

# Intelligent controller for improved efficiency of micro wind turbine generators

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# Declaration

I, Stefan Botha, hereby declare that the dissertation entitled "*Intelligent Controller for Improved Efficiency of Micro Wind Turbine Generators*" is my own original work and has not already been submitted to any other university or institution for examination.

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Signed on the 11th day of November 2016 at Potchefstroom.

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# Executive Summary

Wind turbines are one of the fastest growing forms of renewable energy. This is mainly due to wind turbines being one of the cleanest and cheapest form 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 in order to control the rotational speed and ensure the maximum amount of power is extracted from the wind. This usually involves altering the pitch of the blades or the direction of the wind turbine with regards to the incoming wind. Using these active control techniques to control the rotational speed of micro wind turbine creates mechanical and economical difficulties.

This results in micro wind turbines incorporating passive control techniques with the disadvantage of lower efficiency in controlling the rotational speed, and therefore the amount of power extracted, when compared to active control techniques. For this project a controller was developed that altered the rotational speed of a micro wind turbine in order to increase the amount of power extracted from the incoming wind.

This was done by using a DC-DC boost converter controlled by a fuzzy logic controller on the output of the generator. The controller only requires the rotational speed and power output of the wind turbine generator whereas the majority of controllers require the wind speed and therefore eliminates the difficulties in obtaining exact wind speed due to the wake effect of the wind turbine tower. 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.

After the controller was developed, the design was simulated in Matlab<sup>®</sup>/Simulink<sup>®</sup> and practically implemented using Control Desk<sup>®</sup> and a dSPACE<sup>®</sup> 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<sup>®</sup>, Duty Cycle, Fuzzy Logic, Matlab<sup>®</sup>/Simulink<sup>®</sup>, PMSG

# Opsomming

Windturbines is een van die vinnigste groeiende vorms van hernubare energie. Dit is hoofsaaklik te danke aan die feit dat wind energie een van die skoonste en goedkoopste vorms van hernubare energie is. Die hoeveelheid drywing wat 'n windturbine uit die inkomende wind onttrek is afhanklik van die rotasiespoed en vir elke wind spoed is daar 'n optimale rotasiespoed wat die meeste drywing sal onttrek van die inkomende wind.

Groot windturbines maak gebruik van aktiewe beheer tegnieke om die rotasiespoed te beheer en te verseker dat die maksimum hoeveelheid drywing uit die wind onttrek word. Dit behels gewoonlik om die lem steek of die rigting van die windturbine met betrekking tot die inkomende wind te verander. Om hierdie aktiewe beheer tegnieke op mikro-windturbines te gebruik lei na meganiese en ekonomiese probleme.

Dit het die gevolg dat mikro-windturbines gebruik maak van passiewe beheer tegnieke wat die nadeel het van laer effektiwiteit om die rotasiespoed te beheer in vergelyking met aktiewe beheer tegnieke. 'n Beheerder moet ontwerp word wat die rotasiespoed van 'n mikro-windturbine kan beheer en sodoende die hoeveelheid drywing wat uit die inkomende wind onttrek word verhoog.

Dit kan gedoen word deur 'n GS-GS opstapversterker wat beheer word met wasige logika op die uitset van die generator te koppel. Die beheerder benodig slegs die rotasiespoed en uitset drywing van generator waar die meerderheid van beheerders die spoed van die inkomende wind benodig. Die beheerder oorkom dus die probleme wat geasosieer word om presiese wind spoed te meet as gevolg van die nasleep effek van die windturbinetoring. Die beheerder bepaal die nodige verandering in die dienssiklus van die GS-GS opstapversterker wat die elektromeganiese wringkrag van die generator beheer.

Na die beheerder ontwikkel was, was die ontwerp gesimuleer in Matlab<sup>®</sup>/Simulink<sup>®</sup> en prakties toegepas deur gebruik te maak van Control Desk<sup>®</sup> en 'n dSPACE<sup>®</sup> DS1104 beheerbord op 'n 1 kW mikro-windturbinegenerator. Beide die simulasies en eksperimentele resultate bevestig dat die beheerder die hoeveelheid drywing wat deur die wind turbine onttrek word verhoog, veral vir 'n toenemende wind spoed.

**Slutelwoorde:** dSPACE<sup>®</sup>, Dienssiklus, GS-GS Opstapversterker, Matlab<sup>®</sup>/Simulink<sup>®</sup>, PMSG, Wasige logika

# Table of Contents

|                                                           |             |
|-----------------------------------------------------------|-------------|
| <b>Declaration</b>                                        | <b>ii</b>   |
| <b>Acknowledgements</b>                                   | <b>iii</b>  |
| <b>Executive Summary</b>                                  | <b>iv</b>   |
| <b>Opsomming</b>                                          | <b>v</b>    |
| <b>List of Figures</b>                                    | <b>vi</b>   |
| <b>List of Tables</b>                                     | <b>vi</b>   |
| <b>List of Acronyms</b>                                   | <b>xv</b>   |
| <b>List of Symbols &amp; Units</b>                        | <b>xvii</b> |
| <b>1 Introduction</b>                                     | <b>1</b>    |
| 1.1 Background . . . . .                                  | 1           |
| 1.1.1 Eskom's Alternative Energy . . . . .                | 1           |
| 1.1.2 Eskom's Wind Energy . . . . .                       | 1           |
| 1.2 Wind Energy . . . . .                                 | 2           |
| 1.2.1 Wind Power . . . . .                                | 2           |
| 1.2.2 Wind Turbine Orientation Types . . . . .            | 3           |
| 1.2.3 Control System . . . . .                            | 4           |
| 1.2.4 Wind Turbine Advantages and Disadvantages . . . . . | 5           |
| 1.2.5 Wind Turbine Limitations . . . . .                  | 6           |
| 1.3 Problem Statement . . . . .                           | 7           |
| 1.4 Objectives . . . . .                                  | 8           |
| 1.5 Research Methodology . . . . .                        | 8           |
| 1.5.1 Problem Identification . . . . .                    | 9           |
| 1.5.2 Literature Study . . . . .                          | 9           |
| 1.5.3 Design . . . . .                                    | 9           |
| 1.5.4 Simulation . . . . .                                | 9           |
| 1.5.5 Experimental Implementation . . . . .               | 10          |
| 1.5.6 Analysis . . . . .                                  | 10          |
| 1.5.7 Verification and Validation . . . . .               | 10          |

---

|          |                                                              |           |
|----------|--------------------------------------------------------------|-----------|
| 1.5.8    | Key Research Questions . . . . .                             | 10        |
| 1.6      | Dissertation Overview . . . . .                              | 11        |
| 1.7      | Publications and Peer Reviews . . . . .                      | 12        |
| 1.8      | Conclusion . . . . .                                         | 13        |
| <b>2</b> | <b>Literature Study</b>                                      | <b>14</b> |
| 2.1      | General Wind Turbine Overview . . . . .                      | 14        |
| 2.1.1    | Rotational Orientation . . . . .                             | 16        |
| 2.1.2    | Generator Driven . . . . .                                   | 20        |
| 2.2      | Wind Turbine Power . . . . .                                 | 22        |
| 2.2.1    | Wind Power . . . . .                                         | 22        |
| 2.2.2    | Power Control . . . . .                                      | 24        |
| 2.2.3    | Maximum Power Point Tracing . . . . .                        | 28        |
| 2.3      | Generator . . . . .                                          | 32        |
| 2.3.1    | Fixed Speed Generator . . . . .                              | 32        |
| 2.3.2    | Limited Variable Speed Generator . . . . .                   | 34        |
| 2.3.3    | Variable Speed Generator (Partial scale converter) . . . . . | 34        |
| 2.3.4    | Variable Speed Generator (Full scale converter) . . . . .    | 36        |
| 2.4      | Control Topology . . . . .                                   | 39        |
| 2.4.1    | Fuzzy Logic . . . . .                                        | 40        |
| 2.4.2    | Neural Network . . . . .                                     | 43        |
| 2.4.3    | Neuro-Fuzzy . . . . .                                        | 45        |
| 2.4.4    | Proportional Integral Derivative . . . . .                   | 48        |
| 2.5      | Controller . . . . .                                         | 50        |
| 2.5.1    | Arduino . . . . .                                            | 50        |
| 2.5.2    | BeagleBoard . . . . .                                        | 52        |
| 2.5.3    | dSPACE® . . . . .                                            | 53        |
| 2.5.4    | PandaBoard . . . . .                                         | 54        |
| 2.5.5    | Programmable Logic Controller . . . . .                      | 55        |
| 2.5.6    | Raspberry Pi . . . . .                                       | 55        |
| 2.6      | Software . . . . .                                           | 56        |
| 2.6.1    | FAST . . . . .                                               | 57        |
| 2.6.2    | Matlab®/Simulink® . . . . .                                  | 58        |
| 2.7      | Standards . . . . .                                          | 59        |
| 2.7.1    | Germanischer Lloyd Rules for Certification . . . . .         | 59        |
| 2.7.2    | International Electrotechnical Commission . . . . .          | 59        |
| 2.8      | Conclusion . . . . .                                         | 60        |

---

---

|          |                                                  |            |
|----------|--------------------------------------------------|------------|
| <b>3</b> | <b>Design</b>                                    | <b>62</b>  |
| 3.1      | Overhead Control Scheme . . . . .                | 62         |
| 3.2      | Functional Flow . . . . .                        | 63         |
| 3.2.1    | Overhead Functional Flow . . . . .               | 63         |
| 3.2.2    | Lower Level Functional Units . . . . .           | 64         |
| 3.3      | Detail Design . . . . .                          | 68         |
| 3.3.1    | Design Considerations . . . . .                  | 68         |
| 3.3.2    | Lower Level Functional Units . . . . .           | 69         |
| 3.3.3    | Fuzzy Logic Controller . . . . .                 | 77         |
| 3.3.4    | Simulation and Experimental Parameters . . . . . | 82         |
| 3.4      | Verification and Validation . . . . .            | 88         |
| 3.5      | Conclusion . . . . .                             | 88         |
| <b>4</b> | <b>Simulation Results</b>                        | <b>89</b>  |
| 4.1      | Functional Units . . . . .                       | 89         |
| 4.1.1    | Primary Power Supply . . . . .                   | 89         |
| 4.1.2    | Low Pass Filter . . . . .                        | 90         |
| 4.1.3    | Voltage Clamper . . . . .                        | 90         |
| 4.1.4    | Voltage Divider and Isolation . . . . .          | 91         |
| 4.1.5    | Signal Inverter . . . . .                        | 95         |
| 4.1.6    | Boost Converter . . . . .                        | 96         |
| 4.2      | Complete System . . . . .                        | 97         |
| 4.2.1    | Start-Up Conditions . . . . .                    | 98         |
| 4.2.2    | Steady State Conditions . . . . .                | 99         |
| 4.3      | Verification and Validation . . . . .            | 105        |
| 4.4      | Conclusion . . . . .                             | 106        |
| <b>5</b> | <b>Experimental Results</b>                      | <b>107</b> |
| 5.1      | Functional Units . . . . .                       | 107        |
| 5.1.1    | Primary Power Supply . . . . .                   | 107        |
| 5.1.2    | Current Sensor . . . . .                         | 108        |
| 5.1.3    | Voltage Sensor . . . . .                         | 109        |
| 5.1.4    | Boost Converter . . . . .                        | 109        |
| 5.1.5    | Controller Protection . . . . .                  | 112        |
| 5.2      | Experimental Setup . . . . .                     | 113        |
| 5.2.1    | Functional Units . . . . .                       | 114        |
| 5.2.2    | Complete System . . . . .                        | 119        |

---

---

|          |                                           |            |
|----------|-------------------------------------------|------------|
| 5.3      | Complete System Results . . . . .         | 123        |
| 5.3.1    | Fixed Wind Speed . . . . .                | 123        |
| 5.3.2    | Fluctuating Wind Speed . . . . .          | 127        |
| 5.4      | Verification and Validation . . . . .     | 130        |
| 5.5      | Conclusion . . . . .                      | 130        |
| <b>6</b> | <b>Conclusion and Recommendations</b>     | <b>132</b> |
| 6.1      | Dissertation Overview . . . . .           | 132        |
| 6.2      | Results . . . . .                         | 133        |
| 6.2.1    | Design . . . . .                          | 133        |
| 6.2.2    | Simulations . . . . .                     | 133        |
| 6.2.3    | Experimental . . . . .                    | 133        |
| 6.3      | Pay-off Period . . . . .                  | 134        |
| 6.4      | Verification and Validation . . . . .     | 134        |
| 6.5      | Key Research Questions . . . . .          | 135        |
| 6.6      | Recommendations for Future Work . . . . . | 136        |
| 6.6.1    | Simulations . . . . .                     | 136        |
| 6.6.2    | Generator . . . . .                       | 136        |
| 6.6.3    | Capacitor . . . . .                       | 136        |
| 6.6.4    | Wind Speed . . . . .                      | 136        |
| 6.6.5    | Complete Controller . . . . .             | 137        |
| 6.7      | Conclusion . . . . .                      | 137        |
|          | <b>Bibliography</b>                       | <b>138</b> |
|          | <b>Appendices</b>                         |            |
| <b>A</b> | <b>Publications and Presentations</b>     | <b>149</b> |
| A.1      | Publications . . . . .                    | 149        |
| <b>B</b> | <b>Turnit-In Report</b>                   | <b>166</b> |
| B.1      | Turnit-In Report . . . . .                | 166        |
| <b>C</b> | <b>Folder Content</b>                     | <b>167</b> |
| C.1      | Folder Content . . . . .                  | 167        |

# List of Figures

|             |                                                                                                                                           |    |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.1  | HAWT and VAWT [16]                                                                                                                        | 3  |
| Figure 1.2  | Typical output power curve of HAWT [20]                                                                                                   | 4  |
| Figure 1.3  | Verification and validation process                                                                                                       | 10 |
| Figure 2.1  | Literature study chapter overview                                                                                                         | 14 |
| Figure 2.2  | Citations and case studies                                                                                                                | 15 |
| Figure 2.3  | General wind turbine overview section overview                                                                                            | 16 |
| Figure 2.4  | Upwind and downwind wind turbine [42]                                                                                                     | 18 |
| Figure 2.5  | Counter rotating wind turbine (a) output power and (b) construction [44]                                                                  | 18 |
| Figure 2.6  | (a) Different types of VAWTs [9] and (b) savonuis working principle [16]                                                                  | 19 |
| Figure 2.7  | Gearbox driven and direct driven wind turbine [47]                                                                                        | 21 |
| Figure 2.8  | Wind turbine power section overview                                                                                                       | 22 |
| Figure 2.9  | Lift and drag forces for increasing angle of attack [62]                                                                                  | 25 |
| Figure 2.10 | Blade angle change for active pitch control and active stall control [7]                                                                  | 27 |
| Figure 2.11 | (a) Pitch and (b) yaw control [20]                                                                                                        | 28 |
| Figure 2.12 | Power coefficient ( $C_p$ ) vs. tip speed ratio ( $\lambda$ ) [33]                                                                        | 28 |
| Figure 2.13 | Optimal tip speed ration control configuration [66]                                                                                       | 29 |
| Figure 2.14 | Optimal torque control configuration [67]                                                                                                 | 30 |
| Figure 2.15 | Power signal feedback control configuration [67]                                                                                          | 31 |
| Figure 2.16 | Optimal tip speed ration control configuration [67]                                                                                       | 32 |
| Figure 2.17 | Generator section overview                                                                                                                | 33 |
| Figure 2.18 | (a) Fixed speed squirrel cage induction generator and (b) limited variable speed wound rotor induction generator [17]                     | 35 |
| Figure 2.19 | Double fed induction generator with partial scale converter [17]                                                                          | 36 |
| Figure 2.20 | Direct drive (a) electrically excited synchronous generator and (b) permanent magnet synchronous generator with full scale converter [17] | 38 |
| Figure 2.21 | Variable speed squirrel cage induction generator with full scale converter [17]                                                           | 38 |
| Figure 2.22 | Controller section overview                                                                                                               | 39 |
| Figure 2.23 | Closed loop control system [78]                                                                                                           | 39 |
| Figure 2.24 | Control system step response [80]                                                                                                         | 40 |
| Figure 2.25 | Fuzzy system [83]                                                                                                                         | 41 |

---

|             |                                                                                            |    |
|-------------|--------------------------------------------------------------------------------------------|----|
| Figure 2.26 | Most common types of membership functions [87] . . . . .                                   | 42 |
| Figure 2.27 | Structure of an artificial neuron [94] . . . . .                                           | 44 |
| Figure 2.28 | (a) Feed-forward and (b) feed-back architecture [97] . . . . .                             | 44 |
| Figure 2.29 | (a) Concurrent system and (b) cooperative system structure [90] .                          | 45 |
| Figure 2.30 | (a) ANFIS [98] and (b) EFuNN structure [99] . . . . .                                      | 46 |
| Figure 2.31 | (a) FALCON and (b) GARIC structure [91] . . . . .                                          | 47 |
| Figure 2.32 | Controller section overview . . . . .                                                      | 50 |
| Figure 2.33 | Arduino Uno development board [107] . . . . .                                              | 51 |
| Figure 2.34 | dSPACE <sup>®</sup> development board [114] . . . . .                                      | 53 |
| Figure 2.35 | Matlab <sup>®</sup> /Simulink <sup>®</sup> dSPACE <sup>®</sup> connections [113] . . . . . | 54 |
| Figure 2.36 | Software section overview . . . . .                                                        | 56 |
| Figure 2.37 | Simulation packages available for wind turbines [129] . . . . .                            | 57 |
| Figure 2.38 | Standards section overview . . . . .                                                       | 59 |
| Figure 3.1  | Design chapter overview . . . . .                                                          | 62 |
| Figure 3.2  | Overhead control scheme . . . . .                                                          | 63 |
| Figure 3.3  | Overhead functional flow . . . . .                                                         | 63 |
| Figure 3.4  | Second level functional unit (Controller Protection) . . . . .                             | 64 |
| Figure 3.5  | Input signals functional unit (Controller Protection) . . . . .                            | 65 |
| Figure 3.6  | Output signals functional unit (Controller Protection) . . . . .                           | 65 |
| Figure 3.7  | Second level functional unit (Prime Mover) . . . . .                                       | 66 |
| Figure 3.8  | Second level functional unit (Prime Mover) . . . . .                                       | 66 |
| Figure 3.9  | Second level functional unit (Power Converter) . . . . .                                   | 67 |
| Figure 3.10 | Sensors functional flow . . . . .                                                          | 68 |
| Figure 3.11 | Primary power supply functional unit . . . . .                                             | 70 |
| Figure 3.12 | Primary power supply flow diagram . . . . .                                                | 70 |
| Figure 3.13 | Low pass filter . . . . .                                                                  | 71 |
| Figure 3.14 | Voltage divider circuit . . . . .                                                          | 72 |
| Figure 3.15 | Voltage sensor equivalent circuit . . . . .                                                | 74 |
| Figure 3.16 | Boost converter general circuit . . . . .                                                  | 75 |
| Figure 3.17 | Overhead control approach . . . . .                                                        | 78 |
| Figure 3.18 | Fuzzy logic control approach . . . . .                                                     | 78 |
| Figure 3.19 | Detailed fuzzy logic control approach . . . . .                                            | 79 |
| Figure 3.20 | Fuzzy logic controller sub system . . . . .                                                | 79 |
| Figure 3.21 | Rotational speed membership function . . . . .                                             | 80 |
| Figure 3.22 | Power membership function . . . . .                                                        | 80 |
| Figure 3.23 | Duty cycle membership function . . . . .                                                   | 81 |
| Figure 3.24 | Fuzzy rules surface view . . . . .                                                         | 82 |

---

---

|             |                                                                             |     |
|-------------|-----------------------------------------------------------------------------|-----|
| Figure 3.25 | Overhead simulation/experimental scheme . . . . .                           | 83  |
| Figure 3.26 | Matlab®/Simulink® wind emulator subsystem . . . . .                         | 84  |
| Figure 3.27 | Fluctuating wind speed profile . . . . .                                    | 85  |
| Figure 3.28 | Complete system simulation model . . . . .                                  | 87  |
| Figure 4.1  | Simulation results chapter overview . . . . .                               | 89  |
| Figure 4.2  | Primary power supply simulation circuit . . . . .                           | 90  |
| Figure 4.3  | First order low pass filter simulation result . . . . .                     | 90  |
| Figure 4.4  | Voltage clamper simulation circuit . . . . .                                | 91  |
| Figure 4.5  | Voltage clamper simulation result . . . . .                                 | 91  |
| Figure 4.6  | Voltage sensor simulation circuit . . . . .                                 | 92  |
| Figure 4.7  | Voltage sensor simulation result . . . . .                                  | 92  |
| Figure 4.8  | Isolation amplifier simulation circuit (Current) . . . . .                  | 93  |
| Figure 4.9  | Isolation amplifier simulation result (Current) . . . . .                   | 94  |
| Figure 4.10 | Isolation amplifier simulation circuit (Voltage and speed) . . . . .        | 94  |
| Figure 4.11 | Isolation amplifier simulation results (Voltage and speed) . . . . .        | 95  |
| Figure 4.12 | Signal inverter simulation circuit . . . . .                                | 95  |
| Figure 4.13 | Signal inverter simulation result . . . . .                                 | 96  |
| Figure 4.14 | Boost converter boost ratio simulation result . . . . .                     | 96  |
| Figure 4.15 | Boost converter output power and output voltage simulation result . . . . . | 97  |
| Figure 4.16 | Start up rotational speed and power coefficient simulation result . . . . . | 98  |
| Figure 4.17 | Start up power and power difference simulation result . . . . .             | 99  |
| Figure 4.18 | Rated wind speed power coefficient (simulation) . . . . .                   | 99  |
| Figure 4.19 | Rated wind speed rotational speed (simulation) . . . . .                    | 100 |
| Figure 4.20 | Rated wind speed power (simulation) . . . . .                               | 100 |
| Figure 4.21 | Rated wind speed voltage (simulation) . . . . .                             | 101 |
| Figure 4.22 | Rated wind speed power difference (simulation) . . . . .                    | 101 |
| Figure 4.23 | Fluctuating wind speed power coefficient (simulation) . . . . .             | 103 |
| Figure 4.24 | Fluctuating wind speed rotational speed (simulation) . . . . .              | 103 |
| Figure 4.25 | Fluctuating wind speed power (simulation) . . . . .                         | 104 |
| Figure 4.26 | Fluctuating wind speed voltage and current (simulation) . . . . .           | 104 |
| Figure 4.27 | Fluctuating wind speed duty cycle (simulation) . . . . .                    | 105 |
| Figure 5.1  | Experimental results chapter overview . . . . .                             | 107 |
| Figure 5.2  | Current sensor experimental result . . . . .                                | 108 |
| Figure 5.3  | Voltage sensor experimental result . . . . .                                | 109 |
| Figure 5.4  | Boost converter efficiency and boost ratio (Experimental) . . . . .         | 110 |
| Figure 5.5  | Boost converter input and output voltage (Experimental) . . . . .           | 111 |
| Figure 5.6  | Boost converter input and output power (Experimental) . . . . .             | 111 |

---

---

|             |                                                                                                               |     |
|-------------|---------------------------------------------------------------------------------------------------------------|-----|
| Figure 5.7  | Controller protection experimental result (Current) . . . . .                                                 | 112 |
| Figure 5.8  | Controller protection experimental result (Voltage and speed) . .                                             | 113 |
| Figure 5.9  | Primary power supply illustration (experimental) . . . . .                                                    | 114 |
| Figure 5.10 | (a) VSD (b) Prime mover and generator coupling illustration (ex-<br>perimental) . . . . .                     | 115 |
| Figure 5.11 | Generator (experimental) . . . . .                                                                            | 116 |
| Figure 5.12 | Base values for generator under different load conditions (exper-<br>imental) . . . . .                       | 117 |
| Figure 5.13 | Boost converter illustration (experimental) . . . . .                                                         | 117 |
| Figure 5.14 | Controller protection illustration (experimental) . . . . .                                                   | 118 |
| Figure 5.15 | Complete experimental setup illustration (experimental) . . . . .                                             | 119 |
| Figure 5.16 | Experimental Control Desk <sup>®</sup> Model . . . . .                                                        | 121 |
| Figure 5.17 | Experimental dSPACE <sup>®</sup> Matlab <sup>®</sup> /Simulink <sup>®</sup> model . . . . .                   | 122 |
| Figure 5.18 | Rated wind speed power (experimental) . . . . .                                                               | 123 |
| Figure 5.19 | Rated wind load voltage and load current (experimental) . . . . .                                             | 124 |
| Figure 5.20 | Experimental fixed wind speed percentage power increase (resis-<br>tive load) . . . . .                       | 125 |
| Figure 5.21 | Experimental fixed wind speed percentage power increase (inductive-<br>resistive) . . . . .                   | 125 |
| Figure 5.22 | Experimental load voltage measurement for (a) uncontrolled and<br>(b) controlled (Fluke Multimeter) . . . . . | 126 |
| Figure 5.23 | Experimental load voltage measurement (TiePie Scope) . . . . .                                                | 127 |
| Figure 5.24 | Fluctuating wind speed power (experimental) . . . . .                                                         | 128 |
| Figure 5.25 | Fluctuating wind speed voltage and current (experimental) . . . .                                             | 128 |
| Figure 5.26 | Fluctuating wind speed duty cycle (experimental) . . . . .                                                    | 129 |
| Figure 6.1  | Verification and validation . . . . .                                                                         | 135 |
| Figure B.1  | Turnit-In report . . . . .                                                                                    | 166 |

# List of Tables

|           |                                                                                                       |     |
|-----------|-------------------------------------------------------------------------------------------------------|-----|
| Table 1.1 | Eskom's alternative electricity generation and their capabilities . . .                               | 1   |
| Table 1.2 | Klipheuwel wind turbine ratings . . . . .                                                             | 2   |
| Table 2.1 | Comparison between HAWT and VAWT . . . . .                                                            | 17  |
| Table 2.2 | Effect of increasing controller gain . . . . .                                                        | 49  |
| Table 2.3 | Comparison between Arduino Uno, Arduino Mega2560 and Arduino Due . . . . .                            | 52  |
| Table 2.4 | Comparison between BeagleBone Black, xM and x15 . . . . .                                             | 53  |
| Table 2.5 | Comparison between Raspberry Pi Model A+, Raspberry Pi Model B+ and Raspberry Pi 2 Model B . . . . .  | 56  |
| Table 3.1 | Fuzzy logic rule table . . . . .                                                                      | 81  |
| Table 3.2 | Wind Turbine Parameters . . . . .                                                                     | 86  |
| Table 3.3 | PMSG Parameters . . . . .                                                                             | 86  |
| Table 4.1 | Percentage power increase for various fixed wind speeds (simulation) . . . . .                        | 102 |
| Table 5.1 | Experimental signal inverter output voltage and duty cycle error .                                    | 113 |
| Table 5.2 | Prime mover specifications . . . . .                                                                  | 115 |
| Table 5.3 | Experimental generator specifications . . . . .                                                       | 115 |
| Table 5.4 | Generator output base values (experimental) . . . . .                                                 | 116 |
| Table 5.5 | Updated controller parameters simulation results (percentage power difference) . . . . .              | 119 |
| Table 5.6 | Fixed wind speed resistive and inductive-resistive percentage power increase (experimental) . . . . . | 126 |

# List of Acronyms

|               |                                                             |
|---------------|-------------------------------------------------------------|
| <b>AC</b>     | Alternating current                                         |
| <b>AEN</b>    | Action state evaluation                                     |
| <b>ANFIS</b>  | Adaptive neuro-fuzzy inference system                       |
| <b>ANN</b>    | Artificial neural network                                   |
| <b>ASN</b>    | Action selection network                                    |
| <b>CPU</b>    | Central processing unit                                     |
| <b>DC</b>     | Direct current                                              |
| <b>DFIG</b>   | Doubly fed induction generator                              |
| <b>DSP</b>    | Digital signal processor                                    |
| <b>EESG</b>   | Electrically excited synchronous generator                  |
| <b>EFuNN</b>  | Evolving fuzzy neural network                               |
| <b>FALCON</b> | Fuzzy adaptive learning control network                     |
| <b>FAST</b>   | Fatigue aerodynamics structures and turbulence              |
| <b>FBD</b>    | Functional block diagram                                    |
| <b>FIS</b>    | Fuzzy inference system                                      |
| <b>FUN</b>    | Fuzzy net                                                   |
| <b>GARIC</b>  | Generalized approximate reasoning based intelligent control |
| <b>GCIG</b>   | Grid connected induction generator                          |
| <b>HAWT</b>   | Horizontal axis wind turbine                                |
| <b>HCS</b>    | Hill climb searching                                        |
| <b>IEC</b>    | International electro-technical commission                  |
| <b>IED</b>    | Intelligent electronic devices                              |
| <b>IL</b>     | Instruction list                                            |
| <b>LD</b>     | Ladder logic                                                |
| <b>MPPT</b>   | Maximum power point tracking                                |
| <b>NdFeB</b>  | Neodymium                                                   |
| <b>OT</b>     | Optimal torque                                              |
| <b>PD</b>     | Proportional derivative                                     |
| <b>PI</b>     | Proportional integrative                                    |
| <b>PID</b>    | Proportional integrative derivative                         |
| <b>PLC</b>    | Programmable logic controller                               |
| <b>PMSG</b>   | Permanent magnet synchronous generator                      |
| <b>PSF</b>    | Power signal feedback                                       |
| <b>PSO</b>    | Particle swarm optimization                                 |
| <b>PWM</b>    | Pulse width modulation                                      |

---

|              |                                      |
|--------------|--------------------------------------|
| <b>RBFNN</b> | Radial basis function neural network |
| <b>SCIG</b>  | Squirrel cage induction generator    |
| <b>SEIG</b>  | Self-excited induction generator     |
| <b>SFC</b>   | Sequential function chart            |
| <b>SISO</b>  | Single input single output           |
| <b>ST</b>    | Structured text                      |
| <b>TSR</b>   | Tip speed ratio                      |
| <b>VAWT</b>  | Vertical axis wind turbine           |
| <b>VSD</b>   | Variable speed drive                 |
| <b>WRIG</b>  | Wound rotor induction generator      |

# List of Symbols & Units

## List of Symbols

|           |                    |
|-----------|--------------------|
| $T_M$     | Aerodynamic torque |
| $\rho$    | Air density        |
| $\beta$   | Blade pitch angle  |
| $A_s$     | Blade swept area   |
| $D$       | Duty Cycle         |
| $f$       | Frequency          |
| $\pi$     | Pi                 |
| $P$       | Power              |
| $C_p$     | Power coefficient  |
| $\omega$  | Rotational speed   |
| $R$       | Rotor diameter     |
| $\lambda$ | Tip speed ratio    |
| $C_T$     | Torque coefficient |
| $v$       | Velocity           |

## List of Units

|          |                          |
|----------|--------------------------|
| $A$      | Ampere                   |
| $dB$     | Decibel                  |
| $F$      | Farad                    |
| $H$      | Henry                    |
| $Hz$     | Hertz                    |
| $kB$     | Kilobyte                 |
| $kg/m^3$ | Kilogram per cubic meter |
| $m$      | Meter                    |
| $m/s$    | Meter per second         |
| $\Omega$ | Ohm                      |
| $pu$     | Per unit                 |
| $rad/s$  | Radials per second       |
| $rpm$    | Revolutions per minute   |
| $m^2$    | Square meter             |
| $V$      | Volt                     |
| $W$      | Watt                     |

# Introduction

---

*This chapter provides a brief introduction to the project. A in depth discussion of the problem statement and the objectives of the project is given. It also provides a brief overview on the layout of the document with a brief discussion as to what can be expected in each chapter.*

---

## 1.1 Background

Eskom is the primary generator and distributor of electricity in South Africa, producing 95% of all the electricity used in South Africa and 45% of the electricity used in the rest Africa [1]. The majority of this electricity is generated by Eskom's coal-power stations, which accounts for 34 745 MW of the 44 048 MW Eskom is capable of supplying [2]. Two additional coal-power station are currently in construction which, when completed, will provide an additional 9 600 MW of electricity [2].

### 1.1.1 Eskom's Alternative Energy

Eskom's alternative methods for generating electricity include nuclear, hydro, gas and wind. These alternative methods, as well as their contributions to Eskom's grid, can be seen in descending order in table 1.1 [2].

Table 1.1: Eskom's alternative electricity generation and their capabilities

| Alternative energy method | Contribution |
|---------------------------|--------------|
| Gas fire                  | 2 426 MW     |
| Nuclear                   | 1 910 MW     |
| Pumped storage            | 1 400 MW     |
| Hydro station             | 580 MW       |
| Wind                      | 3.16 MW      |

### 1.1.2 Eskom's Wind Energy

The first wind farm in South Africa was commissioned in 2003 and located at Klipheuwel in the Western Cape. The wind farm consists of three different wind turbines with a combined capacity of 3.16 MW [3]. Table 1.2 illustrates the three types, as well as the rated output for each wind turbine erected at Klipheuwel [3].

The purpose of the Klipheuwel wind farm was to test the feasibility of wind turbines in South Africa, as well as compare the performance of each of the above mentioned wind turbines in order to find a suitable wind turbine type. During the testing of the

Table 1.2: Klipheuwel wind turbine ratings

| Wind turbine | Rated output |
|--------------|--------------|
| Vestas V66   | 1 750 kW     |
| Jeumont J48  | 750 kW       |
| Vestas V47   | 660 kW       |

Klipheuwel wind farm, it was found that wind turbines can be considered as a viable renewable energy source in multiple areas of South Africa. This inspired Eskom to create the Sere wind farm project, which is located within the Matzikama municipality in the Western Cape. The first wind turbine was erected in December 2013 and the project was completed in early 2016. The wind farm consists of 46 wind turbines, each capable of providing 2.3 MW of power and contributes 105.8 MW of power to Eskom's grid through the Skaapvlei substation [1], [2]. South Africa's department of Science and Technology predicts that the amount of energy South Africa produces by means of renewable energy sources, will increase to 5% by 2018 [4].

## 1.2 Wind Energy

Wind energy is sometimes referred to as indirect solar energy. This is due to sunlight unevenly heating the surface of the earth, causing high and low pressure areas. The air moves from the higher pressure areas to the lower pressure areas and this movement of air is known as wind [5].

### 1.2.1 Wind Power

The idea of harnessing the power of the wind has been around for centuries [6]. Wind turbines convert the kinetic energy of wind into another form of energy and were initially used for grinding grain and pumping water [7], with the first electricity only being produced in the late 1800's [8], [9]. The first turbine used to produce electricity was an off-grid wind turbine with a rating of only 12 kW [7], [8]. Today the largest on shore wind turbine has a output power rating of 6 MW at a height of 135 m, and the largest off shore wind turbine is rated at 8 MW with a height of 140 m [10]. These wind turbines are classified as large wind turbines, due to their high power production capabilities and usually provides power directly to the grid. Wind turbines that have a rating below 30 kW are generally known as micro wind turbines [11] and are usually used for residential and rural purposes. These small wind turbines are seldom connected to the grid and usually provides direct power or charges batteries.

## 1.2.2 Wind Turbine Orientation Types

Wind turbines can broadly be categorized into either horizontal axis wind turbine (HAWT) or vertical axis wind turbine (VAWT), with the former being the more popular design choice [9], [12], [13], [14] due to their higher levels of controllability. This classification refers to the axis of rotation of the wind turbine blades [15], a more in depth discussion on HAWTs and VAWTs is provided in the literature study. Figure 1.1 (a) illustrates the structural difference between HAWTs and VAWTs [16].

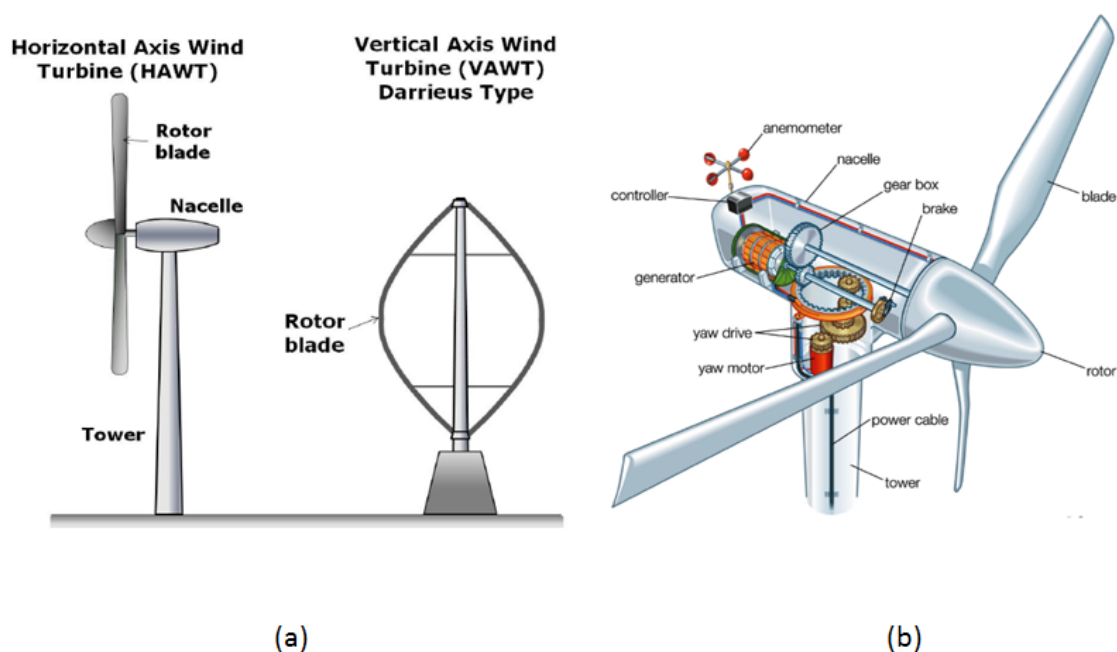


Figure 1.1: HAWT and VAWT [16]

A standard to which all wind turbines designs are measure is referred to as a Danish concept and this design consists of the following [12], [17]:

- Horizontal axis design;
- Upwind design;
- Three blade design;
- Asynchronous generator;
- Active yaw control.

The basic construction and components of a HAWT can be seen in figure 1.1 (b) [18]. Most modern HAWTs rely on lifting forces to rotate the blades of the wind turbine.

These lifting forces have been found to be more efficient, rather than dragging forces certain VAWT rely on to rotate the blades [5].

### 1.2.3 Control System

As can be seen from figure 1.2, a wind turbine has three main regions of power production, depending on the speed of the incoming wind. The regions are as follows [5], [16], [19]:

- **Cut-in speed:** The wind speed at which the blades will start rotating and the wind turbine will start to generate power.
- **Rated speed:** The wind speed at which the generator will produce the rated power.
- **Cut-out speed:** The wind speed where it becomes hazardous for the wind turbine to operate and therefore shuts down to prevent damage.

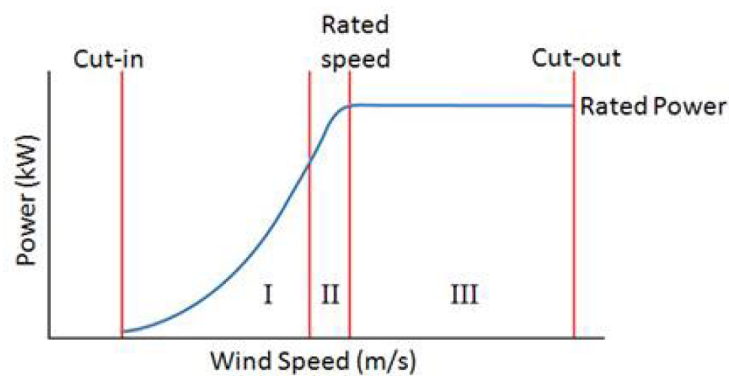


Figure 1.2: Typical output power curve of HAWT [20]

The output power of the generator remains constant with an increase in the wind speed once the rated wind speed has been reached (as can be seen in figure 1.2) [7]. This is due to the control system adapting to the increasing wind speed and ensuring the wind turbine produces the maximum amount of power from the available wind [12]. The maximum amount of power will be produced when the blades of the wind turbine rotate at the optimal tip speed ratio, which will vary according to the wind speed [21]. A more in depth discussion on the tip speed ratio will be provided in the literature study. A wind turbine can either use active or passive control techniques in order to control the rotational speed of the generator and usually controls the following [7]:

**Yaw:** This refers to the vertical orientation of the wind turbine (only applicable for HAWTs). This is done to ensure the wind turbine is faced directly into the wind during low wind speeds and therefore extracts the maximum amount of power from the wind.

The orientation of the wind turbine can also be altered to face slightly out of the wind during high wind speeds [7].

**Pitch:** The pitch refers to the amount the blades are turned around its axis and is sometimes also referred to the angle of attack. During active pitch control the pitch is increased or decreased by using hydraulic or electric motors [14]. Passive pitch control usually relies on aerodynamic or centrifugal forces to alter the pitch of the blade and alter the rotational speed [7].

**Brake:** Once the operating conditions become hazardous, the control system will activate a braking system to slow down, or completely stop the blades from rotating. The brake is also used to prevent to turbine from rotating during maintenance [12]. The braking of a wind turbine can be mechanical, electrical or aerodynamic [12].

**Power:** The control system monitors the output power and will dump the excess power produced by the generator to prevent damage to the wind turbine [7], [12]. The control system also optimizes the amount of power produced during low wind speeds.

## 1.2.4 Wind Turbine Advantages and Disadvantages

Wind turbine energy is one of the fastest growing renewable energy sources and is estimated to increase by a factor of five by 2030, compared to 2006 [10], [15], [17]. This will result in wind power providing 12% of the global power needs by 2020 and 22% by 2030 [15], [17], [22]. This interest in wind turbines leads to wind energy becoming one of the most developed and promising renewable energy sources [22–25].

Using wind turbines to generate power has its advantages and disadvantages, as with any other form of power generation. The primary advantages of using wind turbines to generate power are:

- Wind energy is one of the fastest growing forms of renewable energy, with an annual growth rate of roughly 30%. This leads to wind energy becoming of the more developed renewable energy sources [17], [21], [26];
- Wind energy is inexhaustible [23];
- Wind energy is the cheapest form of renewable energy [22], [27];
- Wind energy has a high efficiency of converting the primary energy source to electrical power (around 45%, compared to 29% - 37% for coal) [13];
- Wind turbines are one of the cleanest forms of renewable energy [22].

Some of the disadvantages of using wind turbines to generate power include:

- Fluctuations in wind speed makes wind turbines a more reliable year to year power source, rather than a day to day source of power [6], [21], [26], [28], [29];
- Generate low levels of noise pollution (mechanical or aerodynamic) [22];
- Wind speed fluctuates, leading to difficulties capturing maximum energy from the wind (if fixed speed wind turbine design is used) [26].

## 1.2.5 Wind Turbine Limitations

Wind turbines hold certain limitations when used to generate electrical power, this section provides a brief discussion on some of these limitations.

### 1.2.5.1 Betz Limit

Wind turbines work by extracting the kinetic energy from the wind and converting that energy into another form of energy (usually mechanical) and rely on the principles of conservation of mass and energy [30]. The amount of power a wind turbine is able to extract from the incoming wind can be calculated by using equation (1.1) [7], [12], [30–32].

$$P_{turbine} = \frac{1}{2} \rho A_S v^3 C_p(\lambda, \beta) \quad (1.1)$$

with:

$P_{turbine}$  - Power extracted by wind turbine (W)

$\rho$  - Air density at sea level (1.225 kg/m<sup>3</sup>)

$A_S$  - Swept area of the blades (m<sup>2</sup>)

$v$  - Wind velocity (m/s)

$C_p(\lambda, \beta)$  - Power coefficient (maximum of 0.593)

The power coefficient ( $C_p$ ) is essentially the efficiency of the wind turbine for extracting power from the incoming wind. During 1919, Albert Betz calculated that this value cannot exceed 0.593 as no more 59.3% of the wind's kinetic energy can be converted into mechanical energy [12], [30], [31]. This is due to air still requiring energy to keep moving after it has passed through the wind turbine's blades and this limitation is known as the Betz limit. Most wind turbines have a power coefficient between 0.25 and 0.45 as the system experiences losses [33], [34].

### 1.2.5.2 Power Extraction

The amount of mechanical power a wind turbine produces is dependent on the power coefficient, which in turn is dependent on the tip speed ratio ( $\lambda$ ), as can be seen in equation (1.1) [7], [21]. As the tip speed ratio varies with the wind speed, the power coefficient will also vary and in turn the amount of power extracted from the wind [7] (as can be seen in equation (1.1)). This can be problematic as the wind speed varies significantly (even on a daily basis) and in turn the amount of power the wind turbine produces. For optimal power extraction from the incoming wind, the generator rotational speed has to change with the wind speed to ensure the optimal tip speed ratio is obtained [7], [21].

### 1.2.5.3 Output power curve

The power produced by a wind turbine can be illustrated by means of a power curve, which displays the amount of power produced against the wind speed (an example of a typical power curve for a large wind turbine can be seen in figure 1.2) [35], [36].

Each power curve will differ for a specific wind turbine and is only an indication to the typical shape of a power curve for a wind turbine [35]. The shape predominantly depends on the control topology used to control the wind turbine, which will be discussed more in depth in the literature study. The power curve illustrated in figure 1.2 represents a typical power curve for a variable speed wind turbine using active control techniques for the yaw and pitch.

From figure 1.2 it can be seen that the amount of power produced, increases exponentially with an increase in the wind speed and levels out afterwards, producing the rated power of the wind turbine. This exponential increase of power to the wind speed can be confirmed by equation (1.1), where it can be seen that the power is dependent on the cube of the wind speed [7]. This can be problematic, as a wind turbine does not generate copious amounts of power at low wind speeds. A site can only be considered for a micro wind turbine where the average annual wind speed exceeds 4 m/s [37], [38].

## 1.3 Problem Statement

Eskom is struggling to cope with the electricity demand due to an increase in the load size. This leads to Eskom having load shedding, which is an inconvenience to most residential users but can result in a loss of income for some businesses. More and

more users and businesses are seeking alternative means to provide an uninterrupted supply of power.

A viable solution to this problem is to harness the energy of the wind, as wind energy is one of the fastest growing renewable energy sources due to wind turbines being the cleanest and cheapest forms of renewable energy [22], [27]. Wind is an abundant energy source and it's estimated that the world's power needs could be satisfied with only 10% of the energy of the wind [21].

Maximum energy capture for fluctuating wind speeds is not one of the key elements when designing a micro or stand-alone wind turbine [7] as these control techniques can become expensive and complicated. This leads to micro wind turbines generally having low levels of efficiency for operation outside their rated wind speed. Micro wind turbine usually makes use of passive control techniques in order to control the amount of output power, which has lower levels of efficiency when compared to active control techniques. This led to studies, as was done in [39], that tested the feasibility of intelligent control for micro wind turbines and simulation results show a 47% increase in the energy capture when compared to a wind turbine generator of similar size.

## 1.4 Objectives

The main objective of this project was to determine whether a real world intelligent micro wind turbine controller could be developed that improves the efficiency of a micro wind turbine generator and therefore increase the power capture from the incoming wind. The controller was designed, simulated and tested in order to determine whether an intelligent controller is a viable solution to control micro wind turbines, both practically and economically.

The controller primarily focused on the electrical power generation of a wind turbine and methods to improve the efficiency of the generator and therefore excludes the design of a complete micro wind turbine.

## 1.5 Research Methodology

The research methodology used for this project consists of identifying the problem, gathering research on the problem, designing the controller, simulating the controller, experimental testing of the controller, analysing the results and verifying and validating the controller.

### 1.5.1 Problem Identification

The first step was to identify the problem and determine why the problem needs to be addressed. This also included determining the objectives and scope of the project.

### 1.5.2 Literature Study

Research was done on the various aspects of wind turbines in order to ensure a thorough understanding of wind turbines and their control techniques. The research will primarily focus on the following:

- **Wind Turbines:** Research was done on the different types of wind turbines and the methods used to control the rotational speed of the generator (and therefore the efficiency) and output power of the wind turbine.
- **Control Topologies:** Different types of control topologies were researched and the applications of each type of control topology were investigated. A correlation between the control topologies and the requirements to control a wind turbine was investigated to find a suitable control topology that was implemented.
- **Controller Types:** Different controller types were investigated and compared in order to find a suitable controller for the control topology that was implemented. The controller was chosen based on the control topology used for the system.
- **Case Studies:** Prior work done on the various controllers and control topologies used for wind turbine control was investigated. This was done in order to determine how well the controllers and control topologies integrate with each other.

### 1.5.3 Design

After a comprehensive literature study was done, a design was developed for the project. This included the conceptual design, detailed design and engineering trade-offs. All the relevant flow diagrams were also created during this phase.

### 1.5.4 Simulation

The controller design was simulated as both the individual sub systems and as the complete system controller. This was done in order to determine whether the sub systems integrated with each other, if the controller is viable and to serve as a base to compare the practical results with.

### 1.5.5 Experimental Implementation

The design was practically implemented in order to determine if a real world application of the controller is viable. Measures were taken in order to ensure the practical implementation is as close as possible to the simulated controller.

### 1.5.6 Analysis

The practical results of the controller was compared to simulation results and the real world application viability of the controller was discussed. Recommendations regarding the implementation of the controller and future studies in the area is also be discussed.

### 1.5.7 Verification and Validation

Verification and validation is done for each of the chapters in order to determine if the project was on the right track (refer to figure 1.3 for the flow of verification and validation). Verification consists of referring each chapter to the previous chapter while validation consists of referring each chapter with the problem statement.

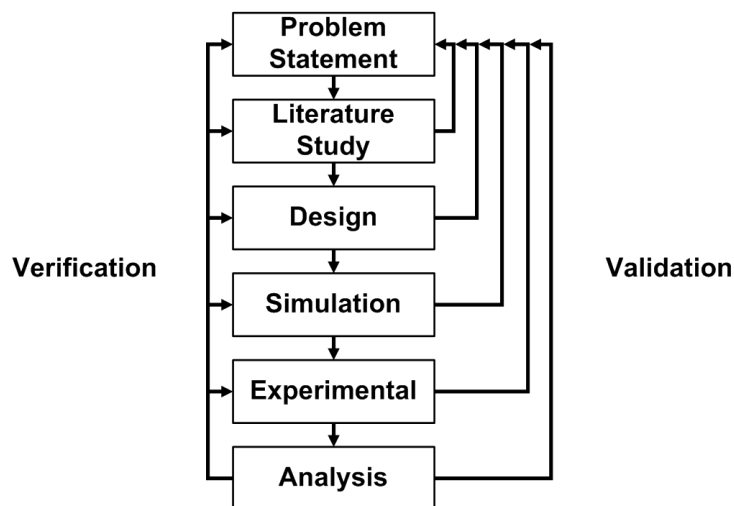


Figure 1.3: Verification and validation process

### 1.5.8 Key Research Questions

At the end of the project key research questions had to be answered, this included the following:

- Could a controller be developed that improves the overall power capture and efficiency of a micro wind turbine?

- Does using a controller to improve the power capture and efficiency of a micro wind turbine make economic sense?

## 1.6 Dissertation Overview

This section provides a brief discussion as to what can be expected in each chapter. In Chapter 1 an introduction to project and research is given. This chapter provides an overview of the dissertation as well as discussing the problem statement and research methodology.

Chapter 2 serves as the literature study on all the various aspects of the project. This was done in order to obtain an in depth understanding of the aspects of wind turbines. The primary focus in this chapter is the controller, control methodology and techniques that can be incorporated to improve the power extraction and efficiency of a micro wind turbine generator.

Chapter 3 serves as the design chapter and focuses on the functional flow, operational flow and design calculations. During this chapter the functional flow was determined and calculations was done in order to determine successfully integration of the sub systems. The completion of this chapter leads to a system that can be simulated and experimentally tested.

Chapter 4 consists of the simulation results obtained for both the individual systems as well as the complete system. The complete system simulation results were obtained for both fixed and fluctuating wind speeds.

Chapter 5 discusses the experimental setup and experimental results obtained for the controller. This chapter mainly focuses on the complete system results but briefly discusses the key sub system experimental results.

Chapter 6 serves as the closing chapter and mainly consists of a conclusion and recommendations for future work in the field. During this chapter the viability of using a controller to improve the power extraction and efficiency of a micro wind turbine is discussed.

The Appendix contains the peer reviewed publications, Turnit-in report and discusses the content of the submitted folder. The contents of the submitted folder can be obtained upon request.

## 1.7 Publications and Peer Reviews

The research in this project was presented at the Natural Science Symposium (SAAWK) and the International Conference on Commercial Use of Energy (ICUE) as well as an article submitted to SAIEE Africa Research Journal (ARJ) with feedback still pending. The conferences yielded a presentation and a publication on the work presented. Further information on the publications is given below and the full articles are given in Appendix A.

- S. Botha and R. Gouws, " 'n Intelligente beheerder vir verbeterde effektiwiteit van n mikrowindturbinegenerator", Studentesimposium in die Natuurwetenskappe (SAAWK), Florida, South Africa, Nov. 2014, pp. 23.

**Article Abstract (Afrikaans):** *Windenergie is die vinnigste groeiende vorm van hernubare energie, wat hoofsaaklik te danke is aan die feit dat dit een van die skoonste en goedkoopste alternatiewe maniere is om krag op te wek. Windturbines wat gebruik word vir residensie doeleindes staan as mikro-windturbines (windturbines wat minder as 50 kW lewer) bekend. Hierdie klas van windturbines word ontwerp om maksimum krag slegs by 'n vasgestelde windspoed te voorsien. Dit is problematies aangesien die spoed van wind gedurig fluktueer en die windturbine dan effektief selde die hoeveelheid krag produseer as wat die generator in staat is om te kan produseer. Die probleem kan opgelos word deur gebruik te maak van 'n intelligente beheerder vir die windturbine wat sal sorg dat soveel as moontlik krag geproduseer word, ongeag wat die spoed van die wind mag wees.*

**Article Abstract:** *Wind turbines smaller than 50 kW are known as micro wind turbines and the efficiency of these wind turbines are not the primary objective during designing. An intelligent controller will be designed that improves the efficiency of a micro wind turbine, which will in turn yield a greater power output.*

- S. Botha and R. Gouws, "Intelligent controller for improved efficiency of micro wind turbine generators", in Proceedings of the Thirteenth International Conference on the Industrial & Commercial Use of Energy, Cape Town, South Africa: Cape Peninsula University of Technology, Aug. 2016, pp. 278-285, ISBN:978-0-9946759-1-0.

**Abstract:** *Due to an ever increasing demand for electricity Eskom is struggling to cope, which inevitably leads to load shedding. Although this is a minor inconvenience for residential users, the effects can be detrimental for businesses. This increases the need for alternative provision of an uninterrupted power supply. Wind energy is a viable solution for this problem as wind turbines proved to be one of the cleanest and fastest growing*

forms of renewable energy. Although micro wind turbines are the most common type of wind turbines used for homes, businesses, farms or other rural areas, the major drawback is that the majority of these wind turbines are designed to produce maximum efficiency only for a single wind speed. The consequence of a deviation from this designed wind speed is that the overall efficiency of the wind turbine decreases. This problem can be overcome by designing an intelligent controller that allows variable speed operation of the wind turbine and therefore increases the overall efficiency of power extraction from the incoming wind. The method proposed uses a fuzzy logic controller connected to the generator that continuously adapts the rotational speed of the generator to ensure the optimal rotational speed is obtained and therefore extracts the maximum amount of energy from the wind.

- S. Botha and R. Gouws, "Fuzzy Logic Controller for Improved Power Extraction of Micro Wind Turbines", Submitted to SAIEE African Research Journal (ARJ) on 27 December 2016.

**Abstract:** The amount of power a wind turbine extracts from the incoming wind is dependent on the rotational speed and a change in the wind speed requires a change in the rotational speed for optimal power extraction. Micro wind turbines are designed for maximum power extraction only for a single wind speed and a deviation from this wind speed results in reduced efficiency of the wind turbine. A controller was developed that alters the rotational speed of a micro wind turbine in order to improve the power extraction from the incoming wind. Speed control is achieved by using a fuzzy logic controller that alters the duty cycle of a DC-DC boost converter. Both simulation and experimental results indicate an improvement on the amount of power captured by the micro wind turbine generator.

## 1.8 Conclusion

This chapter provided a brief overview as to what can be expected throughout the rest of the dissertation. It provided a brief introduction into wind turbines and the shortcomings of micro wind turbines. The problem statement was given and discussed, as well as the approach that was used to complete the project.

The next chapter contains the literature study done for the project. This section provided an insight on the workings of wind turbines and techniques used that could help develop a controller that met the objectives of the project. This was done by extensive research on wind turbines and case studies for the relevant aspects of the wind turbine.

# Literature Study

*This chapter provides the literature study done for the project. This was done in order to obtain a more in depth understanding on the workings of a wind turbine as well as techniques and hardware used to control the output power of wind turbines. An overview of what is discussed in this chapter can be seen in figure 2.1. Figure 2.2 provides a summary of the citations used during the literature study as well as provide the case study connections between the various aspects of the wind turbine.*

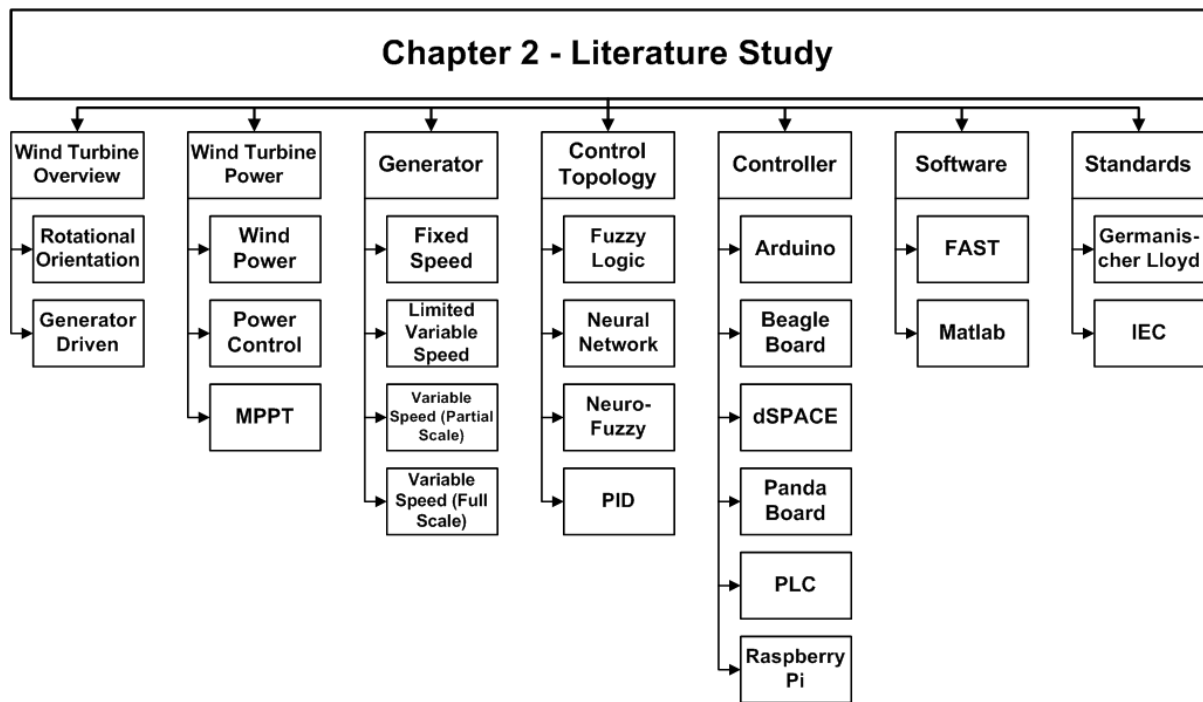


Figure 2.1: Literature study chapter overview

## 2.1 General Wind Turbine Overview

Various wind turbine topologies exist, each having its own advantages and disadvantages. The basic construction and types of wind turbines available is discussed and compared in this section. Figure 2.3 provides a graphical illustration of what is discussed in this section.

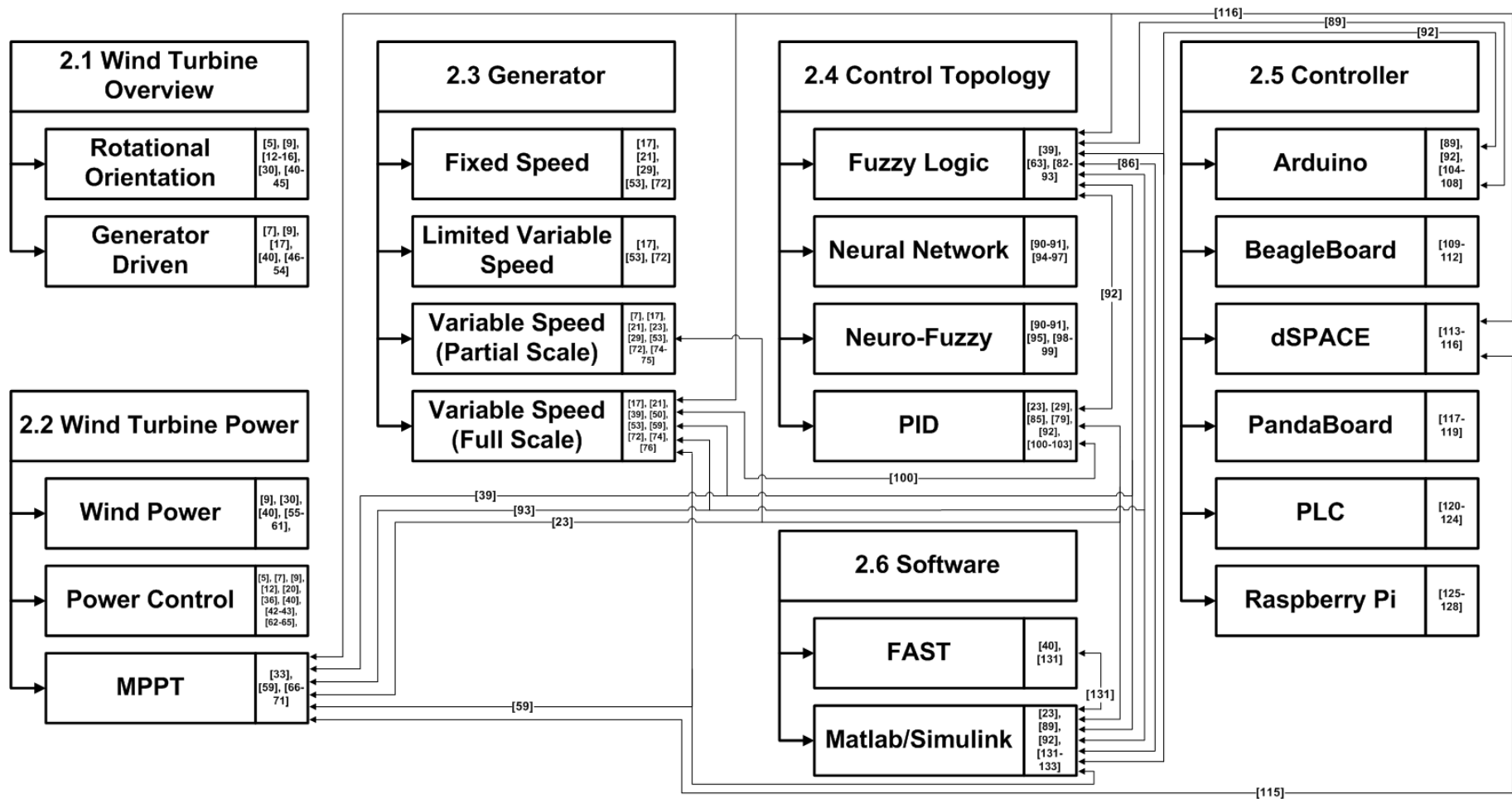


Figure 2.2: Citations and case studies

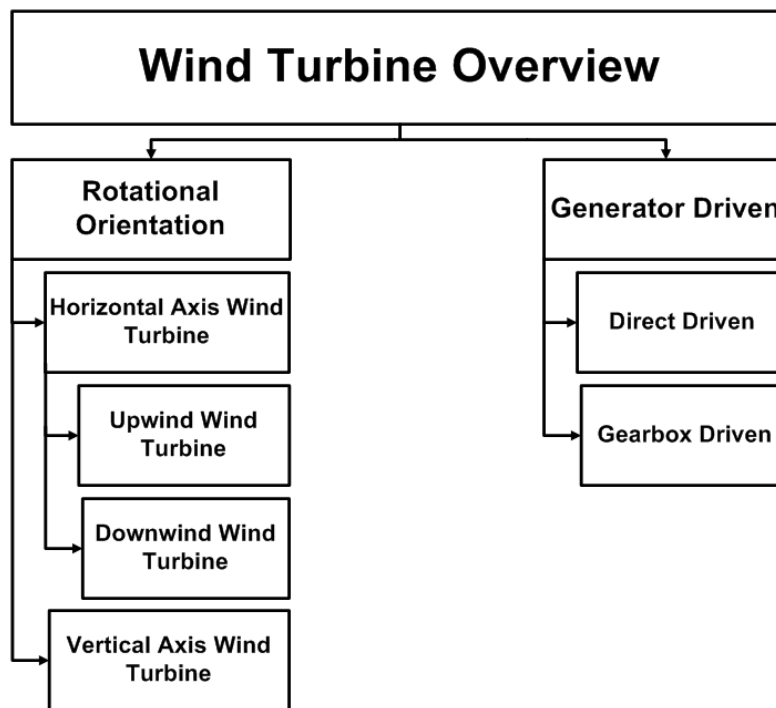


Figure 2.3: General wind turbine overview section overview

## 2.1.1 Rotational Orientation

The rotational orientation of a wind turbine refers to the rotation of the generator axis and can either be classified as a HAWT or a VAWT (refer to figure 1.1 (a)). This section briefly discusses and compares the types of wind turbines (refer to table 2.1 for a comparison between HAWTs and VAWTs).

### 2.1.1.1 Horizontal Axis Wind Turbine

A HAWT allows the air to move parallel with respect to the axis of rotation of the generator and are more common in modern wind turbines than VAWTs [5], [12–14]. All modern grid connected wind turbines utilizes a horizontal axis design due to the advantage of higher tip speed ratios over a wider range of wind speeds [12]. Horizontal axis wind turbines can be categorized into one of the following:

- Upwind wind turbine;
- Downwind wind turbine.

This refers to the orientation of the nacelle with respect to the direction of the incoming wind and can be seen in figure 2.4 [42]. Each design has the following properties.

Table 2.1: Comparison between HAWT and VAWT

|                                   | <b>Horizontal Axis Wind Turbine</b>                                                           | <b>Vertical Axis Wind Turbine</b>                                        |
|-----------------------------------|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| <b>Wind Direction</b>             | Requires to be faced into the wind [5], [9], [40]                                             | Wind direction is irrelevant [5], [9], [40]                              |
| <b>Gearbox/Generator Location</b> | Generator and gearbox are located in nacelle [5], [9], [14]                                   | Generator and gearbox are located on ground [5], [9], [14]               |
| <b>Blade Location</b>             | Blades are higher; therefore more energy can be extracted from the wind [14]                  | Blades are located closer to the ground where wind speeds are lower [14] |
| <b>Development</b>                | More popular design choice, i.e. more developed [5], [15]                                     | Lower efficiency due to under development [5], [15]                      |
| <b>Noise Pollution</b>            | Higher levels of noise pollution [9]                                                          | Less noise pollution [9]                                                 |
| <b>Rotor Control</b>              | Greater ease in controlling the speed of the rotor (using pitch and rotor control) [15], [41] | More difficult to control the speed of the rotor [15], [41]              |

**Upwind Wind Turbine** In an upwind wind turbine design, the wind passes the rotor blades before the nacelle (as can be seen from figure 2.4 [42]) [40]. This is the most common design for wind turbines as more of the wind's kinetic energy can be extracted as well allowing a smoother operation of the wind turbine [42]. The main advantages of upwind wind turbines is the smooth operation and increased efficiency in extracting power from the wind [9], [40], [42]. The biggest disadvantage of upwind wind turbines is the complex drive yaw mechanism required to rotate the wind turbine [42].

**Downwind Wind Turbine** In a downwind wind turbine design, the wind passes the nacelle before the rotor blades (as can be seen in figure 2.4 [42]) [40]. This design is rarely used and is favoured for micro wind turbines as the efficiency is lowered due to the tower (or shadow) effect caused by the tower of the wind turbine. The main advantages of using a downwind wind turbine is that it theoretically doesn't require a yaw mechanism as it will passively follow the wind [12], [40], [43]. This will also result in no power losses for the yaw drive mechanism [9]. The disadvantages of downwind wind turbines is the higher levels of noise pollution and power fluctuations and reduced efficiency due to the tower affecting the airflow [9], [40], [42].

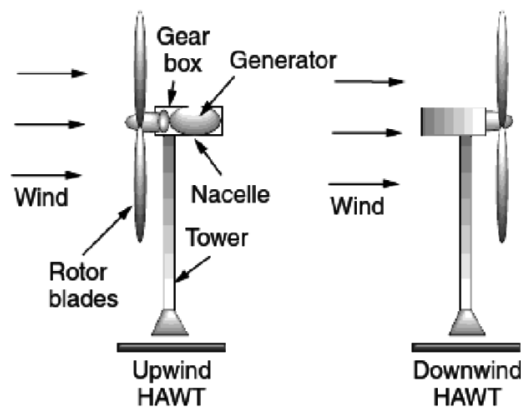


Figure 2.4: Upwind and downwind wind turbine [42]

**Upwind and Downwind Combination** Research found a manufacturer that utilizes both an upwind and downwind combination, namely Infinite Wind Energy. This construction consists of blades on both the upwind and downwind side of the wind turbine and can be seen in figure 2.5 (b) [44]. The manufacturer states an increase of 40% when compared to conventional wind turbines of similar size. This can be seen in figure 2.5 (a), which compares the output power of the counter rotating wind turbine design with a conventional wind turbine of similar size [44]. The advantages of using an upwind and downwind combination wind turbine is the increased efficiency and decreased noise pollution [44]. The disadvantage of using an upwind and downwind combination is the increased size [44].

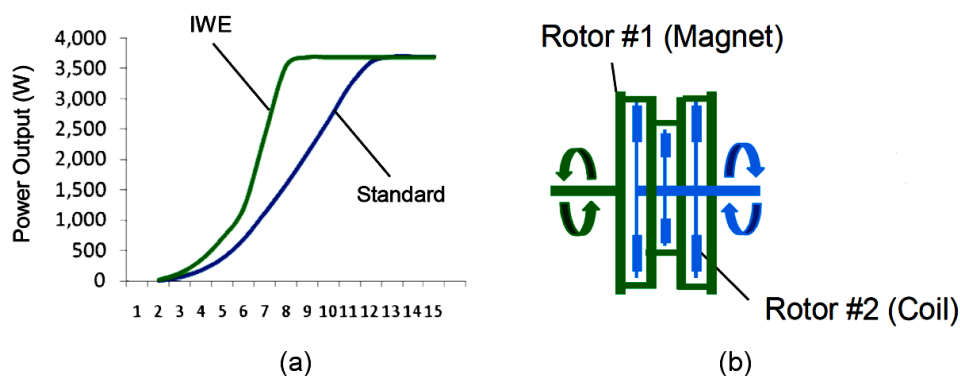


Figure 2.5: Counter rotating wind turbine (a) output power and (b) construction [44]

### 2.1.1.2 Vertical Axis Wind Turbine

A VAWT allows the air to move perpendicular with the axis of rotation of the generator [5], [12], [15]. Vertical axis wind turbines can be sub-categorized into one of the follow-

ing categories, depending on whether they rely on lifting forces or dragging forces to rotate the blades [5], [16]:

- Darrieus
  - Darrieus troposkien (Egg-beater shape)
  - Gyromill
  - Musgrove
- Savonius

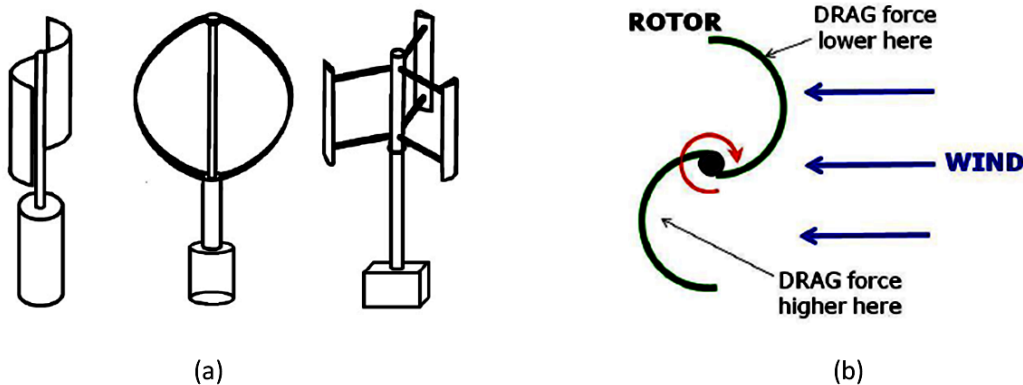


Figure 2.6: (a) Different types of VAWTs [9] and (b) savonius working principle [16]

Figure 2.6 (a) illustrates the three most common construction types of VAWTs [9]. From left to right and followed by a discussion they are:

**Savonius:** The Savonius wind turbine consists of two or more cups/scoops/buckets and rely on dragging forces to rotate the blades. When the wind passes over these scoops, the drag differs on each side, causing the blade to rotate. Figure 2.6 (b) illustrates the working principle of a Savonius VAWT [16]. A Savonius blade can only reach a maximum efficiency of about 30% [5], [30] and the tip speed ratio of these drag based turbines cannot exceed 1 [13]. Drag based wind turbines are usually used to drive mechanical equipment, due to their low rotational speeds. Wind turbines relying on lifting forces (rather than dragging forces) to rotate the rotor have been found to be the more efficient [5].

**Darrieus (Egg-beater shape)** A Darrieus wind turbine has a curved blade that relies on lifting forces to rotate the blade. Darrieus wind turbines are patented under GJM Darrieus and states that the blades should have a streamline curve, in the form of a skipping rope [5]. A Darrieus wind turbine is not self-starting and therefore requires a small motor to start rotating the blades, which will shut down once the blade has

reaches speed. Often the generator itself is used as a motor in order to start rotating the blades [9].

**Giromill (H-shape) and Musgrove:** A Giromill and Musgrove wind turbine rely on lifting forces to rotate the blade of the wind turbine [45]. The basic construction and working principles for a Giromill and Musgrove wind turbine are similar, with the only difference being that the Musgrove has the ability to fold (or feather) the blades in increasing wind speeds and therefore lower the torque and control the power being produced [9], [45].

### 2.1.2 Generator Driven

Wind turbines can be designed with or without a gearbox, which is also known as gearbox driven or direct driven, respectively [17]. The purpose of the gearbox is to increase the rotational speed of the blades (usually around 15 - 100 rpm for larger wind turbines and 150 - 500 rpm for smaller wind turbines) to higher speeds (usually around 1000 - 1500 rpm) if a high speed generator is used [7], [46], [47]. This significant increase in rotational speeds is usually done via a multi-stage gearbox [7], [17]. The output power of a rotating machine can generally be described by equation (2.1) [7], [48].

$$P = KD^2L\omega \quad (2.1)$$

with:

$P$  - Power output

$K$  - Constant

$D$  - Diameter of rotor

$L$  - Length of rotor

$\omega$  - Rotational speed

From equation (2.1) it can be seen that the output power of the generator is dependent on the rotational speed of the rotor. The rotational speed of direct driven wind turbines is slower, as the rotor rotates at the same speed of the blades. Therefore, in order to produce the same amount of power, either the length or the diameter of the generator has to be increased [7], [17]. Usually the latter is changed, as it will result in a square increase in power production, as can be seen from equation (2.1) [7], [49], [50]. Other benefits of altering the diameter rather than the length include lower end winding losses and reduced weight of active parts [17].

Figure 2.7 illustrates the difference in rotational speed of the gearbox and blades for gearbox driven and direct driven wind turbines [47].

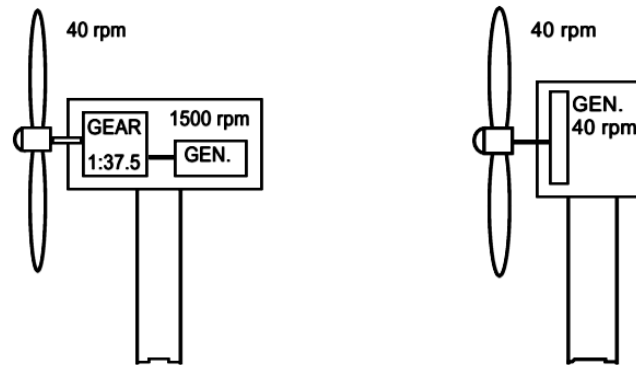


Figure 2.7: Gearbox driven and direct driven wind turbine [47]

### 2.1.2.1 Direct Driven

During a direct drive configuration the rotor of the blades are directly connected to the shaft of the generator [7], [9], [46]. The generators used in direct driven wind turbines are usually specially designed for wind turbine applications, as they have an increased diameter to deliver the same amount of power [17]. Direct drive generators are usually synchronous generators and can be classified into two categories [17]:

- Electrically excited synchronous generator (EESG);
- Permanent magnet synchronous generator (PMSG).

The advantages of using direct driven generators is the increase in efficiency, reliability and noise pollution as well as the ability to react faster to changes in the wind speed [9], [17], [47], [50]. The disadvantages of using a direct drive wind turbine is increase in generator size and production cost as well as the possibility of requiring a frequency converter due to the low output frequency [9], [47], [50]. Another disadvantage of using a direct drive wind turbine is that an increase in size will cause a decrease in rotational speed due to the tip speed limitation which generally does not exceed 75 m/s [49–51].

### 2.1.2.2 Gearbox Driven

For a gearbox driven configuration, the rotor of the blades is connected through a gearbox to the generator. The side with the blades of the turbine is usually referred to as the low speed shaft and the shaft connected to the generator is usually referred to as the high speed shaft [40], [52], [53]. The advantages of using gearbox driven generators

are the reduced size and production cost of the generator [50]. The disadvantages of using a gearbox driven wind turbine is the increase in losses, mechanical noise, nacelle weight and maintenance requirements [9], [46], [47], [54].

## 2.2 Wind Turbine Power

This section discusses the power produced by wind turbines and the most commonly used means of controlling the power. Figure 2.8 provides a graphical illustration as to what is discussed in this section.

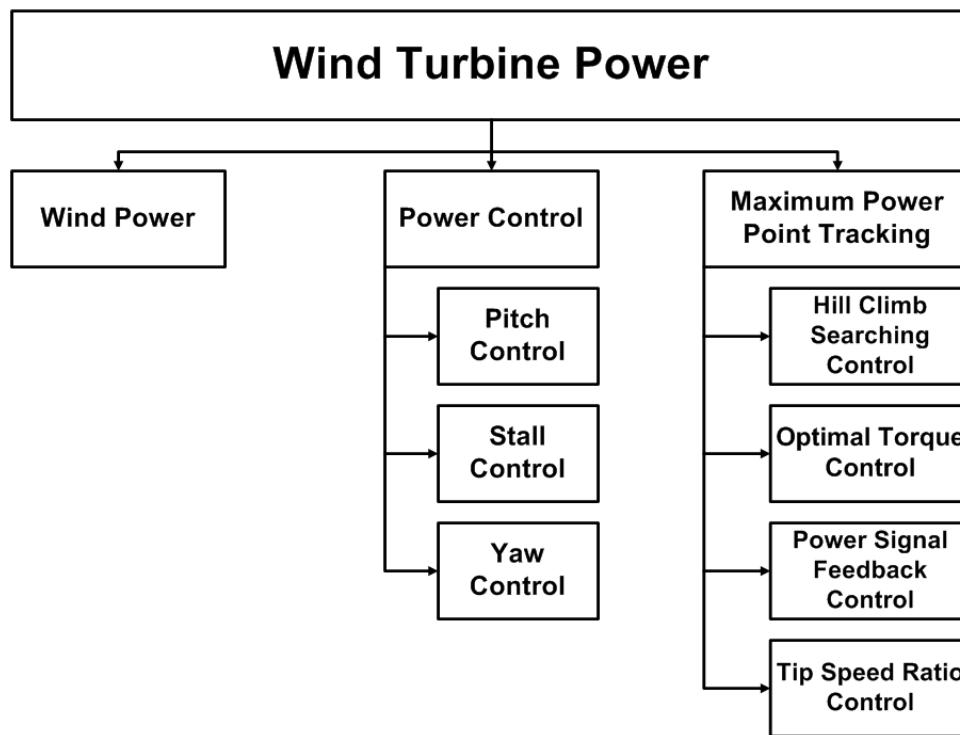


Figure 2.8: Wind turbine power section overview

### 2.2.1 Wind Power

At any given time, the amount power available in the wind can be calculated using equation (2.2) [9], [40], [55–58].

$$P_{available} = \frac{1}{2} \rho \pi R^2 v^3 \quad (2.2)$$

with:

$P_{available}$  - Power available in the wind (W)

$\rho$  - Air density at sea level (1.225 kg/m<sup>3</sup>)

$R$  - Radius of the blades (m)

$v$  - Wind velocity (m/s)

Equation (2.2) calculates the amount of power available at a given wind speed and varies for each wind turbine as it is dependent on the radius of the blades. As previously discussed in 1.2.5.1 *Betz Limit*, the power a wind turbine extracts from the incoming wind can be calculated with equation (1.1) [40], [56], [57], [59].

The efficiency of the wind turbine is determined by the power coefficient  $C_p(\lambda, \beta)$  which is a function of both the tip speed ratio ( $\lambda$ ) and the blade pitch angle ( $\beta$ ). The value of  $C_p$  is the ratio of the amount of power extracted by the wind turbine to the amount of power available in the wind and can be calculated using equation (2.3) [40], [56], [58], [60].

$$C_p = \frac{P_{turbine}}{P_{available}} \quad (2.3)$$

The tip speed ratio ( $\lambda$ ) can be defined as the ratio between the speed of the tip of the blade to the speed of the incoming wind and can be calculated using equation (2.4) [9], [30], [40], [56], [57], [59].

$$\lambda = \frac{\omega R}{v} \quad (2.4)$$

with:

$\lambda$  - Tip speed ratio

$\omega$  - Rotational speed (rad/s)

$v$  - Speed of incoming wind (m/s)

The tip speed ratio is an important factor in the maximum power production of a wind turbine and has the following effect on the amount of power captured by the wind turbine:

- If the tip speed ratio is too low (i.e. the blades are rotating too slow), not enough energy is extracted from the wind as it passes through the blades, which results in reduces power capture of the wind turbine [30].

- If the tip speed ratio is too high (i.e. the blades are rotating too fast), the blades of the wind turbine appear as a disc (or obstruction) to the wind which slows the wind speed and also increases the drag and therefore lowers the amount of power extracted by the wind turbine [30].

The amount of aerodynamic torque in the wind can be determined by using equation (2.5) [56–58], [60], [61].

$$T_M = \frac{P_{turbine}}{\omega} \quad (2.5)$$

From equation (2.4), the rotational speed ( $\omega$ ) can be written as (refer to equation (2.6)):

$$\omega = \frac{\lambda v}{R} \quad (2.6)$$

Substituting (2.6) into equation (2.5) results in equation (2.7):

$$T_M = \frac{1}{2} \rho \pi R^3 v^2 C_T \quad (2.7)$$

with  $C_T$  the torque coefficient of the wind turbine and can be calculated using equation (2.8):

$$C_T = \frac{C_p}{\lambda} \quad (2.8)$$

Substituting equation (2.8) into equation (2.7) results in equation (2.9):

$$T_M = \frac{\rho \pi R^3 v^2 C_p}{2\lambda} \quad (2.9)$$

### 2.2.2 Power Control

Wind turbines can either use active or passive control techniques to control the rotational speed of the wind turbine and therefore the amount of power produced, as discussed in 1.2.3 *Control System* [7], [12]. This section contains an in depth comparison for active and passive control techniques for pitch, stall and yaw control.

### 2.2.2.1 Pitch Control

The pitch of the blade is also referred to as the angle of attack ( $\alpha$ ). Figure 2.9 illustrates the effect increasing the angle of attack has on the lift and drag forces of the blade [62]. As the angle of attack increases, the lift produced by the blade decreases and the drag increases. The point at which no lift will be generated is known as the critical angle of attack [36]. If the pitch passes this point, the blades will be forced into a stall [36]. Pitch control can be seen in figure 2.11 (a) [20].

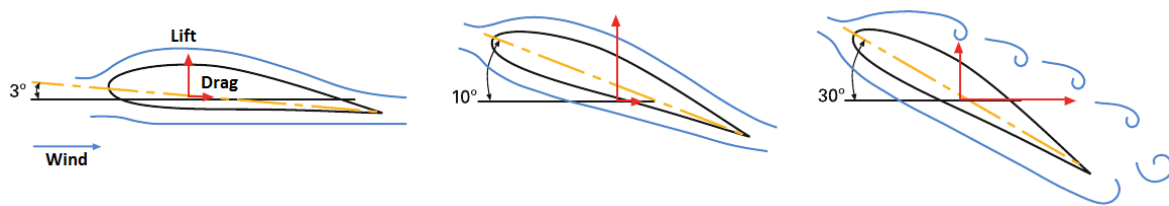


Figure 2.9: Lift and drag forces for increasing angle of attack [62]

**Active Pitch Control** Active pitch control is the most common form of power control and refers to altering the pitch of the blades, i.e. rotating the blades around its axis to lower the lift produced by the blades [7]. Some wind turbines even incorporate a design which allows each blade to be pitch individually for higher levels of efficiency [63]. During shut-down conditions or for maintenance purposes, the blades will be feathered a full  $90^\circ$  which will produce the lowest amount of lift and the mechanical brake will be applied, bringing the blades to a complete stop [7]. The biggest advantage of using active pitch control is the improved power capture from the wind [7]. The biggest disadvantage of using active pitch control increased cost, decreased reliability, more complex design and the power fluctuations during high wind speed [7], [12].

**Passive Pitch Control** Passive pitch control consists of altering the pitch of the blade during certain loading conditions [7]. Usually the turbine is designed for a specific wind speed, with the blades at a fixed pitch [7]. Once the blades exceeds a predetermined rotational speed, a mechanism (usually centrifugal based) will force part of, or the entire blade, to change its angle of attack and therefore lowering the lift and rotational speed [64]. The advantages of passive pitch control is the reduced cost, increased reliability and no losses due to controlling mechanisms [7], [63]. A disadvantage of passive pitch control is its difficulty to incorporate [7].

### 2.2.2.2 Stall Control

The speed of the blades can be controlled by increasing the drag of the blades [12] (as can be seen in figure 2.9). This will cause the blades to stall and therefore reduce the rotational speed. Generally, using stall control methods to control the output power of wind turbines are less effective when compared to pitch control [12].

**Active Stall Control** Active stall can also be referred to as negative pitch control [7]. During high wind speeds the blades would be altered to increase the drag, therefore forcing the blades into a stall [7]. A disadvantage of using active stall control is the difficulties of accurately predicting the aerodynamic stall force behaviour [7]. The advantages of using active stall control includes its ability to compensate for air density fluctuations as well as lower power fluctuations during high wind speed [7], [12]. Another advantage of stall active stall control (compared to pitch control) is that the mechanism does not have to be as responsive as well as requiring less travel (refer to figure 2.10) [7].

**Passive Stall Control** A wind turbine using passive stall techniques to regulate the output power has the blades attached at a fixed angle and is considered as the simplest way to regulate the output power of the wind turbine [7], [64]. The blades are designed to decrease the lift and increase the drag once a predetermined speed is reached; thus slowing the rotational speed for increasing wind speeds [7]. The biggest advantage of using passive stall control is that it's the simplest form of power control for wind turbines [7]. The disadvantages of using passive stall control are increased tower loads and blade fatigues (due to vibrations), reduced efficiency and the possibility of inaccurate power level predictions during high wind speeds [7].

Figure 2.10 illustrates the change required in the blade angle for active pitch control and active stall control [7]. From this figure it can be seen that the required change in blade angle is significantly less for active stall control when compared to active pitch control.

### 2.2.2.3 Yaw Control

The yaw refers to the orientation of the wind turbine towards the flow of air (refer to figure 2.11 (b)) [20]. Maximum power extraction occurs when the blades are perpendicular to the wind and is only applicable for HAWTs, as VAWT accepts the flow of air from any direction [5], [7], [9], [40].

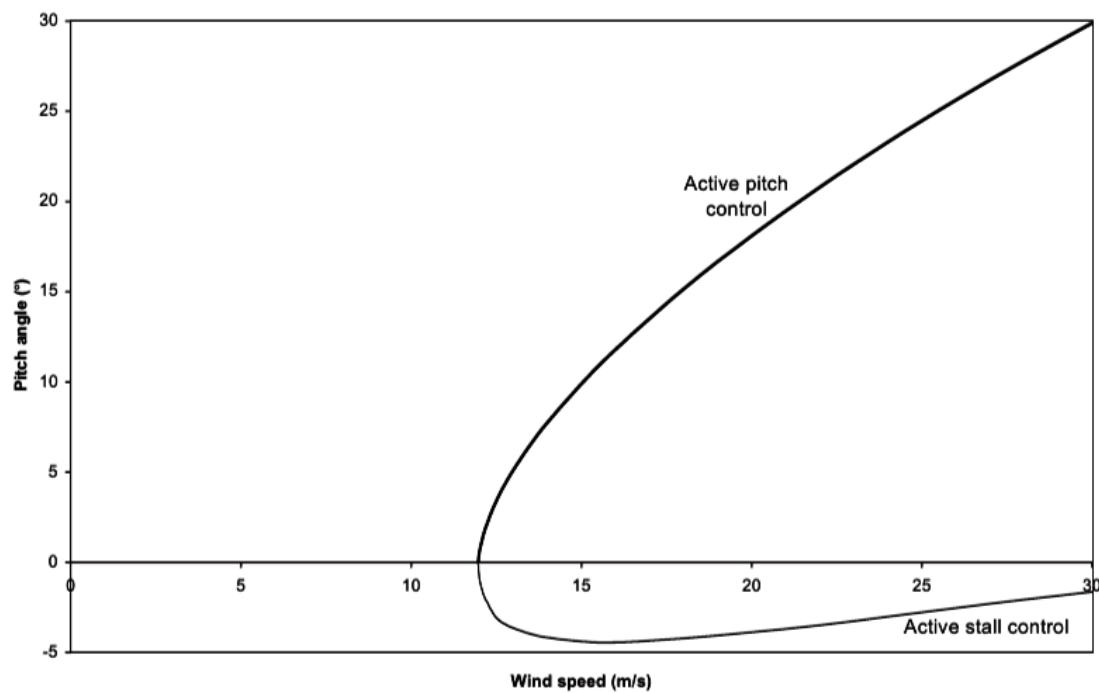


Figure 2.10: Blade angle change for active pitch control and active stall control [7]

**Active Yaw Control** Active yaw control is the most commonly used form of yaw control used for modern large scale wind turbines and follows the direction of the wind by altering the nacelle of the wind turbine [42], [43]. The advantages of using active yaw control is that the wind turbine could be faced out of or into the wind during low and high power level requirements, respectively [7]. The disadvantages of using active yaw control is the requirement of a yaw drive and braking mechanism, only applicable for variable speed generators and it's not as effective power control method as pitch control [7], [43].

**Passive Yaw Control** Wind turbines that use passive yaw are also known as free-yaw [65]. This method is more suited for downwind wind turbines, which will follow the change in direction of the wind [43]. When using free yaw in a downwind wind turbine, the blades are usually coned downwind in order to increase the efficiency of the wind turbine [43]. Some designs incorporate a yaw damper in order to prevent the wind turbine from altering its position too rapidly and limit the strain on the wind turbine, due to the gyroscopic forces [43]. An advantage of using passive yaw control is that it does not create yaw moments on the yaw bearing [7]. The disadvantages of using passive yaw control is that uncontrolled yawing could result in a twisted cable and the increased levels of gyroscopic forces on the blades [12], [43].

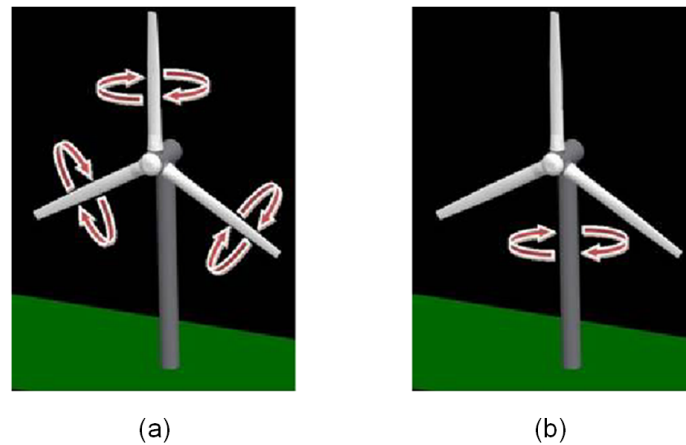


Figure 2.11: (a) Pitch and (b) yaw control [20]

### 2.2.3 Maximum Power Point Tracing

Figure 2.12 illustrates the power coefficient ( $C_p$ ) vs. tip speed ratio ( $\lambda$ ) characteristics of a given wind speed for a typical small wind turbine [33], [59]. The peak of the graph is the optimal tip speed ratio that will produce the most amount of power at the given wind speed. For every wind speed there is an optimal tip speed ratio and a change in wind speed therefore requires a change in the rotational speed [59].

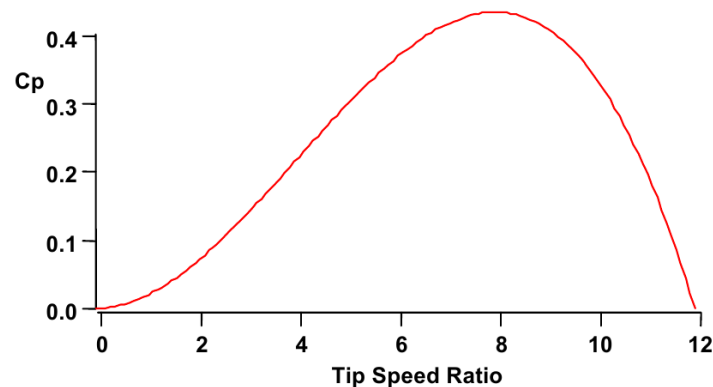


Figure 2.12: Power coefficient ( $C_p$ ) vs. tip speed ratio ( $\lambda$ ) [33]

Maximum power point tracking (MPPT) is a technique that ensures the most amount of power is captured by the wind turbine during different wind speeds by altering the rotational speed and usually consists of a tracking algorithm that can broadly be categorized into one of the following [59]:

- A tracking algorithm that has a predefined knowledge of the wind turbine and its characteristics.

- A tracking algorithm that has no predefined knowledge of the wind turbine and its characteristics.

The former requires an in depth knowledge of the  $C_p(\lambda, \beta)$  characteristics of the wind turbine and maximum power is extracted by altering the rotational speed of the wind turbine using this information [59]. This method allows a maximum power coefficient to be obtained for all wind speeds and therefore extract the maximum amount of power [59]. The most common types of maximum power point tracking include the following:

### 2.2.3.1 Hill-Climb Searching

The working principle for a hill climb searching (HCS) controlled wind turbine can be seen in figure 2.13 which displays the wind turbine output power against rotational speed [66]. This method uses an algorithm that searches for the peak power output of the wind turbine and has two sections of operation (i.e. up-hill and down-hill) [66]. During the up-hill section of operation, the generator speed has to be increased and during the down-hill section the generator speed has to be reduced [66]. The advantages of using HCS include:

- The controller can track the optimal tip speed ratio with measurements on either the wind speed or rotational speed of the wind turbine [67];
- Does not require predefined knowledge of wind turbine [68].

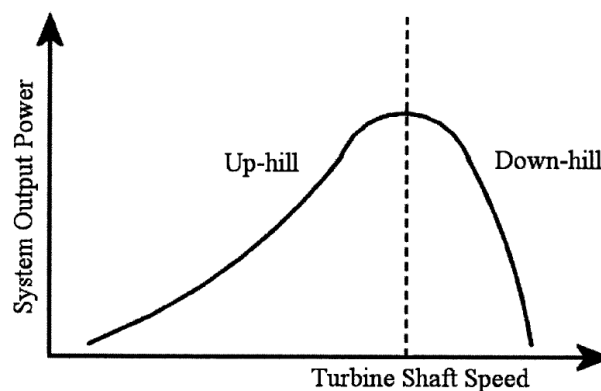


Figure 2.13: Optimal tip speed ratio control configuration [66]

The disadvantage of using HCS includes:

- Controlling algorithm can be difficult to implement [68];
- Using HCS is more suited for small wind turbines with low inertia as it requires a faster change in rotational speed for a change in wind speed [66], [69];

- Prefers constant wind speeds over changing wind speeds as settling times can become large [70].

### 2.2.3.2 Optimal Torque Control

The configuration of optimal torque (OT) control can be seen in figure 2.14 and tracks the optimal torque point of the wind turbine that will in turn extract the most amount of power from the incoming wind [67]. The optimal torque point can be calculated using equation 2.10 [67]. A disadvantage of this configuration is that it requires a measurement of the wind speed [67].

$$T_{opt} = K_{opt} \times \omega_{opt}^2 \quad (2.10)$$

with:

$$K_{opt} = \frac{1}{2} \rho A_S \left( \frac{R}{\lambda_{opt}} \right)^3 C_{p, max} \quad (2.11)$$

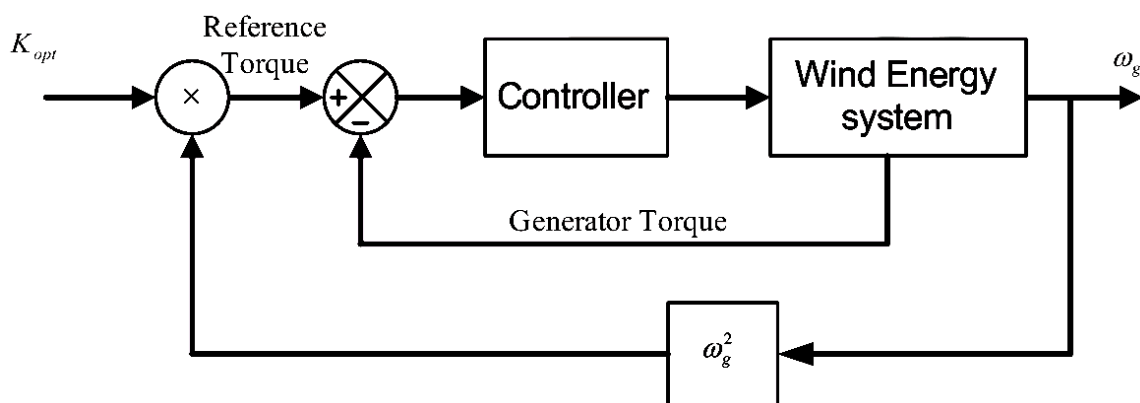


Figure 2.14: Optimal torque control configuration [67]

### 2.2.3.3 Power Signal Feedback Control

The configuration for a power signal feedback (PSF) controlled wind turbine can be seen in figure 2.15 and involves using calculations to determine reference power and altering the rotational speed according to this value [67]. The method requires measurements on the power and rotational speed [67]. The power losses of the system should be considered if this technique is used. This could be problematic as this affects the rotational speed and therefore complicates finding the maximum power point [68].

An advantage of this configuration is that it can either use the rotational speed or wind speed as an input [68], [71]. Disadvantages of using PSF include:

- Power losses of the system could affect maximum power point [68];
- Requires predefined knowledge of wind turbine's power curve [66–69];
- The power curve of the output power of the wind turbine is obtained with experimental and simulation results, this leads to reduced accuracy in a practical system [66], [67], [69].

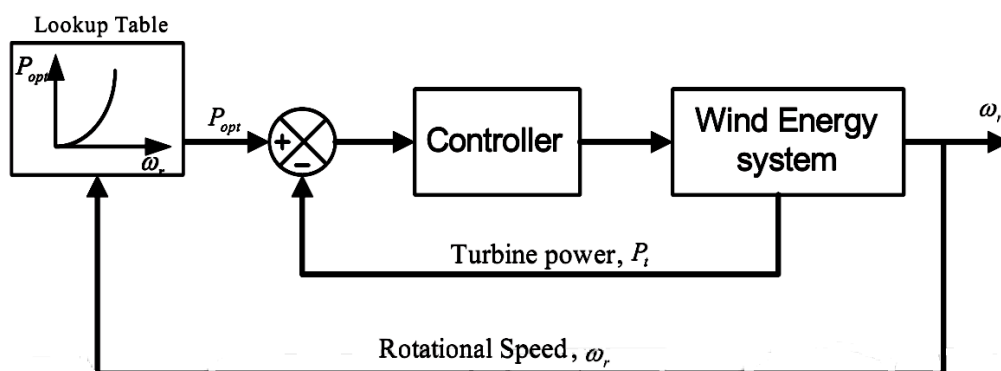


Figure 2.15: Power signal feedback control configuration [67]

### 2.2.3.4 Tip Speed Ratio Control

As previously discussed, a wind turbine will extract the maximum amount of power when the optimal tip speed ratio is obtained. This value differs for each wind speed and therefore a change in the wind speed will require a change in the rotational speed in order to ensure the maximum amount of power is extracted (refer to 2.2.1). The maximum amount of power can be calculated using equation 2.12 [67].

$$P_{max} = K_{opt} \times \omega_{opt}^3 \quad (2.12)$$

with:

$$K_{opt} = \frac{1}{2} \rho A_S \left( \frac{R}{\lambda_{opt}} \right)^3 C_{p, max} \quad (2.13)$$

and

$$\omega_{opt} = \left( \frac{\lambda_{opt}}{R} \right) v \quad (2.14)$$

The configuration for tip speed ratio (TSR) control can be seen in figure 2.16 [67]. This configuration relies on measuring the wind speed and generator speed in order to ensure the wind turbine blades are rotating at the optimal rotational speed [67]. This control configuration also requires a predefined knowledge of the optimal tip speed ratio of the wind turbine [67]. The disadvantage of using TSR includes the following:

- Requires measurement of the wind speed and rotational speed (which results in an increase in cost and more complicated design) [66], [67], [69];
- This design can only be applied to a specific wind turbine as the optimal tip speed ratio differs for each wind turbine [66], [67];
- Requires a detailed model of the wind turbine [67].

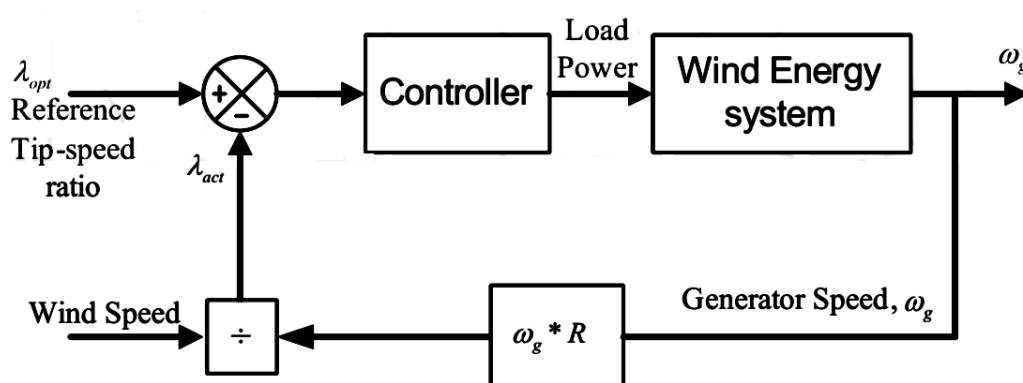


Figure 2.16: Optimal tip speed ratio control configuration [67]

## 2.3 Generator

The generator of the wind turbine converts the mechanical energy captured by the wind into electrical energy and can either be classified as a fixed speed generator, a limited variable speed generator or a variable speed generator [17], [72], [53]. This section discusses and compares the most widely used generator topologies, as was done in [17], [53], [73]. Figure 2.17 provides a graphical illustration of what is discussed in this section.

### 2.3.1 Fixed Speed Generator

The generator of a fixed speed wind turbine rotates at a fixed speed, regardless of the speed of the wind [53]. This design is also referred to as a Danish concept, as it was developed in Denmark [53], [72].

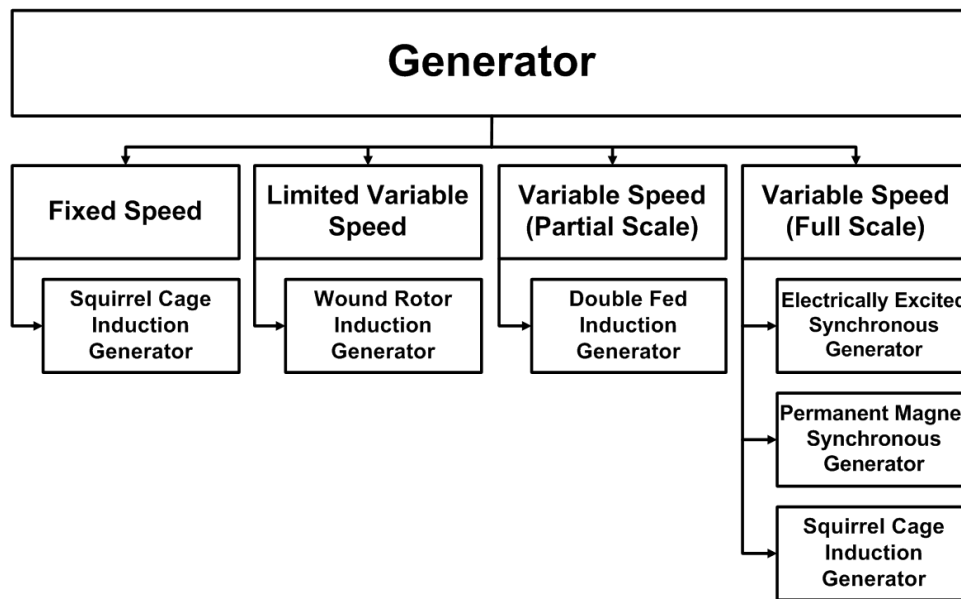


Figure 2.17: Generator section overview

### 2.3.1.1 Squirrel Cage Induction Generator

Squirrel cage induction generators (SCIG) (with the stator directly connected to the grid) are the most commonly used generator for a fixed speed wind turbines [21], [53], [72]. This is known as a grid connected induction generator (GCIG) and can be seen in figure 2.18 (a) [17], [72]. If the turbine is used as standalone wind turbine, a capacitor bank will be connected across the stator in order to provide the reactive power and is known as a self excited induction generator (SEIG) [72].

These wind turbines are usually designed to produce maximum efficiency at a specific wind speed [53]. Some designs have two winding sets, which allow the wind turbine to operate at maximum efficiency at two different wind speeds [53], [72]. The advantages of using a SCIG include:

- Doesn't require complex electronics for operation of the wind turbine [53];
- Simple robust/construction, which increase reliability (compared to variable speed permanent magnet synchronous generator) [17], [29], [53], [72];
- Cost effective design (compared to variable speed permanent magnet synchronous generator) [17], [29], [72];
- Provides stable control frequency (especially when the wind turbine makes use of stall control methods [17]) [72].

The disadvantages of using a SCIG include:

- The generator operates at higher rotational speed and therefore requires a multi-stage gearbox [17], [72];
- Consumes reactive power, which leads to lower power quality control and voltage fluctuations under steady state operation [29];
- Unable to extract all the energy from the wind [21];
- Increased difficulty in controlling the rotational speed of the rotor [53], [72];
- An increase in active power production leads to an increase in reactive power consumption which results in a low full load power factor [53];
- More sensitive to changes in the wind speed which leads to electrical fluctuations for fluctuations in the wind speed [53], [72].

### 2.3.2 Limited Variable Speed Generator

This concept is also referred to as the optislip concept and was developed in Denmark and allows some control over the speed of the generator [17]. Two major companies that utilize this design include Vestas and Suzlon [17].

#### 2.3.2.1 Wound Rotor Induction Generator

Limited speed operation can be obtained by using a wound rotor induction generator (WRIG) (as can be seen in figure 2.18 (b)) [17], [53]. This is done by connecting the stator to the grid and the rotor to a variable resistance by means of a power converter [53], [72]. The rotor resistance is controlled by electronics which adjusts the slip of the generator [53], [72]. The advantage of using a WRIG is that allows some control over the rotational speed of the generator [53], [72]. The disadvantages of using a WRIG include:

- Consumes reactive power [17], [72];
- Requires a soft starter [17], [72];
- Increased cost due to complex electronics [72];
- Requires a multi-stage gearbox to increase the rotational speed of the blades [72].

### 2.3.3 Variable Speed Generator (Partial scale converter)

Most modern wind turbines use a variable speed generator, which allows a reasonable amount of control over the speed of the generator [53]. By using a variable speed gen-

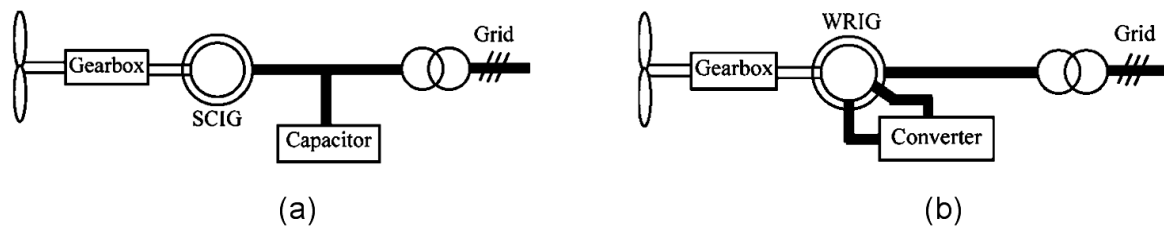


Figure 2.18: (a) Fixed speed squirrel cage induction generator and (b) limited variable speed wound rotor induction generator [17]

erator the maximum efficiency can be obtained for changing wind speeds by altering the rotational speed of the generator [21].

### 2.3.3.1 Double Fed Induction Generator

A doubly fed induction generator (DFIG) is the most commonly used generator for variable speed wind turbines, especially for large wind turbines [53], [74]. During this configuration, the stator is directly connected to the grid and the rotor is connected to a power converter (partial scale of full output), which controls the rotor frequency [7], [72], [74]. The generator will provide power when the slip is negative and absorb power when the slip is positive [53]. This configuration can be seen in figure 2.19 [17]. The advantages of using a DFIG include:

- Maximum power could be captured due to the high levels of rotational speed controllability [53];
- The rotor energy could be fed into the grid, instead of being wasted [72];
- The amount of control that is required determines the size of the converter, not the output of the generator (Typically around 30% of the synchronous speed [17], [74]). This leads to a reduction in cost (compared to using topologies that require a full scale converter) [53], [72], [74];
- Highest annual power yield per cost [74];
- Does not require excitation power [29];
- Produces high torque at low rotational speed [75].

The disadvantages of using a DFIG include:

- Operates at high rotational speed and therefore requires a multi-stage gearbox [17], [72], [74];
- Requires a cooling system [74];

- High cut in wind speed [74];
- Requires slip ring which could attribute to system losses or increase the amount of maintenance [17], [72];
- The power converter requires protection for grid fault conditions [72].

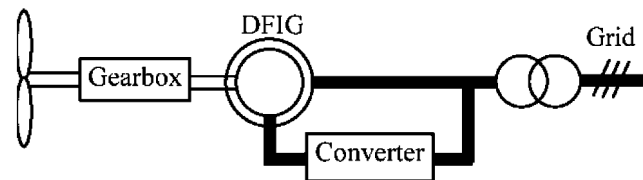


Figure 2.19: Double fed induction generator with partial scale converter [17]

B. Reddy [23] used a PID controller for MPPT of a DFIG. The control system is simulated in Matlab<sup>®</sup>/Simulink<sup>®</sup> and found an improvement of the amount of energy captured by controlling the active power of the wind turbine, which allows variable speed operation.

### 2.3.4 Variable Speed Generator (Full scale converter)

This section discusses variable speed operation of the generator. Each configuration requires a full scale power converter which will in turn allow full control over the rotational speed of the generator.

#### 2.3.4.1 Electrically Excited Synchronous Generator

An EESG has windings on the rotor which are excited by direct current (DC) [17], [74]. The poles of the rotor can either be salient or cylindrical; with the former being the more popular design choice as they are more applicable for the low rotational speeds associated with direct drive wind turbines [17]. An EESG configuration is favoured over a PMSG as it allows full control over the amplitude and frequency, which in turn allows full speed control of the generator and can be seen in figure 2.20 (a) [17]. The advantages of using an EESG include:

- Can operate at low rotational speed and therefore doesn't require a gearbox [72], [74];
- Doesn't require magnets, which contributes to losses during harsh operating conditions [72], [74].

The disadvantages of using an EESG include:

- Increase in generator diameter, weight and cost [72], [74];
- Rotor requires DC for excitation [72];
- Lower torque density (compared to PMSG) [50].

#### 2.3.4.2 Permanent Magnet Synchronous Generator

Rather than relying on a current flow to excite the rotor, a PMSG relies on magnets [74]. This design consists of a wound stator with permanent magnets on the rotor [53] (as can be seen in figure 2.20 (b) [17]. This is becoming an increasingly more attractive design choice as the high prices of permanent magnets are decreasing, as well as the performance increase of these generators [17]. Permanent magnet machines with neodymium (NdFeB) magnets are becoming increasingly popular due their high performance as these magnets are considered the most advanced magnetic material available [76]. These generators can be classified into sub categories, depending on their flux penetration direction [17]. The main types for wind generators are [17]:

- Axial flux generator
- Radial flux generator
- Transverse flux generator

The advantages of using a PMSG include:

- High efficiency [50], [72], [74], [76];
- Doesn't require additional energy for excitation [53], [72];
- Increased reliability (compared to EESG) [72], [76];
- Increased power to weight ratio (compared to EESG) [72];
- Low cut in wind speed and can be designed to operate at low rotational speed therefore doesn't require a gearbox [53], [72], [74];
- Most attractive solution for wind energy [74].

The disadvantages of using a PMSG include:

- Cost increase due to magnets [72], [74];
- Could require a cooling system as magnet's performance decreases with an increase in temperature [53], [72], [74];
- Can be problematic during voltage regulation and synchronization [53].

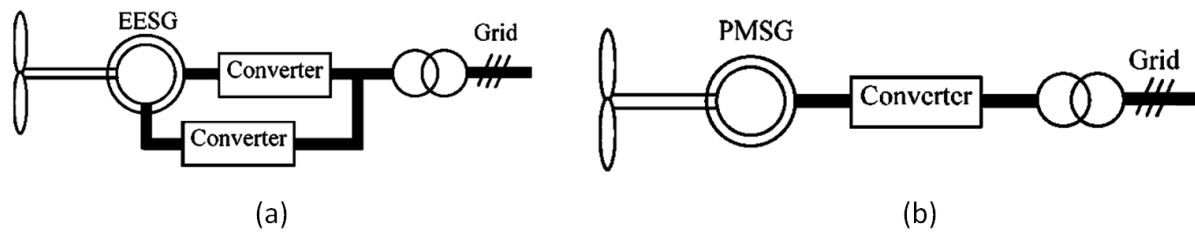


Figure 2.20: Direct drive (a) electrically excited synchronous generator and (b) permanent magnet synchronous generator with full scale converter [17]

G. Putrus *et al.* [39] designed a MPPT controller for a fixed pitch, variable speed PMSG for a small wind turbine. The MPPT is done by controlling a full scale back to back converter. The system was simulated in Matlab<sup>®</sup>/Simulink<sup>®</sup> and the result indicates a 47% increase in the amount of energy captured when compared to the simulations of a currently available wind turbine that doesn't implement a controller.

S. Belakehal *et al.* [59] modelled and simulated a MPPT controller for a PMSG using Matlab<sup>®</sup>. The controller uses a full scale back to back converter which controls the duty cycle by means of an algorithm. The results indicate the controller is a viable solution for small scale wind turbines as well as increases the efficiency of the generator.

### 2.3.4.3 Squirrel Cage Induction Generator

This configuration consists of connecting the stator of the generator to the grid by means of a full scale power converter [17] and can be seen in figure 2.21 [17]. The advantages of using a SCIG with a full scale converter include:

- Improved reactive power compensation [72];
- Full control over electrical torque and rotational speed [21].

The disadvantages of using a SCIG with a full scale converter include:

- Increased cost due to full scale power converter [72];
- Power converter could lower the system's efficiency [72].

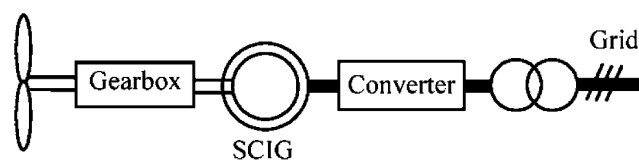


Figure 2.21: Variable speed squirrel cage induction generator with full scale converter [17]

## 2.4 Control Topology

Figure 2.22 provides a graphical illustration of what is discussed in this section.

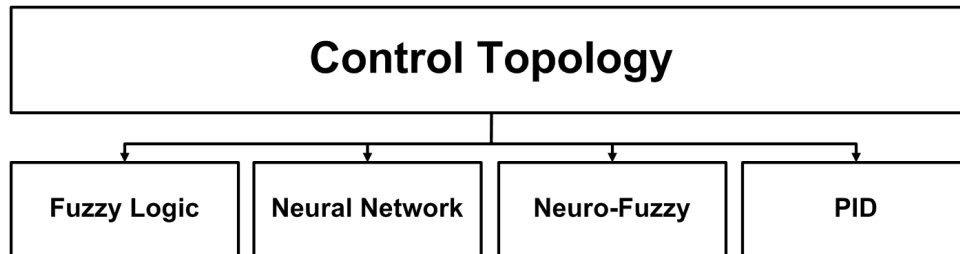


Figure 2.22: Controller section overview

A controller can either be a closed loop or an open loop controller [77]. The output of an open loop controller has no influence on the input of the system [77]. A closed loop controller monitors the outputs of the controller and makes adjustments to the inputs in order to obtain the desired output [77]. This is done by comparing the measured output of the system with a reference value that will determine the required change in the input [77]. A closed loop controller for a single input single output (SISO) system can be seen in figure 2.23 [78].

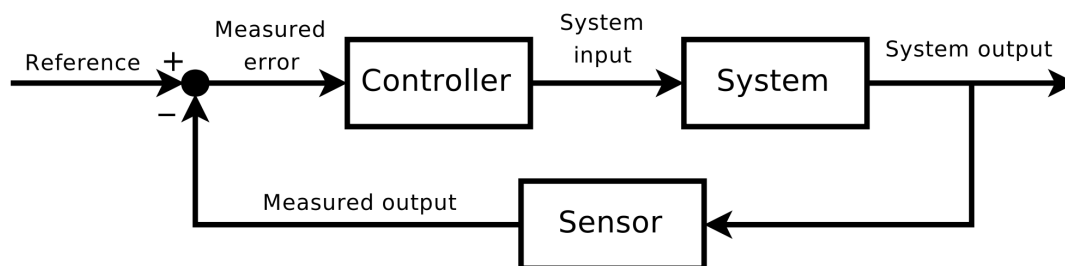


Figure 2.23: Closed loop control system [78]

A closed loop control system consists of the following elements [79]:

- **Reference:** This is the point at which the system is desired to operate.
- **Sensor:** The sensor measures the current point the system is operating at.
- **Error:** The current operating point is measured and compared to the desired point. The difference between the points is known as the error.
- **Controller:** The controller determines the error at which the system is operating at and determines the amount of correction required to operate at the desired point. The controller then alters the system in order to reach the desired point.

A convenient means of describing the behaviour of a closed loop control system is by using a step response, which describes the output of a system for a step input. Figure 2.24 illustrate a typical step response of a closed loop system for a step input [80]. The following can be noted from the step response of a system [81]:

- **Rise time:** The time the system takes to respond and produce a value equal to that of a step input.
- **Overshoot:** The amount by which the system exceeds the desired value, expressed as a percentage.
- **Settling time:** The time the system takes to produce a value that falls within a certain percentage of the input.
- **Steady state error:** The error the system produces once the transient response has passed (i.e. error during the continuous response of the system).

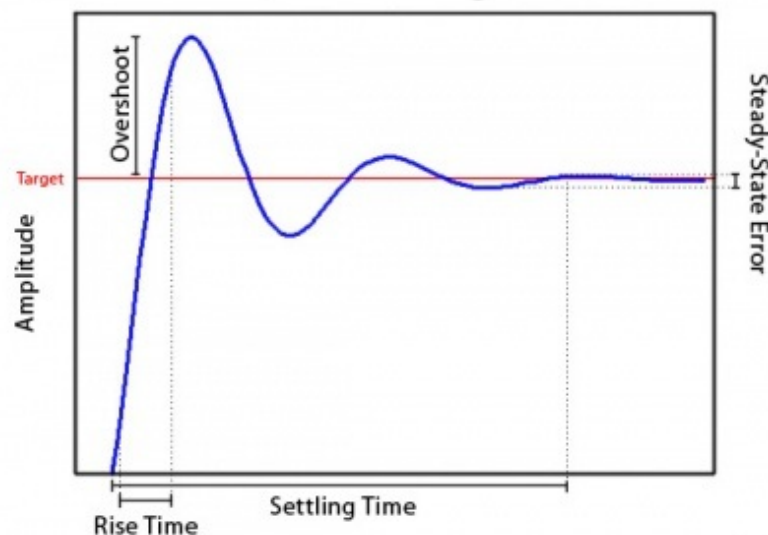


Figure 2.24: Control system step response [80]

### 2.4.1 Fuzzy Logic

Fuzzy logic is another way to describe binary logic and is becoming increasingly popular, especially where conventional control systems have difficulty being implemented [82] (refer to figure 2.25 for a fuzzy logic system structure [83]). Rather than allowing either true or false conditions (1 or 0), fuzzy logic allows partially true conditions [84]. Fuzzy logic is a way for computers to make human like decisions where approximate information can produce precise outputs [85]. A fuzzy logic control system has three stages, which are: [85]:

- **Fuzzification:** During this stage, the real (or crisp) values of the inputs of the system are transformed into fuzzy sets (or linguistic variables) [84–86].
- **Fuzzy rules:** During this stage, the fuzzy rules are applied to the sets [84], [85]. This stage also contains the fuzzy inference unit, which contains various ‘if’ statements.
- **Defuzzification:** During this stage, the fuzzy sets are converted back to real values, which are used to control the output of the system [84], [85].

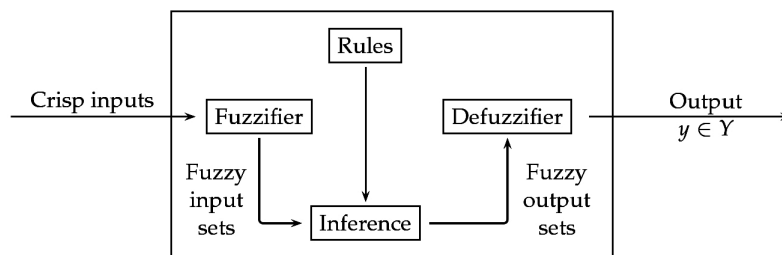


Figure 2.25: Fuzzy system [83]

The membership functions are used to evaluate the input (crisp) values to a degree of truth after which the required output is determined by the rule set. The membership functions of fuzzy logic controller can have various shapes, but the most common types of membership functions used for fuzzy logic control are [86]:

- Triangular
- Trapezoidal
- Gaussian
- Generalized bell

The mentioned membership functions are graphically illustrated in figure 2.26 [87]. For systems requiring high levels of accuracy, Gaussian or S-curve membership functions are recommended and for high levels of variation in short periods of time, triangular or trapezoidal membership functions are recommended [88]. The advantages of using a fuzzy logic control system include:

- Produce less overshoot, oscillation and provides a faster steady state operation (when compared to PID controllers) [63], [85];
- Doesn't require an in depth understanding of the system (i.e. doesn't require a mathematical model or transfer function of the system) [85], [86], [89];
- Low development costs, due to ease of design and implantation [85], [89];
- Less susceptible to disturbances (when compared to PID controller) [85], [90];

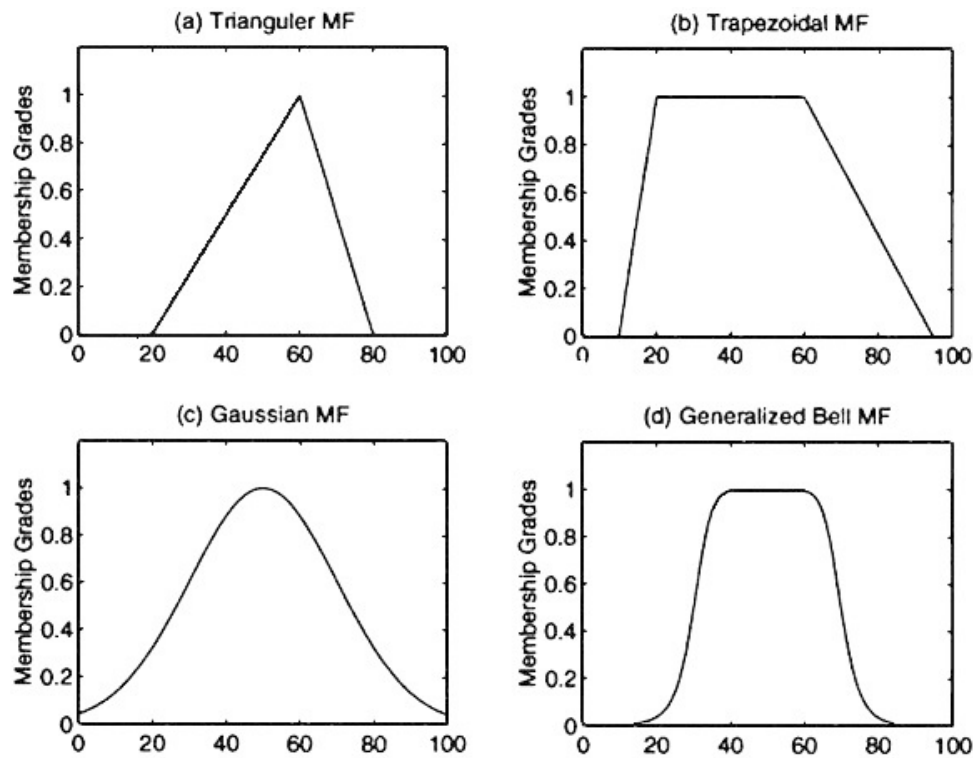


Figure 2.26: Most common types of membership functions [87]

- Can be used on non-linear systems (and simplifying non-linear systems) [85], [89];
- Is more flexible because the system adapts to changes in poles and zeros [85].

The disadvantages of using a fuzzy logic control system include:

- Topological changes of the system require changes in the rule base [90];
- Difficulties to determine the inference rules [90];
- Determining the membership functions and rules often leads to a trial and error method [90];
- Needs to specify fuzzy sets, fuzzy operators and knowledge base [91].

G. Putrus *et al.* [39] simulated a fuzzy logic controller system in Matlab<sup>®</sup>/Simulink<sup>®</sup> utilizing a back to back converter on a PMSG design. The study focused on turbulent wind conditions and the simulation results found a 47% increase in the captured energy when compared to a commercially available wind turbine.

D. Bawa *et al.* [89] used a fuzzy logic system for a MPPT of a solar tracker. The test result show an efficiency increase of 33.416% using a fuzzy logic control system, compared to a system with no tracking system.

J. Monicka *et al.* [86] evaluated and compared the four types of membership functions in figure 2.26 in Matlab®/Simulink® for an induction motor controller. The results found the triangular membership function superior in the speed response and steady state error during rated speed.

S. Kumar [92] implemented a fuzzy logic control system to control the water level of a tank rather than the traditional PID control system. Fuzzy logic control was found to be a viable control solution due to the non-linearities associated with the tank.

H. Sefidgar *et al.* [93] presented a fuzzy logic MPPT controller for a PMSG wind turbine. The controller measures the load voltage and load current and alters the duty cycle of a DC-DC boost converter in order to extract the most amount of power. Simulation results in Matlab®/Simulink® indicate an overall improvement in the wind turbine performance.

## 2.4.2 Neural Network

A large number of different types of networks exist, but all of them are characterized by [94]:

- **A set of nodes:** The nodes receive the inputs to the system and process them in order to acquire an output [94]. The process can either be simple mathematical calculations or more complex where it contains another network [94].
- **Connections between nodes:** The connections determine the flow of information between the nodes and can either be unidirectional (when information can only be passed in one direction) or bidirectional (when information can be passed in both directions) [94]. The interaction between the nodes leads to a global behaviour of the system which cannot be observed or altered by the elements of the network, i.e. the abilities of the network override the abilities of the elements [94].

Neural networks are similar to the functioning of the human brain with the structures having the ability to learn from examples [90], [95]. These networks are known as artificial neural network (ANN) and consist of a processing unit, artificial neurons and connections between the neurons [94], [96]. These neurons can either have a real value between (0, 1) or between (-1, 1) [97]. The neurons consist of inputs that are multiplied by weights depending on the strength of the signal and a mathematical function that determines the activation of the neuron and in turn the output [94], [96]. Several neurons are combined to form an ANN with the purpose of processing information [94]. Figure 2.27 graphically illustrates the structure of an artificial neuron [94].

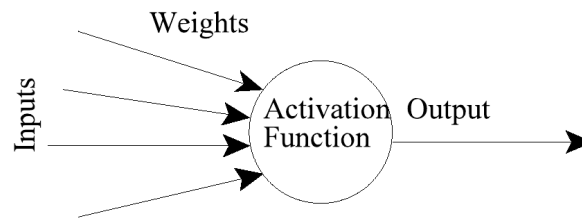


Figure 2.27: Structure of an artificial neuron [94]

The weights of the inputs can be adjusted to produce a desired output and can either be excitatory (positive) or inhibitory (negative) [94], [96], [97]. However, this can become complicated when the network consists of multiple neurons; therefore algorithms are used to determine the correct weights in order to produce the desired output of the network [94]. This process is known as learning or training the network [94]. Two different architectures can be used for neural networks, they are [97]:

- **Feed-forward:** During this architecture type, the bottom layer represents the input to the network. Each layer processes the signals entering the neuron until the top layer is reached, which is the output of the network [97]. This architecture can be seen in figure 2.28 (a) [97].
- **Feed-back:** This architecture allows bidirectional exchange of signals achieved. The neurons will exchange signals between each other until a desired output is reached [97]. This architecture can be seen in figure 2.28 (b) [97].

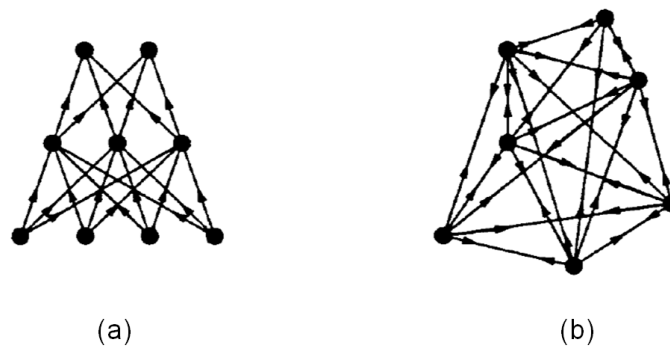


Figure 2.28: (a) Feed-forward and (b) feed-back architecture [97]

The advantages using an artificial neural network include:

- Has the ability to learn [90], [97];
- Low levels of susceptibility to disturbances [90].

The disadvantages using an artificial neural network include:

- Impossible interpretation of the functionality [90];
- Difficult to determine the correct amount of layers and neurons [90];
- Needs to specify system architecture and learning algorithm [91].

### 2.4.3 Neuro-Fuzzy

Neuro-fuzzy controllers are a combination of neural networks and fuzzy systems with the idea of combining the advantages of each type of control topology and eliminating their individual disadvantages [90], [91], [95]. Neuro-fuzzy can be categorized into the following types [90], [91]:

- **Concurrent neuro-fuzzy:** In this combination, the neural network assists the fuzzy controller to determine the required parameters of the system [91]. The neural network could also process the fuzzy outputs if they are not directly applicable to the system process [91]. This method is especially useful if the inputs cannot directly be measured [91].
- **Cooperative neuro-fuzzy:** The fuzzy membership functions or rules are determined by the neural network from the data using a clustering or fuzzy clustering algorithm [91]. The neural networks only have an effect on the inputs of the fuzzy system and the output is determined by the fuzzy system [90].
- **Fully fused neuro-fuzzy:** This combination shares data structures and knowledge representations and can be achieved by using a special neural network structure for the fuzzy system [91]. Differential functions or non-standard neural learning algorithms are used as conventional learning algorithms cannot be applied to a fuzzy inference system (FIS) [91].

Figure 2.29 illustrates the difference in structure of a concurrent neuro-fuzzy system and a cooperative neuro-fuzzy system [90].

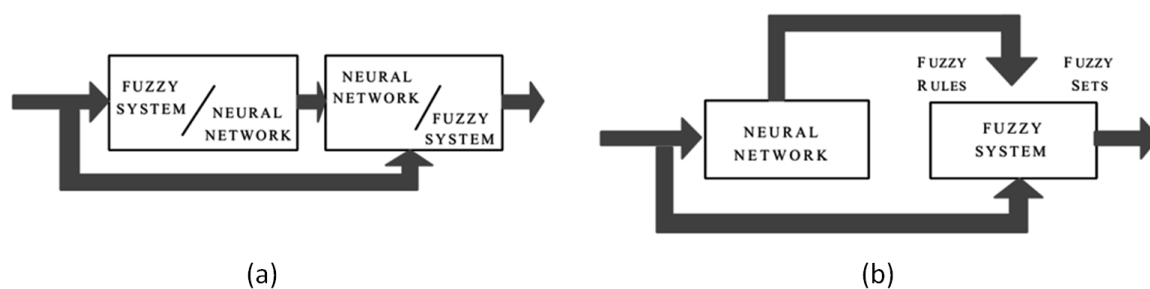


Figure 2.29: (a) Concurrent system and (b) cooperative system structure [90]

The following models of fused neuro-fuzzy includes but are not limited to [90], [91]:

- **ANFIS:** Adaptive neuro-fuzzy inference system (ANFIS) consists of a five layered architecture and uses back propagation learning and least mean square estimation to determine the membership function parameters and consequent parameters, respectively [91]. Fuzzification of the inputs is done in the first layer and T-norm operators are used in the second layer [91]. During the third and fourth layer, the rule strengths and rule parameters are determined, respectively [91]. The structure of an ANFIS system can be seen in figure 2.30 (a) [98].
- **EFuNN:** Evolving fuzzy neural network (EFuNN) consist of five layers and the first layer only passes the data to the second layer, which calculates the degree of truth of the inputs to the predefined fuzzy rules [91]. The fuzzy rule nodes, each connected with 2 weights, are present in layer three which are in turn adjusted with a hybrid learning algorithm [91]. The fourth and fifth layer determines the degree to which output membership functions match the inputs and defuzzifies the data, respectively [91]. The nodes are created during the learning process for this system [91]. The structure of an EFuNN system can be seen in figure 2.30 (b) [99].

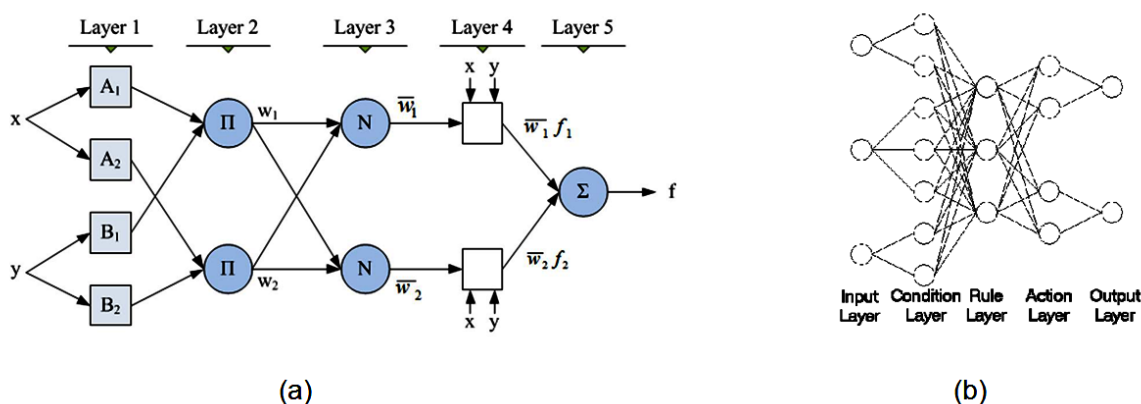


Figure 2.30: (a) ANFIS [98] and (b) EFuNN structure [99]

- **FALCON:** Fuzzy adaptive learning control network (FALCON) consists of a five layered architecture with two nodes for each output [91]. One is the desired output of the system and the other is the actual output of the system [91]. Fuzzification is done in the first layer which can either be a single node with a simple membership function or multiple nodes with a complex membership function [91]. The desired outputs are obtained by locating the initial membership functions or rule base and using gradient descent learning to adjust the parameters of the membership functions [91]. The structure of a FALCON system can be seen in figure 2.31 (a) [91].

- **FUN:** The first layer of a fuzzy net (FUN) system contains the membership functions and performs the fuzzification of the inputs, while the second layer performs the conjunctions (AND statements) of the system [91]. The third layer contains the membership functions of the output variables (OR statements) [91] and defuzzification is performed in the fourth layer [91]. A set of fuzzy rules and membership functions are provided and the system randomly alters the parameters of the membership functions and observes the output [91]. If the modification improves the system performance the modification is kept, otherwise the modification will be undone [91].
- **GARIC:** Generalized approximate reasoning based intelligent control (GARIC) uses two neural networks, namely an action selection network (ASN) and an action-state evaluation network (AEN) [91]. The action selection network consists of five layers and is monitored by the action state evaluation [91]. The values of the inputs are stored in the first layer and the fuzzy rules are implemented in the second layer [91]. The third layer consists of the control outputs, which are calculated by means of a mean of maximum method [91]. The node parameters are determined by means of gradient descent and reinforcement learning [91]. The structure of a GARIC system can be seen in figure 2.31 (b) [91].

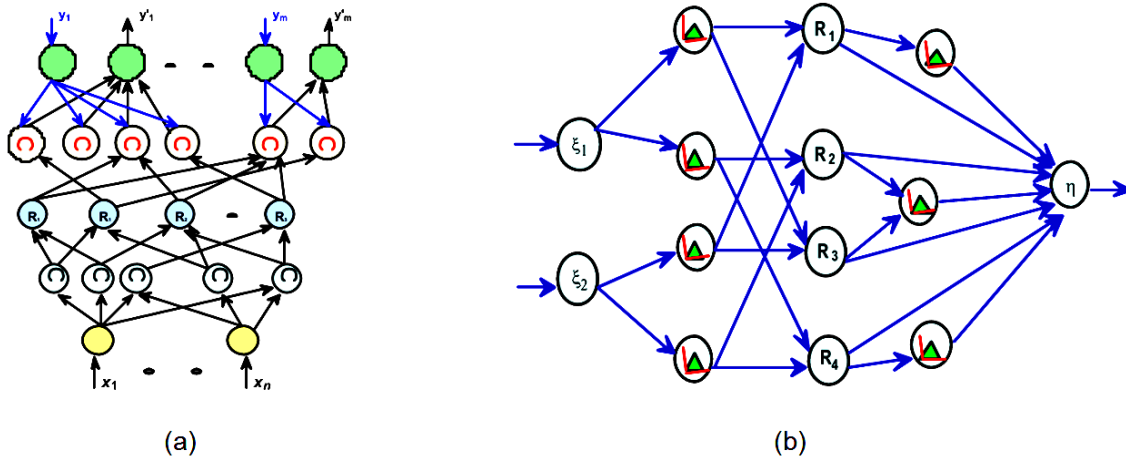


Figure 2.31: (a) FALCON and (b) GARIC structure [91]

The advantages of using a neuro-fuzzy controller include:

- Has the ability to learn [90];
- Low levels of susceptibility to disturbances [90].

The disadvantages of using a neuro-fuzzy controller include:

- Impossible interpretation of the functionality [90];
- Difficult to determine the correct amount of layers and neurons [90];
- Needs to specify system architecture and learning algorithm [91].

#### 2.4.4 Proportional Integral Derivative

Proportional integrative derivative (PID) controllers is the most commonly used type of closed loop controller and consist of three different controller types, which are [100]:

- Proportional (P)
- Integrative (I)
- Derivative (D)

Often P and I are used as single control modes but D is rarely used alone [101], [102]. Each controller type has the following effects on the output:

##### 2.4.4.1 P (Proportional)

The output of the system changes proportionally to the input of the system and the change occurs without any lag [102]. A P controller is usually used where the system allows steady state errors for disturbances in the system [102]. A disadvantage of using a P controller type is that it produces a steady state error [102]. An advantage of a P controller is the rapid response time and stable control [102].

##### 2.4.4.2 I (Integrative)

The output is changed by a set value, regardless of the input of the system (given the input does not equal zero) [102]. An advantage of an I controller is that it doesn't produce a steady state error [102]. The disadvantages of I controllers is the slow response time and the probability of instabilities developing in the control system [102].

##### 2.4.4.3 D (Derivative)

The output is changed according the rate of change in the error of the system, which in turn yield a faster reaction time when compared to P controllers. An advantage of using a D controller is the rapid change in the system output [102]. The disadvantages of D controllers is that is does not recognise steady state errors and usually requires an alternate controller type (P or I) [102].

Other variations also exists that combine the controller types which includes a proportional integrative (PI) and proportional derivative (PD) controller with the former being the more popular choice [101]. The combining of the controller types lead to the following properties:

#### 2.4.4.4 PI (Proportional-Integrative)

Adding an integral component to a proportional controller results in a reduced steady state error, overshoot and rise time [101]. However, it slows the response time of the system and reduces the stability of the control system [101]. PI controllers are the most common type of combination controllers mainly due to their low susceptibility to disturbances and noise [101].

#### 2.4.4.5 PD (Proportional-Derivative)

Adding a derivative component to a proportional controller leads to increased prediction of the error and a more stable system, as well as lowering the overshoot, rise time and settling time [101]. PD controllers are commonly found in moving systems as they are more stable during heading changes [101].

#### 2.4.4.6 PID (Proportional-Integrative-Derivative)

When P, I and D controllers are combined it is known as a PID controller (Proportional-Integrative-Derivative) [103]. This is done in order to combine the advantages of PI and PD controllers and the controller can either be an open loop or closed loop system [103], [79]. Increasing the gain of each controller component (P, I and D) result in changes in the system as can be seen in table 2.2 [101].

Table 2.2: Effect of increasing controller gain

|       | <b>Rise time</b> | <b>Overshoot</b> | <b>Settling time</b> | <b>Steady state error</b> |
|-------|------------------|------------------|----------------------|---------------------------|
| $K_P$ | Decreases        | Increases        | Little effect        | Decreases                 |
| $K_I$ | Decreases        | Increases        | Increases            | Decreases                 |
| $K_D$ | Decreases        | Decreases        | Decreases            | No effect                 |

The advantages of using a PID control system are its simplicity and good performance of a wide range of operating conditions [29], [100]. The disadvantages of using a PID controller is the requirement of a transfer function and difficulty controlling systems that are non-linear or have changing parameters [29], [85], [92]. A PID controller doesn't adapt to changes in system which results in a retuning of the controller for a change in the system [85].

B. Reddy *et al.* [23] simulated a PID controller system in Matlab®/Simulink® for a MPPT. The controller focuses on controlling the stator current of the generator to allow variable speed operation of the generator. Utilizing this technique yielded an improvement of the amount of energy captured by the wind.

J. Perng *et al.* [100] proposed a method that uses a PID controller, combined with intelligent algorithms to determine the optimal operating point of a wind turbine generator. These algorithms include particle swarm optimization (PSO) and a radial basis function neural network (RBFNN) and are intelligent artificial learning algorithms. The controller was used in conjunction with a DFIG. This configuration was successfully simulated and the boundaries of the control system were determined.

## 2.5 Controller

The controller contains and executes the control strategy with analog and digital inputs and outputs. This section discusses various controllers that were considered for the system (refer to figure 2.32 that provides a graphical illustration of the controllers discussed in this section).

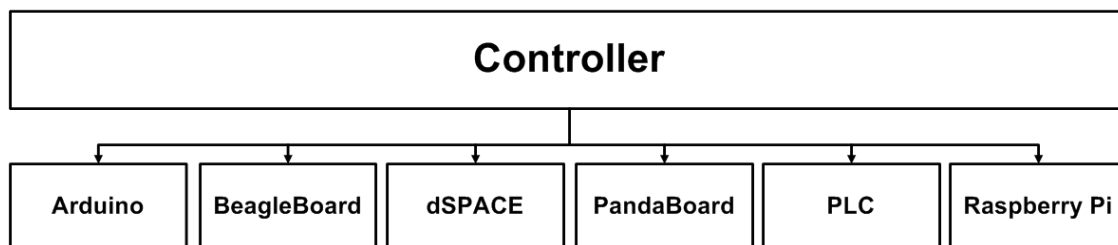


Figure 2.32: Controller section overview

### 2.5.1 Arduino

The Arduino is a development board and was developed to provide a low cost, easy integration of designs [104]. An Arduino board consists of microcontroller, SRAM, flash memory (to store program code) and EEPROM (to store parameters) [104]. The software programming language of an Arduino is a simplified version of C/C++ [104], [105]. There are various different types of Arduino development boards available, each designed for different tasks. Matlab®/Simulink® offers support packages for a number of Arduino boards that allows an interface with the Arduino board. If the support package is installed, Matlab®/Simulink® can be used to control the board with the USB cable connected [105]. The control can either be direct control or scripted control [105].

Another advantage of the support package is the ability to compile and program the Arduino by developing and converting the Simulink<sup>®</sup> models to C/C++ [105]. Ranging from least to most powerful, they provide support packages for the following (refer to table 2.3 for a hardware comparison between the boards [106]):

- Arduino Uno
- Arduino Mega
- Arduino Due

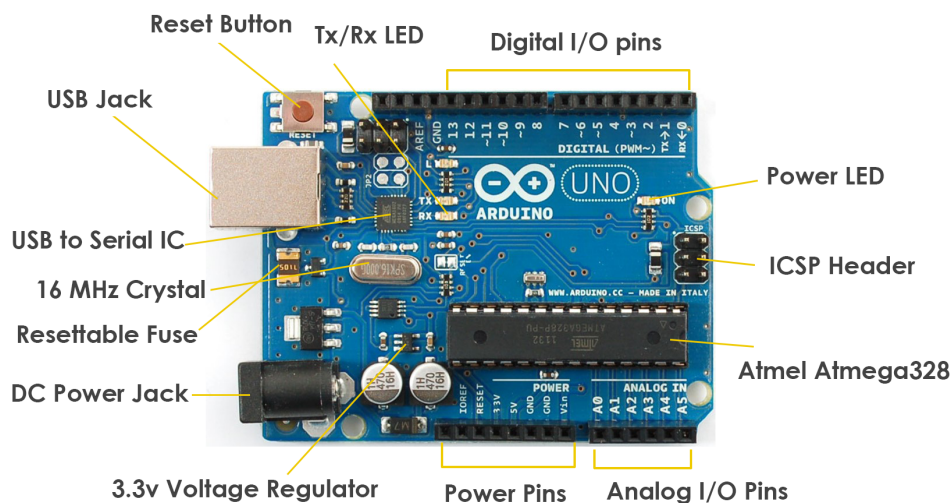


Figure 2.33: Arduino Uno development board [107]

Figure 2.33 illustrates the basic layout and pin allocations of the Arduino Uno development board [107]. A disadvantage of the Arduino development board is its limited memory and performance which limits its capabilities [108]. The advantages of using an Arduino board include:

- Has open source software, i.e. free development software [89], [104];
- Has the ability to interface with Matlab<sup>®</sup>/Simulink<sup>®</sup> which allows programming of the board in C/C++ from models as well as real time modelling [105].

D. Bawa *et al.* [89] used an Arduino Uno for a MPPT for a solar panel. The control system used a fuzzy logic based controller and the test results indicate an efficiency increase of 33.416%.

S. Kumar [92] used an Arduino Uno to control the water level using a fuzzy logic control system. The study found the controller as a viable solution and therefore confirms the compatibility of the Arduino development board with both fuzzy logic control and Matlab<sup>®</sup>.

Table 2.3: Comparison between Arduino Uno, Arduino Mega2560 and Arduino Due

|                    | Arduino Uno | Arduino Mega2560 | Arduino Due |
|--------------------|-------------|------------------|-------------|
| Processor          | ATmega328   | ATmega2560       | AT91SAM3X8E |
| CPU speed (MHz)    | 16          | 16               | 84          |
| Analog input pins  | 6           | 16               | 12          |
| Analog output pins | 0           | 0                | 2           |
| Digital I/O        | 14          | 54               | 54          |
| EEPROM (kb)        | 1           | 4                | -           |
| SRAM (kb)          | 2           | 8                | 96          |
| Flash memory (kb)  | 32          | 256              | 512         |

### 2.5.2 BeagleBoard

The BeagleBoard is an open source development board equipped with an OMAP3530 processor and is intended for development, demonstration and evaluation [109]. The BeagleBoard was developed with audio, visual and digital signal processing in mind and is essentially a pocket sized single board computer [110]. It has the ability of adding external peripherals to further increase its features [110]. In addition to being able to add external peripherals, the BeagleBoard has the ability to integrate with Matlab<sup>®</sup>/Simulink<sup>®</sup> by installing the BeagleBoard support package which makes it perfect for rapid prototyping [110]. This allows for the following:

- Generate C code from Matlab<sup>®</sup>/Simulink<sup>®</sup> models (for board and peripherals) [110].
- Run models in standalone or real time [110].
- Interactive parameter tuning [111].

The BeagleBoard comes in a variety of boards with different applications, ranging from least to most powerful they are:

- BeagleBone
- BeagleBoard
- BeagleBone Black
- BeagleBoard xM
- BeagleBoard x15

Table 2.4 compares the hardware specifications of the BeagleBone Black, BeagleBoard xM and BeagleBoard x15 [112].

Table 2.4: Comparison between BeagleBone Black, xM and x15

|                 | <b>BeagleBone Black</b> | <b>BeagleBoard xM</b> | <b>BeagleBoard x15</b> |
|-----------------|-------------------------|-----------------------|------------------------|
| Processor       | ARM Cortex-A8           | ARM Cortex-A8         | ARM Cortex-A15         |
| CPU speed (GHz) | 1                       | 1                     | 1.5                    |
| Analog pins     | 7                       | 0                     | 12                     |
| Digital I/O     | 65                      | 53                    | 54                     |
| Memory (MB)     | 512                     | 512                   | 2048                   |
| DSP             | -                       | TMS320C64x            | Dual TMS320C66x        |
| DSP Speed       | -                       | 800                   | 700                    |

### 2.5.3 dSPACE®

dSPACE® is developed for high speed digital controllers and allows real time interface for both analog and digital signals (inputs and outputs) and has the ability to interface with Matlab®/Simulink® through Real Time Workshop [113]. The dSPACE® DS1104 controller board can be seen in figure 2.34 [114].



Figure 2.34: dSPACE® development board [114]

Figure 2.35 illustrates the connections between the dSPACE® board and Matlab®/Simulink® [113]. The Matlab®/Simulink® model is converted into C and Control Desk® is used for the real time interface [113]. This uses integrated instruments and scopes that allow real time running and parameter tuning of the Matlab®/Simulink® model and blocks [113]. The layout of Control Desk® can be altered in order to suit the simulation needs, as well as capturing data during real time implementation of the model [113].

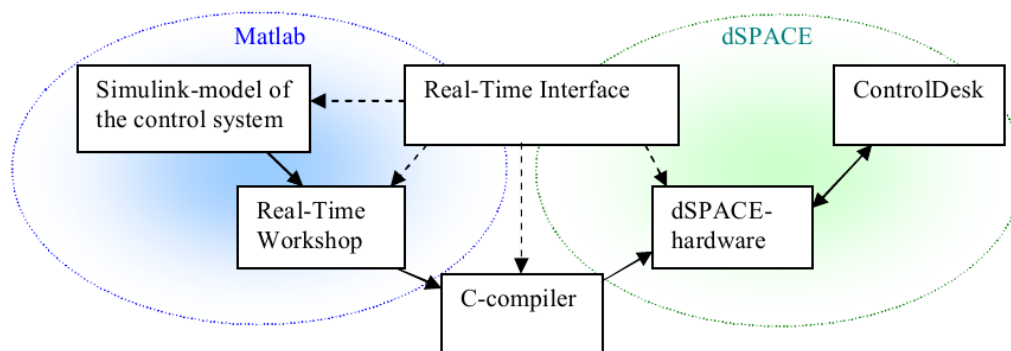


Figure 2.35: Matlab®/Simulink® dSPACE® connections [113]

I. Serban *et al.* [115] proposed a sensor-less control method for a fixed pitch, direct driven PMSG wind turbines. The system was implemented on a DS1103 controller board using Control Desk® and the results indicate that the rotational speed with the controller follows the optimal rotational speed and therefore extracts more power, especially during partial load conditions.

D. Petrila *et al.* [116] developed a fuzzy logic controller for a MPPT on a PMSG with a hybrid DC-DC converter. The controller tracks the optimal rotational speed of the generator, both simulation results and experimental results indicated an improvement in the amount in the amount of power extracted from the wind. The experimental implementation consisted of dSPACE controlling an induction motor which in turn rotates the PMSG.

### 2.5.4 PandaBoard

A PandaBoard is a single board computer equipped with the OMAP4430 Processor and is widely used due to its low cost and high performance with relative low power consumption [117], [118]. The high performance of the PandaBoard is mainly due to the 1 GHz dual-core processor (ARM Cortex-A9) equipped with 1 GB of DDR2 ram [117]. The PandaBoard has connectors which allow additional connection of peripherals that further increases its functionality [119], [118]. The hardware on the PandaBoard consist of a multimedia processor, GPU, multimedia hardware accelerator with a programmable DSP and various peripheral connections including ethernet, bluetooth, USB, RS-232, SD card as well as audio and video outputs [118]. The PandaBoard is capable of running various operating systems installed on a SD card which includes Symbian OS™, Linux®, Palm OS™ and Windows CE™ [118].

### 2.5.5 Programmable Logic Controller

A programmable logic controller (PLC) is a solid state device that uses a program code to control the output of a system by receiving inputs from the system [120]. The fundamental parts of a PLC consist of the following:

- **Input and output module** These are the connections to the process that is being controlled and a typical PLC has 8 - 32 I/O connections available [121], [122]. For most PLCs, the connectors are either inputs or outputs, but some models have the ability to be set to either an input or output [122].
- **Processor** The processor, also known as the central processing unit (CPU), controls the PLC by executing the program within the PLC [121].
- **Memory** The memory is tied to the processor and contains the program code and ranges between 1 k and 48 k, depending on the PLC [121].
- **Programming device** This is used to program the PLC and most often is detachable from the PLC itself [121].

A PLC can be programmed in different ways but all these fall within two main categories (i.e. alphanumeric and graphical). The possible ways to program a PLC are [123]:

- Alphanumeric
  - Instruction list
  - Structured text
- Graphical display
  - Function block diagram
  - Ladder diagram
  - Sequential function chart

The advantages of a PLC are its reuse-ability, compact design and ease of installation and maintenance [121]. The disadvantages are difficulty in controlling systems with multiple inputs and outputs and difficulty in controlling intelligent electronic devices (IED) [124].

### 2.5.6 Raspberry Pi

The Raspberry Pi is a single board computer and was developed in order to increase the exposure to computers which was achieved with the low cost of the board [125],

[126]. Since its launch in 2012, various models and upgrades have been done from the first model (refer to table 2.5 for a comparison between some of these models [127]).

Table 2.5: Comparison between Raspberry Pi Model A+, Raspberry Pi Model B+ and Raspberry Pi 2 Model B

|                    | Raspberry Pi Model A+ | Raspberry Pi Model B+ | Raspberry Pi 2 Model B |
|--------------------|-----------------------|-----------------------|------------------------|
| Processor          | ARMv6 (Single)        | ARMv6 (Single)        | ARMv7 (Quad)           |
| CPU Speed (MHz)    | 700                   | 700                   | 900                    |
| GPIO               | 40                    | 26                    | 40                     |
| Memory (MB)        | 256                   | 512                   | 1024                   |
| Memory Speed (MHz) | 400                   | 400                   | 400                    |

The Raspberry Pi is the size of a credit card and is equipped with a BCM2835 processor at a frequency of 700 or 900 MHz, depending on the model, which performance can be compared to that of a 300 MHz Pentium 2 processor [127], [128]. The Raspberry Pi also has the ability to connect external peripherals which includes GPIO, SD card, HDMI, ethernet, USB as well as audio and video output [128].

## 2.6 Software

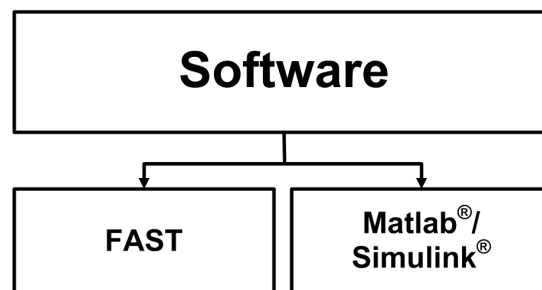


Figure 2.36: Software section overview

A variety of software packages are available which can be used to design, simulate and build the control system of the wind turbine (refer to figure 2.36 for a graphical illustration of the packages discussed in this section). The majority of this software was developed only for a specific part of the wind turbine (i.e. aerodynamic, electrical or mechanical). Figure 2.37 illustrates a few of the different software packages that can be used in order to simulate a specific part of the wind turbine [129]. Some packages also offer the ability to be integrated with each other in order to generate a more realistic simulation of the wind turbine system by considering all the different factors that influence it's working.

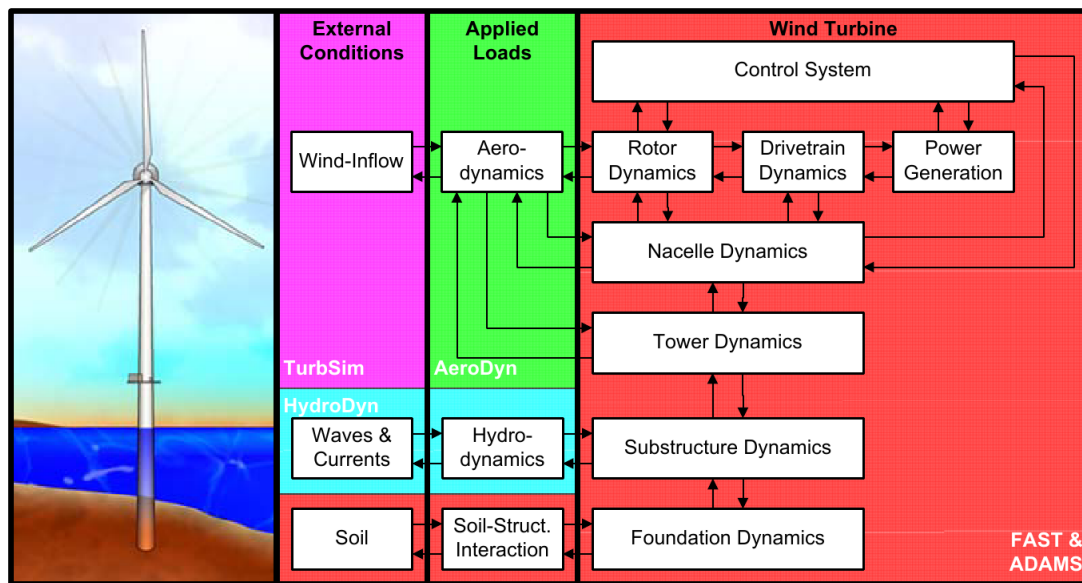


Figure 2.37: Simulation packages available for wind turbines [129]

This section discusses some of the available software that can be used to develop the controller. This includes simulation packages, as well as software that will help compile the project.

### 2.6.1 FAST

Fatigue aerodynamic structures and turbulence (FAST) was developed in order to simulate the dynamic response of two bladed and three blades wind turbines and has the ability to interface with Matlab®/Simulink® [40], [129]. The FAST model is integrated with Matlab®/Simulink® in the form of an S-function block [129]. The S-function block is separately compiled using Fortran or C++ and added to the Matlab®/Simulink® model [129]. FAST has the ability to simulate the pitch, torque and yaw of wind turbines [129].

A disadvantage of FAST is that a change in the system requires the model to be recompiled [129]. The advantages of using FAST is that it has the ability to interface with Matlab®/Simulink® and that its open source software [129], [130].

R. Fadaeinedjad *et al.* [131] simulated a wind turbine using a doubly fed induction generator. The purpose of this simulation was to create a model of a wind turbine that considers the aerodynamic, mechanical and electrical aspects. This was done by integrating TurbSim, FAST and Simulink®. The results indicate a successful integration of these simulation packages and show the dependency of the factors with each other, for example the electrical effect a mechanical change has etc.

### 2.6.2 Matlab<sup>®</sup>/Simulink<sup>®</sup>

Matlab<sup>®</sup> is a technical computing software package and has become an increasingly popular simulation software package, especially for dynamic systems [132]. It provides a user friendly environment for the following:

- Data analysis and acquisition
- Algorithm development
- Modelling and simulation

Simulink<sup>®</sup> is a software package included in Matlab<sup>®</sup> and allows a graphical user interface for modelling, simulating and analysing dynamic systems [132]. Models can be created by a simple drag and drop operation of the block diagrams for the system [132]. The library includes a comprehensive array of block diagrams with the added benefit of the S-function, which allows custom blocks to be created [132]. S-functions can be written in multiple languages, including Matlab<sup>®</sup>, C and C++ [132]. After the model has been created, it can be simulated either by using pre-set commands or using the Matlab<sup>®</sup> command window, which allows an increase in the customization of the simulation parameters [132]. The advantages of using Matlab<sup>®</sup>/Simulink<sup>®</sup> include:

- Support linear and non-linear systems [132];
- Modelling can be done in continuous time, sampled time or a combination thereof [132];
- Allows drag and drop operations of models (i.e. allowing ease of operation) [132].

The disadvantages of using Matlab<sup>®</sup>/Simulink<sup>®</sup> include:

- Could be time consuming to develop models [133];
- Difficulties in modelling effects like friction [133].

B. Reddy *et al.* [23] used Matlab<sup>®</sup>/Simulink<sup>®</sup> to simulate a DFIG utilizing a PID controller. The controller was simulated for various increasing wind speeds. Simulations indicate an improvement of the amount of energy captured from the wind.

D. Bawa *et al.* [89] the feasibility of an Arduino Uno was investigated for a MPPT system for a solar tracker, using fuzzy logic. The system was both implemented and tested using Matlab<sup>®</sup> and the test results indicated a 33.416% increase in efficiency.

S. Kumar [92] simulated the control of a non-linear tank. The system implemented fuzzy control on an Arduino Uno. The system was designed using Matlab<sup>®</sup> and simu-

lated in Simulink<sup>®</sup>. The simulations found fuzzy logic to be a viable solution to control non-linear systems.

R. Fadaeinedjad *et al.* [131] did a full simulation for a wind turbine by combining TurbSim, FAST and Simulink<sup>®</sup>. This allowed the wind turbine to be simulated for the aerodynamic, mechanical and electrical aspects. The configuration used for this simulation was a DFIG with a partial scale converter. Combining these simulation packages allowed an illustration of the effect each aspect have on each other.

## 2.7 Standards

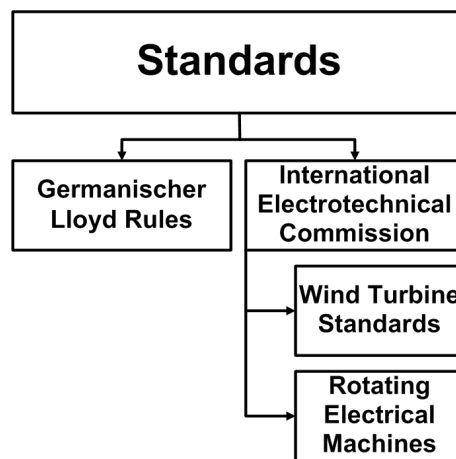


Figure 2.38: Standards section overview

This section discusses the various standards that will be considered whilst developing the controller. Figure 2.38 provides a graphical illustration of the standards discussed in this section.

### 2.7.1 Germanischer Lloyd Rules for Certification

The Germanischer Lloyd rules are standards set by an organization situated in Germany and focuses on standards for ships, offshore oil and gas and wind energy. The Germanischer Lloyd rules are similar to the standards set by the IEC, but focus more on the design of wind turbines [7].

### 2.7.2 International Electrotechnical Commission

The international electrotechnical commission (IEC) is the world's largest organization that provides standards for electrical and electronic technologies. This section discusses the standards that are relevant to the project.

### 2.7.2.1 Wind turbine standards

The IEC61400 - # is an international standard set by the IEC, which lists the design and testing requirements for wind turbines. The following will be considered during the development of the project:

- **IEC61400-1:** These design requirements focuses on the wind turbine (of all sizes) as a whole and ensures the wind turbine is not hazardous while operating. It focuses on the control, protection mechanisms, electrical and mechanical systems and structures.
- **IEC61400-2:** These design requirements focuses on small wind turbines. It specifically focuses on the safety, quality and integrity of the wind turbine in order to ensure non-hazardous operation.
- **IEC61400-12:** These requirements focus on the power performance testing of wind turbines. It focuses on the measurement and analysis of the power generated by the wind turbine.

### 2.7.2.2 Rotating electrical machines

The IEC60034 - # is an international standard set by the IEC, which lists the standards for rotating electrical machines. The following will be considered during the development of the project:

- **IEC60034-1:** This is the standard set for the rating a performance of the electrical machine.
- **IEC60034-2-1:** This is the standard set in order to determine the efficiency and losses of the electrical machine.
- **IEC/TS60034-2-3:** This is the standard set in order to determine the efficiency and losses of a converter fed induction machine.

## 2.8 Conclusion

The purpose of this section was to obtain an in depth understanding of wind turbines and all the different elements required to develop the controller. This section provided an understanding on the workings of wind turbines, control techniques commonly used on wind turbines and controller types available that could be implemented on the system. The case studies done in this chapter provided an insight to the compatibility of control topology with the various controller types.

This chapter provided the knowledge required for the design phase of the project. An insight to the functional flow of the subsystems was obtained which lead to the required calculations for the integration of the sub systems to a complete working system. The next chapter contains the design of the controller. This includes the functional flow of the sub systems, calculations as well as simulation and experimental parameters of the controller.

# Design

*This section discusses the design of the controller and functional units. The design of the individual functional units as well as the simulation and experimental parameters of controller is discussed. The required calculations for the integration of the various functional units are also discussed in this chapter. An overview of what can be expected in this chapter can be seen in figure 3.1.*

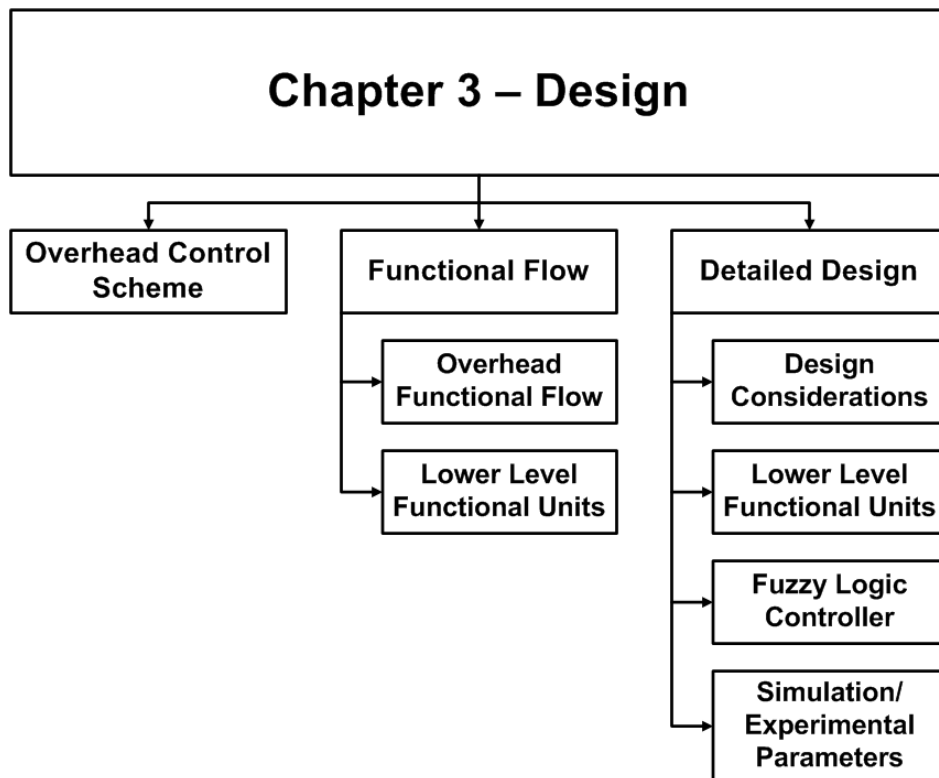


Figure 3.1: Design chapter overview

## 3.1 Overhead Control Scheme

The overhead control scheme for the system can be seen in figure 3.2. The controller is applicable for a stand-alone, fixed pitch, direct drive wind turbine utilizing a PMSG design and is similar to the controllers presented by D. Petrilă *et al.* [116] and H. Sefidgar *et al.* [93]. The system requires measurements on the rotational speed, load voltage and load current and the output of the system is the duty cycle to the DC-DC boost converter. The blades of the wind turbine were replaced with a prime mover during the experimental implementation of the controller in order to ensure consistency in the results.

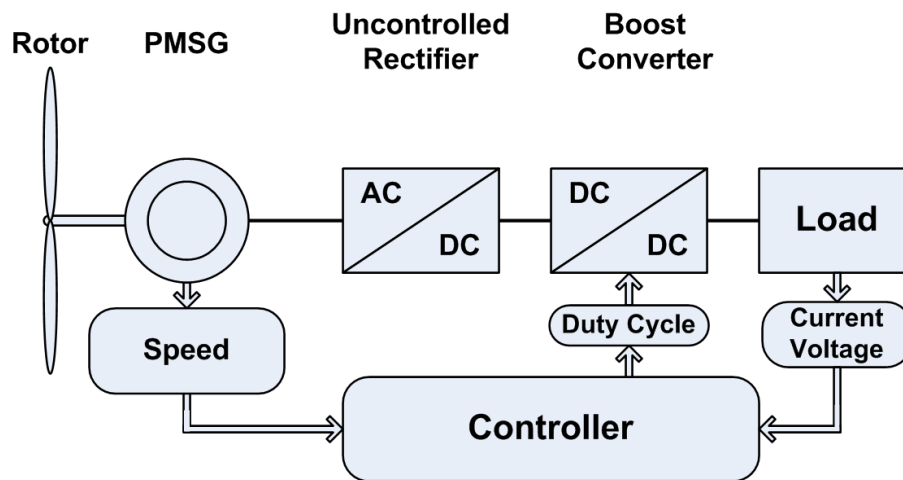


Figure 3.2: Overhead control scheme

## 3.2 Functional Flow

This section provides the functional flow of the project and will graphically illustrate the interaction of the various sub systems with respect to each other.

### 3.2.1 Overhead Functional Flow

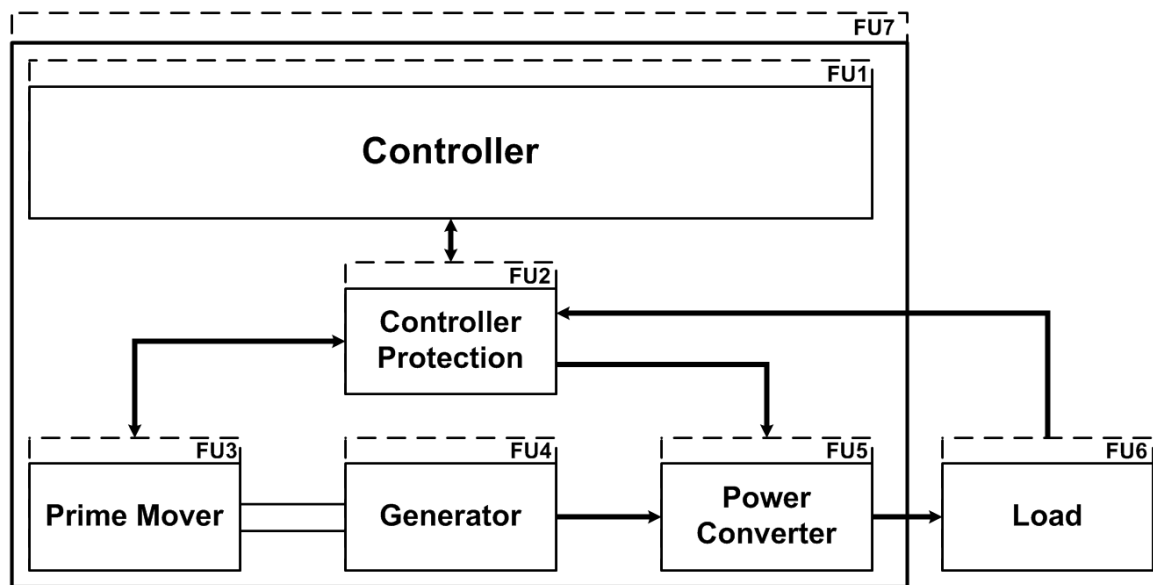


Figure 3.3: Overhead functional flow

The overhead functional flow of the project can be seen in figure 3.3. As can be seen from figure 3.3, FU 3 (Prime mover), FU 4 (Generator), FU 5 (Power Converter) and FU 6 (Load) has to interact with FU 1 (Controller). Two additional functional units can

also be considered that is not illustrated but also requires isolation i.e. power supply (FU 7) and sensors (FU 8). Protection (FU 2) has to be added between FU 1 and FU 3 - FU 8, which will prevent damage to FU 1 if a fault occurs on the remaining functional units. This was done by electrically isolating these functional units (FU 3 - FU 8) from the controller (FU 1).

### 3.2.2 Lower Level Functional Units

This section discusses the lower level functional units of the project. The functional units in figure 3.3 are expanded into the second and third level functional units and the interaction and purpose of the lower level functional units is discussed.

#### 3.2.2.1 Functional Unit 1

FU 1 is the controller of the system and consists of various input and output signals. The input signals consist of measurements on the load current, load voltage and rotational speed of the generator. The outputs of the controller are the duty cycle for the boost converter and the torque set point for the prime mover.

#### 3.2.2.2 Functional Unit 2

The purpose of FU 2 (controller protection) is to provide electrical isolation from FU 1 (controller) if any faults may occur on FU 3 - FU 8. This functional unit can be broken up into two different functional units (i.e. input signal and output signals) and the second level functional unit can be seen in figure 3.4.

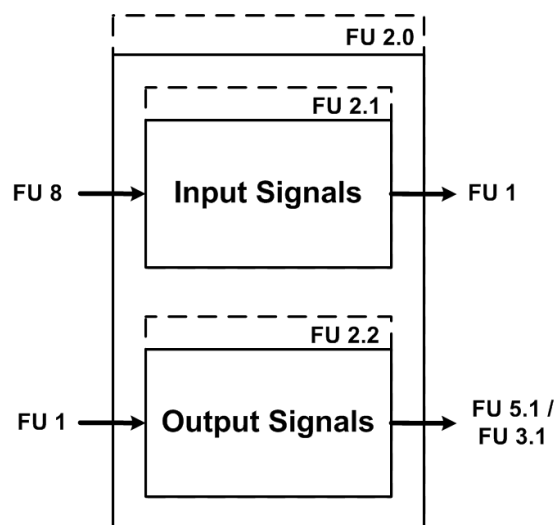


Figure 3.4: Second level functional unit (Controller Protection)

The third level functional unit for the input and output signals can be seen in figure 3.5 (input signals) and figure 3.6 (output signals), respectively.

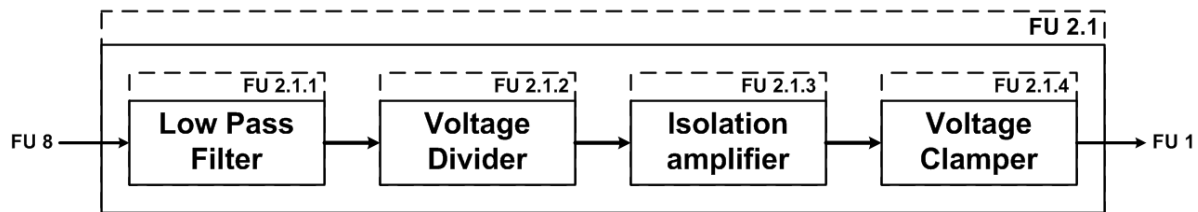


Figure 3.5: Input signals functional unit (Controller Protection)

The first functional unit of FU 2.1 consists of a low pass filter (FU 2.1.1) that filters out any noise the signal may have accumulated from the sensors to the controller protection board (FU 2). The second functional unit (FU 2.1.2) is a voltage divider circuit that lowers the voltage to an acceptable level for the isolation amplifier. After an acceptable voltage has been obtained, the input and output is electrically isolated from each other by means of an isolation amplifier (FU 2.1.3). The final functional unit consists of a voltage clamper (FU 2.1.4) that will ensure no fault on the secondary side of the controller protection causes damage to the controller. The output of FU 2.1 is sent to the controller (FU 1).

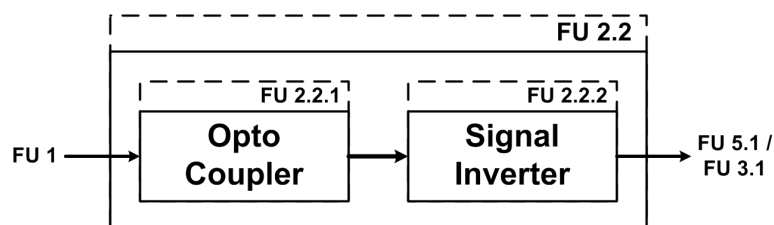


Figure 3.6: Output signals functional unit (Controller Protection)

FU 2.2 consists of opto coupler (FU 2.2.1) and a signal inverter (FU 2.2.2) which is required to provide protection to the controller for the digital output signals. The signal inverter is required as the opto coupler inverts the output signal from the input signal. The two output signals are the boost converter duty cycle (FU 5) and the torque set point to the VSD (FU 3.1) from Matlab<sup>®</sup>/Simulink<sup>®</sup>.

### 3.2.2.3 Functional Unit 3

FU 3 is used to emulate the power capture from the blades of the wind turbine and provides the rotational force on the shaft of the generator (FU 4). This functional unit can be expanded into the second level functional unit as can be seen in figure 3.7. The

second level functional unit consists of a variable speed drive (VSD) (FU 3.1) and an induction motor (FU 3.2).

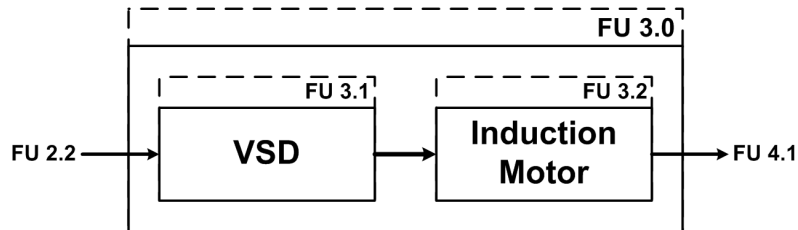


Figure 3.7: Second level functional unit (Prime Mover)

The amount torque the blades would extract from the incoming wind for a specific wind speed, rotational speed and blade pitch angle is sent to the prime mover (FU 3.1) from Matlab®/Simulink® and is used as the set point to the amount of torque the induction motor (FU 3.2) applies on the shaft of the generator (FU 4).

#### 3.2.2.4 Functional Unit 4

FU 4 consists of a PMSG (FU 4.1) and an uncontrolled rectifier (FU 4.2) and the second level functional flow of the PMSG can be seen in figure 3.8. The input of the PMSG is mechanically connected to the induction motor (FU 3.2) and the output is electrically connected to the uncontrolled rectifier which is in turn electrically connected to the input of the DC-DC boost converter (FU 5.2). The parameters for the simulation and practical PMSG are discussed more in depth in section 3.3.

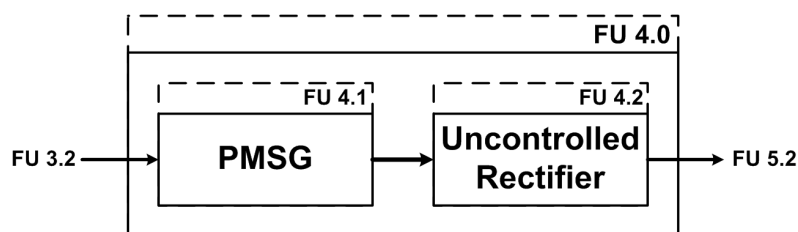


Figure 3.8: Second level functional unit (Prime Mover)

#### 3.2.2.5 Functional Unit 5

FU 5 consists of a DC-DC boost converter that controls the amount of power delivered to the load. An additional functional unit can be considered with the purpose of driving the switch of the boost converter.

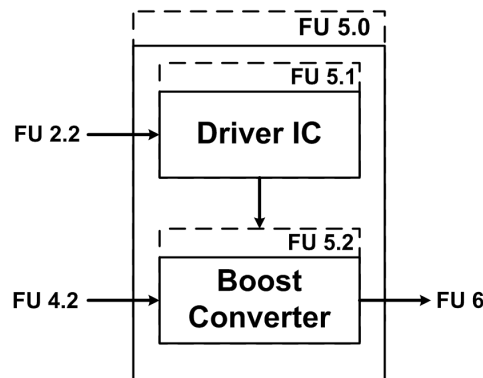


Figure 3.9: Second level functional unit (Power Converter)

### 3.2.2.6 Functional Unit 6

FU 6 is the load connected to the output of the boost converter (FU 5.2). The controller was tested under various load conditions for both a resistive and a restive-inductive load. The load voltage (FU 8.2) and load current (FU 8.3) is measured and interacts with the controller protection (FU 2). Refer to figure 3.10 for the functional flow of the load voltage and load current sensors.

### 3.2.2.7 Functional Unit 7

FU 6 consists of the power supplies to the system and is provided by two different power supplies in order to provide electrical isolation for the controller protection (FU 2). The primary power supply supplies power to the following:

- Current sensor (FU 8.3)
- Boost converter driver circuitry (FU 2.2)
- Controller protection primary side

An additional supply of 380 V<sub>AC</sub> is required for the VSD during the experimental setup but does not fall within the design scope of the project as it only supply power to the prime mover.

### 3.2.2.8 Functional Unit 8

FU 8 consists of the sensors used by the controller and requires measurements on the rotational speed (FU 8.1), load voltage (FU 8.2) and load current (FU 8.3), the functional flow of the sensors can be seen in figure 3.10. The rotational speed of the generator is obtained from the VSD (FU 3.1) as it has an integrated function to output a voltage proportional to the rotational speed.

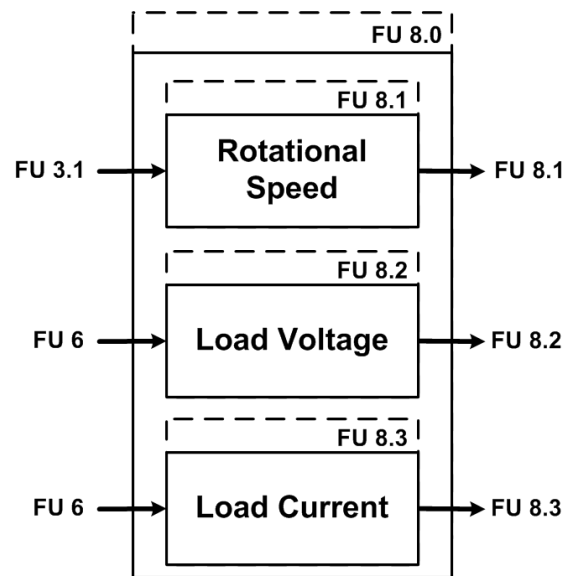


Figure 3.10: Sensors functional flow

### 3.3 Detail Design

This section provides an in depth design of the functional units discussed in the previous section. It discusses the design considerations, components and calculations required for the successful integration of the functional units previously discussed.

#### 3.3.1 Design Considerations

This section provides a discussion on the design considerations made for the control topology, controller, electrical isolation component and boost converter switch.

##### 3.3.1.1 Control Topology

Fuzzy logic was chosen as the control topology as case studies revealed this the most promising control topology for wind turbine power control. The design of the fuzzy logic controller is discussed more in depth in section 3.3.

##### 3.3.1.2 Controller

A dSPACE® DS1104 controller board was chosen as the controller of the system during experimental implementation. This was mainly due to the free availability of the controller and that it offers the most amount of flexibility during the experimental implementation.

### 3.3.1.3 Electrical Isolation

The components used for electrical isolation for the controller protection (FU 2) are as follows:

**Input Signals** An ACPL-7900 isolation amplifier was used to provide electrical isolation for the analog signals for FU 2. This was mainly due to the high linearity and dynamic performance with a minimal external component requirement. The ACPL-7900 has a input voltage range between 0 - 0.3 V and produces a differential output ranging from 0 - 2.4 V.

**Output Signals** A H11L1M optocoupler was used to provide electrical isolation for the digital signals of FU 2. This was mainly due to the high frequency capabilities and low cost. The only disadvantage of the H11L1M is that it inverts the output signal from the input signal and therefore requires a signal inverting circuit.

### 3.3.1.4 Switch and Driver IC

An IRFP4768PbF MOSFET switch was used for the boost converter. This was mainly due to the low cost and high efficiency applications associated with this MOSFET. A TC4427CPA driver IC was used to switch the MOSFET. This was mainly due to the low cost and ease of implementation (mainly due to past experience with this driver).

## 3.3.2 Lower Level Functional Units

This section discusses the design of the lower level functional units, as can be seen in figure 3.3. This includes the required calculations and component discussion.

### 3.3.2.1 Power Supply

This section discusses the approach for the power supply of the system which, as previously discussed, is divided into two different sections in order to create electrical isolation for the controller protection (FU 2). A detailed description of the voltage requirements and isolation barrier for the functional units can be seen in figure 3.11.

**Primary Power Supply** The primary power supply consists of a 12 V<sub>DC</sub> and 5 V<sub>DC</sub> power supply. This only supplies power to the following functional units:

- Current Sensor (FU 8.3)
- Boost converter driving circuitry (FU 2.2)
- Controller protection primary side

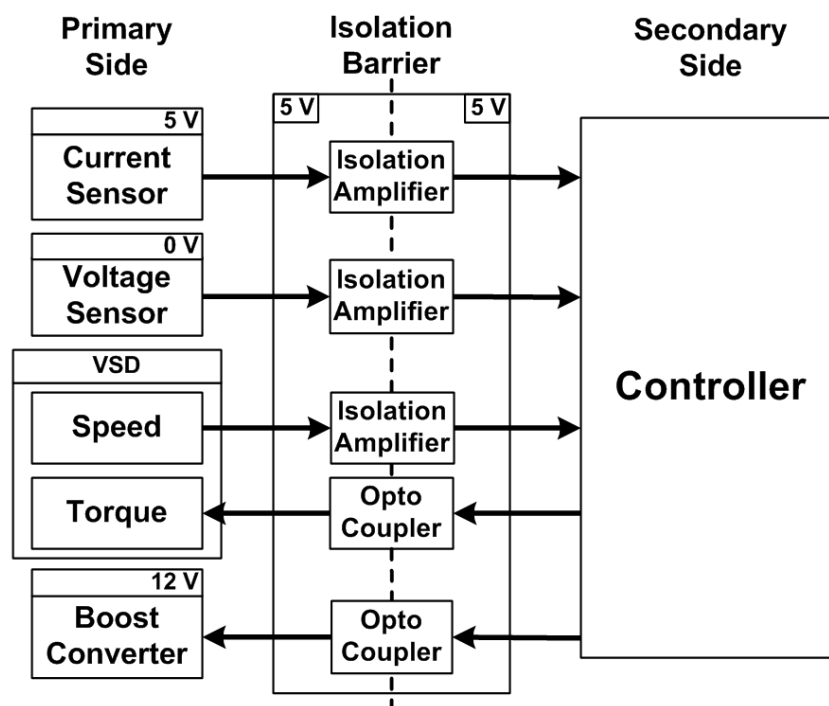


Figure 3.11: Primary power supply functional unit

The flow diagram for the primary power supply can be seen in figure 3.12. The first voltage conversion is from the mains AC to  $15\text{ V}_{\text{DC}}$  using an isolated AC to DC converter. The second conversion is from  $15\text{ V}_{\text{DC}}$  to  $12\text{ V}_{\text{DC}}$  and  $5\text{ V}_{\text{DC}}$  using an LM7812 and an LM7805, respectively. These linear voltage regulators provide a low ripple DC source with minimal external components. Refer to the *Datasheets and Technical Documents* folder for the datasheet of the LMxx regulators and the *Additional Design Calculations and Considerations* folder for calculations for the rating of the AC to DC converter.

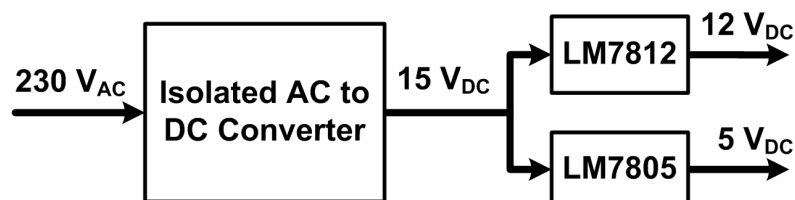


Figure 3.12: Primary power supply flow diagram

**Secondary Power Supply** The secondary power supply only supplies power to the secondary side of the controller protection (FU 2) and consists of a  $5\text{ V}_{\text{DC}}$  isolated switch mode power supply and shares a ground with the controller.

### 3.3.2.2 Low Pass Filter

A first order low pass filter (FU 2.1.1) reduces the noise on the input signals and can be seen in figure 3.13. Equation 3.1 can be used in order to calculate the cut off frequency of the filter.

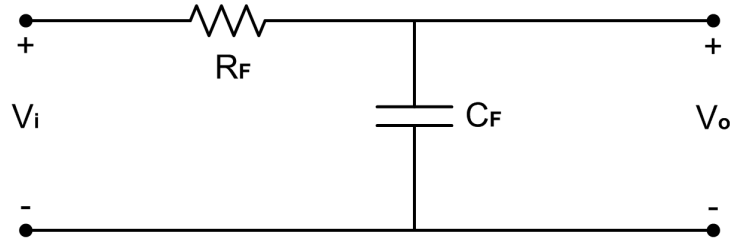


Figure 3.13: Low pass filter

$$f = \frac{1}{2\pi R_f C_F} \quad (3.1)$$

A value of  $R_f = 1$  and a cut off frequency of 1000 Hz was chosen and substituting into equation 3.1, results in equation 3.2.

$$1000 = \frac{1}{2\pi(1)C_F} \quad (3.2)$$

Solving for  $C_F$  yields  $C_F = 1.591 \times 10^{-4} \text{ F}$  or  $C_F = 159 \text{ } \mu\text{F}$ . Choosing  $C_F = 100 \text{ } \mu\text{F}$  and substituting into equation 3.1 results in equation 3.3.

$$f = \frac{1}{2\pi(1)(100 \times 10^{-6})} \quad (3.3)$$

Solving equation 3.3 results in a cut off frequency of  $f = 1591.59 \text{ Hz}$ .

### 3.3.2.3 Voltage Divider

A voltage divider was used to measure the load voltage as well as stepping down the voltage within the controller protection. The general circuit for a voltage divider can be seen in figure 3.14.

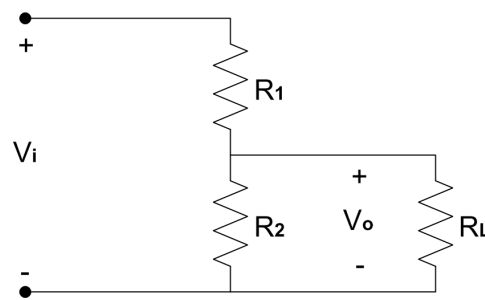


Figure 3.14: Voltage divider circuit

Equation 3.4 is used to calculate the values of the components in figure 3.14 [134].

$$V_o = \frac{R_2}{R_1 \left(1 + \frac{R_2}{R_L}\right) + R_2} V_i \quad (3.4)$$

In order to calculate the required resistor values ( $R_1$  and  $R_2$ ) a value has to be chosen for one of the resistor and the other resistor value calculated using equation 3.4. This was done by using 10 k $\Omega$  for  $R_1$  and using the following values for the remaining parameters:

**Current Sensor:** FU 8.3 measures the amount of current on the output of FU 5 (Boost converter). The current sensor used was an ACS713ELCTR-30A-T hall effect current sensor. The main advantages of this sensor are the size, linearity and minimal external component requirement. The ACS713ELCTR-30A-T is capable of current levels of up to 30 A and has a peak voltage output of 4.5 V. FU 2.1.3 (Isolation amplifier) has a maximum input voltage of 0.3 V and an input impedance of 22 k $\Omega$ . Substituting these values into equation 3.4 results in equation 3.5.

$$0.3 = \frac{R_2}{10000 \left(1 + \frac{R_2}{22000}\right) + R_2} 4.5 \quad (3.5)$$

Solving for  $R_2$  yields  $R_2 = 738.26 \Omega$ . The closest available resistor values are:

$$R_1 = 732 \Omega$$

$$R_2 = 10 \text{ k}\Omega$$

Substituting the available values of  $R_1$  and  $R_2$  into equation 3.4 yields the following (refer to equation 3.6):

$$V_o = \frac{732}{10000(1 + \frac{732}{22000}) + 732} 4.5 \quad (3.6)$$

Solving equation 3.6 results in  $V_o = 0.298$  V.

**Voltage and Speed Sensor:** FU 8.1 - FU 8.2 measures the rotational speed and output voltage and has a peak output voltage of 10 V. FU 2.1.3 (isolation amplifier) has a maximum input voltage of 0.3 V with an input resistance of 22 k $\Omega$ , substituting these values into equation 3.4 results in equation 3.7.

$$0.3 = \frac{R_2}{10000(1 + \frac{R_2}{22000}) + R_2} 10 \quad (3.7)$$

Solving equation 3.7 results in  $R_2 = 313.69$   $\Omega$ . The closest available resistor values are:

$$R_1 = 316 \Omega$$

$$R_2 = 10 \text{ k}\Omega$$

Substituting the available values of  $R_1$  and  $R_2$  into equation 3.4 yields the following (refer to equation 3.8):

$$V_o = \frac{316}{10000(1 + \frac{316}{22000}) + 316} 10 \quad (3.8)$$

Solving equation 3.8 results in  $V_o = 0.302$  V.

**Load Voltage:** FU 8.2 measures the output voltage of FU 5 (Boost converter) and has a peak output of 127.28 V. An output voltage of 10 V is desired for an input voltage of 130 V as an input to FU 2.1 (controller protection). In order to calculate the output resistance the following circuit has to be considered (refer to figure 3.15).

$$\frac{1}{R_{Total}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n} \quad (3.9)$$

After the equivalent circuit was determined, the load resistance  $R_L$  was calculated using equation 3.9 for all the parallel resistors.  $R_L$  is the equivalent of the low pass filter,

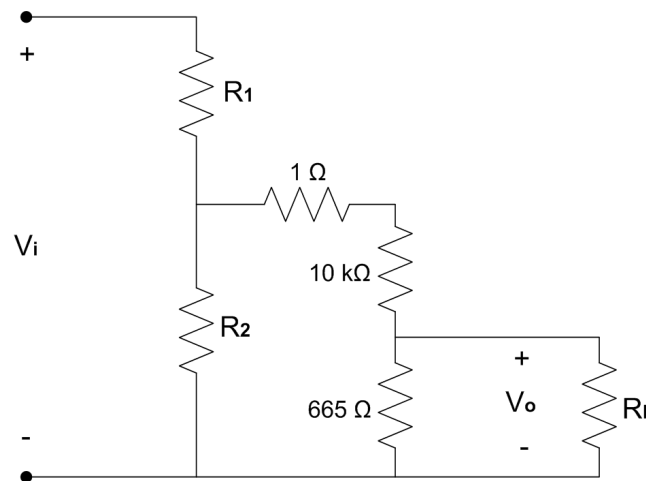


Figure 3.15: Voltage sensor equivalent circuit

voltage divider for the isolation amplifier and input impedance of the isolation amplifier. The total of  $R_L$  was calculated as:

$$R_L = 10\,646.49\,\Omega$$

Substituting the calculated value of  $R_L$  and a value of  $R_1 = 100\,\text{k}\Omega$  into equation 3.4, yields the following equation (refer to equation 3.10).

$$10 = \frac{R_2}{100000(1 + \frac{R_2}{10646.48}) + R_2} 130 \quad (3.10)$$

Solving equation 3.10 results in  $R_2 = 38354.83\,\Omega$ . The closest available resistor values are:

$$R_1 = 100\,\text{k}\Omega$$

$$R_2 = 38.3\,\text{k}\Omega$$

Substituting the available values of  $R_1$  and  $R_2$  into equation 3.4 yields the following (refer to equation 3.11):

$$V_o = \frac{38300}{100000(1 + \frac{38300}{10646}) + 38300} 130 \quad (3.11)$$

Solving equation 3.11 results in  $V_o = 10.82\,\text{V}$ .

### 3.3.2.4 Boost Converter

A boost converter (FU 5) was used to control the amount of power to the load which in turn controls the rotational speed of the PMSG (FU 4). The general circuit for a boost converter can be seen in figure 3.16.

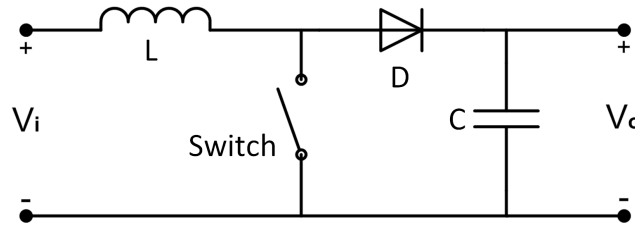


Figure 3.16: Boost converter general circuit

The output of the PMSG has an RMS value of 45 V and equation 3.12 has to be used to determine the peak output voltage.

$$V_{Peak} = \sqrt{2} \times V_{RMS} \quad (3.12)$$

Substituting the values and solving equation results in a peak output of 63.64 V (this is  $V_{IN}$  of the boost converter). The boost converter was chosen to have a boost ratio of 2 and therefore the peak output voltage ( $V_{OUT}$ ) is 127.28 V. Equation 3.13 was used to determine the peak output current of the PMSG.

$$P_{OUT} = V_{OUT} \times I_{OUT} \quad (3.13)$$

Substituting the values into equation 3.13 results in equation 3.14.

$$1000 = 45 \times I_{OUT} \quad (3.14)$$

Solving equation 3.14 for  $I_{OUT}$  yields  $I_{OUT} = 22.22$  A. A switching frequency of 1000 Hz was chosen due to the low sampling time of the controller. The maximum switch current can be calculated using equation 3.15 with an estimated efficiency ( $\eta$ ) of 80% [135].

$$D = 1 - \frac{V_{IN(min)} \times \eta}{V_{OUT}} \quad (3.15)$$

Substituting the values into equation 3.15 results in equation 3.16.

$$D = 1 - \frac{63.64 \times 0.8}{127.28} \quad (3.16)$$

Solving for D results in  $D = 0.6$ . An estimation has to be made for the ripple current in order to determine the value of the inductor. The estimated ripple current of the inductor was made as 20%. Equation 3.17 was used to calculate the amount of ripple on the output [135].

$$\Delta I_L = \% \text{ ripple current estimation} \times I_{OUT(MAX)} \times \frac{V_{OUT}}{V_{IN}} \quad (3.17)$$

Substituting the values into equation 3.17 results in 3.18.

$$\Delta I_L = 0.2 \times 22.22 \times \frac{127.28}{63.64} \quad (3.18)$$

Solving equation 3.18 results in  $\Delta I_L = 8.888$ . The value of the inductor can be calculated using equation 3.19 [135].

$$L = \frac{V_{IN} \times (V_{OUT} - V_{IN})}{\Delta I_L \times f_s \times V_{OUT}} \quad (3.19)$$

Substituting the values in equation 3.19 results equation 3.20.

$$L = \frac{63.64 \times (127.28 - 63.64)}{8.888 \times 1000 \times 127.28} \quad (3.20)$$

Solving equation 3.20 with  $f_s = 1000$  Hz results in  $L = 3.58 \times 10^{-3}$  H or 3.58 mH. In order to determine the minimum output capacitor value, an output ripple voltage was chosen as 10% of the maximum output voltage. This result in a ripple voltage of (refer to equation 3.21):

$$\Delta V_{OUT} = \% \text{ ripple} \times V_{OUT(max)} \quad (3.21)$$

Solving equation 3.21 yields  $V_{ripple} = 12.728$  V. The minimum value of the output capacitor was calculated using equation 3.22 [135].

$$C_{OUT(min)} = \frac{I_{OUT(max)} \times D}{f_s \times \Delta V_{OUT}} \quad (3.22)$$

Substituting the values into equation 3.22 results in equation 3.23.

$$C_{OUT(min)} = \frac{22 \times 0.6}{1000 \times 12.728} \quad (3.23)$$

Solving equation 3.23 yields a minimum output capacitor value of  $C_{OUT(min)} = 1.047 \times 10^{-3}$  F or 1 mF. A Schottky diode was used in order to minimize the losses of the converter. The maximum power dissipation of the diode was calculated using equation 3.24 [135].

$$P_D = I_F \times V_F \quad (3.24)$$

Substituting the values of  $I_F$  and  $V_F$  (22.22 A and 0.86 V respectively) results in a power dissipation of 19.109 W during full load. The maximum switch current was calculated using equation 3.25 in order to determine the maximum current the switch has to withstand [135].

$$I_{SW(max)} = \frac{\Delta I_L}{2} + \frac{I_{OUT(max)}}{1 - D} \quad (3.25)$$

Substituting the values into equation 3.25 results in equation 3.26.

$$I_{SW(max)} = \frac{8.8}{2} + \frac{22.22}{1 - 0.6} \quad (3.26)$$

Solving equation 3.26 results in a maximum switching current of  $I_{SW(max)} = 59.994$  A. Refer to the *Datasheets and Technical Documents* folder for the datasheet of the IGBT and the *Additional Design Calculations and Considerations* folder for calculations for the requirement of a heat sink for the IGBT.

### 3.3.3 Fuzzy Logic Controller

This section discusses the design and implementation of the fuzzy logic controller which primarily consist of the membership functions and fuzzy logic rules.

### 3.3.3.1 Control Scheme

The overhead control scheme can be seen in figure 3.2. The controller measures the rotational speed of the generator as well as the voltage and current output of the boost converter in order to determine the power delivered to the load. The duty cycle of the boost converter is altered according to the change in the speed and change in power of the PMSG.

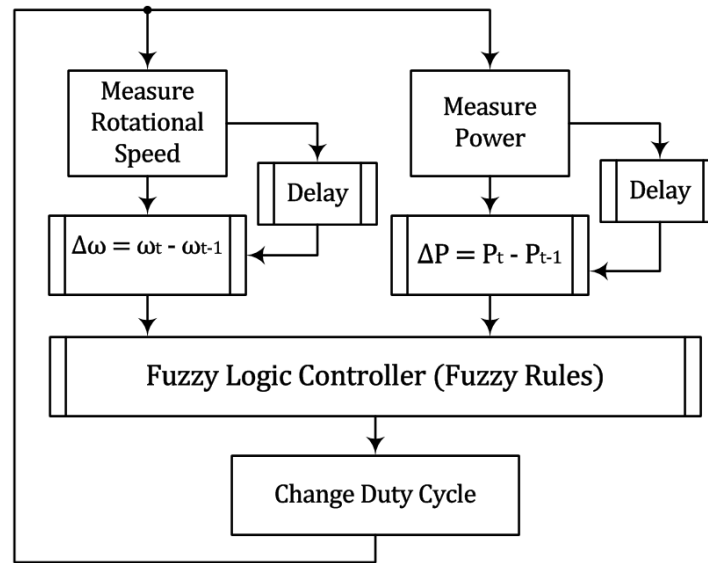


Figure 3.17: Overhead control approach

In order to determine the change of both the rotational speed and power, a delay is added between the measurements and the delayed value is subtracted from the current measured value. This change is used to determine the output and the overhead control approach can be seen in figure 3.17.

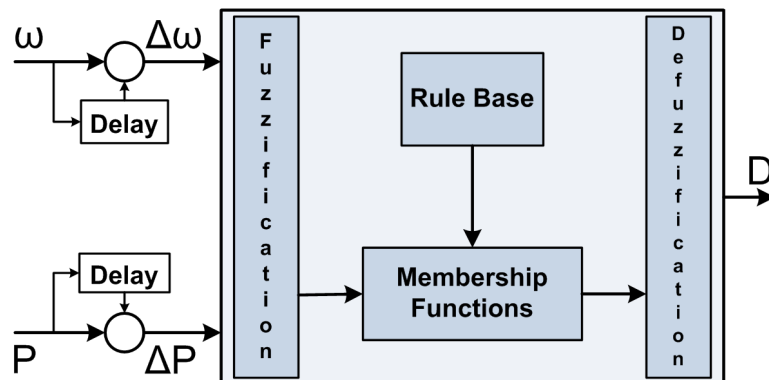


Figure 3.18: Fuzzy logic control approach

The fuzzy logic overhead control approach for the controller can be seen in figure 3.18 which illustrates the operational flow of the fuzzy logic controller. The measurements are fuzzified and compared to the rule base after which the defuzzification occurs and the change duty cycle is determined.

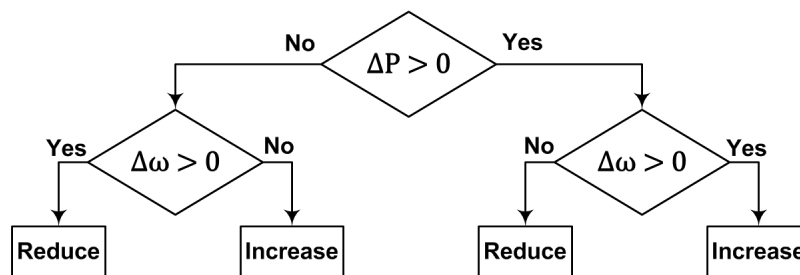


Figure 3.19: Detailed fuzzy logic control approach

The detailed fuzzy logic control approach consists of measuring the change in power and subsequently measuring the change in rotational speed, after which the required change in duty cycle is determined. The detailed fuzzy logic control approach can be seen in figure 3.19.

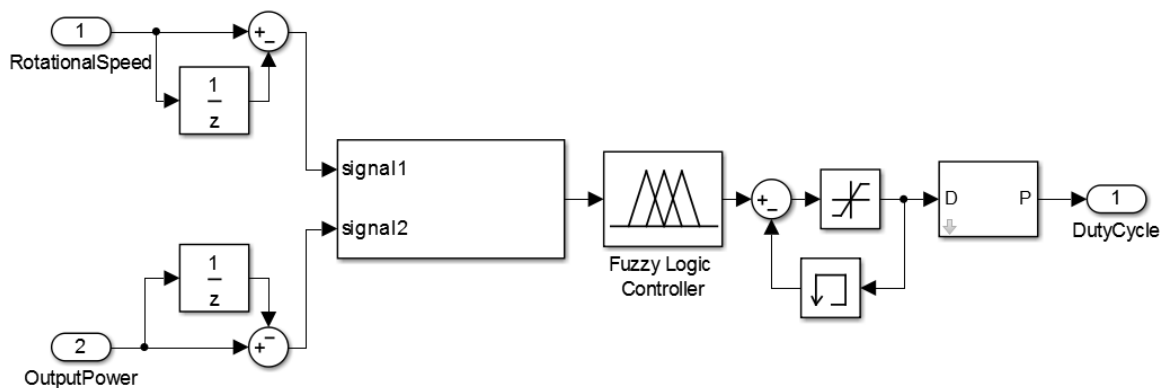


Figure 3.20: Fuzzy logic controller sub system

Figure 3.20 illustrates the fuzzy logic controller sub system. A unit step delay is added to both the rotational speed and output power and used as the inputs for the fuzzy controller. A saturation block is added that limits the duty cycle between specified thresholds. The previous value of the controller is stored in a memory block and the required value of the change in duty cycle is added to the value in the memory block. A pulse width modulation (PWM) generator block is used to produce the PWM for the boost converter.

### 3.3.3.2 Membership Functions

The controller consists of two inputs and therefore requires two input membership functions (i.e. change in rotational speed and change in power). The two input membership functions is the change in rotational speed and change in power and can be seen in figure 3.21 and figure 3.22, respectively. Both the input membership functions consist of 7 variables and makes use of triangular membership functions.

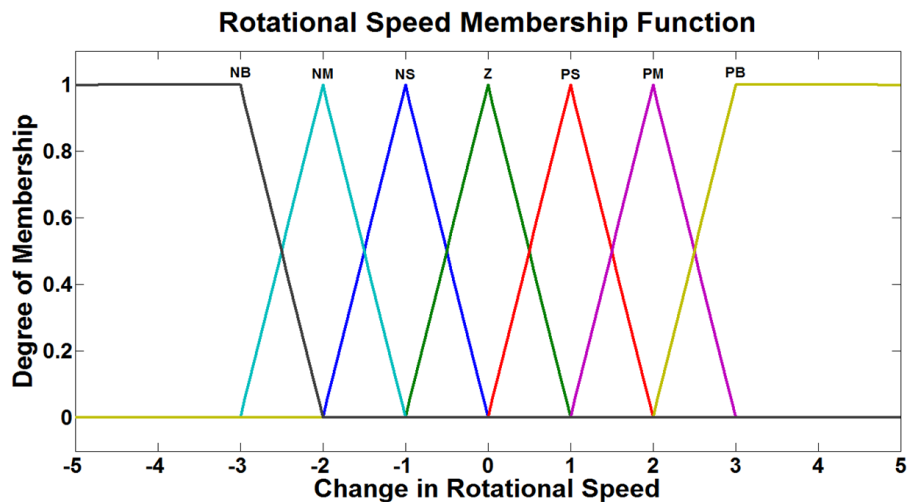


Figure 3.21: Rotational speed membership function

The seven rules used for the two input membership functions are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB).

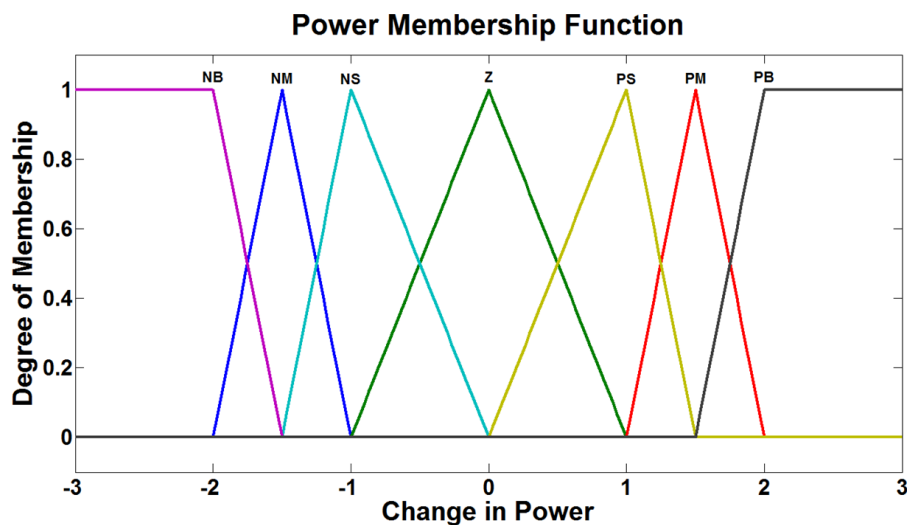


Figure 3.22: Power membership function

The input membership functions were chosen to have relatively small coordinates (compared to the rated output power of the generator), which allows for increased efficiency but sacrifices response time of the controller.

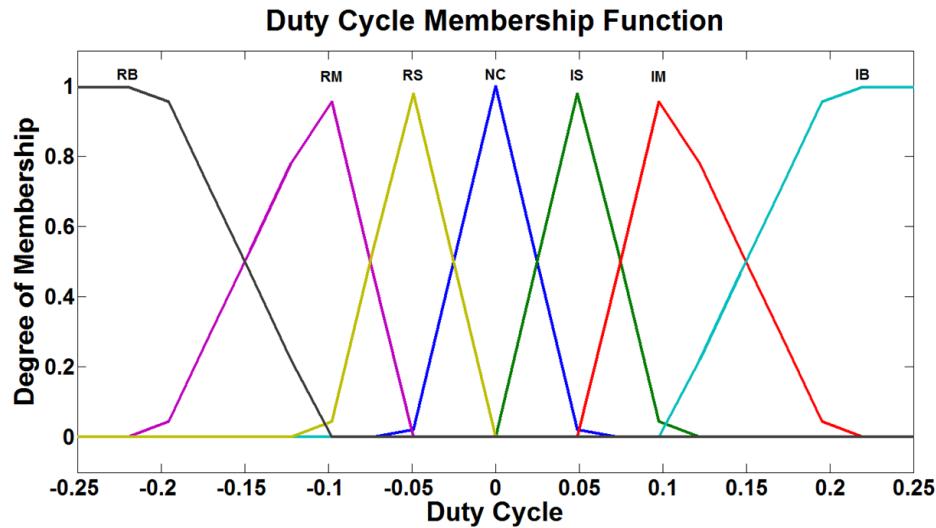


Figure 3.23: Duty cycle membership function

The controller has a single output (required change in duty cycle for the boost converter) and therefore only requires a single output membership function. The output membership function consist of triangular membership functions and can be seen in figure 3.23. The seven rules used for the output membership functions are reduce big (RB), reduce medium (RM), reduce small (RS), no change (NC), increase small (IS), increase medium (IM) and increase big (IB).

### 3.3.3.3 Fuzzy Rules

Table 3.1: Fuzzy logic rule table

|            |    | $\Delta\omega$ |    |    |    |    |    |    |
|------------|----|----------------|----|----|----|----|----|----|
|            |    | NB             | NM | NS | Z  | PS | PM | PB |
| $\Delta P$ | NB | IB             | IB | IM | RB | RM | RB | RB |
|            | NM | IB             | IM | IS | RM | RS | RM | RB |
|            | NS | IM             | IS | IS | RS | RS | RS | RM |
|            | 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 |

with:

|                     |                   |                       |
|---------------------|-------------------|-----------------------|
| <b>Z</b> - Zero     | <b>S</b> - Small  | <b>NC</b> - No Change |
| <b>N</b> - Negative | <b>M</b> - Medium | <b>I</b> - Increase   |
| <b>P</b> - Positive | <b>B</b> - Big    | <b>R</b> - Reduce     |

The fuzzy rule base determines the output by comparing the two input membership functions and can be seen in table 3.1 and the surface rule view can be seen in figure 3.24. The fuzzy controller consists of a total of 49 rules.

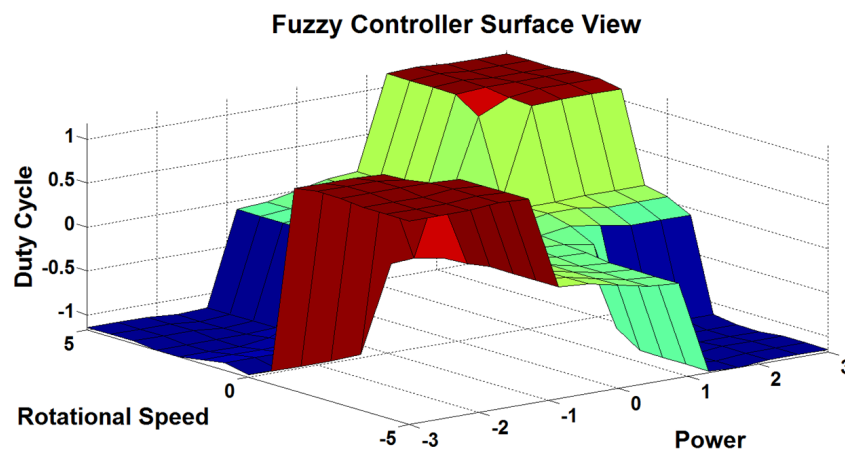


Figure 3.24: Fuzzy rules surface view

The fuzzy rules of the controller (presented in table 3.1 and figure 3.24) can be summed up into the following:

- If there is no change in power, keep the duty cycle at the current value.
- If there is an increase in both the power and speed, increase the duty cycle.
- If there is an increase in power and a decrease in speed, decrease the duty cycle.
- If there is a decrease in power and an increase in speed, decrease the duty cycle.
- If there is a decrease in power and a decrease in speed, increase the duty cycle.

### 3.3.4 Simulation and Experimental Parameters

The complete controller system was simulated in Matlab®/Simulink®. This section provides the parameters used for the simulation and is also applicable for the experimental setup of the project.

### 3.3.4.1 Overhead Control Scheme

In order to obtain consistent results figure 3.2 had to be adapted in such a way that it eliminates any inconsistencies during simulations and experimental setup. The main inconsistency in the system is the wind speed, as it constantly changes and therefore could produce incorrect results. This leads to a simulation and experimental setup as can be seen in figure 3.25.

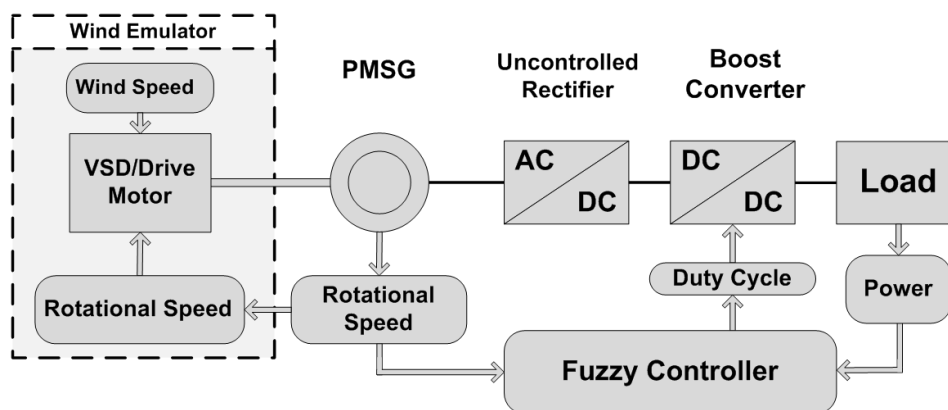


Figure 3.25: Overhead simulation/experimental scheme

The simulation/experimental scheme (as can be seen in figure 3.25) have the rotor replaced with a wind emulator (as can be seen in figure 3.26) that was controlled with Matlab<sup>®</sup>/Simulink<sup>®</sup>. The prime mover (VSD and drive motor) received a torque set point sent from Matlab<sup>®</sup>/Simulink<sup>®</sup> that calculated the amount of torque applied to the shaft of the generator.

### 3.3.4.2 Wind Turbine Parameters

As the construction of a complete wind turbine does not fall within the scope of the project, alternative means must be used to simulate the system. This was done by using a drive motor as the prime mover for the PMSG. The motor emulates the rotational force the turbine blades would provide to the generator.

### 3.3.4.3 Wind Emulator

In order to provide the PMSG with a rotational force, a subsystem had to be used that emulates the power capture from the blades of the wind turbine. Equation (3.27) and equation (3.28) are commonly used equations used to compute the power coefficient vs. tip speed ratio of a small wind turbine, for a fixed pitch wind turbine  $\beta = 0$ . The subsystems used calculate the required values.

$$C_p = C_1 \left( \frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6 \lambda \quad (3.27)$$

with:

$$\begin{array}{lll} C_1 = 0.5176 & C_2 = 116 & C_3 = 0.4 \\ C_4 = 5 & C_5 = 21 & C_6 = 0.0068 \end{array}$$

The value of  $\lambda_i$  can be calculated using equation 3.28:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3.28)$$

Figure 3.26 illustrates the Matlab®/Simulink® subsystem used to provide the rotational force to the PMSG in pu. The system receives the wind speed and rotational speed as inputs and determines the torque (in pu) developed by the blades for the given parameters and uses this value to rotate the PMSG.

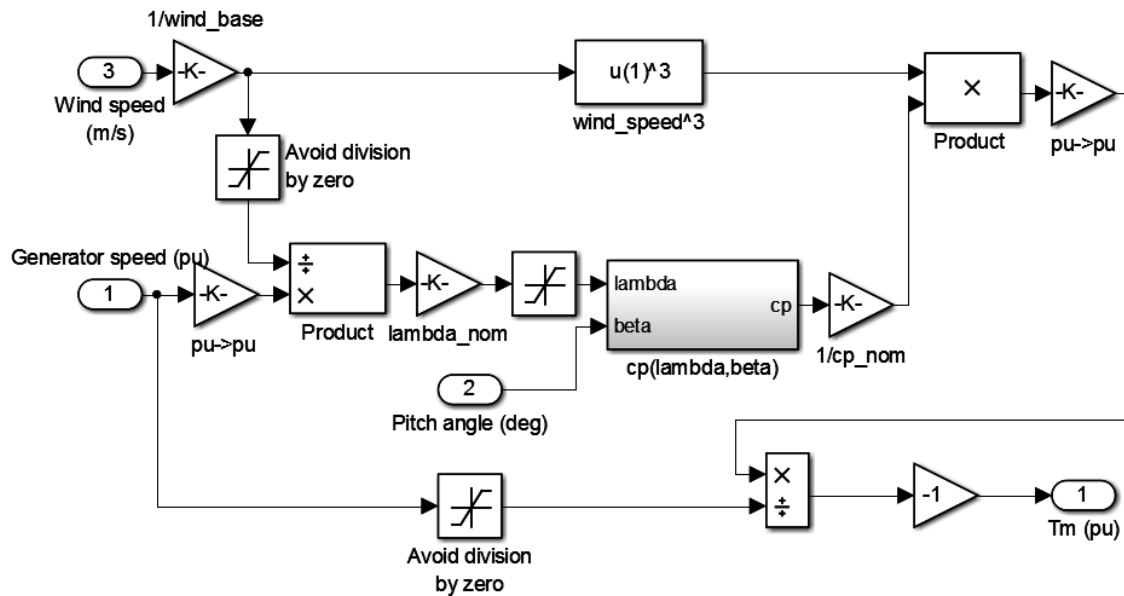


Figure 3.26: Matlab®/Simulink® wind emulator subsystem

### 3.3.4.4 Torque Control

A torque set point was provided to the VSD that represents the amount of torque the wind turbine's blades applies to the shaft of the generator. This value is the amount

of torque the drive motor provides on the shaft of the generator and is calculated by using Matlab®/Simulink®'s integrated wind turbine block. The wind turbine block provides this in a pu value and therefore needs to be converted into an actual value.

### 3.3.4.5 Wind Speed

The controller was tested under various wind speed conditions in order to determine its viability; the wind speeds used to test the controller are as follows:

- **Fixed Wind Speed:** Fixed wind speeds were used to test the controller that ranges from 5 m/s to 15 m/s.
- **Fluctuating Wind Speed:** The controller was also tested for fluctuating wind speeds in order to represent more realistic application results. This fluctuating wind speed varied between 6 m/s to 14 m/s and the fluctuating wind speed profile can be seen in figure 3.27. The fluctuating wind speed had a total duration of 20 s for the simulations and a total duration of 50 s for the experimental implementation.

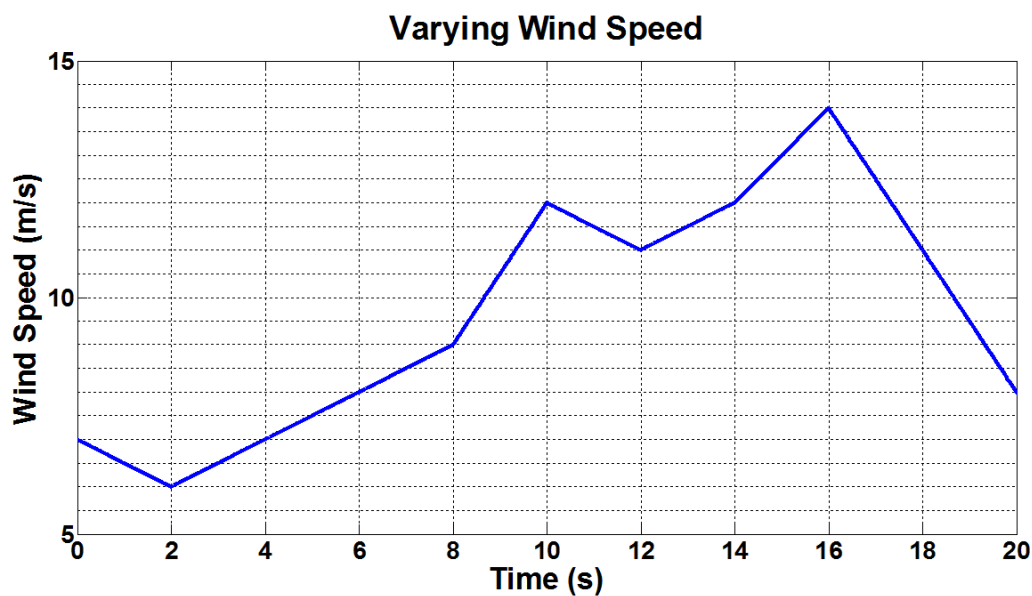


Figure 3.27: Fluctuating wind speed profile

### 3.3.4.6 Wind Turbine Parameters

Table 3.2 displays the parameters of the wind turbine that was used for the simulation and experimental implementation of the controller. The parameters were chosen to represent the typical values of a micro wind turbine with a rated output of 1 kW.

Table 3.2: Wind Turbine Parameters

| Parameter                        | Unit    |
|----------------------------------|---------|
| Rated power                      | 1 kW    |
| Base power                       | 1 kVA   |
| Base wind speed                  | 12 m/s  |
| Maximum power at base wind speed | 0.48 pu |
| Base rotational speed            | 1.2 pu  |
| Pitch angle (Fixed pitch)        | 0°      |

### 3.3.4.7 Generator Parameters

Table 3.3 illustrates the parameters of the generator that was used for the simulation and experimental implementation of the controller. The parameters were chosen to represent the values of a typical micro wind turbine generator of the wind turbine described in table 3.2.

Table 3.3: PMSG Parameters

| Parameter                      | Unit                       |
|--------------------------------|----------------------------|
| Rated power                    | 1 kW                       |
| Rated speed (rpm)              | 1800                       |
| Rated speed (rad/s)            | 188.5                      |
| Stator resistance              | 0.2 $\Omega$               |
| Inductance ( $L_d$ and $L_q$ ) | 8.5 mH                     |
| Flux linkage                   | 0.175 V · s                |
| Inertia                        | 0.0089 kg · m <sup>2</sup> |
| Viscous damping                | 0.005 N · m · s            |
| Number of poles                | 4                          |

### 3.3.4.8 Complete System

The complete system Matlab®/Simulink® simulation model can be seen in figure 3.28. The model consists of Matlab®/Simulink®'s integrated wind turbine block sub system, a PMSG, the fuzzy logic controller sub system and the boost converter. The voltage and current is measured to determine the power which is used as an input to the fuzzy logic controller sub system, in addition to the rotational speed.

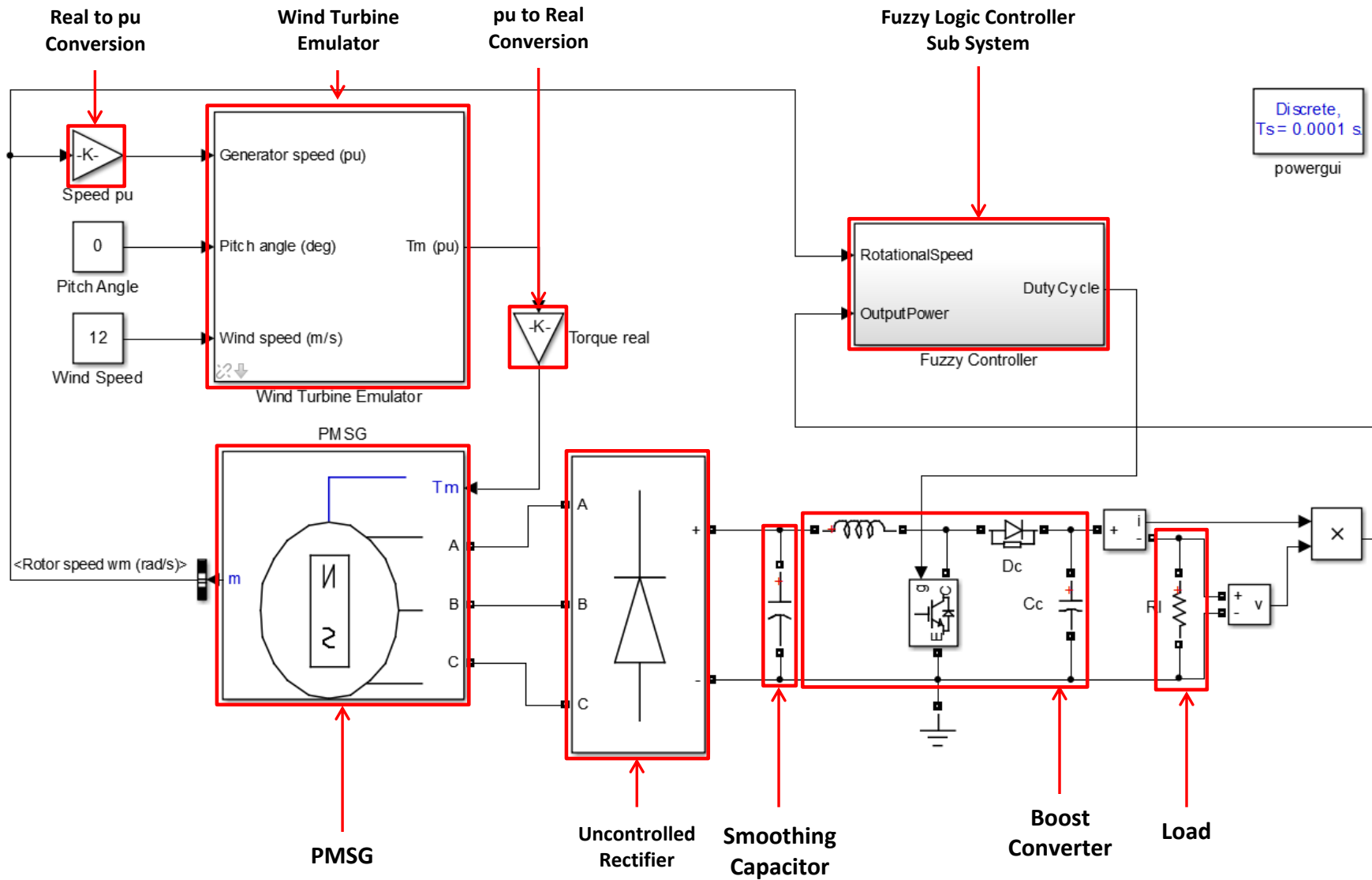


Figure 3.28: Complete system simulation model

### 3.4 Verification and Validation

The verification of this chapter was done by the functional flow diagrams and calculations of the various sub systems which ensured successful integration between the sub systems. This successful integration of the sub systems inevitably lead to a successful complete system controller.

Validation of this chapter was done by the identification of the simulation and experimental parameters. This ensured that the results obtained from the following chapters (i.e. simulation results and experimental results) are applicable to micro wind turbines.

### 3.5 Conclusion

The main purpose of this chapter was to create a detailed design of the controller. The first step was to generate an overhead control strategy for the controller (refer to figure 3.2). After to overhead control strategy was determined, all the various sub systems could be determined by means of functional flow diagrams. A detailed design of the controller was done by using the functional flow diagrams of all the various sub systems which ensured successful integration of the various sub systems.

A fundamental part of this chapter was to determine the simulation and experimental parameters of the controller. This ensured that the simulation and experimental results were applicable to micro wind turbines and ensured consistency between the simulation and experimental results when replacing the rotor with a prime mover.

Another part of this chapter was the design and layout of the PCBs for all the functional units. Research was done for recommendations and guidelines on the specific applications and applied for best results. All the circuit schematics and PCB layouts of the functional units discussed in this chapter can be seen in the *Schematics & PCB* folder.

The following chapter contains the simulation results of the subsystems and complete system under the simulation parameters discussed within this chapter. This was done in order to ensure the detailed design done in this chapter was successfully completed and ensures validity during the experimental results.

# Simulation Results

*This chapter provides and discusses the simulation results obtained for the proposed design. Where applicable the simulation software and simulation parameters is discussed and a brief explanation is provided regarding the output of the simulation. Figure 4.1 provides an overview of this chapter.*

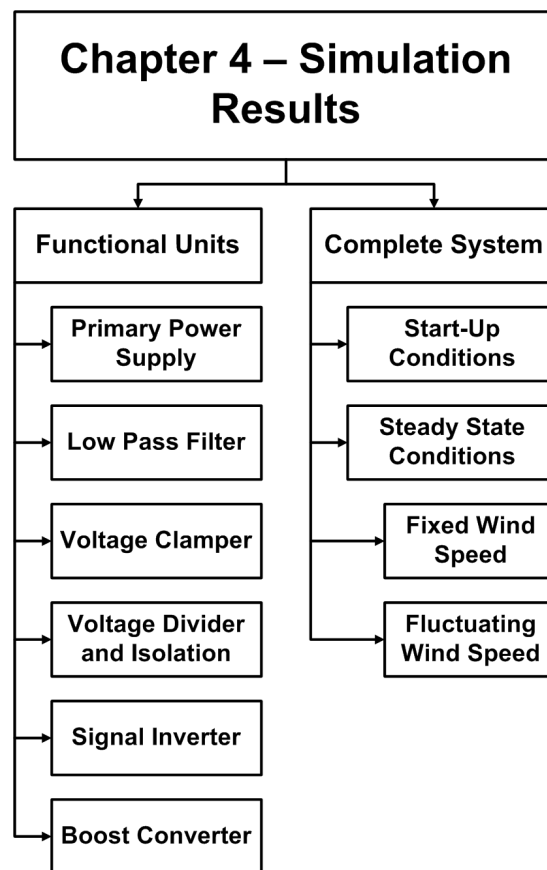


Figure 4.1: Simulation results chapter overview

## 4.1 Functional Units

This section discusses the simulation results of the lower level functional units of the controller. The simulation software used is also discussed throughout the section.

### 4.1.1 Primary Power Supply

The simulation used for the primary power supply can be seen in figure 4.2. The circuit was simulated using MultiSim with an input voltage of 15 V<sub>DC</sub>.

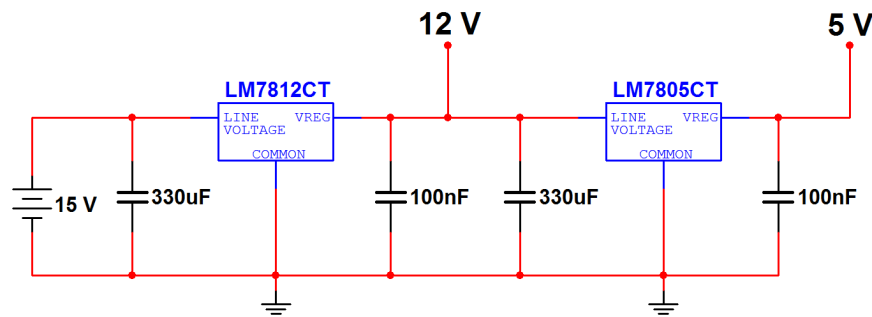


Figure 4.2: Primary power supply simulation circuit

The simulation of figure 4.2 yielded an output voltage of 12.29 V and 5.01 V under no load conditions for an input voltage of 15 V. This can be calculated as a 2.42% and 0.2% error for the 12 V and 5 V designed values, respectively.

### 4.1.2 Low Pass Filter

A first order low pass filter (FU 2.1.1) was added to the controller protection (FU 2) in order to filter out any noise the signal may have accumulated from the sensor to the protection board. The filter was simulated in MultiSim between 1 Hz and 1 MHz and the results of the simulation can be seen in figure 4.3. As can be seen from figure 4.3, the output is equal to 0 dB until a frequency of 300 Hz is reached, after which the output gradually decreases. The input signal experiences a -2 dB loss at a frequency of 1.23 kHz.

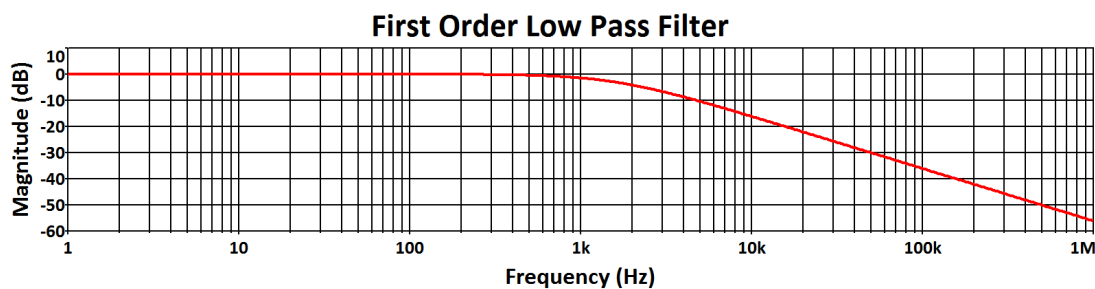


Figure 4.3: First order low pass filter simulation result

### 4.1.3 Voltage Clamper

A voltage clamper circuit (FU 2.1.4) was added for additional protection for the controller protection (FU 2) if any faults may occur on the secondary side of the controller protection. The circuit that was simulated in MultiSim for the voltage clamper circuit can be seen in figure 4.4. The circuit consists of a 1 k $\Omega$  resistor and a 100 nF capacitor

with two 5.1 V zener diodes. A DC sweep ranging from 0 V to 10 V for the input was performed on the voltage clamping circuit in order to determine the output.

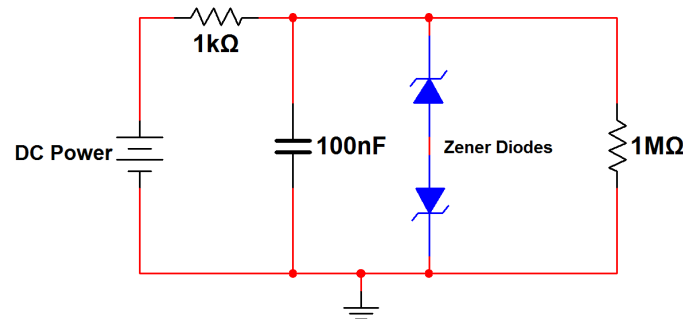


Figure 4.4: Voltage clammer simulation circuit

Figure 4.5 illustrates the results of the simulation of circuit 4.4 and the simulation results indicate the output voltage is linearly dependent on the input voltage until 5.2 V, where after the output voltage settles at 5.5 V regardless of the input voltage. It can also be noted from figure 4.5 that at the maximum output (2.4 V) of the optocoupler (FU 2.1.3), the output is also 2.4 V.

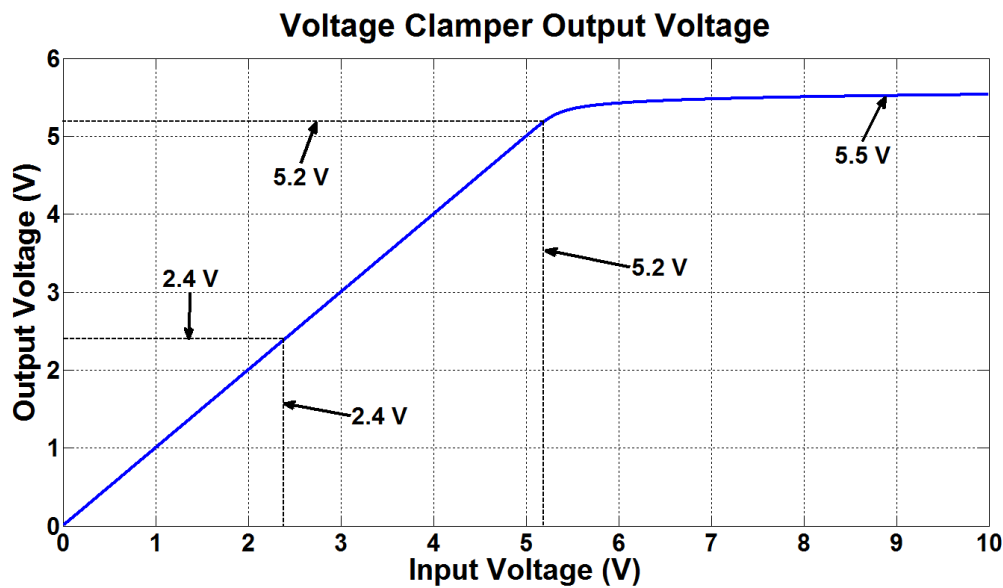


Figure 4.5: Voltage clammer simulation result

#### 4.1.4 Voltage Divider and Isolation

This section discusses the simulation results for the voltage divider circuit for the voltage sensor (FU 8.2) and protection circuit for the controller (FU 2). Both circuits were analyzed in MultiSim by means of a DC sweep.

#### 4.1.4.1 Voltage Sensor

FU 8.2 measures the output voltage of the boost converter (FU 5) and therefore represents the voltage directly applied to the load. The circuit analysed for the voltage divider circuit for the voltage sensor can be seen in figure 4.6.

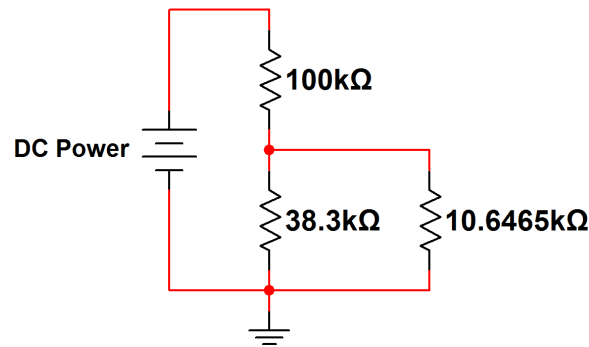


Figure 4.6: Voltage sensor simulation circuit

The results of the DC sweep performed on figure 4.6 can be seen in figure 4.7. From figure 4.7 it can be seen that the output voltage increases linearly with the input voltage with a peak output of 9.996 V for an input voltage of 130 V. This concurs with the results found in section 3.3.2.3 with a percentage difference of 7.62%. This variation was addressed by using a trimmer resistor for  $R_1$  (refer to figure 3.14) that provides the ability to set the output exactly as required without a concern for tolerances on resistor values.

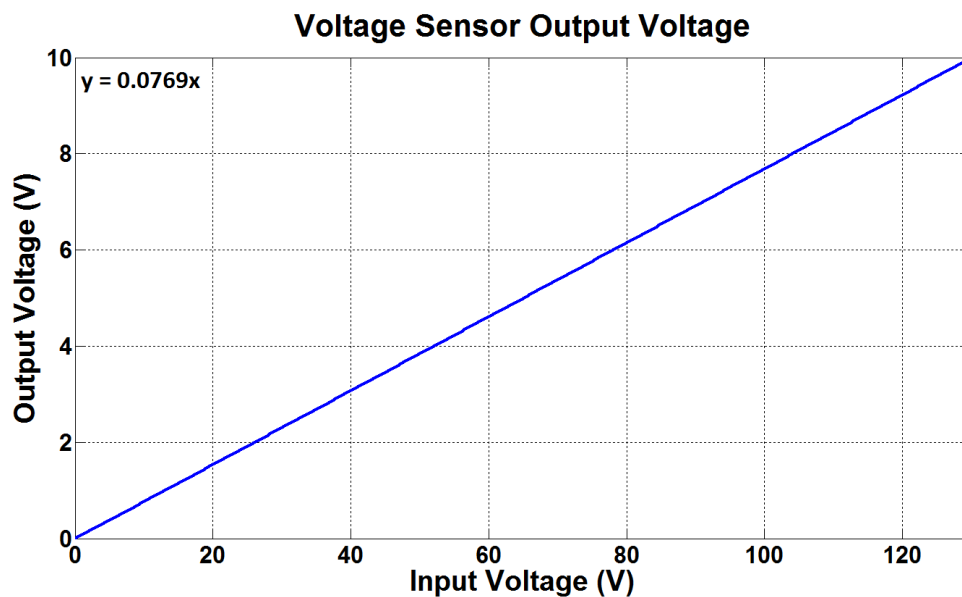


Figure 4.7: Voltage sensor simulation result

#### 4.1.4.2 Controller Protection

This section provides the simulation results for the complete controller protection (FU 2) for both the 0 - 5 V and 0 - 10 V inputs. This includes the low pass filter (FU 2.1.1), voltage divider (FU 2.1.2), isolation amplifier (FU 2.1.3) and voltage clamper (FU 2.1.4).

**Current (0 - 4.5 V)** FU 8.3 measures the load current with an output voltage directly proportional to the amount of current and has a peak output of 4.5 V for 30 A. The input to the isolation amplifier (FU 2.1.3) has a maximum input voltage of 0.3 V. The circuit used to proportionally lower the voltage and provide electrical isolation can be seen in figure 4.8.

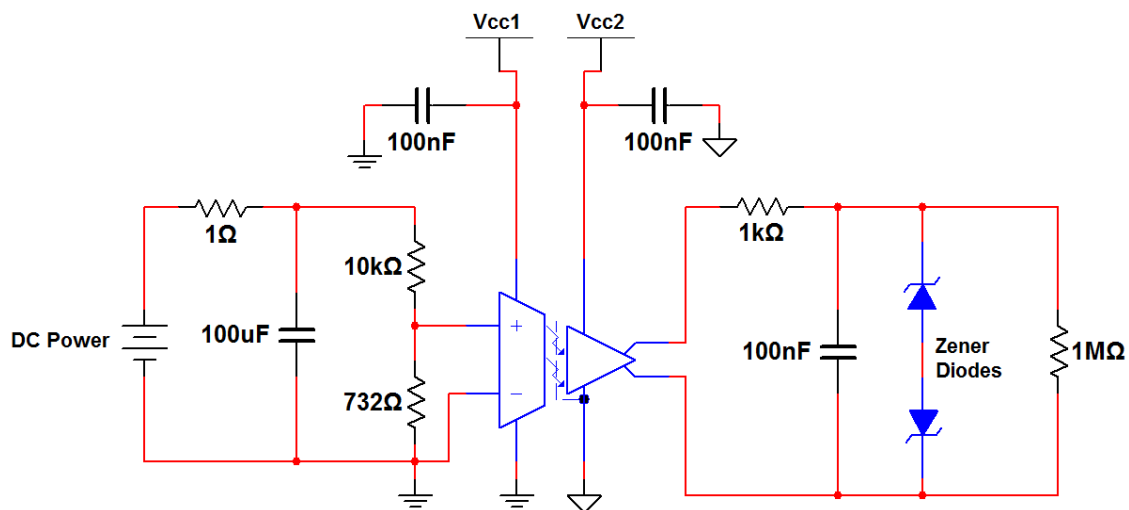


Figure 4.8: Isolation amplifier simulation circuit (Current)

A DC sweep, that ranging from 0 V to 10 V was performed on the circuit in figure 4.8 in order to determine the output of the protection circuit and the result of the simulation can be seen in figure 4.9. From figure 4.9 it can be seen that the output voltage has a linear dependency on the input voltage until a voltage of 5.3 V is reached, after this point the output voltage settles at 2.499 V regardless of the input. The input voltage has a maximum of 4.5 V, at this value the output voltage is 2.365 V which can be calculated as an error of 1.46% from the designed value.

**Voltage and Rotational Speed (0 - 10 V)** The rotational speed and output voltage (FU 8.1 and FU 8.2) has a peak input voltage of 10 V, with the maximum allowable input voltage of 0.3 V into isolation amplifier (FU 2.1.3). The circuit used to proportionally lower the voltage and provide electrical isolation can be seen in figure 4.10.

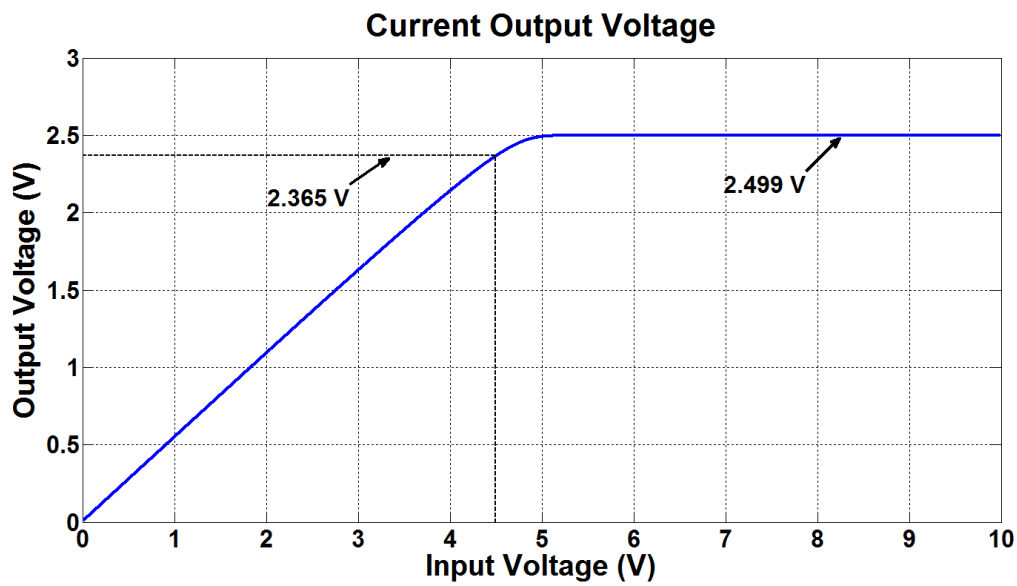


Figure 4.9: Isolation amplifier simulation result (Current)

A DC sweep, ranging from 0 V to 20 V was performed in order to determine the output of the protection circuit and the result of the simulation can be seen in figure 4.11. From figure 4.11 it can be seen that the output voltage has a linear dependency on the input voltage until a voltage of 11.6 V is reached, after this voltage the output voltage settles as 2.502 V regardless of the input. The peak input voltage is 10 V, at this value the output voltage is 2.405 V which can be calculated as an error of 0.21% from the designed value.

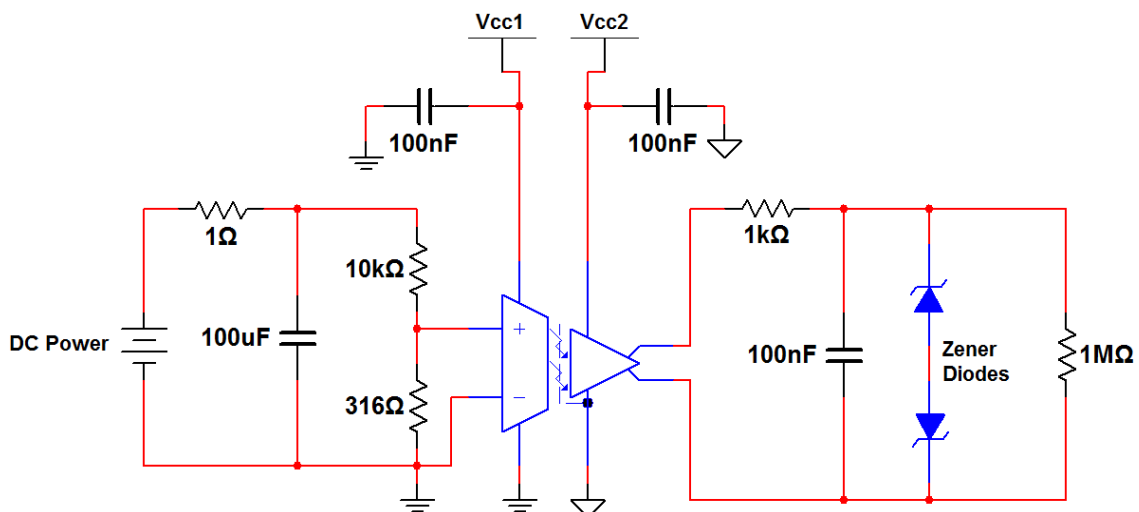


Figure 4.10: Isolation amplifier simulation circuit (Voltage and speed)

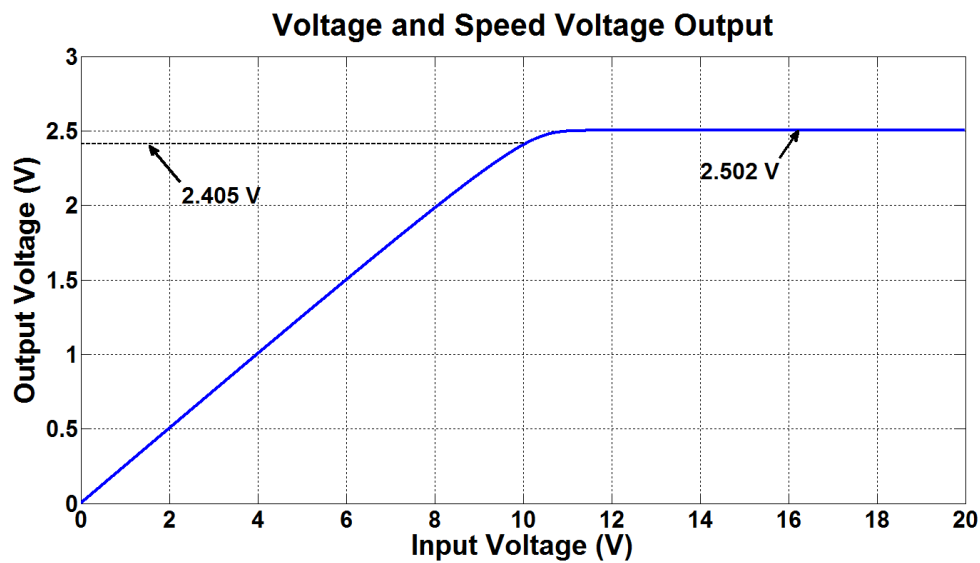


Figure 4.11: Isolation amplifier simulation results (Voltage and speed)

### 4.1.5 Signal Inverter

The purpose of the signal inverter (FU 2.2.2) is to invert the digital output signals from the controller (FU 2.2) back to the original signal as the optocoupler (FU 2.2.1) produces an output that is an inverted signal from the input. The simulation circuit used to invert the signal back to its original state can be seen in figure 4.12.

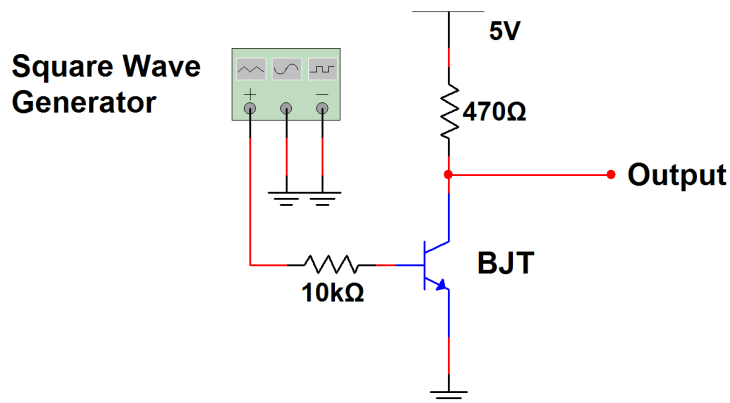


Figure 4.12: Signal inverter simulation circuit

A transient analysis (ranging from 0 s to 500  $\mu$ s) was performed in MultiSim in order to determine the output of the circuit in figure 4.12 and the results can be seen in figure 4.13. The signal illustrated in blue is the original signal and the signal illustrated in green is the inverted signal. The simulation was performed on a 10 kHz signal with a 50% duty cycle.

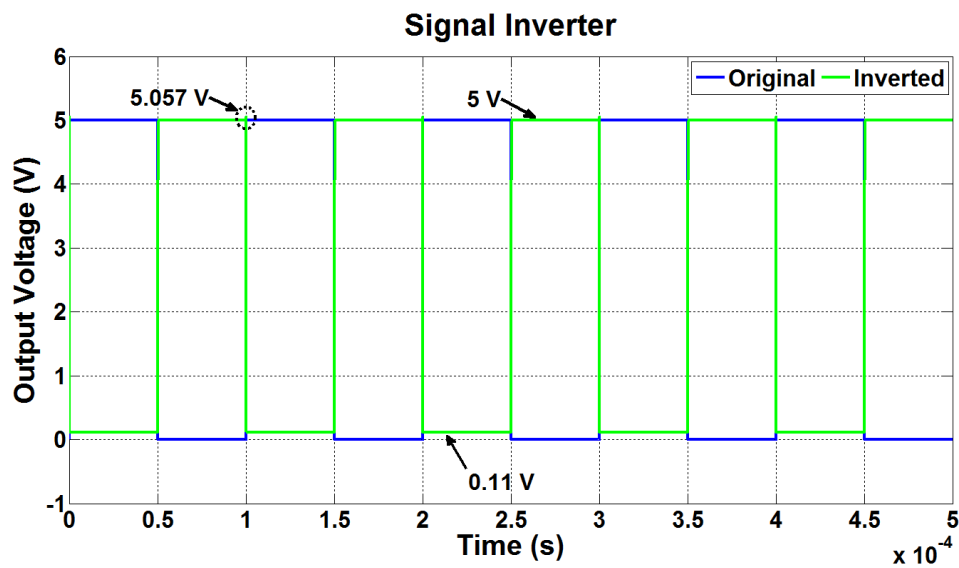


Figure 4.13: Signal inverter simulation result

From figure 4.13 it can be noted that the output signal is an invert of the input signal with a off value of 0.111 V and an on value of 5 V. It can also be noted that the inverted signal produces a 5.057 V peak during turn off.

#### 4.1.6 Boost Converter

The boost converter was simulated in Matlab<sup>®</sup>/Simulink<sup>®</sup>. During the simulation it was found that the boost converter had improved performance when changing the switching frequency to 10 kHz rather than the designed 1000 Hz.

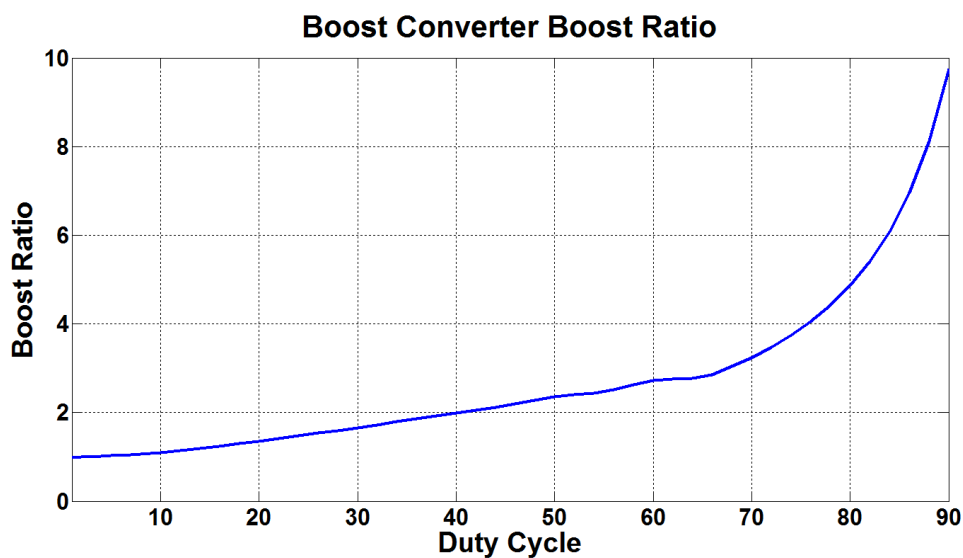


Figure 4.14: Boost converter boost ratio simulation result

The boost converter was simulated with an input voltage of 30 V and a load of 1 k $\Omega$  and the calculated values for the inductor and output capacitor as was done in section 3.3.2.4. An input voltage of 30 V was used for the simulation as it is a closer approximation to the output of the PMSG during the rated wind speed of the wind turbine. Figure 4.14 illustrates the boost ratio of the boost converter with a duty cycle ranging from 0 - 90 %. The output power and output voltage of the boost converter with a duty cycle ranging between 0 - 90% can be seen in figure 4.15.

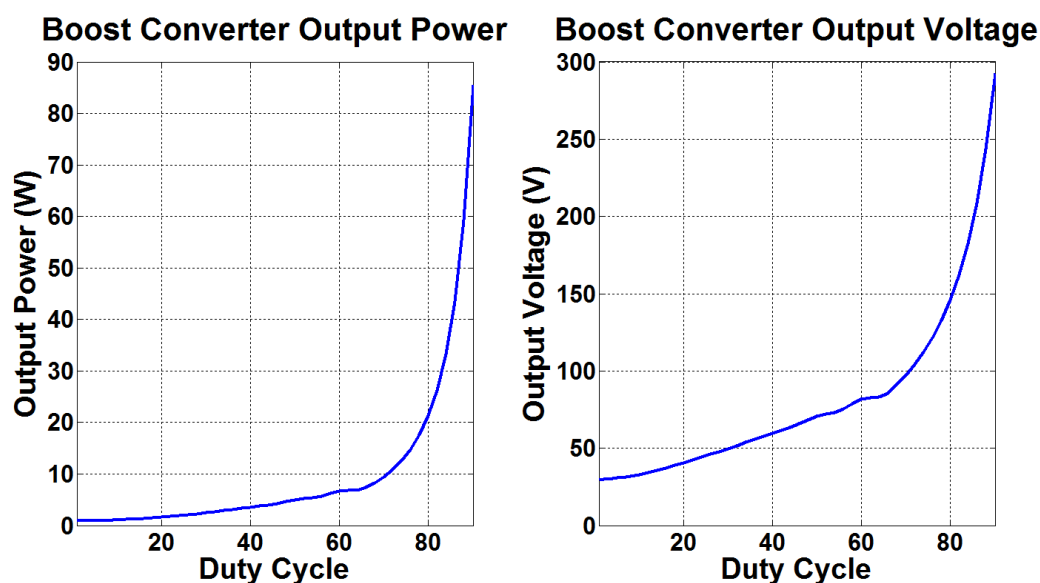


Figure 4.15: Boost converter output power and output voltage simulation result

## 4.2 Complete System

This section discusses the Matlab<sup>®</sup>/Simulink<sup>®</sup> simulation results of the complete controller with a sampling frequency of 10 kHz and all calculations were done with 4th decimal place values. The primary focus of this section is the fuzzy logic controller and boost converter and therefore excludes the circuitry of the sensors and controller protection. The optimal rotational speed at the rated wind speed was calculated using equation 4.1 (with  $\lambda_{opt} = 7$ ) [67].

$$\omega_{opt} = \frac{\lambda_{opt}v}{R} \quad (4.1)$$

### 4.2.1 Start-Up Conditions

This section discusses the effect the controller has on the system during start up conditions (i.e. controlling the generator from 0 rad/s). The start-up simulation result for the rotational speed and power coefficient can be seen in figure 4.16. The simulation was performed for duration of 0.3 s and 0.5 s at the wind turbines rated wind speed of 12 m/s and a resistive load of 30  $\Omega$ .

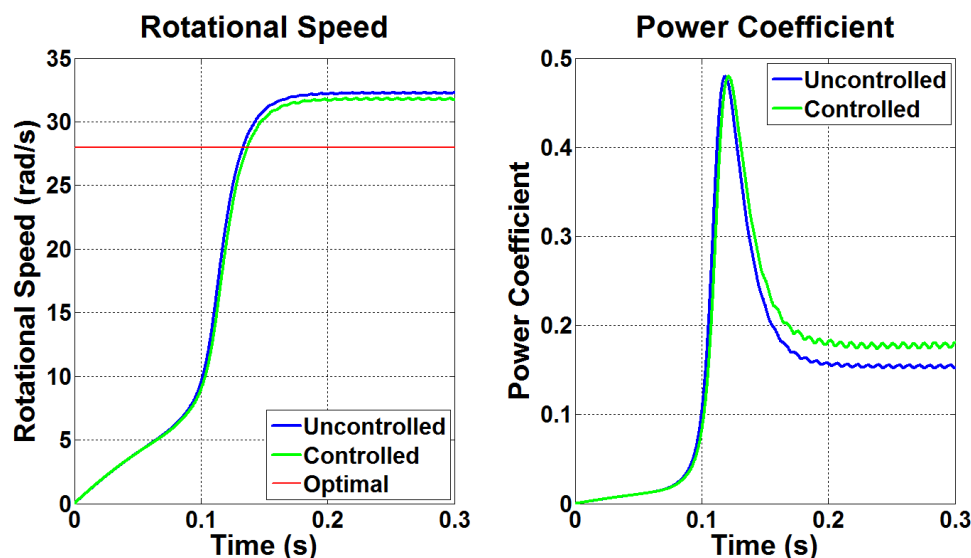


Figure 4.16: Start up rotational speed and power coefficient simulation result

The optimal rotational speed of the generator at 12 m/s is indicated in red (28 rad/s) and it is evident that the controlled generator has a rotational speed closer to the optimal speed, compared to the uncontrolled generator (31.79 rad/s compared to 32.27 rad/s) and both reaches their steady state operational speed at 0.225 s. Both the controlled and uncontrolled generator has a peak power coefficient of 0.48 after which they settle at 0.18 and 0.15 at 0.2 s, respectively.

The start-up (first 0.5 s of operation) simulation result for the power output and the percentage power difference between the controlled and uncontrolled generator can be seen in figure 4.17. The controlled and uncontrolled generator produces an average of 49.80 W and 43.20 W respectively. The output of the controlled generator varies between 65.59 W and 36.57 W while the output of the uncontrolled generator varies between 51.13 W and 34.35 W. It can also be seen that the controlled generator takes longer to react to a change in the rotational speed (compared to the uncontrolled generator) as the uncontrolled generator produces significantly more power during the first 0.1 s of operation.

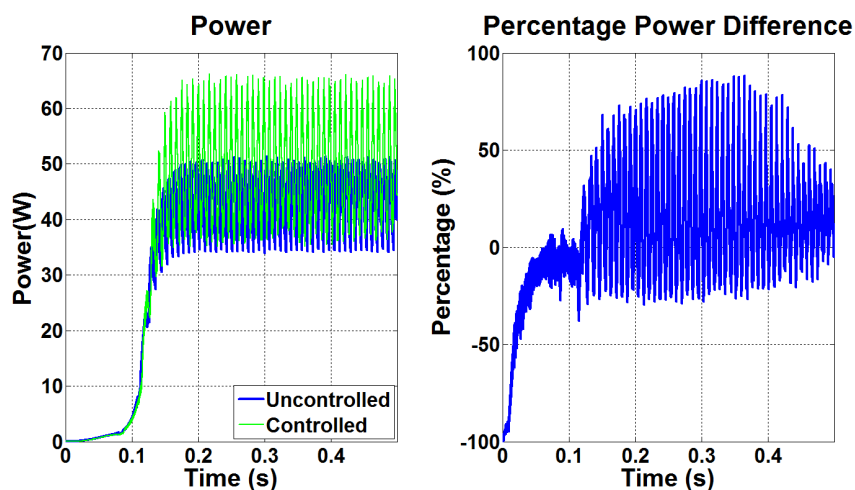


Figure 4.17: Start up power and power difference simulation result

## 4.2.2 Steady State Conditions

This section discusses the effect the controller has on the system once the operational speed of the generator has been reached, which differs depending on the wind speed and load on the generator. The generator has been given an initial rotational speed of 30 rad/s and all simulations were done for duration of 5 s in this section.

### 4.2.2.1 Fixed Wind Speed

This section discusses the results for the various fixed wind speeds (ranging from 6 m/s to 16 m/s) but only provide graphical illustrations for the rated wind speed of the wind turbine (12 m/s with a load of 30  $\Omega$ ).

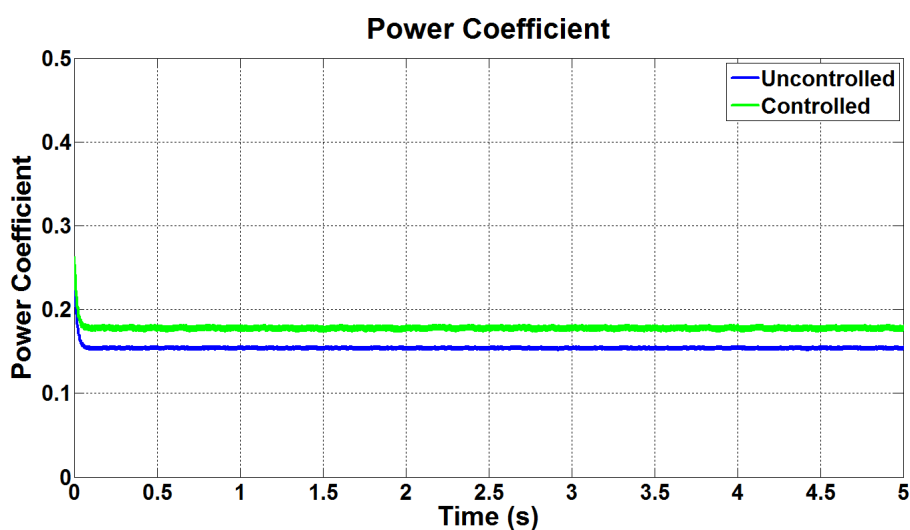


Figure 4.18: Rated wind speed power coefficient (simulation)

Figure 4.18 illustrates the difference in the power coefficient for the generator with and without the controller and it can be seen that the uncontrolled generator has a power coefficient of 0.15 and the controlled generator has a power coefficient of 0.18 which indicates an improvement of 15.36%. Figure 4.19 illustrates the difference in the rotational speed for the generator with and without the controller.

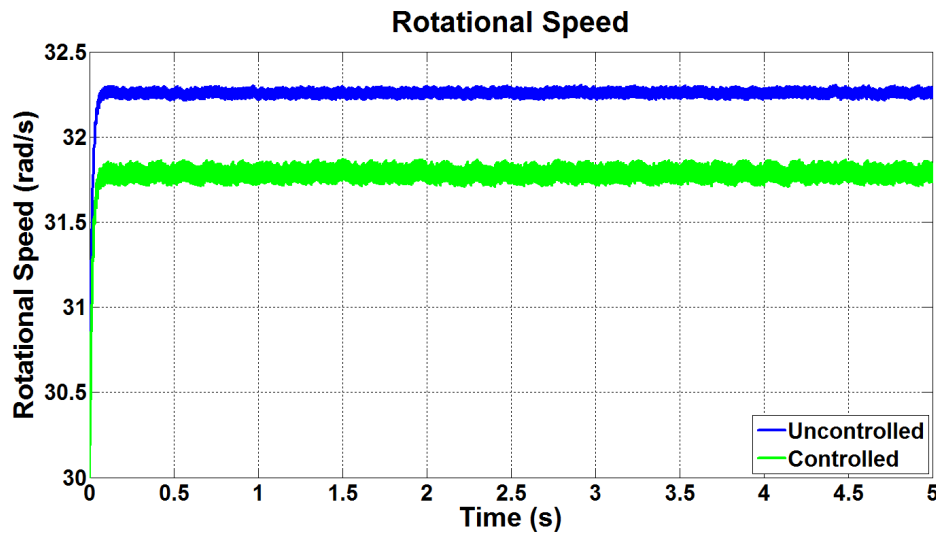


Figure 4.19: Rated wind speed rotational speed (simulation)

From figure 4.19 it can be seen that the uncontrolled generator has a rotational speed of 32.25 rad/s and the controlled generator has a rotational speed of 31.77 rad/s. Figure 4.20 illustrate the difference in the power produced by the generator with and without the controller.

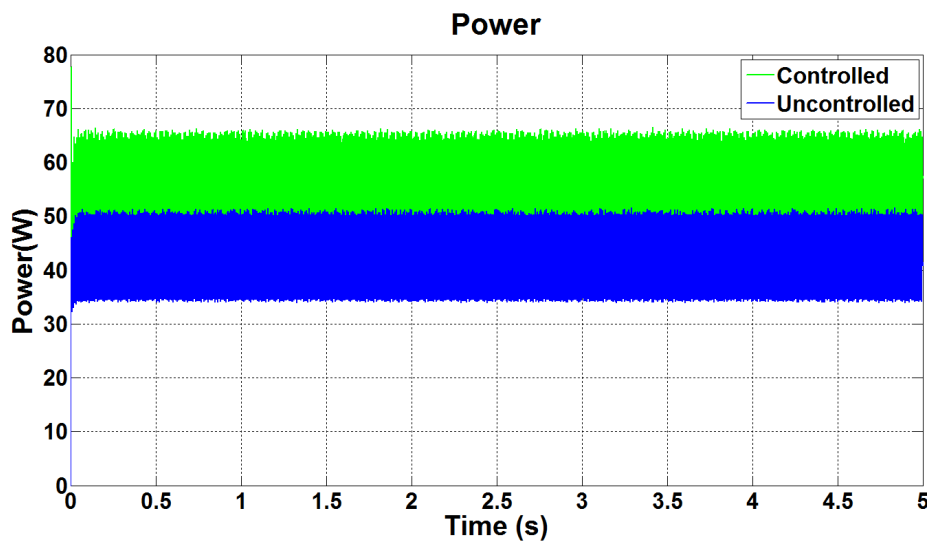


Figure 4.20: Rated wind speed power (simulation)

From figure 4.20 it can be seen that the controlled generator produces more power than the uncontrolled generator. The uncontrolled generator produces an average of 43.20 W and the controlled generator produce an average of 49.80 W which can be calculated as a difference of 20.36 W and a percentage increase of 17.12%. Figure 4.21 illustrates the load voltage and current of the controlled and uncontrolled generator.

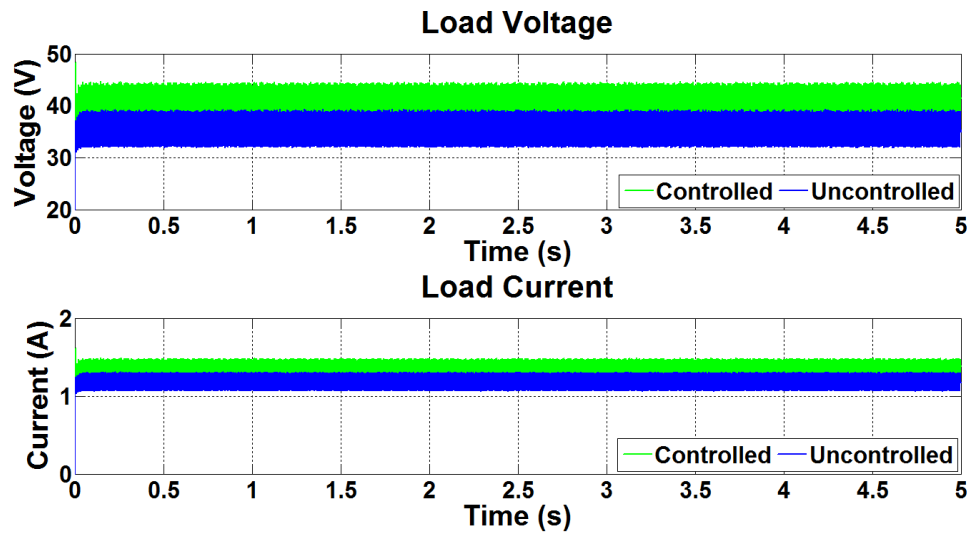


Figure 4.21: Rated wind speed voltage (simulation)

From figure 4.21 it is evident that the controlled generator produces more voltage and current on the load. The uncontrolled generator produces a voltage of 33.90 V and a current of 1.69 A while the controlled generator produces a voltage of 39.39 V and a current of 1.97 A.

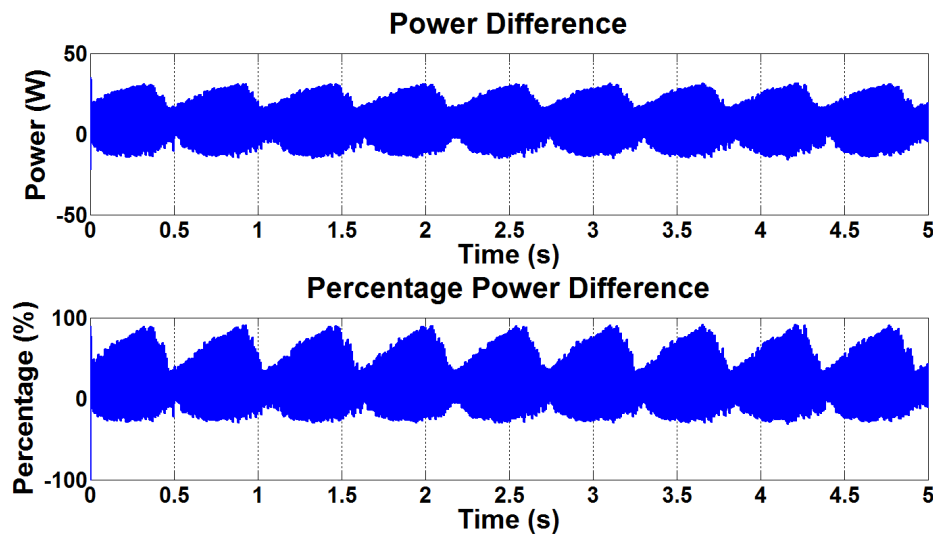


Figure 4.22: Rated wind speed power difference (simulation)

Figure 4.22 illustrates the power difference and power difference percentage produced by the generator with the controller, compared to the generator without the controller. From figure 4.22 it can be seen that the generator with the controller produces an average of 6.59 W more power than the generator without the controller, which can be calculated as an average of 17.20% more power.

Table 4.1: Percentage power increase for various fixed wind speeds (simulation)

| Wind Speed | Load      |        |         |                     |        |         |
|------------|-----------|--------|---------|---------------------|--------|---------|
|            | Resistive |        |         | Inductive-Resistive |        |         |
|            | 30 Ohm    | 64 Ohm | 128 Ohm | 30 Ohm              | 64 Ohm | 128 Ohm |
| 6 m/s      | 11.16%    | 21.18% | 66.44%  | 11.25%              | 21.55% | 66.62%  |
| 7 m/s      | 12.82%    | 19.20% | 57.33%  | 12.91%              | 19.55% | 57.36%  |
| 8 m/s      | 13.51%    | 19.62% | 57.33%  | 13.73%              | 19.59% | 57.28%  |
| 9 m/s      | 13.86%    | 20.61% | 56.98%  | 14.01%              | 20.70% | 56.90%  |
| 10 m/s     | 14.90%    | 21.48% | 58.69%  | 14.98%              | 21.52% | 58.67%  |
| 11 m/s     | 16.34%    | 23.10% | 60.10%  | 16.36%              | 23.16% | 60.04%  |
| 12 m/s     | 17.12%    | 26.67% | 60.86%  | 17.14%              | 24.67% | 61.13%  |
| 13 m/s     | 18.10%    | 26.87% | 61.46%  | 18.12%              | 26.89% | 61.64%  |
| 14 m/s     | 19.22%    | 28.36% | 61.79%  | 19.23%              | 28.41% | 61.92%  |
| 15 m/s     | 19.98%    | 29.38% | 62.36%  | 20.45%              | 29.45% | 62.52%  |
| 16 m/s     | 20.17%    | 30.53% | 63.30%  | 20.26%              | 30.38% | 63.29%  |

Table 4.1 displays the effect the load type has on the percentage power increase between the controlled and uncontrolled generator at different fixed wind speeds (6 m/s to 16 m/s). The load was varied between 30  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  and an inductive component of 1 mH was added.

#### 4.2.2.2 Fluctuating Wind Speed

The controller was simulated for fluctuating wind speed in order to determine its real world application results. The fluctuating wind speed ranges from 6 m/s to 14 m/s and the profile can be seen in figure 3.27. This section discusses the simulation results of the controller for fluctuating wind speeds. The results were obtained with a load of 30  $\Omega$  at a sampling frequency of 10 kHz.

Figure 4.23 illustrates the power coefficient of the controlled and uncontrolled generator for the fluctuating wind speed profile. The uncontrolled generator has a maximum power coefficient of 0.27 and a minimum power coefficient of 0.13 while the controlled generator has a maximum power coefficient of 0.31 and a minimum power coefficient of 0.16.

The controlled generator has an average power coefficient of 0.22 while the uncontrolled generator has an average power coefficient of 0.19 for the fluctuating wind speed profile, which can be calculated as an average increase of 14%.

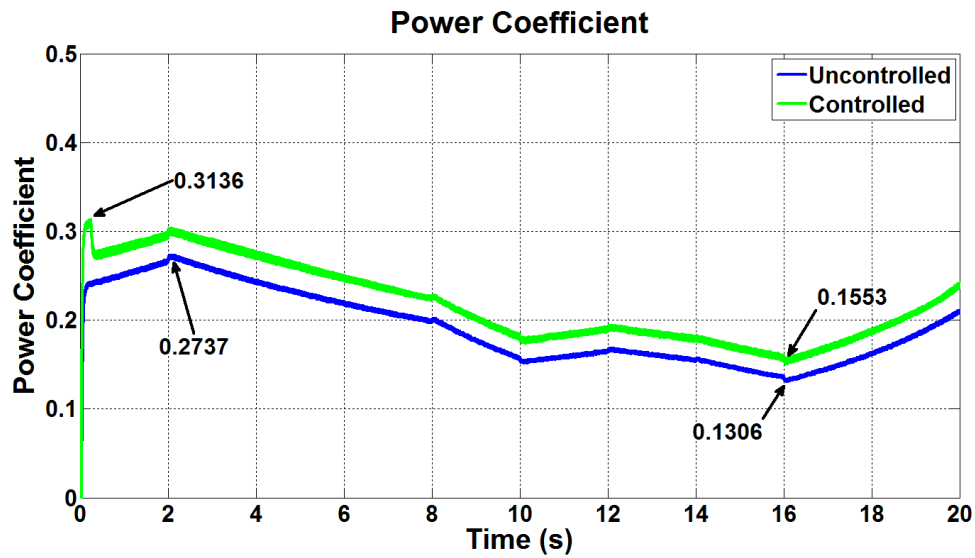


Figure 4.23: Fluctuating wind speed power coefficient (simulation)

The rotational speed of the controlled and uncontrolled generator for the fluctuating wind speed profile can be seen in figure 4.24. The uncontrolled generator has an average rotational speed of 25.75 rad/s while the controlled generator has an average rotational speed of 25.31 rad/s.

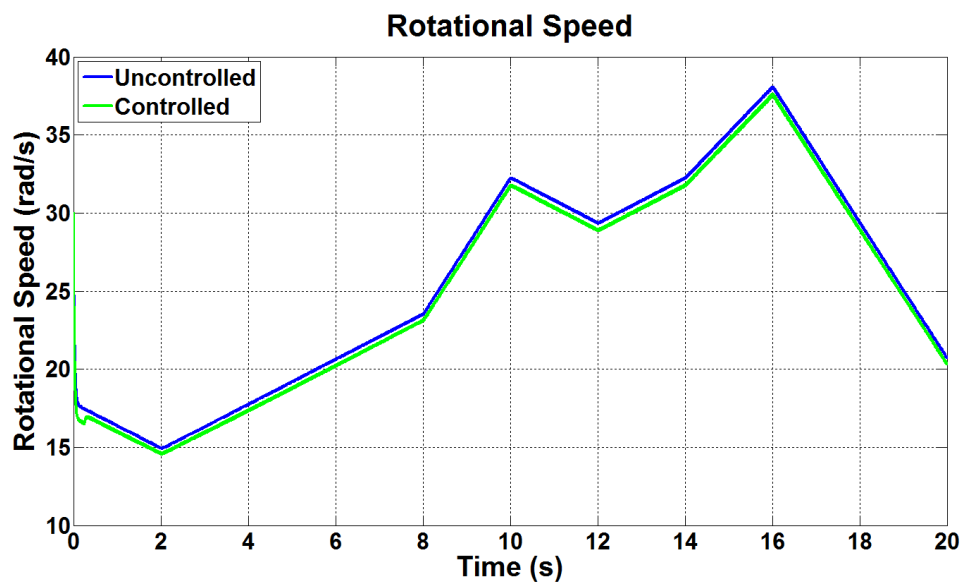


Figure 4.24: Fluctuating wind speed rotational speed (simulation)

The output power of the controlled and uncontrolled generator for the fluctuating wind speed profile can be seen in figure 4.25. The uncontrolled generator produces a maximum of 71.38 W and a minimum of 7.69 W while the controlled generator produces a maximum of 93.44 W and a minimum of 7.36 W.

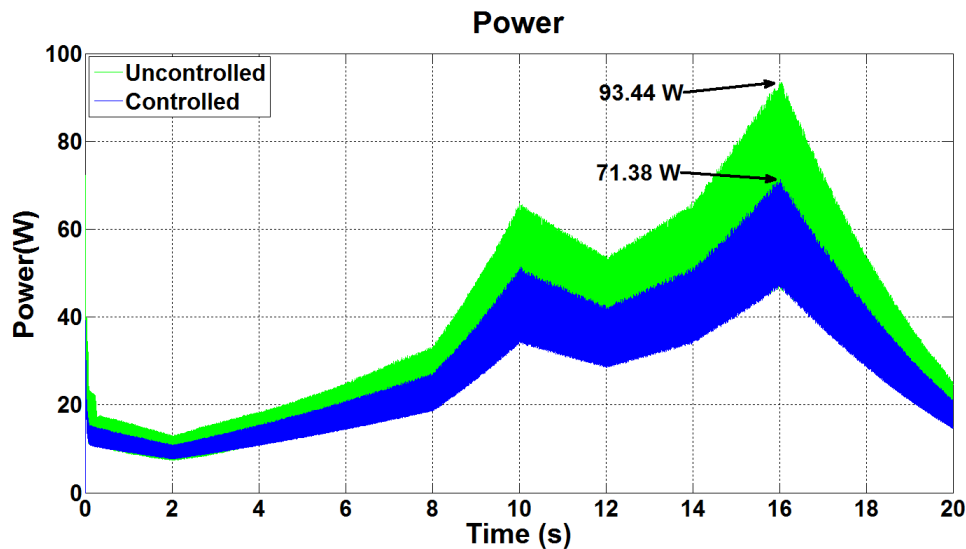


Figure 4.25: Fluctuating wind speed power (simulation)

On average the controlled generator produces 33.84 W while the uncontrolled generator only produces 29.63 W for the fluctuating wind speed profile which can be calculated as a 14.89% increase. The load voltage and load current for the controlled and uncontrolled generator can be seen in figure 4.26.

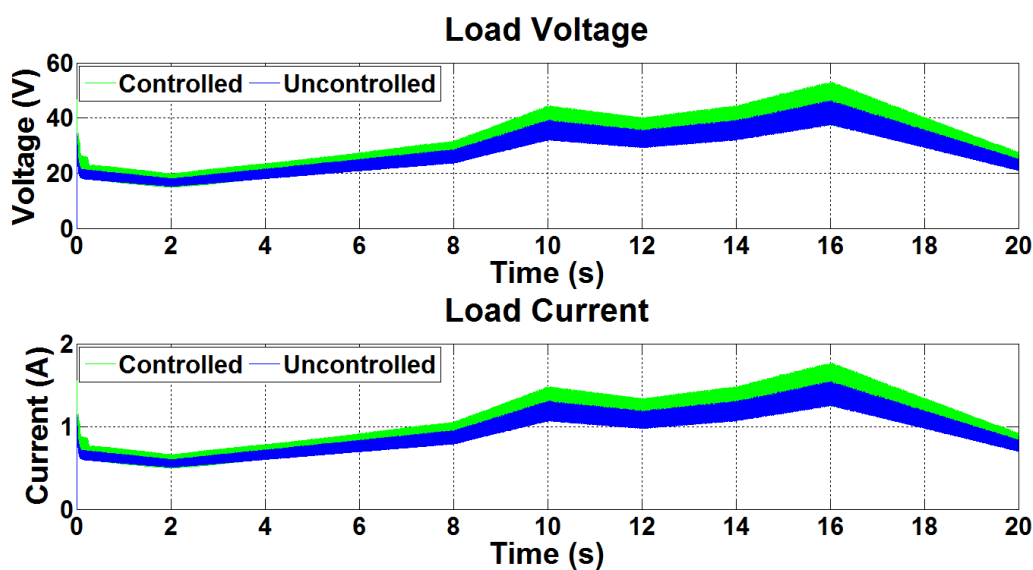


Figure 4.26: Fluctuating wind speed voltage and current (simulation)

The uncontrolled generator produces an average voltage of 28.78 V and output current of 0.96 A while the controlled generator produces an average voltage of 30.67 V and an output current of 1.02 A for the fluctuating wind speed profile. The controlled generator has a peak voltage of 52.95 V while the uncontrolled generator has a peak voltage of 46.28 V. The duty cycle output to the DC-DC boost converter of the controller for the fluctuating wind speed profile can be seen in figure 4.27.

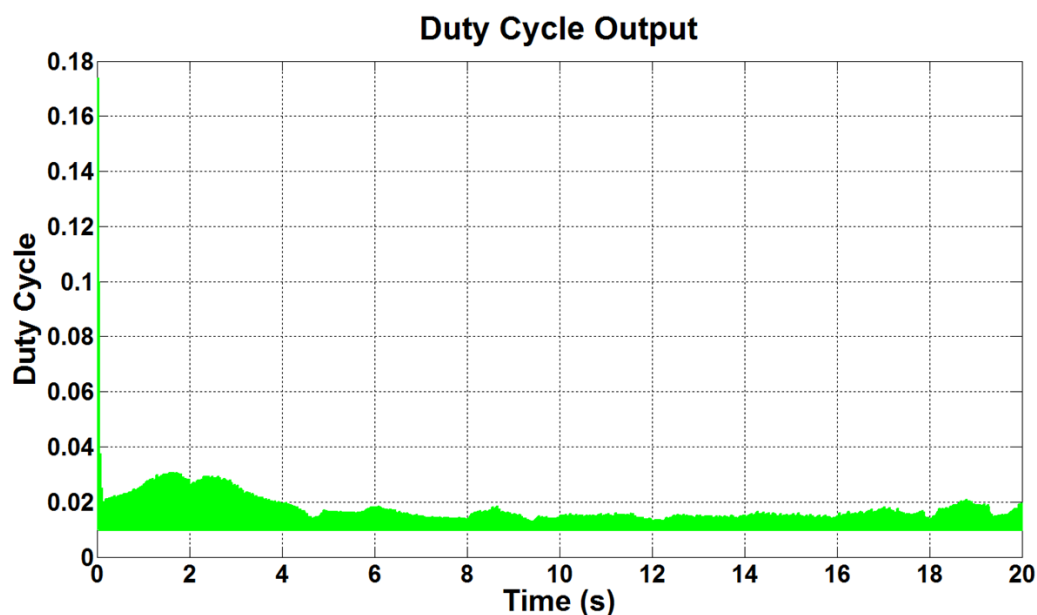


Figure 4.27: Fluctuating wind speed duty cycle (simulation)

### 4.3 Verification and Validation

The simulation results of the functional units were verified with the previous design chapter and overall the simulation results of the functional units match the design chapter with minimal error.

This section is validated by the complete system controller results which indicate an improvement in the power production between the controlled and uncontrolled generator for both fixed wind speeds and fluctuating wind speeds. The controlled generator produces a minimum of 11.16% and a maximum of 66.62% more power than the uncontrolled generator during various fixed wind speed. During the fluctuating wind speed the controlled generator produced 14.89% more power than the uncontrolled generator.

## 4.4 Conclusion

The purpose of this chapter was to determine whether the design of the controller in the previous chapter is viable. This was done by simulating all the functional units in the design chapter as well as the complete controller in Matlab<sup>®</sup>/Simulink<sup>®</sup> under different load conditions both for various fixed and a fluctuating wind speed profile.

The majority of the simulated functional units results match the expected results from the previous design chapter. The complete system controller simulation also indicates an improvement in the overall power production of the controlled generator for both fixed and fluctuating wind speeds.

The next chapter provides and discusses the experimental setup and results of the functional units and complete controller system. The experimental setup was done in such a way that it resembles the simulation as close as possible which lead to consistency between the simulation and experimental results.

# Experimental Results

*This chapter provides and discusses the experimental results obtained for the controller. This includes the results of the complete system as well as the individual functional units. The results from this section was be compared to the simulation results and where applicable the percentage error is calculated and discussed. An overview of this chapter can be seen in figure 5.1.*

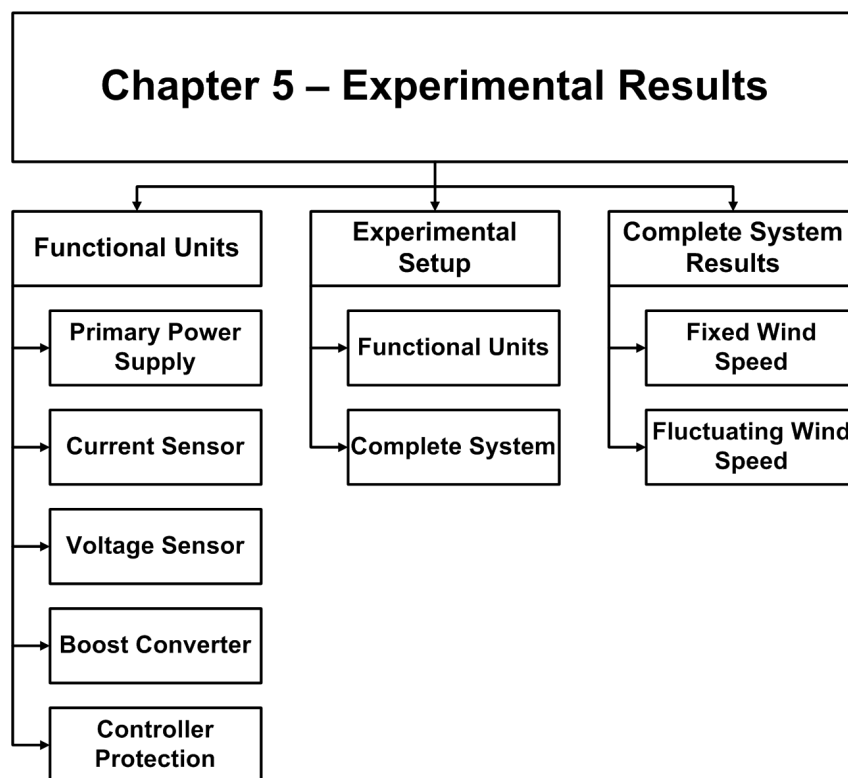


Figure 5.1: Experimental results chapter overview

## 5.1 Functional Units

This section discusses the experimental results of various functional units of the system. This includes the experimental measurements made on the functional units and a discussion on the results.

### 5.1.1 Primary Power Supply

The no load output of the 5 V and 12 V primary power supply was captured using a Velleman PCSGU250 USB oscilloscope and can be seen in the *Graphical Illustrations*

folder. From this capture it can be seen that the outputs are 5.16 V and 12.2 V. This can be calculated as an error of 2.99% for the 5 V and 0.73% for the 12 V output from the simulation results and an error of 3.2% for the 5 V output and 1.67% for the 12 V output from the design.

### 5.1.2 Current Sensor

As previously discussed, the current sensor (FU 8.3) has an output voltage proportional to the input current which ranges from 0.5 V to 4.5 V. The experimental results were obtained by increasing the current in 500 mA increments and measuring the output voltage with a Fluke 115 multimeter (refer to figure 5.2).

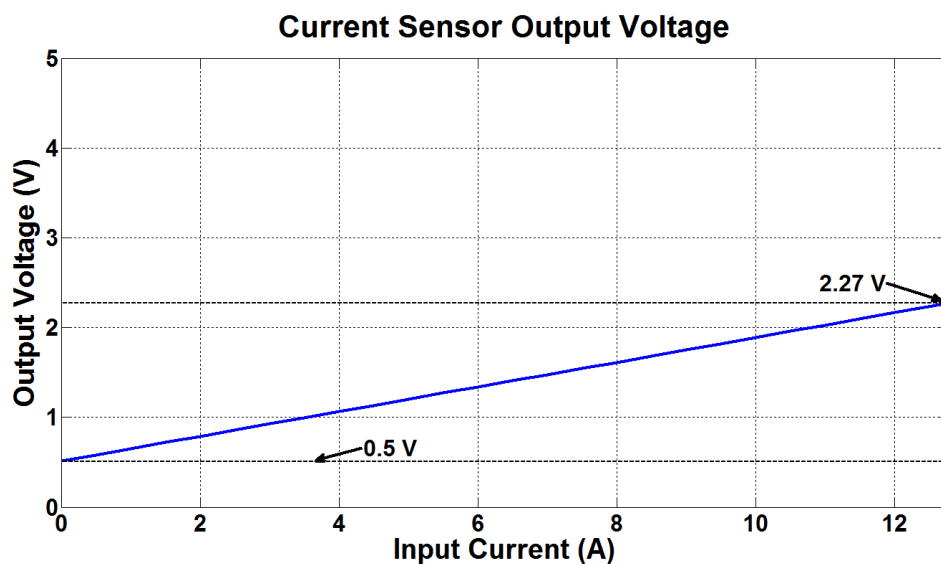


Figure 5.2: Current sensor experimental result

As expected an output voltage of 0.514 V is produced at 0 A and due to hardware limitations, the current sensor could only be tested up to 12.78 A at which the output is 2.27 V (refer to figure 5.2). Interpolation from the available data indicate 29.01 A for a 4.5 V output which can be calculated as a 3.3% error from the design output. Equation 5.1 can be used to describe the output of the current sensor (with  $V_o$  - Sensor output voltage and  $I_i$  - Output current) and was obtained by using Matlab<sup>®</sup>'s integrated curve fitting tool.

$$V_o = 0.1374I_i + 0.514 \quad (5.1)$$

### 5.1.3 Voltage Sensor

This section discusses the experimental results of the voltage sensor (FU 8.2). The measurements were obtained by increasing the input voltage from 0 V - 130 V in 2 V increments and the result can be seen in figure 5.3.

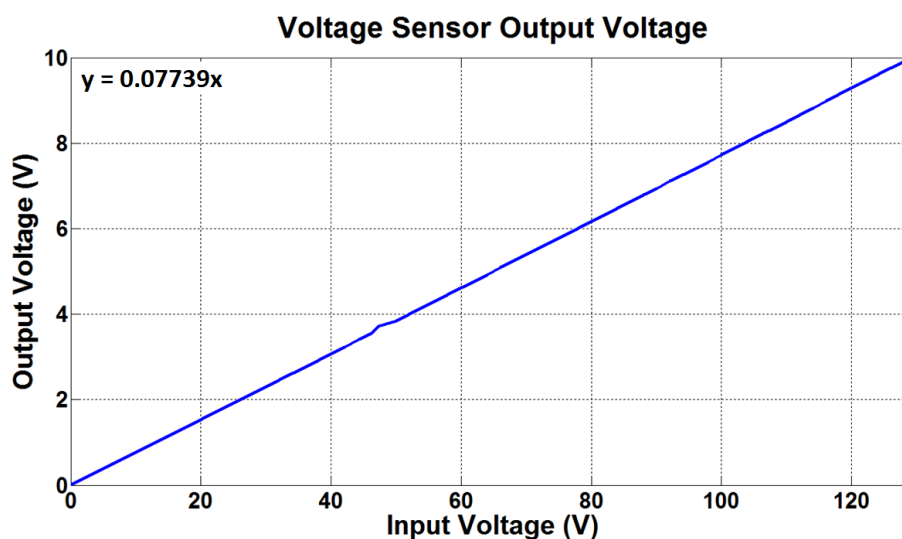


Figure 5.3: Voltage sensor experimental result

As can be seen from figure 5.3 the output voltage has a linear dependency on the input voltage and at an input voltage of 130 V the voltage sensor produces an output voltage of 10.04 V which can be calculated as a 0.4% error from the desired value and a 0.44% and 7.2% error from the simulated and calculated value, respectively.

### 5.1.4 Boost Converter

A load was connected to the boost converter (FU 5) in order to determine its efficiency and the boost ratio between a duty cycle of 0% to 50%. This consisted of a 1 k $\Omega$  load and an input voltage of 30 V and the result of the efficiency and boost ratio can be seen in figure 5.4. The efficiency of the boost converter was calculated using equation 5.2 and the boost ratio was calculated using equation 5.3.

$$Efficiency = \frac{V_o I_o}{V_i I_i} \times 100 \quad (5.2)$$

and

$$\text{BoostRatio} = \frac{V_o}{V_i} \quad (5.3)$$

The variables in equation 5.2 and equation 5.3 are  $V_o$  and  $I_o$  the output voltage and current and  $V_i$  and  $I_i$  the input voltage and input current. Figure 5.4 illustrates the efficiency and boost ratio for the boost converter from 0% - 50% duty cycle. Curve fitting was performed in Matlab<sup>®</sup> on both the efficiency and boost ratio and is displayed in red. The equations of the fitting curves calculated in Matlab<sup>®</sup> for the efficiency and boost ratio are given in equation 5.4 and equation 5.5, respectively.

$$\text{Efficiency} = -0.2306x + 90.07 \quad (5.4)$$

and

$$\text{BoostRatio} = 0.0220x + 0.9538 \quad (5.5)$$

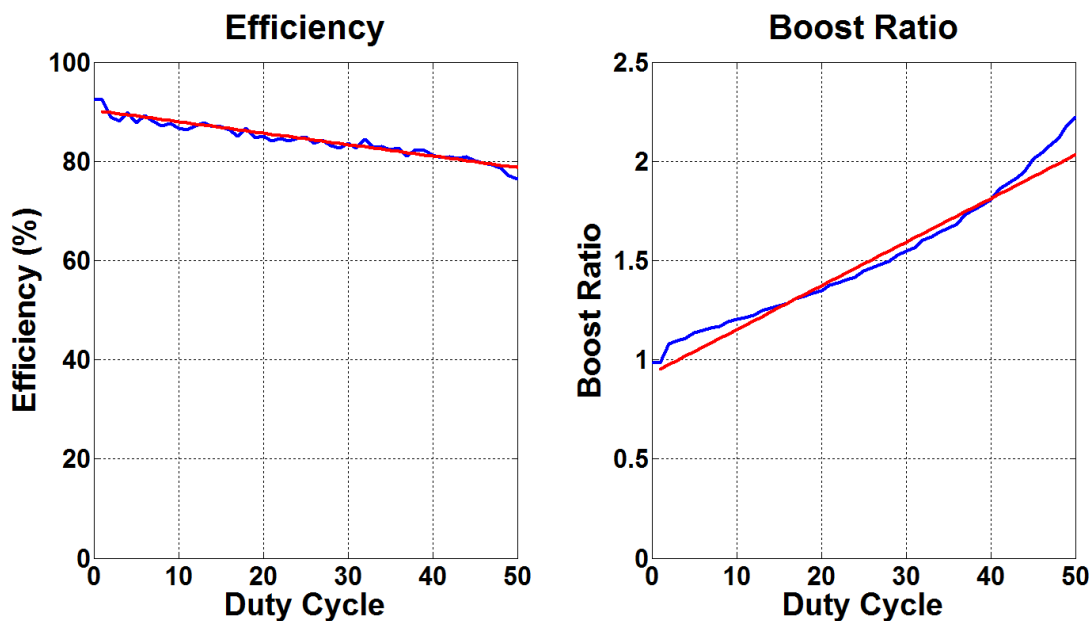


Figure 5.4: Boost converter efficiency and boost ratio (Experimental)

From figure 5.4 it can be noted that an increase in duty cycle results in a decrease in efficiency and an increase in the boost ratio. The boost converter has a maximum and minimum efficiency of 92.38% and 76.39% at a duty cycle of 0% and 50%, respectively. The lowest boost ratio of the boost converter is 0.99 and the highest boost ratio is 2.22.

This is expected as the boost converter will only experience the losses of the diode during off state and therefore results in a lower output compared to the input. The input and output voltage for the boost converter can be seen in figure 5.5. The input voltage was kept at 30 V and the output voltage was measured with a Fluke 115 multimeter between 0% and 50% duty cycle in increments of 1%.

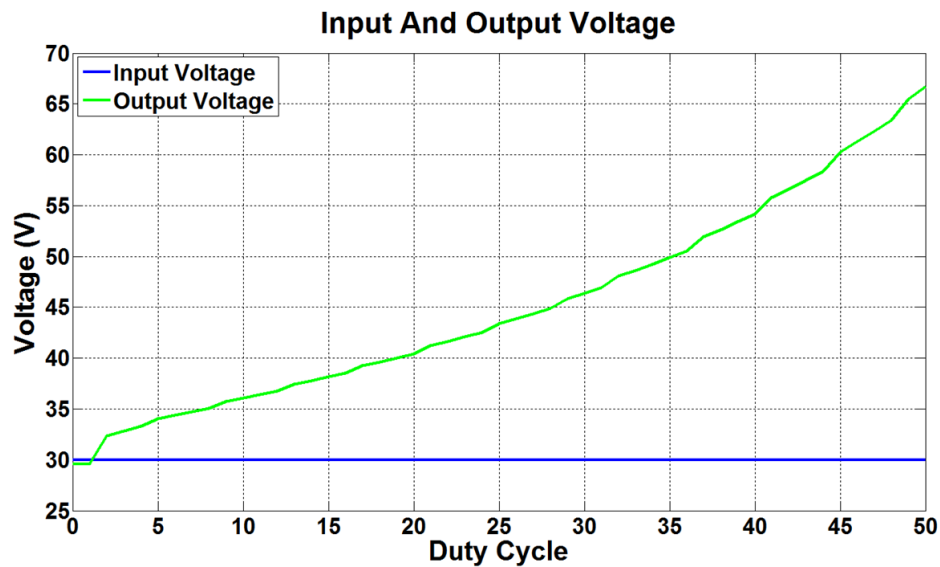


Figure 5.5: Boost converter input and output voltage (Experimental)

The input power and output power against duty cycle of the boost converter can be seen in figure 5.6 and it can be seen that an increase in duty cycle results in an increase in power loss for the boost converter.

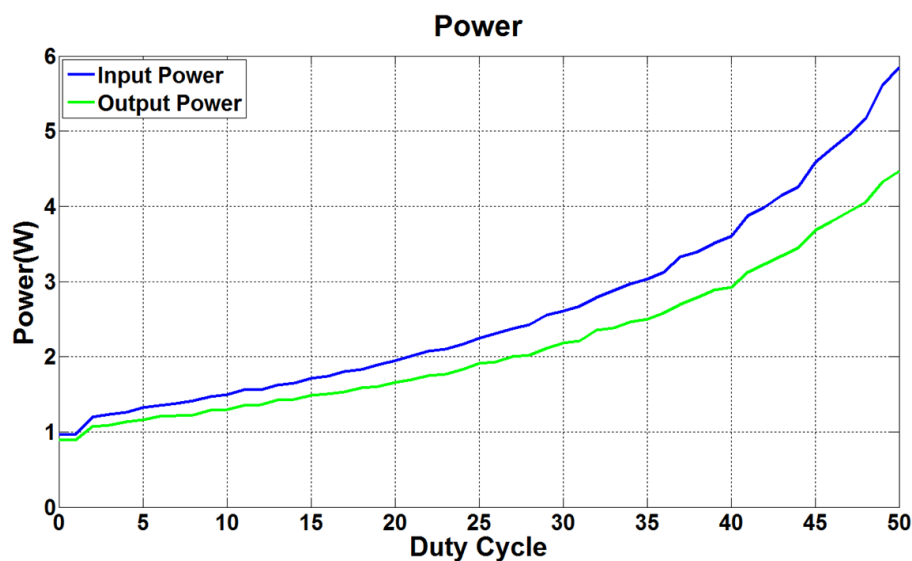


Figure 5.6: Boost converter input and output power (Experimental)

### 5.1.5 Controller Protection

This section discusses the experimental results for the controller protection (FU 2). It provides a discussion of the results for both the 0 - 4.5 V and 0 -10 V inputs, as well as the output signals from the controller protection.

#### 5.1.5.1 Input Signals

This section discusses the results of the complete controller protection for the input signals (FU 2.1). The measurements include the low pass filter (FU 2.1.1), voltage divider (FU 2.1.2), isolation amplifier (FU 2.1.3) and voltage clamper (FU 2.1.4).

**Current** The current sensor (FU 8.3) has an output voltage ranging from 0 - 4.5 V. The experimental results for the controller protection can be seen in figure 5.7. The results were obtained by increasing the input voltage between 0.5 V and 4.5 V in increments of 100 mV and measuring the output voltage with a Fluke 115 multimeter. From figure 5.7 it can be seen that a 4.5 V input produces a 2.44 V output. This can be calculated as an error of 3.17% from the simulation results and an error of 1.67% from the design.

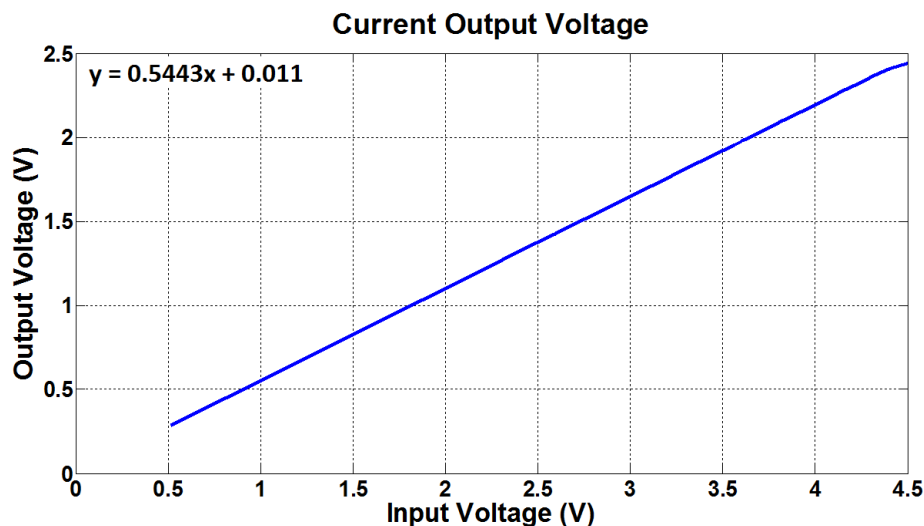


Figure 5.7: Controller protection experimental result (Current)

**Voltage and Speed** The experimental results of the voltage and speed controller protection can be seen in figure 5.8. The measurements were made between 0 - 10 V in increments of 200 mV. From figure 5.8 it can be seen that a 10 V input produces an output of 2.446 V which can be calculated as an 1.70% error from the simulation results and an error of 1.92% from the design.

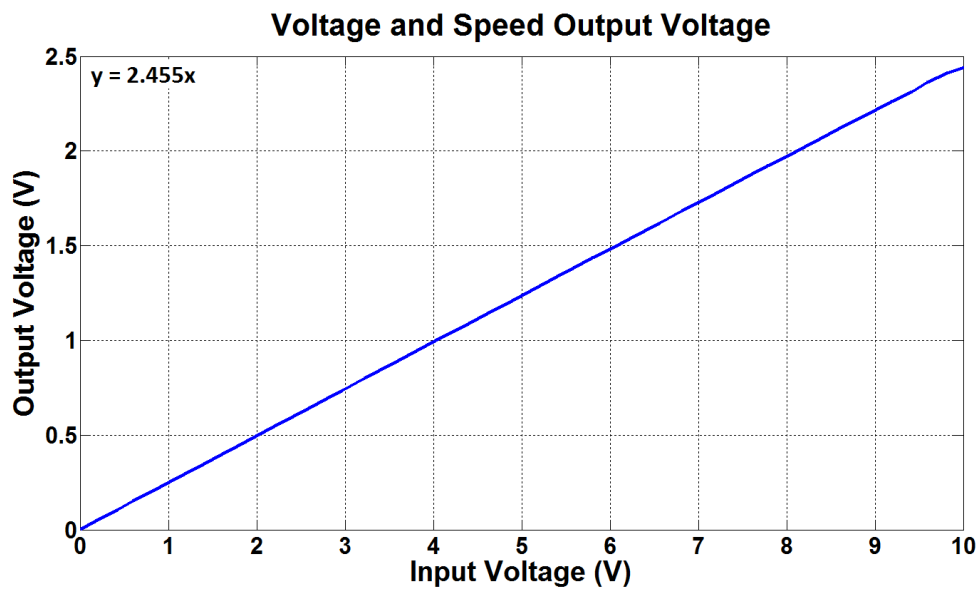


Figure 5.8: Controller protection experimental result (Voltage and speed)

### 5.1.5.2 Output Signals

Refer to the *Graphical Illustrations* folder for experimental measurements of the input and output waveforms for a 30 kHz square wave input at 10%, 50% and 90% duty cycle. The square wave input was done at a high frequency as high frequency components were used, a reduction in frequency will result in an increase in performance of the signal inverter. The results were obtained with a Velleman PCSGU250 USB oscilloscope and include all the functional units of the output signals (i.e. optocoupler and signal inverter). The percentage error of the output signal for the voltage and duty cycle can be seen in table 5.1.

Table 5.1: Experimental signal inverter output voltage and duty cycle error

| Duty Cycle | Voltage Error | Duty Cycle Error |
|------------|---------------|------------------|
| 10%        | 3.82%         | 19.19%           |
| 50%        | 5.74%         | 3.8%             |
| 90%        | 3.69%         | 2.22%            |

## 5.2 Experimental Setup

This section provides a more in depth discussion on the experimental setup used to test the viability of the controller. This is done by providing graphical illustrations, as well as a discussion on the setup.

## 5.2.1 Functional Units

This section illustrates the experimental setup of the functional units. It provides graphical illustrations of the functional units and where applicable discusses design and implementation considerations of the functional units.

### 5.2.1.1 Primary Power Supply

The primary power supply can be seen in figure 5.9. The 15 V<sub>DC</sub> input is converted to a 12 V<sub>DC</sub> and a 5 V<sub>DC</sub> output using a LM7812 and LM7805, respectively. A cooling fan was not required but added to improve the performance of the linear voltage regulators.

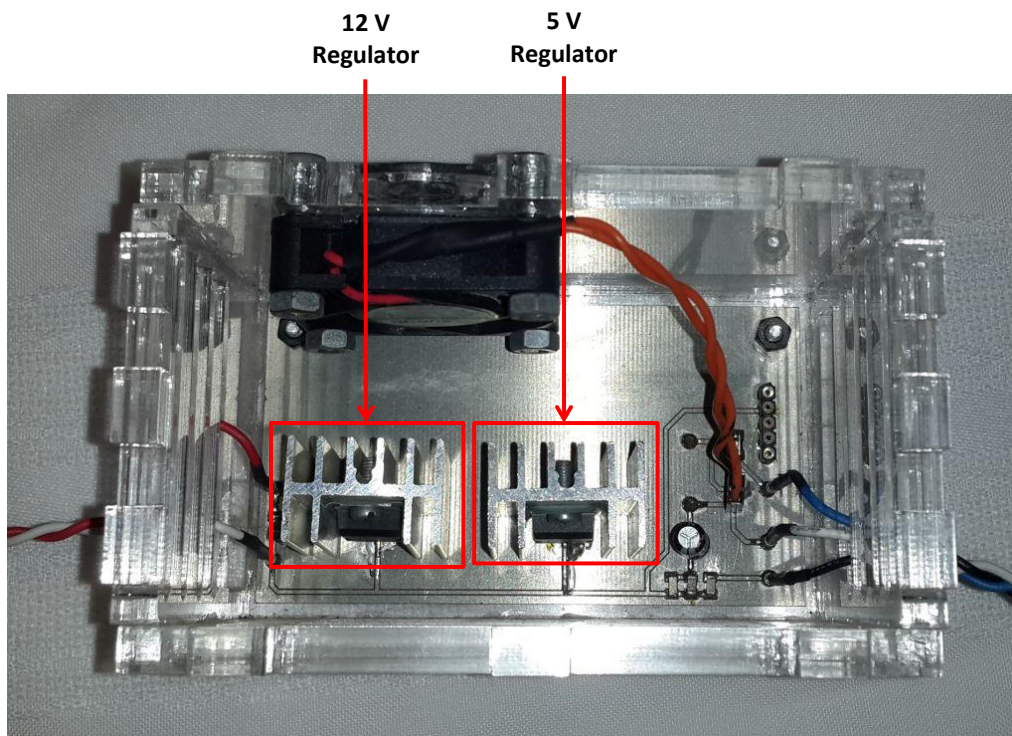


Figure 5.9: Primary power supply illustration (experimental)

### 5.2.1.2 Motor Drive and Prime mover

The VSD and prime mover emulates the power extraction from the wind turbine blades and provides the rotational force to the shaft of the generator. The VSD that was used is a WEG CFW09 and the induction motor that was used is a WEG M1AA (refer to table 5.2 for the specifications of the motor).

Table 5.2: Prime mover specifications

| Parameter       | Value     |
|-----------------|-----------|
| Output Power    | 11 kW     |
| Rated Speed     | 1 390 rpm |
| Power Factor    | 0.91      |
| Connection Type | Y         |

A large induction motor was used to provide smooth rotation at low speeds and was required due to the high cogging torque of the generator (peak value of  $10 \text{ N} \cdot \text{m}$ ). The VSD and prime mover coupling to the generator can be seen in figure 5.10 (a) and figure 5.10 (b), respectively.

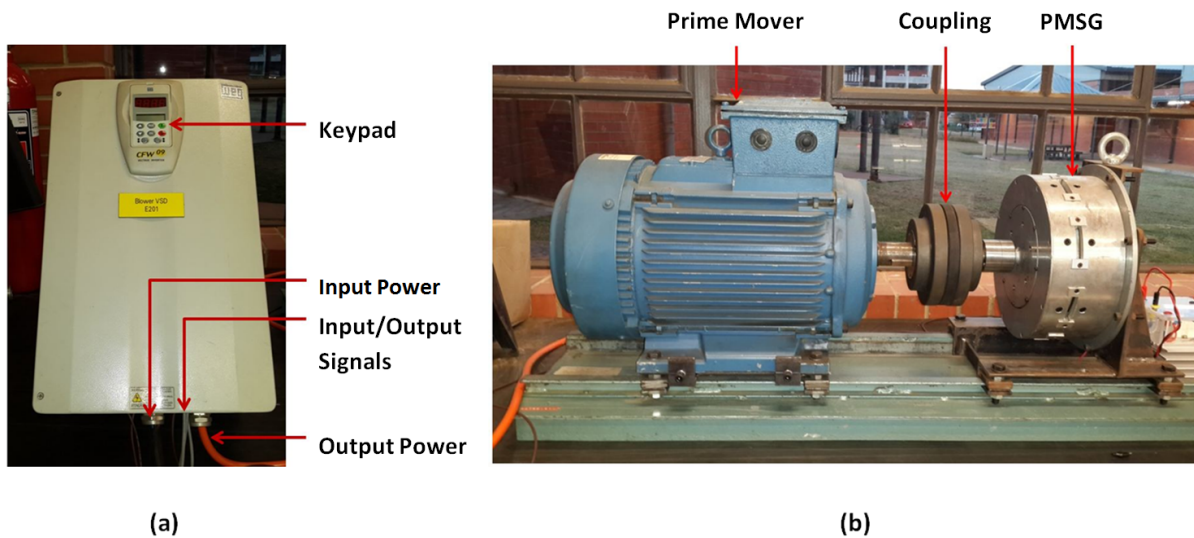


Figure 5.10: (a) VSD (b) Prime mover and generator coupling illustration (experimental)

### 5.2.1.3 Generator

The generator used for the experimental implementation of the controller consists of a transverse flux double coil PMSG design and the the generator and specifications of the generator can be seen in figure 5.11 and table 5.3, respectively.

Table 5.3: Experimental generator specifications

| Parameter                           | Value |
|-------------------------------------|-------|
| Rated Power                         | 1 kW  |
| Number of Phases                    | 1     |
| Output Voltage ( $V_{\text{RMS}}$ ) | 45 V  |

Further information on the generator can be seen in O. Dobzhanskyi *et al.* [136] and O. Dobzhanskyi *et al.* [137] which discusses the design of the generator as well as a technique of inserting magnetic shunts between the stator poles in order to reduce the high cogging torque of the generator.



Figure 5.11: Generator (experimental)

The output of the generator was measured during the different load conditions under different rotational speeds in order to determine a base to which the controlled generator can be compared. The different loads are  $30\ \Omega$ ,  $64\ \Omega$  and  $128\ \Omega$ . Figure 5.12 and table 5.4 displays the power produced by the generator for different rotational speeds under different load conditions. The generator output power could only be tested between 100 rpm and 600 rpm due to the high cogging torque.

Table 5.4: Generator output base values (experimental)

| Speed (rpm) | 30 Ohm Load | 64 Ohm Load | 128 Ohm Load |
|-------------|-------------|-------------|--------------|
| 100         | 1.83 W      | 0.99 W      | 0.52 W       |
| 200         | 7.00 W      | 3.87 W      | 1.99 W       |
| 300         | 14.97 W     | 8.51 W      | 4.45 W       |
| 400         | 24.90 W     | 14.52 W     | 7.67 W       |
| 500         | 36.03 W     | 21.71 W     | 11.63 W      |
| 600         | 48.19 W     | 29.89 W     | 16.72 W      |

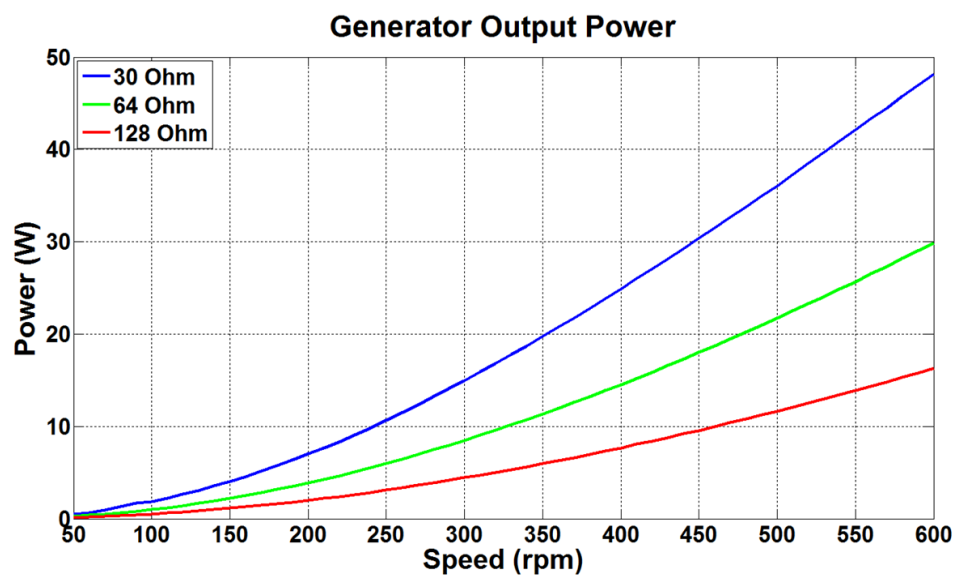


Figure 5.12: Base values for generator under different load conditions (experimental)

#### 5.2.1.4 Boost Converter

The boost converter (as well as the current and voltage sensors) used for the controller can be seen in figure 5.13. The power input and output of the boost converter consist of banana sockets and the input and output signal consist of BNC (Bayonet Neill-Concelman) with twin core shielded wire.

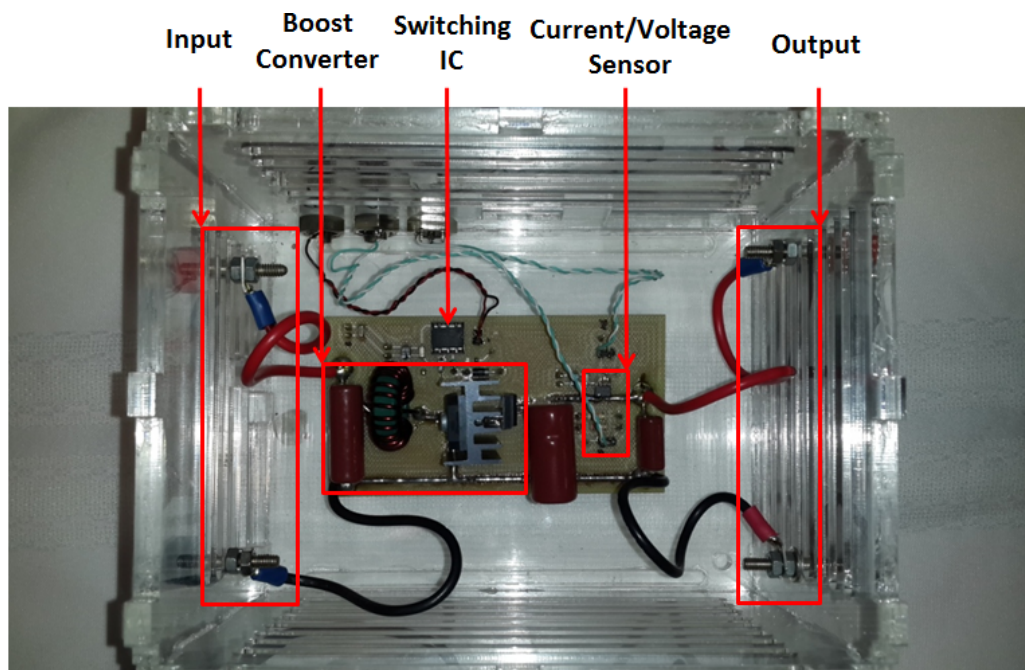


Figure 5.13: Boost converter illustration (experimental)

### 5.2.1.5 Controller Protection

Figure 5.14 illustrates the controller protection circuit used for the controller. The protection contains both the input and output signals connected with BNC connectors using twin core shielded wire. Connection to the dSPACE<sup>®</sup> controller board is done using two 50 pin D-Sub connectors and the primary and secondary power is supplied by two isolated AC to DC power supplies. All connections between the controller protection and inputs/outputs were done according to [138] which provides guidelines for reducing signal noise when connecting external components. This includes recommendations for connector types, wire types and the connection of shielded wire.

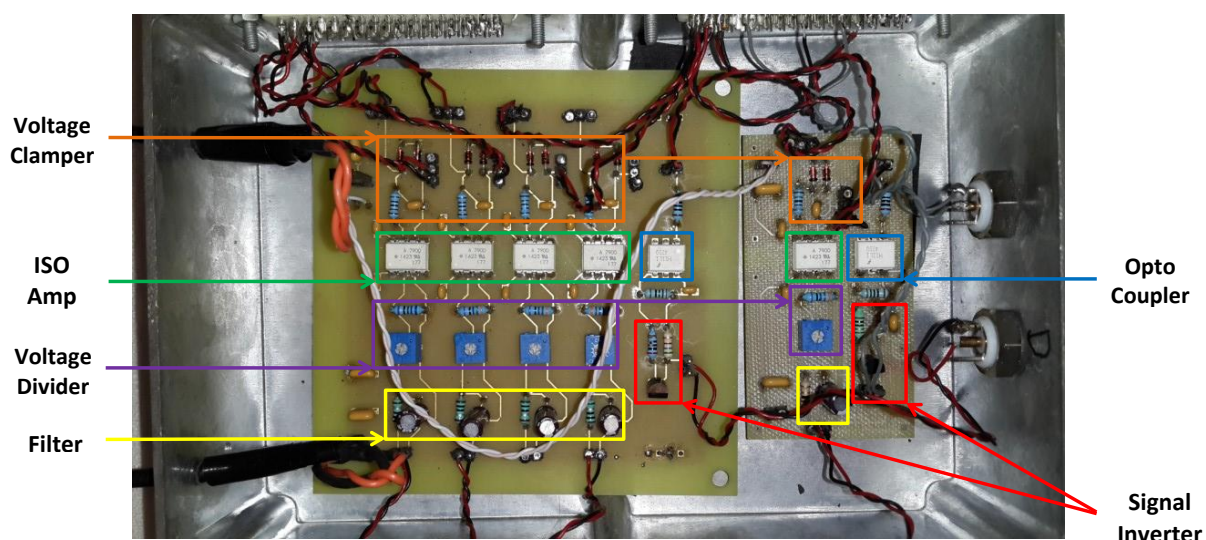


Figure 5.14: Controller protection illustration (experimental)

### 5.2.1.6 Updated Controller Parameters

During the experimental implementation of the controller it was found that dSPACE<sup>®</sup> DS1104 controller board allowed a maximum sampling frequency of 1 kHz for the Matlab<sup>®</sup>/Simulink<sup>®</sup> model. In order to determine the effect the change in sampling time had on the overall performance of the controller, the fixed wind speed simulations was redone at a sampling frequency of 1 kHz and boost converter switching frequency of 1 kHz. The results of the simulation can be seen in table 5.5 which displays the percentage power difference between the controlled and uncontrolled generator.

Comparing table 5.5 to table 4.1 it can be seen that the updated controller parameters reduces the overall efficiency of the controller. This reduction is most profound during low wind speeds for both a resistive and resistive inductive load. The changes

to the controller allow only for a percentage power increase between 1.74% - 32.85% compared to an increase between 11.16% - 66.62% of the previous parameters.

Table 5.5: Updated controller parameters simulation results (percentage power difference)

| Wind Speed | Load      |        |         |                     |        |         |
|------------|-----------|--------|---------|---------------------|--------|---------|
|            | Resistive |        |         | Inductive-Resistive |        |         |
|            | 30 Ohm    | 64 Ohm | 128 Ohm | 30 Ohm              | 64 Ohm | 128 Ohm |
| 6 m/s      | 1.74%     | 6.29%  | 31.43%  | 1.96%               | 7.03%  | 32.85%  |
| 7 m/s      | 1.31%     | 4.51%  | 25.26%  | 1.44%               | 4.69%  | 24.58%  |
| 8 m/s      | 1.88%     | 4.48%  | 19.43%  | 1.81%               | 3.85%  | 19.03%  |
| 9 m/s      | 2.54%     | 3.84%  | 15.94%  | 2.47%               | 3.71%  | 15.73%  |
| 10 m/s     | 3.77%     | 4.01%  | 15.53%  | 3.76%               | 3.94%  | 15.47%  |
| 11 m/s     | 3.52%     | 4.70%  | 15.66%  | 3.48%               | 4.63%  | 15.53%  |
| 12 m/s     | 4.52%     | 6.68%  | 16.00%  | 4.33%               | 6.69%  | 15.81%  |
| 13 m/s     | 5.70%     | 8.56%  | 17.16%  | 5.55%               | 8.48%  | 16.62%  |
| 14 m/s     | 6.22%     | 9.20%  | 17.63%  | 6.17%               | 9.24%  | 17.53%  |
| 15 m/s     | 6.57%     | 9.74%  | 18.00%  | 6.72%               | 9.74%  | 17.86%  |
| 16 m/s     | 6.13%     | 9.39%  | 18.34%  | 6.45%               | 9.30%  | 18.05%  |

### 5.2.2 Complete System

This section discusses the complete setup used to obtain the experimental results. It provides a photo of the complete setup, provides and discusses the Matlab<sup>®</sup>/Simulink<sup>®</sup> model used to obtain the results and provides a graphical illustration of the Control Desk<sup>®</sup> layout. The complete experimental setup used to obtain the experimental results can be seen in figure 5.15.

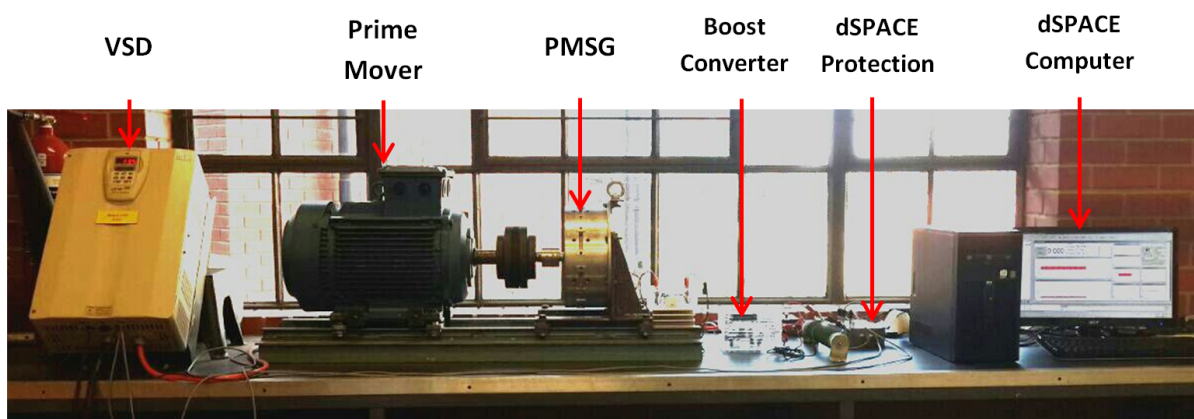


Figure 5.15: Complete experimental setup illustration (experimental)

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 the dSPACE<sup>®</sup> controller board.

Control Desk<sup>®</sup> was used to obtain the experimental results and the layout of the control desk implementation can be seen in figure 5.16. Figure 5.16 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 Control Desk<sup>®</sup> is indicated on the figure. 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 Control Desk<sup>®</sup> 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 5.17 displays the Matlab<sup>®</sup>/Simulink<sup>®</sup> model used for the experimental implementation of the controller. 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 adds 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.



Figure 5.16: Experimental Control Desk® Model

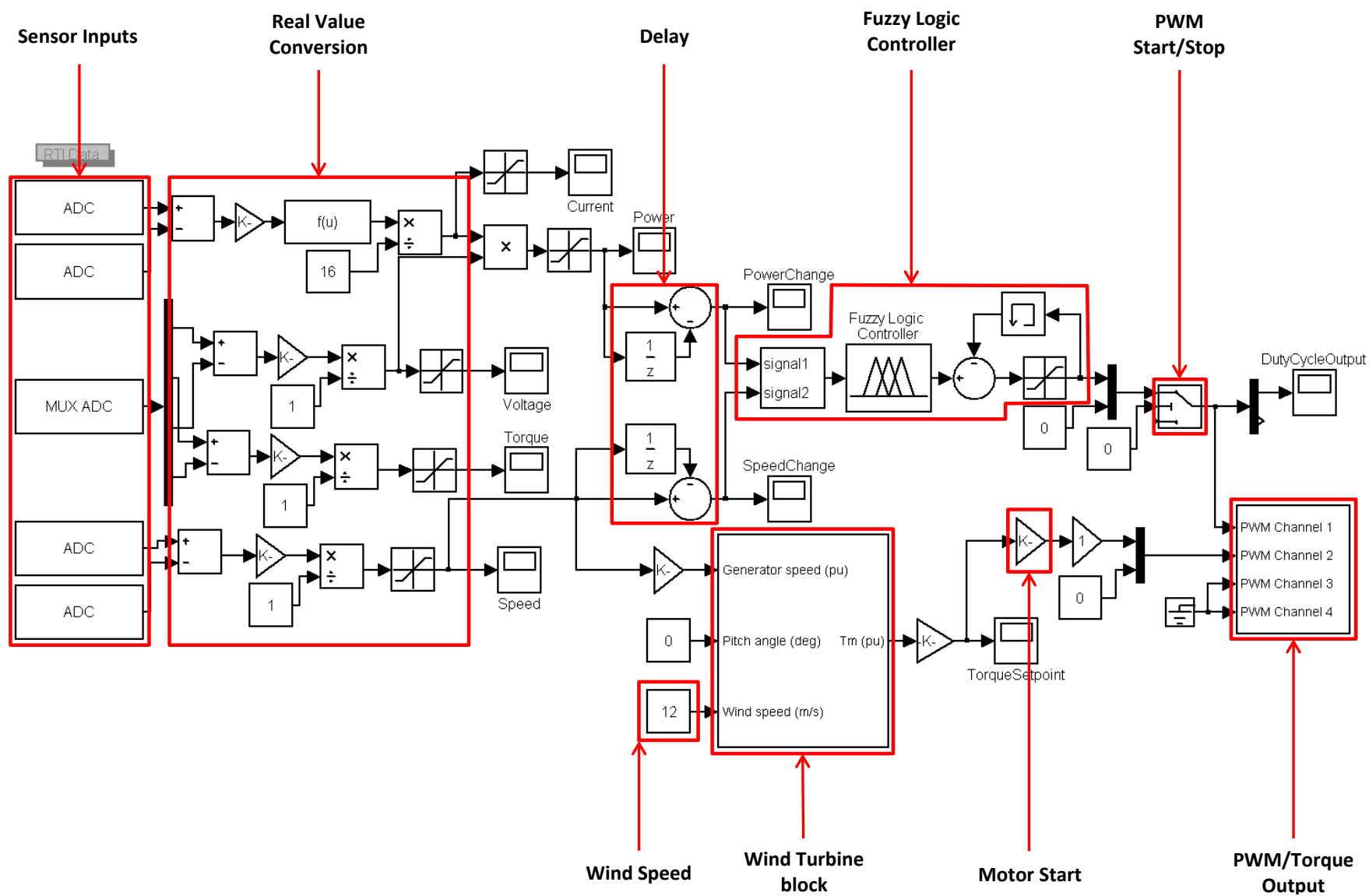


Figure 5.17: Experimental dSPACE® Matlab®/Simulink® model

## 5.3 Complete System Results

This section discusses the results of the complete experimental setup for both a resistive and an inductive-resistive load under fixed and fluctuating wind speeds. The results were obtained by using the data acquisition function in Control Desk<sup>®</sup> with a sampling time of 1 kHz and no down sampling (calculations done with 6th decimal place values).

### 5.3.1 Fixed Wind Speed

The results of the various fixed wind speed previously discussed for the complete experimental setup is discussed in this section. The results were obtained for various fixed wind speeds ranging from 6 m/s to 16 m/s.

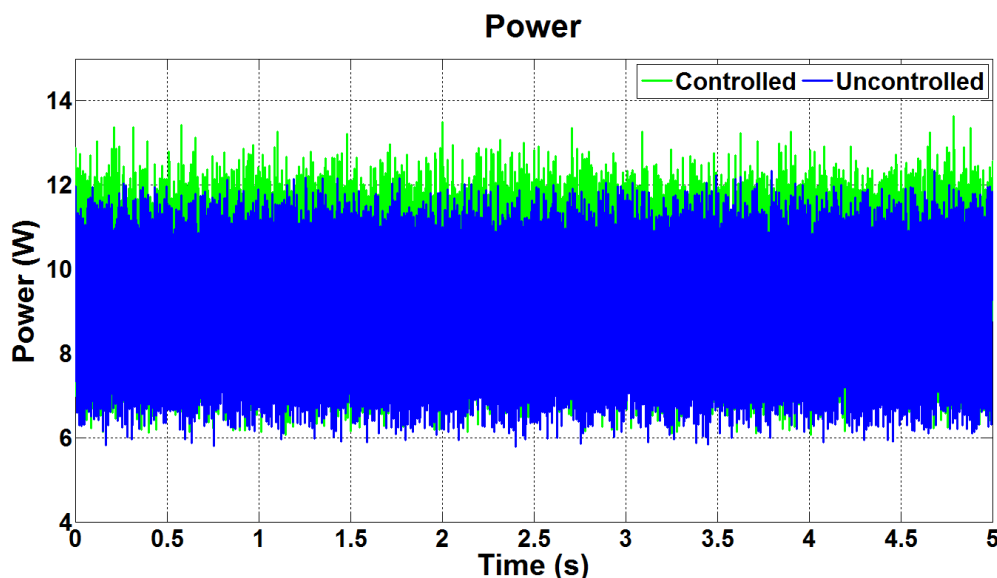


Figure 5.18: Rated wind speed power (experimental)

Figure 5.18 displays the output power of the controlled and uncontrolled generator at the rated wind speed of 12 m/s with a load of  $30\ \Omega$ . On average the uncontrolled generator produces 9.28 W while the controlled generator produces 9.75 W which can be calculated as an 5.01% power increase.

Figure 5.19 illustrates the output voltage and current of the controlled and uncontrolled generator. From figure 5.19 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.

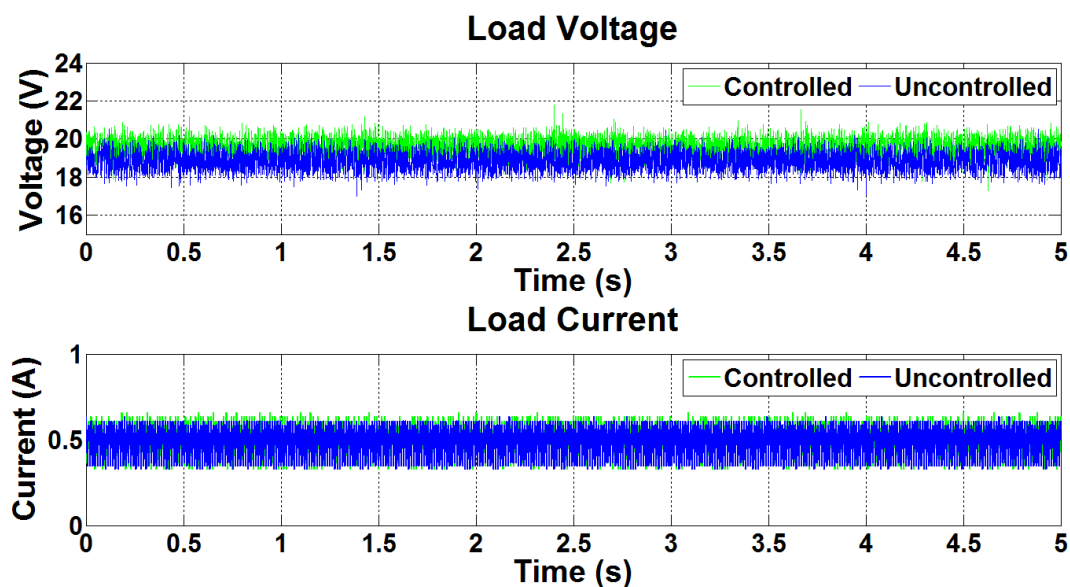


Figure 5.19: Rated wind load voltage and load current (experimental)

During the experimental implementation of the system it was found that the controller only has a marginal effect on the rotational speed of the generator (when compared to the simulation results). 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.

### 5.3.1.1 Resistive Load

This section discusses the results obtained from the complete experimental setup for a resistive load under various fixed wind speeds. The controller was tested with a load of 30  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  and the percentage power increase of the controlled generator compared to the uncontrolled generator can be seen in figure 5.20.

From figure 5.20 it can be seen that the controller increases the overall amount of power extracted by the generator with the exception of a 64  $\Omega$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  increases the amount of power by 5.01%, 3.06% and 1.94% respectively.

### 5.3.1.2 Inductive-Resistive Load

This section discusses the results obtained from the complete experimental setup for an inductive-resistive load under various fixed wind speeds. The controller was tested

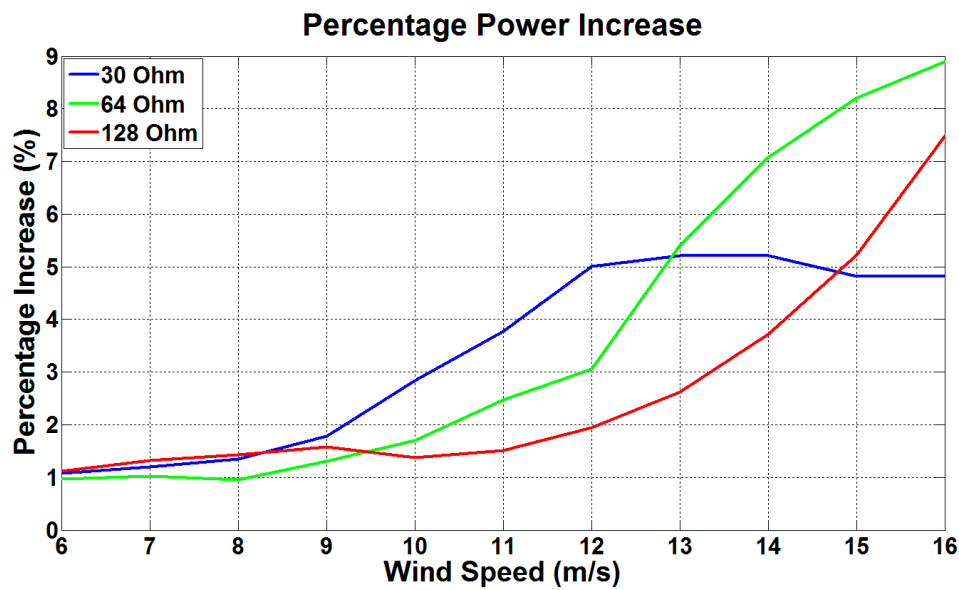


Figure 5.20: Experimental fixed wind speed percentage power increase (resistive load)

under various load conditions of  $30\ \Omega$ ,  $64\ \Omega$  and  $128\ \Omega$  with an inductive component of  $1.4\ \text{mH}$ . The percentage power increase of the controlled generator compared to the uncontrolled generator can be seen in figure 5.21.

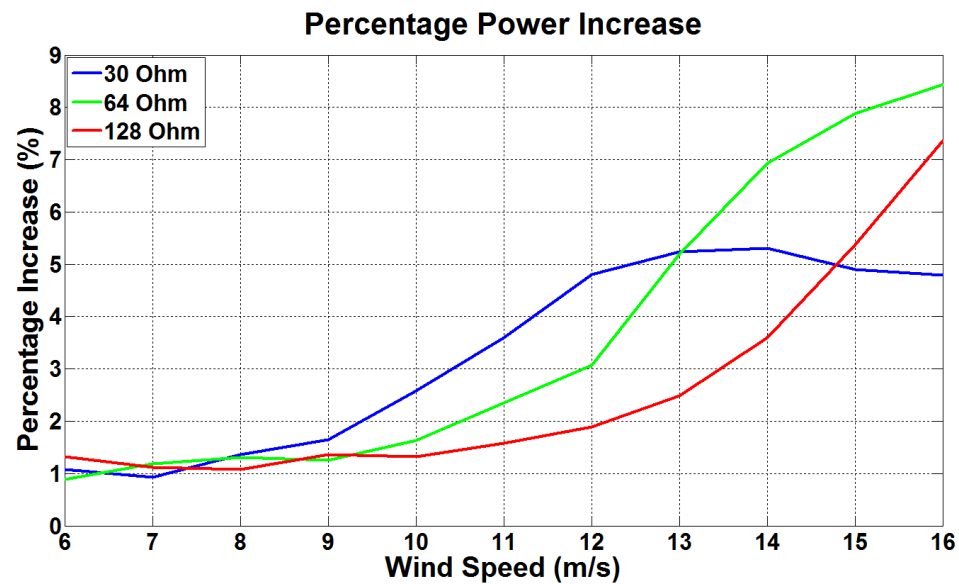


Figure 5.21: Experimental fixed wind speed percentage power increase (inductive-resistive)

From figure 5.21 it can be seen that the controller increases the overall amount of power extracted by the generator with the exception of a  $30\ \Omega$  and  $64\ \Omega$  load at a wind speed of  $7\ \text{m/s}$  and  $6\ \text{m/s}$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  increases the amount of power by 4.80%, 3.07% and 1.90% respectively. Table 5.6 displays the experimental percentage power increase for various wind speeds under various load conditions (both resistive and inductive-resistive).

Table 5.6: Fixed wind speed resistive and inductive-resistive percentage power increase (experimental)

| Wind Speed | Load      |        |         |                     |        |         |
|------------|-----------|--------|---------|---------------------|--------|---------|
|            | Resistive |        |         | Inductive-Resistive |        |         |
|            | 30 Ohm    | 64 Ohm | 128 Ohm | 30 Ohm              | 64 Ohm | 128 Ohm |
| 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%  | 7.49%   | 4.79%               | 8.44%  | 7.37 %  |

### 5.3.1.3 Fixed Wind Speed Experimental Measurements

Figure 5.22 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)

Figure 5.22: Experimental load voltage measurement for (a) uncontrolled and (b) controlled (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 5.23. 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.

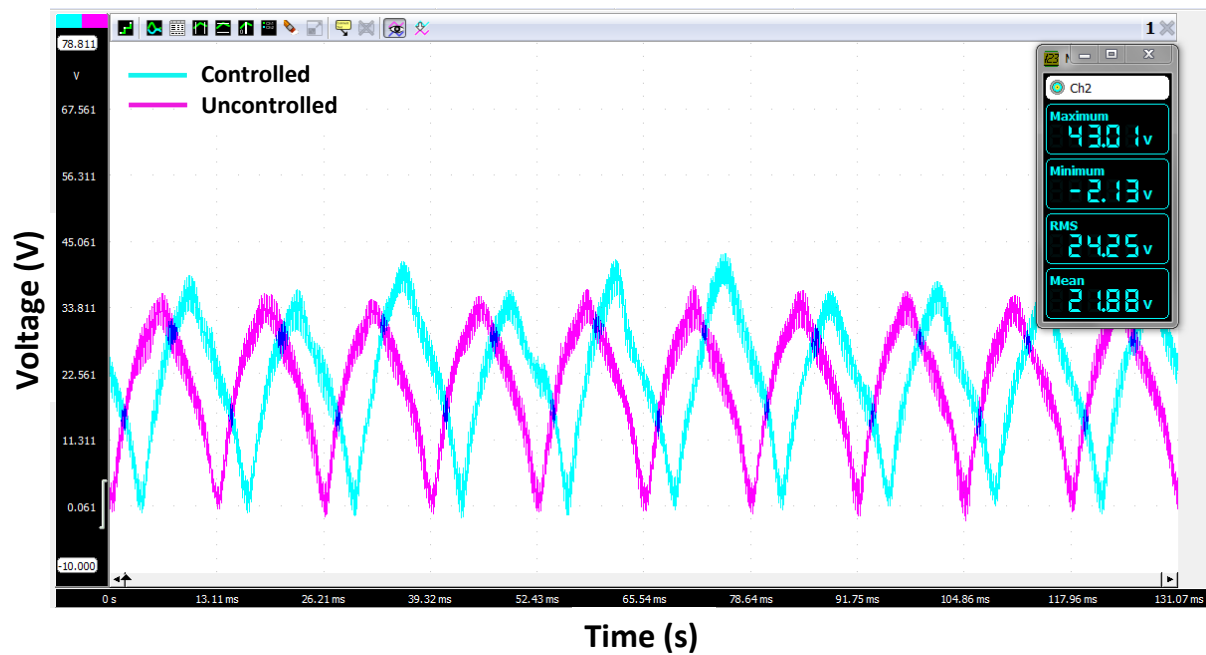


Figure 5.23: Experimental load voltage measurement (TiePie Scope)

### 5.3.2 Fluctuating Wind Speed

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 5.24 displays the power output of the uncontrolled and controlled generator for the fluctuating wind speed profile (refer to figure 3.27).

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.

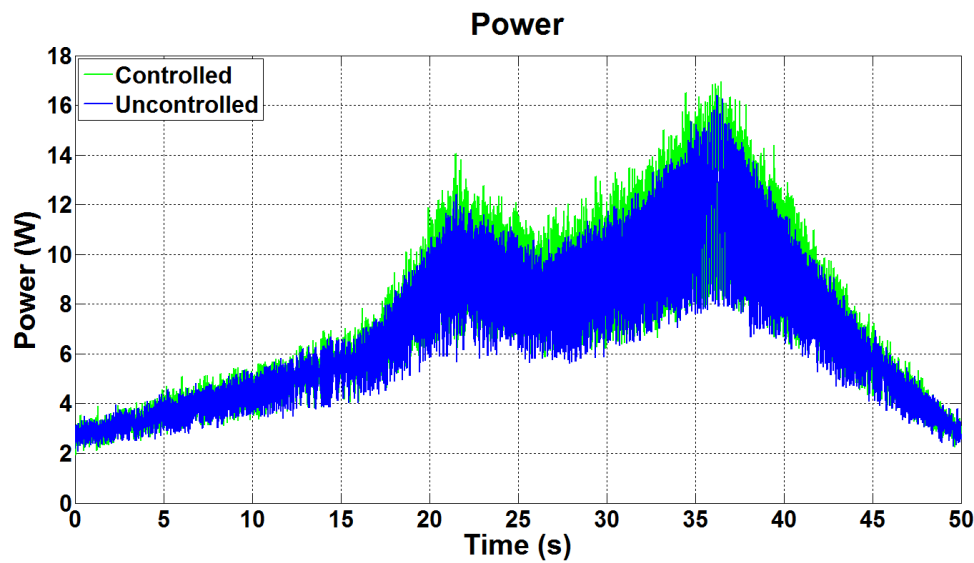


Figure 5.24: Fluctuating wind speed power (experimental)

Figure 5.25 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.

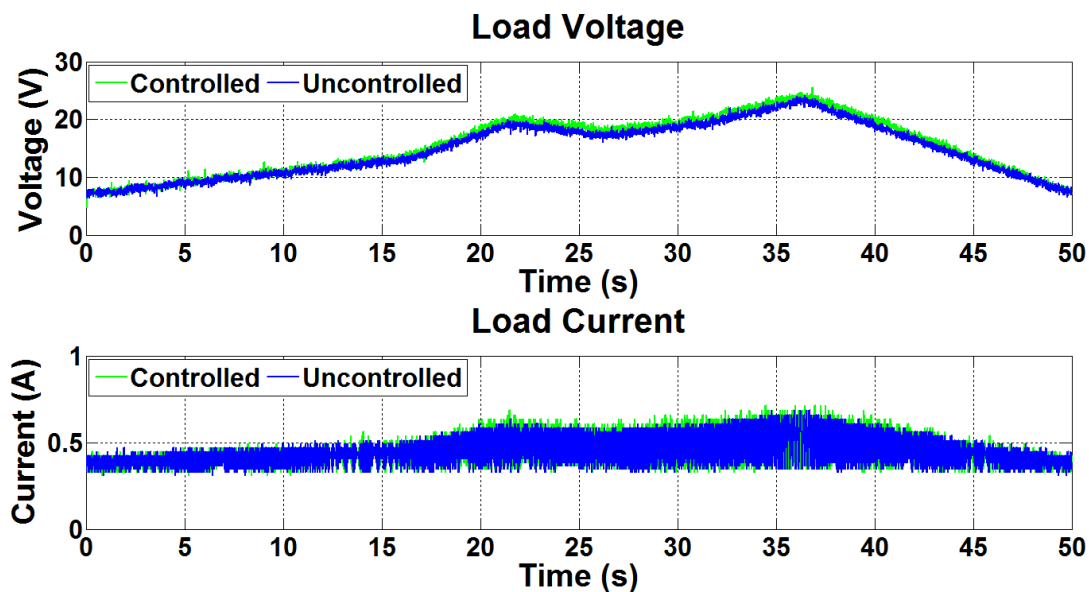


Figure 5.25: Fluctuating wind speed voltage and current (experimental)

Figure 5.26 displays the duty cycle to the DC-DC boost converter for the fluctuating wind speed profile. The duty cycle varies with the wind speed and has a minimum value of 0% and a maximum value of 16.3%.

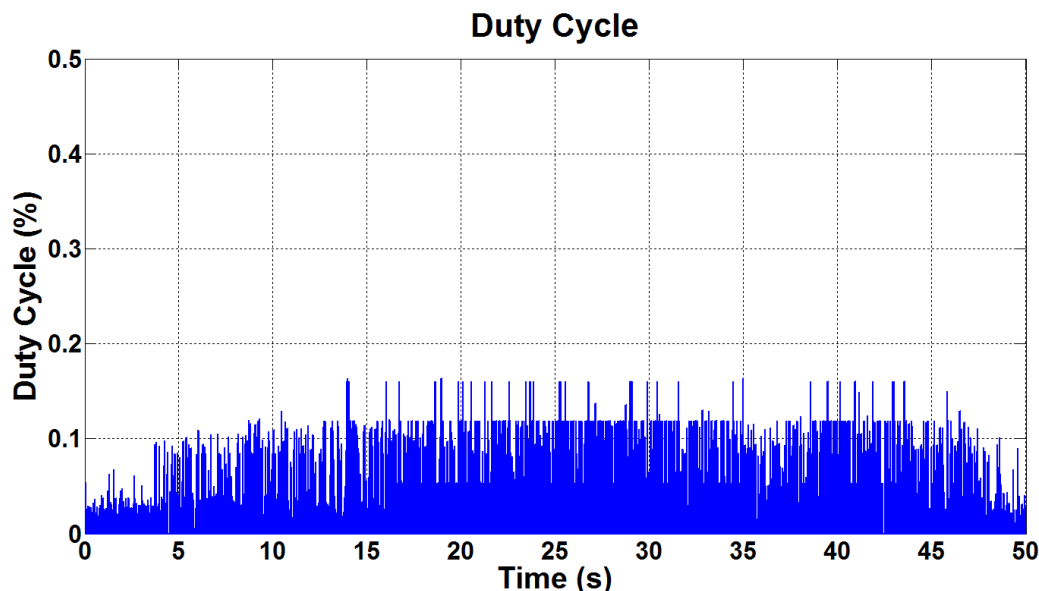


Figure 5.26: Fluctuating wind speed duty cycle (experimental)

### 5.3.2.1 Resistive Load

This section discusses the results obtained from the complete experimental setup for a resistive load for fluctuating wind speeds (refer to figure 3.27 for fluctuating wind speed profile). The load of these results varies between  $30\ \Omega$ ,  $64\ \Omega$  and  $128\ \Omega$ . The percentage power increase between the controlled and uncontrolled generator is 5.55%, 5.26% and 2.33% for the  $30\ \Omega$ ,  $64\ \Omega$  and  $128\ \Omega$  load, respectively.

### 5.3.2.2 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 3.27 for fluctuating wind speed profile). The load of these results varies between  $30\ \Omega$ ,  $64\ \Omega$  and  $128\ \Omega$  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  $30\ \Omega$ ,  $64\ \Omega$  and  $128\ \Omega$  load, respectively.

## 5.4 Verification and Validation

Verification in this chapter was done by comparing the experimental results of the functional units and complete system controller to the simulation results and design requirements (where applicable). The comparison between the results was discussed for each of the functional units and a more in depth comparison on the complete system controller is done in the following section.

The experimental results of the complete system validates that the controller improves the amount of power the controlled generator produces for various fixed and fluctuating wind speeds and with various load conditions. Although the experimental results are lower when compared to the simulation results, the controller still improves the overall power extraction of the wind turbine.

## 5.5 Conclusion

The purpose of this chapter was to determine whether a practical application of the controller would be a viable solution for micro wind turbines. It was found that the simulation results of the complete controller differ significantly from the experimental results. This can be attributed to two main factors. The first is the lower sampling time of the dSPACE<sup>®</sup> controller board which only allowed a maximum sampling frequency of 1 kHz whereas the simulation sampling frequency was done at 10 kHz. The simulations was repeated at the lower sampling frequencies and the results can be seen in table 5.5. As can be seen from table 5.5 the updated parameters significantly lowers the percentage power increase of the controlled generator (when compared to table 4.1). The second is the inaccuracy of the integrated PMSG block in Matlab<sup>®</sup>/Simulink<sup>®</sup> used for simulation in comparison to the experimental PMSG used (the experimental PMSG consist of a transverse flux double coil PMSG design).

Although there is a significant difference between the simulated results and experimental results, the controller has an overall improvement between the controlled and uncontrolled generator. The percentage power increase between the controlled and uncontrolled generator increases with an increase in wind speed with a maximum increase of 8.90%. This is also confirmed by the fluctuating wind speed profile experimental results which indicate an overall improvement during changing wind speeds.

Although the complete system experimental results greatly differs from the simulation results, the experimental results of the functional units has a closer match to the experimental results and design requirements.

The next chapter serves as the final and closing chapter of the project. It provides a summary on the findings of the project as well as recommendations for future work that can be done on the controller. The key research questions as well as the verification and validation done throughout the project is also addressed.

# Conclusion and Recommendations

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*This chapter serves as the closing chapter for the project. It provides an overview and discusses the findings and results throughout the project as well as provide recommendations for further work on the project.*

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## 6.1 Dissertation Overview

Each chapter in this dissertation served a specific purpose in order to ensure the successful completion of the project. The primary purpose of chapter 1 was to serve as an introductory chapter in order to provide an insight to the project and dissertation. During this chapter a brief introduction to wind turbines was given and the problems associated with using wind turbines as a renewable energy source. This chapter also discussed the objectives, research methodology, key research questions and provided a brief summary of the publications and peer reviews done for the project.

Chapter 2 served as the literature study and was done in order to obtain a thorough understanding on the workings and control of wind turbines. This chapter provided the knowledge required in order to develop the controller and included all the relevant aspects of the wind turbine including wind turbine power, MPPT techniques commonly incorporated into wind turbines, the available control topologies, controllers that could be used in the system and the types of generators commonly used for wind turbines. Another fundamental part of this chapter was the case studies done on each of the aspects of the wind turbine. This provided an insight as to what combination of the different parts of the wind turbine would result in the best results and whether combinations are even possible.

After an in depth understanding on the workings of wind turbines were obtained a design could be made, which was the purpose of chapter 3. The first step in the design process was to determine the control strategy and determining the functional flow of the controller. The functional flow was broken up into all the lower level functional units in order to determine the interaction between all the functional units of the controller. A detailed design was done on the lower level functional units in order to ensure successful integration of the functional units. This chapter also discussed the required calculations for the controller.

After a detailed design was made, the system was simulated using a variety of simulation software in chapter 4. The functional units were simulated separately and as a complete system controller in Matlab®/Simulink®. The complete system was simulated both for various fixed wind speeds and a fluctuating wind speed profile and both indicate an overall improvement on the amount of power extracted from the incoming wind.

Chapter 5 discussed the experimental implementation and results of the controller. The functional units were tested separately and as a complete system for both fixed and fluctuating wind speeds and both indicated an improvement in the amount of power produced by the generator. During this chapter it was found that the experimental results differed from the simulation results which was mainly due to the lower sampling frequency the dSPACE® DS1104 controller board permitted and the difference in the construction of the experimental generator compared to the simulation generator.

## **6.2 Results**

This section compares the findings and results of the design, simulation and experimental chapters with each other.

### **6.2.1 Design**

The calculation results in the design chapter was used as the base values for the controller as this was the required values on all the various lower level functional units of the controller.

### **6.2.2 Simulations**

Simulations were done on both the functional units as well as the complete system controller. The simulation results of the lower level functional units were similar to the design results with minimal error. The simulation results of the complete system controller could be compared to the design as no calculations were done for the the complete system controller.

### **6.2.3 Experimental**

Experimental results were obtained for both the functional units as well as the complete system controller. The experimental results of the lower level functional units were similar to both the simulation results as well as the calculation results with min-

imal error. The experimental results of the complete system controller were found to be lower when compared to the simulation results for both the various fixed wind speeds and fluctuating wind speed profile. These differences were caused by a lower sampling frequency during the experimental implementation of the controller and constructional differences between the simulated and experimental generator.

### 6.3 Pay-off Period

It is difficult to determine the pay-off period of the controller as the percentage power increase differs depending on the wind speed, load size, generator output and generator type. It can however be stated that the current system has a high pay of period as the system makes use of dSPACE® DS1104 controller board. The dSPACE® DS1104 controller board has a high cost and is intended for development purposes and therefore makes an practical implementation not economically viable.

This problem can be addressed by using a DSP (researched in 2.5) that can be used in a stand-alone application. This will significantly reduce the cost and make the controller more economically viable.

### 6.4 Verification and Validation

Verification and validation was done throughout the chapters. Verification was done in order to ensure the results and findings in each chapter were viable with each previous chapter. Validation was done in order to ensure the results and findings were viable to the objectives of the project. The verification and validation process of the project can be seen in figure 6.1.

Verification of the design was done throughout the dissertation as the design, simulation and experimental results were compared to each other. This was done for both the individual functional units as well as the complete system results. Were applicable, the percentage error between the different results were calculated for the functional units.

Validation of the design was done between the literature study (predominately case studies), design, simulation results and experimental result and the objectives of the project. This was mainly done for the complete system controller in order to ensure the objectives of the project are met by the controller.

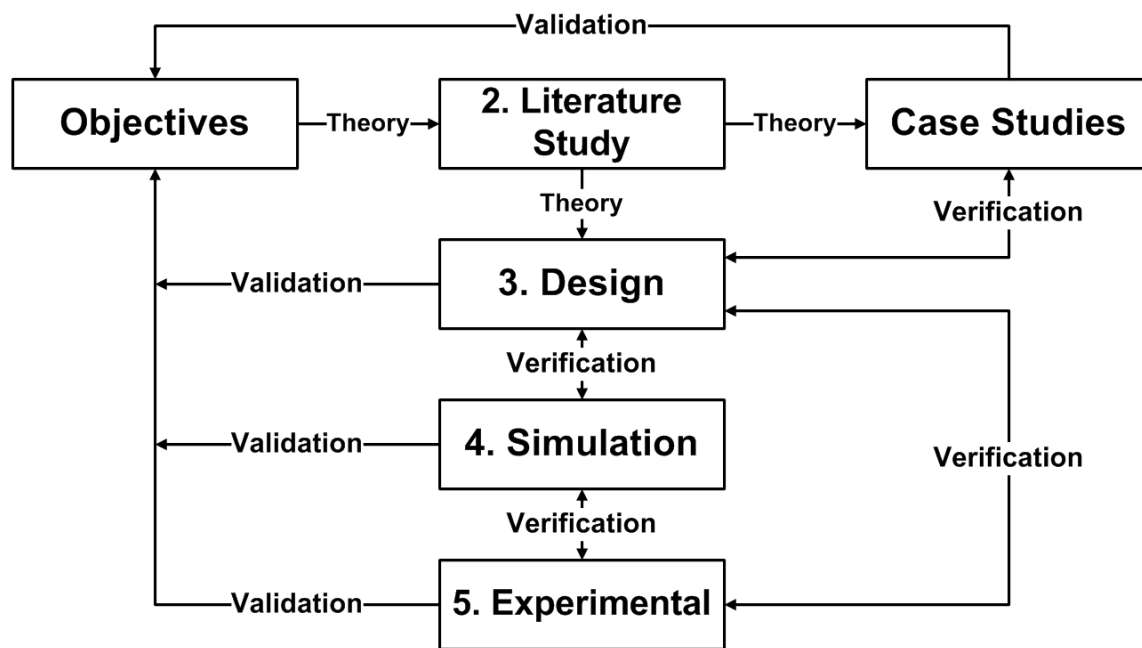


Figure 6.1: Verification and validation

## 6.5 Key Research Questions

In section 1.5.8 it was stated that the completion of this project should provide answers to two key research questions. These questions, as well as the answers, are discussed below.

- Could a controller be developed that improves the overall power capture and efficiency of a micro wind turbine?

*The findings of the simulation and experimental results indicate that a controller could be developed that improves the overall power capture of a micro wind turbine.*

- Does using a controller to improve the power capture and efficiency of a micro wind turbine make economic sense?

*The experimental results obtained during the completion of this project does not make economic sense, especially when being implemented on a micro wind turbine. This is mainly due to the high cost of the dSPACE® DS1104 controller board used during the experimental setup. It's only when the DS1104 controller board is replaced with an alternative controller that the control system will be economically viable. This is discussed more in depth in section 6.3.*

## 6.6 Recommendations for Future Work

This section provides recommendations for future work on the controller. It discusses findings made on various aspects of the controller both during the simulations and experimental implementation of the controller.

### 6.6.1 Simulations

It is advised to avoid the integrated Matlab<sup>®</sup>/Simulink<sup>®</sup> PMSM block for simulations if the experimental generator has constructional differences compared to the integrated block.

### 6.6.2 Generator

Early stage simulations have indicated a PMSG with more poles produce more power and has a higher power coefficient compared to a PMSG containing fewer poles. It would therefore be recommended to use a PMSG containing more poles if the system would be practically implemented. A generator with more poles will also reduce the cogging torque of the generator.

### 6.6.3 Capacitor

During practical implementation it was found that the smoothing capacitor following the uncontrolled rectifier has a profound effect on the performance of the controller. It was found that the capacitor type effects the performance of the controller and that ultimately removing the capacitor produces the best results. This contradicts with the simulation results as using a smoothing capacitor increases the performance of the controller. It is advised to investigate different types of capacitors and the effect they have on the controller. This was not done in order to keep the development costs of the project as low as possible.

### 6.6.4 Wind Speed

Simulation results indicate extremely low power and power coefficient levels for wind speeds under 4 m/s. It would therefore be recommended to only consider practical implementation of the controller in a area with an average wind speed exceeding 4 m/s.

### 6.6.5 Complete Controller

Future work for the project includes the development of a standalone controller of the system. This will require an in depth knowledge of programming a DSP that will make the system more cost effective and economically feasible.

## 6.7 Conclusion

This dissertation discussed the development and implementation (simulations and experimental) of a fuzzy logic controller used to improve the amount of power a micro wind turbine extracts from the incoming wind. Both the simulation and experimental results indicate an improvement in the amount of power extracted by the wind turbine.

An advantage of the developed controller is its independency on the rated power output of the wind turbine generator and could therefore also be used on larger wind turbines with the only difference being the rating of the DC-DC boost converter and adjustments made on the current and voltage sensors.

The next logical step for the controller is to design a stand-alone system which can be practically applied to micro wind turbines. This involves replacing the controller with an alternative DSP in order to reduce the pay-off period of the complete system controller.

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# Publications and Presentations

## A.1 Publications

The project was peer reviewed by the following:

- *Studentesimposium in die Natuurwetenskappe*. This is a symposium where a presentation was given on the project. The symposium consists of various students from various fields of study each presenting their work and presenting their findings between each other.
- *International Conference on Industrial and Commercial Use of Energy*. This is an international conference where the design and results of the project was given in presentation and article format. The presentation and article was published on the ICUE website and the article was published on IEEE Explore ([ieeexplore.ieee.org](http://ieeexplore.ieee.org)). Refer to the following section for the published article (or alternatively <http://ieeexplore.ieee.org/document/7605647/>).
- *SAIEE Africa Research Journal*. This is a peer reviewed research journal and is part of the South African Institute of Electrical Engineers. The journal covers research in all electrical engineering fields and is the only peer reviewed journal in the electrical engineering sector. The article was submitted and is currently under review, refer to the following section for the submitted article.

# Intelligent Controller for Improved Efficiency of Micro Wind Turbine Generators

S Botha and Prof R Gouws

**Abstract**— Due to an ever increasing demand for electricity Eskom is struggling to cope, which inevitably leads to load shedding. Although this is a minor inconvenience for residential users, the effects can be detrimental for businesses. This increases the need for alternative provision of an uninterrupted power supply. Wind energy is a viable solution for this problem as wind turbines proved to be one of the cleanest and fastest growing forms of renewable energy. Although micro wind turbines are the most common type of wind turbines used for homes, businesses, farms or other rural areas, the fundamental drawback is that the majority of these wind turbines are designed to produce maximum efficiency for only a single wind speed. The consequence of a deviation from this designed wind speed is that the overall efficiency of the wind turbine decreases. This problem can be overcome by designing an intelligent controller that allows variable speed operation of the wind turbine and therefore increases the overall efficiency of power extraction from the incoming wind. The method proposed uses a fuzzy logic controller connected to the generator that continuously adapts the rotational speed of the generator to ensure the optimal rotational speed is obtained and therefore extracts the maximum amount of energy from the wind.

**Index Terms**—Boost Converter, Fixed Pitch Wind Turbine, Matlab®/Simulink®, PMSG, Fuzzy Logic.

## 1 INTRODUCTION

Eskom is the primary electricity provider for South Africa, supplying 95% of all the electricity used in South Africa and 45% of all the electricity used in the rest of Africa. Eskom is struggling to cope with the increasing load demand, which in turn leads to load shedding. This is only a minor inconvenience for residential users but could lead to loss of income for businesses relying on electricity for their business to operate. An increasing number of residential users and businesses are seeking alternative means to provide an uninterrupted supply of power.

Wind energy is a viable solution to this problem and even Eskom investigated the feasibility of using the power of the wind to provide electricity. This was done by constructing a wind farm consisting of three different types of wind turbines at Klipheuwel in the Western Cape with a combined output capacity of 3.16 MW [1]. The three different types of wind turbines, as well as the output capacity for each type can be seen in table I [1].

Table I. Klipheuwel wind turbine output ratings [1]

| Wind Turbine | Rated Output (kW) |
|--------------|-------------------|
| Vestas V66   | 1 750             |
| Jeumont J48  | 750               |
| Vestas V47   | 660               |

The results found at the Klipheuwel wind farm inspired Eskom to create the Sere wind farm project, which is also located in the Western Cape. The wind farm consists of 46 wind turbines, each with a rated output power of 2.3 MW. The first wind turbine was erected in December 2013 and since completion in early 2015 the wind farm contributes 105.8 MW to Eskom's grid [2],[3].

It is predicted by the South African department of science and technology (DST) that the amount of power South Africa produces by means renewable energy sources will increase to 5% by 2018 [3].

## 2 WIND TURBINES

Wind turbines convert the kinetic energy of the wind into another form of energy, usually electrical energy [4],[5]. Initially wind turbines were used for pumping water or grinding grains, with the first electricity only being produced in the late 1800's [6],[7].

Using wind turbines to generate electricity have the following advantages and disadvantages (as can be seen in table II):

Table II. Wind turbine advantages and disadvantages

| Advantages                                                                                                                      | Disadvantages                                                                                                  |
|---------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|
| Wind energy is inexhaustible [8].                                                                                               | Wind turbines create low levels of noise pollution [9].                                                        |
| Wind turbines are one of the cheapest and cleanest forms of renewable energy [9],[10].                                          | Fluctuating wind speed complicates optimal power extraction from die wind [11].                                |
| Wind energy is one of the fastest growing forms of renewable energy and therefore becoming one of the most developed [11],[12]. | Wind energy is more reliable as a year to year energy source rather than a day to day energy source [11],[12]. |

Wind turbines are classified into different categories according to the amount of output power they are able to produce. Wind turbines that produce 50 kW and less are generally known as micro wind turbines [1]. These are the most common class of wind turbine used for residential and rural purposes and the majority of these types of wind turbines are designed as fixed speed wind turbines [4],[6].

This allows maximum power production only at a particular wind speed and a deviation from this wind speed will result in a decrease in efficiency for the wind turbine.

This can be overcome by developing a controller that allows variable speed operation by controlling the rotational speed of the wind turbine and therefore increase its overall efficiency.

The most common approaches to control the rotational speed of a wind turbine is to alter the angle of the blades (also referred to as pitch control) or change the alignment of

the wind turbine with regards to the incoming wind (also referred to as yaw control) [13],[14],[15]. Large wind turbines use an active control approach in order to achieve this; however using active control techniques for micro wind turbines creates mechanical and financial difficulties [14],[16]. Usually passive stall techniques are incorporated into micro wind turbines, which have lower levels of efficiency when compared to active control methods [6].

Maximum power point tracking (MPPT) is a technique that tracks the point at which the maximum power will be produced and makes the necessary adjustments to the generator's rotational speed and can be achieved by one of the following commonly used techniques [14],[17],[18],[19]:

**Optimal Torque Control (OT):** The optimal torque point is tracked by means of a predefined knowledge of the torque curve of the wind turbine [15].

**Power Signal Feedback (PSF):** The optimal power point is tracked by means of a predefined knowledge of the power curve of the wind turbine [20].

**Tip Speed Ration Control (TSR):** The generator is controlled by measuring the wind speed and using a predefined knowledge of the wind turbine characteristics in order to achieve the optimal tip speed ratio [5].

**Hill-Climb Searching (HCS):** The peak power production of the wind turbine is tracked by using a tracking algorithm and requires no predefined knowledge of the wind turbine or its characteristics [5],[20].

Permanent magnet synchronous generators (PMSG) are commonly used, especially for small scale wind turbines, due to the high levels of efficiency, reliability and robustness [14],[20]. Another advantage of using a PMSG is the ability to use a multi-pole generator that allows a direct drive system from the turbine's blades to the shaft of the generator and makes the use of a gearbox unnecessary [21]. This also lowers the overall system losses, level of maintenance and construction costs of the system [5],[22],[23],[24].

A common topology used for small scale wind turbines can be seen in figure 1 [25]. This topology consists of a direct drive, permanent magnet generator wind turbine with a full scale power converter and is becoming increasingly more popular due increasing levels of power capture [25],[26].

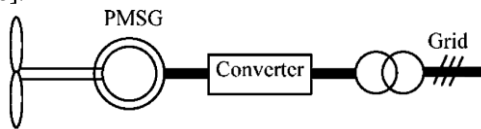


Figure 1. Common small scale wind turbine topology

## 2.1 Wind Turbine Power

The amount of aerodynamic power available for a wind turbine at any given time can be calculated using (1) [19],[22],[27],[28],[29].

$$P_{available} = \frac{1}{2} \rho \pi R^2 v^3 \quad (1)$$

With  $\rho$  the air density,  $R$  the radius of the rotor and  $v$  the velocity of the incoming wind.

The amount of mechanical power a wind turbine extracts from the incoming wind and applies to the shaft of the

generator can be calculated using (2) [22],[27],[28],[29],[30],[31].

$$P_{turbine} = \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda, \beta) \quad (2)$$

With  $C_p$  the power coefficient of the wind turbine [14],[16],[22],[27],[28],[32]. The power coefficient is the ratio between the amount of power extracted by the wind turbine and the amount of power available in the wind and can be calculated using (3) [16],[22],[27],[29].

$$C_p = \frac{P_{turbine}}{P_{available}} \quad (3)$$

The value of  $C_p$ , and therefore the amount of power the wind turbine extracts from the wind, is dependent on the tip speed ratio and the blade pitch angle of the wind turbine blades [31],[33],[34],[35].

The tip speed ratio of a wind turbine is the ratio between the speed of the tip of the blade to the speed of the incoming wind and can be calculated using (4) [22],[27],[28],[30].

$$\lambda = \frac{\omega R}{v} \quad (4)$$

With  $\omega$  the rotational speed of the wind turbine. For every wind speed there is an optimal tip speed ratio that will produce the maximum power coefficient and therefore the maximum amount of power (refer to figure 2 that displays the power coefficient vs. tip speed ratio for a fixed speed wind turbine [4]).

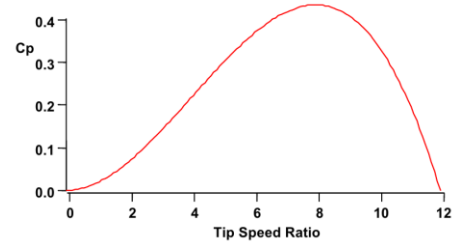


Figure 2. Power coefficient vs. tip speed ratio

For optimal efficiency, a change in the wind speed requires a change in the rotational speed in order to ensure the maximum amount of power is extracted by the wind turbine blades, which can be seen in figure 3 [36].

The value of  $C_p$  cannot exceed 0.593 as it is governed by Betz's law which states that no more than 59.3% of the energy of the incoming wind can be extracted by a wind turbine [4],[16],[31]. However; the power coefficient of a wind turbine is usually between 0.25 – 0.45 as the system experiences losses [4],[15].

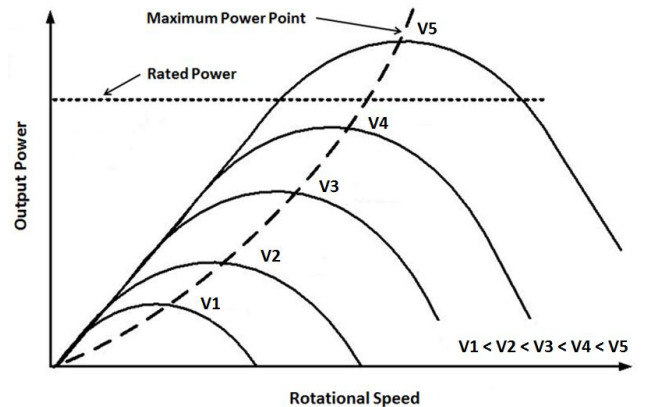


Fig. 3. Maximum power point tracking

### 3 CONTROL APPROACH

The following was done for the control of the system:

#### 3.1 Overall Control Scheme

The control system consists of a fixed pitch, direct drive permanent magnet synchronous generator (PMSG) that alters the rotational speed by using a boost converter. The speed of the wind turbine is controlled by controlling the electromagnetic torque of the generator and requires measurements of the rotational speed and the output power and alters the duty cycle of the boost converter accordingly. The overhead control strategy can be seen in figure 4.

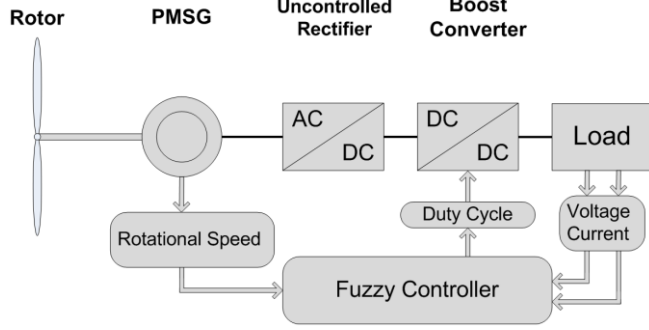


Figure 4. Overhead control strategy

#### 3.2 Wind Modelling

As discussed in 2.1 *Wind Turbine Power*, the power coefficient is a function of the tip speed ratio and the blade pitch angle. Equation (5) and (6) can be used to calculate the value of  $C_p$  for the wind turbine used in the simulation [27],[28],[30],[32],[34],[35].

$$C_p = C_1 \left( \frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6 \lambda \quad (5)$$

With  $C_1 = 0.5176$ ,  $C_2 = 116$ ,  $C_3 = 0.4$ ,  $C_4 = 5$ ,  $C_5 = 21$ ,  $C_6 = 0.0068$ . And

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (6)$$

For a fixed pitch wind turbine,  $\beta = 0$ .

The amount of aerodynamic torque is (refer to (7)) [16],[27],[28],[29],[31]:

$$T_M = \frac{P_{turbine}}{\omega} \quad (7)$$

Or

$$T_M = \frac{1}{2} \rho \pi R^3 v^2 C_T \quad (8)$$

With  $C_T$  the torque coefficient or

$$C_T = \frac{C_p}{\lambda} \quad (9)$$

Therefore:

$$T_M = \frac{\rho \pi R^3 v^2 C_p}{2\lambda} \quad (10)$$

The torque developed at a specific wind speed is calculated, using (10), by a subsystem and used as the input (in p.u.) to the PMSG and provide the rotational force.

The subsystem used to emulate the wind and provide the required torque on the shaft of the generator can be seen in figure 5.

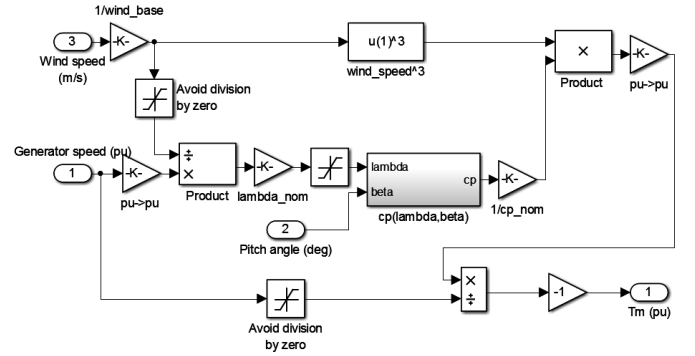


Figure 5. Wind Emulator Subsystem (Simulink)

The controller was tested during a constant wind speed of 12 m/s, as well as varying the wind speed between 6 m/s and 14 m/s (refer to figure 6 for fluctuating wind speed profile).

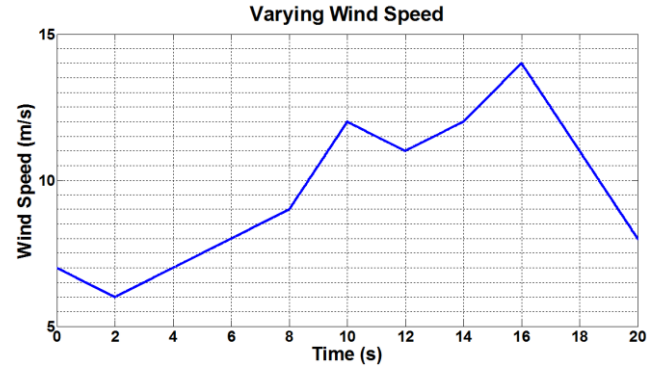


Figure 6. Fluctuating wind speed

#### 3.3 Control Methodology

The majority of controllers for wind turbines require the speed of the incoming wind. The proposed system only requires the rotational speed and power output of the generator to control the generator's speed. This technique is beneficial due to the difficulties involved obtaining exact wind speed measurements with an anemometer (due to wake rotation caused by the wind turbine) [17],[37],[38],[39],[40].

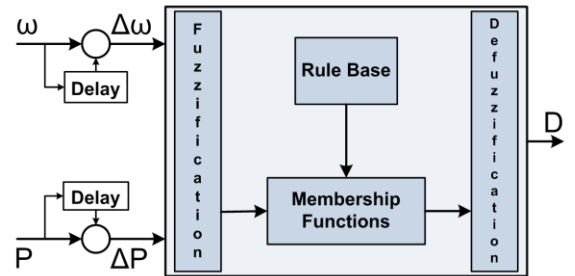


Figure 7. Fuzzy controller

The control system implements a fuzzy logic controller that measures the rate of change in both the rotational speed and power output of the boost converter. The control scheme for the controller and implementation of the controller with Matlab®/Simulink® can be seen in figure 7 and figure 8, respectively. The controller doesn't require a detailed model of the system which increases the flexibility.

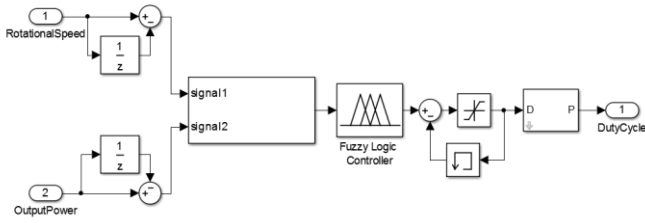


Figure 8. Controller subsystem

The fuzzy membership functions used for the two inputs (change in rotational speed and change in power) and output (duty cycle) can be seen in figure 9 and figure 10, respectively.

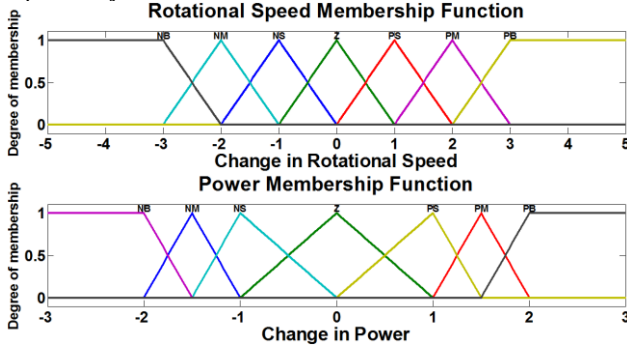


Figure 9. Input membership functions

The change in the input membership functions were chosen to be relatively large compared to the rated power and speed of the generator. This was done in order to allow for a faster change in the output power with the drawback of sacrificing accuracy. This was partially addressed by small values for the change in the duty cycle (output membership function).

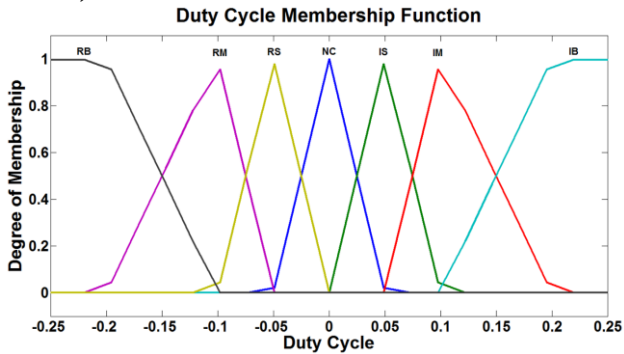


Figure 10. Output membership function

The fuzzy rules for the fuzzy logic control system can be seen in table III.

Table III. Fuzzy rules

|            |    | $\Delta\omega$ |    |    |    |    |    |    |
|------------|----|----------------|----|----|----|----|----|----|
|            |    | NB             | NM | NS | Z  | PS | PM | PB |
| $\Delta P$ | NB | IB             | IB | IM | RB | RM | RB | RB |
|            | NM | IB             | IM | IS | RM | RS | RM | RB |
|            | NS | IM             | IS | IS | RS | RS | RS | RM |
|            | 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 |

With:

**Z** – Zero                      **S** – Small                      **NC** – No Change  
**N** – Negative                  **M** – Medium                      **I** – Increase  
**P** – Positive                      **B** – Big                      **R** – Reduce

The fuzzy rules from table III yields the surface rule view, as can be seen in figure 11.

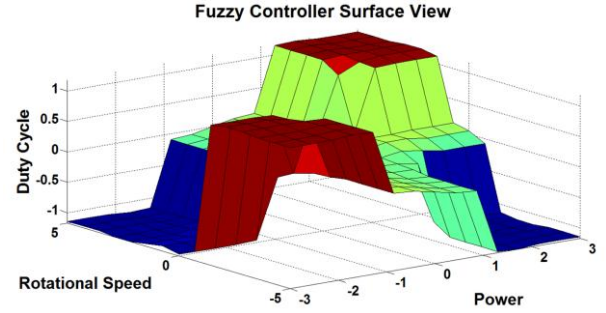


Figure 11. Fuzzy rules surface view

The fuzzy rules for the controller, as can be seen in table III and figure 11, can be summed up to the following:

- If the rotational speed increases and the power increases, increase the duty cycle.
- If the rotational speed increases and the power decreases, decrease the duty cycle.
- If the rotational speed decreases and the power increases, decrease the duty cycle.
- If the rotational speed decreases and the power decreases, increase the duty cycle.
- If there is no change in the power, keep duty cycle at current value.

The defuzzification of the system is achieved by the centre of mass method.

### 3.4 Power Converter

The controller uses a boost converter to control the rotational speed of the wind turbine at a switching frequency of 64 kHz. The general circuit layout for a boost converter can be seen in figure 12 [41],[42].

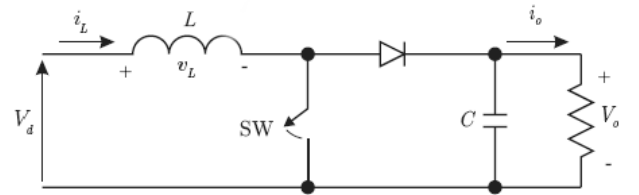


Figure 12. Boost converter

The output voltage and current can be calculated using (11) and (12) respectively [42].

$$V_o = V_d \left( \frac{1}{1-D} \right) \quad (11)$$

And

$$I_o = I_d \left( \frac{1-D}{1} \right) \quad (12)$$

With:

$L = 1.4 \text{ mH}$  and  $C = 1000 \text{ }\mu\text{F}$

### 3.5 System Parameters

The parameters of the wind turbine and generator used for the simulation in Matlab®/Simulink® can be seen in table IV and table V, respectively.

Table IV. Wind turbine parameters

| Wind Turbine                     |        |
|----------------------------------|--------|
| Rated power                      | 1 kW   |
| Base power                       | 1 kVA  |
| Base wind speed                  | 12 m/s |
| Maximum power at base wind speed | 1 pu   |
| Base rotational speed            | 1 pu   |
| Pitch angle                      | 0°     |

Table V. PMSG parameters

| Permanent Magnet Synchronous Generator |                          |
|----------------------------------------|--------------------------|
| Rated power                            | 1 kW                     |
| Rated speed (in rpm)                   | 1800 rpm                 |
| Rated speed (in rad/s)                 | 188.5 rad/s              |
| Stator resistance                      | 0.2 $\Omega$             |
| Inductance ( $L_d$ and $L_q$ )         | 8.5 mH                   |
| Flux linkage                           | 0.175 V·s                |
| Inertia                                | 0.0089 kg·m <sup>2</sup> |
| Viscous damping                        | 0.005 N·m·s              |
| Number of poles                        | 4                        |

## 4 RESULTS

The system was modelled and simulated using Matlab®/Simulink® and the following results were obtained. The graphs displayed in blue represent a PMSG with the absence of the controller and the graphs in green represent a PMSG with the controller.

### 4.1 Fixed Wind Speed

For a fixed wind speed of 12 m/s and a load of 10  $\Omega$ , the following results were obtained from with a sampling speed of 10 kHz:

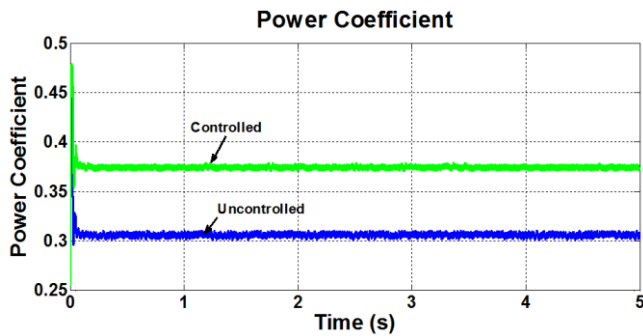


Figure 13. Fixed wind power coefficient

From figure 13 it can be seen that the controlled generator has a higher power coefficient when compared to the uncontrolled generator. The controlled generator has an average power coefficient of 0.3749 while the uncontrolled generator has an average power coefficient of 0.3064.

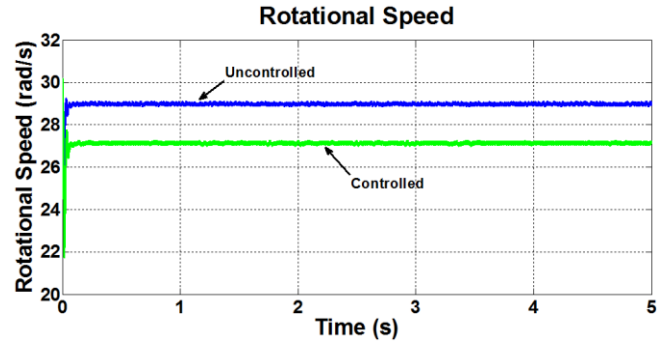


Figure 14. Fixed wind rotational speed

From figure 14 it can be seen that the controlled generator has an average rotational speed of 27.1122 rad/s while the uncontrolled generator has an average rotational speed of 28.9586 rad/s.

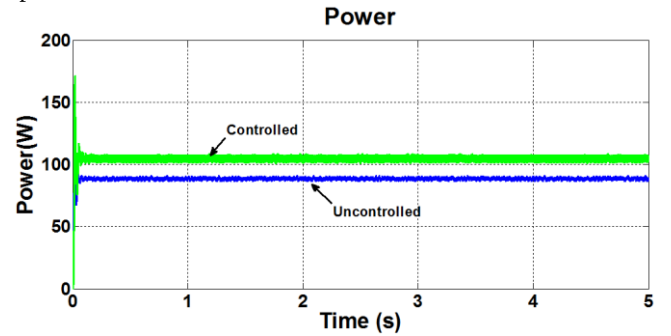


Figure 15. Fixed wind power

Figure 15 illustrates the output power of the generator and it can be seen that the controlled generator produces an average of 104.6549 W while the uncontrolled generator produces an average of 88.4794 W.

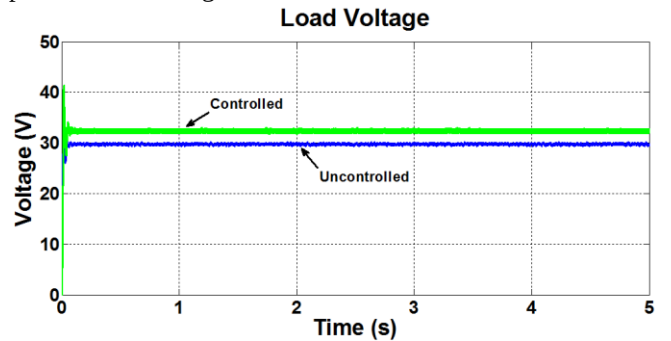


Figure 16. Fixed wind load voltage

From figure 16 it can be seen that the controlled generator produces an average of 32.3275 V while the uncontrolled generator produces an average of 29.3275 V.

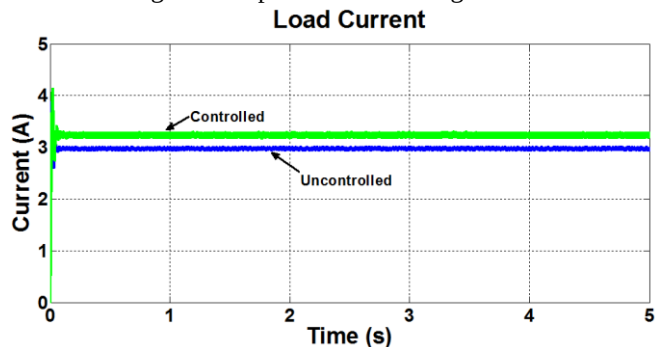


Figure 17. Fixed wind load current

From figure 17 it can be seen that the controlled generator produces an average of 3.2328 A while the uncontrolled generator produces an average of 2.9729 A.

Table VI illustrates the percentage power coefficient increase and percentage power difference between the controlled and uncontrolled generator for various fixed wind speeds. It can be seen that the overall performance of the generator is increased with the exception of a 10  $\Omega$  load at a wind speed of 6 m/s.

Table VI. Fixed Wind Speed Performance

| Wind Speed | Load            |      |                 |      |                 |      |
|------------|-----------------|------|-----------------|------|-----------------|------|
|            | 10 $\Omega$     |      | 50 $\Omega$     |      | 100 $\Omega$    |      |
|            | %C <sub>p</sub> | %P   | %C <sub>p</sub> | %P   | %C <sub>p</sub> | %P   |
| 6          | 5.5             | -1.9 | 36.5            | 28.6 | 78.0            | 63.6 |
| 7          | 11.3            | 4.7  | 37.1            | 32.4 | 76.9            | 72.6 |
| 8          | 15.0            | 9.1  | 37.6            | 35.0 | 76.7            | 79.8 |
| 9          | 17.7            | 12.6 | 38.0            | 37.0 | 76.5            | 84.5 |
| 10         | 19.9            | 15.1 | 37.6            | 37.7 | 76.9            | 88.6 |
| 11         | 21.3            | 16.9 | 37.6            | 38.5 | 75.0            | 88.6 |
| 12         | 22.3            | 18.3 | 37.9            | 39.4 | 76.4            | 92.9 |
| 13         | 39.4            | 33.3 | 38.1            | 40.2 | 77.0            | 95.3 |
| 14         | 50.2            | 42.8 | 38.1            | 40.5 | 76.8            | 95.8 |
| 15         | 56.4            | 48.9 | 37.4            | 39.9 | 76.3            | 95.9 |

#### 4.2 Fluctuating Wind Speed

The following results were obtained from Matlab®/Simulink® for a fluctuating wind speed on a load of 10  $\Omega$  and a sampling speed of 10 kHz:

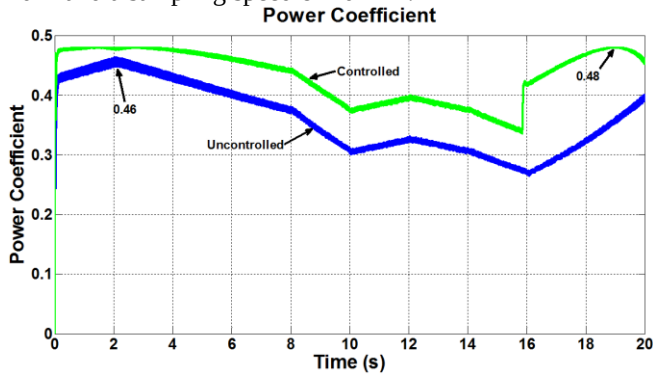


Figure 18. Varied wind power coefficient

From figure 18 it can be seen that the controlled generator has a higher power coefficient when compared to the uncontrolled generator. The controlled generator has minimum value of 0.34 and a maximum value of 0.48 while the uncontrolled generator has a minimum of 0.26 and a maximum of 0.46. The average power coefficient of the controlled generator is 0.43 while the uncontrolled generator has an average power coefficient of 0.36.

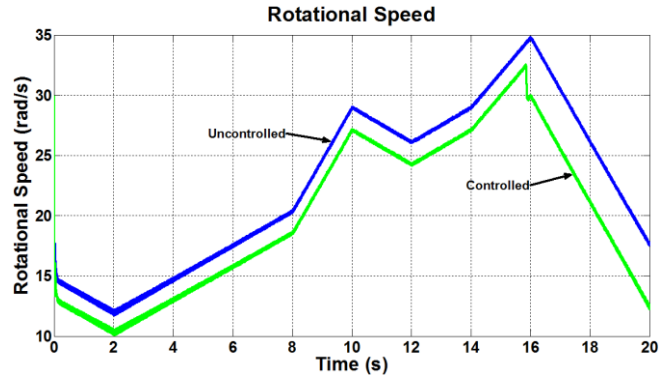


Figure 19. Varied wind rotational speed

From figure 19 it can be seen that the controlled generator has a slower rotational speed for all wind speeds when compared to the uncontrolled generator.

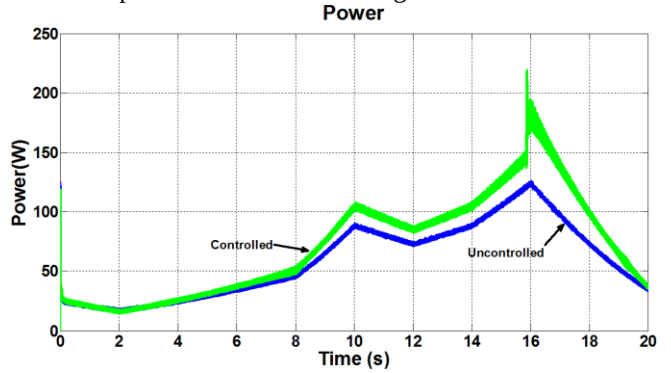


Figure 20. Varied wind power

From figure 20 it can be seen that the controlled generator produces more power than the uncontrolled generator. On average the controlled generator produces 71.7663 W while the uncontrolled generator produces 59.3348 W.

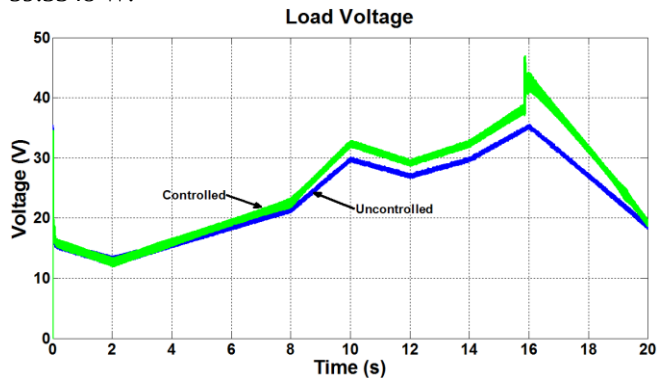


Figure 21. Varied wind load voltage

From figure 21 it can be seen that the controlled generator produces a higher voltage when compared to the uncontrolled generator. On average the controlled generator produces 25.5015 V while the uncontrolled generator produces 23.4402 V.

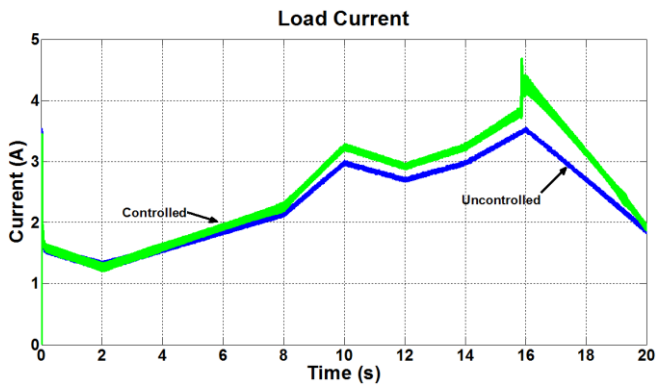


Figure 22. Varied wind load current

From figure 22 it can be seen that the controlled generator produces a higher average current when compared to the uncontrolled generator. On average the controlled generator produces 2.5502 A while the uncontrolled generator produces 2.3440 A.

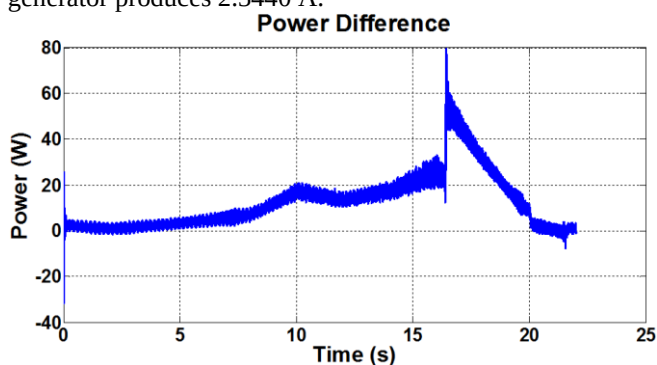


Figure 23. Fluctuating wind speed power difference

Figure 23 illustrates the difference between the power production of the controlled and uncontrolled generator. For the fluctuating wind profile the controlled generator produces an average of 12.4370 W more.

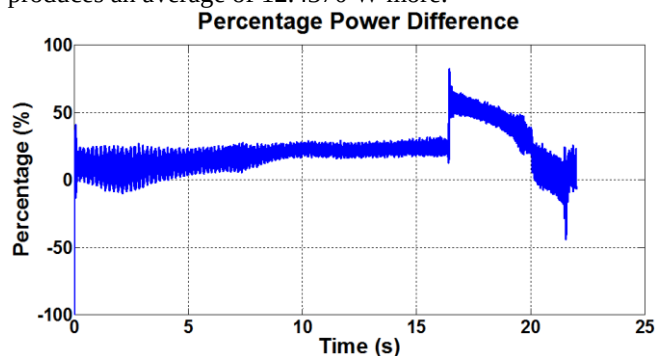


Figure 24. Fluctuating wind speed percentage power difference

Figure 24 illustrates the power difference percentage between the controlled and uncontrolled generator for the simulated fluctuating wind speed profile. For the fluctuating wind profile, the controlled generator produces an average of 21.0210% more power when compare to the uncontrolled generator.

From the above results it can be seen that the amount of power the controlled generator produces at the rated wind speed of 12 m/s is only 104.6549 W even though the generator is rated at 1 kW. This is due to the generator not rotating at its rated speed of 188.5 rad/s. This could be addressed by adding a gearbox to the system with the

drawback of additional power losses. This will result in the wind turbine blades rotating at the optimal rotational speed and the generator rotating at its rated speed.

## 5 CONCLUSION

In this paper, a controller was proposed that increases the amount of power a direct drive wind turbine extracts from the incoming wind by controlling its rotational speed. This was done by using a fuzzy logic controller that measures the change in rotational speed and change in output power delivered to the load and alters the duty cycle of a boost converter accordingly.

The controller was simulated using Matlab®/Simulink® and the results show an increase in the power coefficient for a PMSG utilising the controller when compared to a PMSG lacking the controller.

The results show that a fixed pitch wind turbine design can be altered to capture increased levels of power from the incoming wind without using complex control methods (i.e. pitch and yaw control), which increases the efficiency of the wind turbine.

## ACKNOWLEDGEMENTS

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# FUZZY LOGIC CONTROLLER FOR IMPROVED POWER EXTRACTION OF MICRO WIND TURBINES

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**Abstract:** The amount of power a wind turbine extracts from the incoming wind is dependent on the rotational speed and a change in the wind speed requires a change in the rotational speed for optimal power extraction. Micro wind turbines are designed for maximum power extraction only for a single wind speed and a deviation from this wind speed results in reduced efficiency of the wind turbine. A controller was developed that alters the rotational speed of a micro wind turbine in order to improve the power extraction from the incoming wind. Speed control is achieved by using a fuzzy logic controller that alters the duty cycle of a DC-DC boost converter. Both simulation and experimental results indicate an improvement on the amount of power captured by the micro wind turbine generator.

**Key words:** DC-DC boost converter, dSPACE®, Duty Cycle, 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, 7, 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 but a more in depth discussion of the design, as well as the simulation results, can be seen in [12].

## 2 CONTROLLER

The overhead control scheme for the controller can be seen in figure 1. The system consists of a fixed pitch, direct drive PMSG wind turbine design with a DC-DC boost converter on the output of the uncontrolled rectifier.

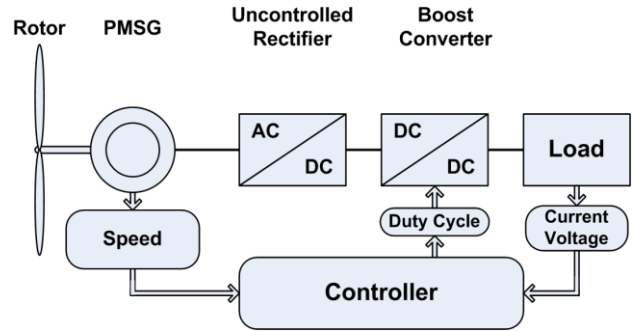


Figure 1. Overhead control scheme

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.

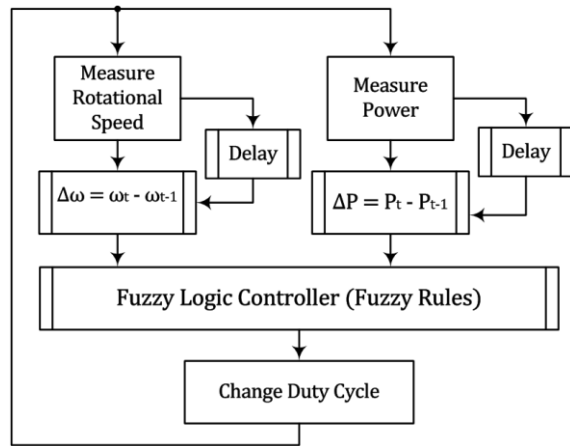


Figure 2. Overhead control approach

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.

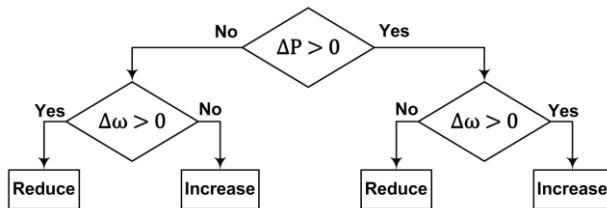


Figure 3. Detailed fuzzy logic control approach

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 function can be seen in [12]. The fuzzy rules for the 2 input membership functions of the controller can be seen in table I.

Table I. Fuzzy logic controller rules

|            |    | $\Delta\omega$ |    |    |    |    |    |    |
|------------|----|----------------|----|----|----|----|----|----|
|            |    | NB             | NM | NS | Z  | PS | PM | PB |
| $\Delta P$ | NB | IB             | IB | IM | RB | RM | RB | RB |
|            | NM | IB             | IM | IS | RM | RS | RM | RB |
|            | NS | IM             | IS | IS | RS | RS | RS | RM |
|            | 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 I 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.

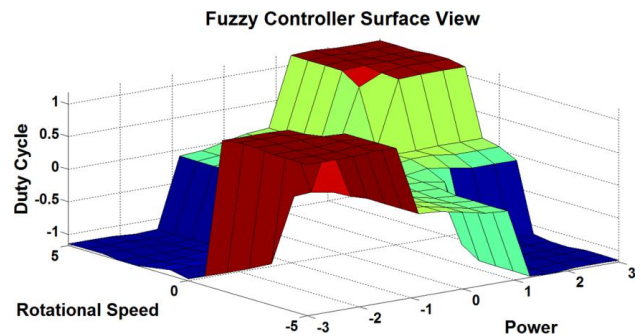


Figure 4. Fuzzy rules surface view

### 3 EXPERIMENTAL SETUP

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

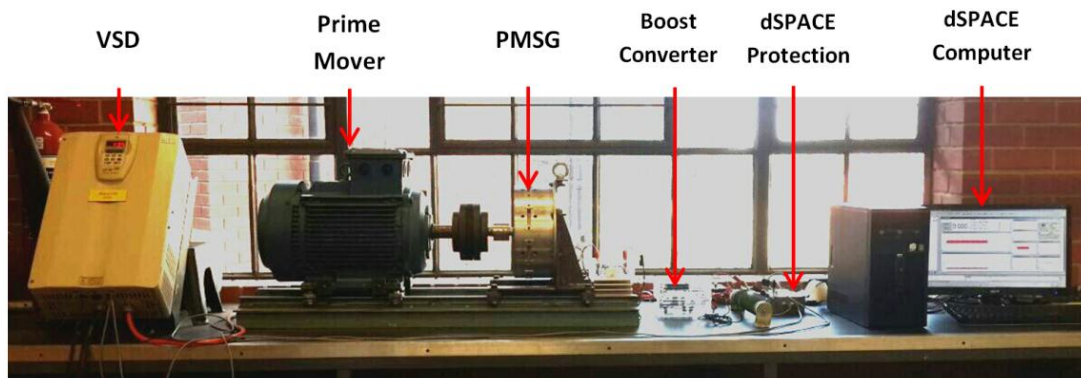


Figure 5. Complete experimental setup

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 6. dSPACE® Control Desk® experimental setup

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 adds 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.

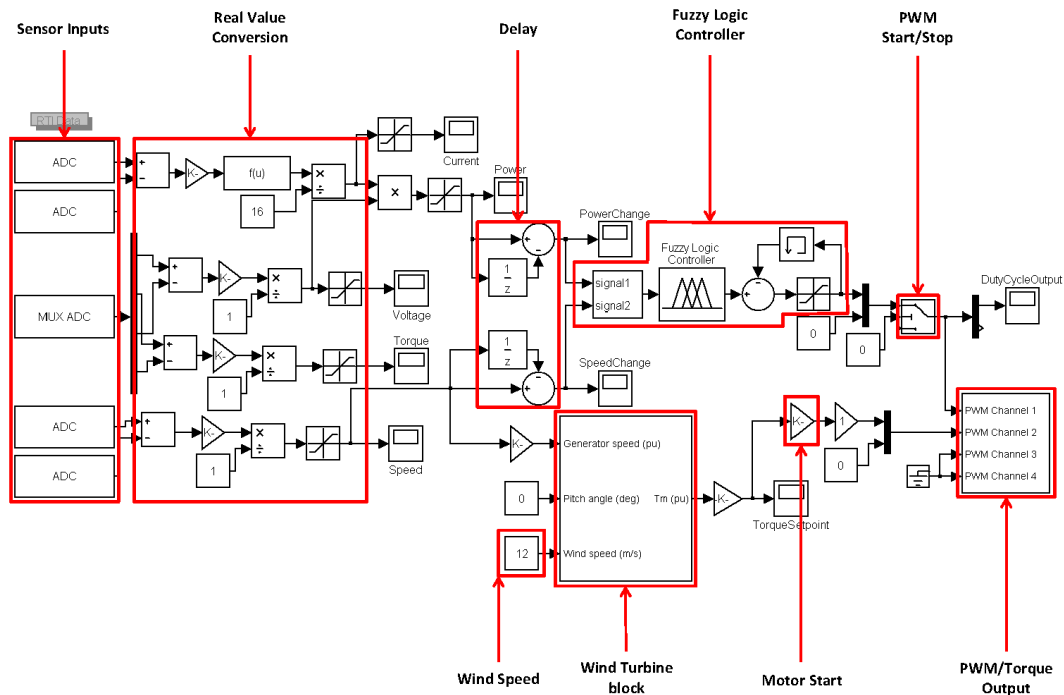


Figure 7. dSPACE® Control Desk® Matlab®/Simulink® model

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.

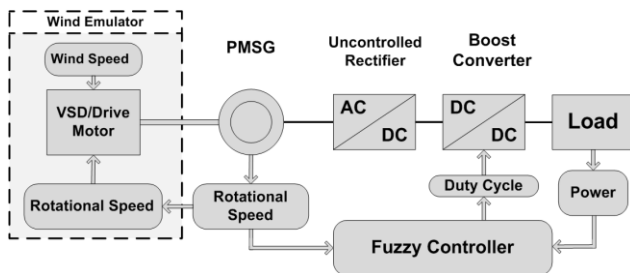


Figure 8. Prime mover blades replacement

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 [13, 14].

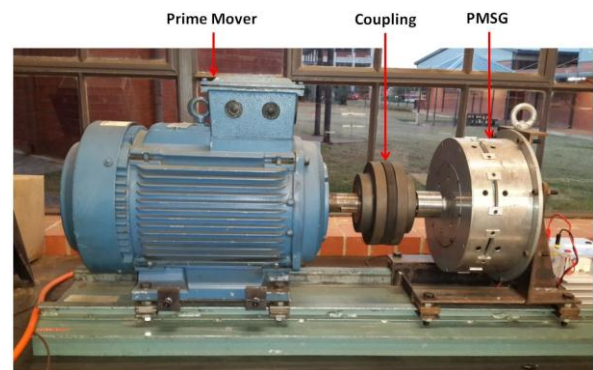


Figure 9. Prime mover and generator coupling

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.

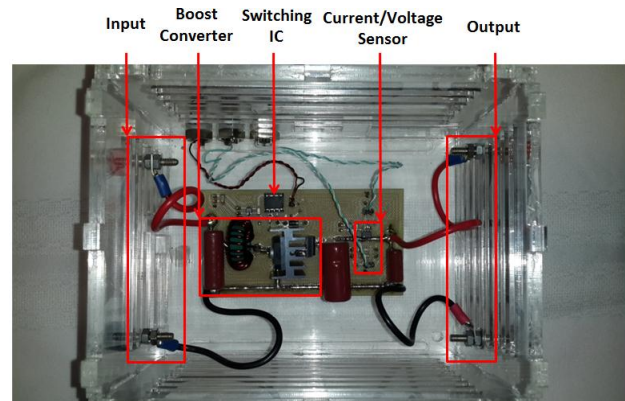


Figure 10. Experimental boost converter

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.

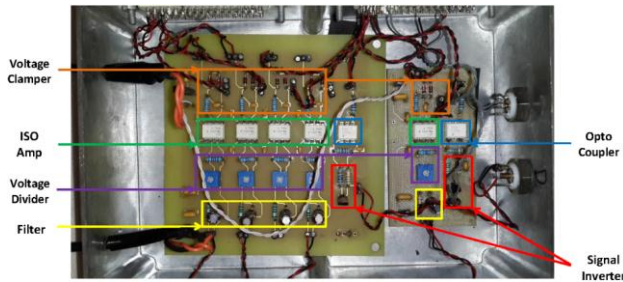


Figure 11. Experimental controller protection

#### 4 RESULTS

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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$ .

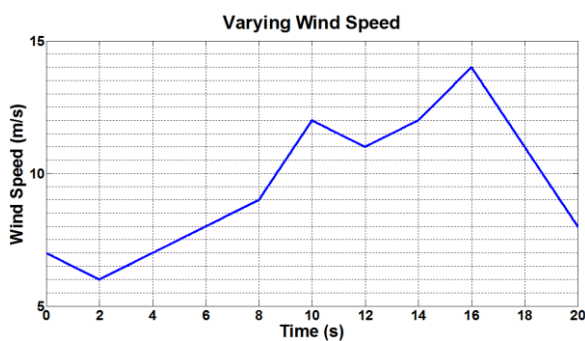


Figure 12. Fluctuating wind speed profile

##### 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 and uncontrolled generator can be seen in figure 13 at the rated wind speed of 12 m/s and a load of 30  $\Omega$ .

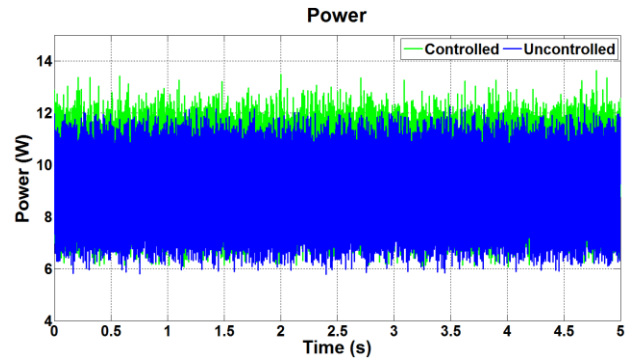


Figure 13. Experimental controlled and uncontrolled generator output power at rated wind speed

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.

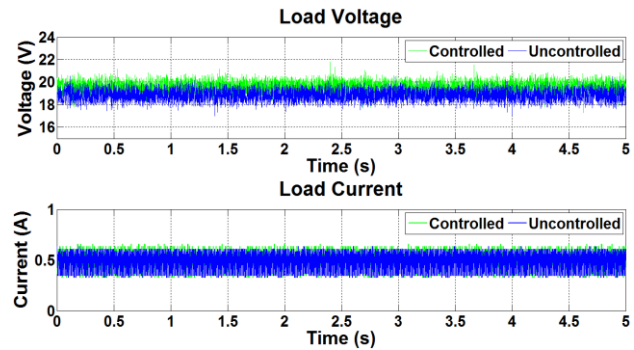


Figure 14. Experimental controlled and uncontrolled generator output voltage and current at rated wind speed

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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  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.

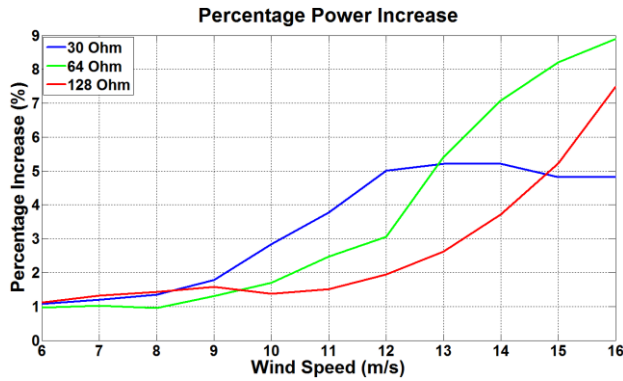


Figure 15. Experimental resistive load percentage power increase (fixed wind speed)

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  $\Omega$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  increases the amount of power by 5.01%, 3.06% and 1.94% respectively.

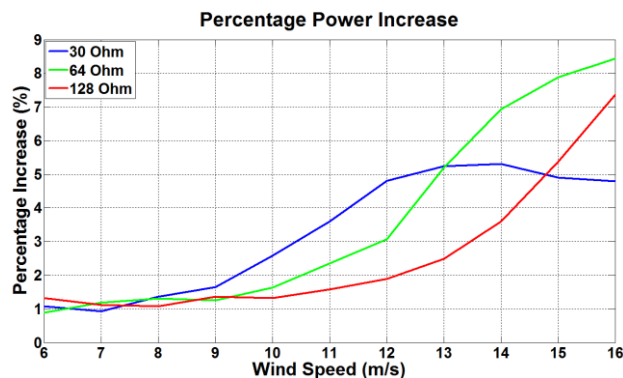


Figure 16. Experimental inductive-Resistive load percentage power increase (fixed wind speed)

**INDUCTIVE-RESISTIVE LOAD:** The controller was tested with an inductive-resistive load of 30  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  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  $\Omega$  and 64  $\Omega$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  increases the amount of power by 4.80%, 3.07% and 1.90% respectively. Table II displays the experimental percentage power increase for various wind speeds under various load conditions (both resistive and inductive-resistive).

Table II. Percentage power increase for different wind speeds under different load conditions

| Wind Speed | Load        |             |              |                     |             |              |
|------------|-------------|-------------|--------------|---------------------|-------------|--------------|
|            | Resistive   |             |              | Inductive-Resistive |             |              |
|            | 30 $\Omega$ | 64 $\Omega$ | 128 $\Omega$ | 30 $\Omega$         | 64 $\Omega$ | 128 $\Omega$ |
| 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).



Figure 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.

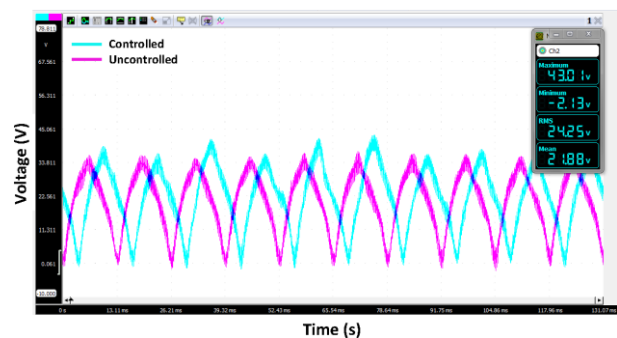


Figure 18. Experimental load voltage measurement (TiePie scope)

#### 4.2 Fluctuating Wind Speed

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).

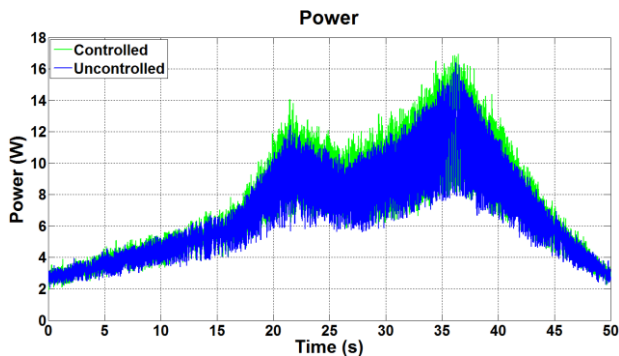


Figure 19. Experimental controlled and uncontrolled generator output power for fluctuating wind speed

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.

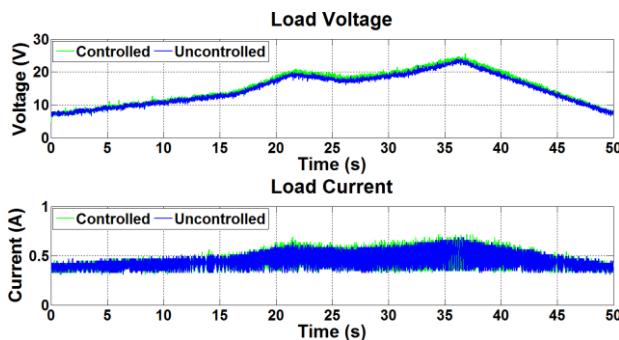


Figure 20. Experimental controlled and uncontrolled generator output voltage and current for fluctuating wind speed

**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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$ . The percentage power increase between the controlled and uncontrolled generator is 5.55%, 5.26% and 2.33% for the 30  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  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  $\Omega$ , 64  $\Omega$  and 128  $\Omega$  load, respectively.

## 5 CONCLUSION

In this paper a fuzzy logic controller is presented that improves the power capture of a micro wind turbine. The controller measures the rotational speed and output power and adds 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 controller presented in this paper has the advantages of not requiring the speed of the incoming wind as well as being independent on the rated output power of the wind turbine.

The amount of power extracted by the generator during the experimental setup is impractically low but the results indicate a percentage improvement between the controlled and uncontrolled generator and a larger generator would therefore produce practical amounts of power.

## 6 ACKNOWLEDGMENTS

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# Turnit-In Report

## B.1 Turnit-In Report

The following score was obtained for the Turnit-In report (refer to figure B.1).

| Submission Info  |                             |
|------------------|-----------------------------|
| SUBMISSION ID    | 735414227                   |
| SUBMISSION DATE  | 11-Nov-2016 12:15AM         |
| SUBMISSION COUNT | 1                           |
| FILE NAME        | ler_for_improved_efficie... |
| FILE SIZE        | 15.5M                       |
| CHARACTER COUNT  | 249615                      |
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| PAGE COUNT       | 191                         |
| ORIGINALITY      |                             |
| OVERALL          | 17%                         |
| INTERNET         | 12%                         |
| PUBLICATIONS     | 10%                         |
| STUDENT PAPERS   | 8%                          |

Figure B.1: Turnit-In report

# Folder Content

## C.1 Folder Content

The following is available on the attached DVD and Dropbox folder which is available upon request:

**Documentation** This folder consists of three sub folders. The first contains a pdf version of the submitted dissertation, the second folder contains the articles, presentations and abstracts of all the peer reviewed documentation in pdf format and the third folder contains additional design considerations and calculations.

**Schematics and PCB** This folder contains all the Altium circuit schematics and PCB layouts used throughout the project in both pdf format and the fabricated outputs within Altium.

**Datasheets and Technical Documents** This folder consists of three sub folders. The first folder contains the WEG CFW09 user manual, the second folder contains the dSPACE® DS1104 controller board user manual and the third folder contains all the miscellaneous electronics data sheets used for the project.

**Graphical Illustrations** This folder consist of two sub folders. The first folder contains additional experimental measurements of various sub systems and the second folder contains two short video clips of the experimental application of the controller. The two video clips displays the Control Desk working of the controller at the rated wind speed and the fluctuating wind speed profile.