Electronically Controlled Actuators for a Micro Wind Turbine Furling Mechanism †

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Abstract: This paper presents two electromechanical systems used for the overspeed protection of small wind turbines. The actuators have the purpose of rotating the back rudder (tail vane) of the wind turbine when the blades are overspeeding. The rudder rotation angle is 90 degrees in order to completely turn the wind turbine blades away from the wind flow direction. The first device is a new limited-angle torque electromechanical actuator consisting of a device with a simplified structure composed of four permanent magnets (two on each side) glued on a rotor mounted between two stator poles built from ordinary rectangular construction pipes and an electronic control unit. The second device is based on a regular stepper motor actuator with a reduction gear and an appropriate control scheme to maximize the energy harvested at high, over-nominal wind speeds. A generic comparison is provided for the proposed solutions.

Keywords: furling; limited-angle torque actuator; stepper motor; micro wind turbine; finite element analysis

1. Introduction

Small wind turbines are struggling to occupy a share of the renewable energy market for residential areas. This is due to the continuous reduction in photovoltaics prices and relatively low average wind speed in most urban areas. Thus, the installation of small and micro wind turbines is limited to locations where the average wind speed is above 5–7 m/s. In order to change this situation, new topologies of urban wind turbines should be developed with the following characteristics: low cost per kWh produced, large surface to convert even low wind speeds into useful energy, low noise operation, and harmless to birds and bats. Usually, wind-direction-orientable turbines have higher efficiencies compared with turbines working in winds from any direction [1] (Figure 1). Furthermore, with a back rudder, the wind turbines can be turned out of the wind. Thus, developing effective braking mechanisms allows for the safe operation of small wind turbines. In order to avoid possible damage to the wind turbine, or even to nearby peoples or animals, a cheap and safe system that allows for the reduction of the rotor speed is required. The most common solutions can be grouped into three main categories: mechanical, aerodynamic, and electric brakes.
Widely used in wind turbines, mechanical brakes suffer from frequent wear, which requires a high maintenance cost or even component replacements. Disk brakes are generally used to stop the wind turbine rotor via friction. Despite this, mechanical braking systems are required in large wind turbines during maintenance or as back-up braking in the case of extreme conditions.

Another solution is controlling the pitch angle of the blades at high wind speeds and thus increasing the angle of attack so the lift force is reduced, a method known as aerodynamic braking. Even though this system provides more control options for the system, it adds weight to the nacelle. Aerodynamic brakes imply high costs but can be used a very high number of times, making them a good solution for high-power systems.

A comparison between soft-stall control and furling control is presented in Muljiadi et al. [2]. In terms of energy production during high winds, soft-stall control is more advantageous.

The rotational speed of the wind turbine can be reduced by controlling the level of interaction between the magnetic fields in the stator and rotor of the generator, which are usually produced by windings and permanent magnets, respectively. The amount of braking force can be adjusted by inserting a variable resistor in the stator electric circuit and is proportional to the electric current passing the windings. More advanced control strategies can be used to adjust the generator load using brake resistors (or thermistors) and power electronics components. A redundant electrical braking system for wind turbine generators was proposed by Wang et al. [3], which consists of a hybrid system that uses a dynamic brake resistor connected on the system’s Direct-Current (DC) link and a dump load resistor connected to the generator terminals, which provides several advantages compared to conventional braking methods, such as higher reliability, modularity, and a higher degree of control. Matsui [4] and Sugawara [5] introduced a cheaper braking method that uses a “Y” connection circuit with negative temperature coefficient (NTC) thermistors that are directly connected to the generator terminals. While in conventional electric braking systems, the generator stator windings are short-circuited to abruptly increase the current, this solution allows for a smoother reduction of the rotating speed of the wind turbine. Gong et al. [6] proposed another safe and cheap method for controlling the braking of a micro wind turbine by using a Pulsed-Width Modulation (PWM)-controlled braking circuit with field-effect transistors (FETs). These solutions are simple and effective but have a drawback: due to high currents in the generator windings, the inside temperature increases and the stator magnetic field...
is strong. This can lead to partial demagnetization of the permanent magnets if the “knee point” of the demagnetization characteristic is attained. This happens especially if the permanent magnets are mounted on the surface of the rotor.

Several solutions for rotary actuators were proposed with different shapes and operating principles and using gear systems to transmit the rotational motion, such as the one developed by Cuches [7]. Different rotor designs were proposed in Cuches et al. [8] that use mechanical springs to provide torque at a certain desired position in the absence of electrical current through the motor. Different types of electromechanical actuators are presented in Oudet and Prudham [9], showing a torque variation that is approximately independent of the rotor’s angular position. An actuator with two stable stationary positions when no current is fed to the windings is introduced in Biwersi and Gandel [10]; the major disadvantage of this solution, which employs only one winding, is that a supply voltage with both polarities is required to move the rotor from one stable position to the other. A unipolar power source can be used if two or more windings are considered and two differential control signals are required to determine the motion of the rotor between the two no-current stable positions.

Regarding the yaw displacement or furling, a solution is detailed in Mohammadi et al. [11], where complex angular movement control is proposed in order to protect the wind turbine and maximize the energy harvested at high winds exceeding the nominal values. In References [12,13], a limited-angle torque (LAT) actuator with a similar construction to the one shown in Figure 1 was presented.

The paper is structured as follows: Section 2 presents the design of the LAT electromechanical actuator and the electronic circuit used to control the LAT actuator, Section 3 provides details regarding the stepper motor actuator and the electronic circuit for angular control, and in Section 4, a discussion regarding the solutions is presented.

2. Limited-Angle Torque Electromechanical Actuator

2.1. Design of the LAT Electromechanical Actuator

The LAT electromechanical actuator was designed to ease the manufacturing process so it can be made by small workshops, reducing the production cost. The developed prototype, presented in Figure 1, was used for a 2.5 kW, 500 rpm wind turbine. The main purpose of this device is to angle the wind turbine blades from facing a direct wind flow if the electric generator is surpassing a certain speed and reaches a threshold voltage, or if a loss of electrical load emerges. This device has a simple and robust design that allows for the furling of the wind turbine. It consists of a rotor having four radially magnetized permanent magnets, mounted on a shaft by gluing. Two copper windings are placed around two stator poles and are made from ordinary rectangular steel profiles. The stator poles are fixed to the tail mounting support (Figure 2), which is also made of steel, allowing for closing the magnetic circuit. A non-magnetic material plate (a 3D printed element was used for the prototype) fixed to the ends of the rectangular steel profiles supports the bearing, together forming a rigid assembly. The rotor movement is limited by a pin mounted through the shaft.

The supply voltage required for the electronic circuit, which powers the winding of the electromechanical actuator, is directly extracted from the generator three-phase rectifier assembly. If the wind generator speed exceeds the limit (voltage threshold is reached), the moving part will rotate from one stationary position to the other, thus furling the wind turbine.

As shown in Figure 2, the LAT actuator is mounted on a wind turbine tail using a dedicated mounting support. During normal operation, when the wind speed value is below the threshold, the nacelle and the tail are aligned with the direction of the wind. For higher wind speed values, once the generated voltage exceeds a certain limit, the LAT is activated, causing the tail to rotate and to form a $90^\circ$ angle with the rest of the wind turbine. In this case, the nacelle is no longer aligned with the wind direction and the blades are not driven efficiently by the wind, causing a decrease in the rotating speed of the generator.
To investigate the performances of the limited-angle torque electromechanical actuator, design analysis was conducted by means of a 3D finite element method (FEM) model (Figure 3) using the commercial software JMAG-Designer, version 19, JSOL Corporation, Tokyo, Japan. Previous studies [13,14] have shown that 3D FEM analysis provides more precise results compared to the simplified 2D FEM analysis, especially for complex structures, such as the proposed LAT.

Figure 2. LAT actuator placement in the wind turbine assembly.

Figure 3. LAT 3D model and mesh in JMAG Designer.
Figure 4 is used to present the operating mode for the limited 90° rotation of the electromechanical actuator: in the initial position of the actuator rotor, presented in Figure 4a, the magnetization axis of the four permanent magnets forms a 45° angle to the magnetization axis of the stator poles.

![Figure 4. Upper view of the electromechanical LAT actuator (a) initial and (b) final rotor positions.](image)

In this position, when no current is fed to the windings, a negative cogging torque is obtained, as shown in Figure 5, which tries to align the magnetization axis of the rotor and the stator. The cogging torque component has a value of approximately −3 Nm, at initial position, which is enough to keep the tail vane aligned with the nacelle and the wind direction.

![Figure 5. Electromagnetic and cogging torque obtained from the 3D analysis.](image)

In the case where the voltage threshold is exceeded, the windings are fed with a DC voltage and the LAT actuator develops a positive electromagnetic torque. Thus, the rotor moves from the initial (Figure 4a) position to the final position shown in Figure 4b, rotating from 0° to 90°; this position is maintained even if the winding is not fed due to positive electromagnetic and cogging torque.

To return to the initial position (Figure 4a), corresponding with normal wind turbine operation, the windings are fed with a reverse polarity voltage from the continuous supply voltage, and the actuator rotor returns from the final position (Figure 4b), backward throughout the rotation range (from 90° to 0°).

The electrical circuit consists of two series-connected coils that are fed from a continuous voltage source; the main properties are included in Table 1. Each coil has 450 turns and a coil resistance of 2.8 Ω. While the coils are fed, during the furling process initiated by the movement of the rotor, a 13.34 A...
current (Root Mean Square (RMS) value) was obtained in the 3D FEM analysis. High values of Joule losses were recorded in the stator coils of about 1000 W. However, there is no major concern about coil insulation damage due to the short time of operation (under 1 second).

Table 1. Electrical circuit properties.

| Parameter            | Value   |
|----------------------|---------|
| Supply voltage       | 200 V   |
| Number of turns/coil | 450     |
| Coil resistance/coil | 2.8 Ω   |
| Rated current RMS    | 13.34 A |
| Coil connection type | Series  |

Figure 6 presents the magnetic flux density distribution obtained by means of 3D FEM analysis, showing that there were small saturated regions in the stator poles with values over 2.2 T. Only one of the two coils is shown to allow for the visualization of the magnetic flux density under the coils.

Figure 6. 3D magnetic flux density distribution in the LAT.

The electronic control device presented in the following section only consumes electrical power while the LAT is in the second stationary position and when the device returns from this position to the initial position. Due to the negative torque given by the cogging component, the system is stable when no current is fed to the stator coils.

2.2. Electronic Circuit for LAT Electromechanical Actuator Control

Based on the principle of an ON-OFF command, with the help of the electromechanical actuator developed and presented in the previous section, Figure 7 presents the practical implementation of a bipolar converter under different working stages and LED signalizations. Figure 8 shows the electronic schematics of the proposed solution that is based on the “comparator stage,” “detection stage,” “fixed-pulse stage,” “shoot-through protection stage,” “power inverter stage,” and the LAT electromechanical actuator. The initial and final positions are considered to be 0° and 90°, respectively, for the control strategy explained below.
The comparator stage is based on the monitoring of the input voltage and evaluation with two predefined values:

- 190 V—minimum detection voltage ($V_{\text{min}}$)
- 210 V—maximum detection voltage ($V_{\text{max}}$).

By using two comparators, the system limits the LAT oscillation at high speeds because between these voltage levels, the actuator is not performing any actions. These detection levels can be changed in order to cope with specific applications and dynamics.

The “detection stage” and the “fixed-pulse stage” are used to determine the right activation time for the command signals and the duration of the pulse. For protection purposes, the “shoot-through protection stage” is implemented to avoid triggering the power stage transistors (T1–T4 or T2–T3) at the

**Figure 7.** Bipolar converter images under different detection stages: (a) minimum voltage level reached and the 0° movement is performed, and (b) the maximum voltage level reached and the 90° movement is performed.

**Figure 8.** Current flow schematic for the proposed angular bipolar control.
same time when very fast input voltage changes are detected. The power inverter stage is developed on a regular H-bridge inverter that performs bipolar voltage across the electromechanical actuator coil.

For the initial testing presented in Figure 9, the “detection stage,” the “fixed-pulse stage,” and the feedback comparator resistances $R_f$ were not used. Thus, in Figure 9a, the input voltage reached the maximum voltage detection level $V_{\text{max}}$ and a command pulse was obtained that triggered the T1 and T2 transistors, applying a positive rectangular voltage across the actuator inductor, as can be seen in Figure 9b. Similarly, in Figure 9c,d, the minimum voltage detection level $V_{\text{min}}$ caused a command signal to be applied to the T3 and T4 transistors and a negative rectangular voltage to be applied across the actuator inductor. In Figure 9e, a detection sequence of the minimum and maximum voltages was being considered, obtaining the command signals, while in Figure 9f, the bipolar voltage across the inductor can be observed. It is important to specify that all the results presented in Figure 9 were individually obtained for different practical experiments with diverse time actions of the input voltage, thus the widths of the command pulse and actuator voltages do not necessarily match between the presented oscilloscope pictures.

![Figure 9. Working principle waveforms of the bipolar current angular command: (a) overvoltage transistor command signal, (b) overvoltage coil voltage, (c) undervoltage transistor command signal, (d) undervoltage coil voltage, (e) overvoltage and undervoltage transistor commands, and (f) overvoltage and undervoltage bipolar coil voltage.](image)

Under slow variations of the input voltage, the comparator stage was performing incorrectly, as can be seen in Figure 10a, where multiple undesired switchings were noticed. One solution was to
perform local feedback using the high resistance $R_{hi}$ from Figure 8. The resistance $R_{hi}$ implementation results can be observed in Figure 10b.

![Figure 10](image_url)

**Figure 10.** Working principle waveforms of the bipolar current angular transistor command under slow slope changes of the input voltage: (a) no stabilization method (no $R_{hi}$ resistance) and (b) with a feedback stabilization method (with $R_{hi}$ resistance).

As one can notice from Figure 9, the transistors’ command signal durations were always correlated with the duration of the overvoltage or undervoltage, which is a negative aspect because the coil can be thermally damaged if the current is applied for a long period. To cope with this problem, the duration of the command pulse needed to be limited, thus the usage of the “detection stage” and the “fixed-pulse stage” from Figure 8 can be one way of increasing the performance of the system. As can be seen in Figure 10, the “detection stage” was used to perform a pulse at the output that determined the crossing detection of the minimum and maximum values. The “fixed-pulse stage” defines the duration of this pulse so that the coil will be powered long enough to perform the coil switching from 0° to 90° and from 90° to 0° without thermally overloading the inductor windings. The results obtained by using all the improvements can be observed in Figure 11, where fixed pulses were applied for every detection. Figure 11a,b show that the time the transistor command voltages were applied was not triggered by the duration of the overvoltage/undervoltage values of the input voltage. Moreover, the command voltage of the T1–T2 transistor was intentionally set to be slightly bigger than the T3–T4 command to show that this time can be controlled via the “fixed-pulse stage.”
3. Geared Stepper Motor Actuator and the Electronic Circuit for Angular Control

Based on the principle of angular control, with the help of a stepper motor, Figure 12 shows two electronic circuits that were developed for the proper management of the detection cases and one maximum 90° angular element driven by the motor. The circuit from Figure 12a was based on a comparator stage that monitored the input voltage and associated the value with four predefined levels, as can be seen in Figure 13 in the “comparator stage.” Based on the proper selection of the comparator resistances, the predefined voltage levels were:

- 190 V—minimum detection voltage ($V_{\text{min}}$)
- 200 V—nominal voltage for the detection stage ($V_{\text{nom}}$)
- 210 V—first maximum voltage level ($V_{\text{max,1}}$)
- 215 V—second maximum voltage level (for supplementary protection) ($V_{\text{max,2}}$).

![Figure 11](image1.png)

**Figure 11.** Working principle waveforms of the bipolar current angular command with a limited activation time: (a) overvoltage transistor command signal, (b) undervoltage transistor command signal, (c) overvoltage and undervoltage transistor commands, and (d) overvoltage and undervoltage bipolar coil voltage.

![Figure 12](image2.png)

**Figure 12.** Developed elements for the stepper motor angular application: (a) input voltage level detection stage, (b) digital control and power stage, and (c) 90° stepper motor driven movement element.
Figure 13. Current flow schematic for the proposed angular motor control.

The electronic circuit from Figure 12b was developed by using the “opto-insulation stage,” “digital controller stage,” and the “stepper power stage” presented in Figure 13. Using the opto-isolated signals from the comparators, the digital controller stage performed certain analyses in order to develop the right command signals for the stepper motor driver. The motor driver was controlled with three signals in direct correlation with the overvoltage/undervoltage detection stages delimited in Figure 14e:

- **Enable**: A signal that activates both H-bridge circuits when the input state is low, and when it is high, the H-bridges are locked; the enable signal is in a high state until the overvoltage detection stage starts, meaning that the $V_{\text{max,1}}$ value of the input voltage is reached. During the overvoltage detection stage, the output signal is low until the $V_{\text{nom}}$ level is reached. Similarly, the high state is present until the undervoltage detection stage starts, meaning that the $V_{\text{min}}$ value of the input voltage is reached. During the undervoltage detection stage, the output signal is low until the $V_{\text{nom}}$ level is reached again.

- **Drive**: A signal by which the rotation direction of the stepper motor can be changed. If the state is high, then the motor rotates clockwise. This is obtained during the overvoltage detection stage and when the $V_{\text{max,1}}$ voltage level is reached. If the $V_{\text{max,2}}$ voltage is also reached, it means that the stepper needs to perform all the rotational steps to obtain a 90° angle as quickly as possible. If the drive signal is in the low state, the motor rotates anticlockwise. This is obtained during the undervoltage detection stage and when the $V_{\text{min}}$ level is reached.

- **Step**: A signal that represents the command pulse or the increment motor step. The slope of the incremental steps is set to a low value so that it responds adequately in relation to the usual voltage behavior. For protection purposes, if the value $V_{\text{max,2}}$ is reached, the slope time is increased so that the 90° angle is reached as soon as possible.
The predefined voltage levels can be used to define the inherent capability of the actuator. The contacts are also used for the software recalibration of the position element after a possible restart of the microcontroller. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation. Thus, the tail angle limitation.

In the following, the experimental results are presented, where Figure 14 shows the oscilloscope waveforms for different working stages of the actuator system. In Figure 14a, the clockwise movement was performed for a time (overvoltage detection stage) after the $V_{\text{max.1}}$ voltage was reached, and the wind system was protected against overvoltage. Figure 14b shows the motor phase voltage sequence for this working stage. In Figure 14c,d, the same information is presented, but in this case, for the anticlockwise movement (undervoltage detection stage), the wind system voltage was working at an output voltage smaller than the $V_{\text{nom}}$ value. Figure 14e combines both clockwise and anticlockwise movements, while Figure 14f shows the test bench setup.

Outside the overvoltage/undervoltage detection stages, no angular movement was completed and the digital controller was not performing any movement command until one of the two limits ($V_{\text{min}}$ and $V_{\text{max.1}}$) was reached. This case can be observed in Figure 14e.
4. Discussion

As can be seen in the presented results, in the case of the bipolar controlled actuator, the proposed solution displayed good dynamic performance with simple electronic schematics. For the input voltage between the minimum and maximum detection levels ($V_{\text{min}}$ and $V_{\text{max}}$), the bipolar electromechanical actuator did not perform any movements; thus, to some extent, it improved the energy harvested at high wind speeds. Further improvements could be achieved in terms of simplifying the schematics of the practical layout by employing specialized integrated circuits that follow the logic schematics presented in the paper. One such example could be the use of the integrated circuit LTC6993 [15] to replace the “detection stage” and the “fixed-pulse stage.” This type of actuator has two major advantages: lower cost and higher reliability. The drawback is represented by the limited wind turbine power regulation capability, which is only achievable by repeating the movement of the rotor between initial and final positions.

Regarding the stepper motor solution, the electronic system performed well and had a unique inherent capability, where under slow changes of input voltage, it acted as an active maximum power limitation. Thus, the tail angle can be changed continuously so that it keeps the wind power around the nominal one. The predefined voltage levels can be rearranged, and the incremental steps characteristics can be also changed to the developer’s needs. Future work can be focused on decreasing the number of detection levels by eliminating the $V_{\text{max}2}$ voltage level. In this case, further control steps are needed to measure and analyze the input voltage slope changes in order to impose the right motor incremental step. This can lead to a more complex control algorithm but with benefits in terms of further increasing the energy harvested at the nominal rotation speed of the wind turbine. This stepper-motor-based actuator has higher implementation costs, and due to its complexity, is more prone to failures, but can allow the wind turbine to work at the rated power, even in high winds.

Table 2 gives a relative comparison of the solution detailed in this paper.

Table 2. Comparison of the proposed solutions.

| Overspeed Protection System | ON-OFF Bipolar Actuator | Geared Stepper Motor-Based Actuator |
|-----------------------------|------------------------|-----------------------------------|
| Cost                        | low                    | low                               |
| Actuator complexity         | low                    | medium                            |
| Electronic control complexity| low                    | medium                            |
| Energy harvested at high speed | medium              | high                              |
| Power consumption when active | high                  | low                               |
| Reliability                 | high                   | medium                            |
| Weight                      | high                   | low                               |
| Volume                      | high                   | low                               |

To conclude, the two solutions presented in this paper each have advantages and drawbacks but help solve an important issue regarding the protection of small wind turbines in high wind conditions or the loss of electrical load.

5. Patents

Breban, S.; Teodosescu, P.D.; Neag, A. V.; Chirca, M. Electromechanical actuator with electronic control device 2018, RO131166B1.

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