Performance and Reliability Comparison of Grid Connected Small Wind Turbine Systems

Doctoral Thesis Defence

By

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Why renewable energy??

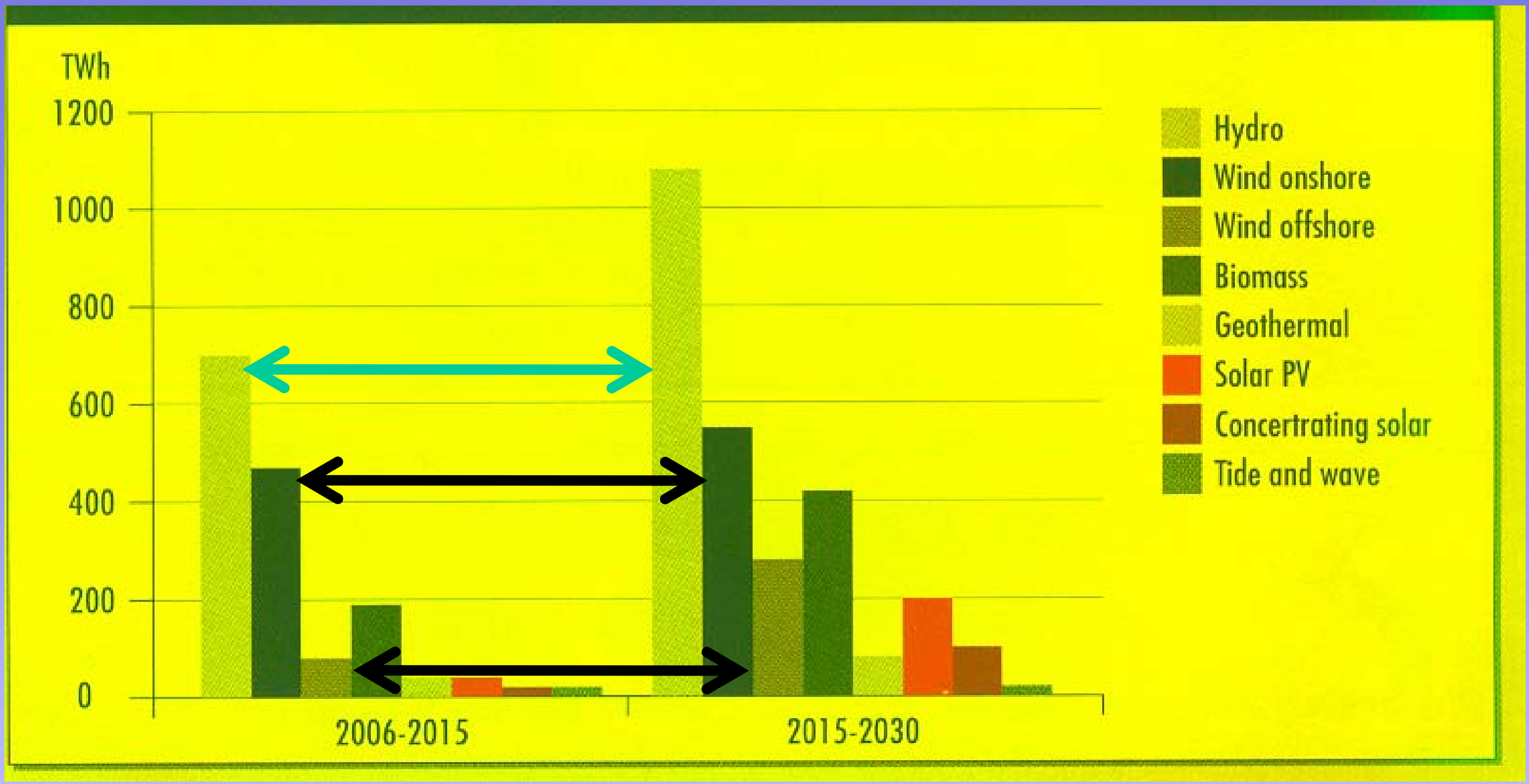
Hydro

Wind

Solar

- **Gain energy independence**
- **Reduce liability on unstable grid price**
- **Reduce air pollution and better life for future**

A Major Point of Concern



World increase in renewables [Source: International Energy Agency (IEA)]

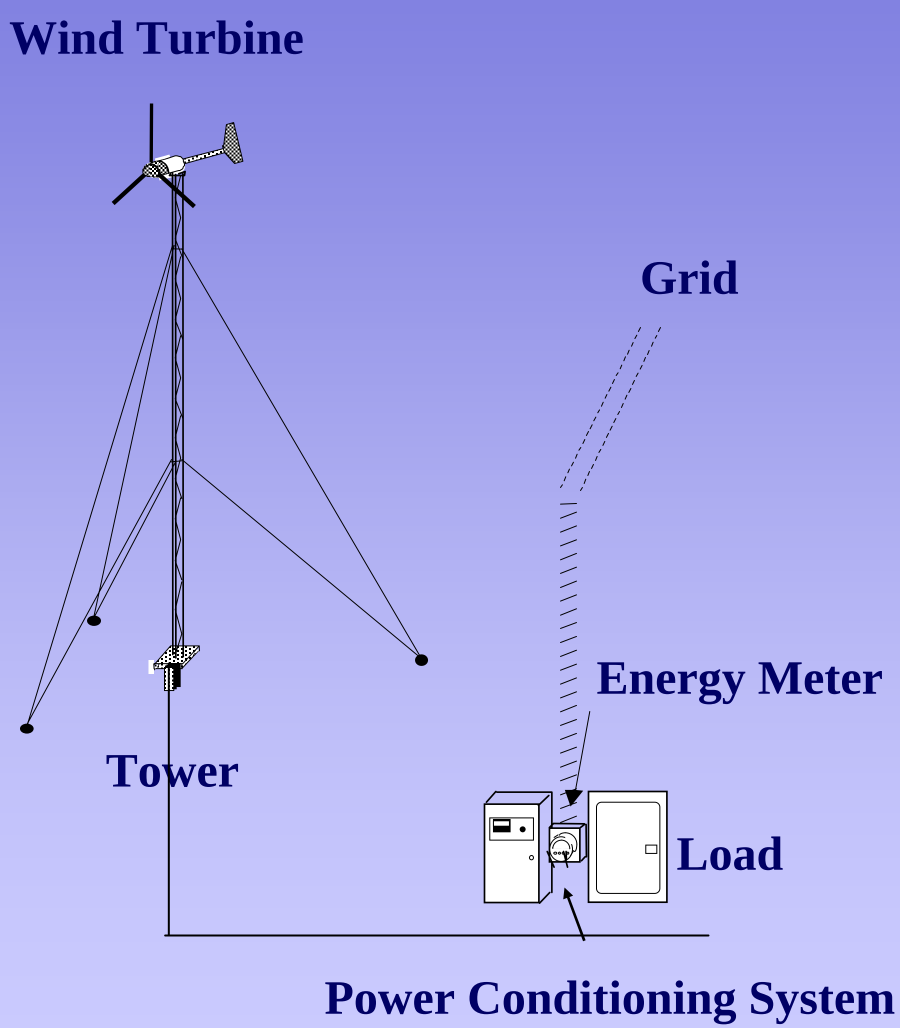
- **The expectation on hydro energy is the highest**
- **Wind energy is expected to be the second largest source of renewable energy**
- **Solar and biomass energy has good potential**

Outline

- Introduction
- Problem statement
- Approach to solve the problems
- Performance and reliability analysis
- Performance and reliability results
- Summary

Introduction

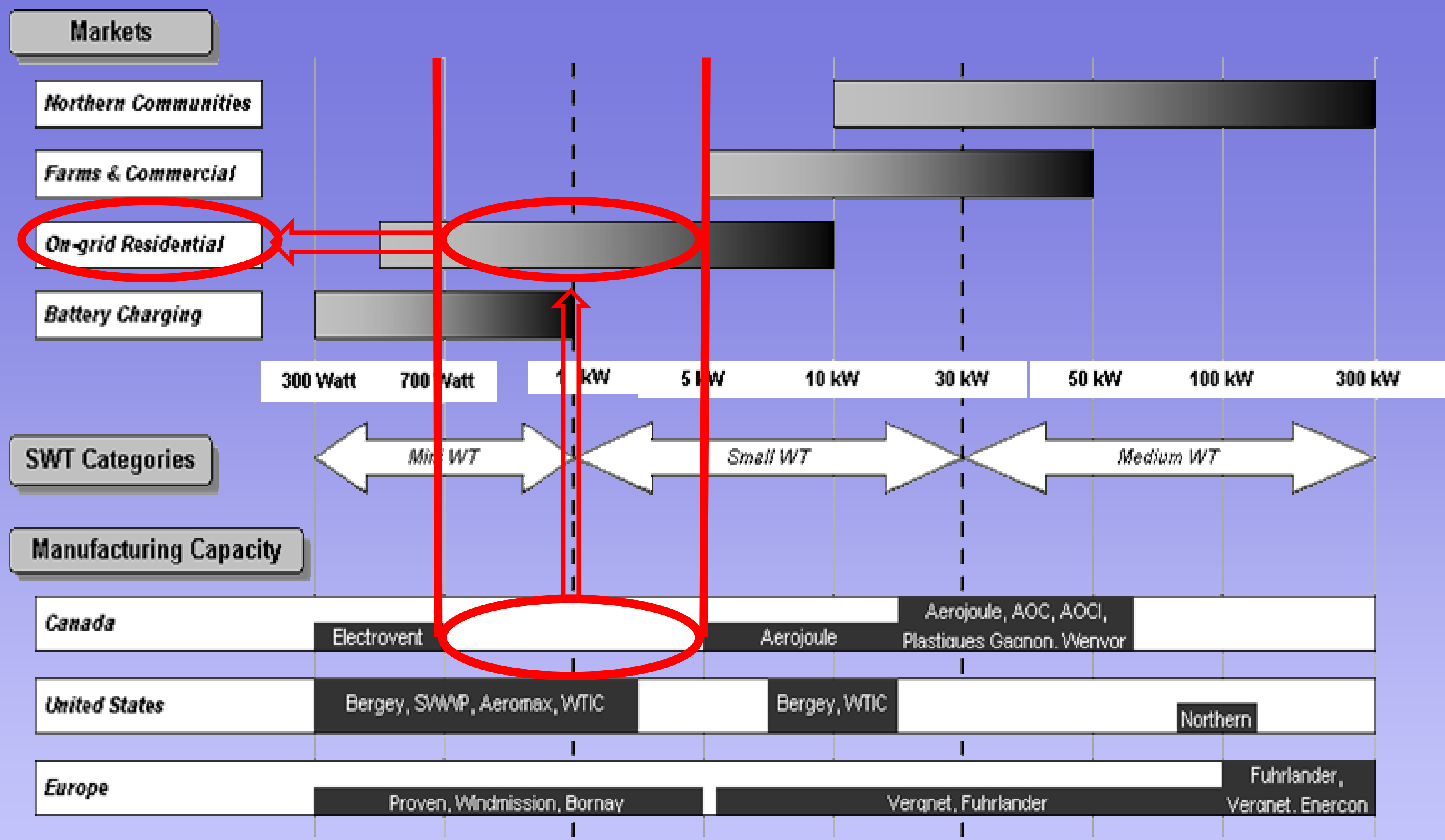
How Small Wind Turbines (SWTs) Work



Typical arrangement of a small wind turbine

Typical applications

- **To supplement the grid power**
- **To supply electricity to remote locations**
- **To reduce the use of diesel generators**



Overview of Canadian Market Demand and International SWT Manufacturing Capacity [Source: Canadian Wind Energy Association (CanWEA)]

Grid connected option has a prominent market potential in Canada

Barriers to Small Wind Turbine Systems

- **Insufficient testing**
- **High costs**
- **Zoning / Permits**
- **Lack of net metering laws**
- **Complex market with a large number of manufacturers**

Solutions to Small Wind Turbine Systems

- **Advanced airfoils**
- **Low cost manufacturing**
- **System level investigation**
- **Smart power electronics**
- **Increase in funding and research activities**

Research Objectives

• Investigate the grid connected wind turbine systems and failures of subsystems

• Develop analytical models to investigate the performance, i.e., power loss, energy capture and energy loss, and finally efficiency

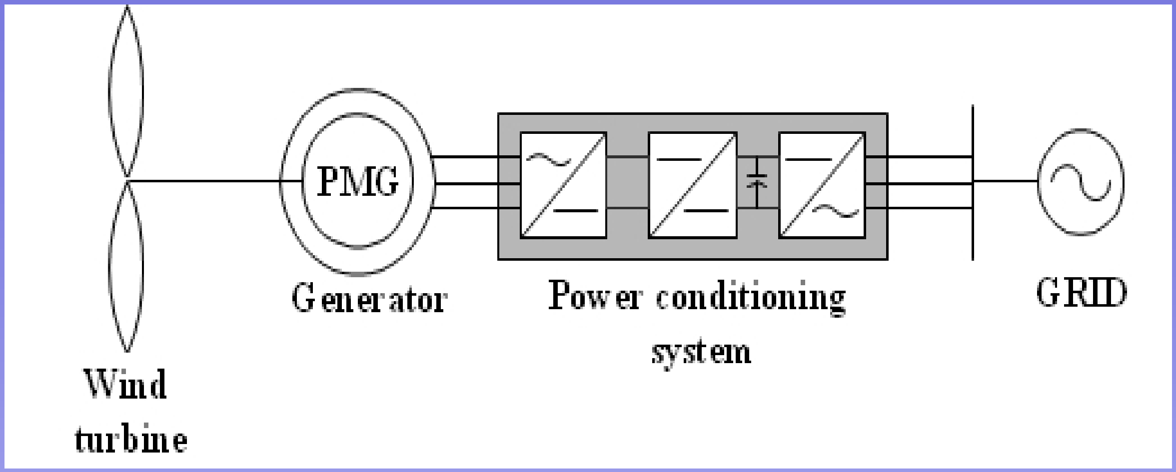
• Testing the systems to observe the performance

• Model the reliability of the power conditioning systems and determine the least reliable subsystems

• Determine an optimum alternative system

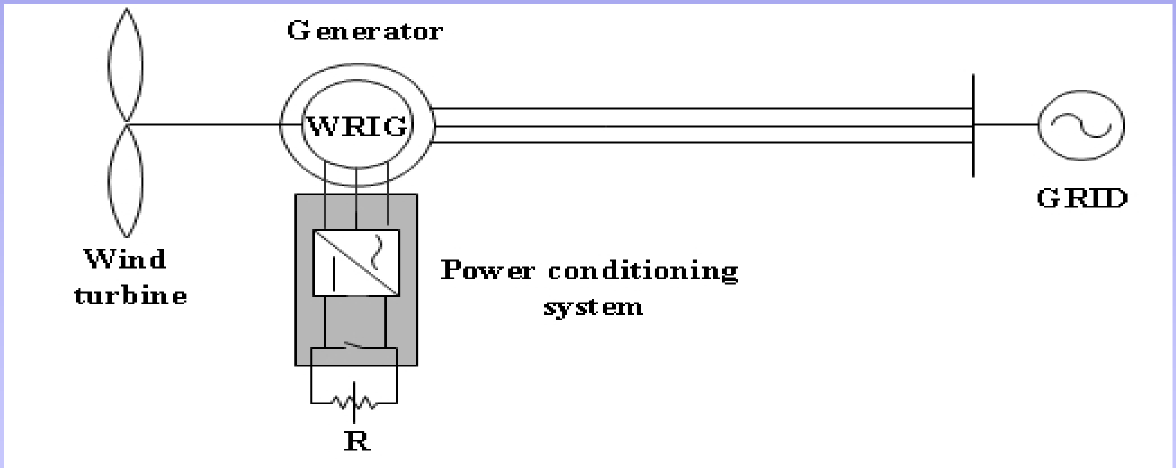
Selected SWT Systems

System 1
PMG-based system



- **Uses Permanent Magnet Generator (PMG)**
- **Power Conditioning System (PCS) consists of rectifier, boost converter and inverter**

System 2
WRIG-based system



- **Uses Wound Rotor Induction Generator (WRIG)**
- **Power Conditioning System (PCS) consists of rectifier, switch and a resistor**

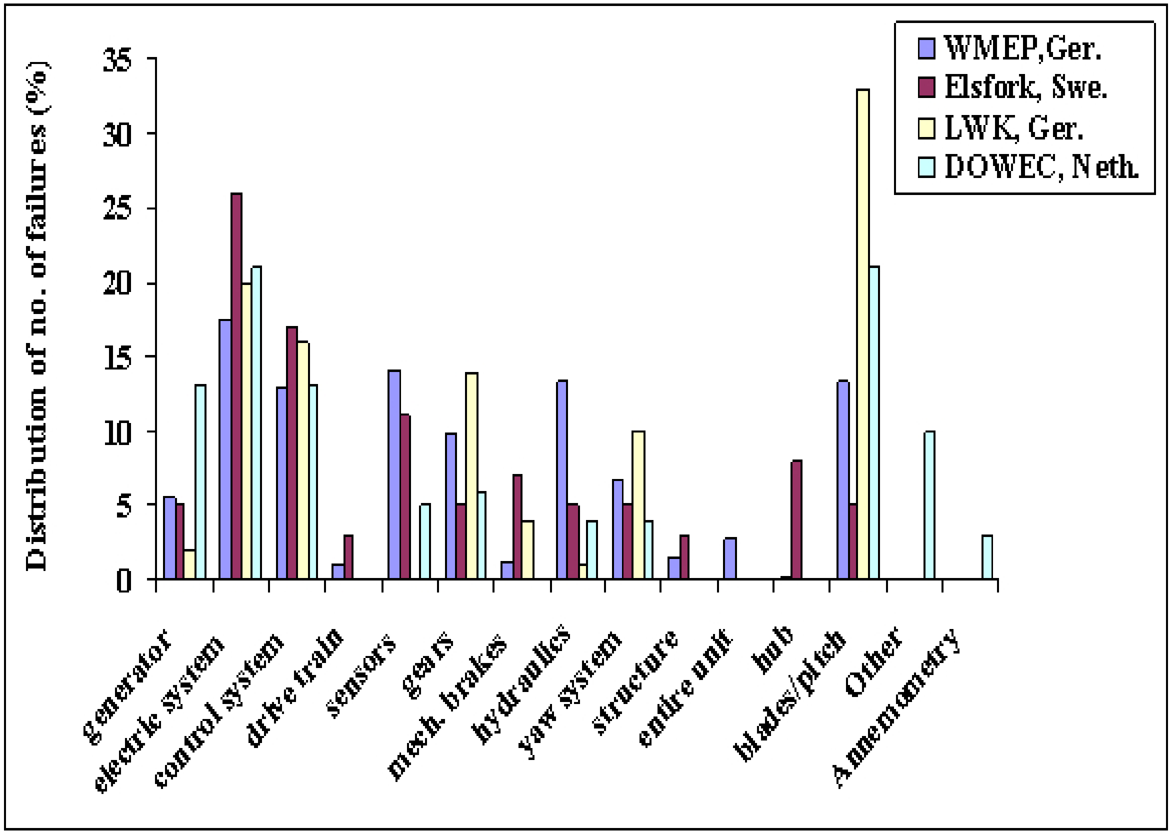
Problem Statement

- **Research is required to compare the effectiveness of any specific system**

Three influences should be explored further:

- **Influence of Electrical Subsystem**
- **Influence of Low Wind Speed**
- **Influence of Reliability**

Problem 1: Influence of Electrical Subsystem



Electrical

• Inverter, converter, fuses, Switches, circuit breakers, cables, and others.

Mechanical

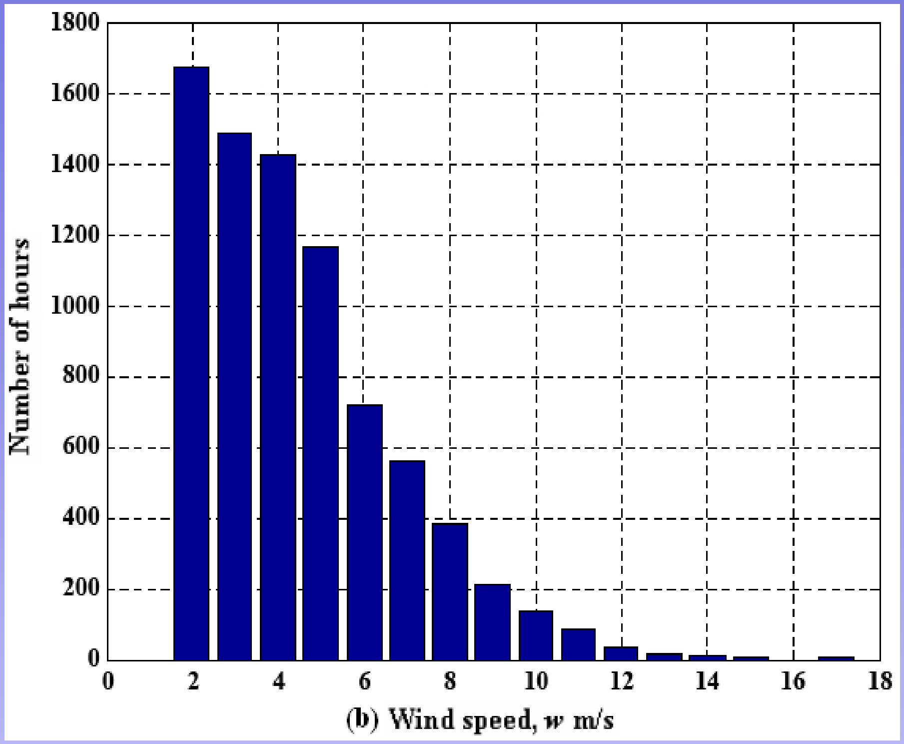
Drive train, yaw mechanism, hydraulic, rotor blade, mechanical brake, rotor hub, and others

Typical arrangement of a small wind turbine

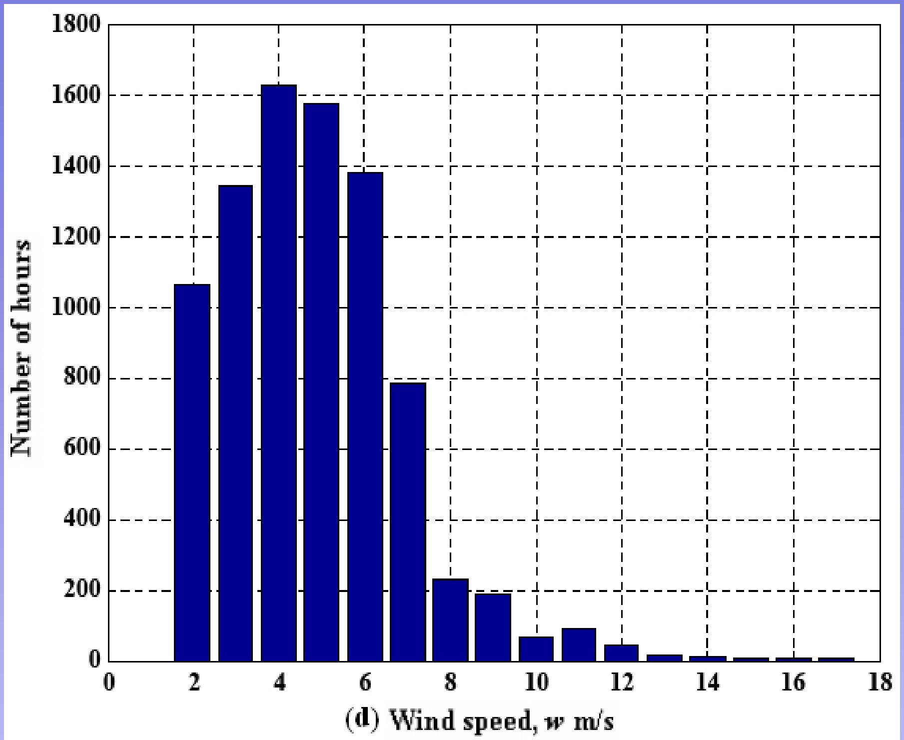
Small Wind Turbine: **Electrical subsystems failures are more than mechanical subsystems**

Large Wind Turbine: **Mechanical subsystems failures are more than electrical subsystems**

Problem 2: Influence of Low Wind Speed



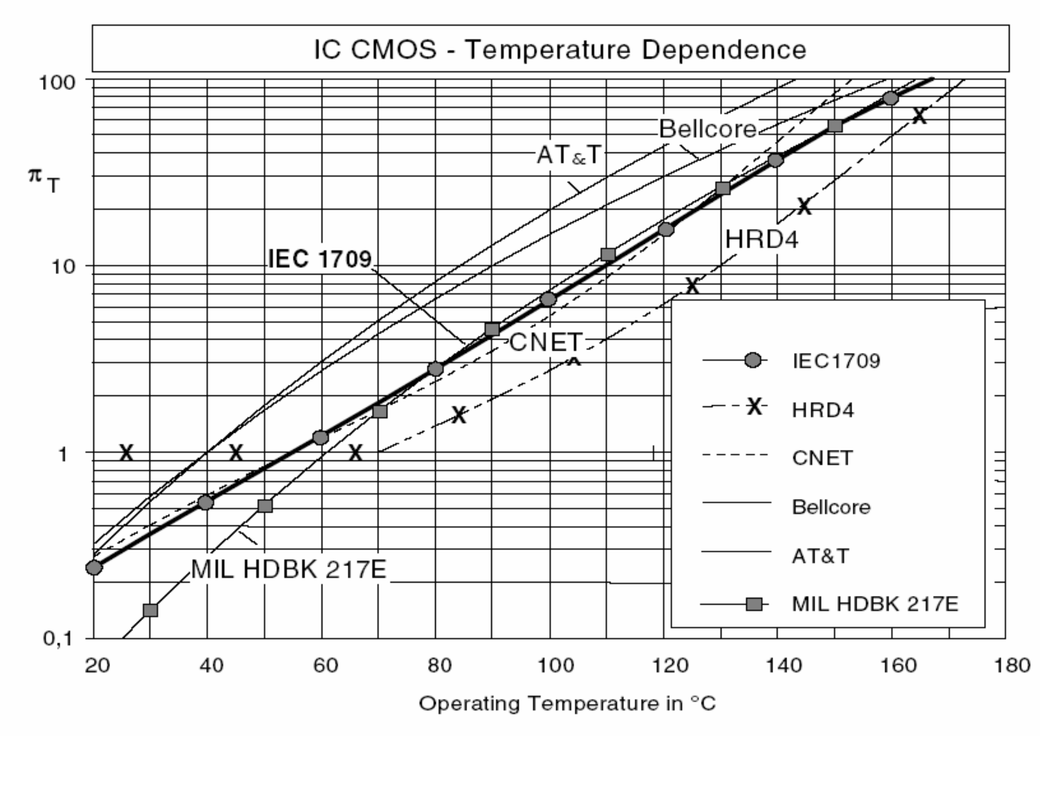
Yearly wind distribution of Ramea



Yearly wind distribution of St. John's

- **Low wind speed is more frequent than high wind speed**
- **Low wind speed carry 20% of total wind energy on a yearly basis based on a typical Eastern Canada wind pattern [Huang *et. al. (2000)*]**
- **A small wind turbine mostly operates at low wind speed [Erickson *et. al. (2004)*]**

Problem 3: Influence of Reliability

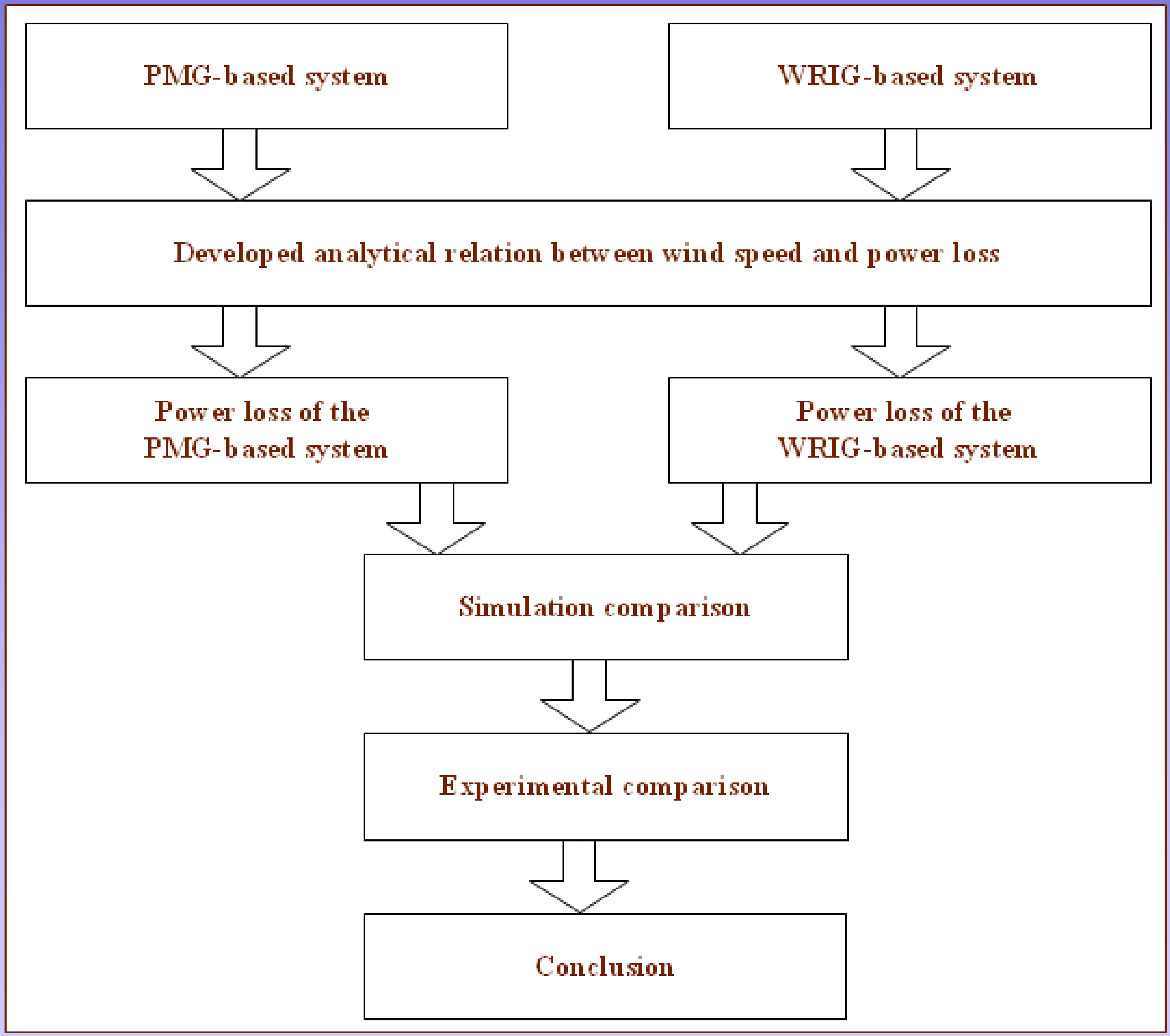


Variation of IC reliability with various handbooks (EPSMA *et. al. (2005)*)

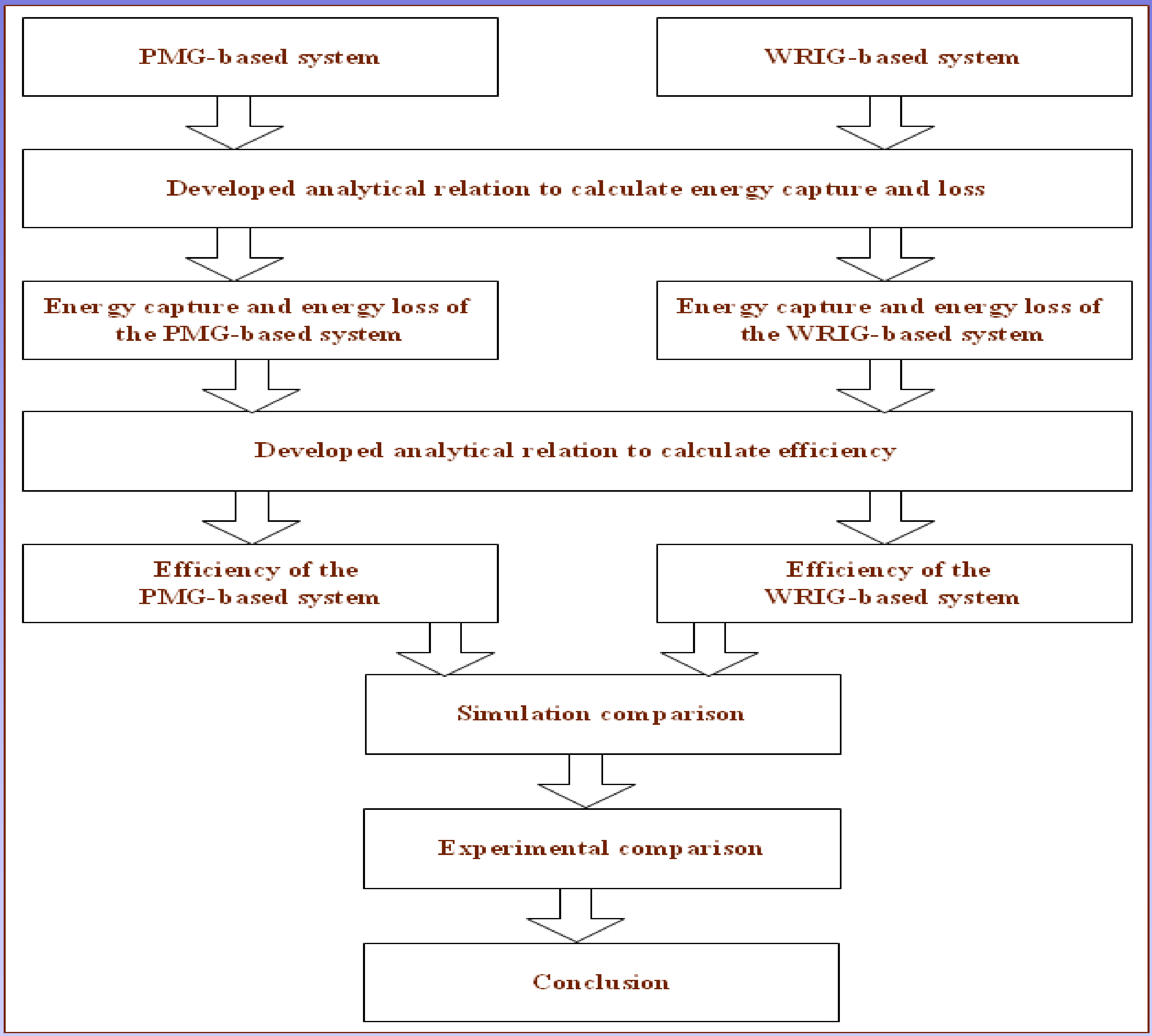
- **Reliability should be a major concern before installment of a system**
- **Electronics reliability calculations are dependent on standard reliability handbooks**

Approach to Solve the Problems

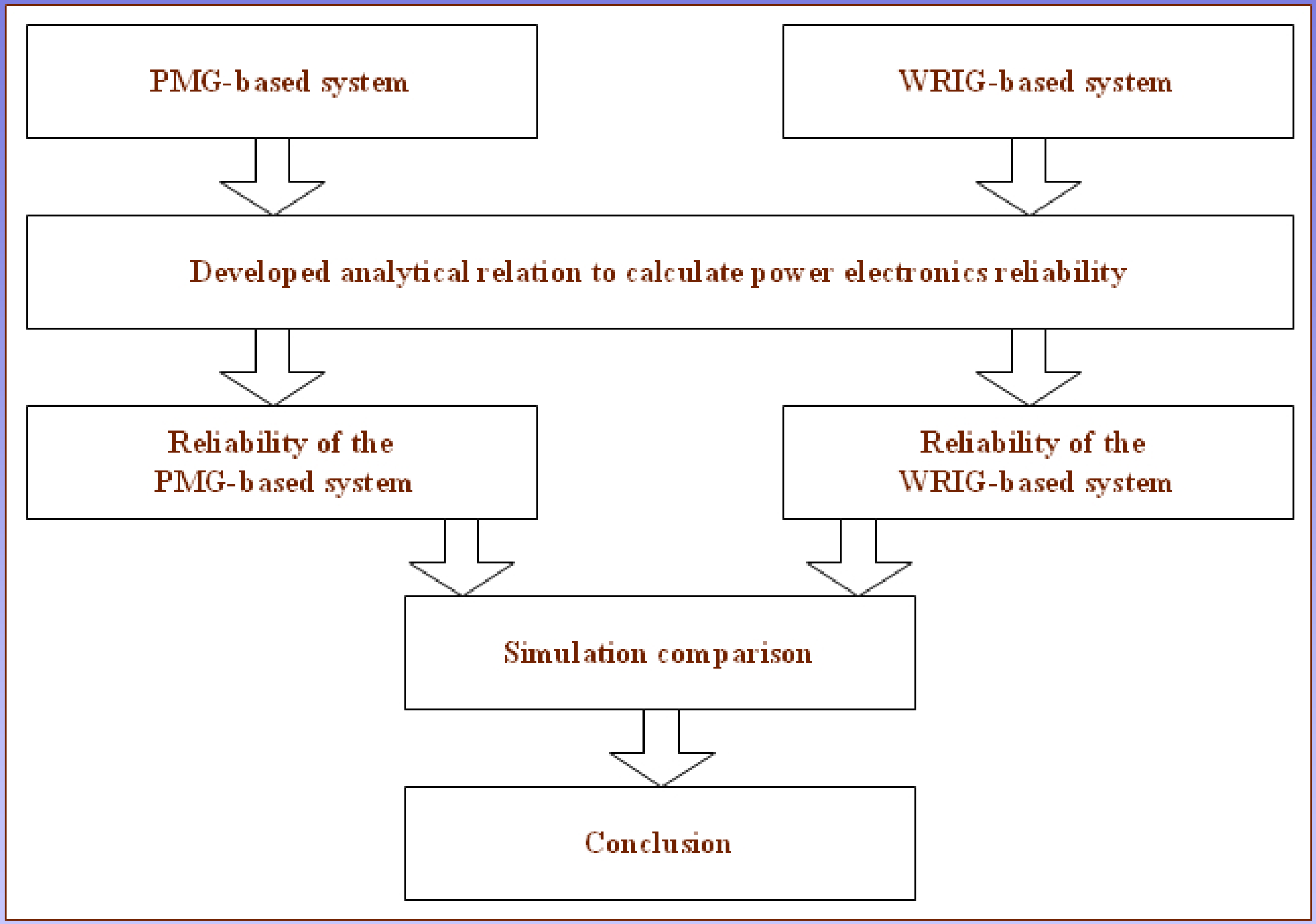
Approach for Problem 1: Analysis of power loss in power electronics



Approach for Problem 2: Analysis of energy capture, energy loss and efficiency



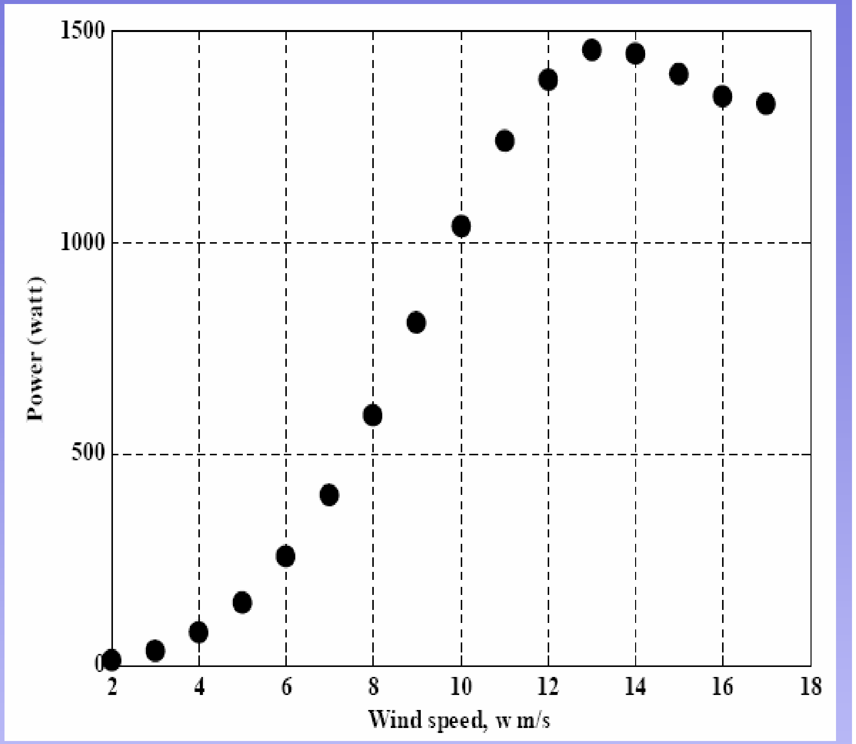
Approach for Problem 3: Analysis of power electronics reliability



Performance Analysis

Small Wind Turbine system

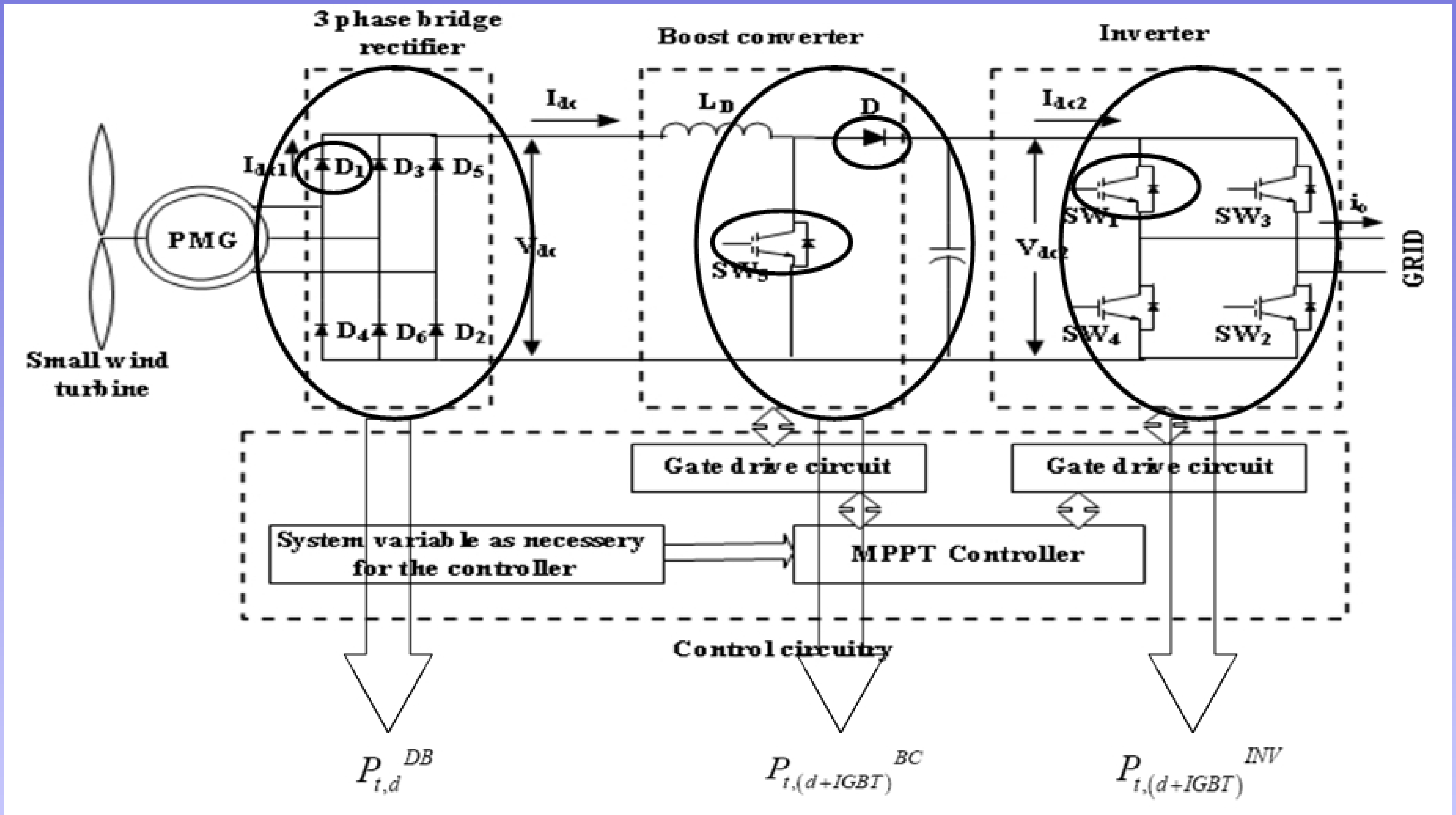
A typical 1.5 kW small wind turbine



Power curve of the small wind turbine

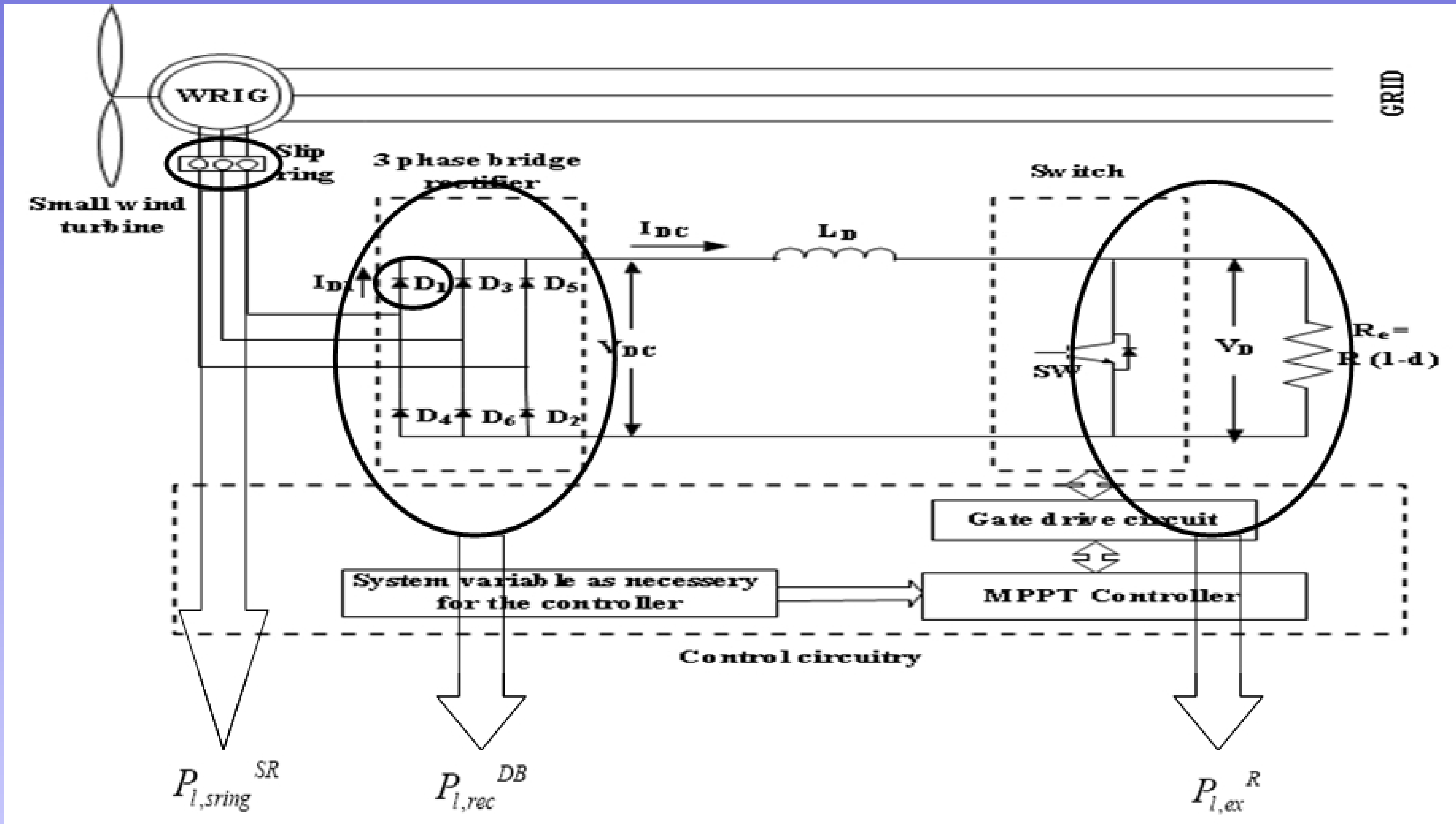
- **Wind turbine operates at optimum tip-speed-ratio**
- **Furling control activates after rated wind/rotor speed**
- **Wind turbine produce optimum power at each wind speed**

Grid Connected PMG-based system



- **Conduction and switching losses of each semiconductor device**
- **Total loss = rectifier loss + boost converter loss + inverter loss**

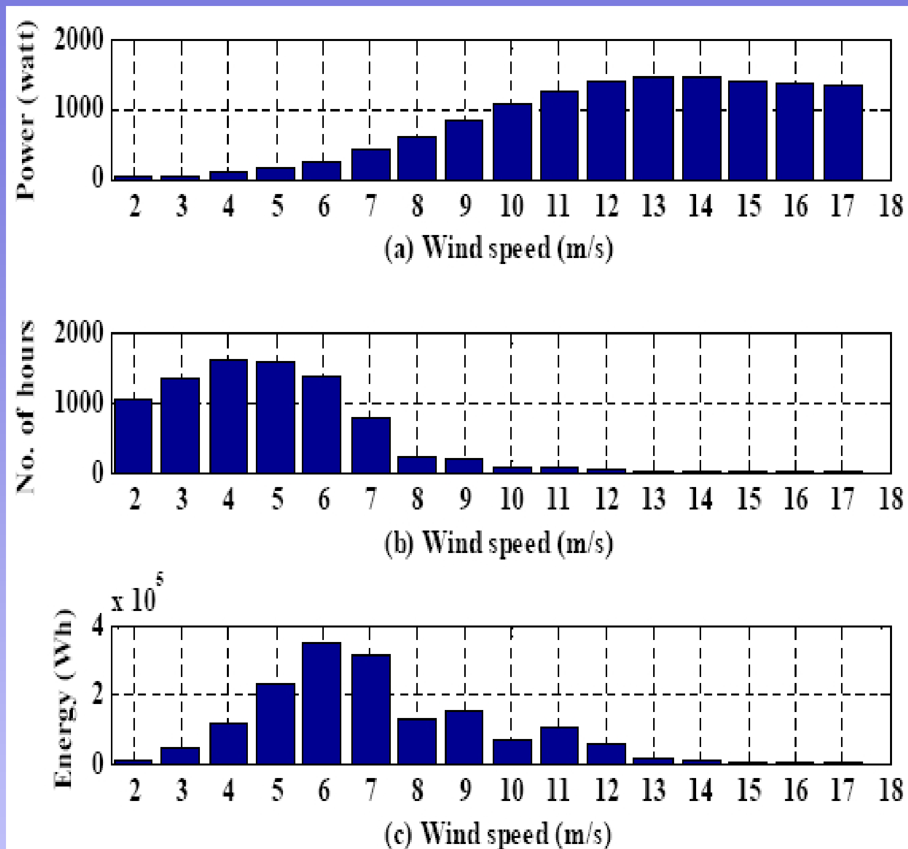
Grid Connected WRIG-based system



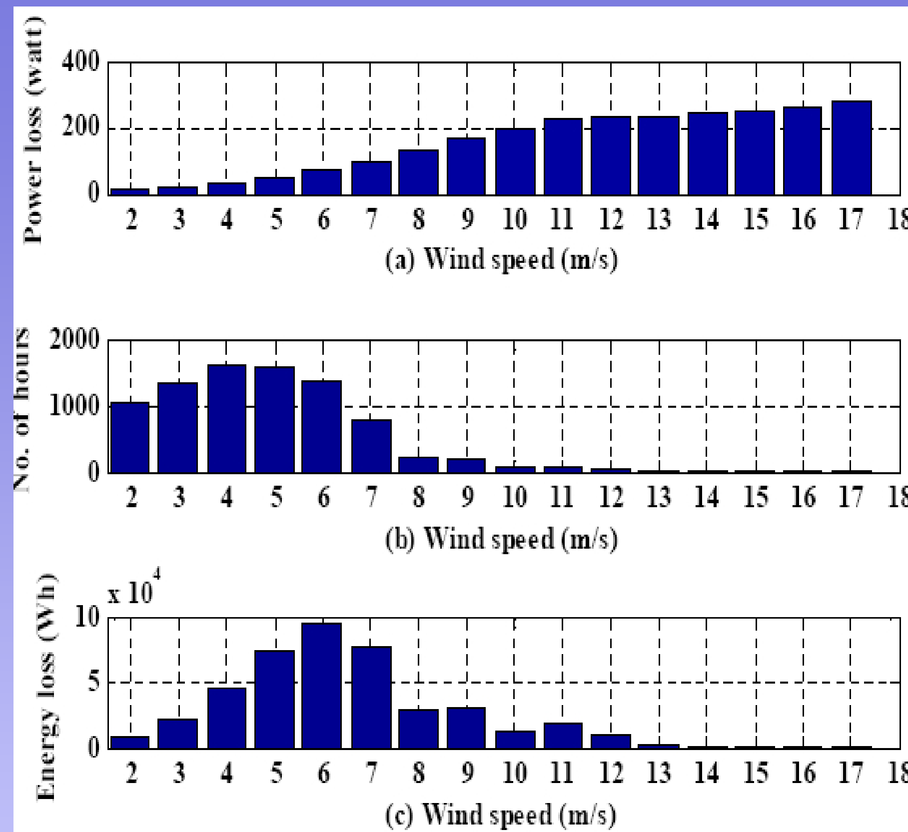
• **Conduction and switching losses of rectifier, electrical and frictional loss of slipring and resistive loss of resistor**

• **Total loss = slipring loss + rectifier loss + resistance loss**

Efficiency calculation



Energy capture

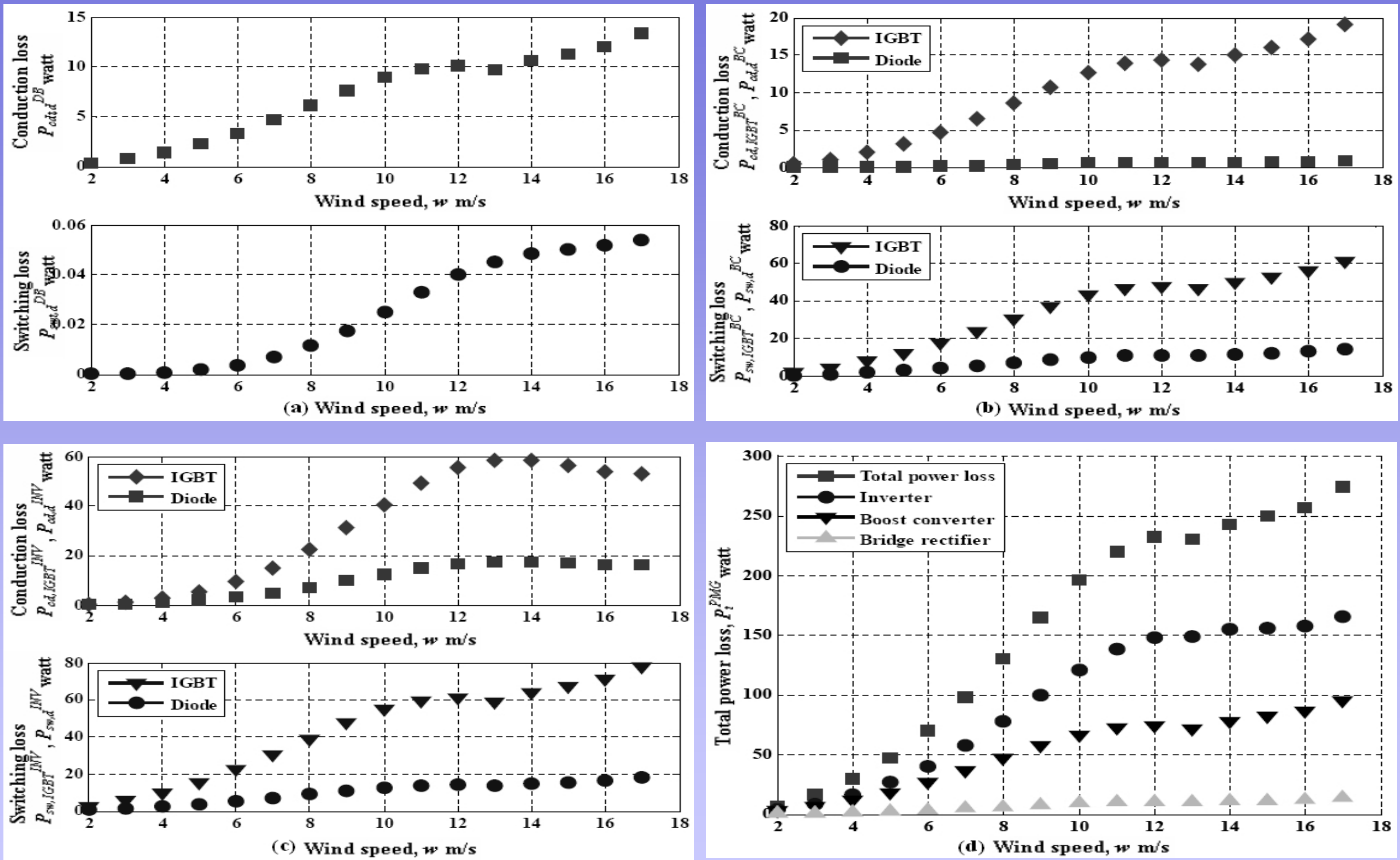


Energy loss

$$\text{Efficiency} = \frac{\text{Energy capture} - \text{Energy loss}}{\text{Energy capture}} \times 100\%$$

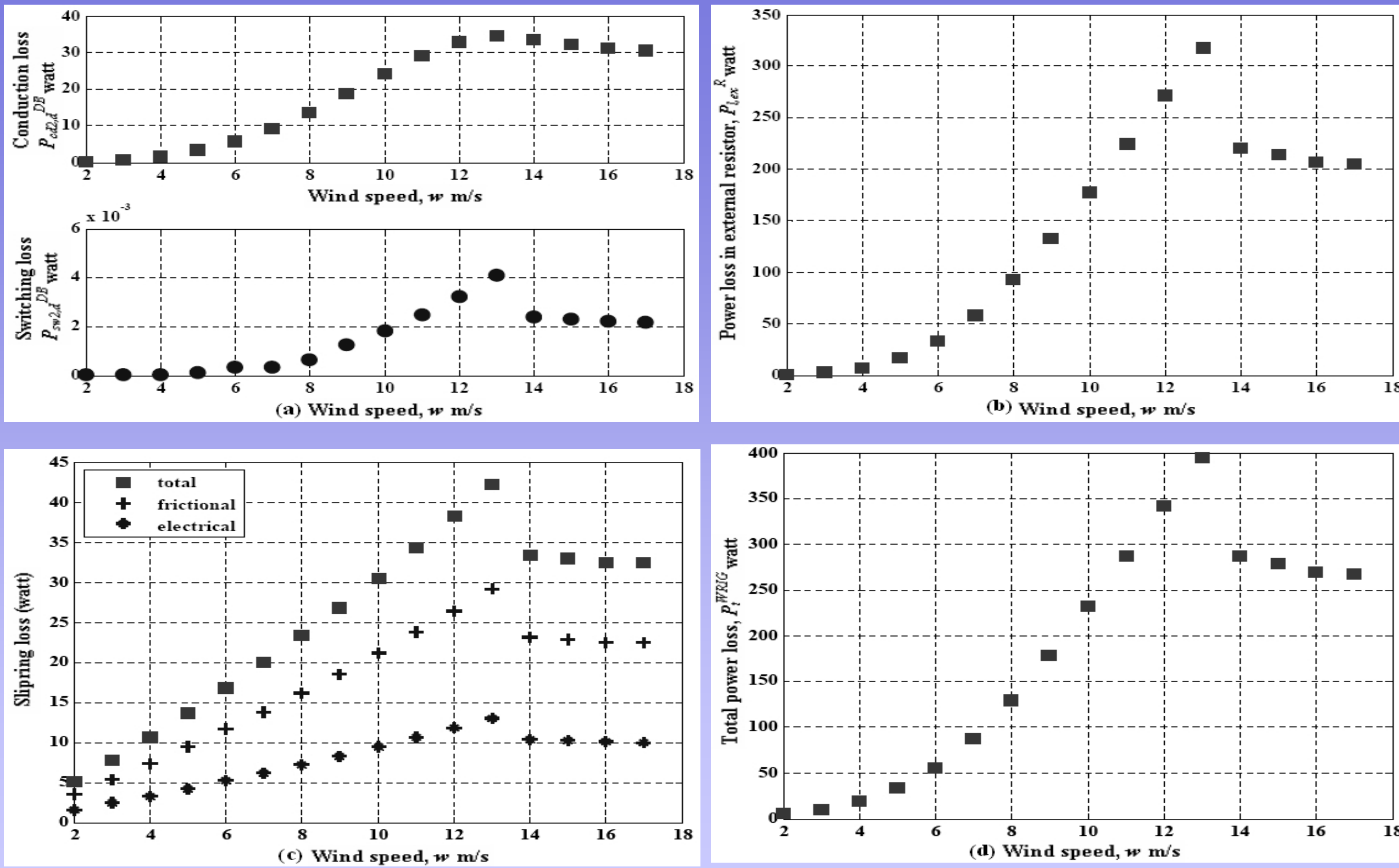
Performance Results

Power loss of the PMG-based system



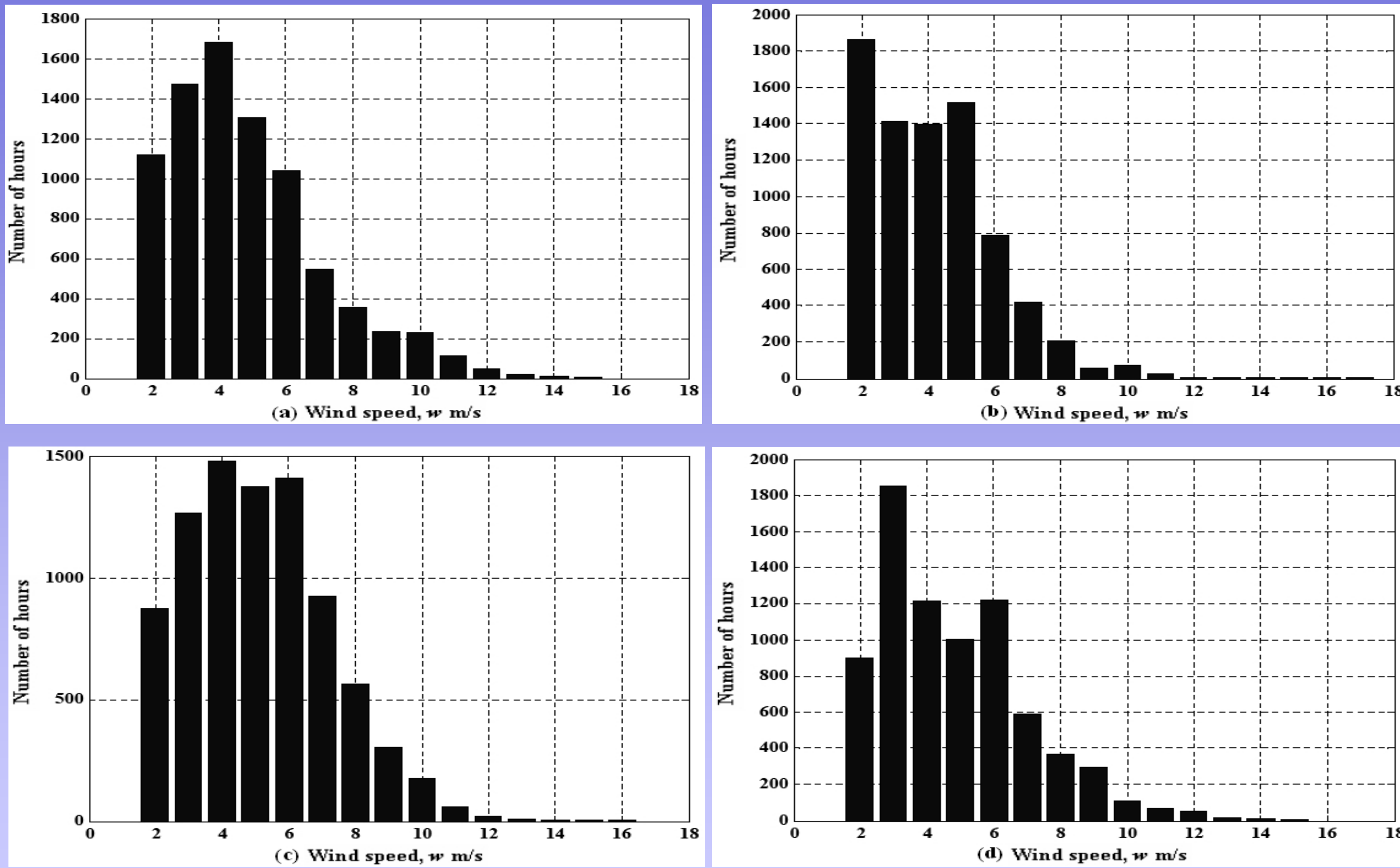
Conduction and switching losses for a) rectifier, b) boost converter, c) inverter, d) total power losses of the PCS

Power loss of the WRIG-based system



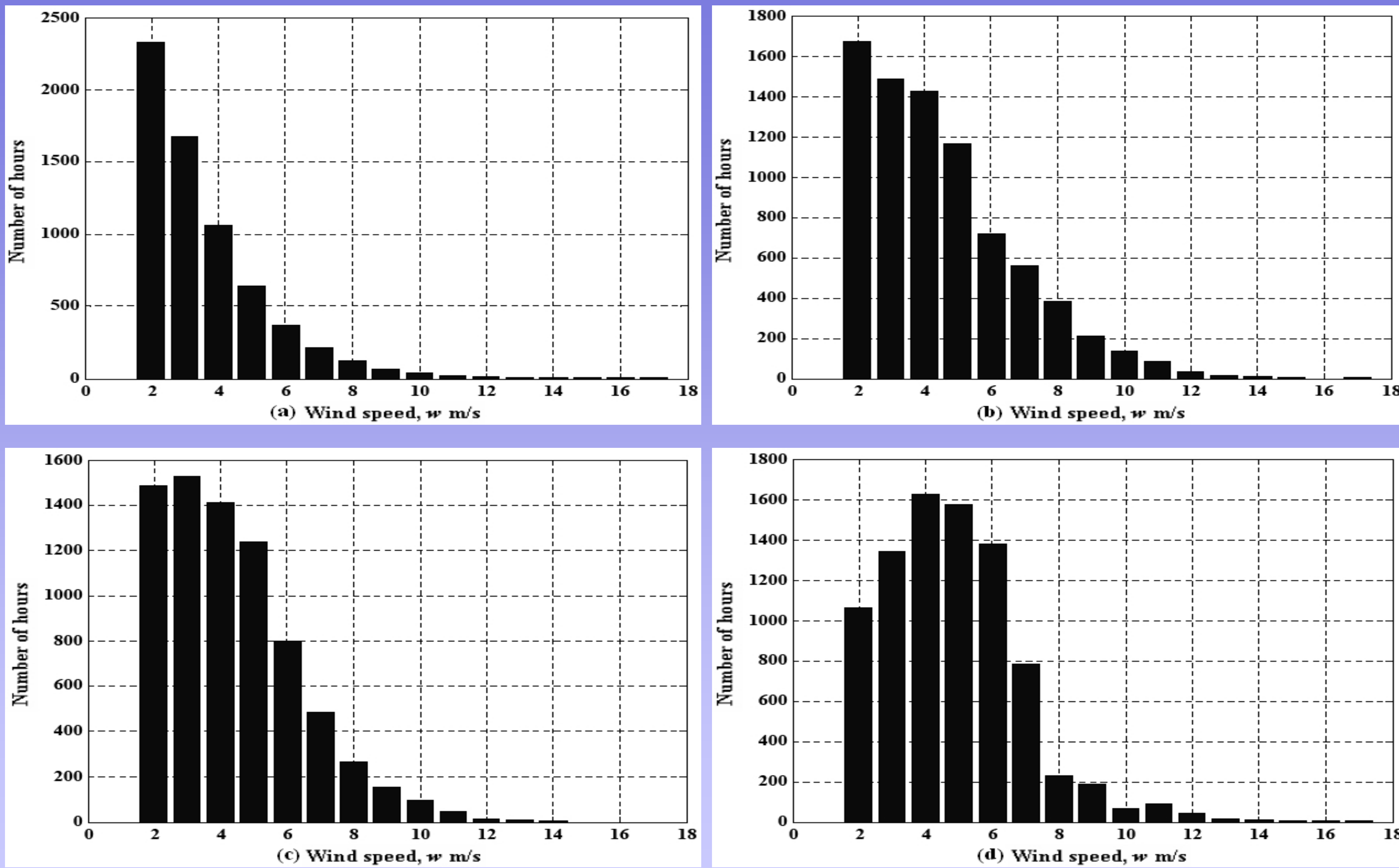
a) Conduction and switching losses for rectifier, b) power loss for resistor, c) electrical and frictional loss of slipring, d) Total power losses of the PCS

Wind speed distribution for selected sites of Newfoundland, Canada



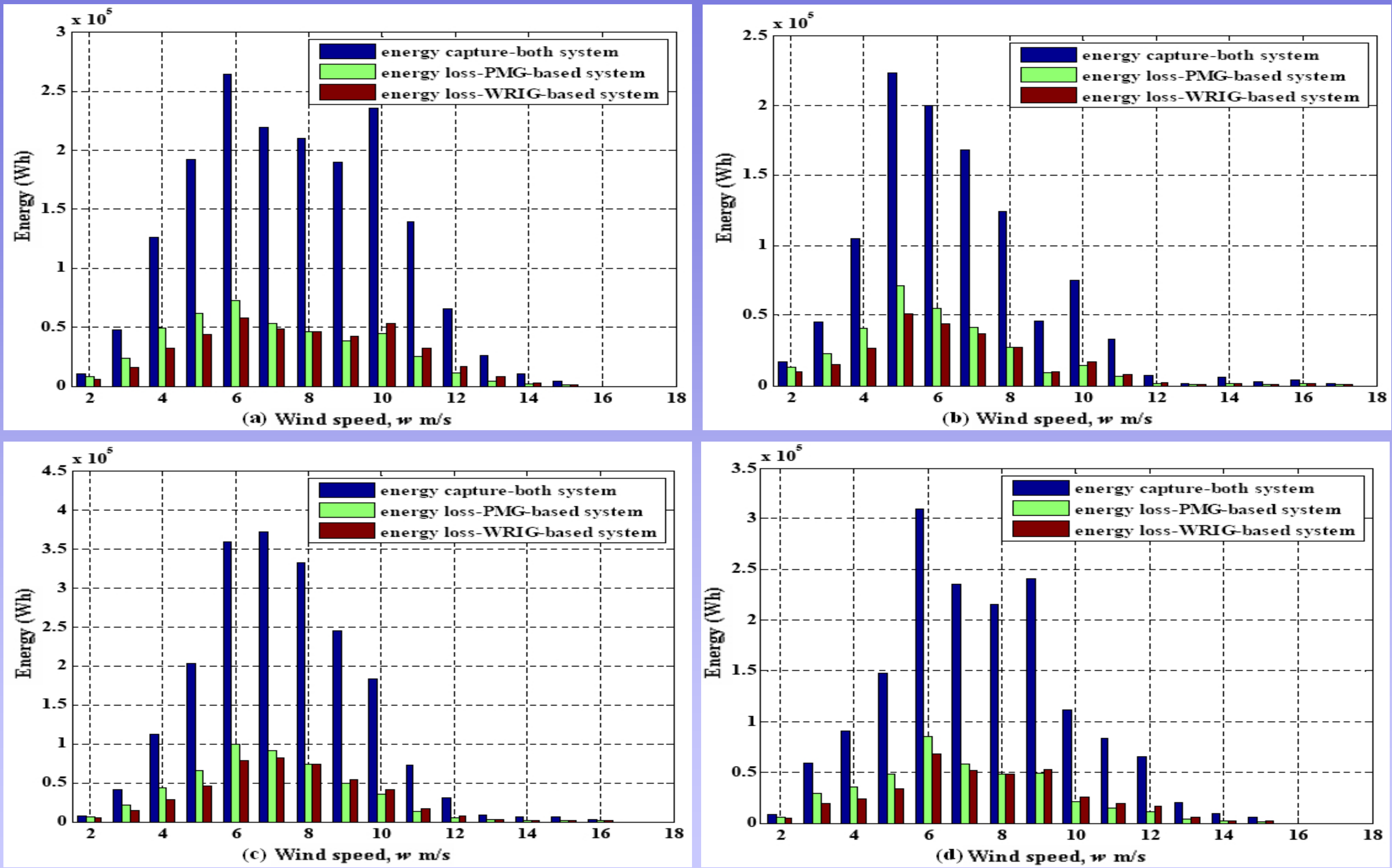
Wind speed distribution for a) Battle Harbour (BH), b) Cartwright (CW), c) Little Bay Island (LB), d) Mary's Harbour (MH)

Wind speed distribution for selected sites of Newfoundland, Canada



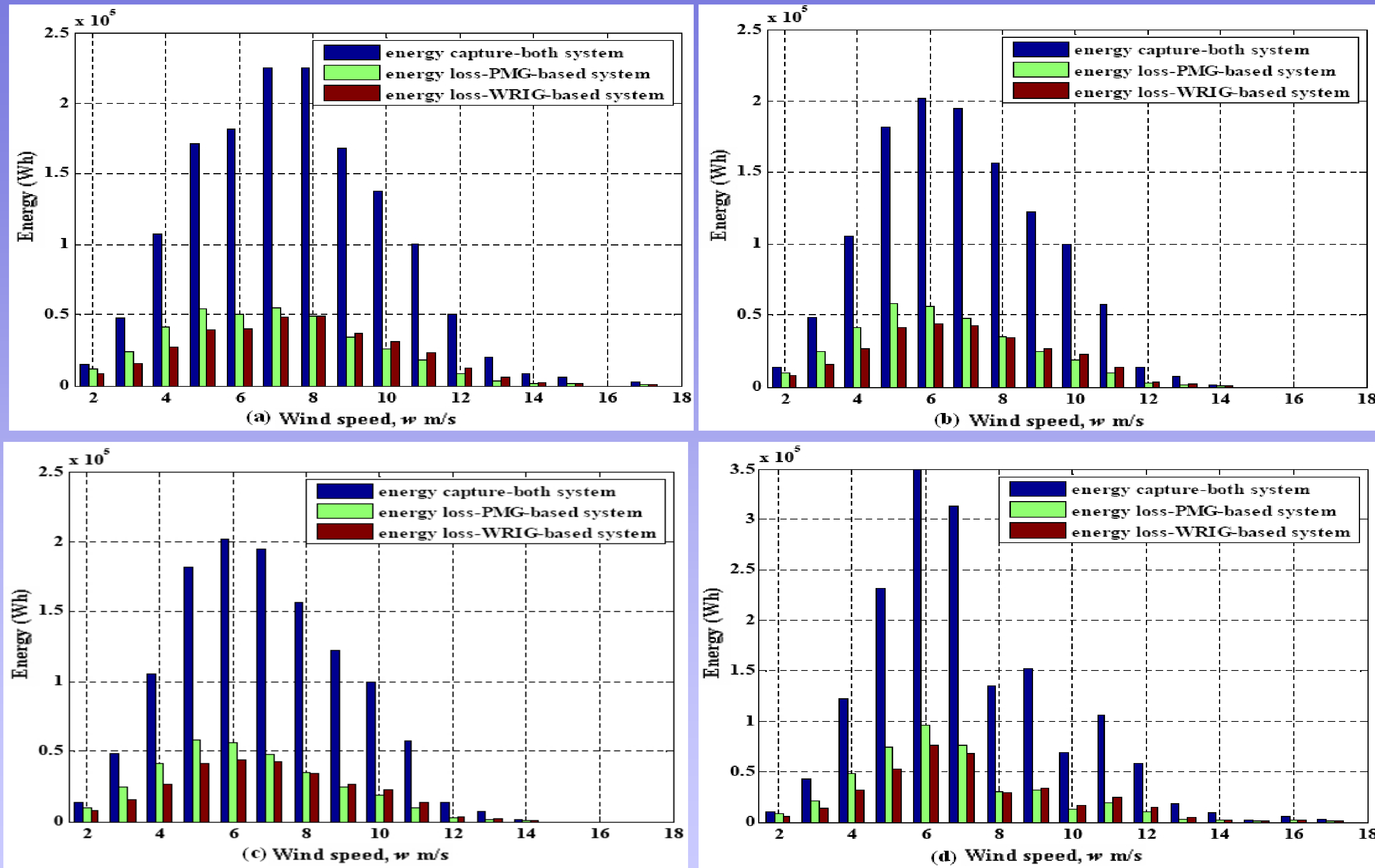
Wind speed distribution for a) Nain (NA), b) Ramea (RA), c) St. Brendan's (SB), d) St. John's (SJ)

Energy capture and loss for selected sites of Newfoundland, Canada

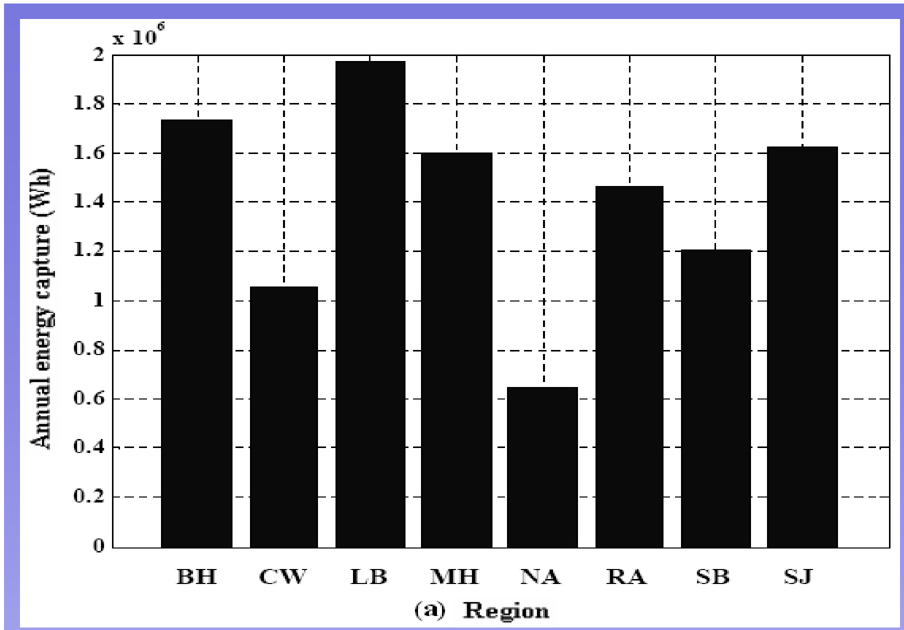


Energy capture and energy loss from cut-in to cut-out wind speed for a) Battle Harbour (BH), b) Cartwright, c) Little Bay Island (LB), d) Mary’s Harbour (MH)

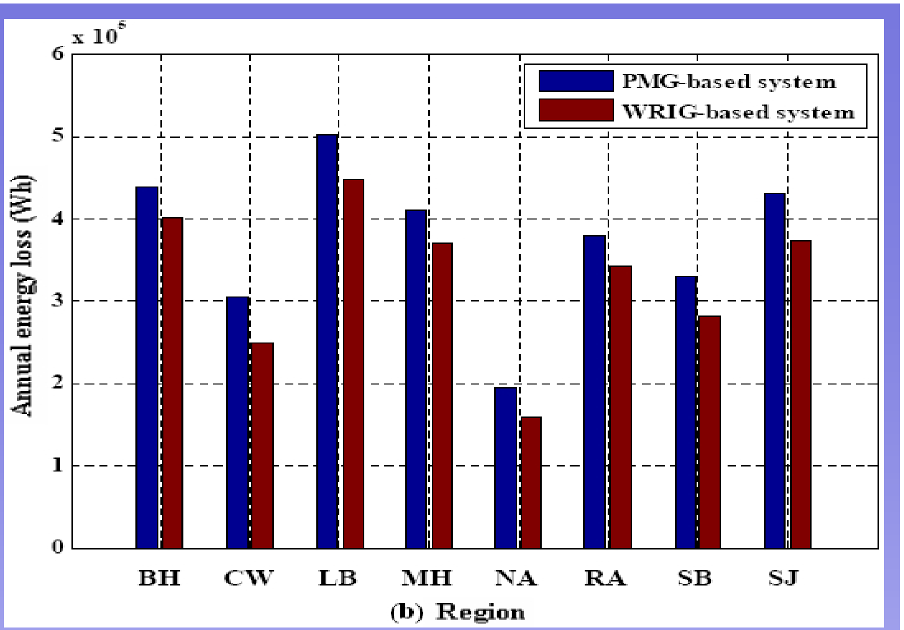
Energy capture and loss for selected sites of Newfoundland, Canada



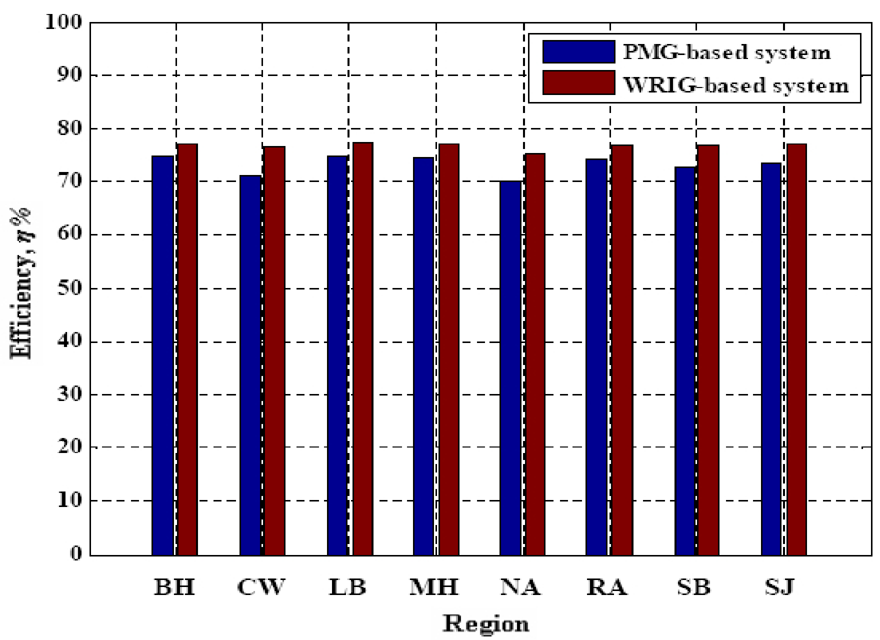
Energy capture and energy loss from cut-in to cut-out wind speed for a) Nain (NA), b) Ramea (RA), c) St. Brendan’s (SB), d) St. John’s (SJ)



Sum of energy capture



Sum of energy loss



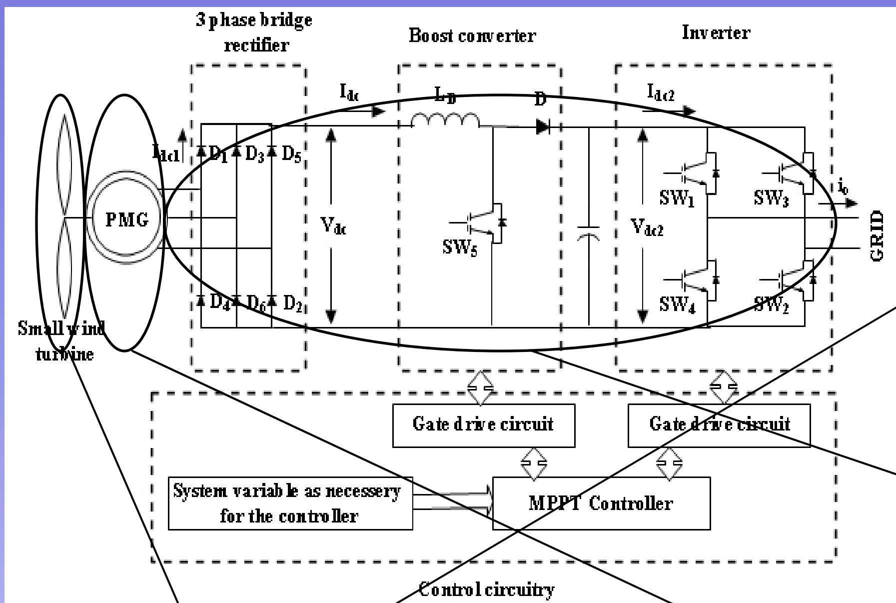
Efficiency of the systems

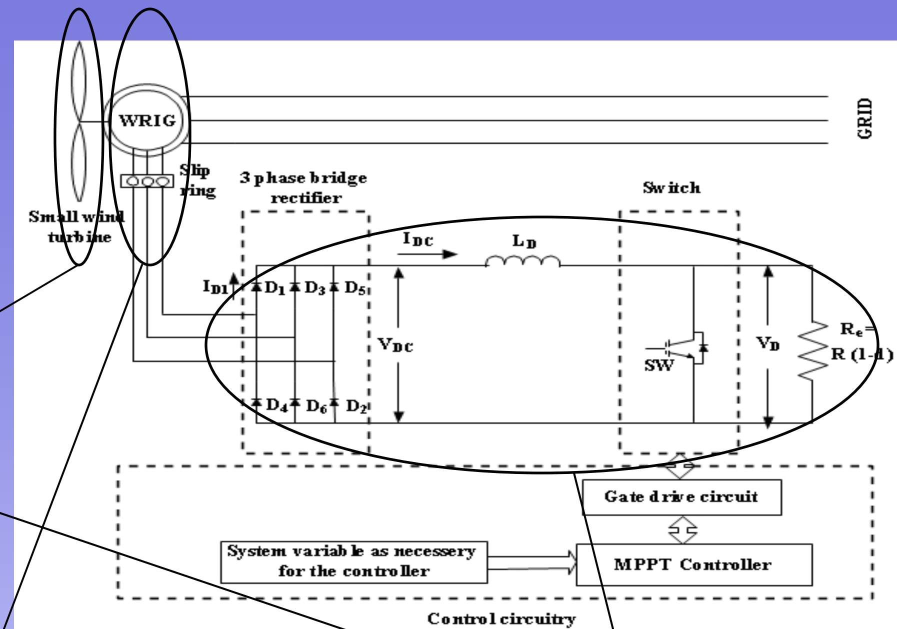
Efficiency of the WRIG-based system is higher than the PMG-based system

The WRIG-based system could be an optimum alternative

Experimental Evaluation

Overview of experimental setup





Small Wind Turbine Emulator (WTE)

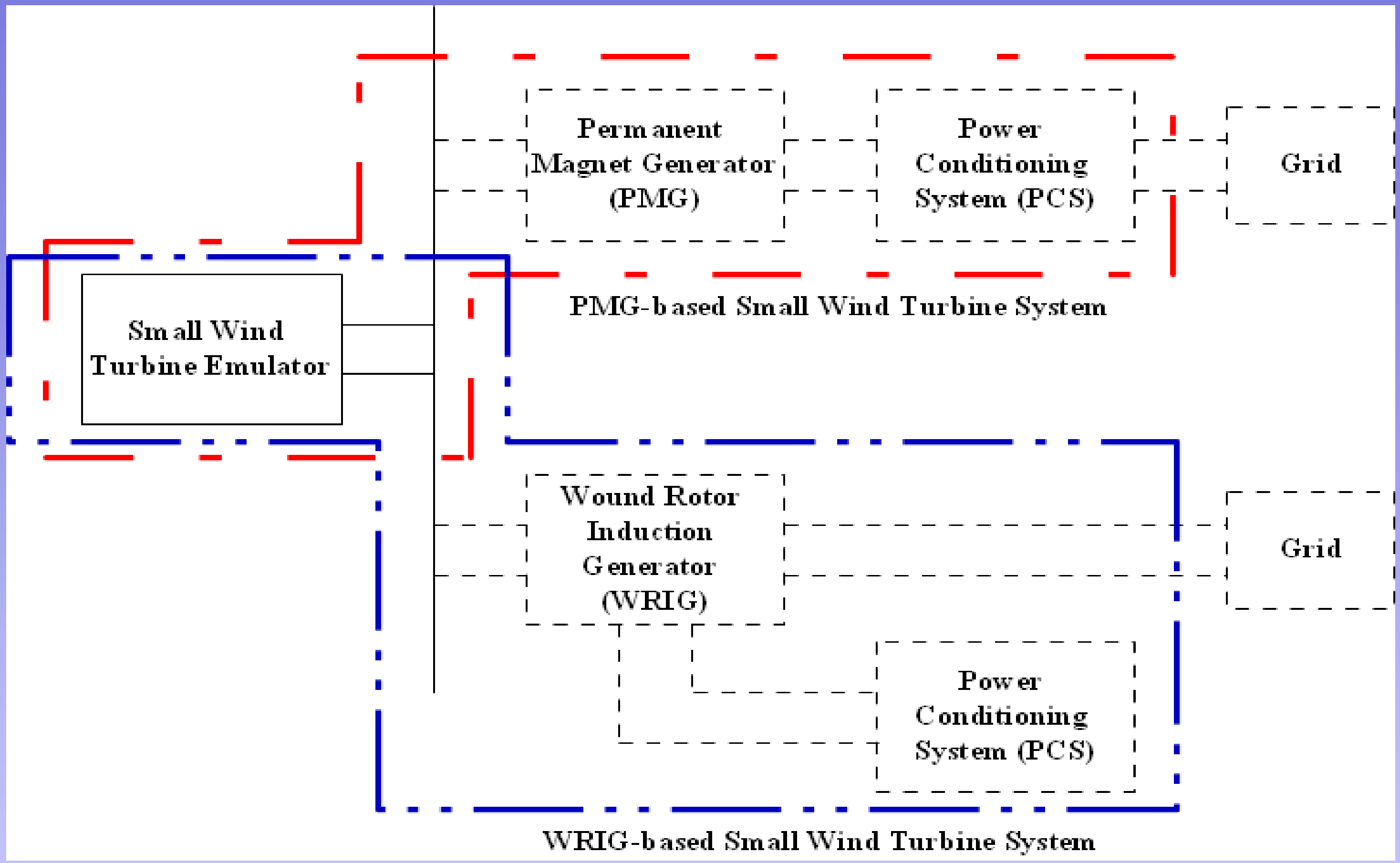
Generator

PMG/WRIG

Power Conditioning System (PCS)

- **Applied wind speed profile to the emulator**
- **Developed formulation to calculate the power losses**
- **Determined energy capture, loss and efficiency of the systems for the selected sites**

Test bench structure

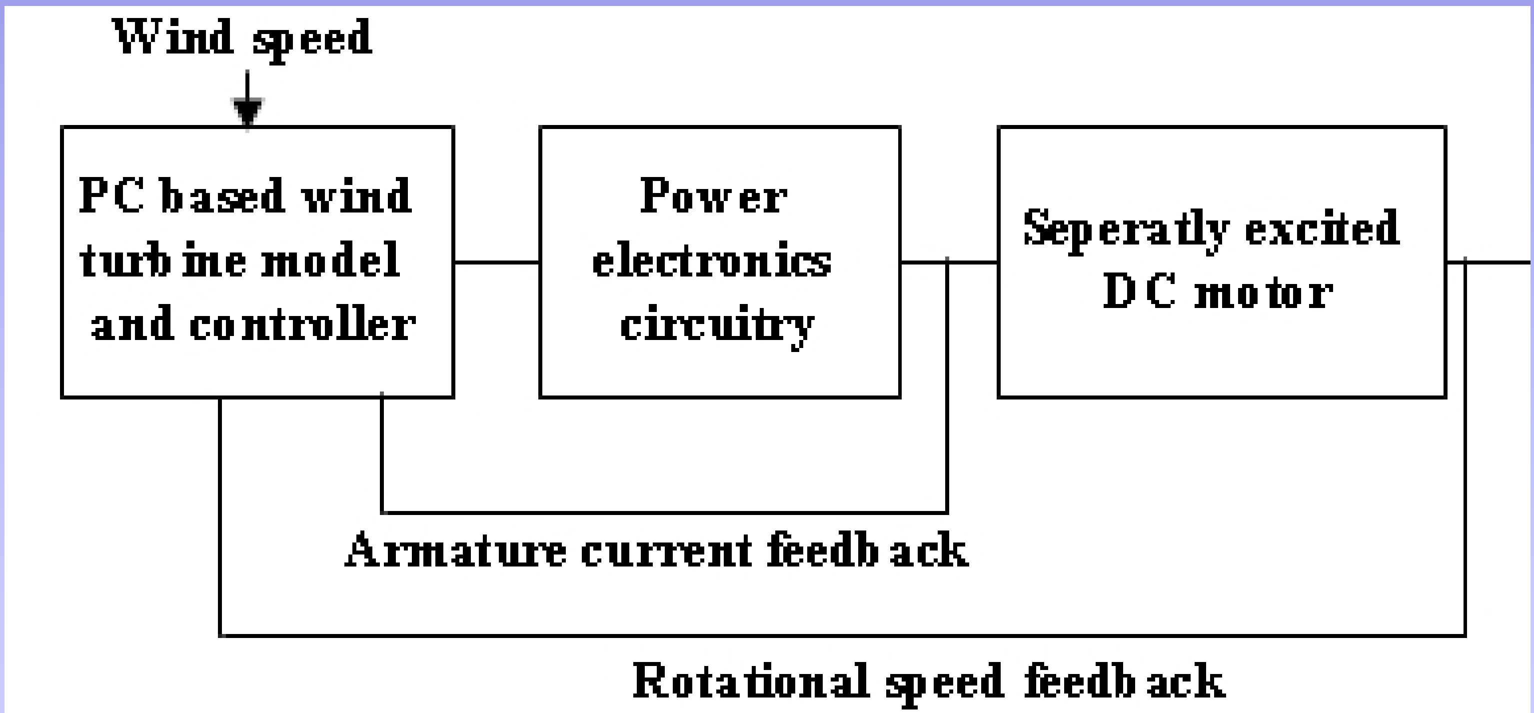


- Same wind turbine emulator coupled with two different generators
- PCS was integrated to ensure variable speed operation
- PCS also carried out the task of maximum power production

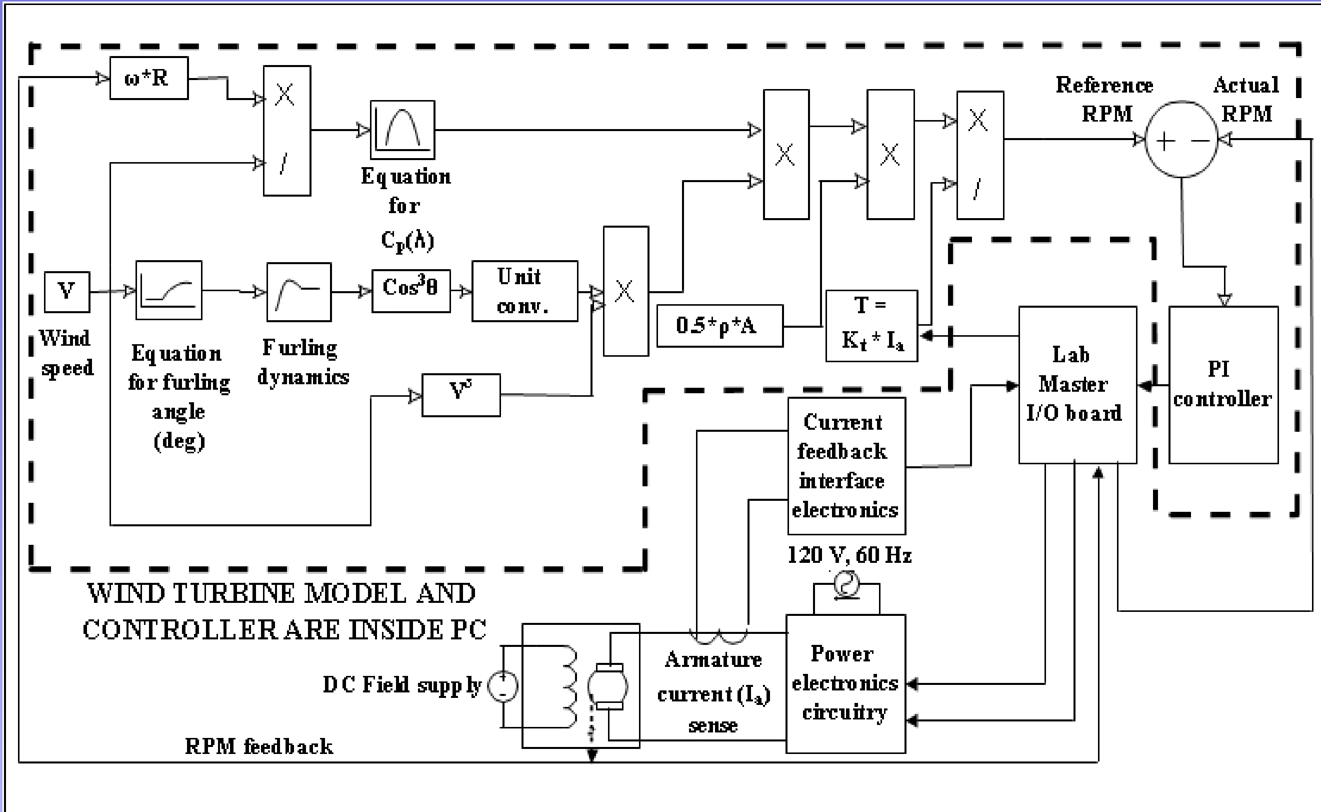
Small Wind Turbine Emulator

Basic Criteria

- **Representation of the furling control and resulting dynamics**
- **Limit the initial armature current of the DC motor**
- **Track the optimum shaft speed of the rotor by the DC motor**

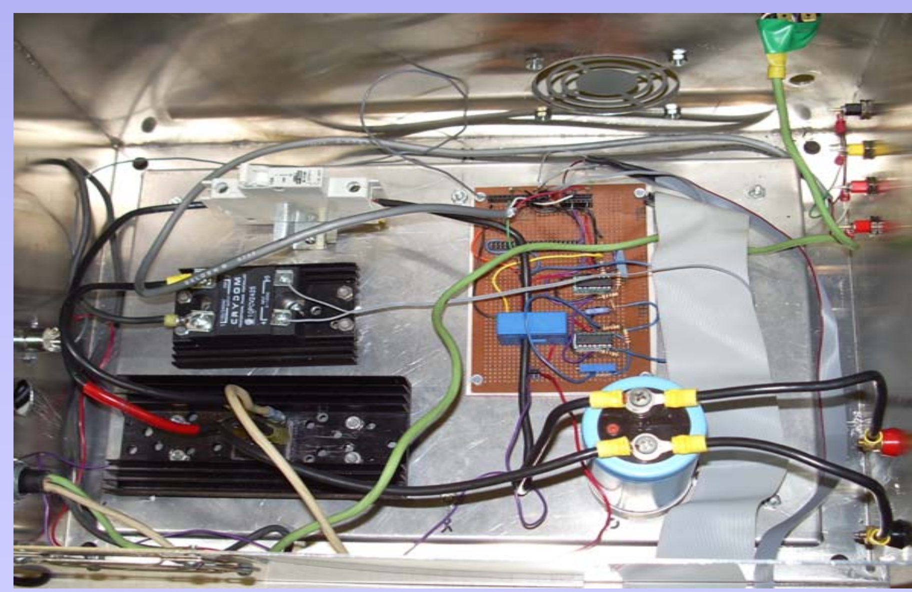


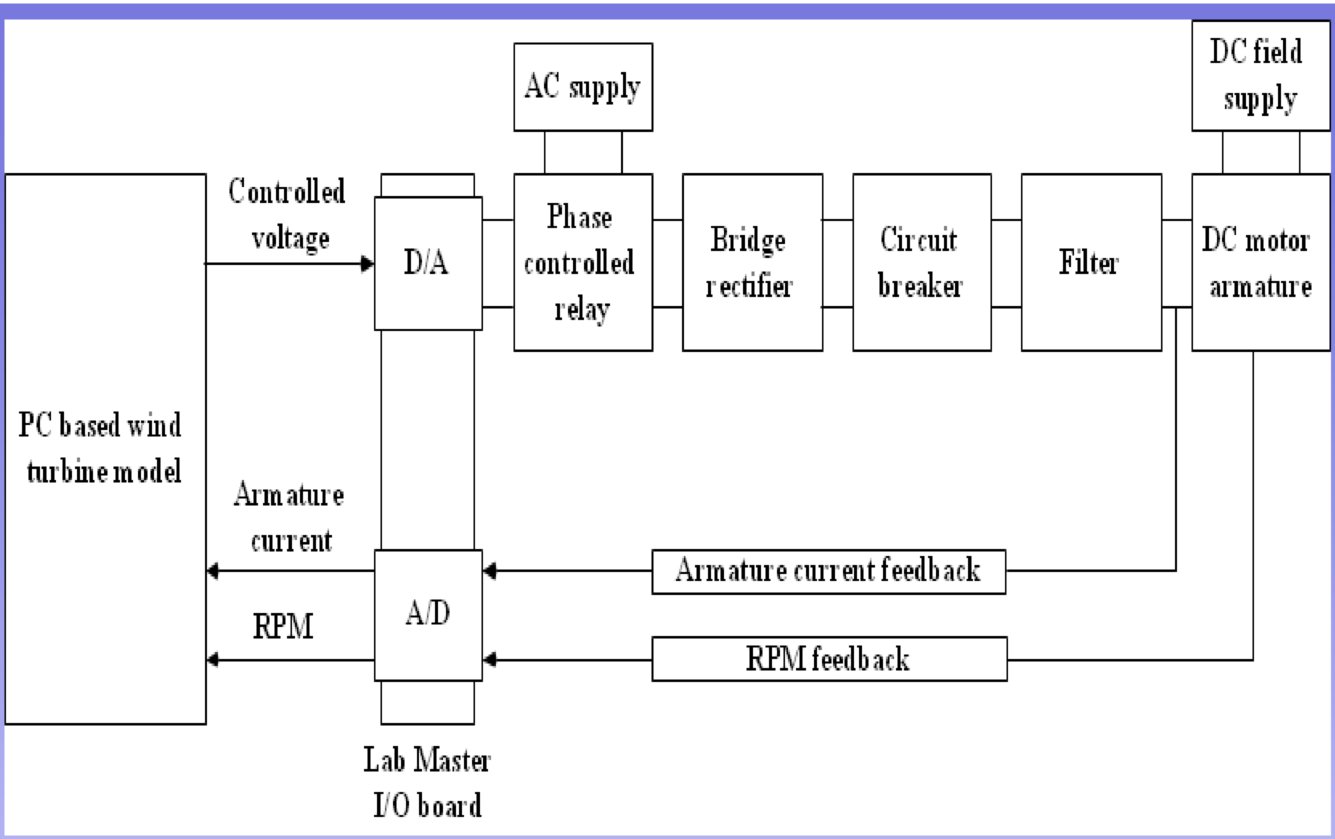
Developed wind turbine emulator



Internal structure

Electronics photograph

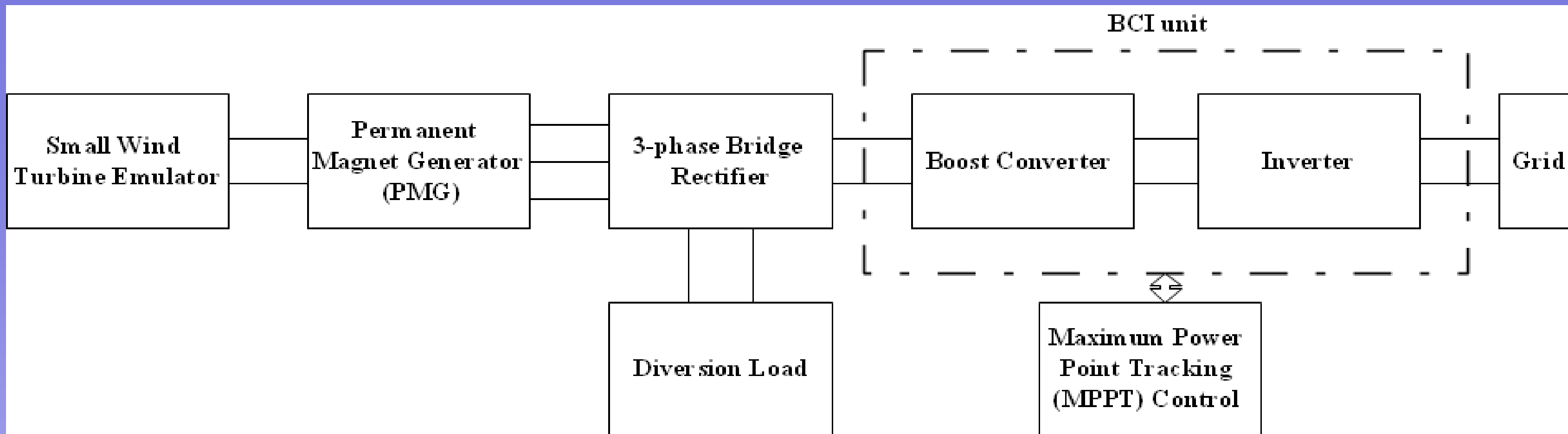




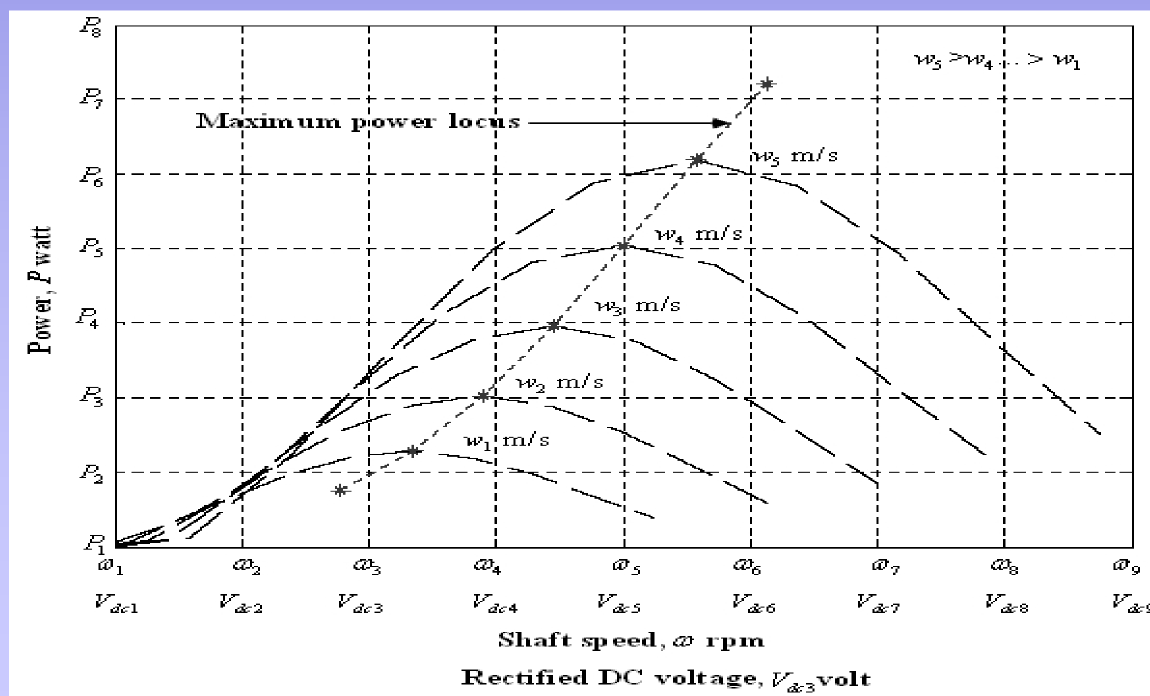
Test bench structure

Test bench photograph

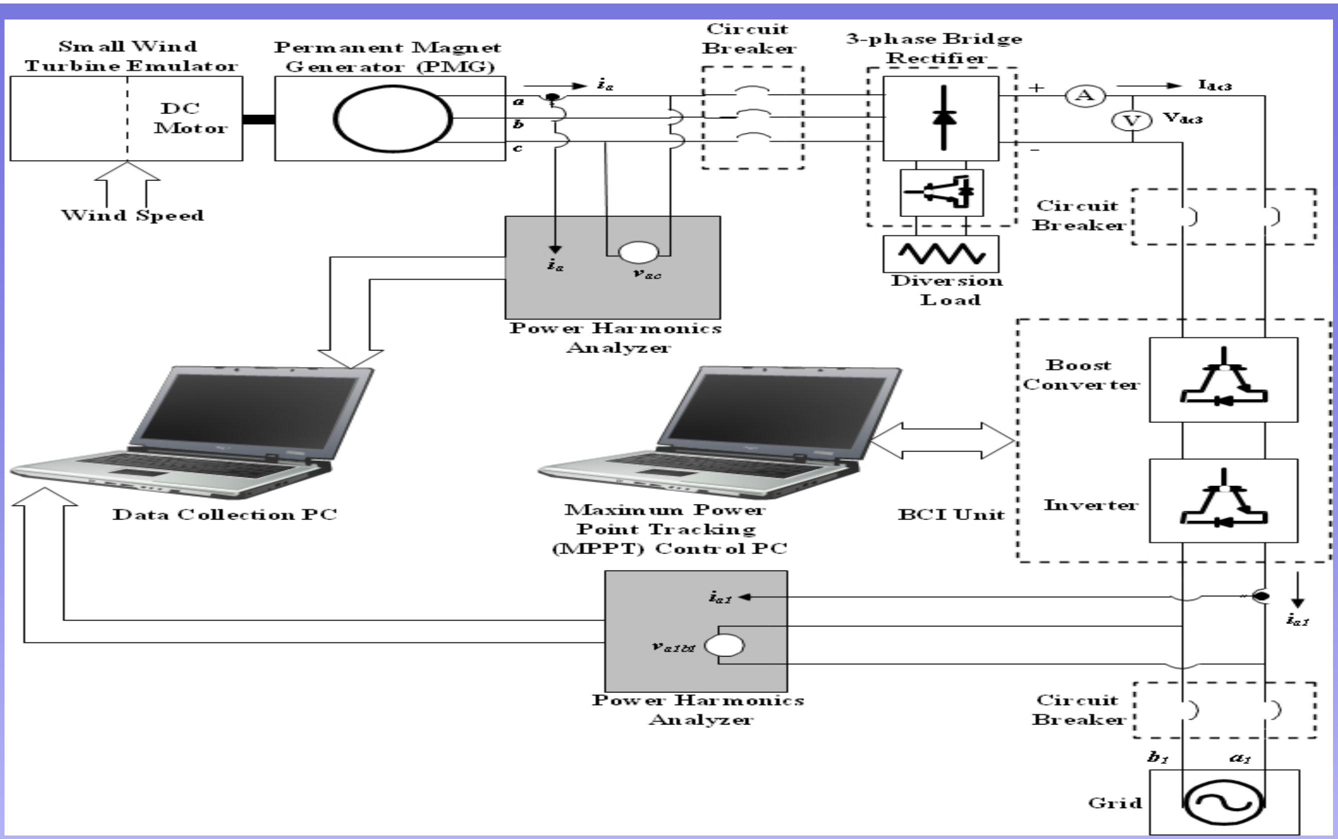
PMG-based system



Test bench structure



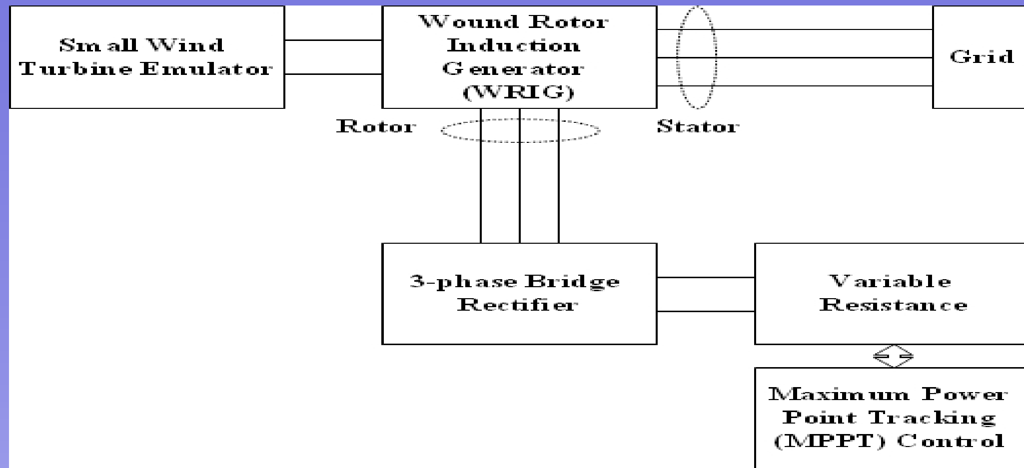
Maximum power point tracking control strategy



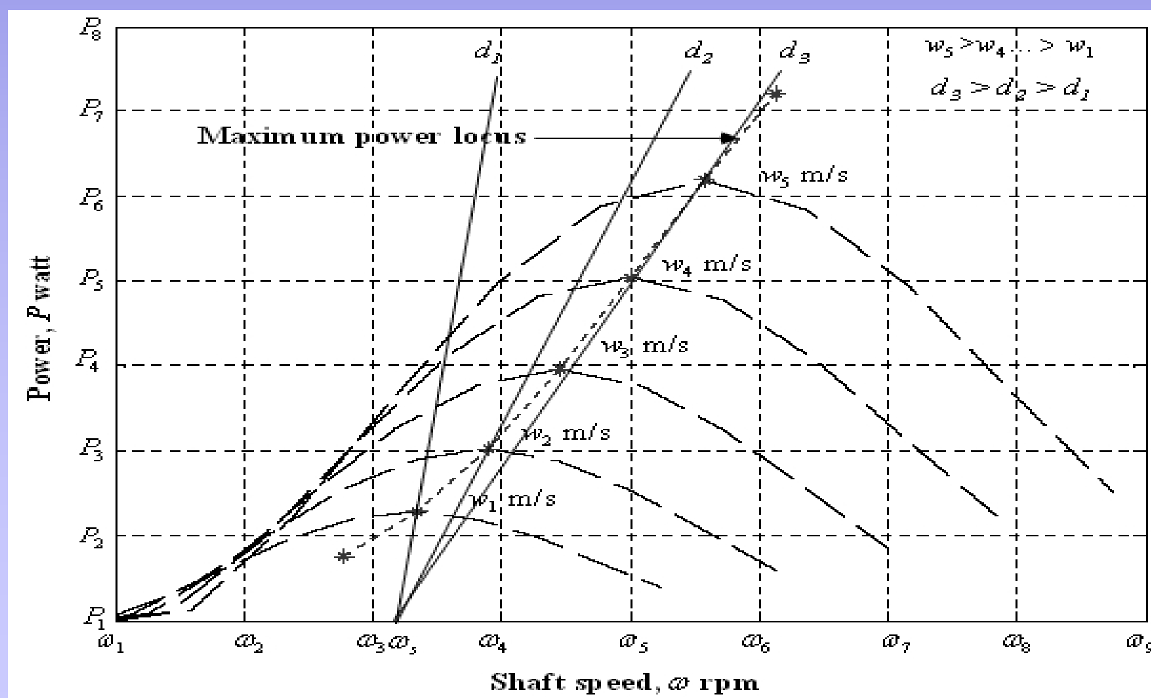
Test bench structure

Test bench photograph

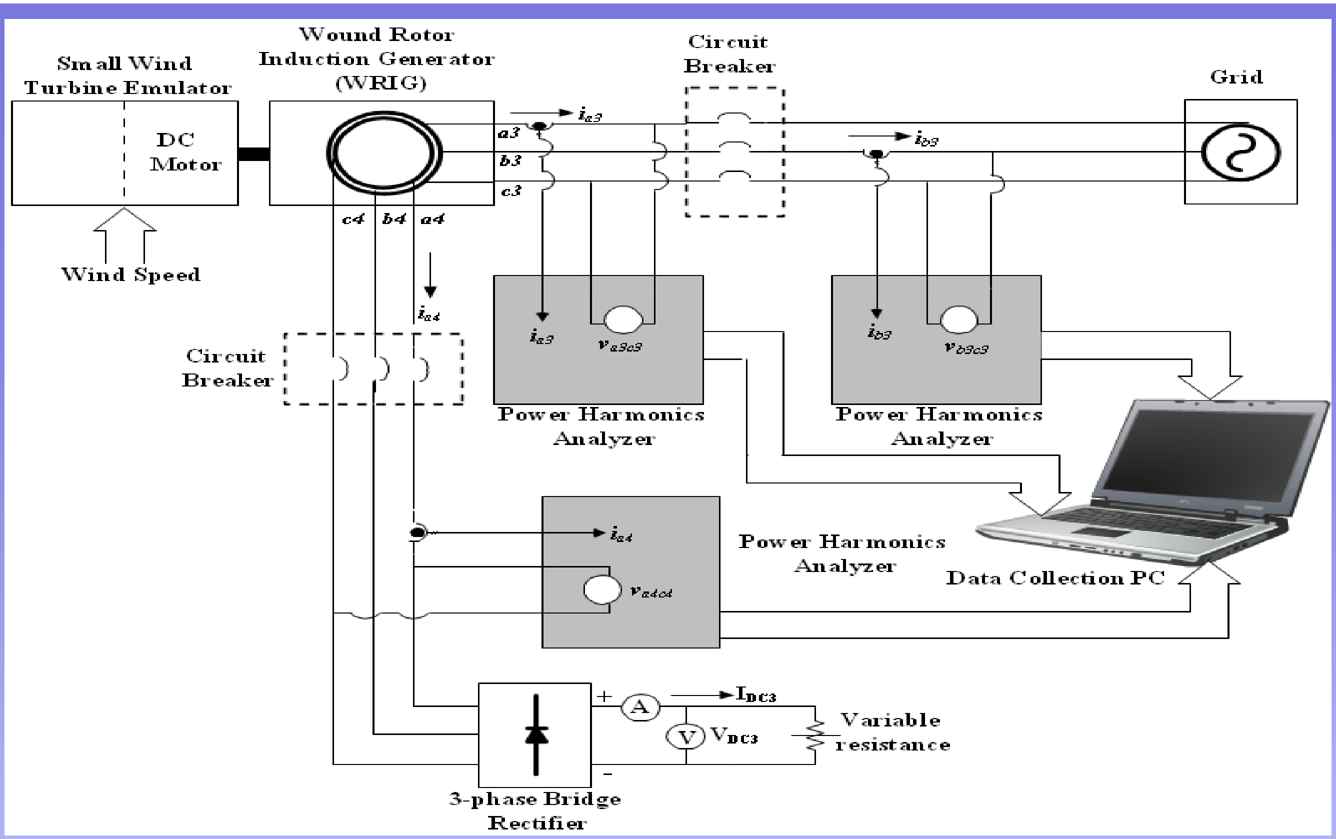
WRIG-based system



Test bench structure



Maximum power point tracking control strategy

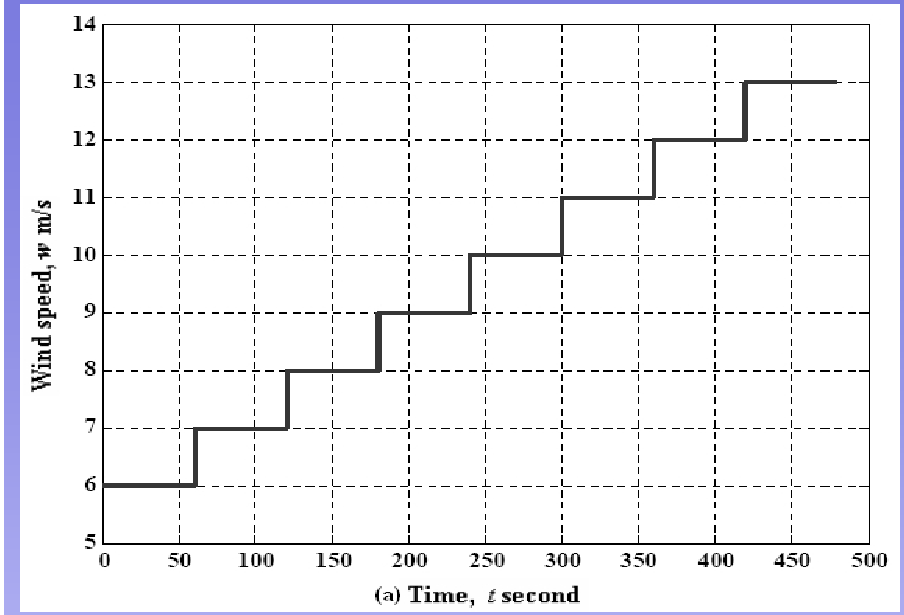


Test bench structure

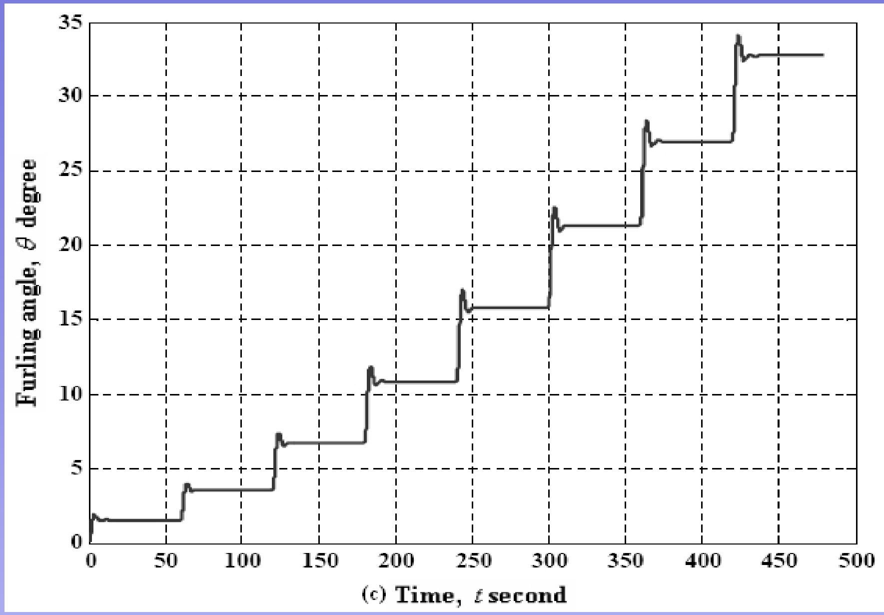
Test bench photograph

Experimental Results

Small Wind Turbine Emulator Performance



Wind speed



Furling control and resulting dynamics

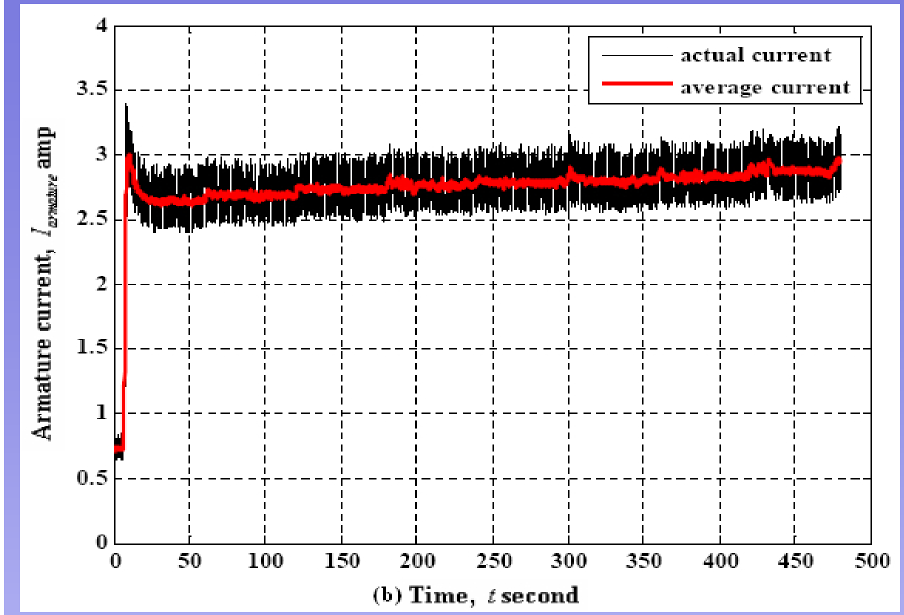
Variation of wind speed with time was applied to the emulator

Basic Criteria of the emulator

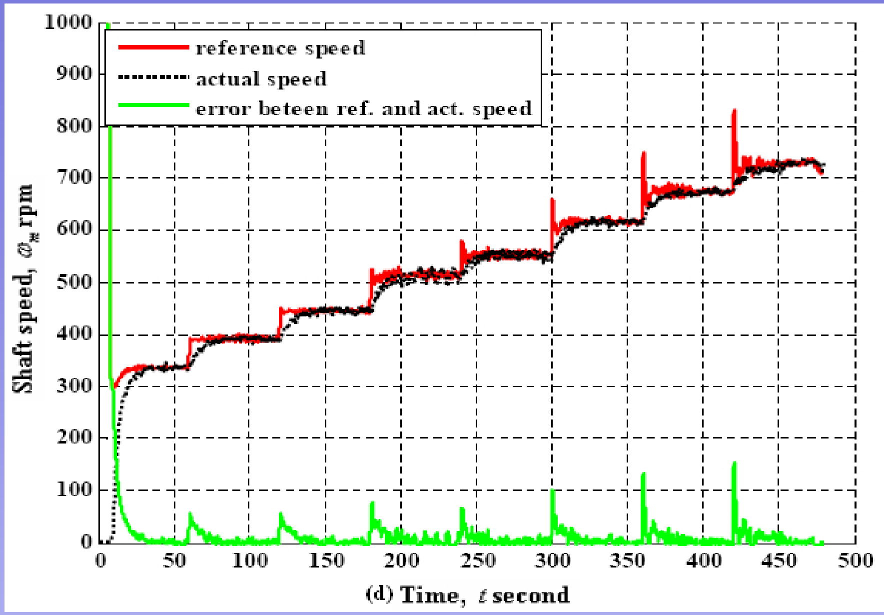
- **Representation of the furling control and resulting dynamics**

Expected furling control and resulting dynamics with the wind variation was achieved

Small Wind Turbine Emulator Performance



Armature current



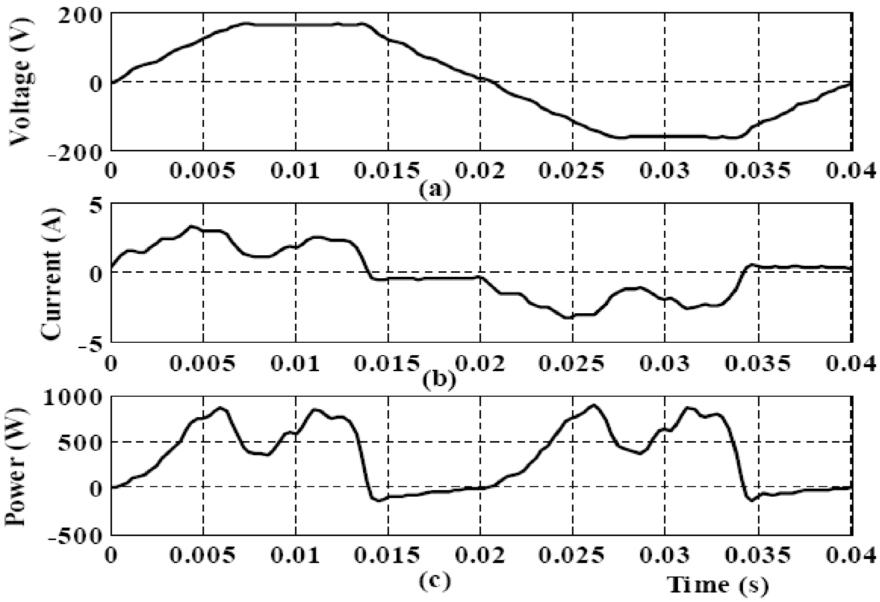
Shaft speed

Basic Criteria of the emulator

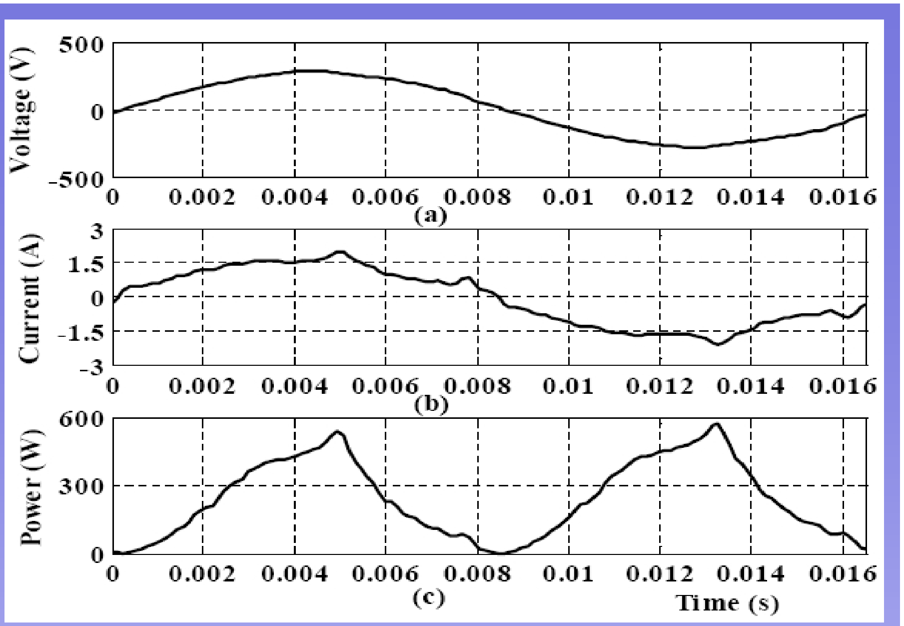
- **Limit the initial armature current of the DC motor**
- **Track the optimum shaft speed of the rotor by the DC motor**

•Armature current variation was within an acceptable level and optimum shaft speed was tracked by the DC motor

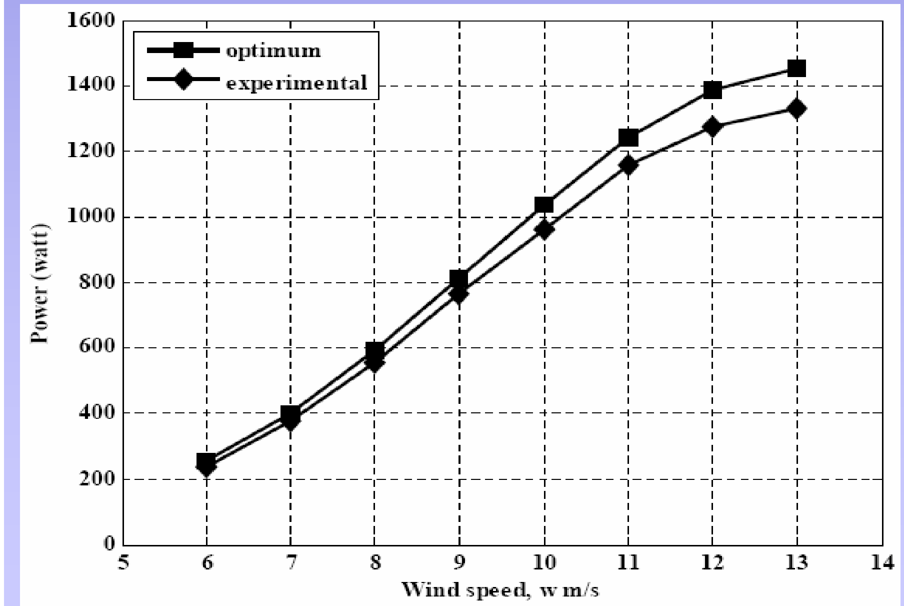
The emulator met the basic criteria and an acceptable performance was achieved



PMG output



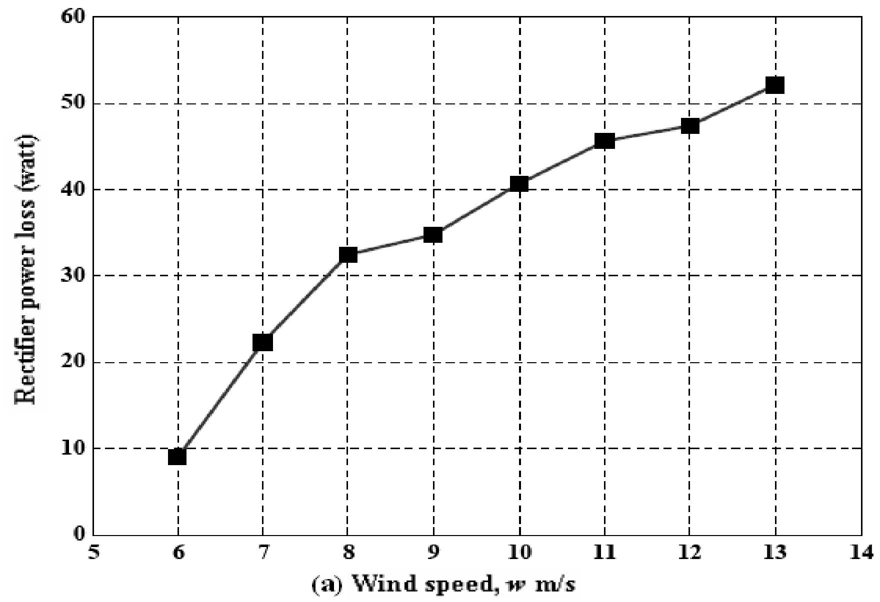
Grid output



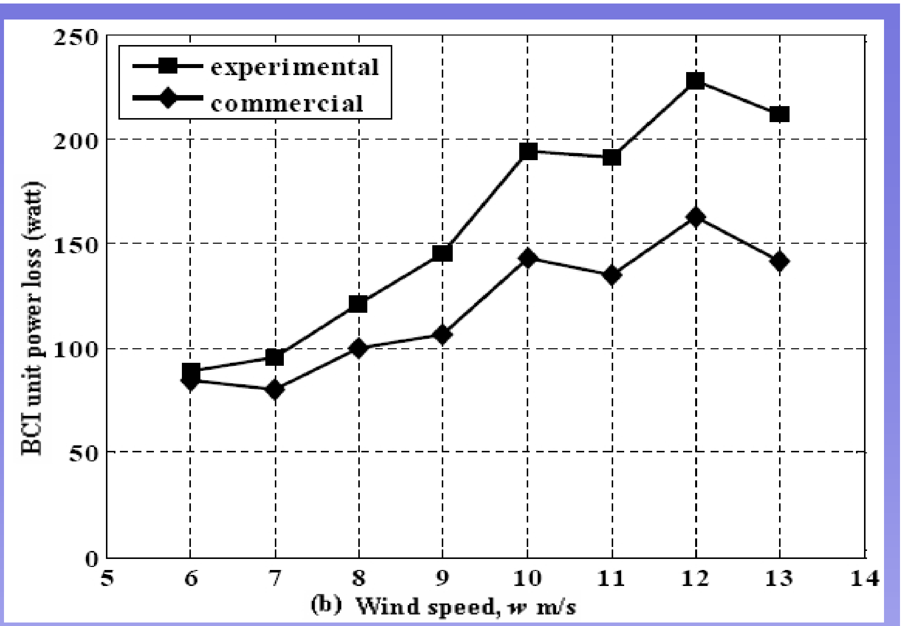
Power

PMG-based system performance

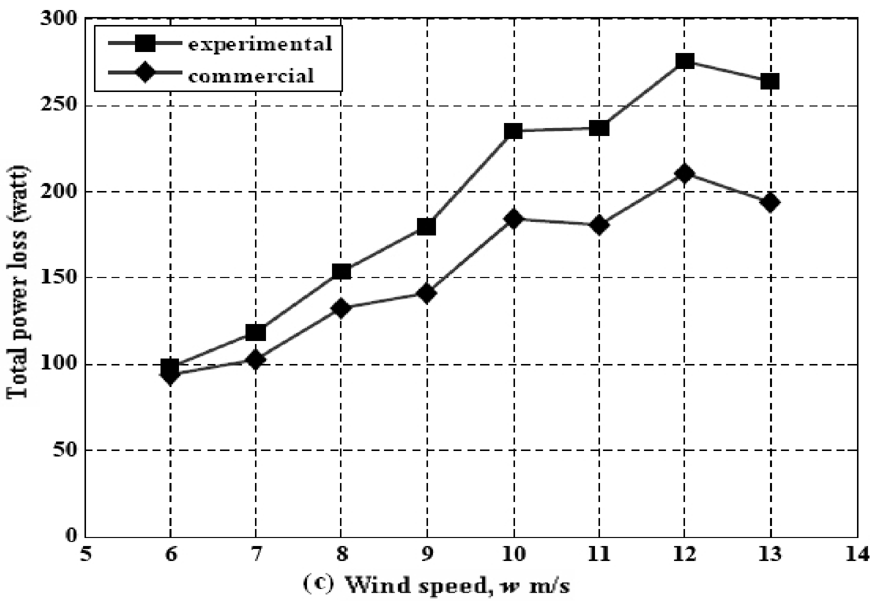
- Wind speed is 6 m/s
- One cycle of voltage and current of PMG and Grid output
- Experimental power follows the optimum power
- Ensured maximum power point control strategy



Rectifier



BCI unit

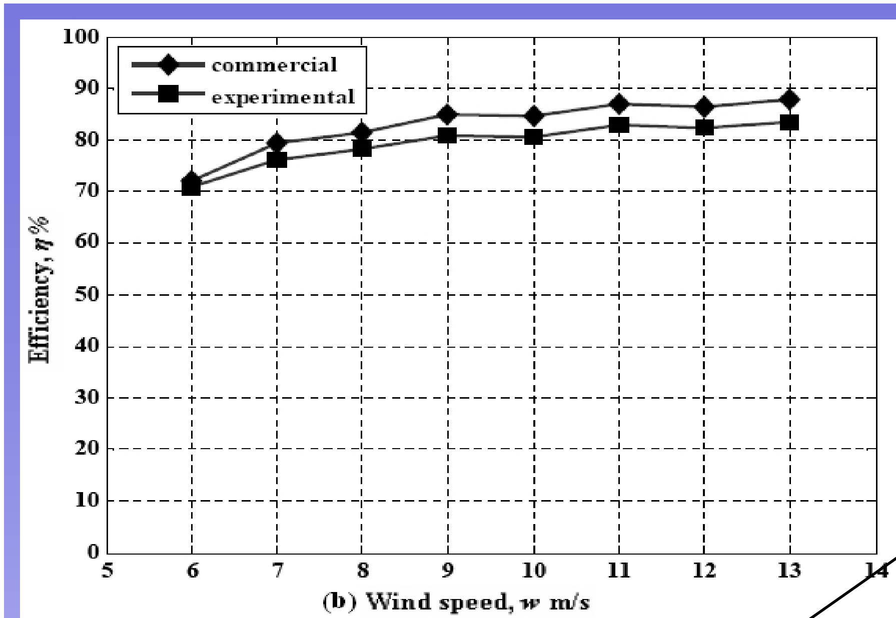


Total power loss

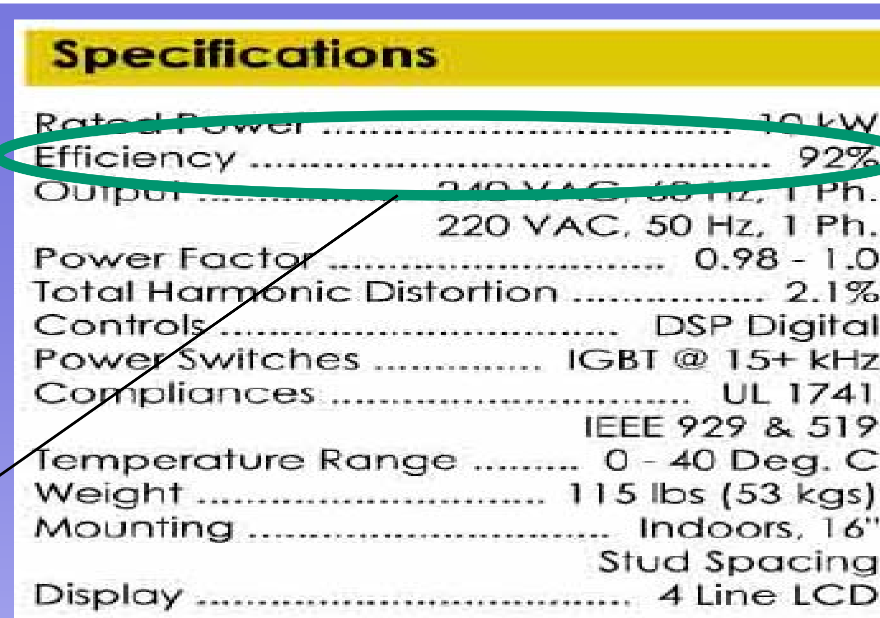
PMG-based system power loss

- **Power loss increases with an increase in wind speed**

- **A difference in experimental and commercial values were observed**



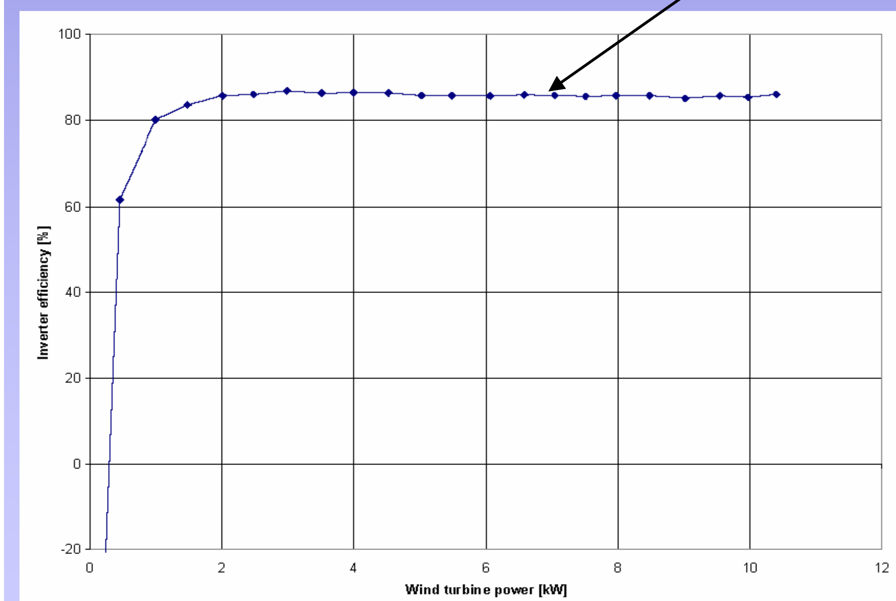
PCS efficiency



Specifications

Rated Power .... 10 kW
Efficiency 92%
Output .... 240 VAC, 60 Hz, 1 Ph.
220 VAC, 50 Hz, 1 Ph.
Power Factor .... 0.98 - 1.0
Total Harmonic Distortion 2.1%
Controls .... DSP Digital
Power Switches .... IGBT @ 15+ kHz
Compliances .... UL 1741
IEEE 929 & 519
Temperature Range .... 0 - 40 Deg. C
Weight .... 115 lbs (53 kgs)
Mounting .... Indoors, 16"
Stud Spacing
Display .... 4 Line LCD

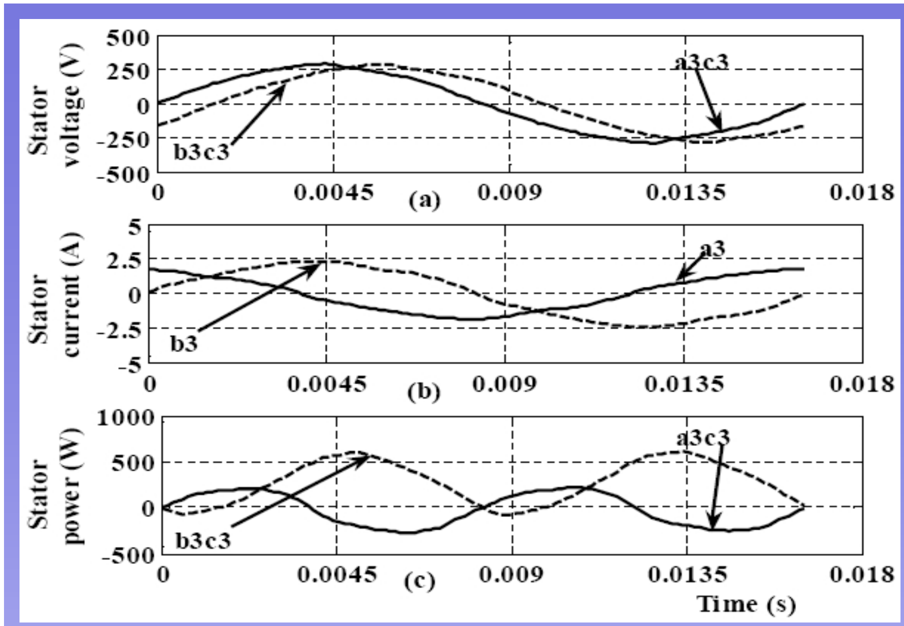
GridTek inverter Specification



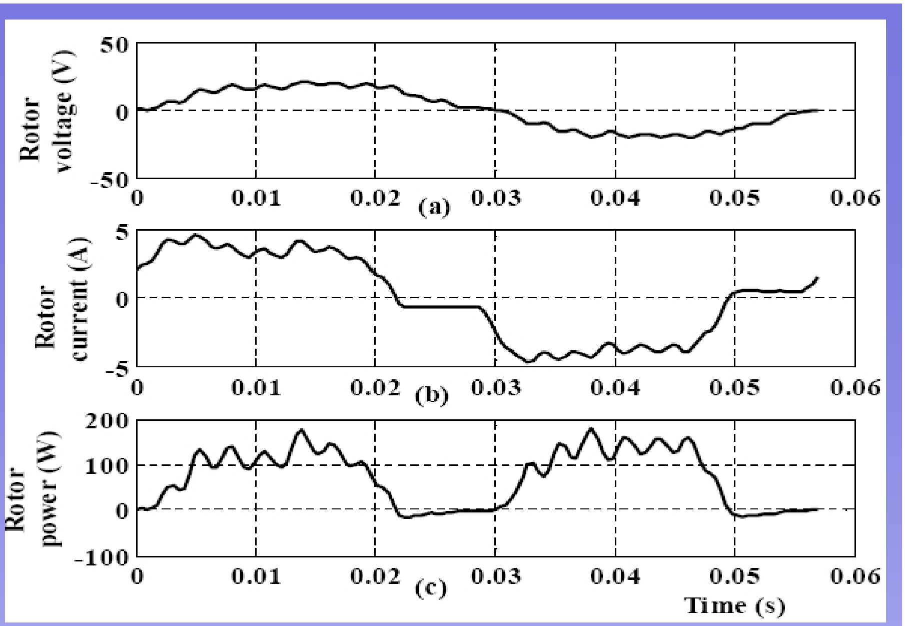
Performance evaluation at NREL lab

Power conditioning system efficiency

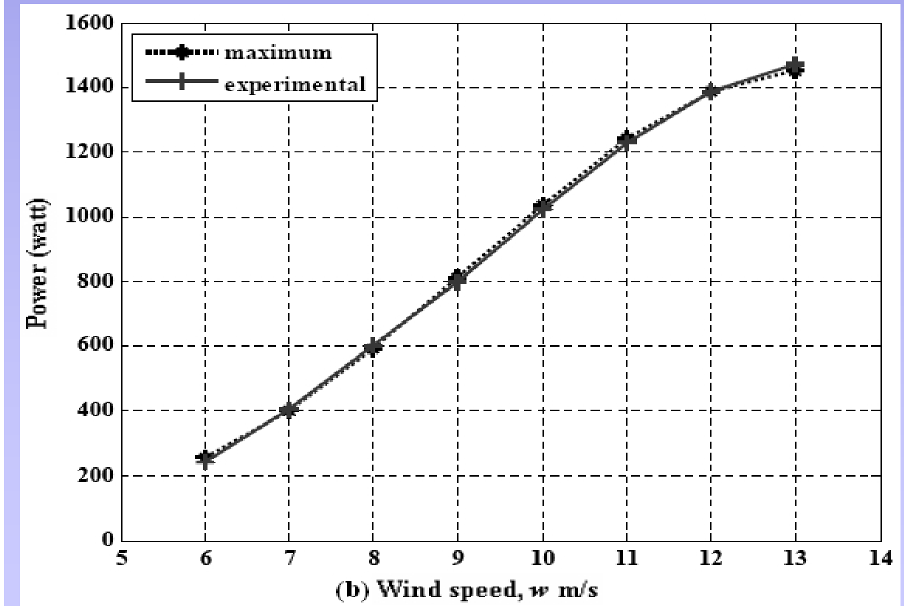
- **Experimental efficiency is lower than the commercial efficiency**
- **Expected efficiency might not be achieved**
- **Expected outcome from a PMG-based system will vary**



WRIG output



WRIG rotor output

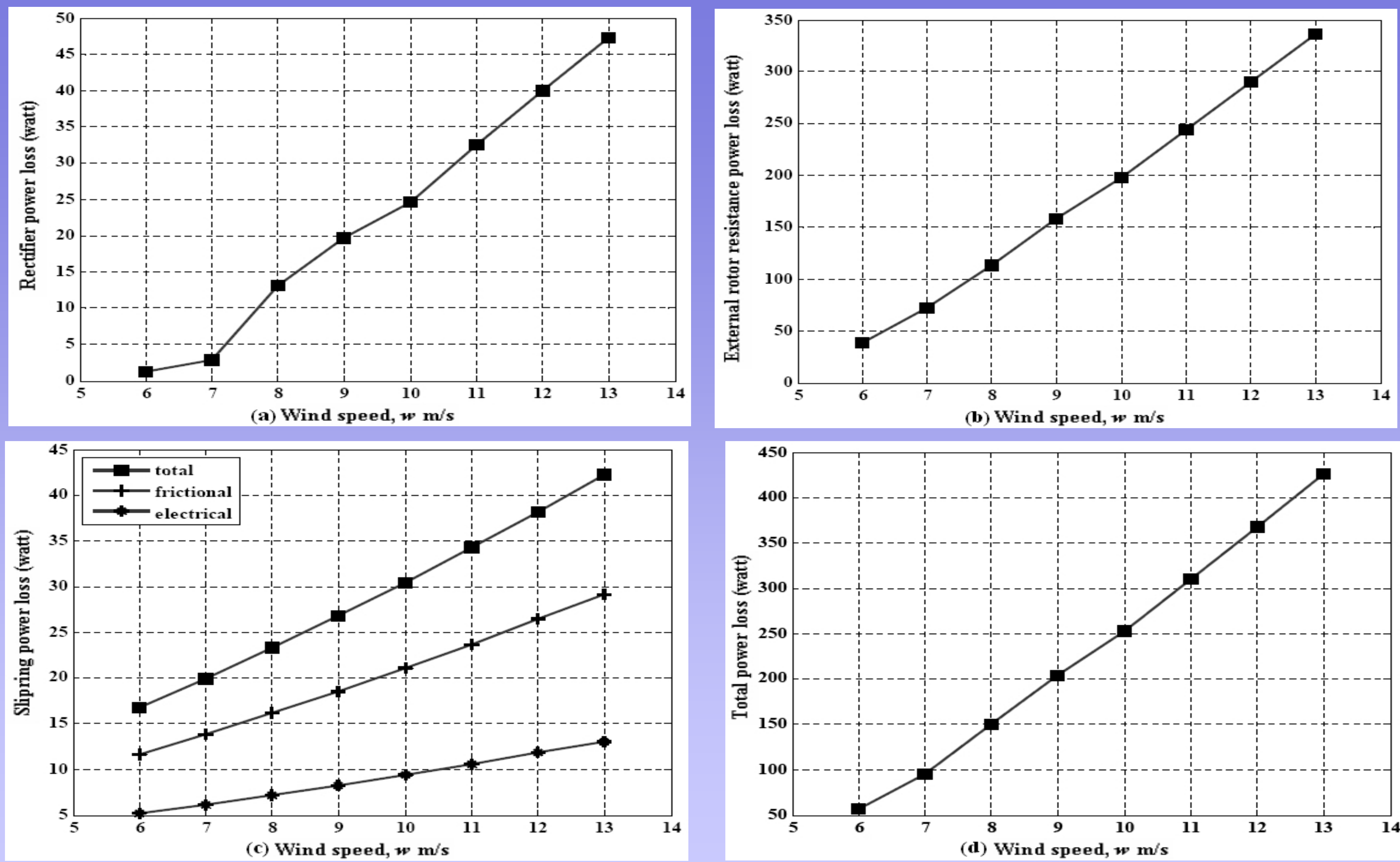


Power

WRIG-based system performance

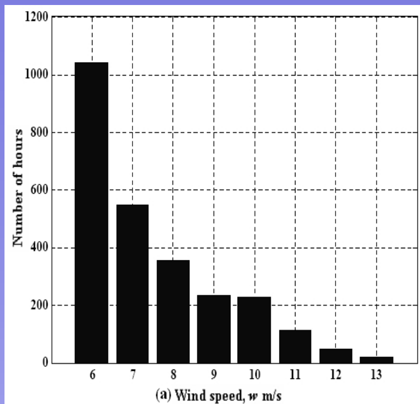
- Wind speed is 6 m/s
- One cycle of voltage and current of WRIG stator and rotor output
- Power flowing into the grid from the WRIG stator
- Ensured maximum power point control strategy

Power loss of the WRIG-based system

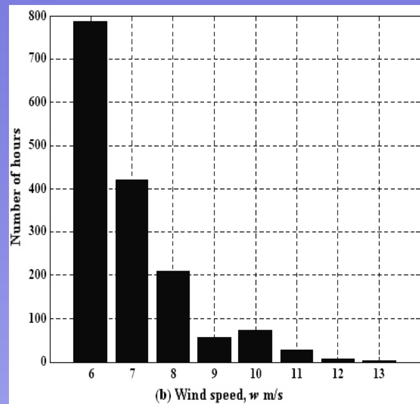


Characteristic of the losses of the WRIG-based system a) Rectifier, b) External rotor resistance, c) Slip ring, d) Total power loss

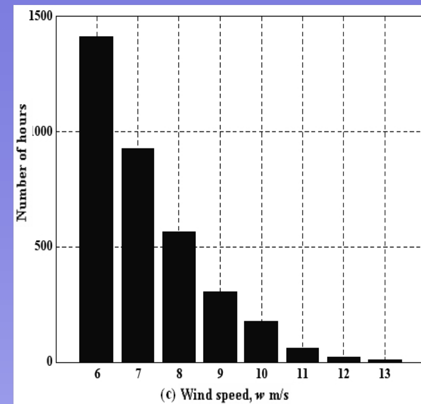
Wind speed distribution for selected sites



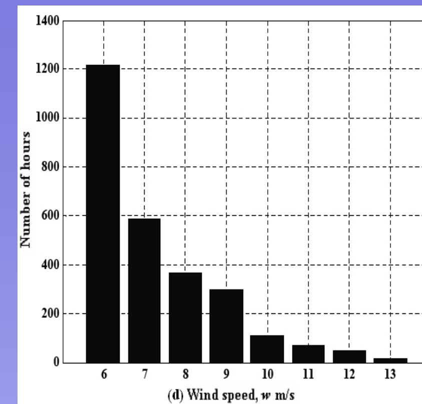
Battle Harbour
(BH)



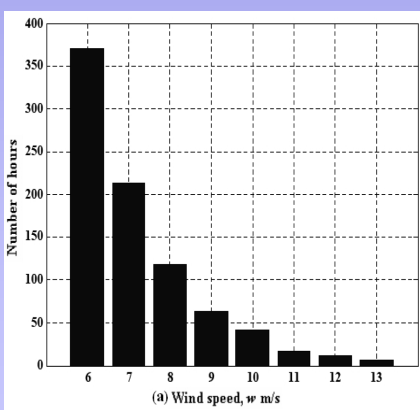
Cartwright
(CW)



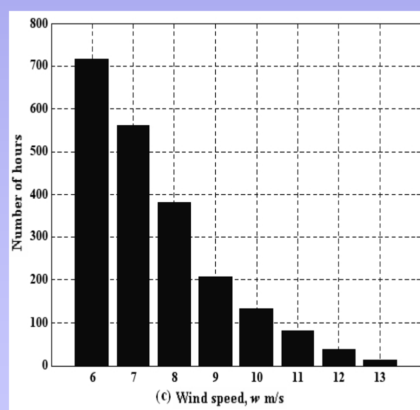
Little bay Island
(LB)



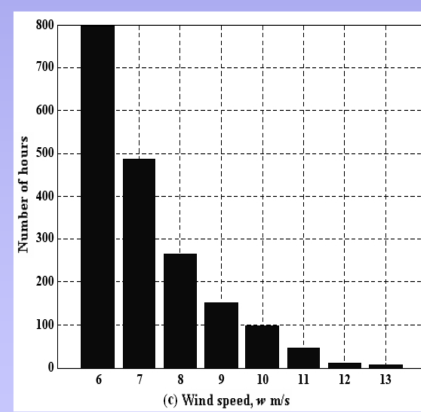
Marry’s Harbour
(MH)



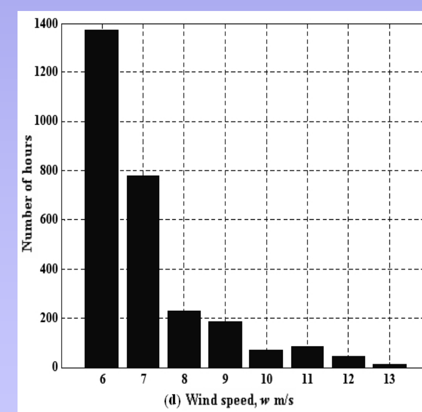
Nain
(NA)



Ramea
(RA)

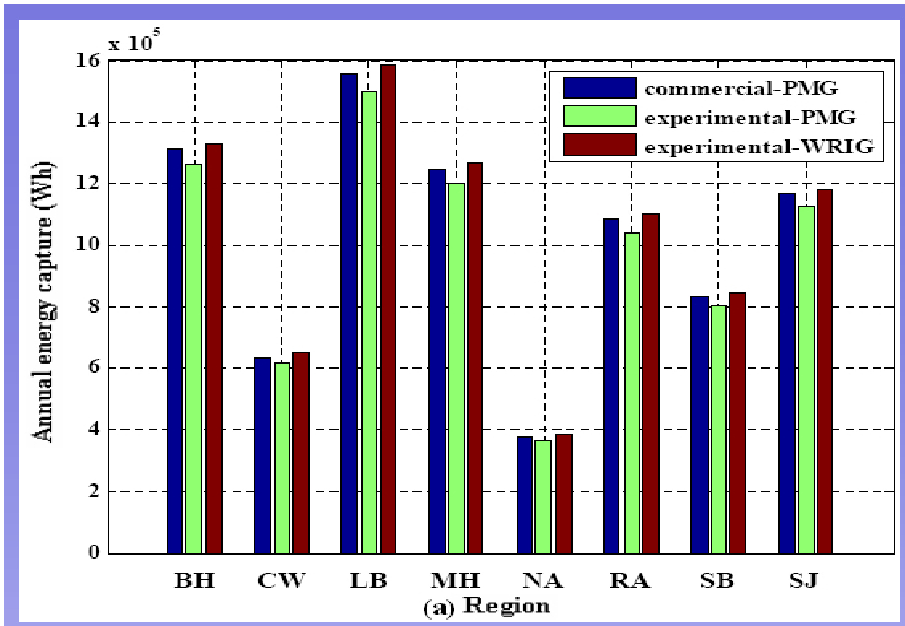


St. Brendan’s
(SB)

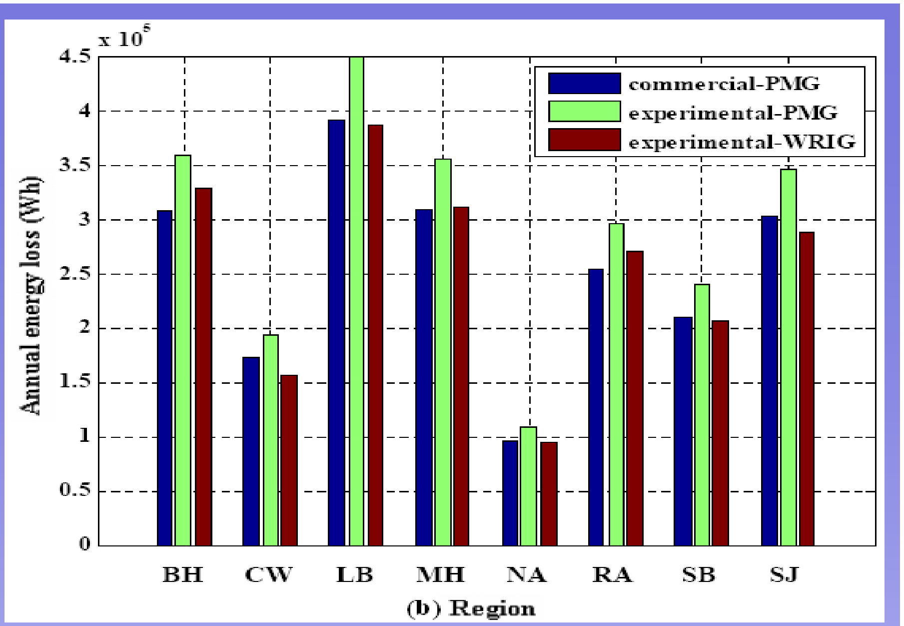


St. John’s
(SJ)

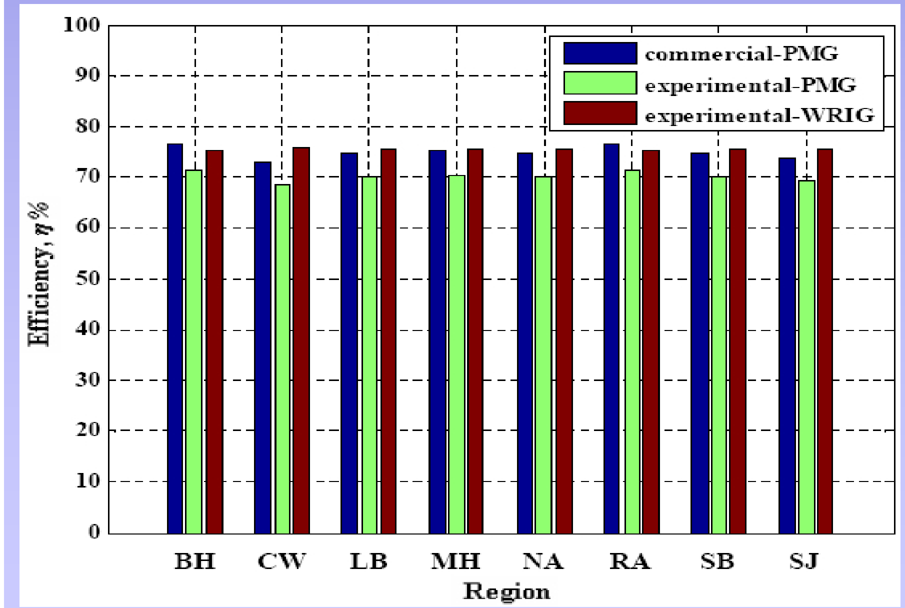
- **Sites are selected from the province of Newfoundland, Canada**



Energy capture



Energy loss

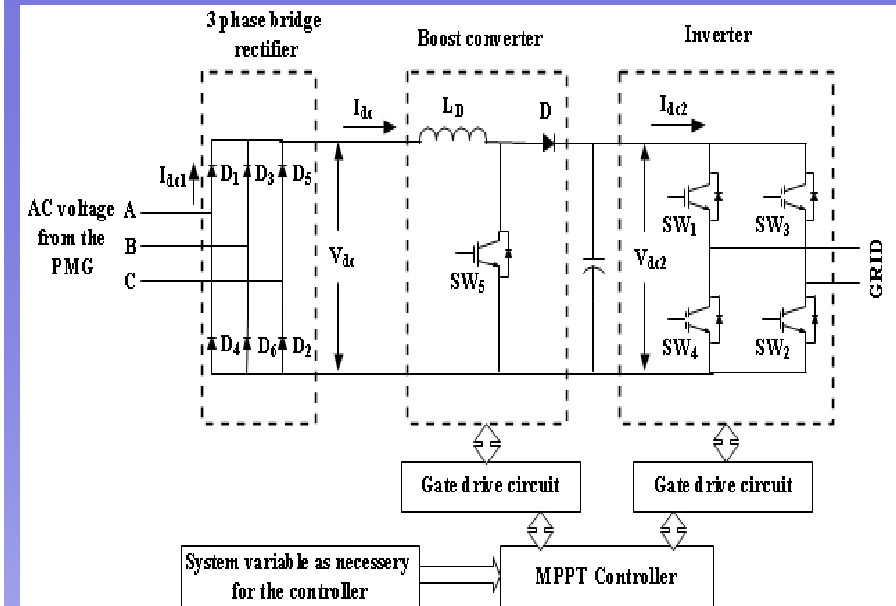


Efficiency

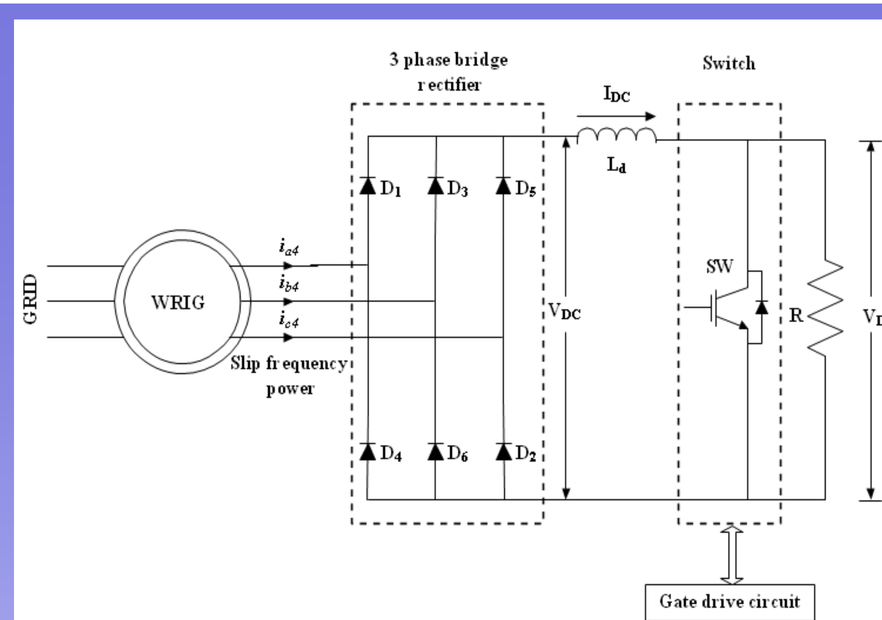
- **Energy capture is about the same for both systems**
- **Energy loss of the PMG-based system is higher**
- **Efficiency of the PMG based system is lower**

WRIG-based system provides a better characteristics than the PMG-based system and considered to be an optimum alternative

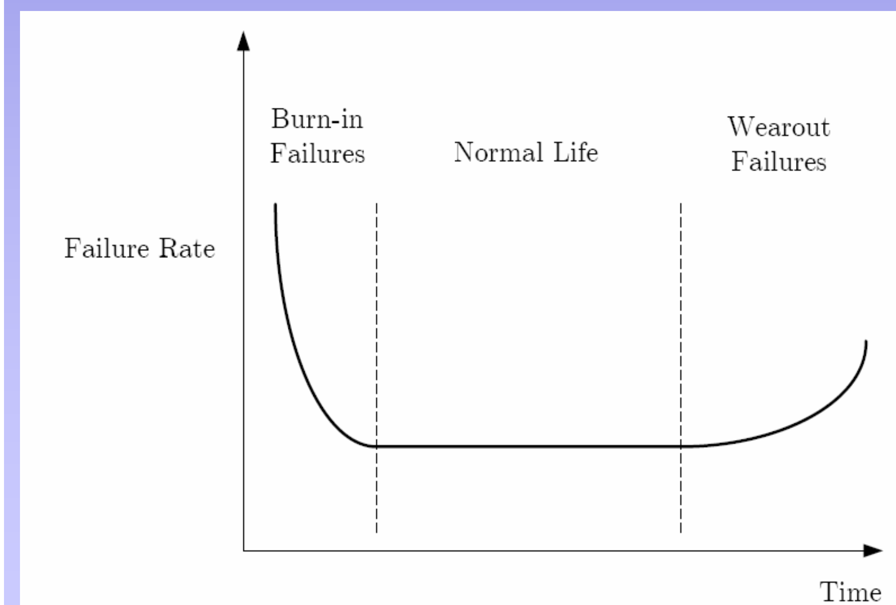
Reliability Analysis



PCS of the PMG



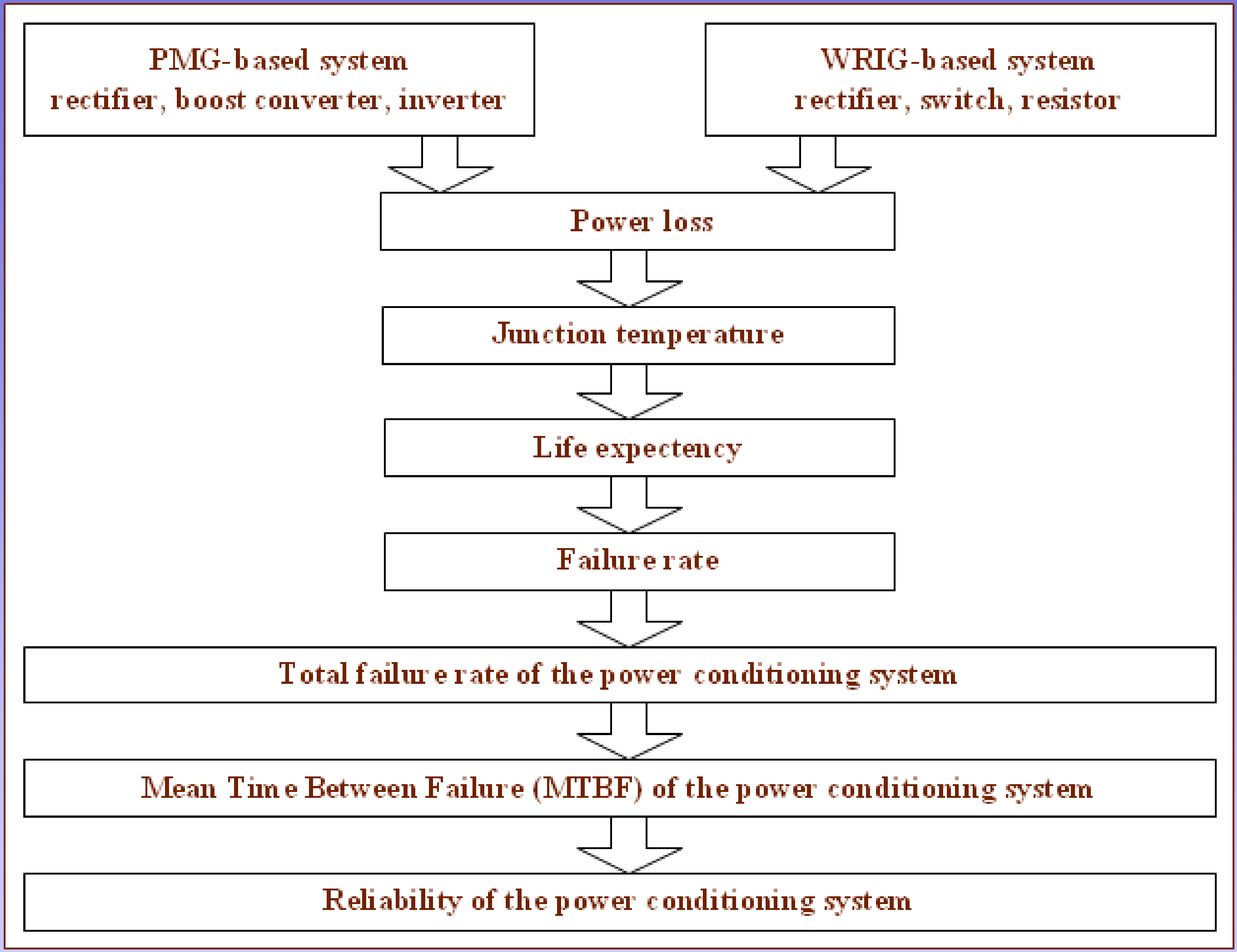
PCS of the WRIG



Bathtub curve

Power conditioning system reliability

- Bathtub curve is used to determine the reliability
- Normal life time is considered where the failure rate is constant
- Burn-in and wear-out period is ignored



Calculation of the reliability for the systems

Reliability Results

Quantity	Rectifier	Boost Converter		Inverter	
	Diode	Diode	IGBT	Diode	IGBT
Power loss [W]	.5587	4.2581	22.3313	2.05459	7.9621
Junction temperature [^{0}K]	298.8101	304.1742	321.4478	303.5238	314.7205
Life expectancy [hr]	9.895×10^5	9.24×10^5	7.5273×10^5	9.3158×10^5	8.1311×10^5
Failure rate [hr^{-1}]	1.0106×10^{-6}	1.0823×10^{-6}	1.3285×10^{-6}	1.0734×10^{-6}	1.2298×10^{-6}

PMG-based system reliability

Quantity	Rectifier	Chopper	External resistor
	Diode	IGBT	
Power loss [W]	.9028	2.0602	31.5280
Junction temperature [^{0}K]	299.3091	302.3264	---
Life expectancy [hr]	9.8311×10^5	9.458×10^5	7.2464×10^6
Failure rate [hr^{-1}]	1.0172×10^{-6}	1.0573×10^{-6}	1.38×10^{-7}

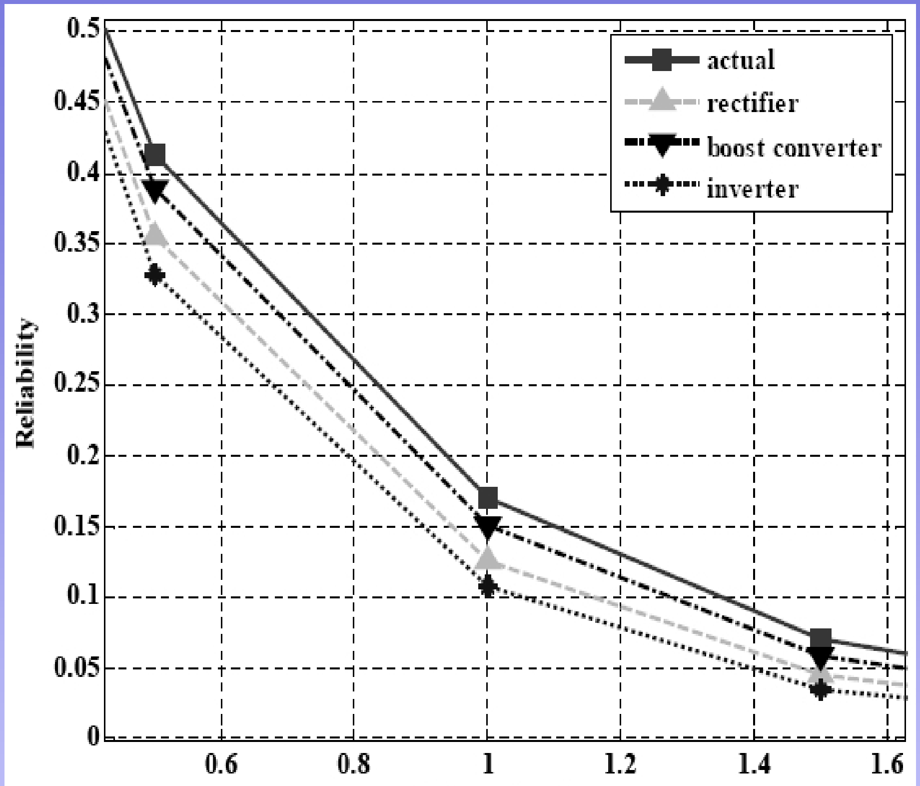
WRIG-based system reliability

Comparison of failure rate and MTBF

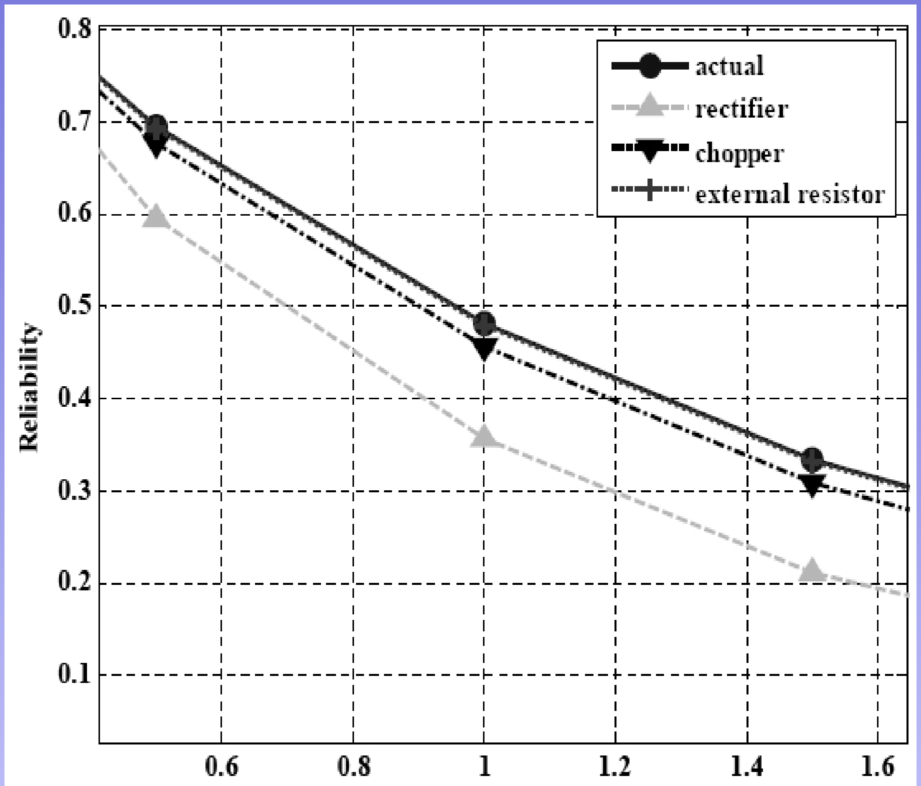
Grid connected system	Failure rate [hr^{-1}]	MTBF [hrs]
PMG-based system	1.7688×10^{-5}	5.6537×10^4 (~6.5 years)
WRIG-based system	7.2984×10^{-6}	1.3702×10^5 (~15 years)

- **A small wind turbine usually designed for 10~20 years**
- **The WRIG-based system is more reliable than the PMG-based system**

Identification of the least reliable component



(a) Time (hour)



(b) Time (hour)

PMG-based system

WRIG-based system

- **The least reliable component in the PMG-based system is inverter, while it is rectifier for the WRIG-based system**

Summary

- **A complete system level analysis, simulation and experimental evaluation of the grid connected PMG and WRIG-based small wind turbine systems has been presented**

- **A small wind turbine emulator development and experimental results have been presented**

- **A comparison has been presented for PMG and WRIG-based systems in terms of**
    - **Power loss**
    - **Energy capture, energy loss**
    - **Efficiency**
    - **Reliability**

- **Identification of the least reliable component of the PMG and WRIG-based system has been presented**

- **The comparison presented in the proposed research validates that the WRIG-based system could be an optimum alternative compared to the PMG-based system**

Thesis Contribution

• Review of grid connected systems and reliability of subsystems (J6, C6)

• Efficiency comparison based on simulation for both systems (J2, J3, C3, C4, C5)

• Experimental evaluation using test bench for both systems (J1, C1)

• Determination of reliability and identify the least reliable component for both systems (J4, C2)

Future Works

• Impact of different modulation techniques on power loss

• Comparison can be extended by using other PCS

• Reliability data can be collected for several years and compare with the theoretical values

List of Publications

Journals

- J1. Md. Arifujjaman, M.T. Iqbal, J.E. Quaicoe, “Experimental Verification of Performances of Grid Connected Small Wind Energy Conversion Systems,” Under review with the Wind Engineering Journal, 2010.
- J2. Md. Arifujjaman, M.T. Iqbal, J.E. Quaicoe, “Performance Comparison of Grid Connected Small Wind Energy Conversion Systems,” Wind Engineering, vol. 33, no. 1, pp. 1–18, 2009.
- J3. Md. Arifujjaman, M.T. Iqbal, J.E. Quaicoe, “Analysis of Conversion Losses in Grid Connected Small Wind Turbine Systems,” The Open Renewable Energy Journal, ISSN 1876-3871, vol. 2, pp. 59–69, 2009.
- J4. Md. Arifujjaman, M.T. Iqbal, J.E. Quaicoe, “Reliability Analysis of Grid Connected Small Wind Turbine Power Electronics,” Applied Energy Journal, vol. 86, Issue 9, pp. 1617–1623, 2009
- J5. Md. Arifujjaman, M.T. Iqbal, J.E. Quaicoe, “Emulation of a Small Wind Turbine System with a Separately-Excited DC Machine,” Journal of Electrical and Electronic Engineering, Istanbul University, vol. 1, Issue 15, no. 1, pp. 569–579, 2008.
- J6. Md. Arifujjaman, M.T. Iqbal, J.E. Quaicoe, “Vector Control of a DFIG based Wind Turbine,” Journal of Electrical and Electronic Engineering, Istanbul University, vol. 9, Issue 18, no. 2, pp. 1057–1066, 2009

Conferences

- C1. Md. Arifujjaman, M.T. Iqbal, J. E. Quaicoe, “Efficiency Comparison of Two Possible Grid Connected Small Wind Turbine Systems,” Accepted to IEEE Electrical Power and Energy Conference (EPEC), August 25 – 27, 2010, Halifax, Nova Scotia, Canada.
- C2. Md. Arifujjaman, M.T. Iqbal, J. E. Quaicoe, “A Comparative Study of Power Electronics Reliability in Grid Connected Small Wind Turbine Systems,” IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), May 3 – 6, 2009, St. John’s, NL, Canada.
- C3. Md. Arifujjaman, M.T. Iqbal, J. E. Quaicoe, “A Comparative Study of Conversion Losses in Grid Connected Small Wind Turbine Systems,” Canadian Wind Energy Association (CanWEA), October 19 – 22, 2008, Vancouver, BC, Canada.
- C4. Md. Arifujjaman, M.T. Iqbal, J. E. Quaicoe, “Loss Calculation in Grid Connected PMG-based Small Wind Turbine Systems,” IEEE Newfoundland Electrical and Computer Engineering Conference (NECEC), November 6, 2008, St. Johns, NL, Canada.
- C5. Md. Arifujjaman, M.T. Iqbal, J. E. Quaicoe, “Conversion Losses in Utility Interfaced Small Wind Turbine Systems,” Aldrich Conference, February 8-10, 2008, St. John’s, NL, Canada.
- C6. Md. Arifujjaman, M.T. Iqbal, J. E. Quaicoe, “Simulation and control of a DFIG based wind turbine,” IEEE Newfoundland Electrical and Computer Engineering Conference (NECEC), November 8, 2007, St. Johns, NL, Canada.

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Thank You for your attention and presence

Questions/Comments