference, to produce the power required for the PS nominal operation;
  4. when the pumping head is higher than the reference, the control strategy regulates the power produced by the WECS according to the PS power demand so that the pressure it is equal to its reference.
- implementing the PSPWECS model and control strategy in Matlab/Simulink and validating them by simulating the operation of the entire system at a wind speed covering the entire operating range (a ramp variation from 0 to 30 m/s) (section ***6.4***).

Future research

The presented issues, as well as the obtained results and solutions, show the industrial applicability of the current work, opening new perspectives for future research on PS powered by RES. As research directions that can continue the results obtained in this thesis and that can be addressed in the upcoming future, are:

- development, implementation, simulation and experimental validation of a Pumping Systems Powered by a wind-photovoltaic hybrid energy conversion system;
- analysis, synthesis and implementation of advanced control strategies such as robust control, model predictive control, fuzzy logic control or neural network-based control, etc.

MAIN ABBREVIATIONS

Short form	Full form
PS	Pumping system;
PSPRES	Pumping system powered by renewable energy sources;
RES	Renewable energy sources;
PVG	Photovoltaic generator;
WEG	Wind electrical generator;
PV	Photovoltaic;
PECS	Photovoltaic energy conversion system;
PSPPECS	Pumping system powered by photovoltaic energy conversion system;
MASLOWATEN	Market uptake of an innovative irrigation Solution based on LOW WATer-Energy consumption;
WECS	Wind energy conversion system,
PSPWECS	Pumping system powered by wind energy conversion system;
WT	Wind turbine;
MM	Mathematical model;
VFD	Variable frequency drive;
PI	Proportional integral;
error	The deviation of the current value from the reference value;
MPPT	Maximum power point tracking;
P&O	Perturb and observed;
DFIG	Doubly fed induction generator;
K_p	Proportional gain;
K_i	Integral time;
$GK(\beta)$	The gains (proportional gain and integral time) scheduling function;
β	The current value of the WT blade-pitching angle;
β_k	The value of the blade-pitching angle where the WT rotor torque has doubled;
PLC	Programmable logic controller;
MPP	Maximum power point;
DC	Direct current.

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