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***Research paper***

# Intelligent Fuzzy Logic Controller for Improved Power Extraction of Micro Wind Turbines

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**Abstract**

Wind turbines are one of the fastest growing forms of renewable energy. The amount of power a wind turbine extracts from the incoming wind is dependent on the rotational speed and for every wind speed there is an optimal rotational speed that will extract the most amount of power from the incoming wind. Large wind turbines incorporate active control techniques whereas micro wind turbines incorporate passive control techniques with the disadvantage of lower efficiency in controlling the rotational speed and therefore a lower amount of power can be extracted. This paper proposes the development of a new control method that alters the rotational speed of a micro wind turbine in order to improve the power extraction from the incoming wind. This was done by using a DC-DC boost converter controlled by an intelligent fuzzy logic controller on the output of the generator. The controller is also unique, since it only requires the rotational speed and power output of the wind turbine generator, therefore eliminating the difficulties in obtaining the exact wind speed due to the wake effect of the wind turbine tower, whereas the majority of controllers currently in use require the wind speed. The required change in the duty cycle of the DC-DC boost converter is determined by the controller which in turn controls the electromechanical torque of the generator. The design was simulated in Matlab®/Simulink® and practically implemented using Control Desk® and a dSPACE® DS1104 controller board on a 1 kW micro wind turbine generator. Both the simulation and experimental results indicate an improvement in the amount of power extracted by the micro wind turbine generator incorporating the controller, especially during high wind speeds.

***Keywords***: *DC-DC Boost Converter; Dspace® Controller; Fuzzy Logic; Matlab®/Simulink®; PMSG.*

## 1. Introduction

Wind turbine energy is becoming an increasingly popular form of renewable energy which can mainly be attributed to the low cost and the clean power of wind turbines [1], [2]. The amount of power a wind turbine extracts from the incoming wind is dependent on the rotational speed and every wind speed has an optimal rotational speed [3]. If the rotational speed is too fast, the blades slows the speed of the wind down and if the rotational speed is too slow, not enough of the wind's energy is extracted by the blades [4]. When the wind turbine rotates at the optimal rotational speed, the most amount of power will be extracted as the wind passes through the blades of the wind turbine [3], [5]. Therefore; a change in wind speed requires a change in the rotational speed of the wind turbine for optimal power extraction.

Large wind turbine usually makes use of active control techniques in order to control the rotational speed and therefore the amount of output power by altering the pitch of the blades or the angle of the wind turbine with regards to the incoming wind [6 - 8]. The majority of micro wind turbine makes use of passive control techniques in order to control the amount of output power and is usually only designed for optimal rotational speed at a single wind speed [9]. The passive control techniques of micro wind turbines have been found to be less effective and incorporating active control techniques have been found to create economical and financial difficulties [7], [10], [11].

This paper presents a design and the experimental implementation results of a fuzzy logic controller that alters the rotational speed of a micro wind turbine generator and therefore controlling the amount of output power. The design and experimental setup is only briefly discussed in this paper, but a more in depth discussion of the design, as well as the simulation results, can be seen in [12].

## 2. Overhead control scheme

This section provides an overview of the control scheme as well as detail on the control approach. The overhead control scheme for the controller can be seen in figure 1. The system consists of a fixed pitch, direct drive Permanent Magnet Synchronous Generator (PMSG) wind turbine design with a DC-DC boost converter on the output of the uncontrolled rectifier.

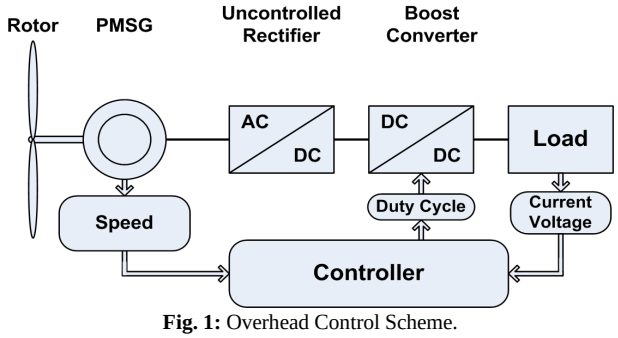



**Fig. 1:** Overhead Control Scheme.

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The controller requires measurements on the rotational speed and output power of the wind turbine generator and determines a change in the duty cycle of the DC-DC boost converter using a fuzzy logic controller. The overhead control approach of the controller system can be seen in figure 2.

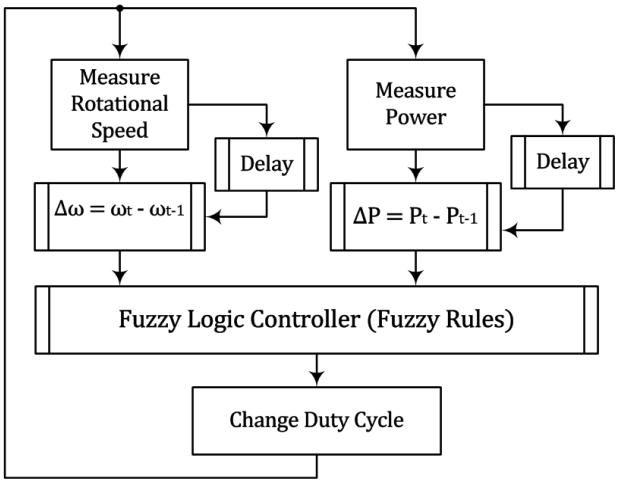



**Fig. 2:** Overhead Control Approach.

The change in the duty cycle of the DC-DC boost converter is determined by adding a unit step delay to the rotational speed and output power in order to determine the change from the previous values of the measurements. The detailed fuzzy logic control approach of the controller can be seen in figure 3.

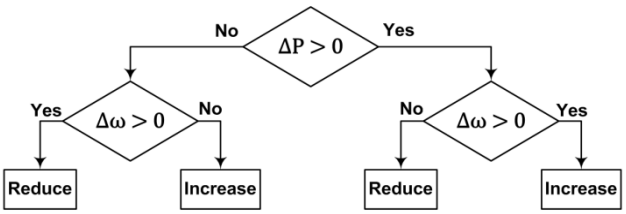



**Fig. 3:** Detailed Fuzzy Logic Control Approach.

The controller consists of two input triangular membership functions (change in rotational speed and output power) with 7 rules for each input which results in a total of 49 fuzzy logic rules. The output consists of a single triangular membership function with 7 rules and determines the required change in the duty cycle of the DC-DC boost converter. A more in depth discussion on the membership functions can be seen in [12]. The fuzzy rules for the 2 input membership functions of the controller can be seen in table 1.

**Table 1:** Fuzzy Logic Controller Rules

| | | *Δω* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | Z | PS | PM | PB |
| | NB | IB | IB | IM | RB | RM | RB | RB |
| | NM | IB | IM | IS | RM | RS | RM | RB |
| | NS | IM | IS | IS | RS | RS | RS | RM |
| *ΔP* | Z | NC | NC | NC | NC | NC | NC | NC |
| | PS | RM | RS | RS | IS | IS | IS | IM |
| | PM | RB | RM | RS | IM | IS | IM | IB |
| | PB | RB | RB | RM | IS | IM | IB | IB |

The fuzzy logic controller rules in table 1 results in the surface rule view for the controller as can be seen in figure 4. From figure 4 it can be seen that the change in rotational speed and output power varies between [-5 5] and [-3 3]. These changes were chosen to have a relatively low value when compare to the output of the generator with the advantage of increased accuracy, but the disadvantage of slower response time for a changing wind speed.

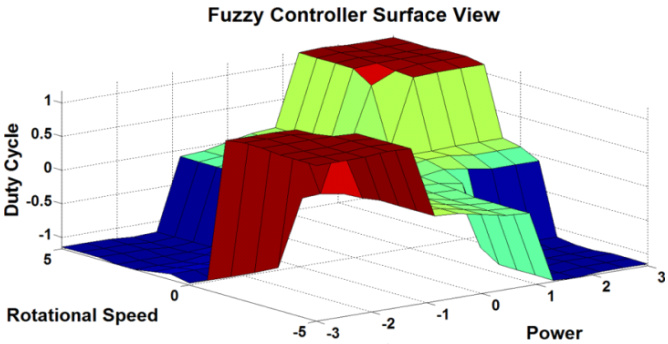



**Fig. 4:** Fuzzy Rules Surface View.

## 3. Experimental setup

This section provides the experimental setup of the system. The complete system controller setup used to obtain the experimental results can be seen in figure 5.

The complete system consists of a VSD, induction motor (prime mover), PMSG, uncontrolled rectifier, DC-DC boost converter, load, controller protection and a computer with a dSPACE® DS1104 controller board.

dSPACE® Control Desk® was used to obtain the experimental results and the layout of the control desk implementation can be seen in figure 6. Figure 6 illustrates the implementation of a repeating sequence of the fluctuating wind speed profile where the controller is off during the first part and on during the second part. The various systems of the dSPACE® Control Desk® are indicated on the figure (refer to figure 6). The model consists of the following:

- PWM start/stop (indicated in yellow). This connects and disconnects the PWM signal to the DC-DC boost converter.
- Duty cycle output (indicated in green). This displays the current duty cycle to the DC-DC boost converter in both a numerical value and in a bar graph.
- System measurements (indicated in purple). This displays the real values of the current, voltage, power and speed of the system with a numerical value. Controller inputs (indicated in blue). The inputs consist of the wind speed and the generator start/stop gain with a numerical input.
- Data acquisition (indicated in red). This uses the data acquisition function of dSPACE® Control Desk® to acquire the data on 1. Power, 2. Duty cycle, 3. Wind speed, 4. Rotational speed, 5. Nominal power coefficient, 6. Current and 7. Voltage.

Figure 7 displays the Matlab®/Simulink® model used for the experimental implementation of the controller in dSPACE® Control Desk®. The first stage of the controller receives the input signals using the analog to digital converters and converts these sensor values to actual values. The second stage involves supply the integrated wind turbine block with the rotational speed and ads a delay to the rotational speed and load power for the fuzzy logic controller. The output of the controller is done by the PWM block which sends the PWM to the boost converter and torque set point to the VSD. A gain was added on the set point to the VSD in order to start rotation (due to the high cogging torque); once rotation has started the value was lowered. A PWM start stop was also added to the output to the boost converter which connects and disconnects the output.

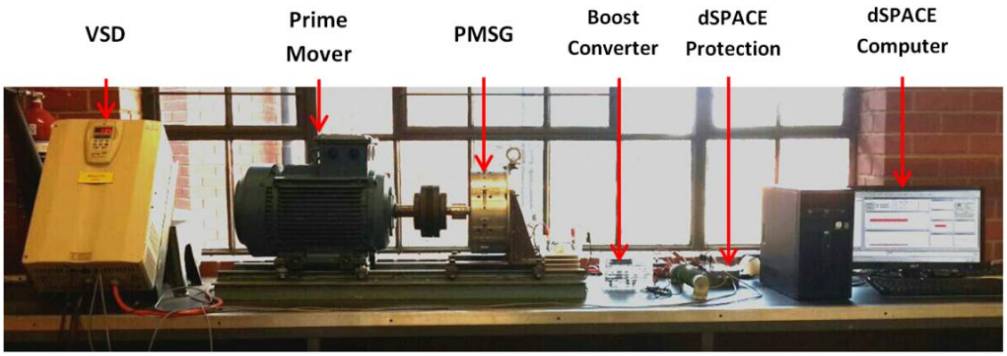



**Fig. 5:** Complete Experimental Setup.




**Fig. 6:** dSPACE® Control Desk® Experimental Setup.

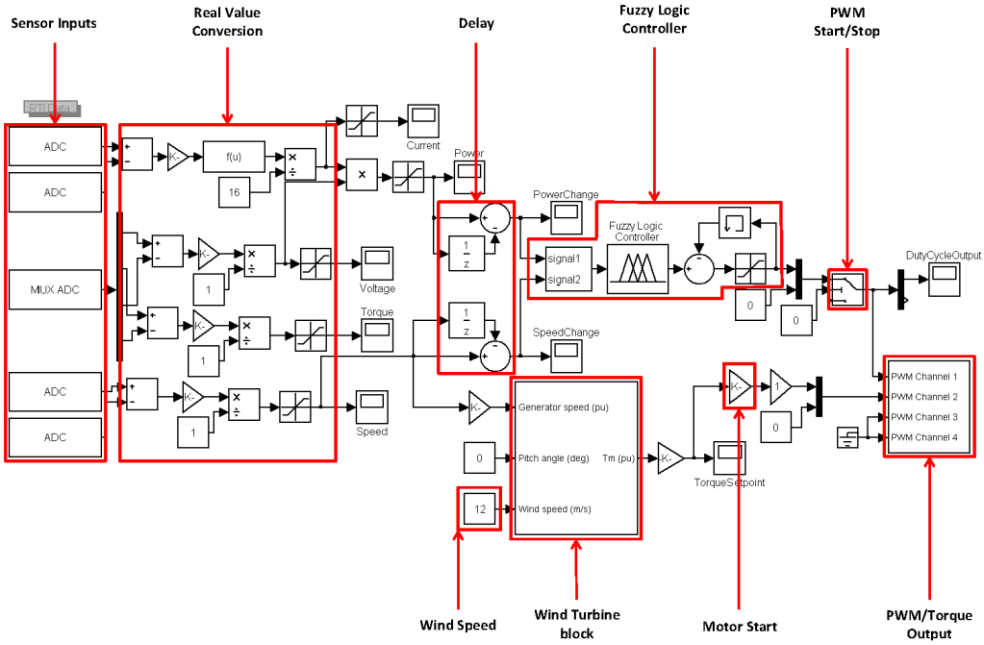



**Fig. 7:** dSPACE® Control Desk® Matlab®/Simulink® Model.

The blades of the wind turbine were emulated using an induction motor as a prime mover which was mechanically connected to a PMSG, as can be seen in figure 8. The blades were replaced with an induction motor prime mover in order to ensure consistency between the measurements of the controlled and uncontrolled generator.

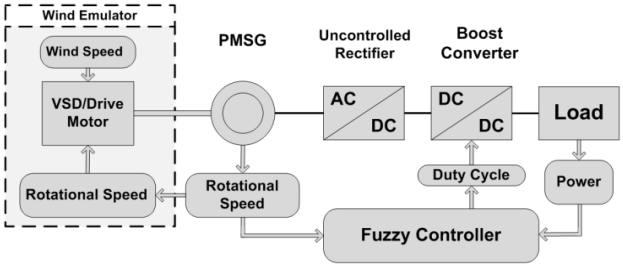



**Fig. 8:** Prime Mover Blades Replacement.

The experimental implementation of figure 8 can be seen in figure 9. The torque of the prime mover was controlled using a VSD that received a torque set point from dSPACE® Control Desk® which emulates the amount of torque the blades of the wind turbine would extract from the incoming wind. The generator used for the experimental setup is a transverse flux double coil PMSG. A large induction motor was used due to the high cogging torque of the PMSG, this allowed smooth rotation at lower rotational speeds. The specifications and parameters of the PMSG used during the experimental implementation can be seen in [13], [14].

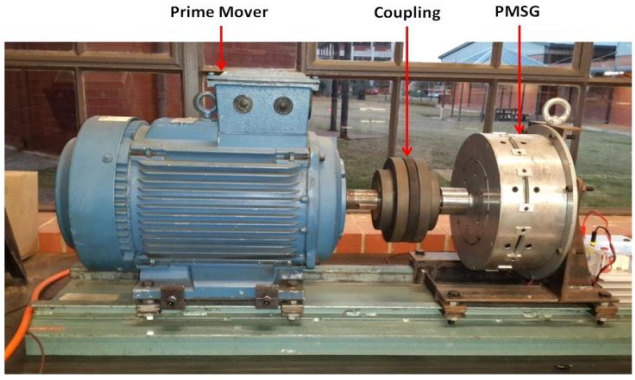



**Fig. 9:** Prime Mover and Generator Coupling.

The boost converter used for the experimental implementation can be seen in figure 10. The boost converter consists of a switching IC, boost converter circuit and voltage and current sensors on the output of the boost converter.

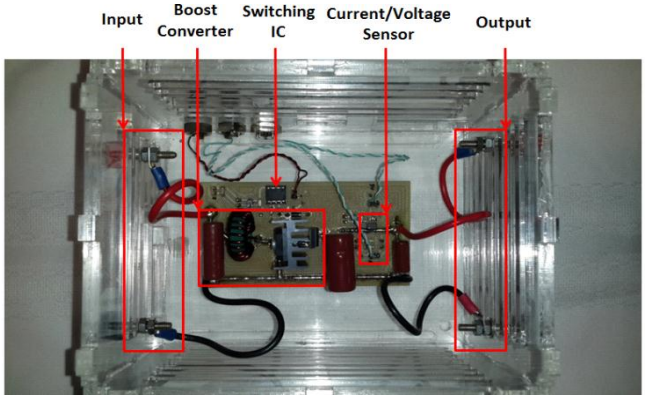



**Fig. 10:** Experimental Boost Converter.

The dSPACE® controller board requires electrical isolation for the inputs and outputs and the protection circuitry can be seen in figure 11. The inputs for the protection are the measurements on the rotational speed, load voltage and load current. The outputs of the protection are the duty cycle to the DC-DC boost converter and the torque set point to the VSD. The inputs are isolated using isolation amplifiers and the outputs are isolated using opto couplers.

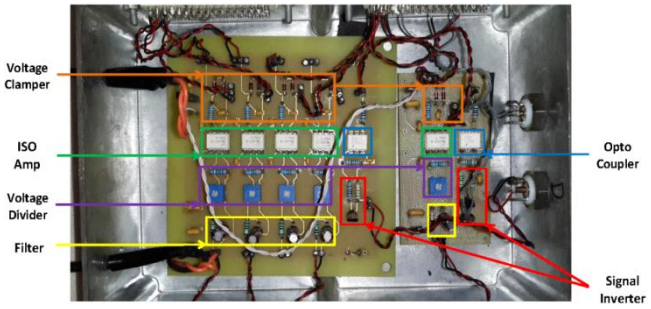



**Fig. 11:** Experimental Controller Protection.

## 4. Experimental results

This section provides the experimental results obtained from the developed system. The controller was tested for both various fixed wind speeds ranging from 6 m/s to 16 m/s as well as a fluctuating wind speed profile under different load conditions. The fluctuating wind speed profile ranges from 6 m/s to 14 m/s and can be seen in figure 12.

The fluctuating wind speed profile was used to represent a realistic representation of the performance of the controller as wind speed constantly changes. The results were obtained under two different load type conditions. The first load type was a purely resistive load of 30 Ω, 64 Ω and 128 Ω and the second load type was an inductive-resistive load with a fixed inductive component of 1.4 mH and a resistive component of 30 Ω, 64 Ω and 128 Ω.

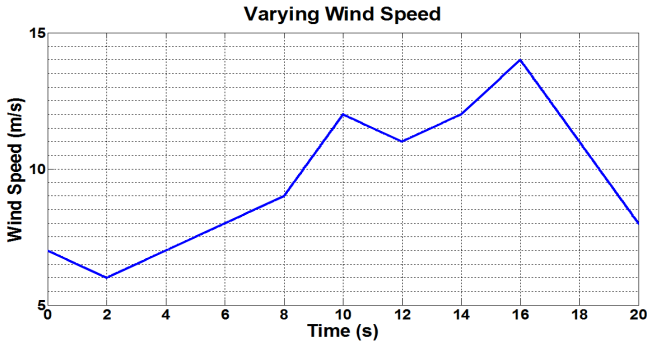



**Fig. 12:** Fluctuating Wind Speed Profile.

### 4.1. Fixed wind speed results

The controller was tested for various fixed wind speeds ranging from 6 m/s to 16 m/s under the different load conditions previously discussed. The results were obtained with a sampling frequency of 1 kHz from dSPACE® Control Desk®'s integrated data acquisition function. The output power of the controlled an uncontrolled generator can be seen in figure 13 at the rated wind speed of 12 m/s and a load of 30 Ω.

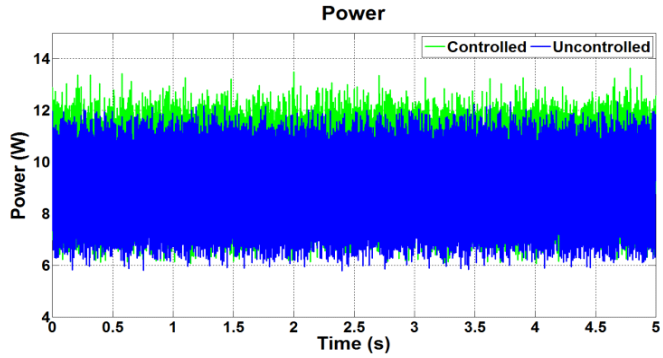



**Fig. 13:** Experimental Controlled and Uncontrolled Generator Output Power at Rated Wind Speed.

On average the uncontrolled generator produces 9.28 W while the controlled generator only produces 9.75 W which can be calculated as a 5.01% power increase for the controlled generator. The output voltage and output current can be seen in figure 14.

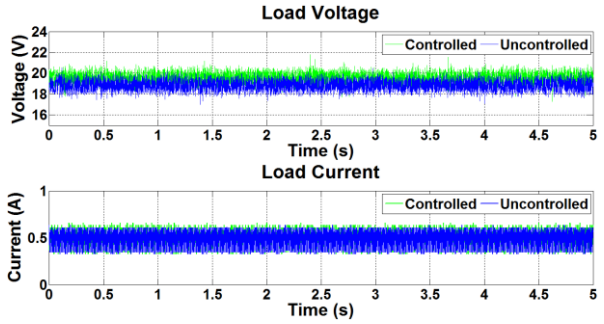



**Fig. 14:** Experimental Controlled and Uncontrolled Generator Output Voltage and Current at Rated Wind Speed.

From figure 14 it can be seen that the uncontrolled and controlled current is similar but the voltage of the controlled generator is higher. On average the uncontrolled generator produces a current and voltage of 0.49 A and 18.85 V while the controlled generator produces a current and voltage of 0.50 A and 19.57 V. The uncontrolled generator has an average rotational speed of 296.28 rpm while the controlled generator has an average rotational speed of 296.21 rpm for the rated wind speed of 12 m/s.

RESISTIVE LOAD: The controller was tested with a purely resistive load of 30 Ω, 64 Ω and 128 Ω at wind speeds ranging from 6 m/s to 16 m/s. The percentage power increase of the controlled generator compared to the uncontrolled generator can be seen in figure 15.

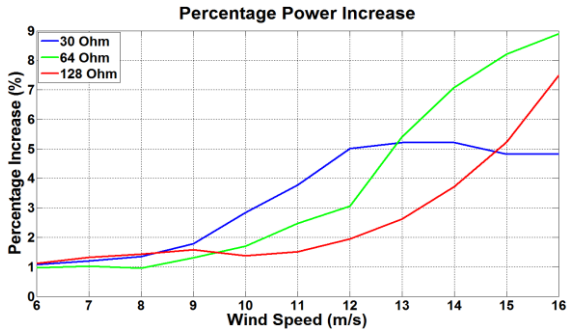



**Fig. 15:** Experimental Resistive Load Percentage Power Increase (Fixed Wind Speed).

From figure 15 it can be seen that the controller increases the overall amount of power extracted by the generator with the exception of a 64 Ω load at a wind speed of 6 m/s and 8 m/s where the controlled generator produces 0.97% and 0.96% of the power of the uncontrolled generator. It can also be seen that at the rated wind speed of 12 m/s the 30 Ω, 64 Ω and 128 Ω increases the amount of power by 5.01%, 3.06% and 1.94% respectively.

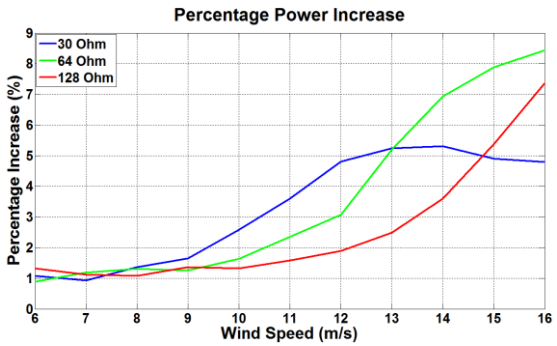



**Fig. 16:** Experimental Inductive-Resistive Load Percentage Power Increase (Fixed Wind Speed).

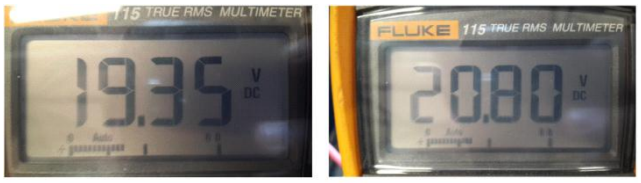
INDUCTIVE-RESISTIVE LOAD: The controller was tested with an inductive-resistive load of 30 Ω, 64 Ω and 128 Ω with an inductive component of 1.4 mH at wind speeds ranging from 6 m/s to 16 m/s. The percentage power increase of the controlled generator compared to the uncontrolled generator can be seen in figure 16.

From figure 16 it can be seen that the controller increases the overall amount of power extracted by the generator with the exception of a 30 Ω and 64 Ω load at a wind speed of 7 m/s and 6 m/s where the controlled generator produces 0.94% and 0.89% of the power of the uncontrolled generator. It can also be seen that at the rated wind speed of 12 m/s the 30 Ω, 64 Ω and 128 Ω increases the amount of power by 4.80%, 3.07% and 1.90% respectively. Table 2 displays the experimental percentage power increase for various wind speeds under various load conditions (both resistive and inductive-resistive).

**Table 2:** Percentage Power Increase for Different Wind Speeds under Different Load Conditions

| Wind Speed | Load Resistive | | | Inductive-Resistive | | |
|---|---|---|---|---|---|---|
| | 30 Ω | 64 Ω | 128 Ω | 30 Ω | 64 Ω | 128 Ω |
| 6 m/s | 1.08% | 0.97% | 1.12% | 1.07% | 0.89% | 1.32% |
| 7 m/s | 1.20% | 1.03% | 1.33% | 0.94% | 1.19% | 1.11% |
| 8 m/s | 1.35% | 0.96% | 1.44% | 1.36% | 1.30% | 1.08% |
| 9 m/s | 1.78% | 1.31% | 1.58% | 1.65% | 1.25% | 1.36% |
| 10 m/s | 2.85% | 1.70% | 1.37% | 2.59% | 1.63% | 1.32% |
| 11 m/s | 3.78% | 2.47% | 1.51% | 3.59% | 2.36% | 1.59% |
| 12 m/s | 5.01% | 3.06% | 1.94% | 4.80% | 3.07% | 1.90% |
| 13 m/s | 5.21% | 5.42% | 2.62% | 5.24% | 5.20% | 2.49% |
| 14 m/s | 5.22% | 7.08% | 3.72% | 5.31% | 6.93% | 3.59% |
| 15 m/s | 4.82% | 8.20% | 5.23% | 4.89% | 7.88% | 5.37% |
| 16 m/s | 4.83% | 8.90% | 7.48% | 4.79% | 8.44% | 7.37% |

EXPERIMENTAL RESULTS: Figure 17 illustrates load voltage measurements taken with a Fluke 115 multimeter at the rated wind speed of 12 m/s and it can be seen that the controlled generator produces a slightly higher load voltage when compared to the uncontrolled generator (19.38 V compared to 21.28 V).




(a) (b)

**Fig. 17:** Experimental Load Voltage Measurements for (A) Uncontrolled and (B) Controlled Generator (Fluke Multimeter).

The load voltage was measured using a TiePie scope at the rated wind speed of 12 m/s and the result can be seen in figure 18. The purple voltage is the uncontrolled load voltage and the blue voltage is the controlled voltage. It can be seen that the controlled generator produces a slightly higher load voltage when compared to the uncontrolled load voltage.

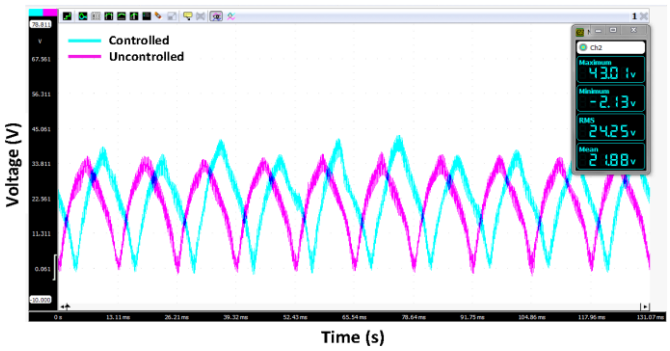



**Fig. 18:** Experimental Load Voltage Measurement (Tiepie Scope).

### 4.2. Fluctuating wind speed results

The results of the fluctuation wind speed previously discussed for the complete experimental setup is discussed in this section. The fluctuating wind speeds used to obtain the results ranges from 6 m/s to 14 m/s and lasts a total of 50 s using the interpolated repeating sequence block in Matlab®/Simulink®. Figure 19 displays the power output of the uncontrolled and controlled generator for the fluctuating wind speed profile (refer to figure 12).

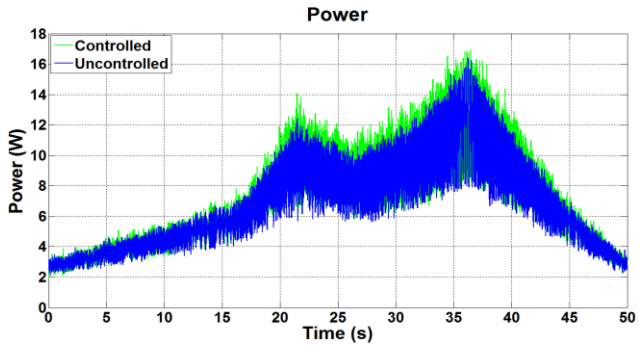



**Fig. 19:** Experimental Controlled and Uncontrolled Generator Output Power for Fluctuating Wind Speed.

On average the uncontrolled generator produces 6.94 W for the fluctuating wind speed profile while the controlled generator produces an average of 7.34 W which can be calculated as a 5.55% increase. The controlled generator produces a minimum and maximum of 2.04 W and 16.95 W while the uncontrolled generator produces a minimum and maximum of 2.01 W and 16.4 W. Figure 20 displays the load voltage and load current of the controlled and uncontrolled generator for the fluctuating wind speed profile. The controlled generator has a peak voltage of 25.47 V while the uncontrolled generator has a peak voltage of 24.15 V. The controlled generator has a peak current of 0.711 A while the uncontrolled generator has a peak current of 0.685 A. The controlled generator has an average current and voltage of 0.46 A and 15.41 V while the uncontrolled generator has an average current and voltage of 0.45 A and 14.81 V for the fluctuating wind speed profile.

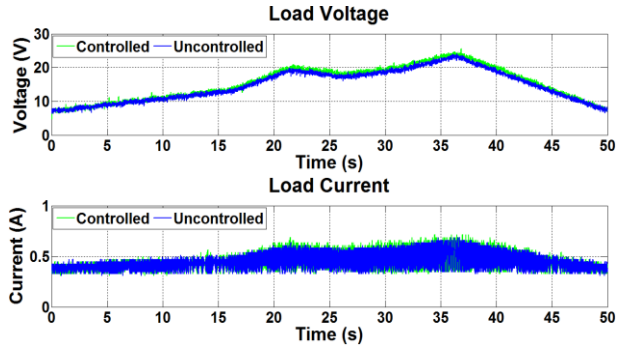



**Fig. 20:** Experimental Controlled and Uncontrolled Generator Output Voltage and Current for Fluctuating Wind Speed.

RESISTIVE LOAD: This section discusses the results obtained from the complete experimental setup for a resistive load for fluctuating wind speeds (refer to figure 12 for fluctuating wind speed profile). The load of these results varies between 30 Ω, 64 Ω and 128 Ω. The percentage power increase between the controlled and uncontrolled generator is 5.55%, 5.26% and 2.33% for the 30 Ω, 64 Ω and 128 Ω load, respectively.

INDUCTIVE-RESISTIVE LOAD: This section discusses the results obtained from the complete experimental setup for an inductive-resistive load for fluctuating wind speeds (refer to figure 12 for fluctuating wind speed profile). The load of these results varies between 30 Ω, 64 Ω and 128 Ω with an inductive component of 1.4 mH. The percentage power increase between the controlled and uncontrolled generator is 5.21%, 4.73% and 2.30% for the 30 Ω, 64 Ω and 128 Ω load, respectively.

## 5. Conclusion

In this paper a new control method that alters the rotational speed of a micro wind turbine in order to improve the power extraction from the incoming wind was presented. The controller measures the rotational speed and output power and ads a delay to both these measurements in order to determine the change from the previous value. The change in both the rotational speed and output power determines the required change in the duty cycle of a DC-DC boost converter.

The experimental results obtained indicate and improvement in the amount of power extracted by the wind turbine both during various fixed wind speeds and fluctuating wind speeds and therefore increases the amount of output power. The control method presented in this paper is also unique since it does not require the speed of the incoming wind as well as the rated output power of the wind turbine.

The amount of power extracted by the generator during the experimental setup is low, since the PMSG is only rated at 1 kW, but the results indicate a percentage improvement between the controlled and uncontrolled generator and a larger generator would therefore produce larger amounts of extracted power.

## Acknowledgments

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## References

[1] C. Clohessy, G. Sharp, and F. Vorster, “Evaluation of noise levels of micro-wind turbines using a randomised experiment,” Nelson Mandela Metropolitan University - Centre for Renewable and Sustainable Energy Studies, Tech. Rep., 2012.

[2] J. van Wijk and M. Kamper, “Double-sided rotor technology for iron-cored permanent magnet wind generators: An evaluation,” IEEE International Conference on Industrial Technology (ICIT), pp. 1892–1897, Feb 2013. https://doi.org/10.1109/ICIT.2013.6505966.

[3] A. Eltamaly, A. Alolah, and H. Farh, Maximum Power Extraction from Utility-Interfaced Wind Turbines, New Developments in Renewable Energy, H. Arman, Ed. InTech Open Access Publisher, 2013. [Online]. Available: http://www.intechopen.com/books/new-developments-in-renewable-energy/maximum-power-extraction-from-utility-interfaced-wind-turbines.

[4] M. Ragheb and A. Ragheb, Wind turbines theory - The betz equation and optimal rotor tip speed ratio, R. Carriveau, Ed. INTECH Open Access Publisher, 2011. https://doi.org/10.5772/21398.

[5] I. Serban and C. Marinescu, “A sensorless control method for variable-speed small wind turbines,” Renewable Energy, vol. 43, pp. 256–266, 2012. https://doi.org/10.1016/j.renene.2011.12.018.

[6] D.N. Veritas, Guidelines for Design of Wind Turbines, 2nd ed., J. Centraltrykkeri, Ed. Det Norske Veritas: Wind Energy Department, Riso, National Laboratory, 2002.

[7] H. Sefidgar and S. Gholamian, “Fuzzy logic control of wind turbine system connection to pm synchronous generator for maximum power point tracking,” I.J. Intelligent Systems and Applications, pp. 29–35, 2014. https://doi.org/10.5815/ijisa.2014.07.04.

[8] R. Shukla, R.D. Tripathi, “Maximum power extraction schemes and power control in wind energy conversion system,” International Journal of Scientific and Engineering Research 3(6), pp. 1–7, June 2012.

[9] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, Wind Energy Handbook. John Wiley and Sons, 2001. https://doi.org/10.1002/0470846062.

[10] G. Putrus, M. Narayana, M. Jovanovic, and P. Leung, “Maximum power point tracking for variable-speed fixed-pitch small wind turbines,” in International Conference on Electricity Distribution (CIRED). CIRED, 2009. https://doi.org/10.1049/cp.2009.0827.

[11] L. Priyadarsini and C. Das, "Emulation of wind turbine using dc motor," Master's thesis, National Institute of Technology, Rourkela, 2014.
[12] S. Botha and R. Gouws," Intelligent controller for improved efficiency of micro wind turbine generators", International Conference on the Industrial and Commercial Use of Energy, Cape Town, South Africa, Aug. 2016, pp. 278-285, ISBN:978-0-9946759-1-0.
[13] O. Dobzhanskyi and R. Gouws, "Performance analysis of a permanent magnet transverse flux generator with double coil," IEEE Transactions on Magnetics 52(1), pp. 1–11, 2016. https://doi.org/10.1109/TMAG.2015.2472371.
[14] O. Dobzhanskyi, R. Gouws, and E. Amiri, "On the role of magnetic shunts for increasing performance of transverse flux machines," IEEE Transactions on Magnetics, 53(2), pp. 1-8, 2016. https://doi.org/10.1109/TMAG.2016.2621047.