Experimental characterization of a protection scheme for a small wind turbine based on fuzzy logic

Salomón Castro, Jorge Elizondo, Jaime Martínez, Oswaldo Monroy, Osvaldo Micheloud, Oliver Probst

Physics Department, Tecnológico de Monterrey, Eugenio Garza Sada 2501 Sur, Monterrey, N.L., CP64849, Mexico. Diseño Eólico y Solar, Monterrey, N.L., Mexico. Electrical and Computer Engineering Department, Tecnológico de Monterrey, Eugenio Garza Sada 2501 Sur, Monterrey, N.L., CP64849, Mexico.

Abstract — A protection scheme for a load-induced stall-regulated small wind turbine prototype rated at 2.7 kW was developed and characterized experimentally on a specially designed test bench. The control strategy was designed based on reliability considerations and a set of maps of turbine states obtained from a detailed electromechanical model of the turbine. A scheme based on fuzzy logic was devised to maintain the system close to a target rotor speed - armature current curve. Compliance with this target curve ensures the avoidance of critical system conditions such as overheating of the stator windings or turbine run-away. The control strategy was studied on the test bench for artificial conditions such as step changes in wind speed and for realistic rotor shaft speed time series, produced from a stochastic wind speed generator and an aerodynamic model of the wind turbine rotor. The proposed scheme is shown to be able to maintain the system in the safe operating zone for wind speed values of up to 20m/s and turbulent conditions with gusts.

Index Terms — Small wind turbine, protection, fuzzy logic, wind speed emulation.

I. INTRODUCTION

Small wind turbines (SWTs) [1] [2] [3] are an important technological option for distributed generation and rural electrification, among others. While similar in their general configuration to their utility-scale counterparts, SWTs pose a number of specific challenges, including operation under more turbulent [4] and gusty [5] conditions, exposure to nearby obstacles, and faster system dynamics and hence more transient operation. Most importantly, however, SWTs do no operate under constant instrumented supervision as do MW-turbines, which are generally connected to a Supervisory Control and Data Acquisition (SCADA) system [6], providing a wealth of status data to the operating team. Even though state-of-the-art internet technologies may eventually pave the way to relatively low-cost solutions for a certain degree of on-line performance and status monitoring, small wind turbines can be expected to work on a largely unsupervised basis for the foreseeable future. Based on these considerations, it is clear that system reliability is a major concern for the design of the control and protection system. A considerable amount of research on SWT control has been published in recent years. A review on SWT control based on permanent-magnet synchronous generators was given by Orlando et al. [7]. They reviewed the most common topologies and provided some simulation results for each case. The assessment was divided in generator-side and grid-side (for interconnected systems) control issues, separated by a braking chopper. Generator-side issues identified included sensor less operation of the generator and power limitation; grid-side issues include reactive power control. The need for studying the interaction of the braking chopper and aerodynamic control mechanisms such as passive blade pitching was identified. Bystryk and Sullivan studied the control of a rooftop-mounted SWT in intermittent gusts [5] by simulating its behavior based on on-site measured wind data. They contrasted “standard” maximum power tracking (MPP) control based on a parabolic torque-frequency relation, fixed voltage and adaptive control, with standard control providing the best results in terms of energy capture. Brando et al. [8] presented a novel methodology for extending maximum power tracking to higher wind speeds. Their conclusions are based on simulations, though the need for test-bench and field testing was identified. Kortabarria et al. [9] presented an adaptive algorithm for maximum power tracking based on a perturb-and-observe approach capable of accurately tracking the MPP under varying conditions of the environment and the physical surroundings of the turbine site. Their conclusions were based both on simulations and rig testing. As it becomes apparent from this brief review, the bulk of the research on SWT control focuses on methods and strategies for maximizing power output below rated power, and little published work addresses matters related with control for reliability. In the present work a contribution to this subject is presented by describing the results obtained with the emulation of a protection strategy for a prototype SWT rated at 2.7 kW. This prototype was developed as part of the design process of a 10-kW pre-commercial small wind turbine. The strategy is based on load-induced (soft) stall achieved by pulse-width modulation and fuzzy logic control.
An experimental setup based on a variable-frequency AC motor coupled to the generator prototype and equipped with a strain gauge-based torque meter was used to test and tune a protection scheme for the 2.7kW wind turbine prototype under a variety of emulated aerodynamic driving conditions. The purpose of this system is to protect the wind turbine from run-away and stator overheating; the system is an essential part of a more comprehensive control strategy fully described in a follow-up publication. In section II the experimental arrangement including the test bench, the instrumentation and data acquisition, as well the control hardware are described. Section III provides some insights into the protection design strategy based on a state map of the wind turbine in the rotor speed – wind speed plane. The control implementation, mainly based on fuzzy logic, is described in section IV. Section V provides the results and their detailed discussion. Section VI summarizes and provides a few concise conclusions.

II. SYSTEM DESCRIPTION AND EXPERIMENTAL SETUP

A. Overall setup

The system studied in the present work consists of (1) a permanent-magnet synchronous generator designed and built to work with a 4m-diam. three-blade rotor, (2) a Sumitomo SM-CYCLO electric motor rated at 230V/34.1A for 60Hz operation with a nominal shaft frequency of 1750 rpm, equipped with a Yaskawa F7U2011 variable-frequency drive (VFD) rated at 17 kVA, and a 6:1 planetary gearbox, (3) a home-designed and -built torque meter based on strain gauges, (4) a measurement system based on Ohio Semitronics power (model P-144X5), voltage (model VTU-010X5), and current (model CTA-201HX5) transducers, (5) a control and data acquisition system programmed in Lab view and using National Instruments DAQ NI USB-6009 data acquisition boards, (6) a home-designed and -built load controller based on load commutation controlled by pulse-width modulation. The torque meter was calibrated against a mechanical setup using a lever and a calibrated digital balance. Ohio Semitronics transducers were factory-calibrated and their calibration was verified using a calibrated Fluke 123 digital oscilloscope. Rotor shaft speed time series were generated from stochastic wind speed time series using an algorithm described in Amezcua et al. [10] and an aerodynamic model of the wind turbine rotor. The rotor shaft profiles were conveniently controlled through the Lab View interface, allowing the study of a variety of wind speed conditions. Resistive loads with forced-air convection were used for experimentation. A sketch of the system is provided in Figure 1. A photograph of the actual laboratory setup is shown in Figure 2. Selected components of the system will be described in some more detail below.
A. Electric generator

The electric generator was custom-designed and built based on a toroidal magnetic core topology with a stator sandwiched by two rotating disks equipped with rare-earth permanent magnets made from NdFeB [11]. The number of pole pairs was chosen to be 12 in order to allow for a direct coupling with the wind turbine rotor without the need of a gearbox. The generator was subjected to a detailed magnetic and electromechanical modeling process as well as test bench testing, allowing for the construction of a detailed model of the generator [11]. The details of the generator design, modeling, and testing will be described elsewhere. A summary of the generator characteristics is provided in Table 1.

B. Controller

The controller was designed to work at the DC side at the output of an uncontrolled (passive) six-pulse rectifier connected to the three-phase generator, as shown in Figure 3. Output power and rotor speed control was achieved through a load-commutation scheme controlled by pulse-width modulation (PWM) using an IGBT solid-state switch Fairchild FGA20S120M and a Microchip PIC18F4550 microcontroller in conjunction with a driver IR2110 to allow for power switching. The control board was equipped with a snubber circuit in order to protect the IGBT during switching. The snubber was simulated and tested prior to the implementation in the control board. A 10nF capacity was added to the snubber circuit in order to absorb the magnetic energy stored in the generator armature windings at rated conditions (10A, 300V) to avoid over voltages which might compromise the integrity of the IGBT and therefore the protection of the system in the case of a loss of load. As discussed further below, rotor speed and generator current were selected as the control variables. The current was measured with an ACS758 Hall effect current sensor after calibrating against a Fluke 123 industrial scopemeter. The rotor speed $n_s$ was determined by measuring the electrical generator frequency $\omega_e$ and using the fixed $n_s/\omega_e$ ratio ($=60/(p \cdot \pi)$, $p$=number of pole pairs = 12). The $\omega_e$ measurement was conducted in two stages, first by generating a square-wave signal using a zero-crossing technique shown in Figure 4 and subsequently generating a frequency-proportional voltage using the LM331 integrated circuit; the zero-crossings detection technique is based on the 74LS14 chip. Before construction the circuit was simulated using PSpice. After implementation a calibration was performed against the set frequency of the Yaskawa frequency drive. It might be argued that the generator frequency in the test arrangement can in principle be calculated from the set frequency of the VFD. It should be noted, however, that the relationship between the two is trivial only for a constant or sinusoidally varying signal and, more importantly, that the results from the test bench have to be carried over to a real-world turbine where the generator is driven by the wind and not a VFD and that in that case the frequency is not in the hand of the experimenter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>Nominal line-to-line voltage</td>
<td>Volt</td>
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<tr>
<td>Number of phases</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Rotor type</td>
<td></td>
<td>2 disks w/ perm. magn. NdFeB</td>
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<tr>
<td>Stator type</td>
<td></td>
<td>Toroidal with Si-steel core</td>
</tr>
<tr>
<td>Nominal output power</td>
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</tr>
<tr>
<td>Nominal shaft speed</td>
<td>rpm</td>
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<tr>
<td>Armature resistance per phase</td>
<td>$\Omega$</td>
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<tr>
<td>Self-inductance per phase</td>
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<tr>
<td>Mutual inductance per phase</td>
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<tr>
<td>Number of pole pairs</td>
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where $\omega$ is the moment of inertia of the rotor/generator, and $I$ is the generator current. The details of the electromechanical model are described in [11].

### III. CONTROL DESIGN CONSIDERATIONS

The protection strategy (PS) described in the present work is focused exclusively on reliability. The full control system has additional elements such as maximum power point tracking (MPPT) and blade pitching for high wind speeds and rotor frequencies, which are not subject of the present work. A description of the full system and the interaction between its parts will be published elsewhere. The principal concern of the PS described here was to avoid run-away of turbine in the event of loss of load and stator coil overheating, maintaining the system in a safe operating zone at all times. The strategy is based on load control and was designed to operate from zero up to cut-out wind speed, taken to be 20m/s, and a range of rotor shaft frequencies of up to 264rpm. It was deemed to allow for a more compact and predictable scheme compared to aerodynamically-driven control mechanisms such as horizontal or vertical furling.

The action of the PS described in the present work is illustrated in Figure 5 where part of the state map of the wind turbine for the case of the armature current (the independent variable) is shown. The rotor speed / wind speed pairs $(n_s, U_{\infty})$ corresponding to maximal power output are highlighted in yellow (on-line version of the manuscript). The areas shown in orange and red indicate stator coil temperatures in the range of 70°C to 100°C and > 100°C, respectively. In order to avoid stator overheating (temperatures in excess of 100°C) at higher wind speeds (11.5m/s and higher) and turbine run-away at lower wind speeds it was decided to limit the rotor speed to a target curve given by maximum power output at wind speeds of up to 8m/s and a constant rotor speed of 264rpm for wind speeds of up to 20m/s. The rotor was designed aerodynamically to produce an approximately constant net power output of 2.7kW under these conditions because of a controlled entry into the stall regime. It can be seen from Figure 5 that by limiting the target rotor frequency to 264rpm for wind speeds ≥8m/s a safety gap against critical system conditions such as turbine run-away and overheating is established. In order to implement this requirement a nominal trajectory for the independent control variable has to be defined. As shown in Figure 5, the armature current is set to follow the optimal $(n_s, U_{\infty})$ values (shown in yellow in the main figure) up to a current value of 4.1A, slightly higher than the value required for optimal operation at 8m/s. At this current value the rotor speed, according to the map in Figure 5, is limited to 264rpm. In order to maintain the rotor speed at this value current values of up to 7.5A are required, with the maximum value occurring at a wind speed of 12m/s (marked in blue in the map of Figure 5). For higher wind speed values and the same fixed rotor speed of 264rpm

## Table 1 Nominal properties of the electric generator designed and built for this work

| Diameter | mm | 460 |
| Magnet-core gap (each side) | mm | 12.5 |

- Where $T_{\text{opp}}$ is the opposing torque provided by the electric generator, and friction and ventilation losses, $\Theta$ is the moment of inertia of the rotor/generator, and $I$ is the generator current.
the required current drops somewhat due to the fact that the rotor enters deeper into the stall regime, resulting in less efficient aerodynamics and hence a lower aerodynamic power coefficient $C_p$. The maximum current of the protection system is set to 9A, maintaining the generator below critical stator temperatures. The considerations described above led to a rotor speed – current set point curve shown in the inset of Figure 5.

Fig 3 Simplified equivalent of the electric generator, the rectifier, and the controller

Fig 4 Frequency measurement by the detection of zero crossings
Fig 5 Part of the state map of the wind turbine for the case of the variable “armature current”. Inset: Proposed target curve in the rotor speed – current plane

Under normal operation, e.g. with a grid-tied inverter as the load, the prescribed operation curve (typically programmed with the help of a maximum power tracking implemented in the inverter itself) will be followed without the intervention of the protection strategy described here, if the set point curve of the protection system and the prescribed power curve are set to coincide; the controller will then be idling. However, under partial or total loss conditions, or a delayed response of the inverter because of self-testing at startup or after a reset, the controller is expected to limit the rotor speed by increasing the generator current, ideally following the trajectory in the rotor speed – current plane shown in the inset of Figure 5. As a possible failure will originate precisely on this target curve and at zero duty cycle the controller has its maximum duty cycle range available once a failure occurs.

IV. FUZZY LOGIC CONTROL

A control strategy based on fuzzy logic [12] was chosen because of the expected presence of noise in the system, e.g. originating from switching elements such as the inverter or the MPP controller, or electromagnetic noise, particularly under field conditions. Another rationale was the non-linear nature of the control loop which includes the possibility of instabilities at the transition to the stall regime. The error is defined as the deviation of the measured rotor speed $n_{r, \text{meas}}$ from its set value

$$e = n_{r, \text{meas}} - n_{\text{set}}$$

In addition to the error $e$ itself, the time derivative $de/dt$ is registered as well. A set of 25 fuzzy rules was defined based on the qualitative values of both $e$ and $de/dt$; the controller response values for these 25 cases are shown in Table 2.

|------------------|-------------|--------|------|--------|-----------|

Table 2 Set of fuzzy rules for the calculation of the controller response as function of the rotor speed error and its time derivate
For fuzzification [12], i.e. assignment of a given input value to a fuzzy class, overlapping triangular membership functions for both $e$ and $de/dt$ were used. Similarly, overlapping triangular output functions were defined for the output variable which was taken to be the increment (positive or negative) in the duty cycle of the pulse width modulator (PWM). Typically, rotor speed errors with an absolute value of less than 5rpm were taken to be null, errors of the order of ±10rpm are considered “positive/negative”, and errors of the order of ±15rpm are “very positive/negative”. The duty cycle increase range was adjusted in the course of this work, with maximum values ranging from 1% to 10% (see results section).

![Diagram](image)

**Fig 6 Block diagram of the control system based on fuzzy logic**

Centroid defuzzification [13] was used to calculate a well-defined numerical value for the control signal (increment in duty cycle). The full control scheme is illustrated in Figure 6. Both the error $e$ and its derivative $de/dt$ were processed in the fuzzy control chain, while the error integral was summed directly to the output of the defuzzified signal. While in principle the integral component could be fuzzified as well, this would lead to a much higher number of required fuzzy rules (125 in case five fuzzy levels were chosen). For computational convenience the hybrid scheme in Figure 6 was implemented. The gain values $G_P$, $G_D$, $G_I$ were carefully adjusted for optimal performance, as described in the results section.

**V. RESULTS AND DISCUSSION**

In all tests described below a relatively high load resistance of 120Ω was connected to the system. At this load the rotor runs relatively freely and readily surpasses the target curve in the rotor speed-current plane if not hindered by the action of the controller.

**A. Tuning of the control loop**

In an initial step only the input proportional to the error signal was considered to explore the dynamics of the control loop, i.e. $G_{I}=G_{P}=0$, $G_{P}≠0$. The wind speed was stepped up from 4.8m/s to 8.5m/s. The initial rotor speed was 0 rpm. After being exposed to the 4.8m/s wind speed the rotor quickly accelerates and passes beyond the target line, before the action of the controller sets in and stabilizes the system at a rotor speed located at the target curve (Figure 7). At subsequent wind speed steps, chosen to be 0.5m/s, overshoots with similar amplitudes can be seen to occur until the operating point is located near the knee area of the curve, where the system starts to oscillate (Figure 7). This zone is particularly critical from a control perspective, as in this area, characterized by the onset of aerodynamic stall an increase in rotational speed (triggered by an increase in wind speed) leads to an increased aerodynamic power coefficient $C_p$ and therefore a higher excursion away from the target curve, as opposed to the situation on the optimal part of the curve where an increase in rotor speed leads to a decreased $C_p$. This is illustrated by the steady-state curves in Figure 8, obtained from the full aerodynamic-electromechanical model of the wind turbine, showing how the aerodynamic power coefficient $C_p$ varies with the armature current for different rotor shaft speeds. The main figure has the current range from 4 to 8.5A, whereas the inset has the smaller current range from 0 to 4A. The target curve for nominal operation ($n_{r}=const.=264rpm$, main figure) and optimal operation (inset) is shown together with the corresponding curves obtained for a slightly higher ($n=n_{r,\text{nom}}+12rpm$) and slightly lower ($n=n_{r,\text{nom}}-12rpm$) rotor speed. It can be seen from the figure that near optimal operation (inset) the power coefficient $C_p$ slightly decreases in response to a change in rotor speed (almost inconspicuously so for the case of increasing rotor speed), whereas the variation in $C_p$ is quite dramatic under stall conditions (main graph of Figure 8). If, e.g., the turbine initially operating at 11m/s with a rotor speed of 264rpm and requiring a current of about 7.3A accelerates to 276rpm because of a gust, a substantial increase in power coefficient occurs, leading to the tendency of further accelerating the rotor. An increase of the current of about 8A is required only to stabilize the rotor at 276rpm once the wind speed has dropped again to 11m/s. (The higher current is supplied by the increased aerodynamic efficiency at the new operating point). Evidently, an even higher current is required to bring the system back to 264rpm. As the required excursions in current for even small variations in rotor speed (such as 12rpm or 4.5% as in the example of Figure 8) are substantial (0.7A or 9.6% in the case of Figure 8) the system was expected to show significantly higher fluctuations in this regime, compared to the optimal operation regime.
It can be seen from Figure 7 that the amplitude of the oscillations indeed increases significantly as the operating point moves first to the knee and then to the horizontal part of the target curve. In that latter area the increase in $C_p$ as the rotor speed increases is much higher than in the knee area, and so is the amplitude of the oscillations. If the experiment is repeated for higher wind speeds the oscillations diminish significantly (not shown). This is consistent with the fact that for a given rotor speed (around 260rpm in this case) the tip speed ratio decreases with increasing wind speed, thereby leading to a smaller aerodynamic power coefficient. It is important to point out, however, that the wind speed ramp from 4.8m/s to 8.5m/s studied in Figure 7 is more representative of the actual situation the controller is likely to encounter; as stated earlier, any loss-of-load situation the controller was designed to handle is likely to occur near the target $\omega$ vs. $I$-curve which by design corresponds to optimal operation for wind speeds up to about 8m/s and near-constant power output for high wind speeds (Figure 5). In order improve the system response under the test conditions described above the differential and integral components of the control loop were enabled. The differential gain was set by adjusting the horizontal range of the triangular membership functions for $de/dr$; the integral gain was adjusted by simply specifying a corresponding factor. The results about for the case of a fuzzy logic-based proportional/differential (PD) control loop are shown in Figure 9. As it can be seen from the figure, the response characteristics of the control loop are now much improved.
Fig 9 System response for the case of a stepping wind speed ramp using a combination of proportional and differential fuzzy control

Fig 10 System response for the case of a fuzzy PD/I hybrid control loop in the case of a severe wind speed step

Fig 11 System response to a 6m/s ->12m/s wind speed step using a sampling rate of 300Hz

For the fuzzy PD control loop the target curve in the optimal operation region is reached by the rpm-signal within some ten seconds after each wind speed step with practically no oscillations. The current converges with similar rapidity but shows some oscillations. In the case of the knee and nominal operations part of the curve slight overshoots are observed for the rpm-signal but higher excursions can be seen for the current signal. Compared to the results of the fuzzy P-only control in Figure 9 the improvement is quite dramatic. Adding the integral component to the control loop (not shown) reduces the ripples on the current signal but leads to an otherwise similar system response.
While the system response for the case of the stepped wind speed ramp shown in the previous examples worked fairly well for the case of hybrid fuzzy-PD/I loop, this case by no means represents the ultimate challenge for the control as the system stays close to the target line most of the time, which is why the required increase in duty cycle is low. In order to somewhat strain the system a wind speed step of 6m/s (changing from 6m/s to 12m/s) was evaluated with the system initially tuned as described above. The initial rotor speed was 200rpm, and the current required to operate on the target curve was a little over 2A. As conspicuous from Figure 10 in this case the system is unable to cope with the requirements, with the rotor speed rising significantly beyond the target line of 264rpm. It can be seen that the rotor speed \( n_s \) increases to about 350rpm before a stronger response from the controller occurs, driving the line current to about 11A. Such conditions eventually lead to stator overheating, which is why the experiment had to be stopped at that point.

A plausible culprit for the delayed controller response in this case was the sampling frequency. In this and the previously described trials the frequency for sampling the rotor speed and the line current was set at 5Hz, which proved to be too low. In order to provide a faster response of the control loop the sampling frequency was increased to 300Hz. The increase, however, comes at a cost. Firstly, the system becomes more sensitive to noise, which has to be compensated by a suitable low-pass filter. Secondly, the alternating current (e.g. with a frequency of \( \omega_e=10\text{Hz for } n_e=100\text{rpm} \)) is now sampled many times during one oscillating period which is why a method had to be devised to detect changes occurring within one oscillation period of the current and provide an accurate instantaneous estimate of the rms current in the presence of harmonics. The following algorithm proved to be effective. (1) The value \( V^{(0)} \) of the last value of the variable containing the current measurement is stored. (2) A new value \( V_i \) of the current is measured. (3) An intermediate variable is defined by \( V^{\text{int}} = \alpha V^{\text{int}} + (1-\alpha)V_i^2 \), where \( \alpha \) is an initially free parameter to be determined from the experiment. (4) A new estimate of the rms current signal is calculated from \( V^{(n+1)} = \beta V^{(n)} + (1-\beta) V^{\text{int}}^{1/2} \). Good results were obtained for \( \alpha = \beta = 0.99 \).

![Fig 12 System response to a 6m/s→12m/s winds speed step for three ranges of the output membership functions. (a) Range = (-1%, 1%) duty cycle change per sampling interval, (b) (-6%,6%), (c) (-10%,10%)](image)

Fig 13 Response of the control loop for stationary wind speed time series with turbulence. Left: Average wind speed =6.5m/s. Center: 8.5m/s. Right: 18.5m/s.

The effect of the increased sampling rate in conjunction with the revised algorithm for the determination of the rms value of the line current is shown in Figure 11. It is evident that the control loop now provides a much faster response and, while missing the target curve during most the stall regime, does limit the rotor speed to a safe value of about 280rpm, with the current excursion limited to about 9A.
located in the orange zone of Figure 5, indicating somewhat increased but not critical stator temperature temperatures, and manages to return the system to the target speed of 264rpm at the of the excursion. While the results presented in Figure 11 were encouraging, they are still significantly missing the target curve. An obvious choice to provide a better control loop response is an adjustment of the output gain. In order to explore this option, the range of the output membership functions (in % of increase / decrease of the duty cycle) was varied. While the initial settings had a maximal increase / decrease of 1% per sampling cycle in order to avoid abrupt system changes, ranges of up to (-10%, 10%) were explored in the next step of the work. The results of the corresponding experiments can be seen in Figure 11. While for the ±1% duty cycle range still a small overshoot can be noticed, in the case of ±6% the system trajectory only slightly surpasses the target curve in the stall regime. In the case of a ±10% range, finally, the target curve is traced almost perfectly by the system trajectory.

A. Testing of the control loop under realistic conditions

After these initial tests under standard conditions it seemed appropriate to expose the tuned system to situations more representative of the field conditions the wind turbine is likely to experience. These conditions include varying degrees of turbulence at different average wind speeds, as well as (positive and negative) gusts. In a first step the response of the system to stationary but fluctuating wind speed time series was evaluated. As mentioned above, the algorithm is based on the work published in Amezcua et al. [10]. Average wind speeds were set at \( \langle U_\infty \rangle = 6.5 \text{m/s}, 8.5 \text{m/s}, \text{and} 19.5 \text{m/s}, \) respectively, to explore different parts of the target system trajectory. The wind speed standard deviation \( \sigma_U \) was similar in the three cases with values of 0.77 m/s, 0.58 m/s, and 0.65 m/s, respectively. The corresponding turbulence intensity values \( \langle U_g \rangle / \sigma_U \) are 12.3%, 6.7%, and 3.5%. Evidently, the turbulence intensity is significantly lower for the highest wind speed, which is consistent with the typical findings in the atmospheric boundary layer where stronger winds are steadier and less turbulent.

![Figure 14](image-url)  
Fig 14 Response of the control loop for the case of two gusts. Grey curves: 15 m/s gust, starting from a 7 m/s base line. Black curves: 20 m/s gust.

As shown in Figure 13, the tuned and optimized control loop readily copes with the stationary fluctuating wind speed time series in all cases, accurately maintaining the system at the set rotor speed with excursions of the line current well below the maximum value of about 8A. In the case of the lowest average wind speed (6.5 m/s) the required line current averaged 2.3A, with a standard deviation of 0.5A or 22%. In the case of \( \langle U_\infty \rangle = 8.5 \text{m/s} \) the average current was 4.9 m/s with a standard deviation of 0.36A or 7%. Finally, for \( \langle U_\infty \rangle = 19.5 \text{m/s} \) the average current was 6.9A with a standard deviation of 0.16A or 2%. A typical disturbance for a wind turbine is the occurrence of a gust, or occasionally, an anti-gust. In order to explore the robustness of the system in these cases the wind speed emulator was programmed to create a 15m/s and a 20m/s gust, both starting from a 7m/s baseline. The gust factors \( G = \Delta U_g / \langle U_\infty \rangle \) in these cases are 1.14 and 1.85, respectively, where \( \Delta U_g = U_g \text{ gust} - \langle U_\infty \rangle \). The results are displayed in Figure 14; the results for the 15m/s gust are shown in grey, while the results for the 20m/s gust were plotted in black. As conspicuous from Figure 14 the total gust duration is about 30 seconds for the 15m/s case and about 50s for the 20m/s gust. The steepest rise within the gusts can be seen to occur on a much shorter time scale, of the order of less than ten seconds, which translates into a significant strain of the control loop. As shown by Figure 14 the control loop handles these situations very well. As the increase in wind speed is very similar for both cases up to about 12m/s (except for some minor differences due to the stochastic nature of the wind speed signal) the increase in rotor speed is also very similar. In both cases the rotor speed can be seen to be held at or below the limiting value of 264rpm. As shown in the lower left part of Figure 14 the current excursion always remains below 8A. It is evident from the graph that this favorable response is in part due to the swift response of the controller,
as illustrated by the fact that in the case of the 20m/s gust the maximum current is reached well before the actual occurrence of the gust, for wind speeds around 12m/s. Under these conditions ($n_r=264\text{rpm}$, $U_r=12\text{m/s}$) the tip speed ratio is 4.6 (compared to the design value of 6.7), indicating that the rotor is already operating under partially stalled conditions. A further increase in wind speed, including the peak region of the gust, drives the rotor deeper into the stall regime, reducing aerodynamic power extraction and allowing to even somewhat decrease the line current. Evidently, the controller response has been significantly slower, the gust peak would have encountered the rotor at or near the optimum tip speed ratio where the decrease in power coefficient upon increasing the wind speed is much smaller, thereby driving the armature current to higher values with a possibility of overheating. A swift response of the control and protection circuit is therefore a key to a safe operation.

VI. SUMMARY AND CONCLUSIONS

A protection system for a small wind turbine system based on load-induced stall control was developed and characterized experimentally on a test bench capable of emulating arbitrary wind turbine rotor behavior, based on artificial or realistic wind speed time series. The wind turbine was fully home-designed and built. The generator is a permanent-magnet synchronous generator with a toroidal magnetic field topology. The test bench was also designed and built in-house. Load control was implemented through pulse width modulation switching of an extra parallel load and controlled by a microcontroller. The control strategy is based on a set of 25 fuzzy logic rules built for 5 x 5 fuzzy states of the rotor speed error and its derivative; an integral control component was added in a conventional way. The output signal of the control circuit is an increase or decrease of the duty cycle of the pulse width modulator. The protection strategy was designed in such a way that any loss-of-load situation occurring under normal operating conditions, assumed to be optimal up to a wind speed of 8m/s, approximately constant at the nominal power output of 2.7kW for wind speeds of 12m/s and higher, with a smooth transition between the two regimes, would occur at zero duty cycle of the control and protection device. Such a design maximizes the system response as the full duty cycle range is available for control. By analyzing an aero-dynamical-electromechanical model of the wind turbine a target system trajectory in the rotor speed–armature current plane was calculated and specified as set point curve. Initial tuning of the control loop was performed by exposing the system to standard excitation patterns, such as a stepped wind speed ramp and a severe wind speed step. After initially experimenting with a proportional-only control, the derivative component was found necessary to suppress oscillations initiating at the knee of the rotor speed–current curve, characterized by initial aerodynamic stall operation where an increase in rotor speed increases the aerodynamic power coefficient. Adding the conventional integral component proved helpful to suppress current ripples but had otherwise no dramatic effect. After initially working with a 5Hz sampling frequency, the frequency was finally set at 300Hz, as the control was unable to cope with severe wind speed steps under certain conditions. As the rms value of the line current was used in this work, at 300Hz the current signal is now sampled many times during an oscillation period; an algorithm was devised to calculate accurate estimates of the local rms value under these conditions. The effect of the increased sampling frequency was found to be dramatic, allowing to accurately trace the target curve even under challenging conditions. Further improvements were achieved through an increase of the duty cycle increment range used for the output membership functions near the end of the fuzzy chain. A duty cycle increment range of ±10% was found sufficient to achieve excellent accuracy. After the tuning of the system the control loop was now exposed to a serious of realistic wind speed conditions, including turbulent but stationary time series, as well as gusts. The target curve was accurately traced in all cases. The control and protection system described in this work is part of a greater control strategy including maximum power point tracking and a passive blade pitching mechanism for high wind speeds and/or high rotor frequencies. The emulation and systematic study of the interaction of these different system components is currently under way and will be studied with respect to its implications for the reliability of small wind turbine control. The results and methods presented in the current work are believed to be useful for researchers in the small wind turbine community and provide some impulses for research into control for reliability.

VII. ACKNOWLEDGMENT

Support from the Nuevo León State Government (Mexico) under the FONLIn 0002 grant and from Tecnológico de Monterrey (internal grant CAT158) is greatly acknowledged. Two of the authors (S.C., O.M.) acknowledge support from CONACYT (Mexico) through a M.Sc. stipend and from Tecnológico de Monterrey for a scholarship of excellence. The last part of this work was conducted as part of the efforts of the CONACYT project P19 “Control for reliability of small wind turbines” inscribed in the Mexican Center for Innovation in Wind Energy (CEMIE Eólico).

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AUTHORS’ PROFILES

Salomón Castro holds a B.Sc. degree in electronics and a M.Sc. degree in energy engineering from Tecnológico de Monterrey (2012). His research interests include control and modeling of renewable energy systems. He currently runs a solar technology and installation business.

Jorge Elizondo received his B.S. degree in Engineering Physics in 2005 and his M.S. degree in Electrical Engineering in 2007, both from Tecnológico de Monterrey (ITESM) in Mexico. In 2008 he co-founded Wind and Solar Design a startup company dedicated to the development of technology for distributed generation based on renewable energy. In 2011 he joined the Laboratory for Electromagnetic and Electronic System at the Massachusetts Institute of Technology, where he is currently pursuing his doctoral degree. His research interests include analysis, design and control of distributed generation systems, energy management strategies, and applications of power electronics to power systems.

Jaime Martínez Lauranacht holds a B.Sc. degree in Mechanical Engineering and a M. Sc. degree in Energy Engineering (2007), both from Tecnológico de Monterrey. He is a co-founder and owner of Wind and Solar Design based in Monterrey, Mexico. His research and development interests include renewable energy for distributed generation, with a focus on solar and wind energy. His expertise includes aerodynamic blade design and electromagnetic design of wind turbine generators. His present activities are focused on mechanical engineering principally for the manufacture of robust wind turbine blades and solar panels structures. Several technological patents have resulted from this research and development, some of them with successful commercial applications.

Oswaldo Monroy has a B.Sc. degree in Engineering Physics and a M.Sc. Energy Engineering from ITESM (2011). His M.Sc. was on the development of a toroidal generator. He is currently a part-time professor in Engineering at ITESM and the owner of a company dedicated to renewable energy technology. His primary research interest is in development and application of alternative energy technologies.

Oswaldo M. Micheloud holds a B.Sc. in Electrical Engineering from the University of Rosario (Argentina) in 1973. In the University of Washington, in Seattle, he obtained the degrees of M.Sc., in 1978, and Ph.D. in 1979, both in Electronics and Automatic Control. From 1979 to 1997 he worked as design engineer for the private sector, and from 1984 to 2006 he worked as professor, director of the Department of Electronics Engineering and vice rector for academic affairs at Instituto Tecnológico de Buenos Aires (ITBA). He served as Vice President of the Federal Council of Engineering Deans of Argentina, CONFEDI, and Director of its Educational Committee. In 2006 he joined Tecnológico de Monterrey (ITESM) where he is currently Director of the Industrial Consortium to Foster Applied Research for Economic Growth at ITESM, holding the Roberto Rocca Endowed Energy Research Chair. He is also the director of the M.Sc. program in Energy Engineering. He is coauthor of the book “Smart Grid: Fundamentals, Technologies and Applications” published by Cengage Learning in 2012.

Oliver Probst received his Diploma in Physics and his Doctorate in Natural Sciences from the University of Heidelberg (Germany) in 1990 and 1994, respectively. He has been a professor of Physics and Renewable Energy at Tecnológico de Monterrey (Mexico) since 1996, serving as the Chair of the Physics Department from 1999 to 2006 and as the Chair for Wind Energy from 2008 to 2014. In 2009 Dr. Probst was a visiting professor at the University of Texas in Brownsville. His professional experience includes consulting and research activities in the fields of wind resource assessment and modeling, small wind turbine technology, and damage modeling in wind turbine blades. He is currently a full professor at Tecnológico de Monterrey and a consultant to a portfolio of commercial wind farm projects in Mexico.