AN ISOLATED SMALL WIND TURBINE EMULATOR

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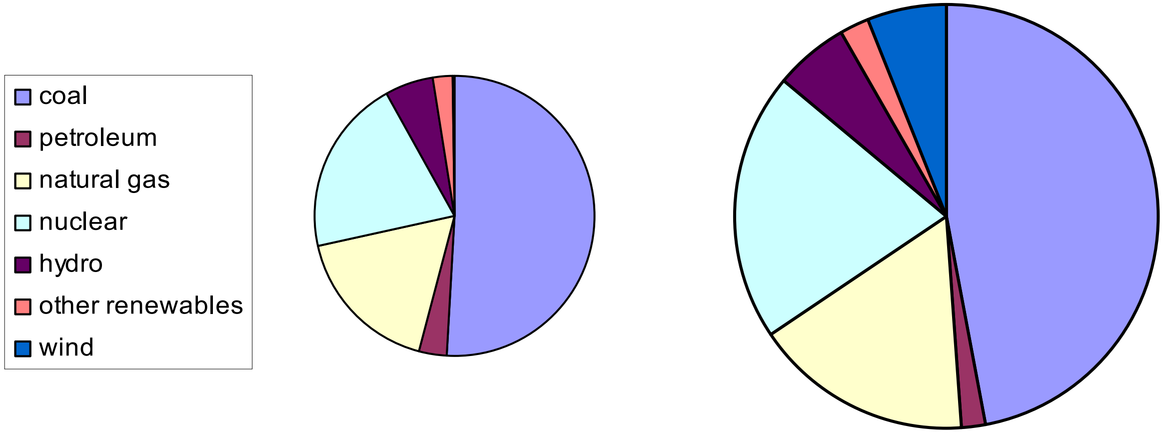
Outline

- Introduction
- Control Objectives of a Wind Turbine
- Control Strategy Selection Principle
- Modeling of the Small Wind Energy Conversion System
- Simulation Results
- Implementation of the Small Wind Turbine Emulator
- Structure of the Maximum Power Point Controller
- Test Results
- Conclusions

Introduction

- **Wind is renewable and cost effective.**
- **Wind causes a little harm to the nature.**



Wind could generate 6% of the nation's power by 2020.

Wind currently produces less than 1% of the nation's power.

Source: Energy Information Agency

- **Ready to become a significant power source.**

Sizes, Applications and A Typical Wind Power Generation System

Small (≤10 kW)
- ⇨ Homes
- ⇨ Farms
- ⇨ Remote Applications

Intermediate (10-250 kW)
- ⇨ Village Power
- ⇨ Hybrid Systems
- ⇨ Distributed Power

Large (660 kW - 2+MW)
- ⇨ Central Station Wind Farms
- ⇨ Community Wind

A Typical Wind Power Generation System

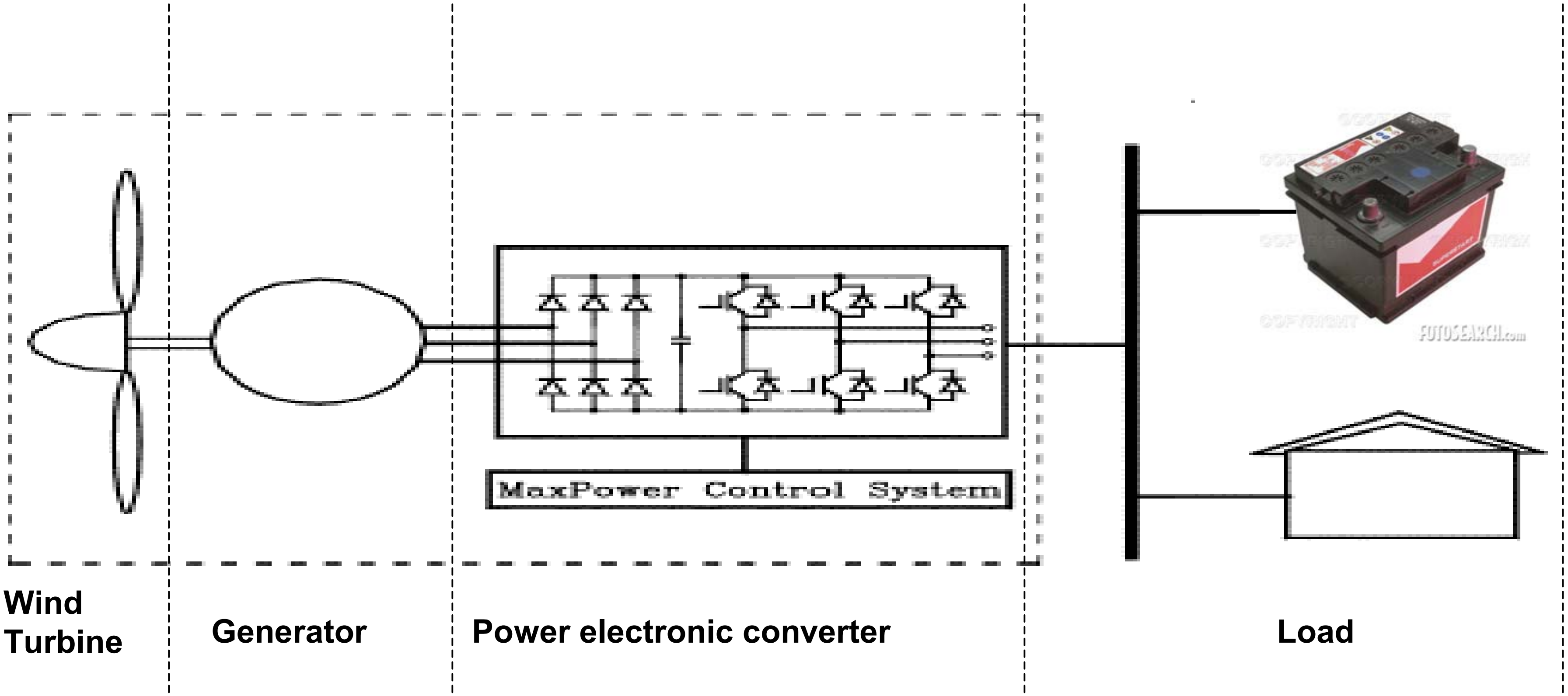


Fig. 1 A typical wind power generation system.

Control Objectives of a Wind Turbine

⇨ Limit the power input to the turbine so that all the mechanical and electrical components of the wind turbine are able to handle.

⇨ Extraction of the maximum power.

⇨ Maximize the energy capture.

⇨ Stabilize the system under all operating conditions.

⇨ Control the grid voltage and power by regulating the output of the wind turbine.

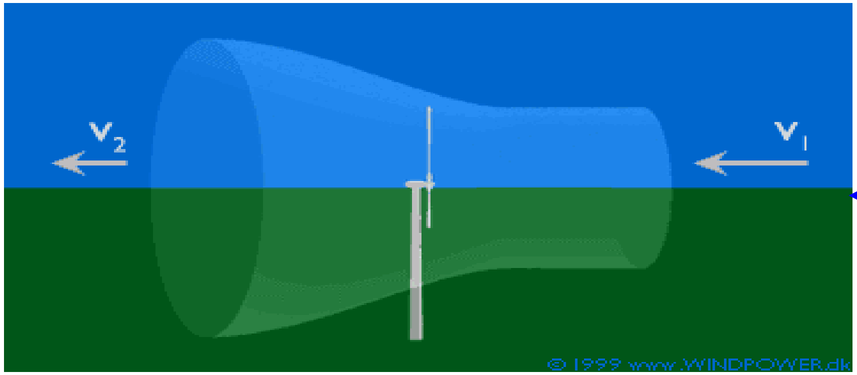
⇨ Reduce the drive train dynamics.

Control Objectives of a Wind Turbine

- ⇨ **Limit the power input to the turbine so that all the mechanical and electrical components of the wind turbine are able to handle.**
- ⇨ **Extraction of the maximum power.**
- ⇨ **Maximize the energy capture.**
- ⇨ **Stabilize the system under all operating conditions.**
- ⇨ **Assuming that the wind turbine will be operated in an isolated mode.**
- ⇨ **Assuming that the wind turbine system is of a direct drive system**

Control Strategy Selection Principle

Aerodynamic Power Control Strategy Selection Principle



Wind passing through the rotor plane

Relation between the aerodynamic power and wind speed is

$$P_{aero} \alpha V^3$$

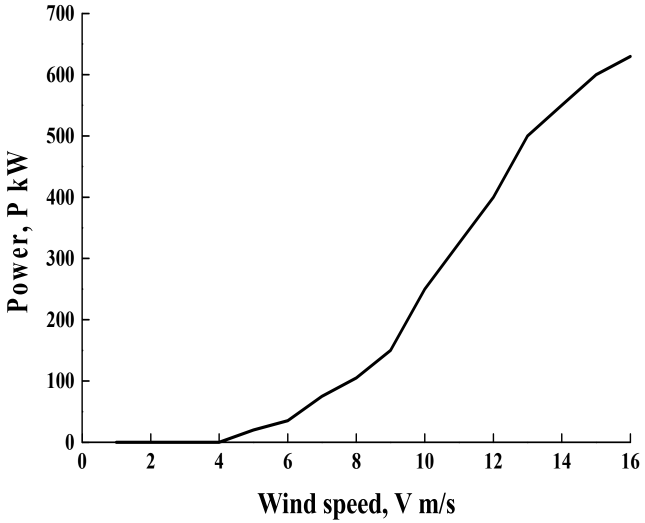
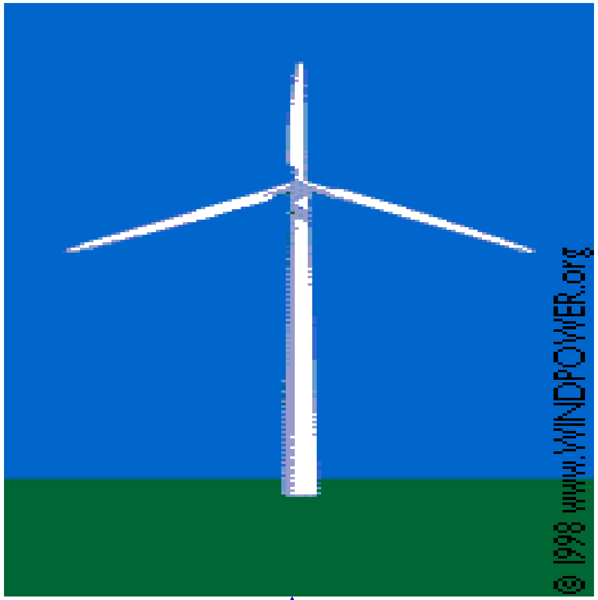


Fig. 2 Power curve

Furling control of Small Wind Turbines



Furling action

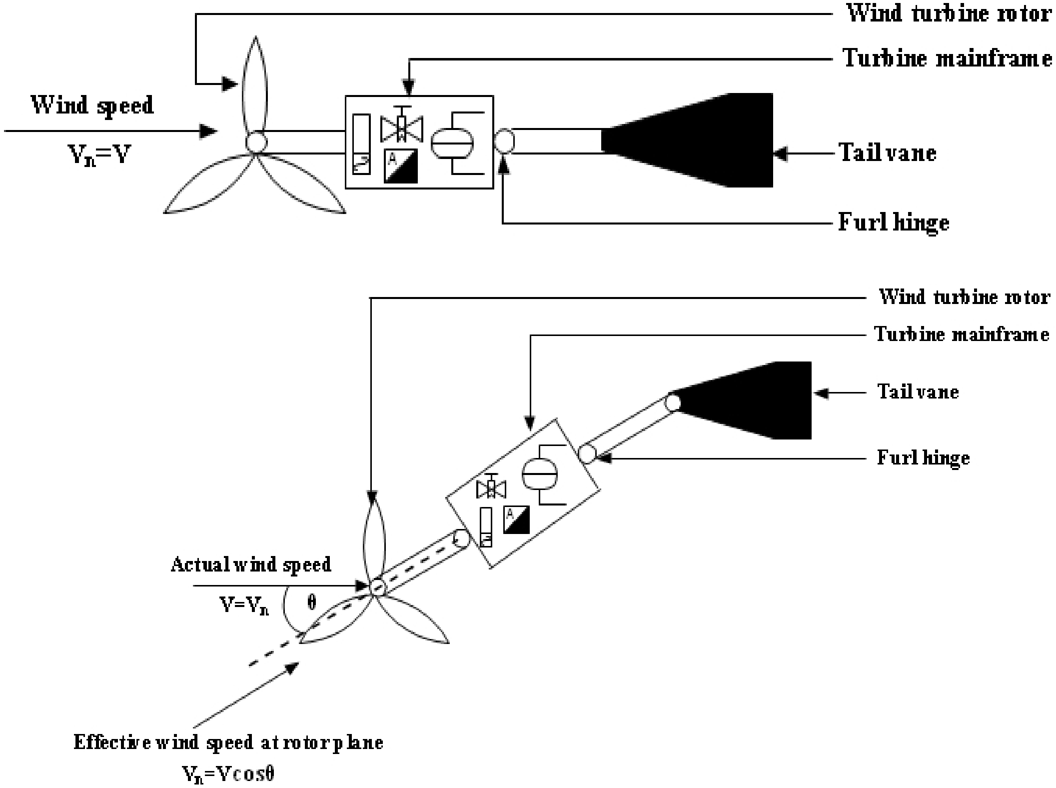


Fig. 3 Non furled and furled condition of a small wind turbine

Normal Condition $P_{aero}\ \alpha\ V^3$

Furled condition $P_{aero}\ \alpha\ (V\cos\theta)^3$

$$\theta = -0.00017327V^5 + 0.0085008V^4 - 0.12034V^3 + 0.4501V^2 + 1.0592V + 0.38972$$

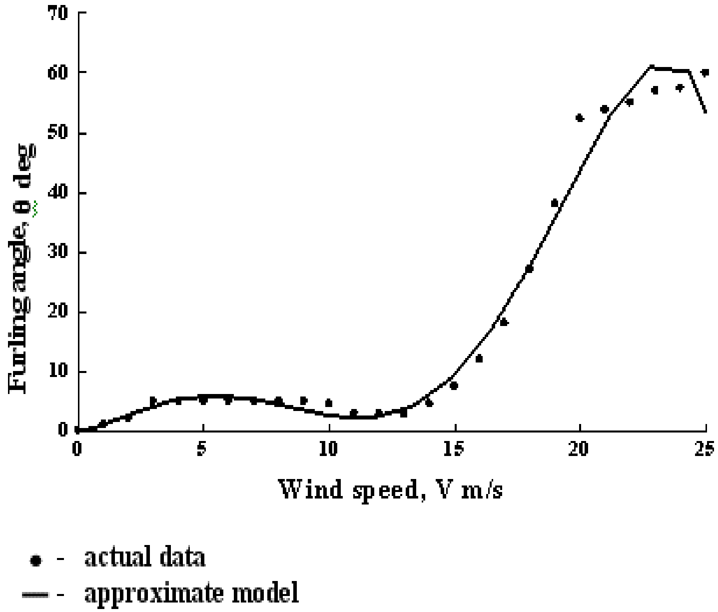


Fig. 4 Furling angle versus wind speed

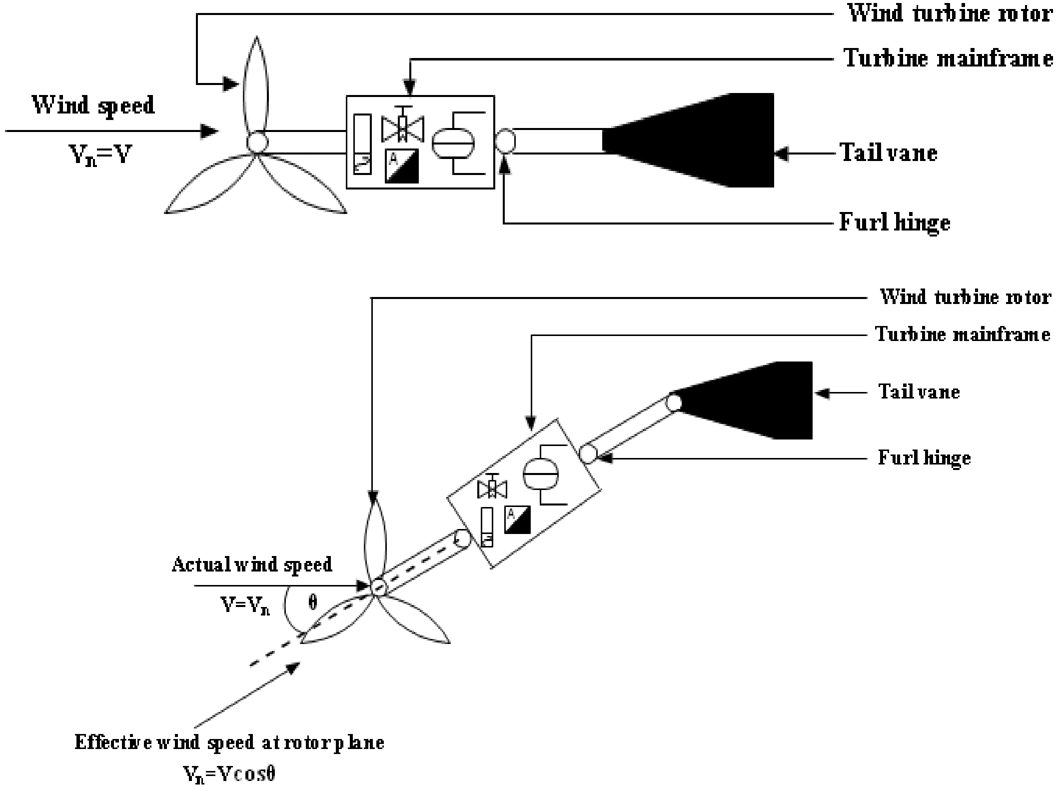


Fig. 3 Non furled and furled condition of a small wind turbine

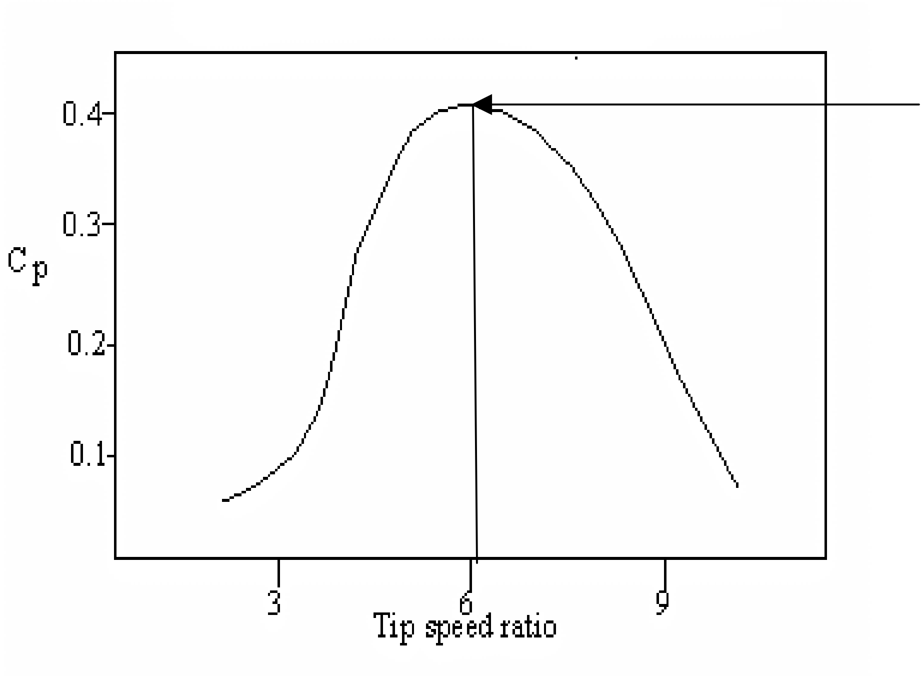
Normal Condition P_{aero} α V^3

Furled condition P_{aero} α $(V\cos\theta)^3$

Maximum Power Extraction Strategy Selection Principle

Tip-speed Ratio (TSR) Control

$$C_p = \frac{\text{Power extracted from the wind}}{\text{Power available in the wind}} \qquad \lambda = \frac{\text{Rotor radius * Rotor speed}}{\text{Wind speed}}$$



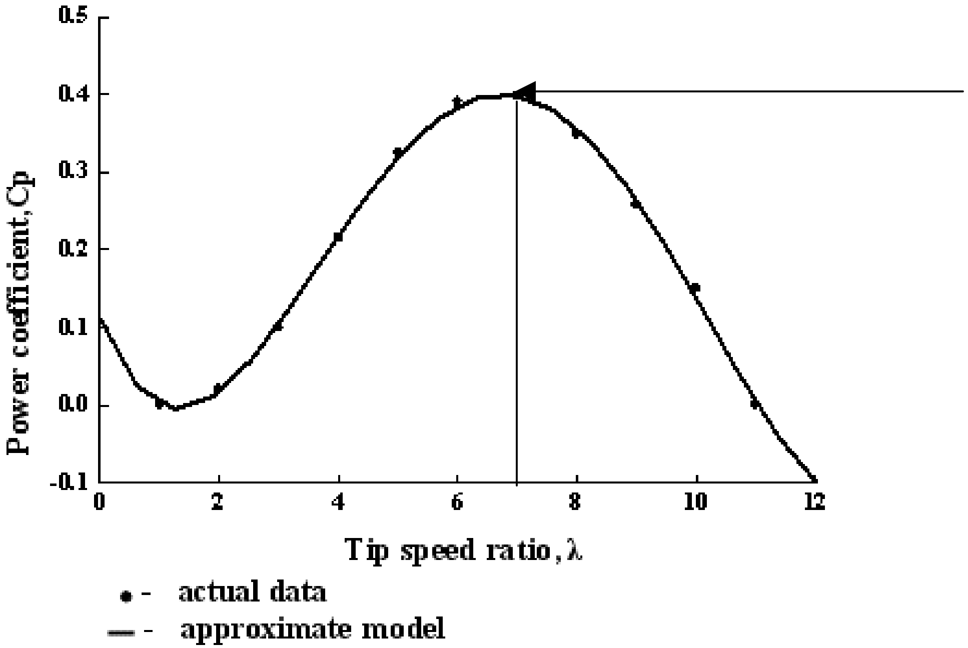
Maximum power will be extracted if the wind turbine operates at this point

Fig. 5 A typical power coefficient versus tip-speed ratio curve

Maximum Power Extraction Strategy Selection Principle

Tip-speed Ratio (TSR) Control

$$C_p(\lambda) = 0.00044\lambda^4 - 0.012\lambda^3 + 0.097\lambda^2 - 0.2\lambda + 0.11$$



Maximum power will be extracted if the wind turbine operates at this point

Fig. 6 Power coefficient versus tip-speed ratio curve

Hill Climbing (HC) Control

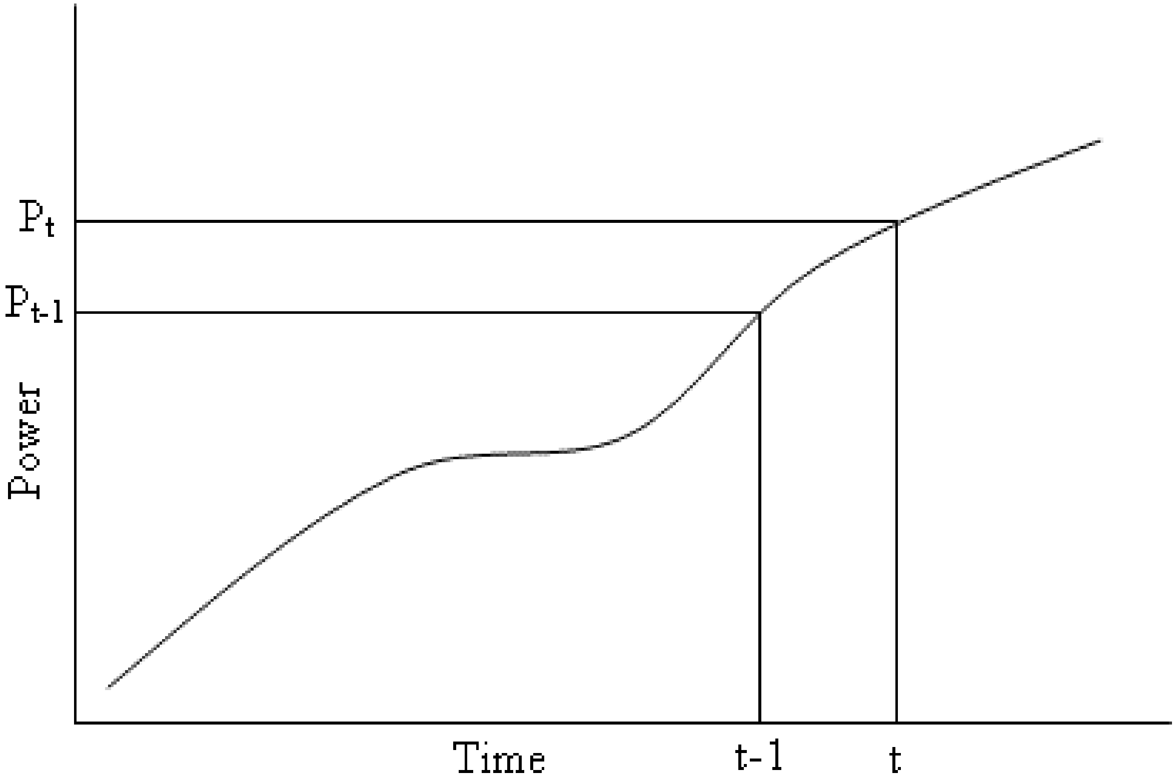
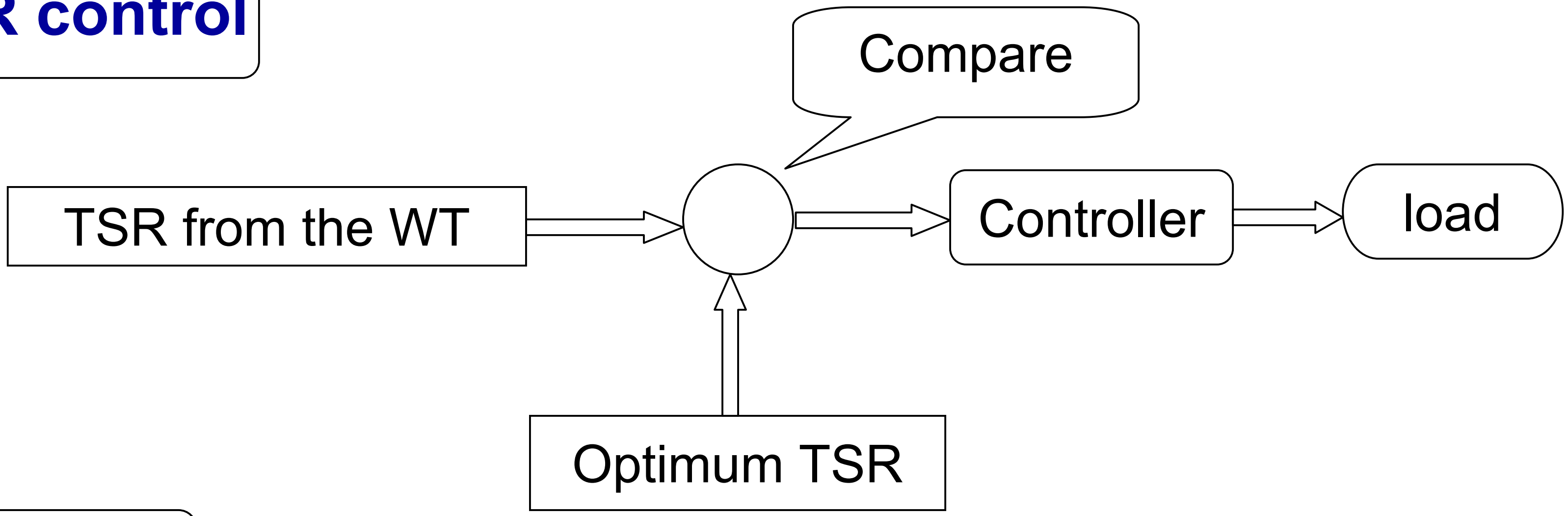


Fig. 7 Output power versus time

TSR control



Compare

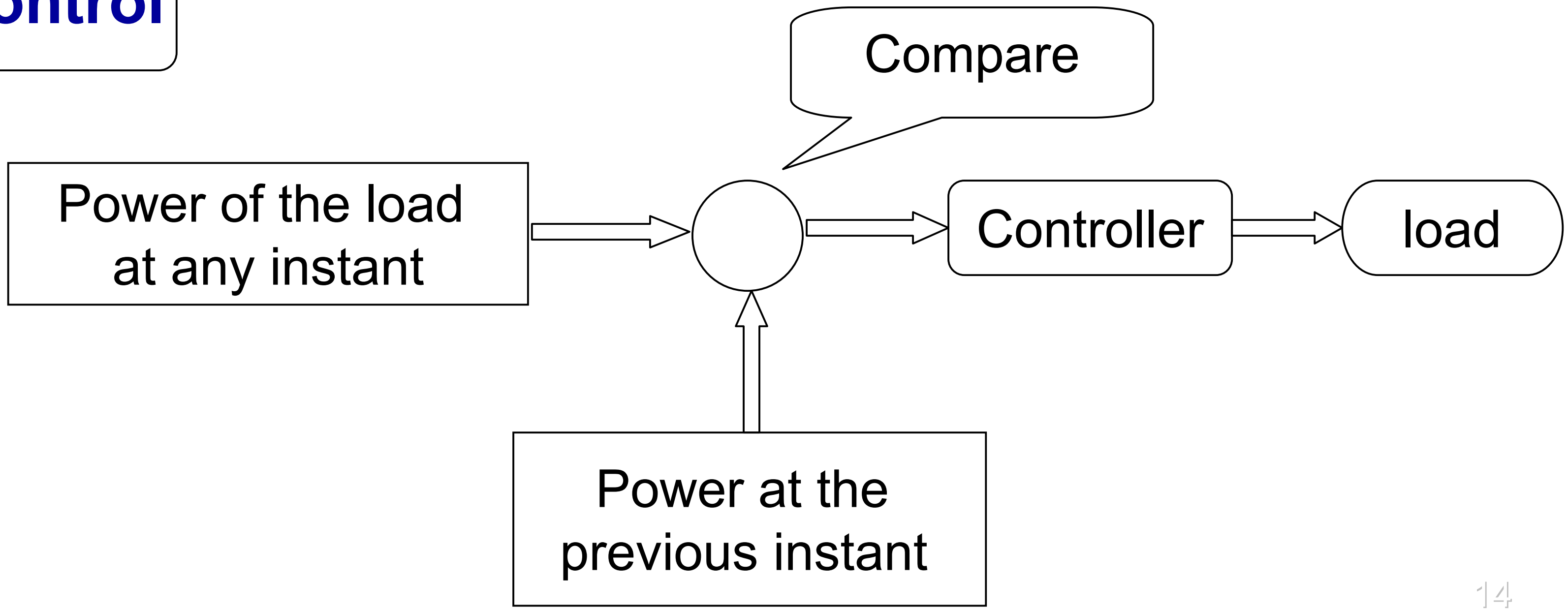
TSR from the WT

Controller

load

Optimum TSR

HC control



Compare

Power of the load at any instant

Controller

load

Power at the previous instant

Annual Energy Capture

Wind speed at the tower height ,X= Y*(H_2/H_1) ^ α

Where, α is the shear exponent and can be expressed as

α= 0.096log10 (Z_0)+0.016(log10 (Z_0))^2+0.24

Where, Z_0 is the Surface roughness of St. John's, Newfoundland.

Annual energy output =P_{mean} * 8765

Where P_{mean} = $\sum$(Average power for a particular wind speed * No. of hour that occurs for a particular wind speed for one year)/ $\sum$the time for which the particular wind speed occurs in one year

Modeling of the Small Wind Energy Conversion System

Wind Turbine:

Power of the wind turbine, $P_{aero} = 0.5\ \rho\ A\ C_p\ (\lambda)\ V^3$

Torque of the wind turbine, $T_w = P_{aero}/\omega_m$

If θ is the furling angle in degree the effective wind velocity on the rotor plane is $V\cos\theta$

So torque term can be expressed as

$T_w = 0.5\ \rho\ A\ R\ C_t\ (\lambda)^*\ (V\cos\theta)^2$

Dynamics due to furling action is $1/(1.3s^2+s+1)$

Permanent Magnet Synchronous Generator:

The electromagnetic torque can be expressed as

$T_e = (3/2)(P/2)\ [(L^g{}_d - L^g{}_q\ )\ i^g{}_q\ i^g{}_d\ - \lambda_m i^g{}_q]$

The rotational speed and torque produced by the wind turbine can be related as

$T_w = J\ p\omega_m - T_e + B\ \omega_m$

Stator voltage can be expressed as

$V^g{}_s = -\ (R^g + p\ L_g)\ i^g{}_q + \lambda_m\ \omega_r$

Rectifier:

Rectifier voltage can be expressed as

$V_R = (3 * \sqrt{3} / \Pi) * V^g_s$

Rectifier current can be expressed as

$I_R = P_{load} / V^g_s$

Inverter:

Inverter has been modeled using the PWM principle.

Load:

Load has been considered as a series resistance and inductance .

Simulation Results

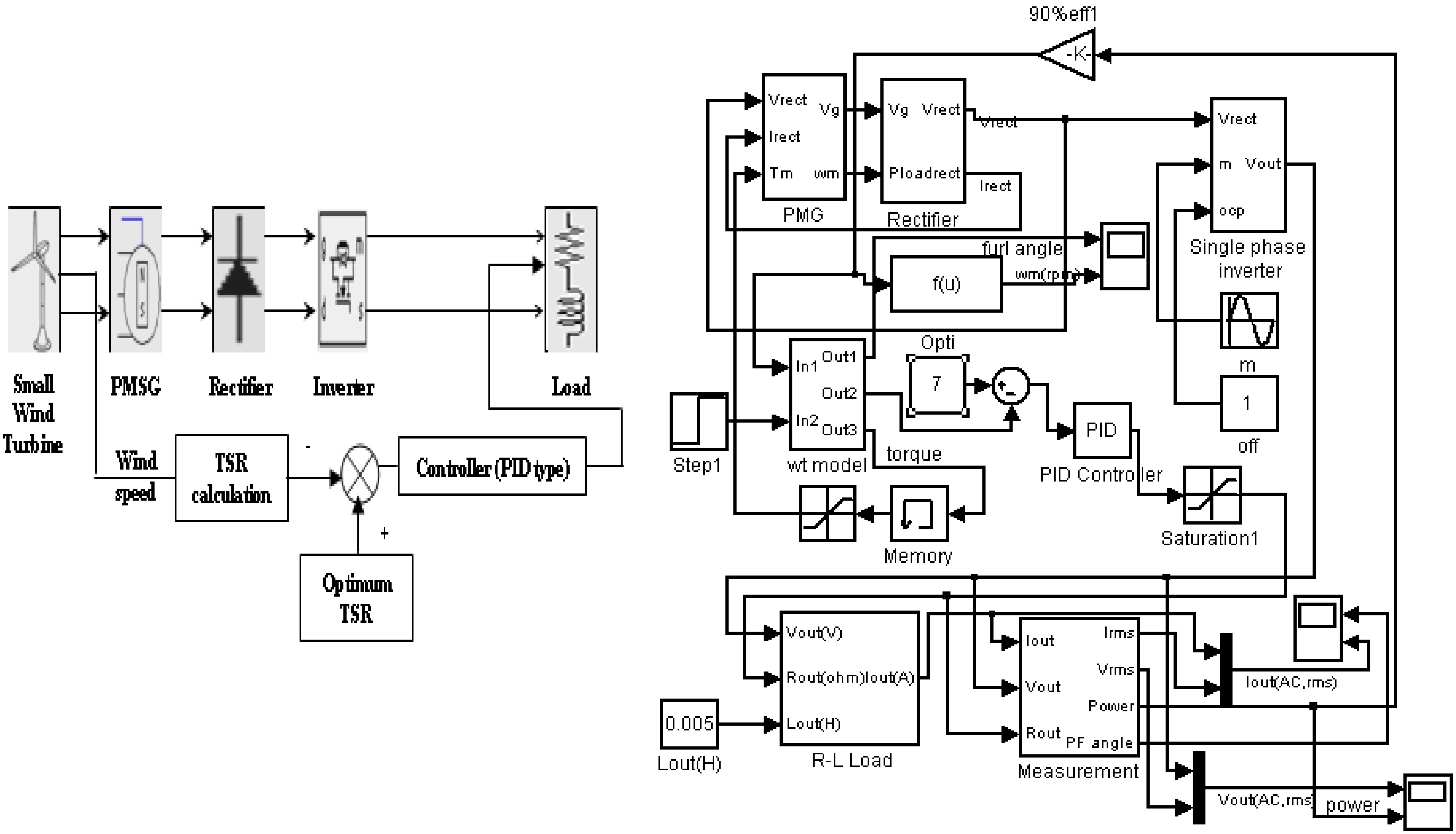


Fig. 8 Tip-speed ratio control of the wind turbine

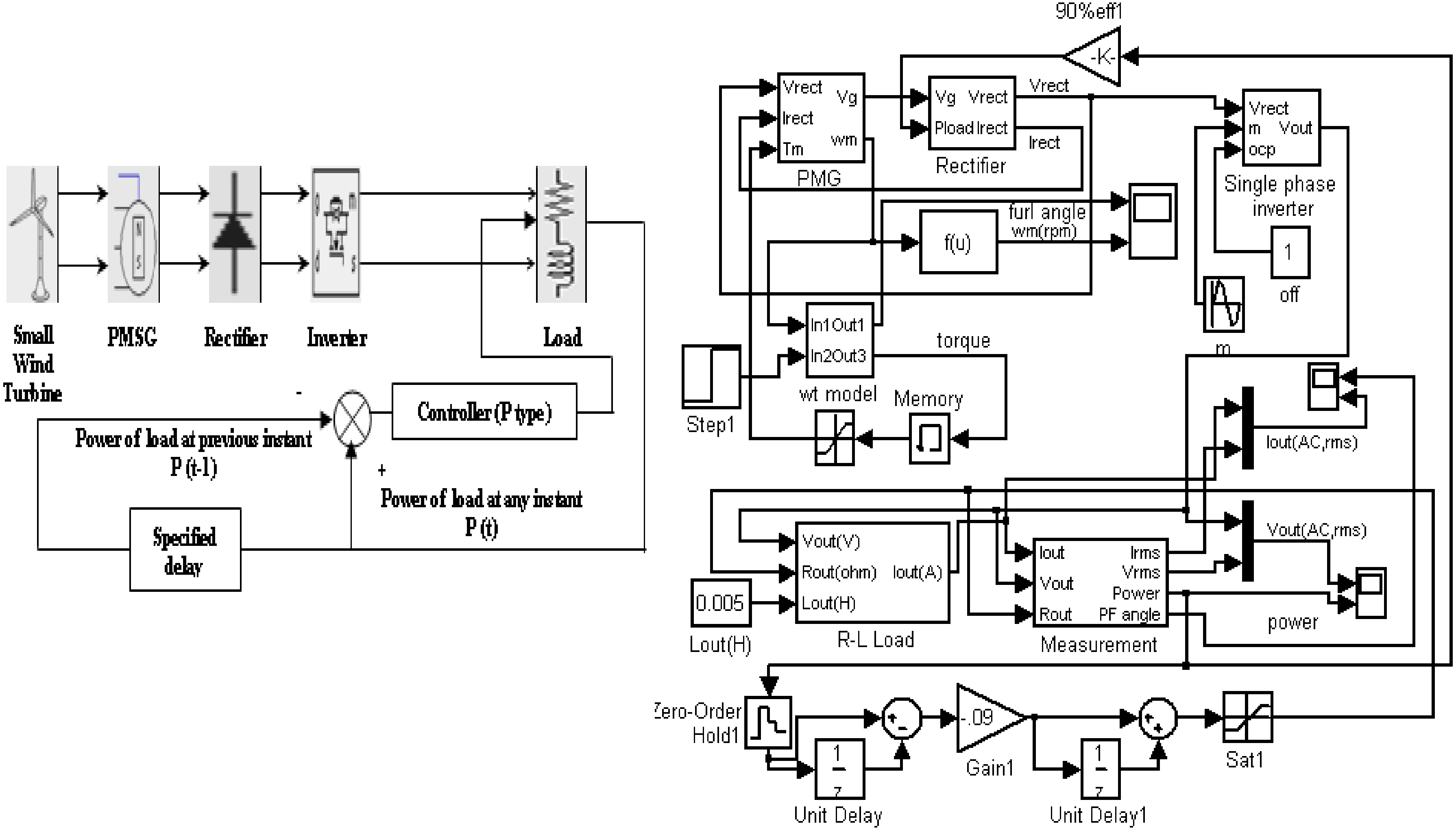


Fig. 9 Hill climbing control of the wind turbine

Simulation results during the Tip-speed ratio control:

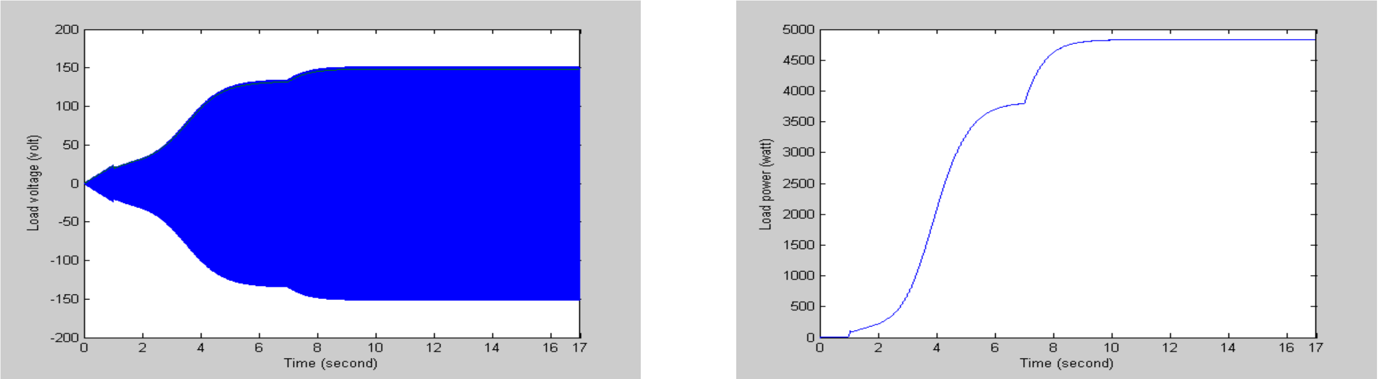


Fig. 10 PWM output of the inverter during the TSR control

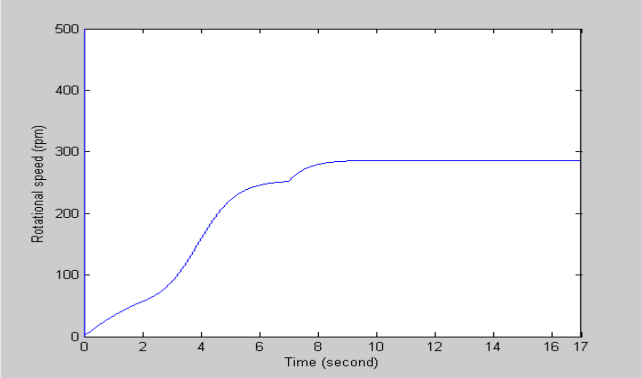


Fig. 11 Step response of the turbine with the TSR control

Simulation results during the hill climbing control:

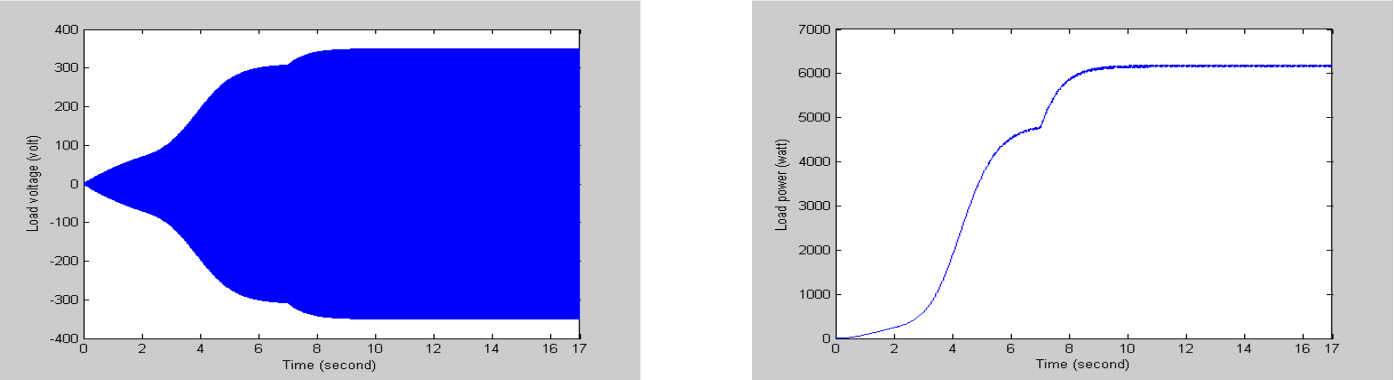


Fig. 12 PWM output of the inverter during the HC control

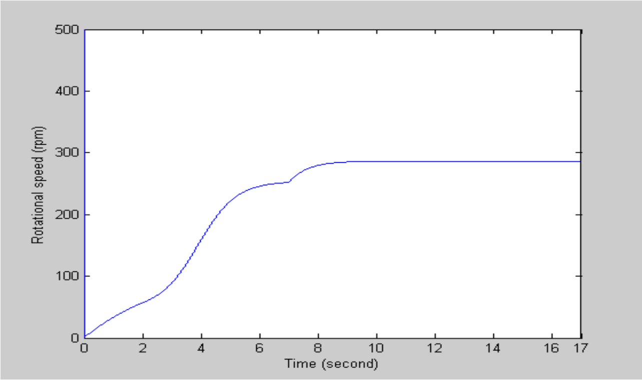


Fig. 13 Step response of the turbine with the HC control

Simulation results of furl action during the tip-speed ratio and hill climbing control:

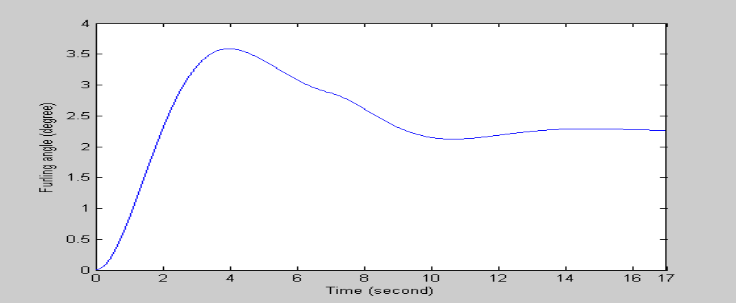


Fig. 14 Step response of the turbine with the TSR control

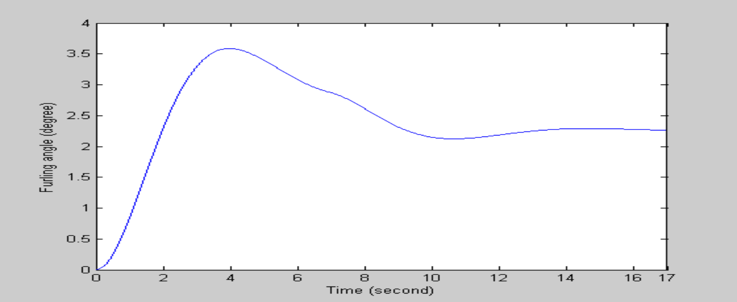


Fig. 15 Step response of the turbine with the HC control

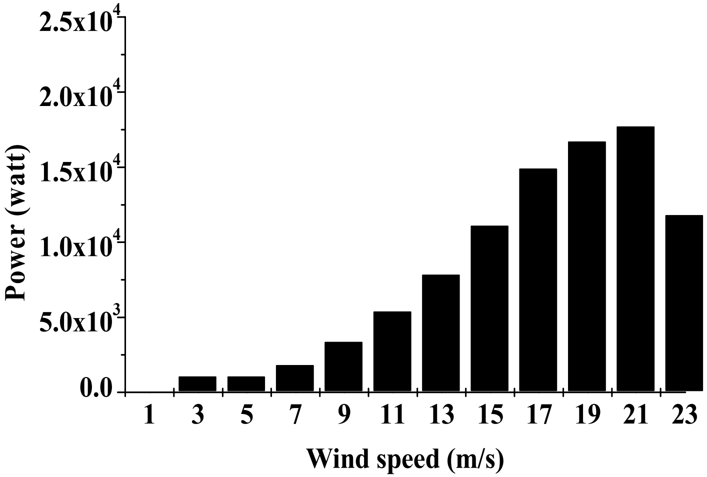


Fig. 16 Power output for the TSR control

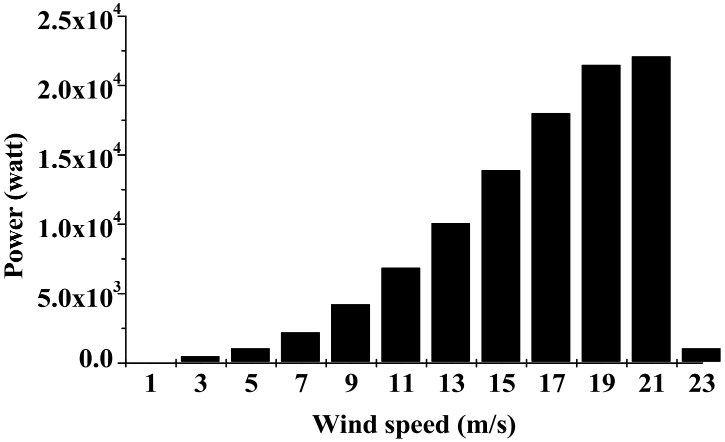


Fig. 17 Power output for the HC control

Annual energy capture during the tip-speed ratio and hill climbing control:

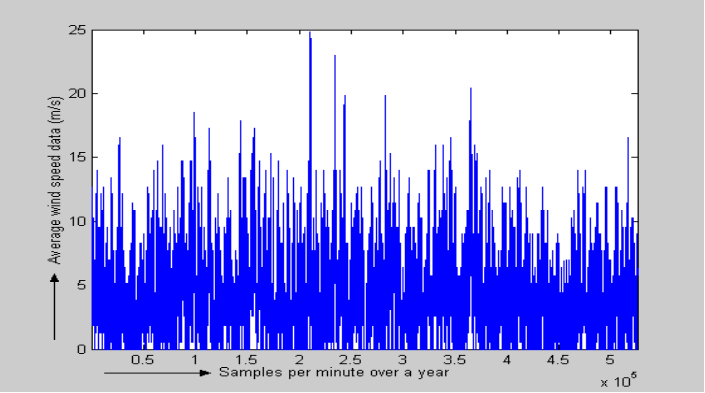


Fig. 18 wind speed at 30 meter height above ground

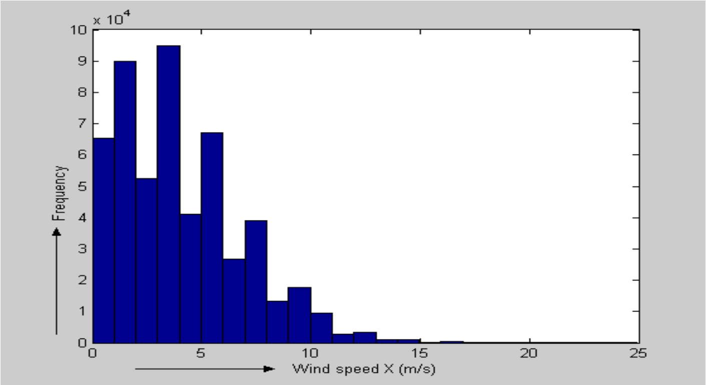


Fig. 19 Rayleigh distribution for St. John’s, Newfoundland

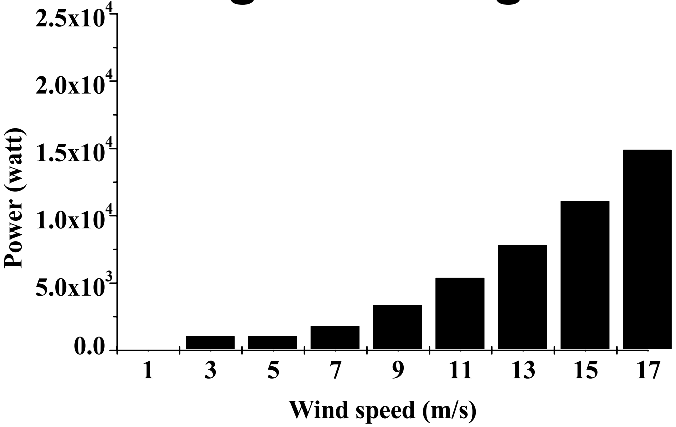


Fig. 20 Power output for the TSR control within St. John’s wind speed

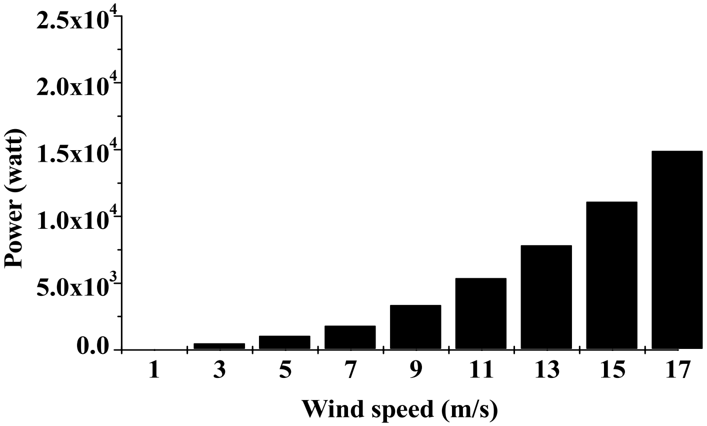


Fig. 21 Power output for the HC control within St. John’s wind speed

Suitable Parameter Values of the Strategies

Tip-speed ratio control:

K_p= 2.31 ; K_i = 49.5 ; K_d = 0.01675

Hill climbing control:

K_p = 0.009

Energy

The annual energy capture for the HC control strategy gives 4.94% more energy than the TSR control strategy.

Summary

- A PMSG based small wind turbine with furling dynamics has been modeled.
- A PID controller has been designed to control the load during the tip-speed ratio control.
- A Proportional controller has been designed to control the load during the hill climbing control.
- Annual energy capture has been calculated using the Bin’s power curve method and found that the hill climbing control strategy leads to a more energy capture than the tip-speed ratio control strategy.

Implementation of the Small Wind Turbine Emulator

Motivation and Challenges

- In order to deploy any wind turbine system it is necessary to emulate the steady state and dynamic behavior of the system.
- Test the power electronics and the controller performance in a laboratory environment to avoid problems at installation.
- Electricity generation using renewable energy sources is crucial for remote and isolated locations.
- In remote locations we would like to power the associated power electronics circuitry of the wind turbine from the wind turbine itself.

Wind Turbine Emulator can be a strong platform to deal with the above issues

Wind Turbine Emulator

A wind turbine emulator (WTE) is fundamentally a demonstration of a practical wind turbine in a laboratory environment.

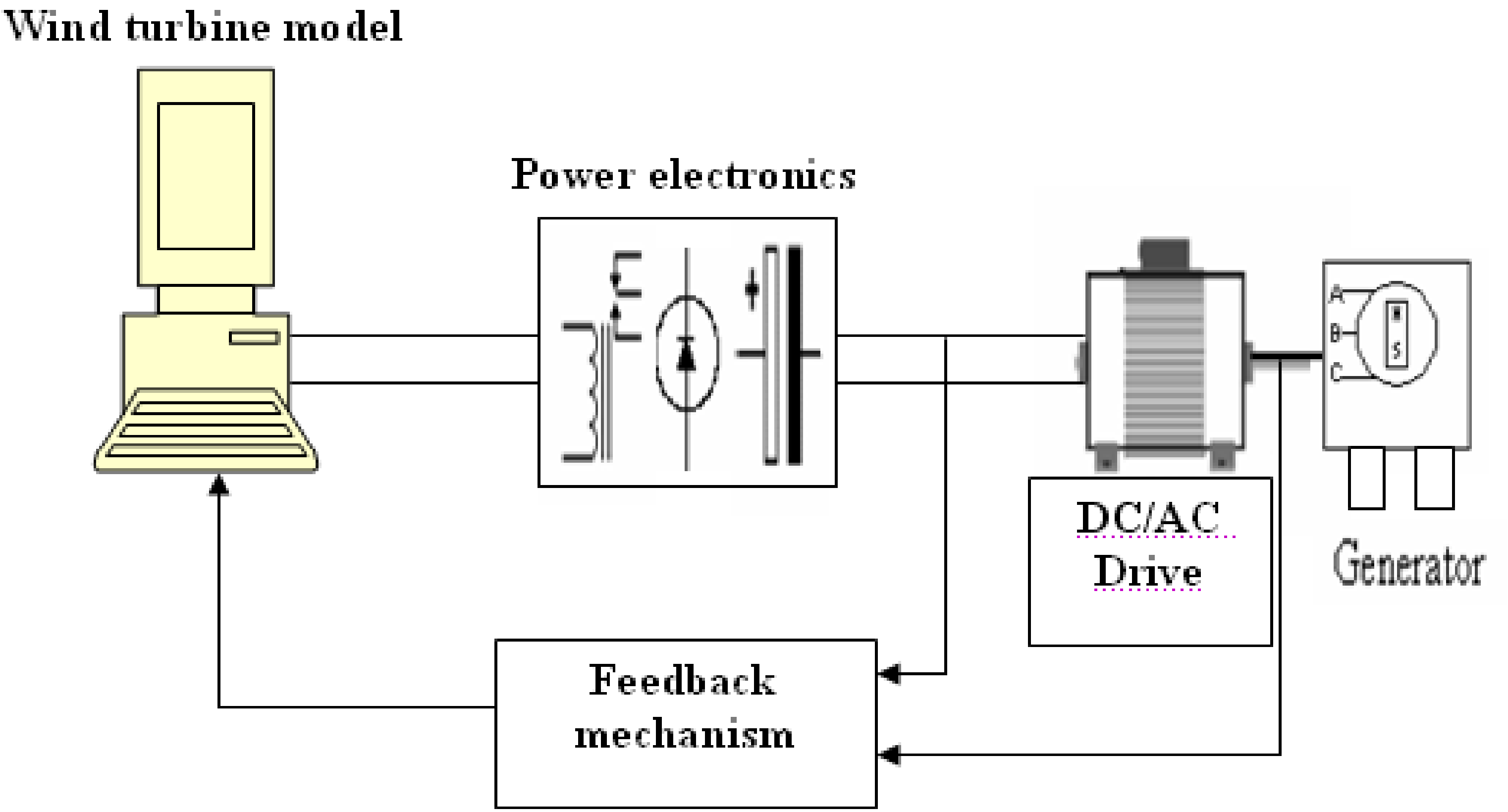


Fig. 22 A basic structure of wind turbine emulator

Wind Turbine Emulator characteristic

- Wind turbine model has been written in QBASIC 4.5 and furling dynamics are incorporated with the model.
- The small wind turbine emulator consists of a 3HP separately excited DC motor that drives a constant-field excited three phase synchronous generator.
- An inertia disk is coupled to the system to represent the inertia of a wind turbine rotor.
- Parameters of the separately excited DC motor have been determined by experimentation instead of going through manufacturers manual.
- Starting armature current has been limited through coding.

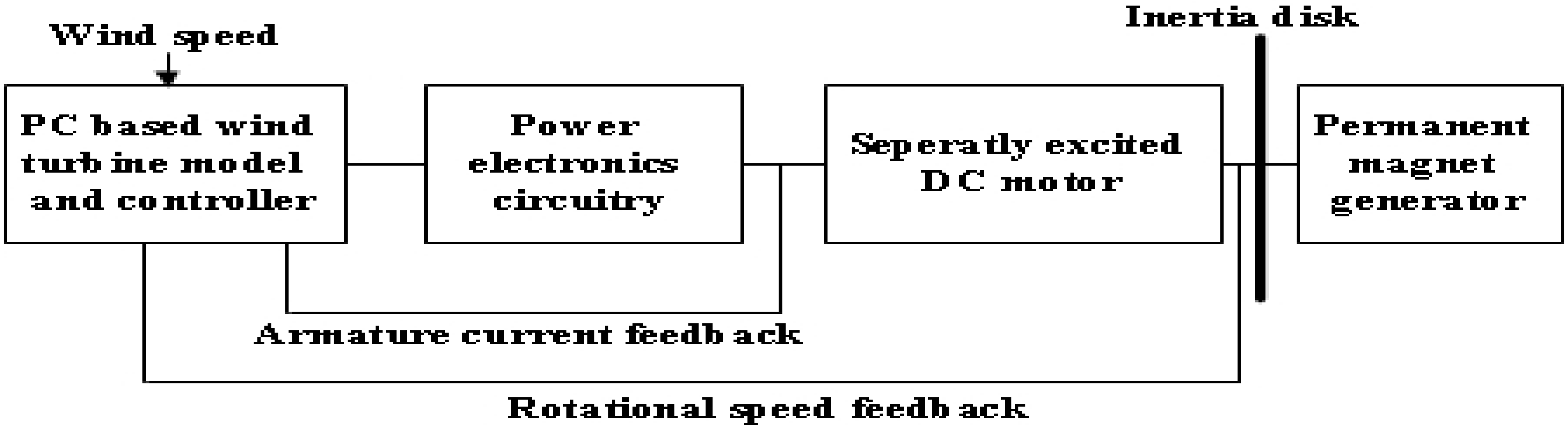


Fig. 23 A block diagram representation of the small wind turbine emulator

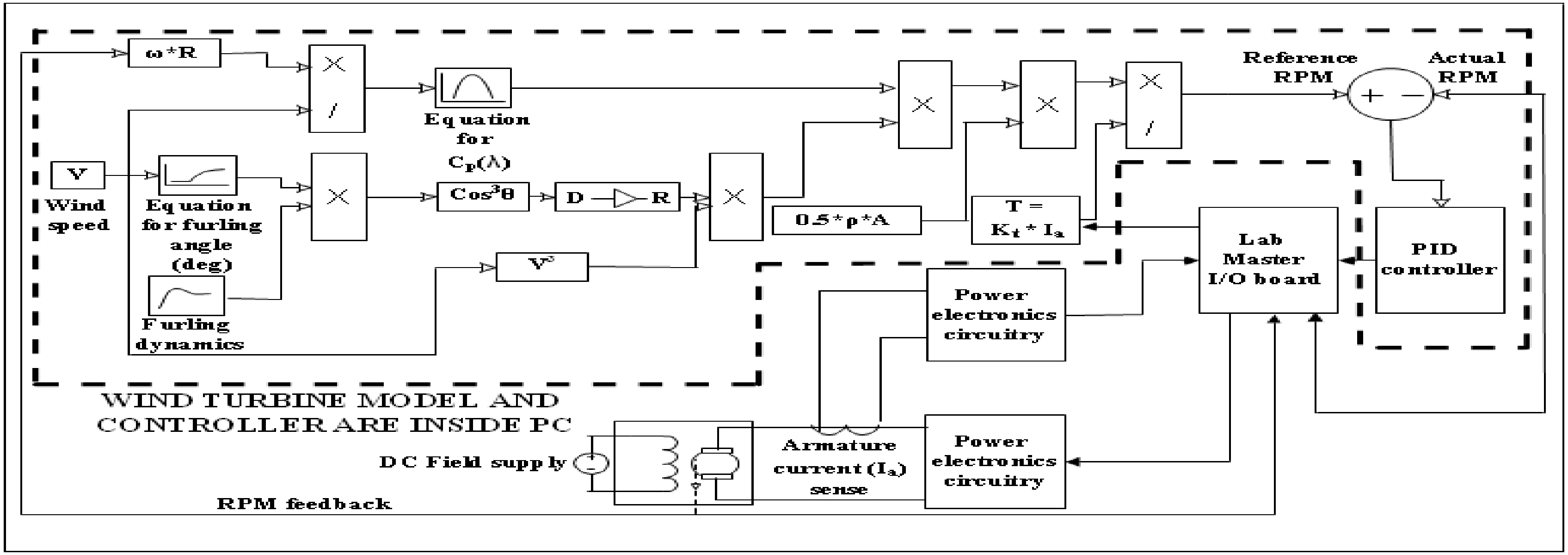


Fig. 24 The small wind turbine emulator structure with peripheral

Wind Turbine Section Power Electronics of the Emulator

Fig. 25 Photograph of the test-Rig

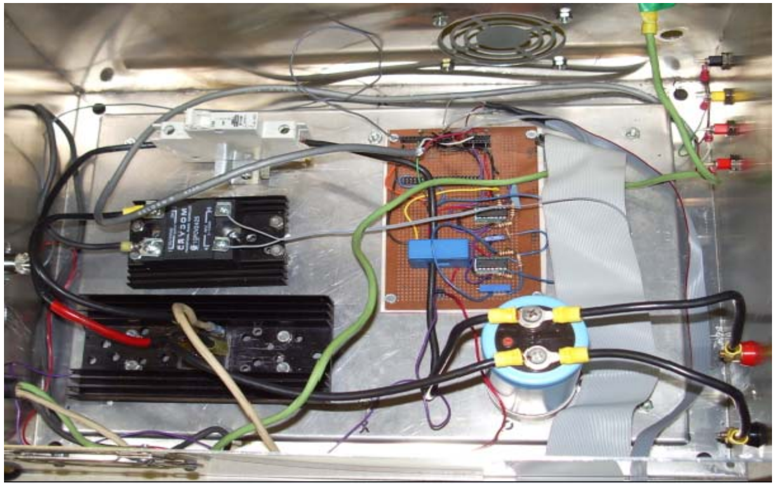


Fig. 26 Photograph of the power electronics circuitry

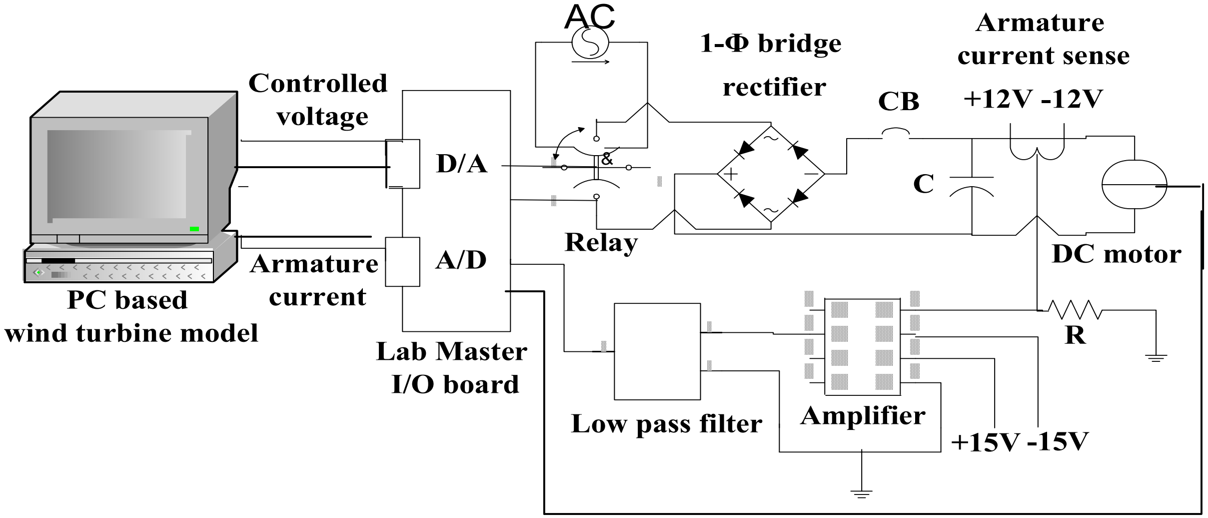


Fig. 27 Schematic of the wind turbine side of the emulator

Motor Parameter Calculation

Armature Resistance Calculation

Armature Resistance (R_a) =

Voltage at the motor armature/Current through the armature

Inertia Calculation

Inertia of the motor (J) = $T_m * K_t * K_e/R_a$

where, J is the moment of inertia of the motor,

T_m is the mechanical time constant of the motor,

K_t is the torque co efficient of the motor,

K_e is the back emf constant of the motor,

R_a is the armature resistance of the motor.

Back emf constant Calculation

$Ke = V_0/\omega_0$,

where, V_0 is the no load voltage of the armature

ω_0 is the no load speed of the motor

Torque co-efficient Calculation

$K_t = 9.5439e\text{-}3 * K_e$,

where, K_e is the back emf constant in V/krpm

K_t is the torque coefficient in N.m/A

Specification of the Inertia Disk for the Wind Turbine

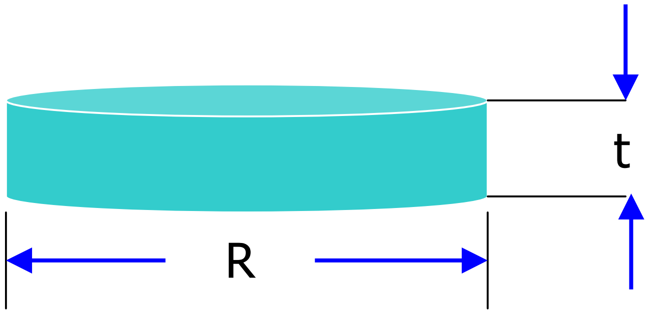


Fig. 28 Inertia disk of the small wind turbine rotor

For a solid cylinder inertia = (½) * MR^2

where, M is the mass of the solid disk

R is the radius of the disk and t is the thickness of the disk

Mass = Area * thickness * Density

Cast steel C 10/20 has been chosen as the disk material.

Results

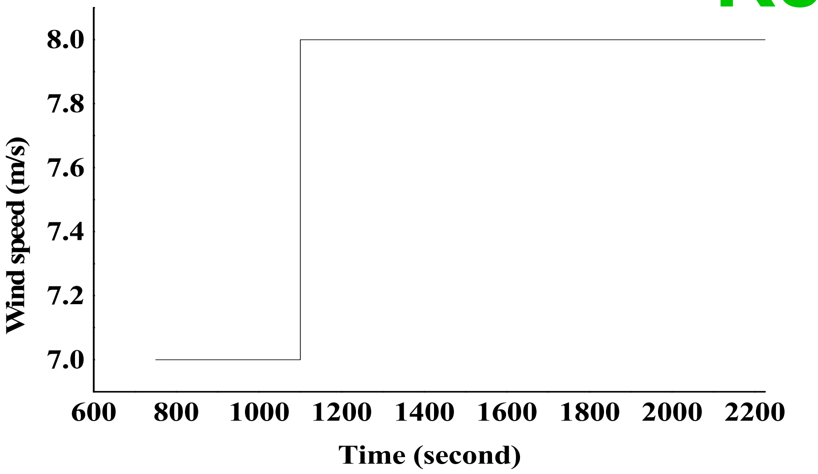


Fig. 29 Wind speed profile applied to the wind turbine emulator

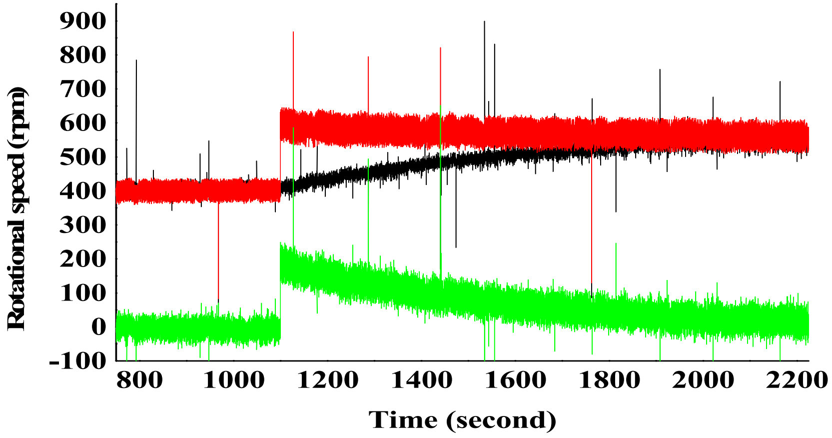


Fig. 30 Variation of the rotational speed

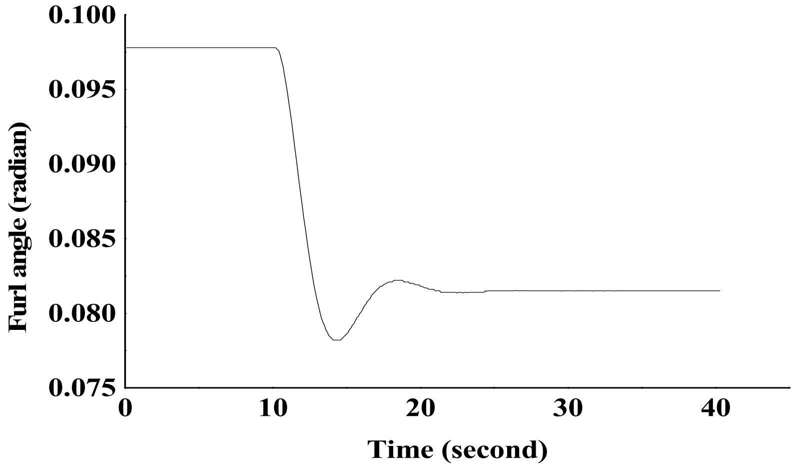


Fig. 31 Representation of the expected furl dynamics

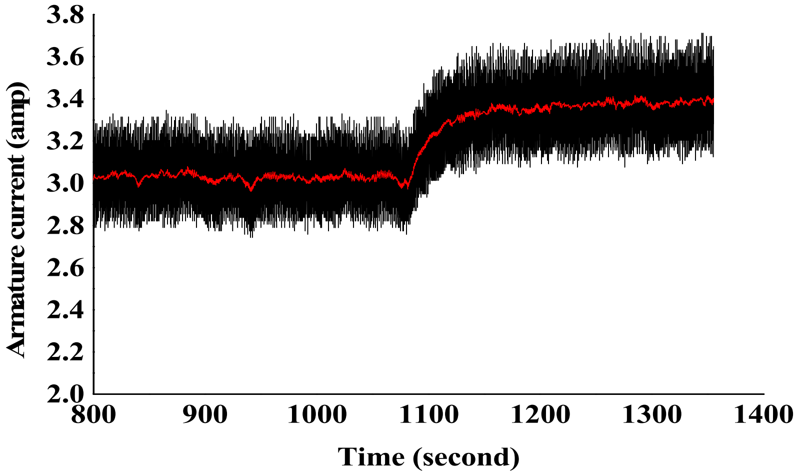


Fig. 32 Variation of the armature current with a step change in the load

Motivation and Challenges

- In order to deploy any wind turbine system it is necessary to emulate the steady state and dynamic behavior of the system.

- Test the power electronics and the controller performance in a laboratory environment to avoid problems at installation.
- Electricity generation using renewable energy sources is crucial for remote and isolated locations.
- In remote locations we would like to power the associated power electronics circuitry of the wind turbine from the wind turbine itself.

?????

- Maximum power extraction.
- Test the power electronics of the system.
- Power the associated power electronics circuitry of the wind turbine from the wind turbine itself.

Structure of the Maximum Power Point Controller

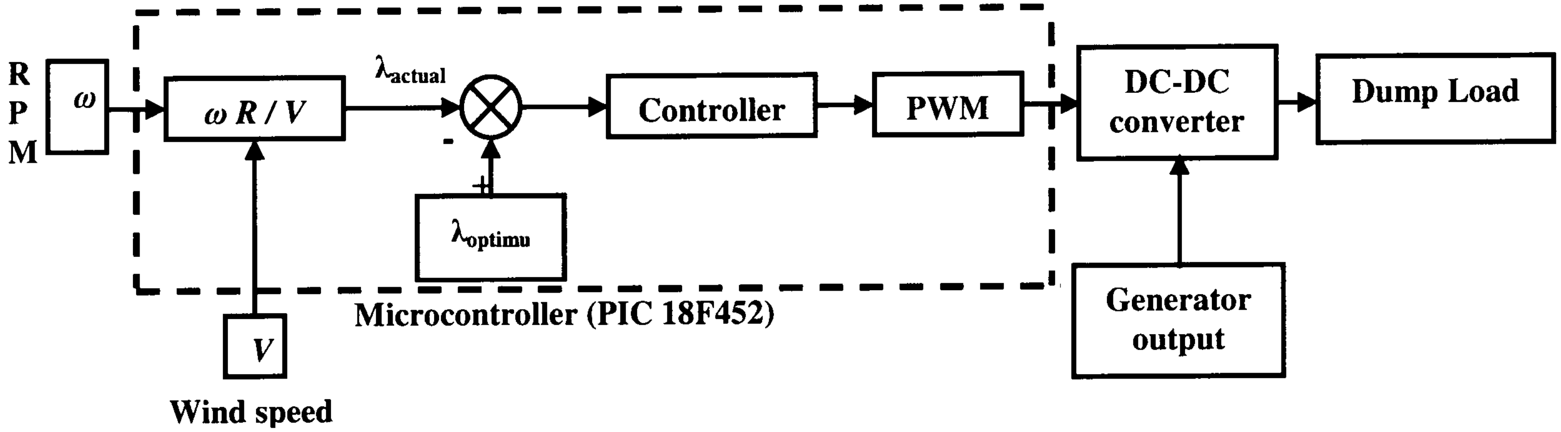


Fig. 33 Structure of the maximum power controller

- MikroBasic 2.0.0.4 has been used to implement the control algorithm.
- The DC-DC converter topology has been selected as the buck-boost.
- Load has been considered as resistive.

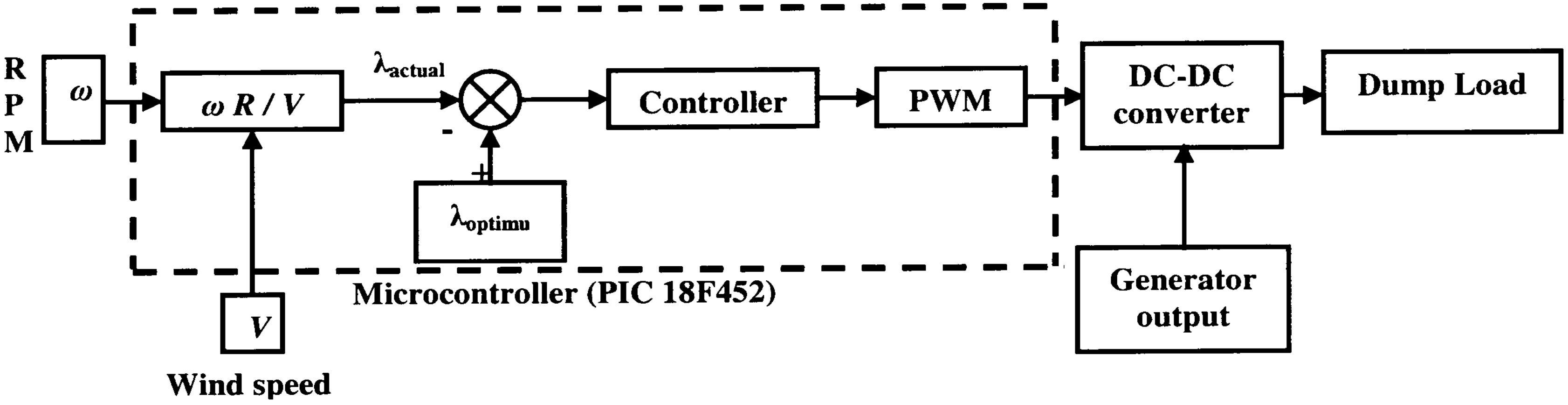


Fig. 33 Structure of the maximum power controller

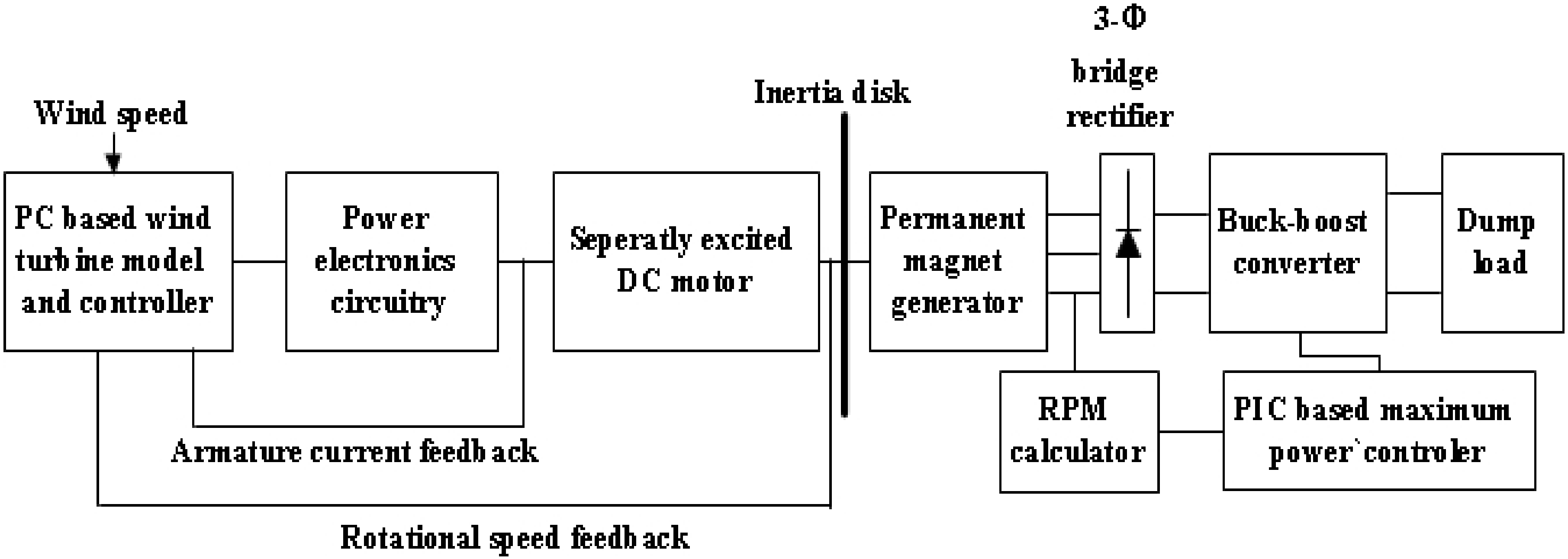
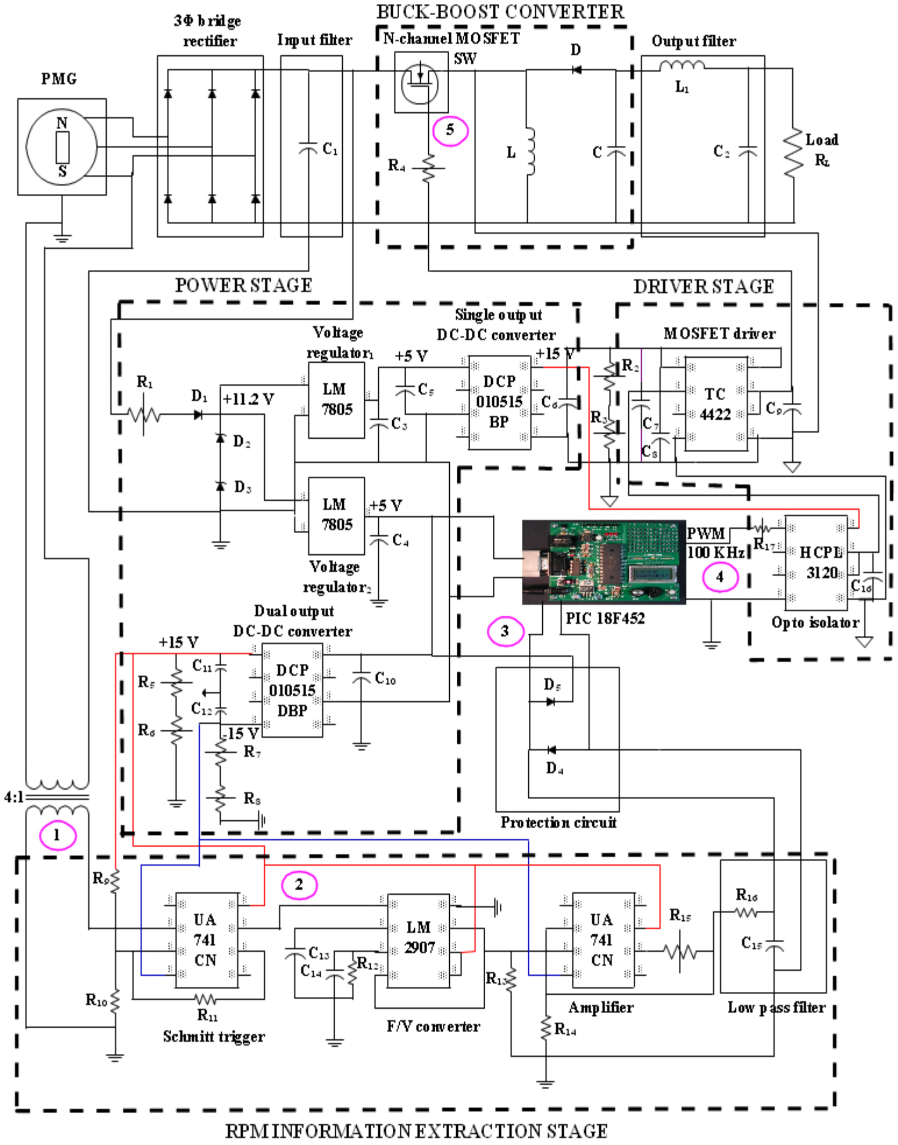


Fig. 34 Basic structure of the wind turbine emulator with the maximum power controller

Maximum Power Point Controller Power Electronics of the Emulator



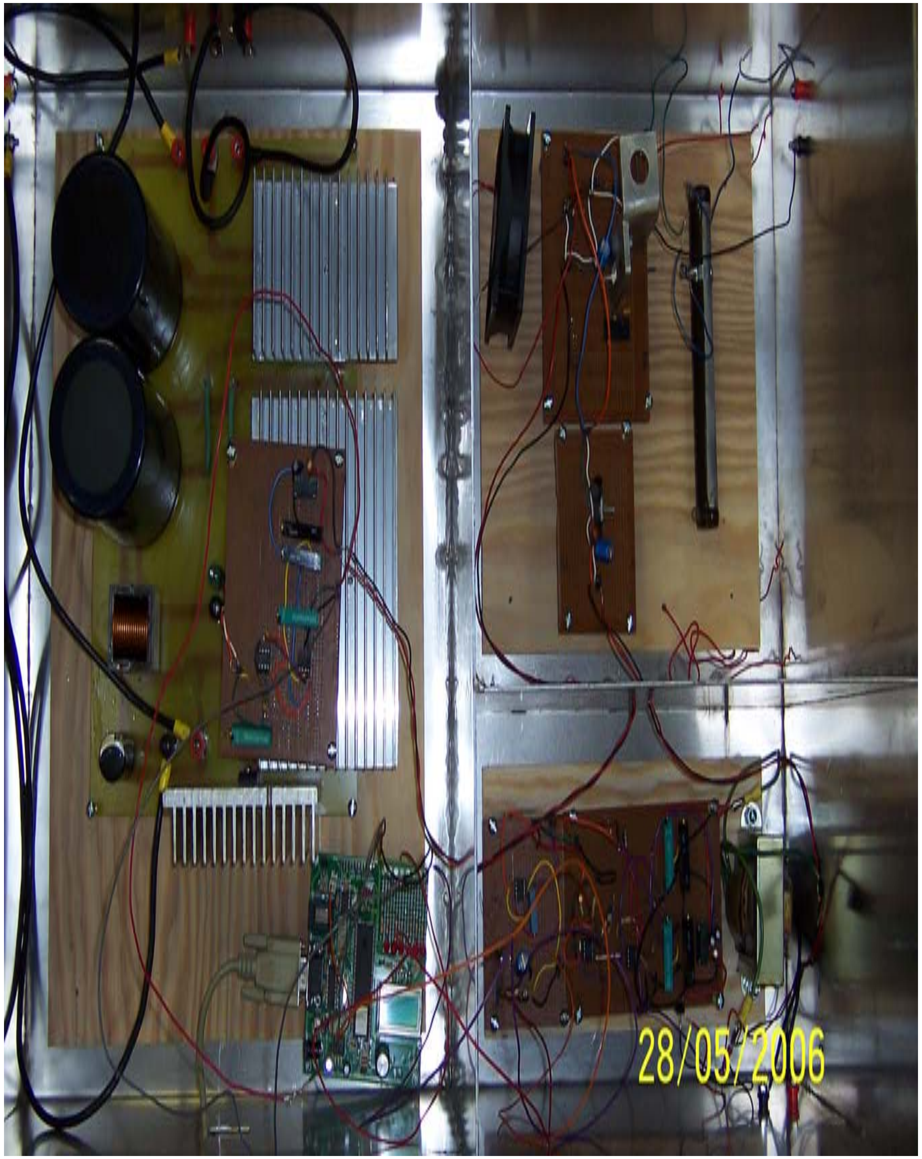


Fig. 35 MPP Controller power electronics and photograph

Results for 7 m/s wind speed

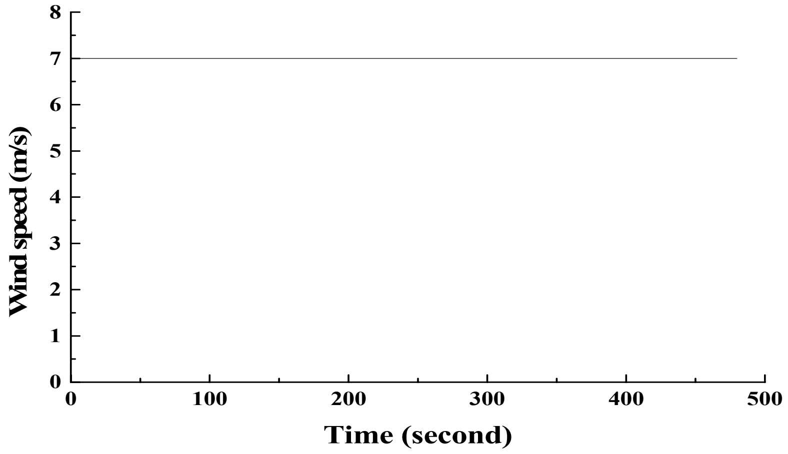


Fig. 36 Wind speed profile applied to the wind turbine emulator

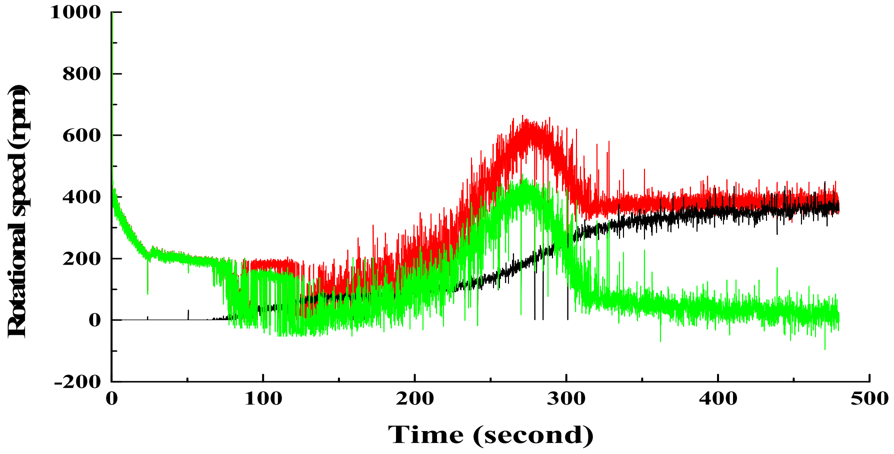


Fig. 37 Variation of the rotational speed

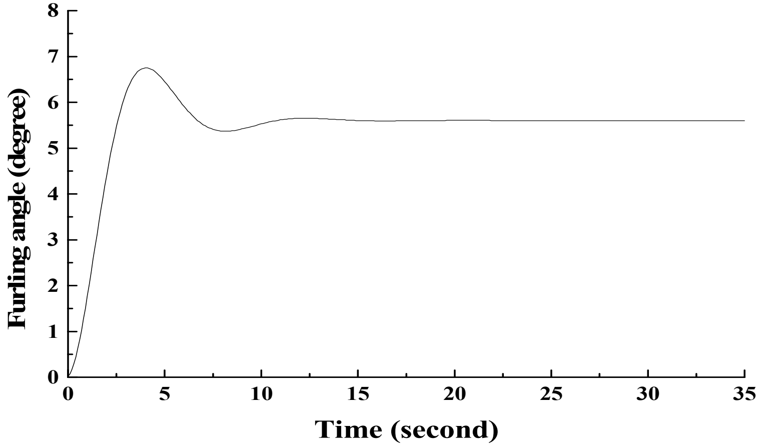


Fig. 38 Representation of the expected furl dynamics

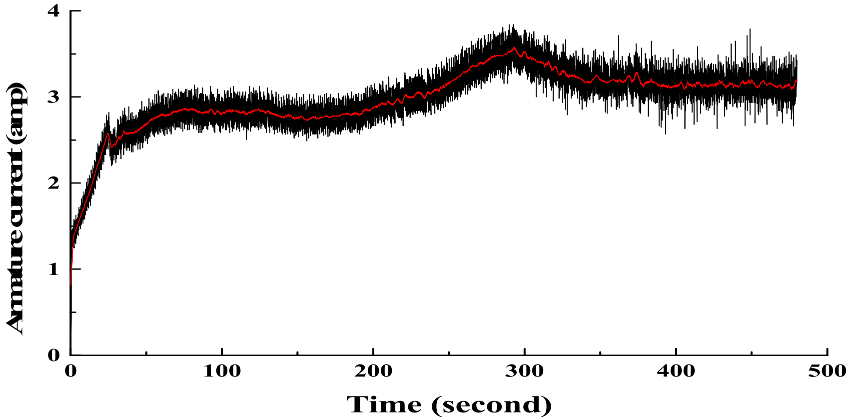
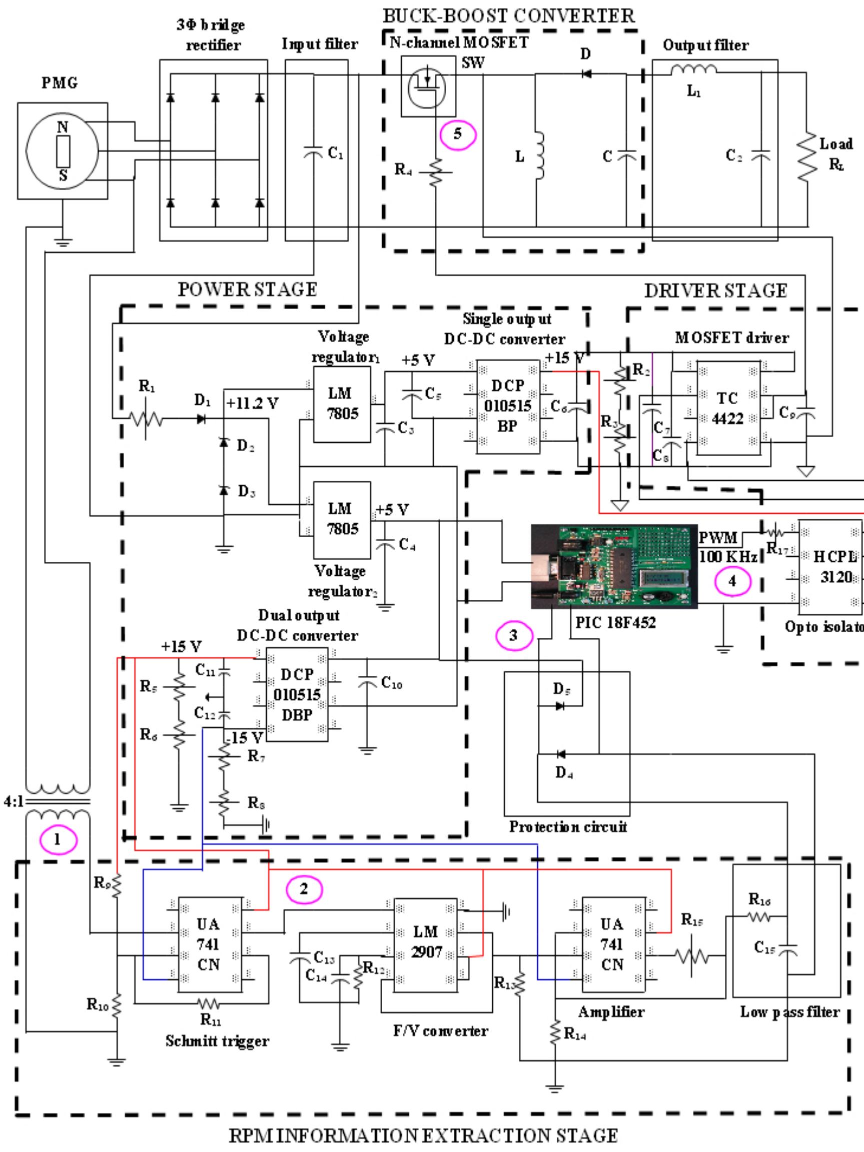
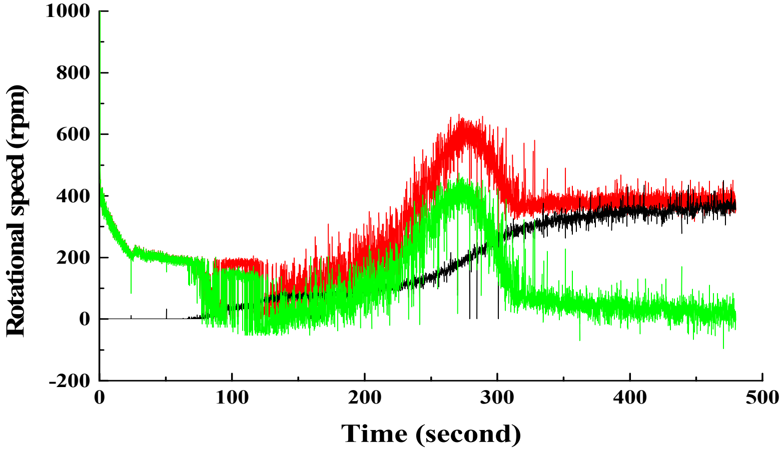


Fig. 39 Variation of the armature current



MPPC power electronics



Frequency = (RPM*No. of Pole)/120

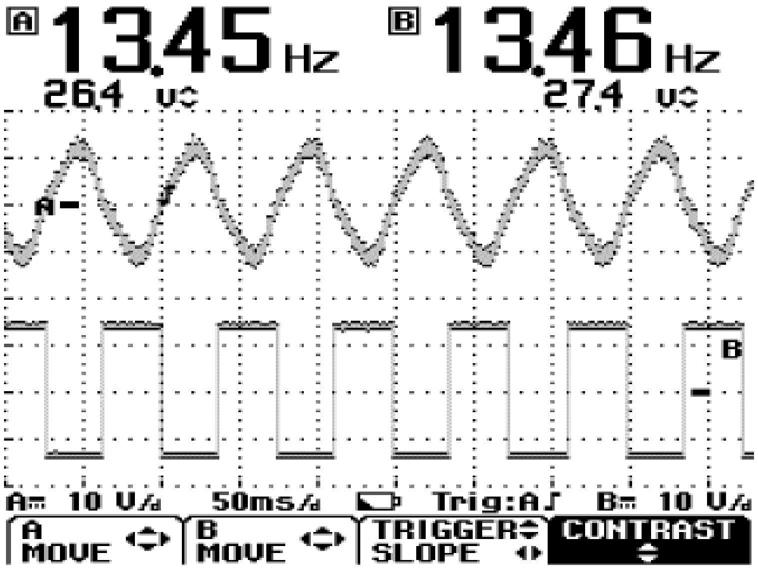
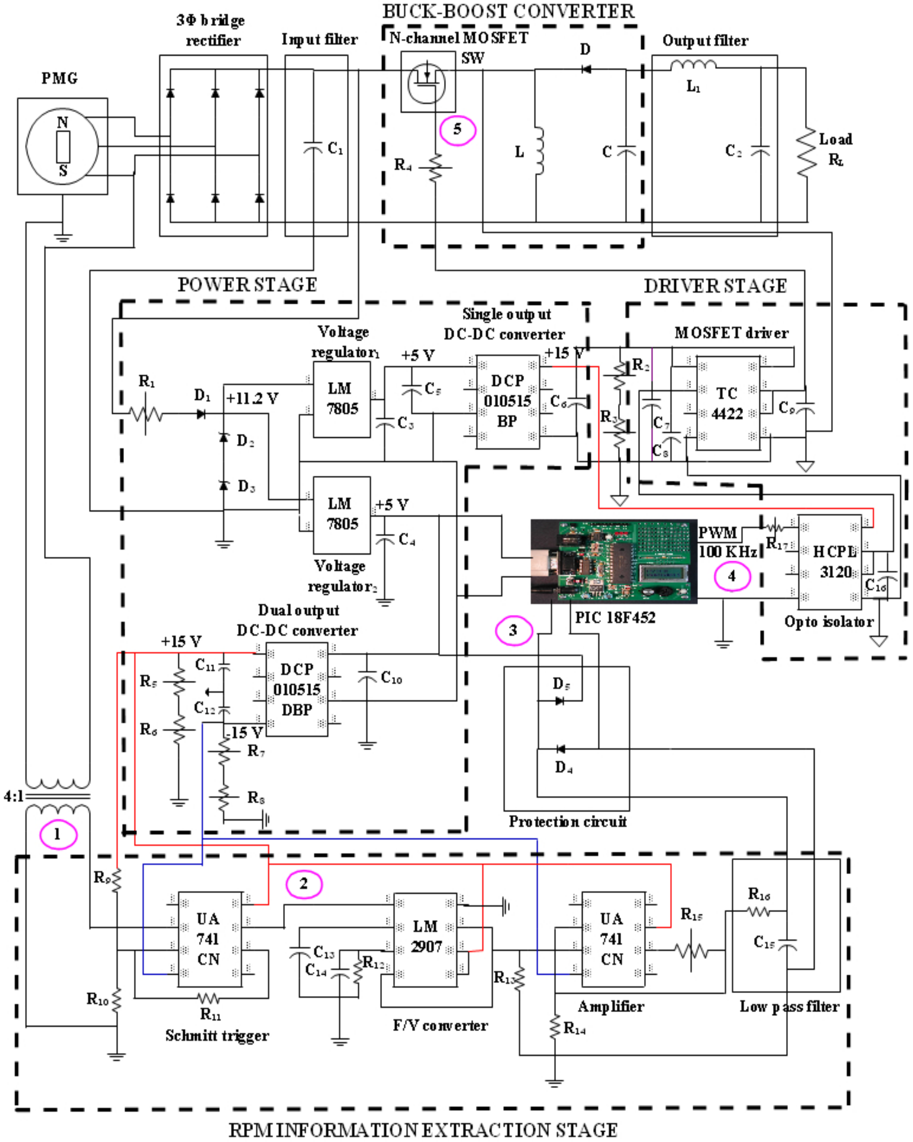


Fig. 40 Output at the point 1 & 2



MPPC power electronics

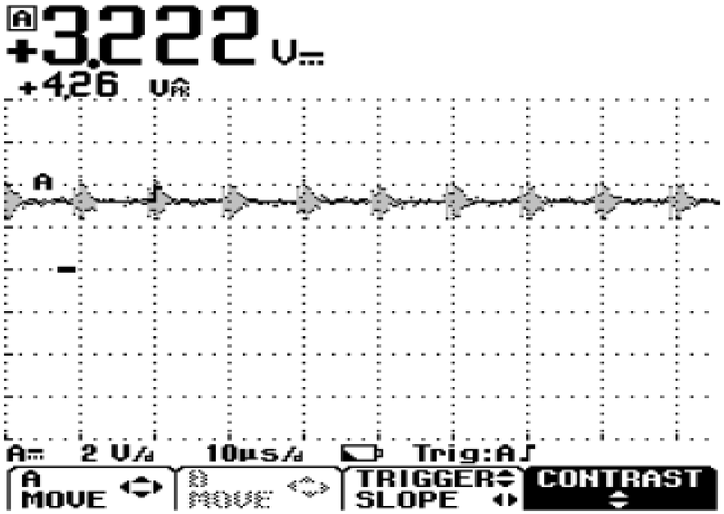


Fig. 41 Output at point 3

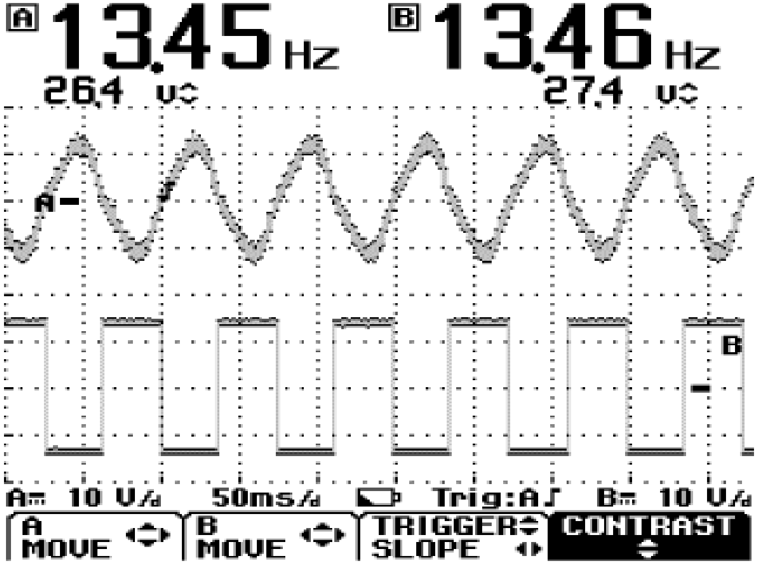
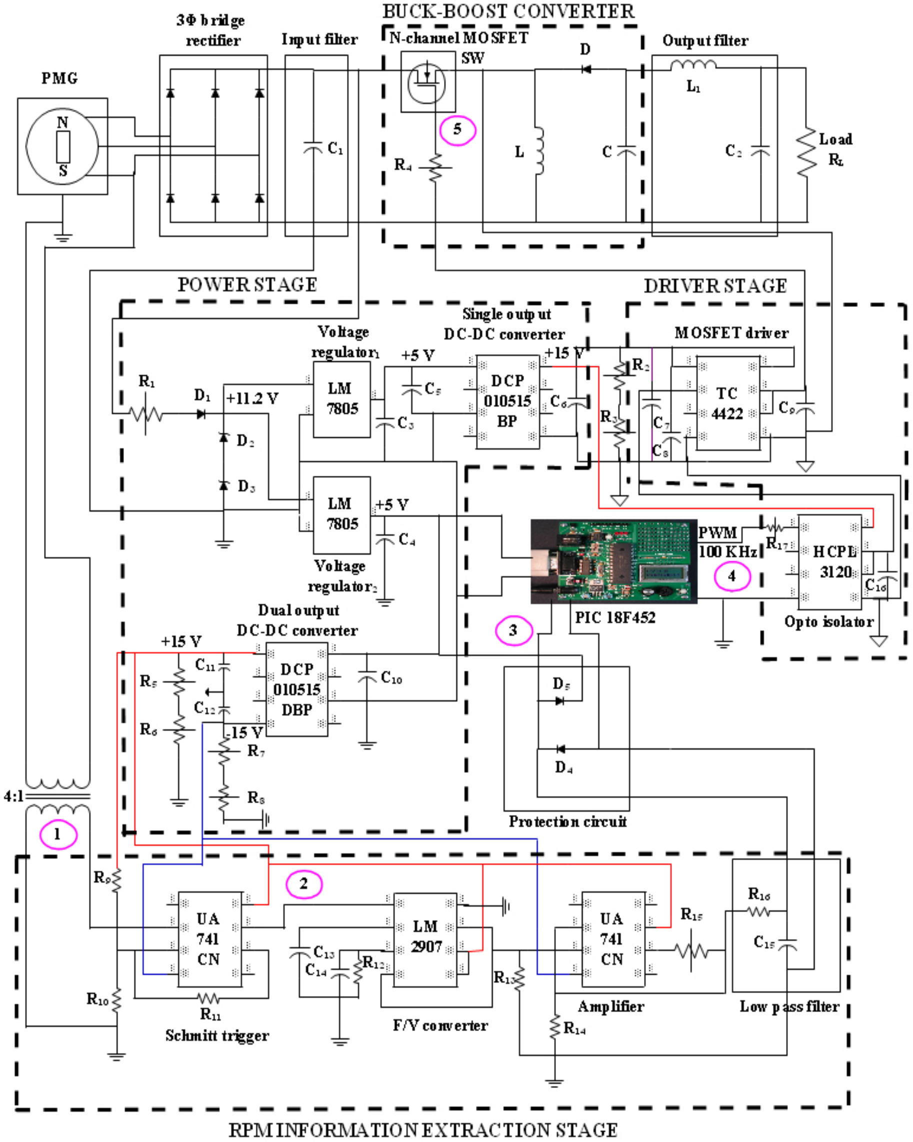


Fig. 40 Output at the point 1 & 2



MPPC power electronics

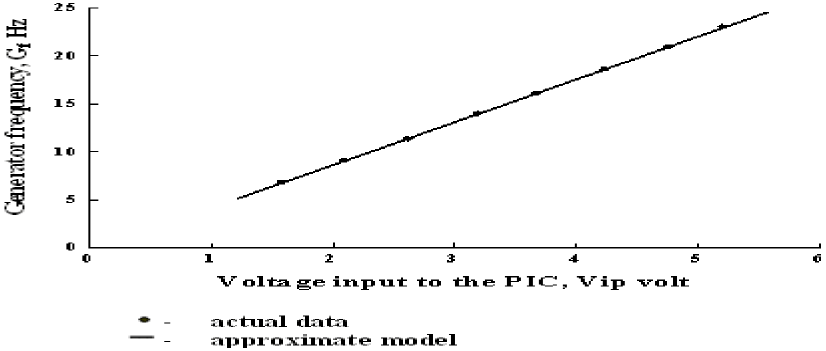


Fig. 42 Characteristic of the RPM extraction signal circuit

Frequency (Hz)

= 4.4571 * Voltage – 0.2933

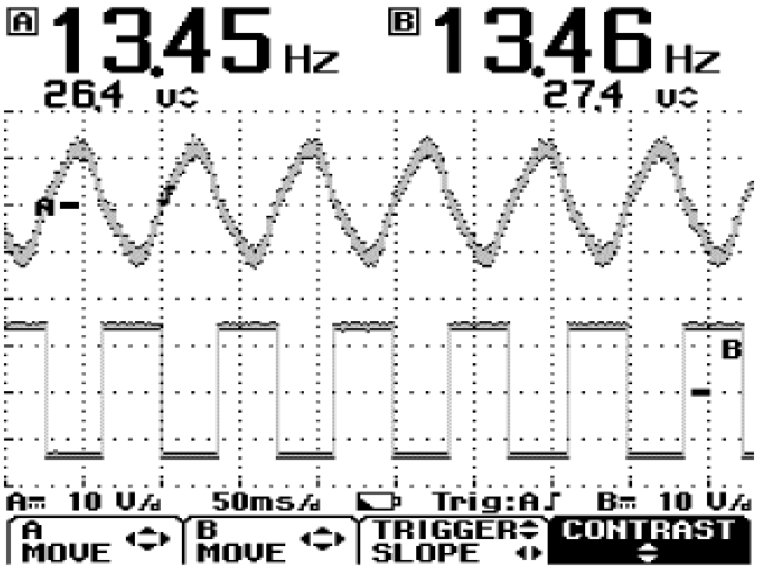
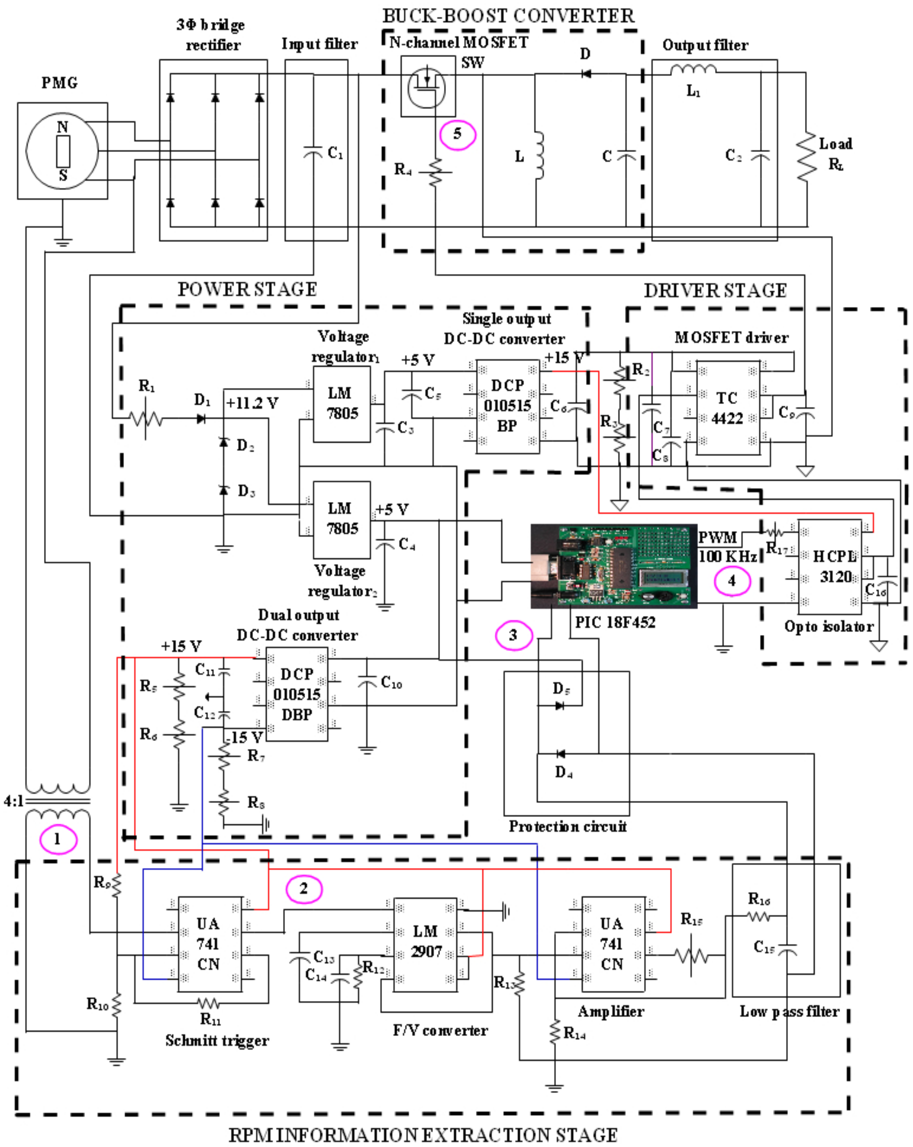


Fig. 40 Output at the point 1 & 2



MPPC power electronics

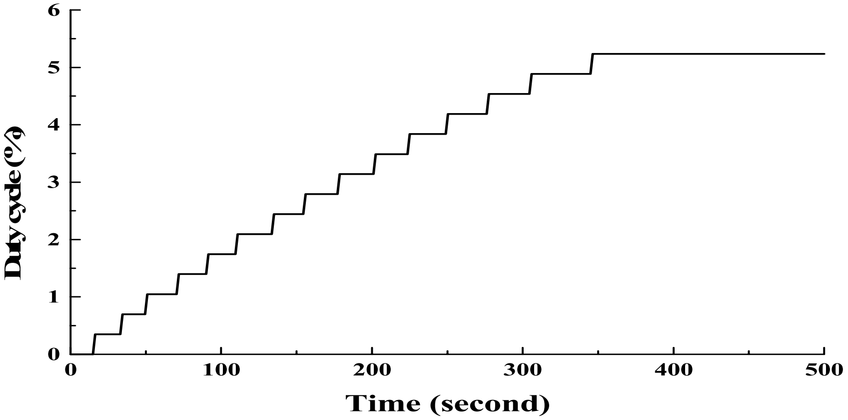


Fig. 43 Variation of the PWM duty cycle with time

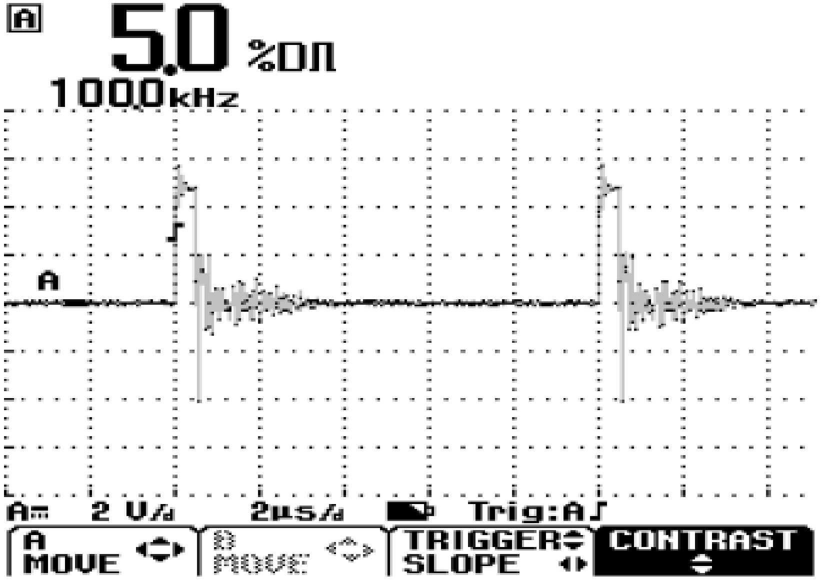
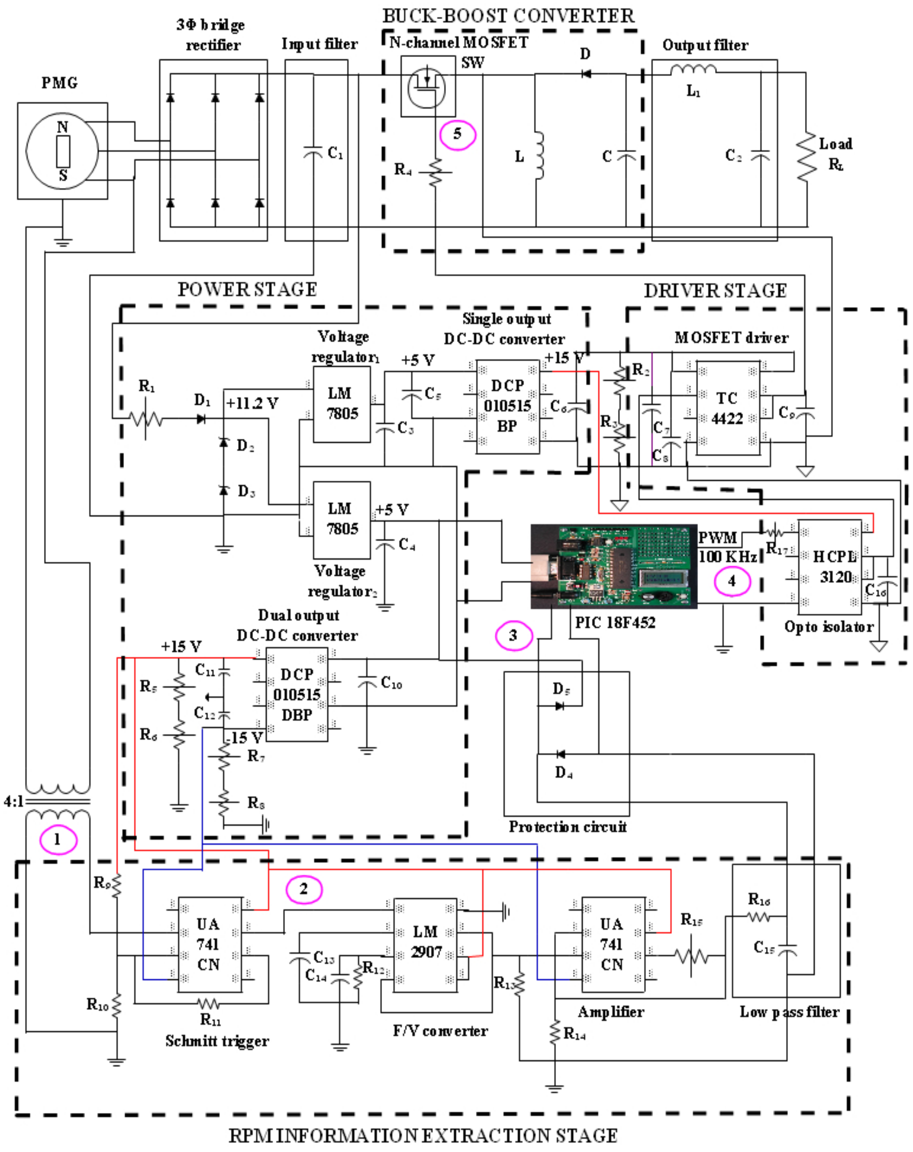


Fig. 44 Output at the point 4



MPPC power electronics

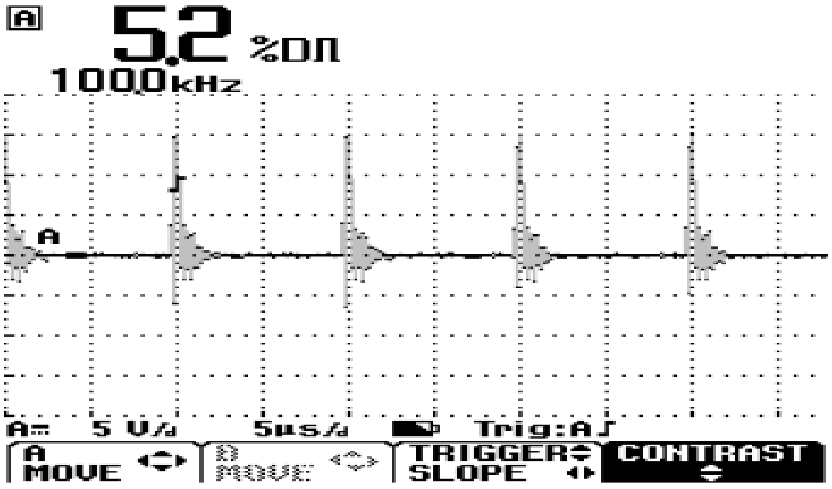


Fig. 45 Output at the point 5

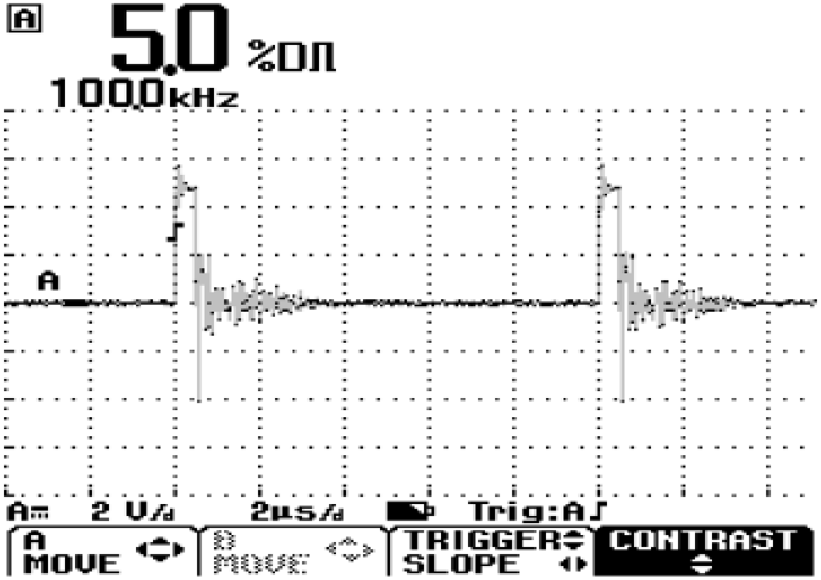
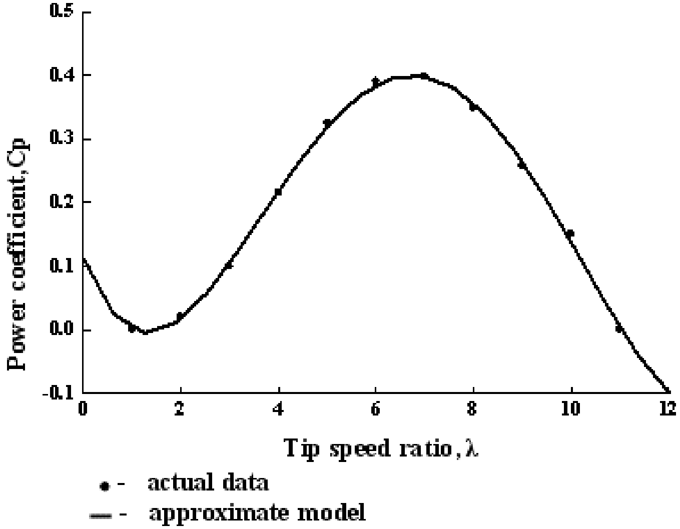
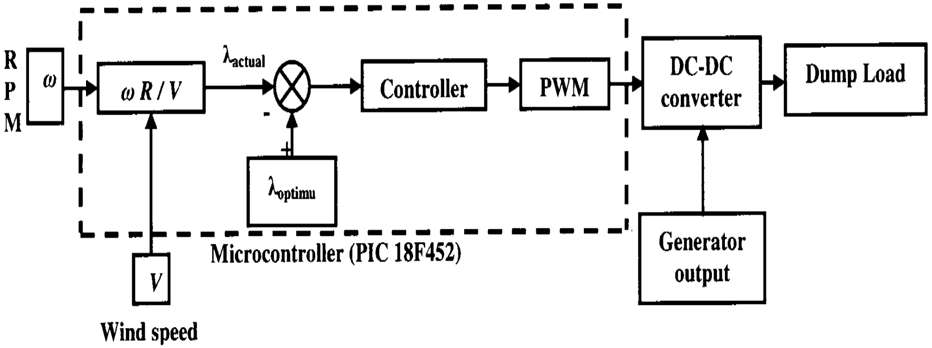


Fig. 44 Output at the point 4



Power coefficient as a function of tip-speed ratio



Maximum power controller

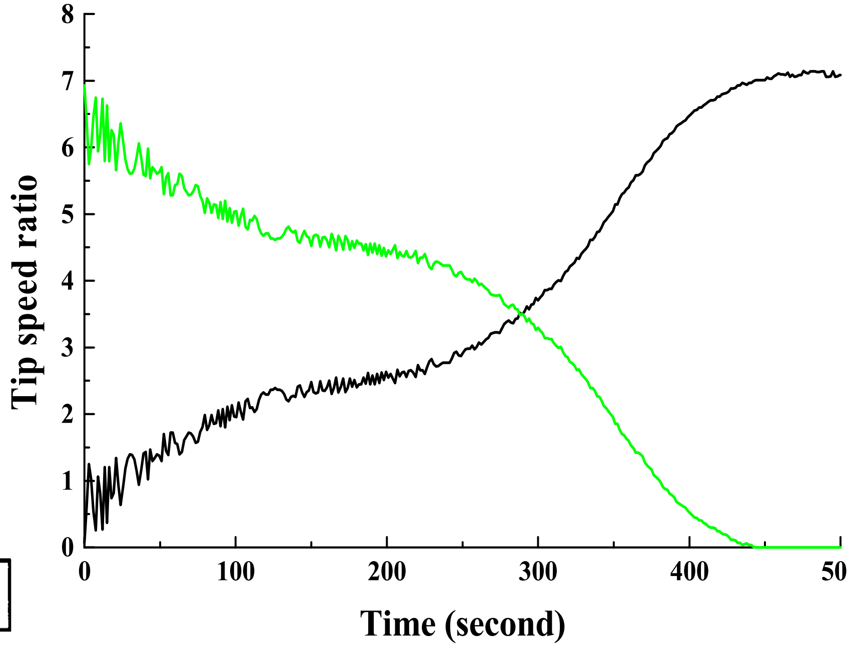


Fig. 46 Variation of the TSR with time

Results for 8 m/s wind speed

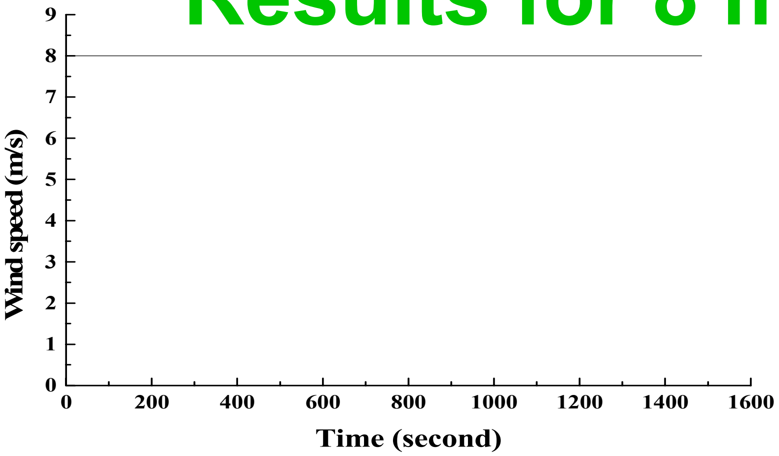


Fig. 47 Wind speed profile applied to the wind turbine emulator

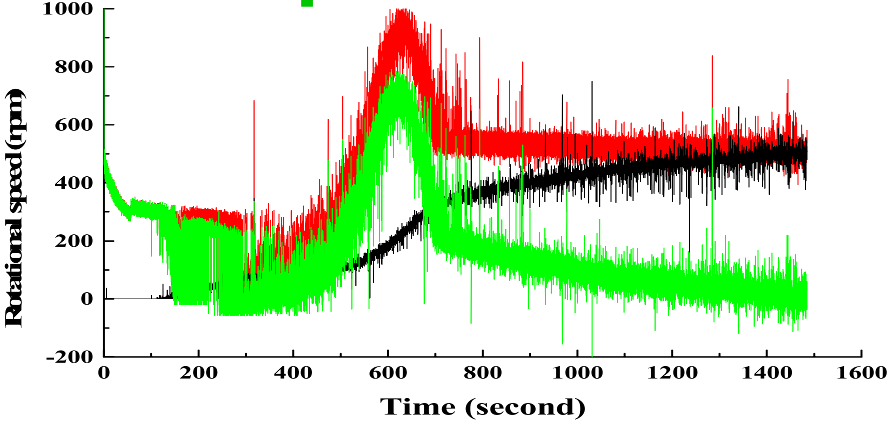


Fig. 48 Variation of the rotational speed

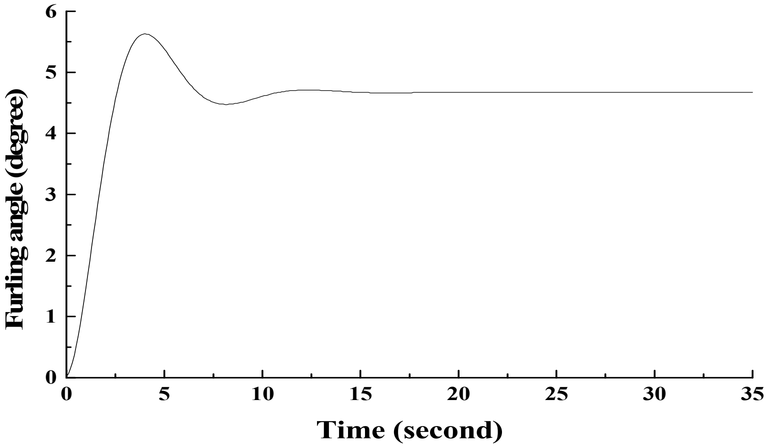


Fig. 49 Representation of the expected furl dynamics

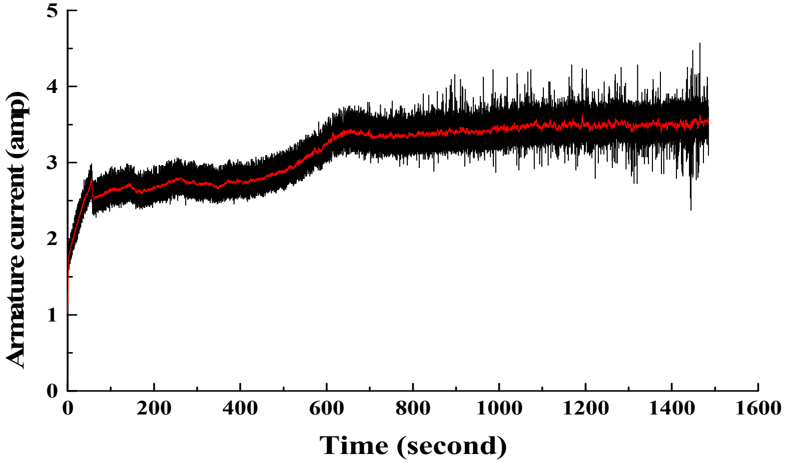


Fig. 50 Variation of the armature current

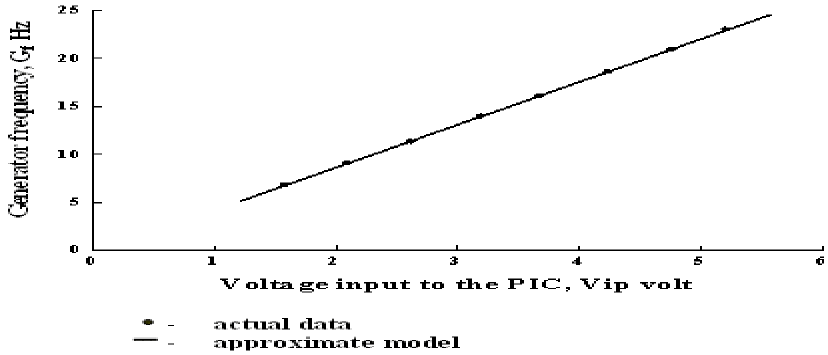


Fig. 51 Characteristic of the RPM extraction signal circuit

Frequency (Hz)

= 4.4571 * Voltage – 0.2933

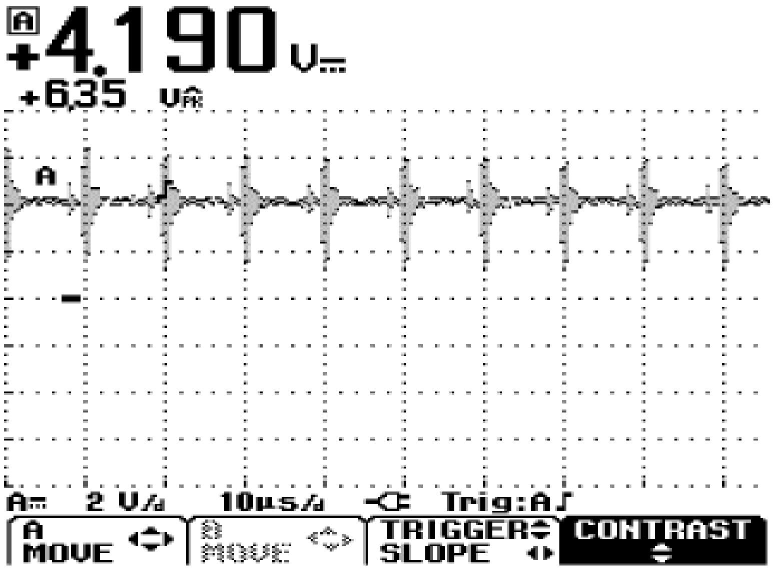


Fig. 52 Output at the point 3

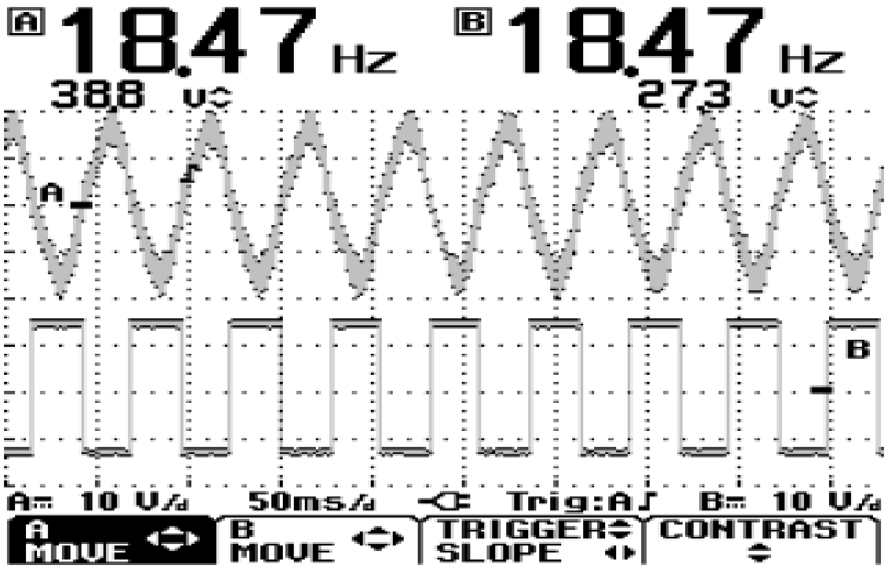


Fig. 53 Output at the point 1 & 2

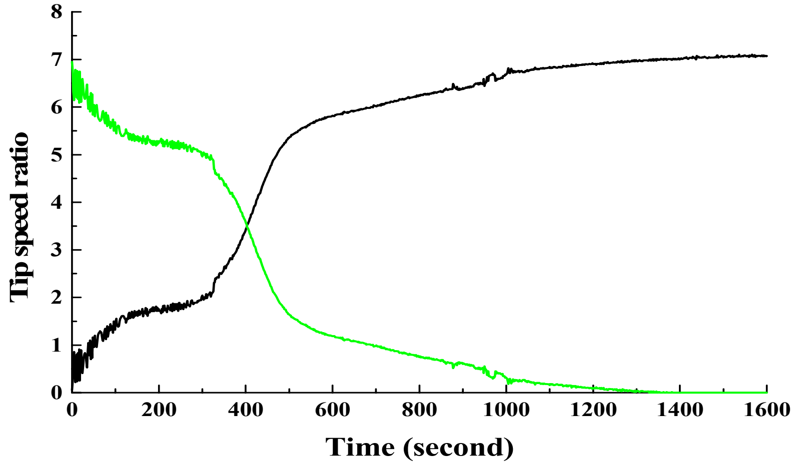


Fig. 54 Variation of the TSR with time

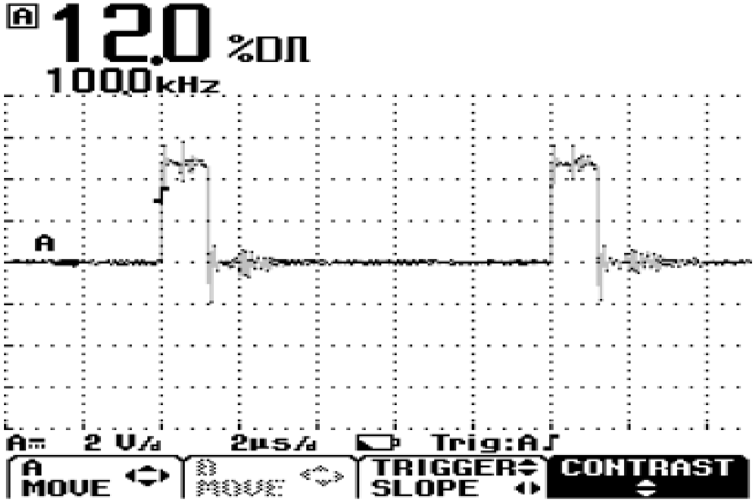


Fig. 55 Output at the point 3

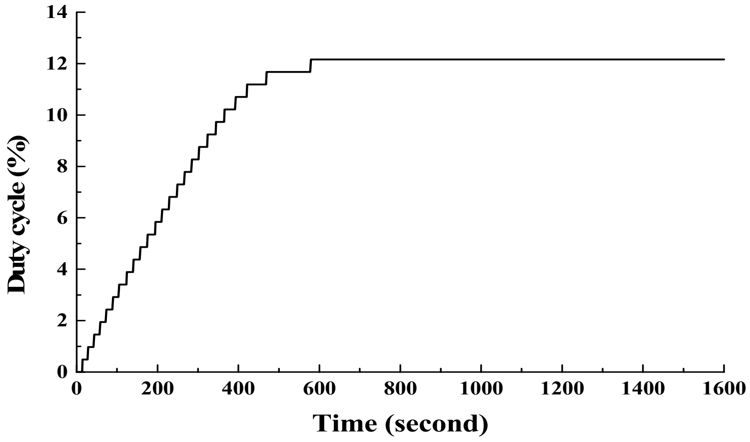


Fig. 56 Variation of the PWM duty cycle with time

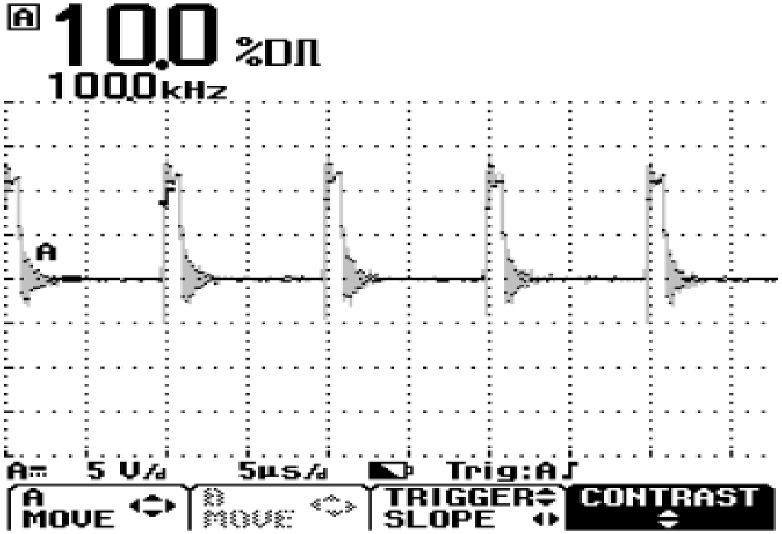


Fig. 57 Output at the point 5

Results for a step change in wind speed

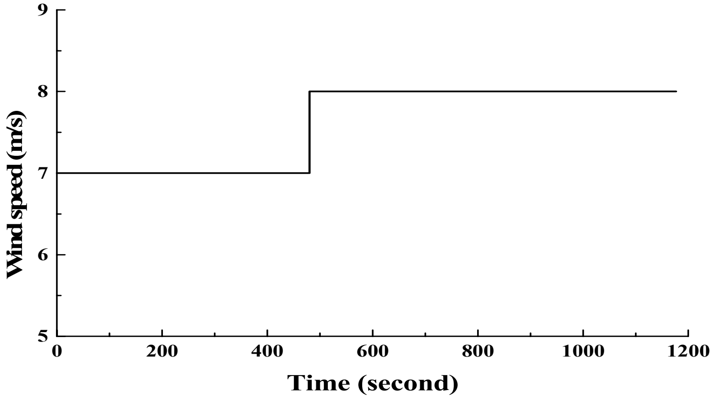


Fig. 58 Wind speed profile applied to the wind turbine emulator

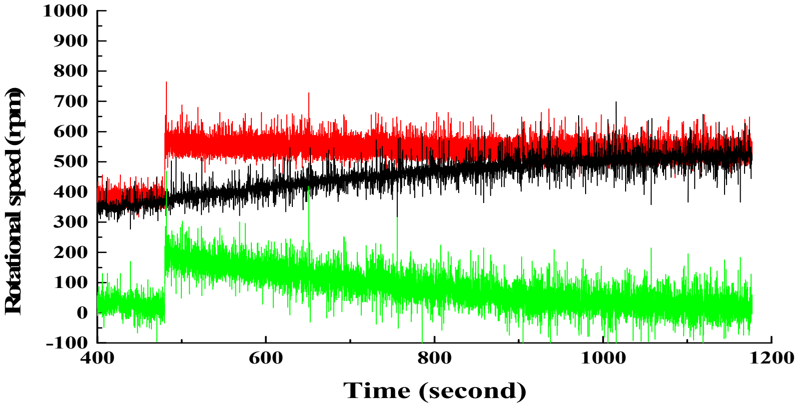


Fig. 59 Variation of the rotational speed

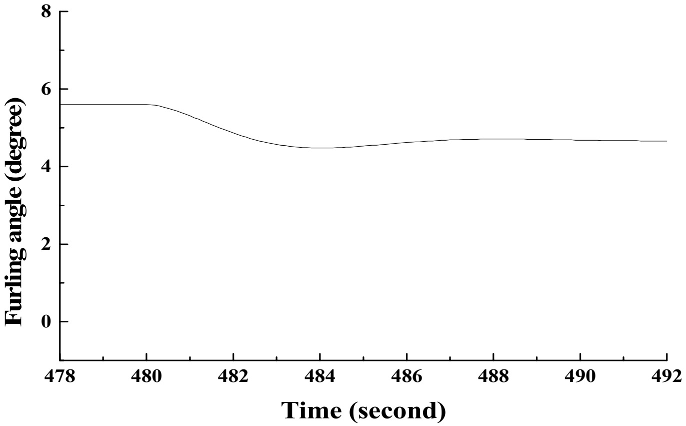


Fig. 60 Representation of the expected furl dynamics

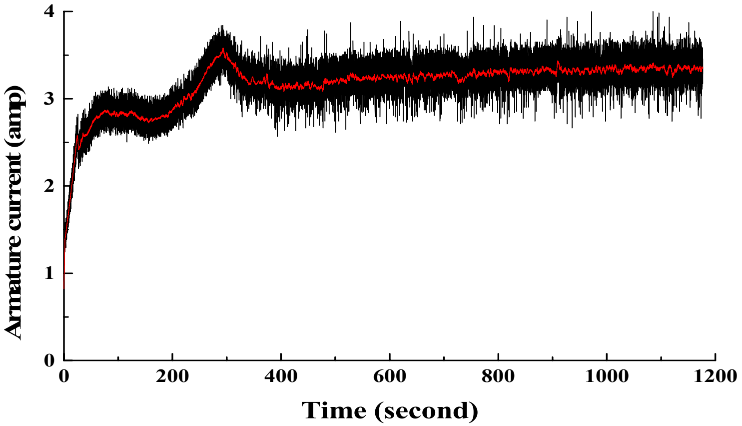
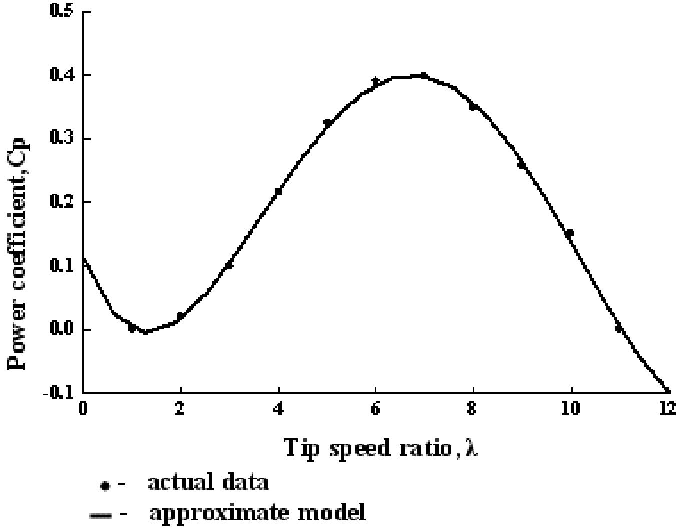
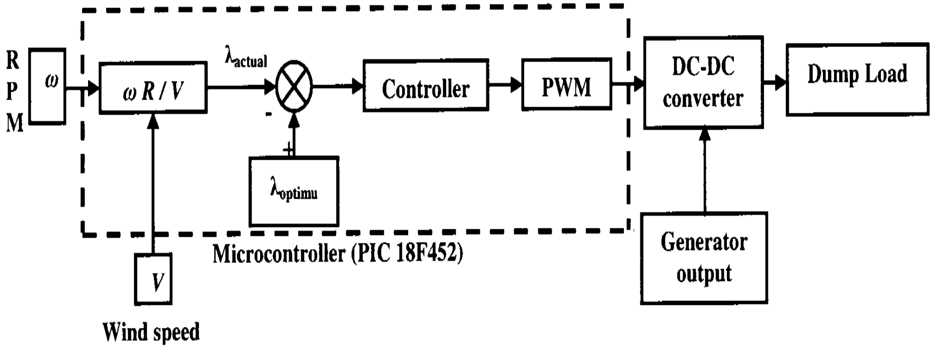


Fig. 61 Variation of the armature current



Power coefficient as a function of tip-speed ratio



Maximum power controller

$$\lambda = \frac{\text{Rotor radius * Rotor speed}}{\text{Wind speed}}$$

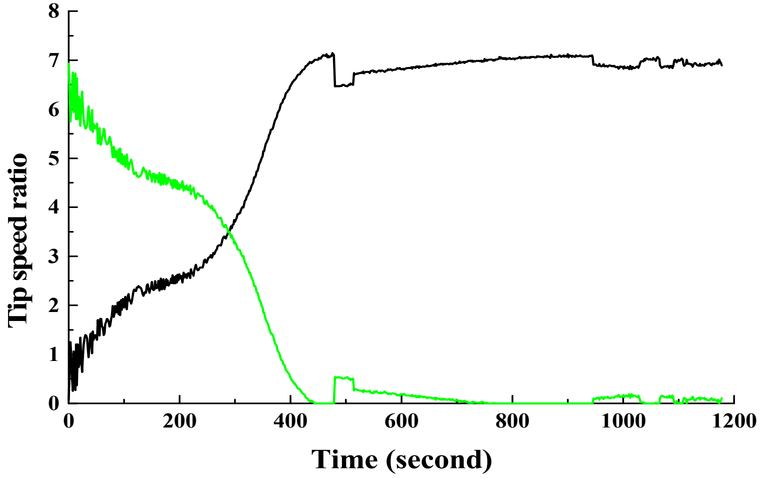


Fig. 62 Variation of the TSR with time

Conclusions

- A separately excited DC motor based an isolated small wind turbine emulator has been implemented for small wind turbine system.
- Inertia of the wind turbine has been considered by coupling an inertia disk with the system.
- A maximum power point controller along with required power electronics has been implemented and tested.
- Emulator test results show acceptable performance.

Supervisors

Dr. M.Tariq Iqbal

Dr. John E. Quaicoe

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Thank you

Questions/Comments?????