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# Control Strategy for Isolated Small Wind Generators for Countryside Uses

Ll. Pacheco[1], N. Luo[1], I. Ferrer[1], J. Vilà,[1] J. R. Gonzalez[2]

[1] Department of Electrical Engineering, Electronics and Automation, University of Girona, Campus Montilivi, 17003 Girona (Spain)
[2] Department of Mechanical Engineering and Industrial Construction, University of Girona, Campus Montilivi, 17003 Girona (Spain)

*Corresponding author: +0034 686 750 724, e-mail: lluis.pacheco@udg.edu

**Abstract.** Rural areas are considered suitable applications for small, isolated wind generators. In this study, the energy produced is used to fill water storage tanks that can support agricultural and livestock activities. The small horizontal-axis wind turbine has a power rating of approximately 2 kW; the electrical output is primarily used to supply a water pump that fills two water tanks, although the remaining energy can be used to power an electrical system. Wind energy can be regulated through an active pitch control system that is capable of reducing wind-induced forces on the blades. In addition, the control actions aim to match the load to the energy produced. The control strategy consists of a set of states that generate different actions on the electrical system.

**Key words.** Small-wind horizontal generator, control strategy, off-grid, electrical load

## 1. Introduction

Isolated regions are typically off-grid electrical areas, and electrical generators are usually required for the population. Sustainable sources such as photovoltaic plants or wind generators can be considered. Sustainable energies are clean energy sources that have the potential to minimize environmental impacts, including waste generation, and to enhance social well-being in accordance with current and future needs [1].

The electrical design of an intelligent control system for small-scale horizontal-axis wind turbines is a technological advancement required to promote the adoption of small wind turbines for micro-scale power generation [2]. In addition, small wind generators are an available solution that does not require extensive infrastructure, and their cost is relatively low. These systems can be used as off-grid generators in rural areas where connection to the electrical grid is difficult, and even when grid connection is also possible [3]. Wind energy extraction is a technology described in various textbooks; see [4–5].

Permanent magnet synchronous machines, PMSM, are normally used for the design of small generators. The adjustment of the pitch angle and the maximum electrical load are useful control strategies to avoid generator damage from strong winds [6]. The machine is controlled at several stages depending on the rotational speed of the blades. Wind turbines must be designed with optimal Tip Speed Ratio, TSR, to get the maximum amount of power from the wind. Maximum Power Point Tracking, MPPT, is implemented by comparing the actual and optimum TSR. Model-based MPPT or Fuzzy logic controllers are proposed for small wind turbines [7]. Regarding the electric machine, AC to DC conversion and DC to DC link are meaningful parts where MPPT control algorithms can be implemented [8]-[9]. Available commercial wind turbine controllers include the MPTT control, rectifier and battery charging functions [10].

Optimal TSR can be achieved by controlling the load of the system. Load-based overspeed control acts by using stalling resistors to limit the generator's output current. It can be employed to protect the turbine from high wind speeds [11]. Stalling methods based on dynamic loads are analyzed as available control methods [12]. Thus, it is proposed that the control of the rotational speed by specifying the demanded generator torque [13]. Rated power or voltage and intensity sensors are used for soft-stalling control [14].

Small turbines are proposed for using the power of the wind for pumping the water for remotely located inhabitants not connected to national power grids. Electricity generation using small wind generators for home or farm use is promoted based on a combination of economic incentives, being in an area with a strong local wind resource and interest in generating their own electricity [15]. The study and design of water pumping mechanisms, when wind energy is used, plays an important role because different pumping power is required according to the intensity and height of the pumping system [16].

In this work, it is assumed that the material, including MPPT that is integrated within the load regulator, is provided by commercially available technology, and control is done by actively modifying the load according to the available wind and state of the system. Section 2 depicts the main parts of the small wind generator used and Section 3, the control strategy. Conclusions are outlined in Section 4.

## 2. The Small-Wind Generator

Wind energy is employed to create electricity using a turbine that consists of a three-phase synchronous generator of permanent magnets where eight pairs of poles are assumed with 1800W of output power with a nominal output tension of 400V. The output power is a function of the rotation speed, as is given by the manufacturer of wind turbines, as shown in Figure 1.

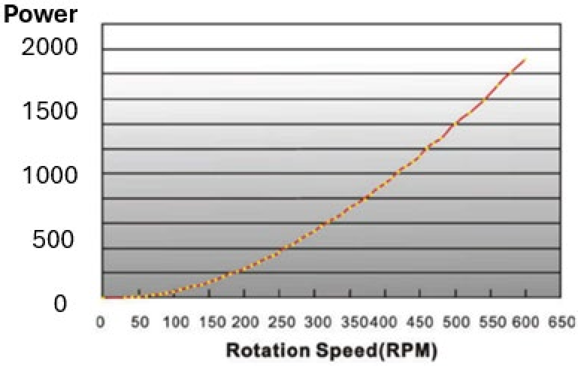


Fig. 1. Output power versus rotation speed

Figure 2 shows the stand-alone configuration, where the reliability is guaranteed by the load regulator that feeds batteries, the inverter, or uses the electric brake for controlling the speed of rotation. The load regulator utilizes a maximum power point tracking, MPPT.

When batteries are full, the regulator disconnects them as possible loads. If an excess of power is produced, then the electric brake system acts. It is pointed out that instant values of power and tension are measured, but actions must be done by root mean square, rms, values.

Battery units play an important role in stand-alone systems because the power accumulated is related to the time that can provide energy. Key considerations include economic aspects such as cost, as well as technological aspects such as load profile, durability, and the time expended for loading from minimum to maximum. Figure 3 depicts the charging voltage and current for a lithium-ion battery, with an expected life of 7 years. When no production is achieved, the power of the batteries should guarantee the system's operation. Extreme weather conditions, where wind power is not produced, must be analyzed since battery capacity should be defined.

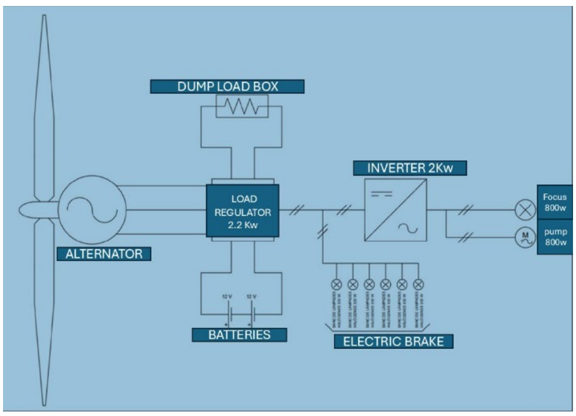


Fig. 2. The stand-alone configuration used

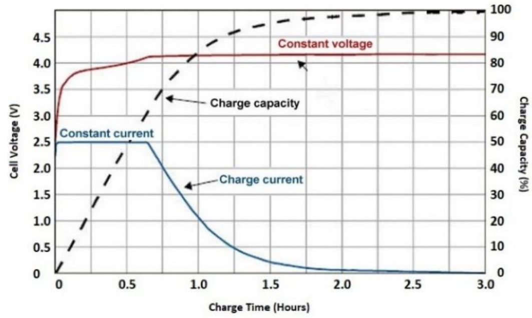


Fig. 3. Charge curve of a lithium-ion cell.

The control core of the system is a microcontroller. At normal operation, minimal consumption of the microcontroller system can be stated, but if the system can go to sleep mode, consumption is reduced to less than one hundred μA and the survival time is increased. The system can wake up from sleep mode when an interruption is produced by peripheral or communication nets. When the speed rotation of the generator exceeds nominal values, control of the pitch and electrical brake systems are available solutions that can reduce the velocity.

### A. Pitch Control

Pitch control can be achieved using a DC linear actuator, which produces a displacement of the pitch angle between different positions that generate different output power levels. When new positions are proposed, the differences can be used as references for different speeds to reach the new position, and they may be commanded using pulse-width modulated, PWM, signals.

Figure 4 describes a pitch control scheme that may be used to regulate the new position. It is noted that reversal of the direction of rotation is implemented through limit switches. A closed-loop system is employed; a linear potentiometer is proposed to measure the pitch position. Temperature measurements may be used to adjust the different resistance values corresponding to actual positions, accounting for variations induced by climatic changes.

Furthermore, the pitch position is a function of both the rotational speed of the blades, measured by an encoder, and the pitch angle of the blades. Noise immunity can be achieved through the RS-485 communication protocol and the pair of differential signals provided by the encoder. Thus, when the rotational speed exceeds the maximum value, a blade orientation closer to being parallel to the wind is sought, whereas if the rotor speed is too low, an opposite motion is commanded.

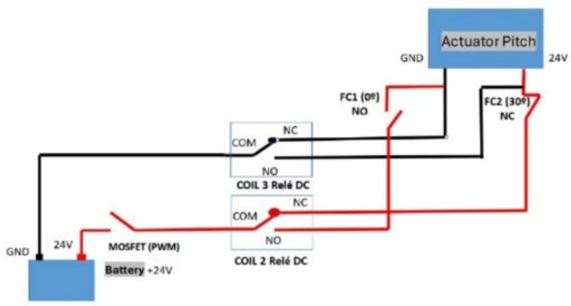


Fig. 4. Pitch control scheme

*B. The Electrical Stall System*

An auxiliary electric braking system is proposed, consisting of six different resistor modules that can be activated independently via PWM signals. A resistance value of 2 Ω and 300 W is proposed for each module. The electric brake can operate under three different scenarios:

• Emergency stop: when it is necessary to protect the system, a full resistive load of 1800 W is applied through the activation of a 100% PWM signal in each module.

• When the battery is fully charged and the generated power exceeds consumption, the surplus must be dissipated using the electric braking system.

• The third case can be used to ensure a long battery service life and may occur when the charging current exceeds the recommended charging value; in this case, part of the current can be diverted to the electric braking system.

Thus, the difference between the output power and the power demanded by the loads can be stored in the battery; however, when excess power is generated, the electric braking system may be activated; see Equation (1).

$$PElectricBrake\ (t_i) = PElectricBrake\ (t_{i-1}) + (POutput\ (t_i) - Pdemanded\ (t_i)) \quad (1)$$

The output power is the generated power, and the time instant $t_i$ refers to the current real time, while $t_{i-1}$ refers to the previous time instant. The demanded power at time $t_i$ includes the electrical braking power at $t_{i-1}$. Using (1), if the demanded power exceeds the output power, then the electrical power is reduced. The system loads are driven by an inverter that supplies a pump and an electrical system. The water pumping system can fill water tanks that may act as hydraulic energy storage units. The primary objective of the designed system is to fill the water tanks. A DC power source must be considered to supply sensors and microcontrollers.

## 3. The Power Control Strategy

The power control strategy manages the output power by taking into account the energy extracted from the wind, the battery charge level, the water reservoirs, and emergency shutdowns or faults when they occur. The analysis is conducted by considering three distinct subsections that describe the required variables, the states used and their associated actions, as well as reflective comments on the proposed strategies.

*A. Control Variables and Conditions*

The power is distributed by considering the following variables:

- The power generated, $P_g$, shows the output power generated by the wind generator.
- The power provided or absorbed by the battery is monitored by the measurement of the current, $I_{bat}$, and voltage, $V_{bat}$, of the battery.
- The water pump is activated when the water tanks are not full, so a water level measure, $W_l$, is necessary.

The wind generator must produce a minimum power output to overcome the losses of the charge controller; consequently, if this condition is met, energy generation can be achieved. Once the system operates as a generator, two scenarios are possible:

• When the battery is charged, it may assist in supplying the loads.

• When the battery is discharged, it is charged by the generator; a current limiting function may be implemented to extend the battery's service life.

Regarding the loads, water pumping is a priority; consequently, the measurement of the water level is mandatory. For this reason, two sensors are used. When the low-level sensor detects that the water is below its position, $W_l$ is set to one, and water pumping may be activated. When the high-level sensor is triggered, $W_l$ is set to zero, and water pumping cannot be activated. In addition, the farm supplies supplementary electrical loads that differ from the water pumping load; however, this possibility is subject to multiple conditions:

• The energy generated is greater than the water pump plus the auxiliary electrical loads.

• If the energy generated is only slightly greater than the auxiliary electrical loads, then this load can be supplied only if the water tank level is full and the batteries are at a certain state of charge.

• The energy generated is lower than the auxiliary electrical loads, but the water tanks are full, and the batteries are at a certain state of charge.

Finally, Table I summarizes the names of the variables and their meanings.

Table I: Names of variables and meaning

| Name of Variable | Meaning |
|---|---|
| $P_g$ | Power generated |
| $P_{gmin}$ | Minimal Power generated |
| $W_l$ | Water level of the tanks |
| $V_{bat}$ | Tension of the battery |
| $V_{batMAX}$ | Maximum tension of the battery |
| $P_{bat}$ | Power consumed by the battery |
| $P_{lights}$ | Power consumed by complementary electrical loads |
| $I_{bat}$ | Current of the battery |
| $V_{batlights}$ | Voltage battery threshold for connecting the lights |
| $V_{batmin}$ | Voltage level for battery discharged |
| $P_{batthres}$ | Power generated threshold for connecting the lights |
| $P_{batDel}$ | Power provided by the battery |

*B. States and Actions*

The control strategy of a small autonomous horizontal-axis wind generator is defined by 16 distinct states, which arise from different input values; Table II presents all the states defined within the control strategy, as well as the values of the relevant inputs and outputs.

Table II: States and related Actions

| state | Water Pumping | Electricity lights | Pulse width Modulated Electric Stall System | Batteries | Generator |
|---|---|---|---|---|---|
| Start | OFF | OFF | OFF | Discharged | OFF |
| State 1 | OFF | OFF | OFF | Discharged | $P_g > P_{gmin}$ |
| State 2 | ON | ON | Is possible | Discharged | $P_g > P_{bat} + P_{lights}$ |
| State 3 | OFF | ON | ON | Discharged | $P_g > P_{bat} + P_{lights}$ |
| State 4 | ON | OFF | Is possible | Discharged | $P_g > P_{bat}$ |
| State 5 | OFF | OFF | Is possible | Discharged | $P_g > P_{bat}$ |
| State 6 | OFF | ON | Is possible | Discharged $V_{bat} > V_{batlights}$ | $P_g > P_{lights}$ |
| State 7 | ON | ON | Is possible | Fully charged | $P_g > P_{bat} + P_{lights}$ |
| State 8 | ON | OFF | Is possible | Fully charged | $P_g > P_{bat}$ |
| State 9 | OFF | ON | ON | Fully charged | $P_g > P_{bat} + P_{lights}$ |
| State 10 | OFF | OFF | ON | charged | $P_g > P_{gmin}$ |
| State 11 | ON | ON | OFF | Fully charged and deliver energy | $P_g > P_{bat}$ |
| State 12 | ON | OFF | OFF | Fully charged and may deliver energy | $P_g + P_{batDel} > P_{bat}$ |
| State 13 | OFF | ON | Is possible | Fully charged and may deliver energy | $P_g > P_{gmin}$ |
| State 14 | OFF | OFF | OFF | Fully charged | OFF |
| State 15 | ON | OFF | OFF | Fully charged | OFF |

The following paragraphs explain the meaning of each state; it is noted that, since all variables are read periodically, transitions between states can be performed automatically.

State Start: the battery is discharged and the system waits for electricity generation.

State 1: This occurs when the generated output power is sufficient to produce a minimum amount of energy that exceeds the losses of the charge regulator. The remaining energy is stored in the battery system.

State 2: Considering the water tank level and the energy produced, the system may connect the water pumping and electrical systems. If the generated power exceeds the demand of both water pumping and electrical lighting, the electric brake may be activated to protect against a possible overload of battery charge that can damage the system. If the power output is too big, a stop can occur.

State 3: The generated energy is sufficient to supply both the electrical load and the water pumping system; however, the water tanks are full. An electrical blocking system is required to prevent excessively high battery current levels. If the output is too high and the electric braking system operates at its maximum capacity, production should be halted.

State 4: The generated energy is sufficient to supply the water pumping system, but insufficient to simultaneously supply the remaining electrical loads. In this case, the remaining production is used to charge the battery system. If faults occur, the electric braking system may be activated.

State 5: The generated energy is sufficient to supply the pumping system while the water tanks are full, or alternatively, it is insufficient to activate the water pumping system. In this case, the output power is directed to battery charging; however, when current limits are exceeded, an electrical blocking system is triggered. If the battery state allows activation of the electrical system, the system transitions to State 6; otherwise, it remains in State 5.

State 6: The generated energy is sufficient to supply the pumping system, but the water tanks are full, and the electrical system is connected. If surplus energy is available, battery charging is performed. Electrical blocking only occurs under abnormal operating conditions.

State 7: The battery is fully charged, and the generated energy can supply both the water pumping system and the electrical system. If there is an energy surplus, it is then diverted to the electrical braking system to protect the battery. If the generated energy exceeds the maximum generator value, or if the electric brake is at its maximum setting, production is stopped to prevent damage.

State 8: The battery is fully charged, and the generated energy can supply the water pumping system but not the electrical system. The generated energy is measured; if it is close to the energy required by the electrical system, the system transitions to State 11. Otherwise, it remains in State 8.

State 9: The battery is fully charged, and the generated energy cannot supply the water pumping system because the water tanks are full, but the electrical system can be connected. If there is a surplus, the electrical energy is used by the braking system.

State 10: The battery is fully charged, and the generated energy is low and cannot supply the electrical system. Furthermore, the water pumping system cannot be supplied because the water tanks are full; consequently, the electrical energy is diverted to the braking system.

State 11: The battery is fully charged, and the generated energy can supply the water pumping system. After measuring the remaining energy generated, it is found to be close to the energy required for electricity. Consequently, the battery is used to help supply the electrical system.

State 12: The battery is fully charged, and the generated energy is insufficient to supply the water pumping system. After measuring the generated energy, it is found to be close to the pumping energy requirements. Consequently, the battery is used to help supply the water pumping system.

State 13: The battery is fully charged, and the tank levels are full; moreover, the generated energy exceeds a threshold used to define that production is close to the electrical system's requirements. Therefore, the batteries complement the energy needed to meet electrical demand.

State 14: The battery is fully charged, there is no generation, and water pumping is not possible because the water tanks are full.

State 15: The battery is fully charged, there is no generation, and the water tanks are not full; therefore, water pumping is carried out.

*C. Emergency and Error Actions*

Emergency actions enable a safe system operation, as a rapid shutdown can be performed. These may occur when wind speed exceeds a threshold, when mechanical stress limits in the structure are reached, or when excessive vibrations are detected.

Pitch control is activated when the measured rotor speed exceeds a maximum or minimum value, which is a function of the pitch position. It adjusts the blade angle to regulate speed, achieving maximum output power within safety constraints. When maximum rotational speed is reached, the pitch control sets the blades parallel to the wind direction. Conversely, when rotational speed is low and the pitch position is not at its reference setting, the pitch angle is reduced in order to increase speed.

If speed limits are exceeded, both pitch control actions and electrical stall control are commanded. The system then waits for a configurable period of a few seconds; if the speed does not decrease, a safety shutdown is triggered by short-circuiting the three-phase generator output. This action requires system inspection, as a communication failure may have occurred and the short-circuit relays may be damaged.

Power generation and emergency shutdown are strongly dependent on sensor readings and the communication network. This relationship must be taken into account by verifying the consistency of sensor values and acting accordingly.

## 4. Conclusions

The implemented control strategy shows a preference for supplying electricity to the water pump; however, tank levels must be taken into account. In this work, the stored water is intended for crop irrigation and livestock feeding. The stored water reaches a volume of 70 $m^3$. Water storage in tanks is considered an efficient form of energy storage; therefore, tank capacity could be increased, and the use of hydraulic turbines and potential energy could be analyzed as a suitable solution in future studies, with the aim of reducing battery size and lowering total cost. Thus, for example, an 18 V, 2 A, 36 W/50 W micro-hydroelectric generator may be a viable option that can reduce battery capacity requirements [17]. It is noted that the proposed batteries have a voltage of 12 V and a capacity of 120 Ah.

The current control of the battery charging system is an important aspect of this work. In this regard, the charging current is adapted to the technology of the batteries used. Lithium-ion cells are employed in this study. Considering the shape of the charging curve is crucial because it affects battery lifespan, see Fig. 3. In this way, the system can be adapted to an electrical cut-off system according to the current required by the battery, in order to protect it from overcurrents and extend its service life. Extending battery life reduces maintenance costs. Moreover, batteries can be considered a costly component of the required electrical system.

In this work, the generated electricity is utilized to power lighting, while the surplus energy is used to brake the generator via different electrical loads, depending on the values of the PWM signals. These losses must be analyzed and minimized; alternative electrical loads with more useful functionalities than lighting may be implemented depending on the specific context.

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