POWER PERFORMANCE INVESTIGATION AND CONTROL SYSTEM DESIGN OF GRID-CONNECTED SMALL WIND TURBINES

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Outline

- Background of small wind turbines
- Power performance of two grid connected small wind turbines
- Power optimization of a novel vertical axis wind turbine
- Control System Design for Active and Reactive Power Control of a Grid Connected Small Wind Turbine
- Conclusion
- Future work

Background

- World's Electricity demand grows almost twice as fast as its total energy consumption.

- Assuming the recent rapid expansion of wind, solar and hydro power, by 2035, renewable industries can account for almost one-third of total electricity output.

- According to British petroleum statistical review of world energy June, 2012, worldwide **wind energy** production has increased by more than **25.8%** in 2011.

Background……

Small wind turbines

- Small wind turbines are generally used to meet small community energy demand and remote power generation.

- It is becoming popular for grid connection & net metering system.

- It is used to power dairy farms, water supplies for small communities, small industry, irrigation and greenhouses.

Background……

Research Objectives & Related works

- **Investigation of small wind turbine's power performance under variable electric load condition.**

Research on small wind turbine's power performance has a very shadowy existence.

- **Derived a MPPT table for a vertical axis wind turbine for maximum power extraction** .

Various type of techniques are available for maximum power extraction-TSR control method, hill climbing method, PSF method but no methodology to derive a MPPT table

- **A control system design for active and reactive power control of a grid connected small wind turbine.**

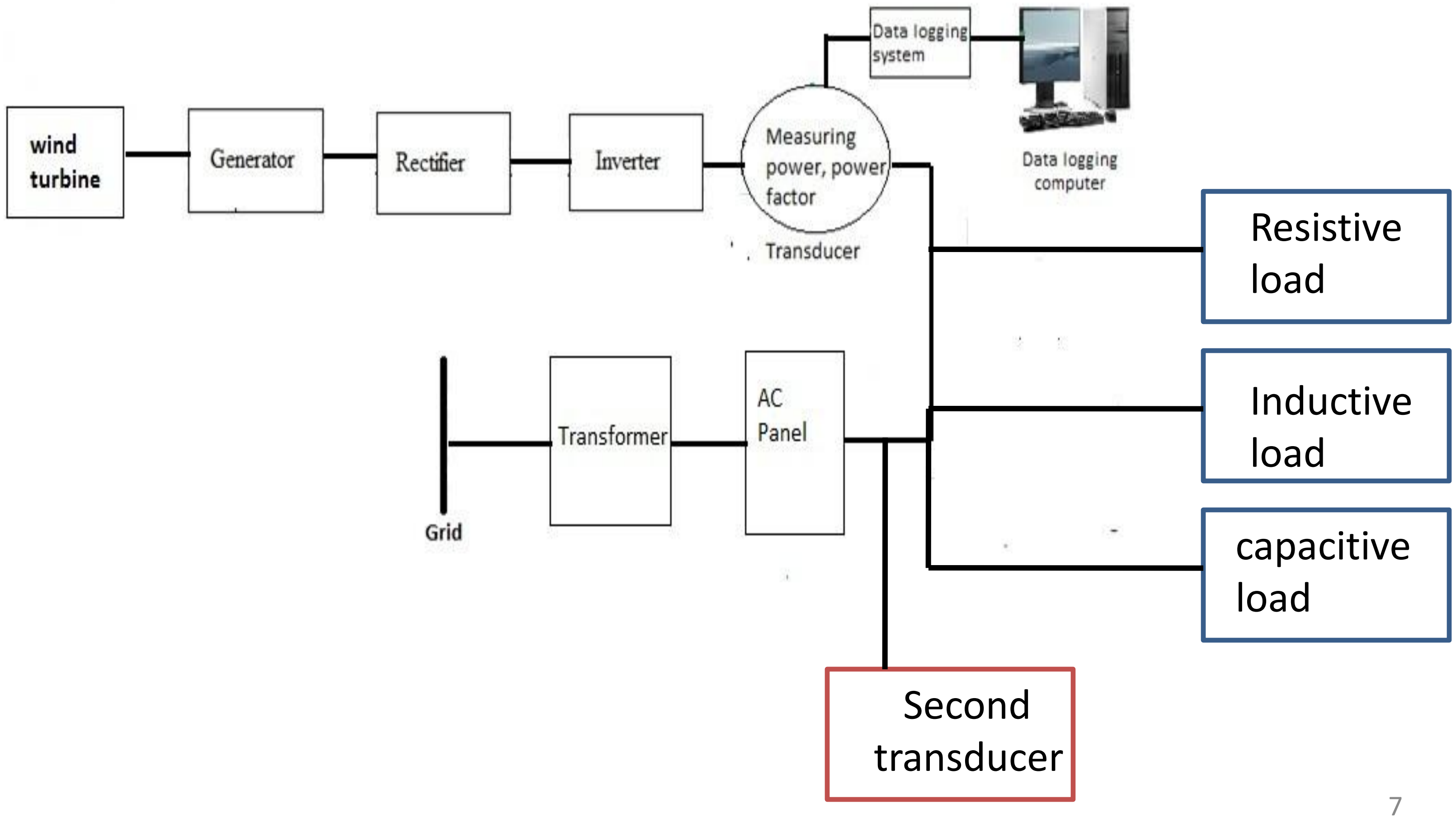
Fuzzy logic control method, predictive control method and nonlinear sliding mode control method are available but they are simulated or experimented with only inverter and DC source.

Power performance of two grid connected small wind Turbines

Experimental Objectives/Motivation

- Wind Energy Institute of Canada (WEICan) is a small wind turbine testing organization. It collects data for a long period and provide a power curve.
- During data collection wind turbine is directly connected to grid.
- The experimental objective is to investigation the small wind turbine behavior when they are connected to variable electrical load.
- Collect data for active power , reactive power and power factor.

Block diagram of small wind turbine and experimental setup



Data Analysis Procedure

Data was analyzed according IEC-61400-12-1 Standard

Procedure:

- Collect one second raw data.
- Convert one second raw data to 10 min average data.
- 10 min average data is normalized to reference air density.
- Normalized data is analyzed according to bins method.
- Data from bin table is used to plot power curve.

Normalized data

$$P_n = P_{10min}\frac{\rho_o}{\rho_{10\,min}}$$

$$V_n = V_{10min}\left(\frac{\rho_{10min}}{\rho_o}\right)^{1/3}$$

P_n = Normalized power output
P_{10min} = Measured Power average over 10min
ρ_o = Reference air density
ρ_{10min} = 10 min average air density
V_n = Normalized wind speed
V_{10min} = 10 min average wind speed

Bins method

$$P_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P_{n,i,j}$$

$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{n,i,j}$$

V_i = Normalized and average wind speed in bin i
$V_{n,i,j}$ = Normalized wind speed of data set j in bin i
P_i = Normalized and average power in bin i
$P_{n,i,j}$ = Normalized power of data set j in bin i
N_i = Number of 10 min data sets in bin i

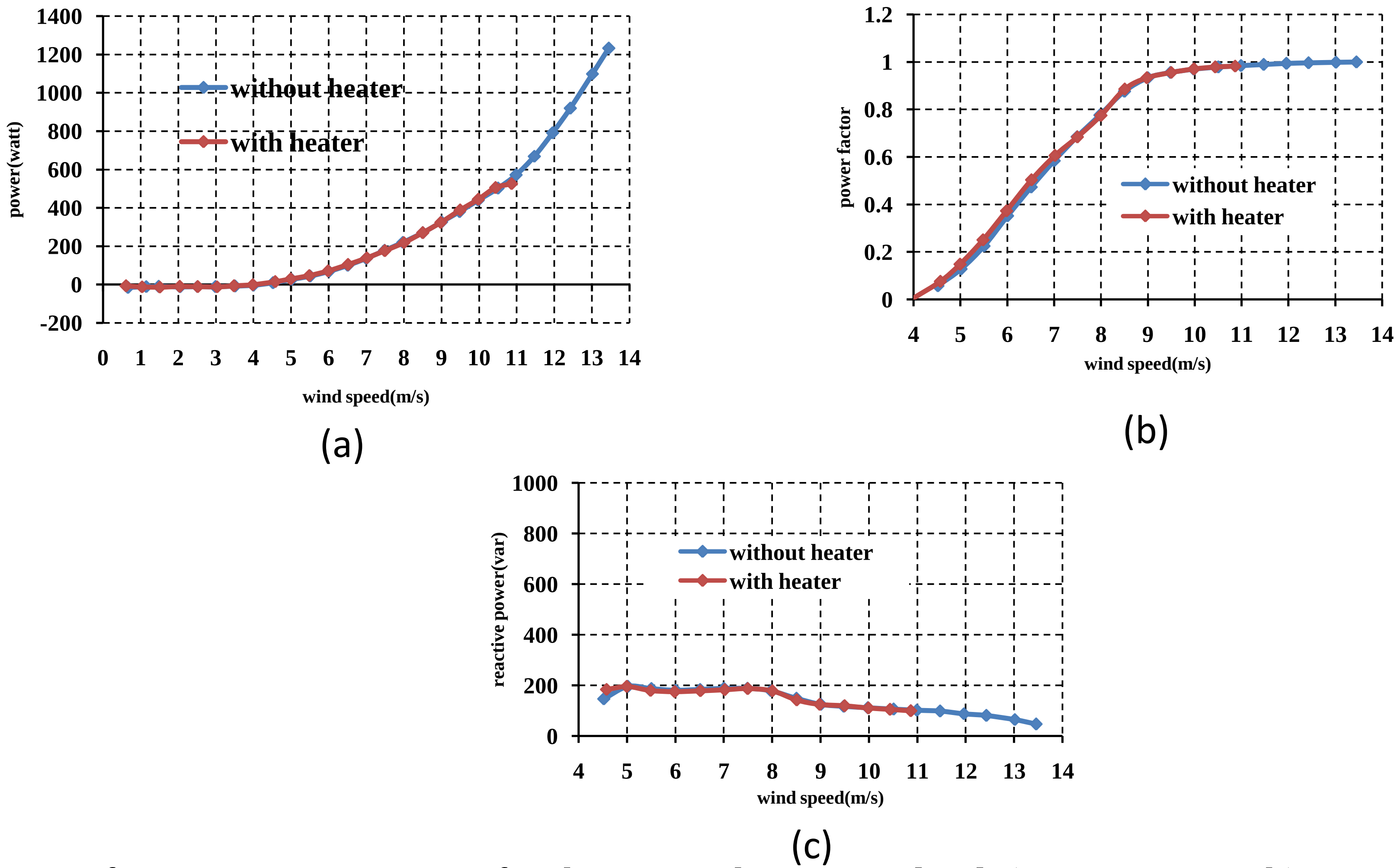
Experimental Turbine

Turbine A

- Rated Power: 1.1 KW
- Rated wind speed: 12.5 m/s
- Maximum Power: 4 kW
- Permanent magnet generator
- Over Speed Control/Protection: Stall Regulation
- Inverter output Voltage: 120V/208V,
- Frequency: 60 HZ
- Grid connected

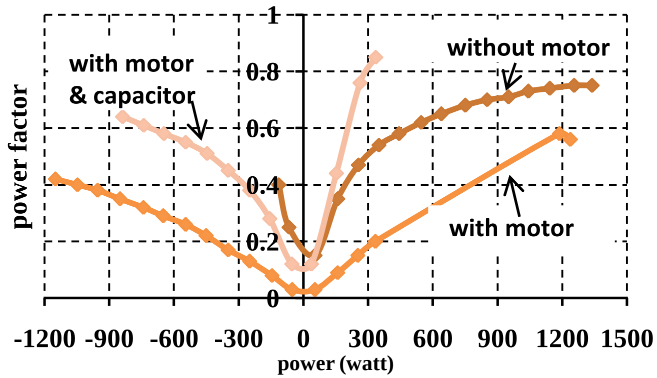
Power performance……..

Experiment with Heater

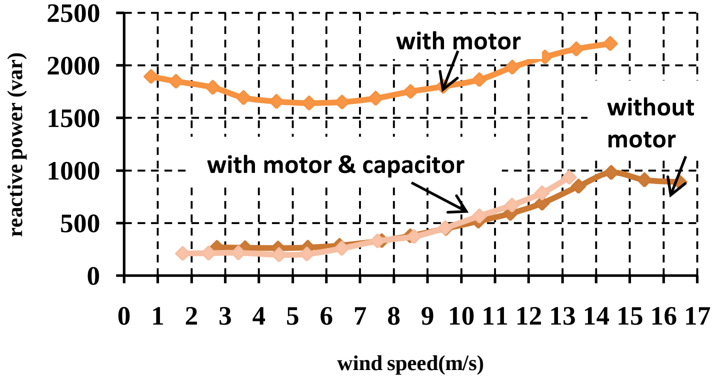


Power performance comparison of turbine A with resistive load a) power curve, b) power factor and c) reactive power

Experiment with inductive & capacitive load



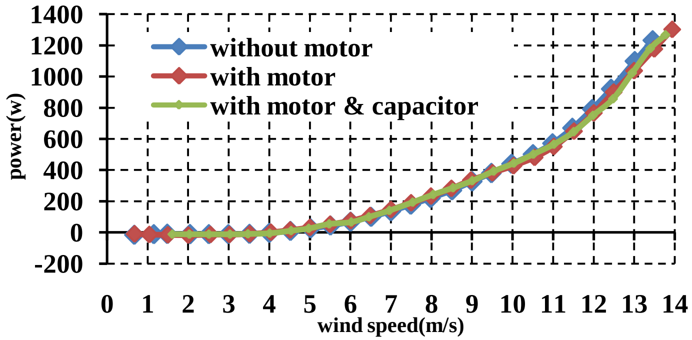
Power factor comparison of the whole building with inductive and capacitive load



Reactive power comparison of the whole building with inductive and capacitive load

Power performance……..

Experimental results comparison



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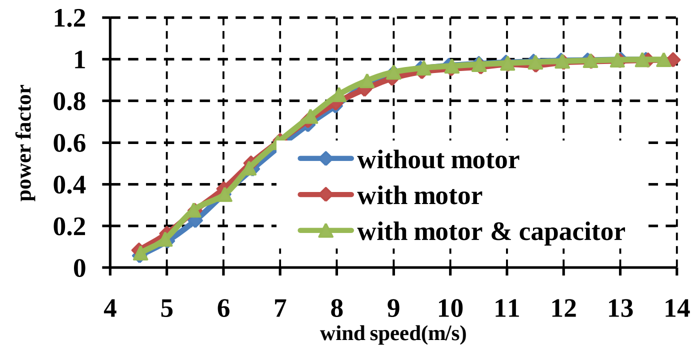

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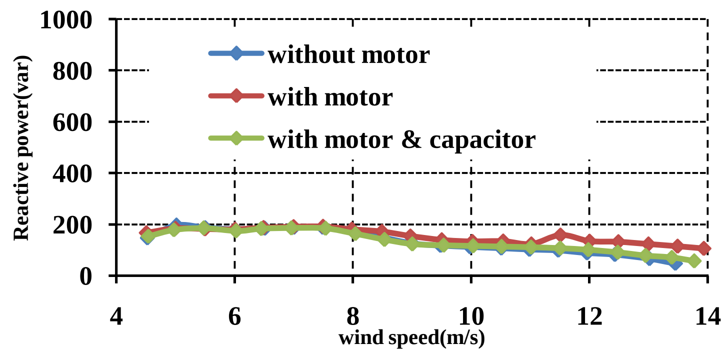


(c)

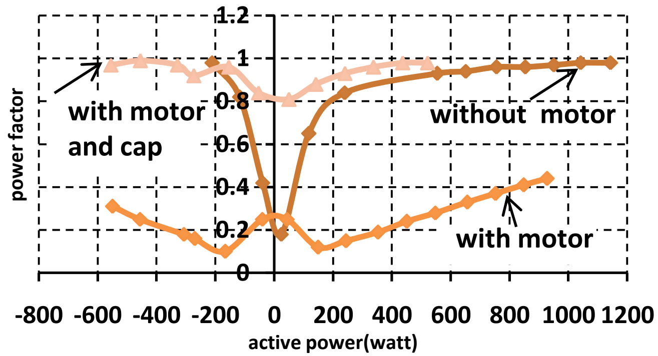
Power performance comparison of turbine A with inductive and capacitive load a) power curve and b) power factor, c) reactive power

Experimental Turbine

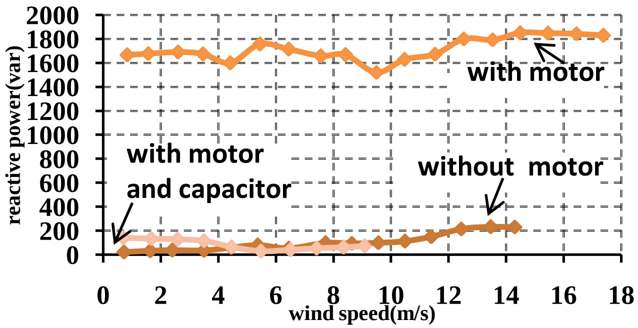
Turbine B

- Rated Power: 1.3 kW
- Rated wind speed: 12 m/s
- Maximum continuous output power: 1.4 kW
- Grid Voltage: Single phase, 208V
- Voltage Tolerance: ± 5%
- Grid frequency: 60 HZ
- Frequency Tolerance: ± 0.00083%
- Control mechanism: Furling control system

Experiment with inductive & capacitive load



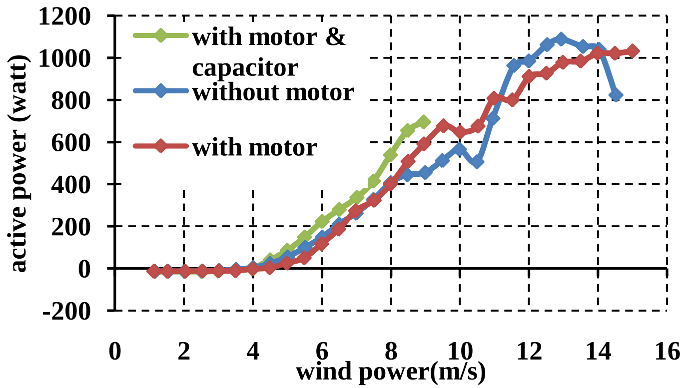
Power factor comparison of the whole building with inductive and capacitive load connected to turbine B



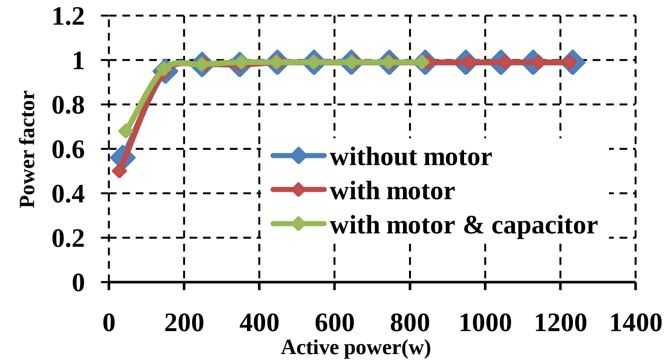
Reactive power comparison of the whole building with inductive and capacitive load connected to turbine B

Power performance……..

Experimental results comparison



(a)



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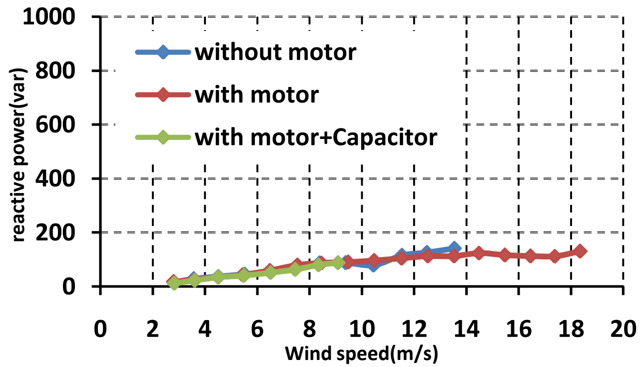


(c)

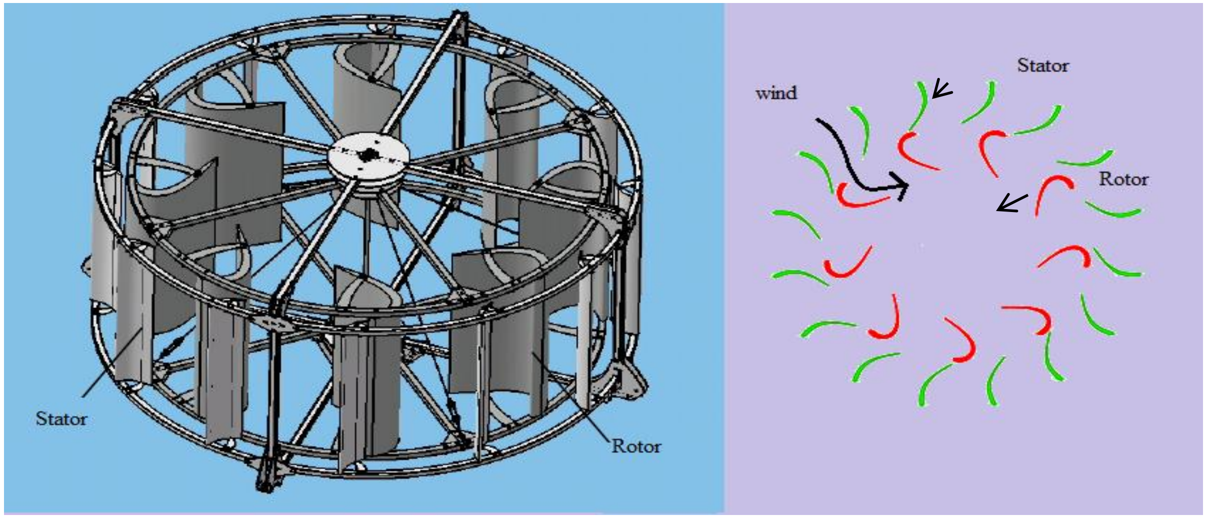
Power performance comparison of turbine B with inductive and capacitive load a) power curve, b) power factor and c) reactive power

Power optimization of a novel vertical axis wind turbine

VAWT Specifications

- Diameter : 4m
- Height: 1.5m
- Cut-in wind speed : 2 m/s
- Maximum wind speed: 60 m/s
- Power at 15m/s: 1.3 kW
- Power at 25 m/s: 4.4 kW
- Power at 40 m/s: 10 kW
- Rotation speed: From 0 to 120 turns/min
- Power control: Electronic Direct Torque Control

VAWT



- Stator is fixed and guides wind into rotating blades
- The rotor blades are distributed symmetrically about the vertical axis
- It is independent of wind direction
- This novel type of stator also provides a rigid structure to the turbine to withstand with wind speed exceeding 60m/s

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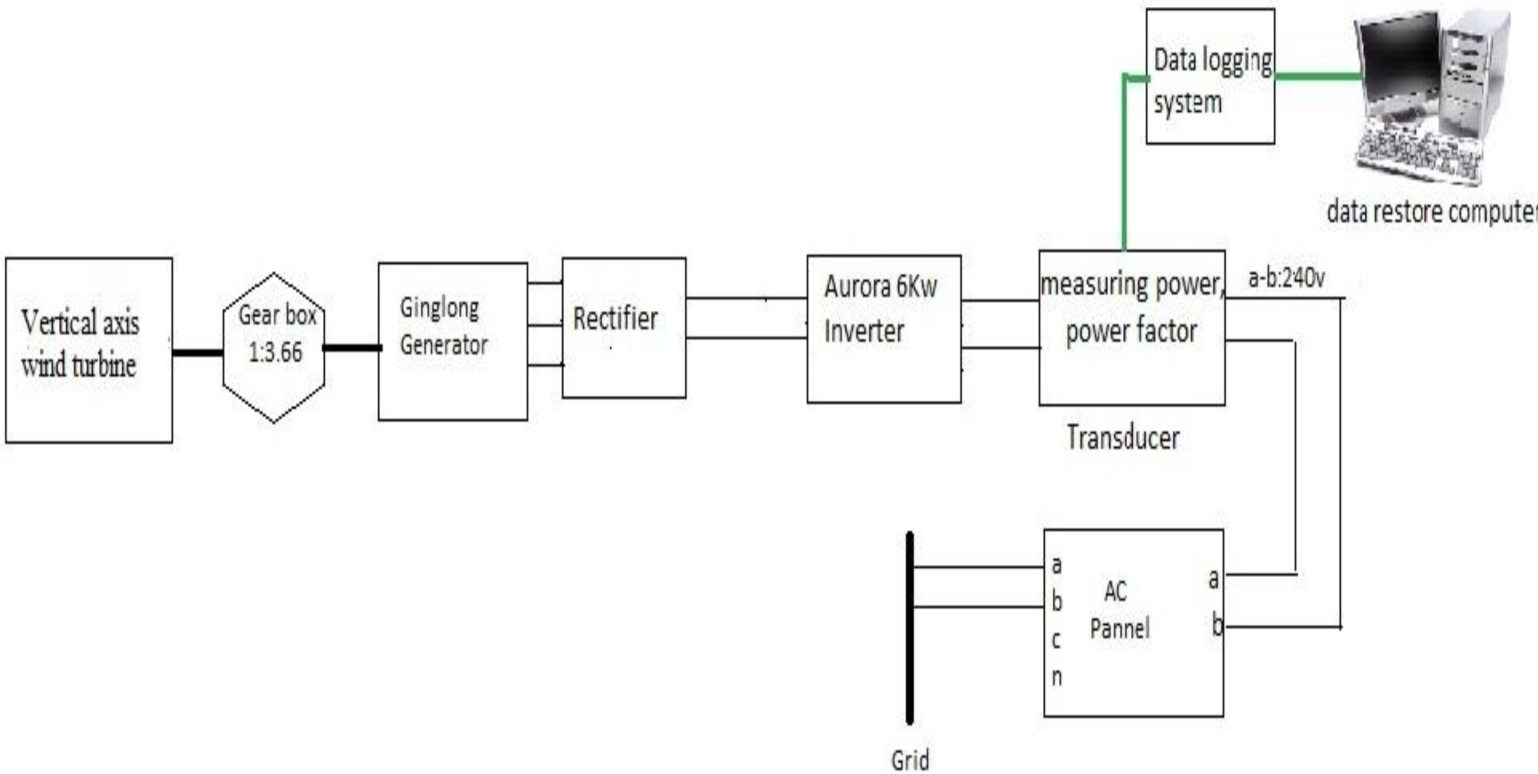
Block Diagram



TSR & MPPT table

- Tip speed ratio (TSR) is a ratio between the rotational speed of wind turbine blade and the wind speed.
- Wind turbine can extract maximum power from wind if the rotor blades run in such a speed that it can maintain an optimum tip speed ratio (TSR).
- To maintain an optimum TSR, this particular wind turbine's inverter depends on a look up table and it is called maximum power point tracking (MPPT) table.
- The MPPT table consist of optimum DC voltage input and corresponding maximum power output of the inverter

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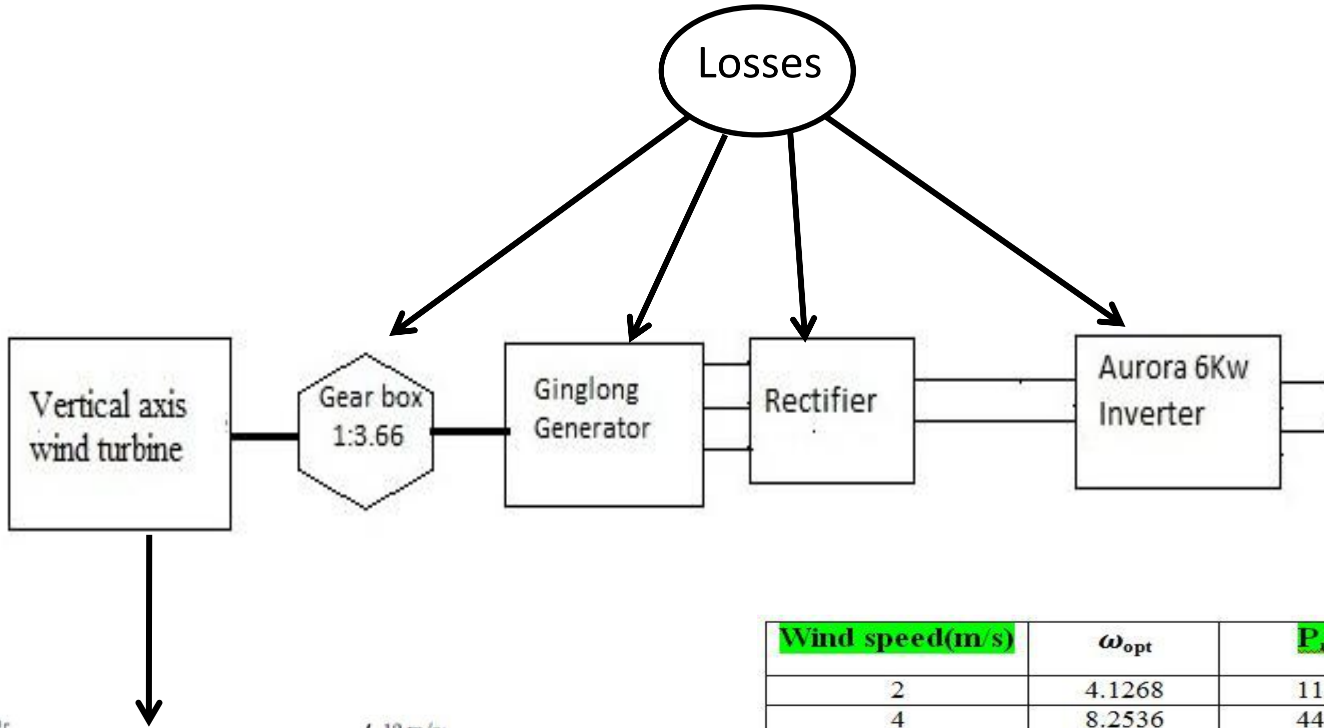
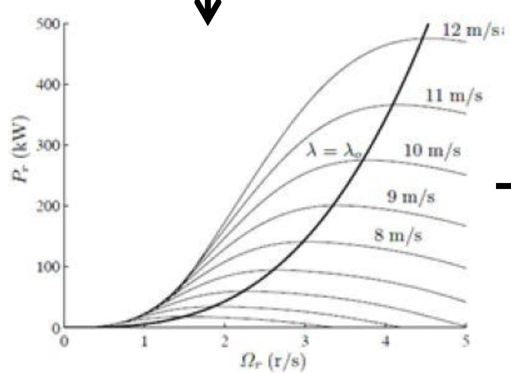
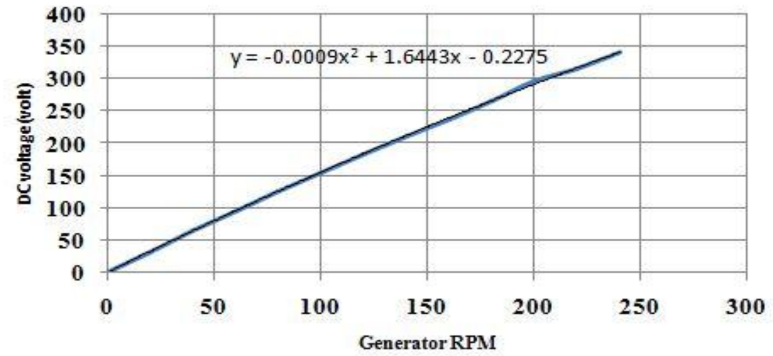
Power of MPPT

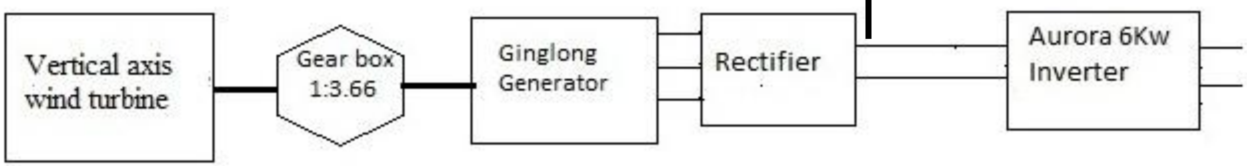


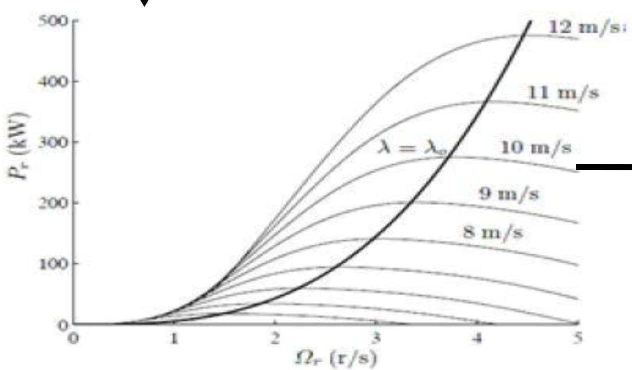


Wind speed(m/s)	ω_{opt}	P_{max}
2	4.1268	11.45
4	8.2536	44.98
6	12.38	116.06
8	16.5072	257.75
10	19.9462	458.23
12	24.34812	773.27
14	27.512	1174.23
16	30.951	1575.19
18	34.39	2133.67
20	38.5168	2906.95
22	42.6436	3665.91
24	46.7704	4439.19
26	50.8972	5155.19
28	55.024	5914.15
30	59.1508	6644.47

Output DC voltage at MPPT







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Derived MPPT table

DC voltage (V)	Power (watt)
50	0
71.23	65.90
94.2	157.62
113.06	311.63
136.78	552.30
153.6	878.84
171.56	1198.63
189.24	1676.65
210.06	2296.16
230.5	2960.03
250.54	3633.97
270.13	4215.74
289.39	4936.09
312.63	5478.34
330.00	6433.00
350.00	7353.25

Inverter start voltage 55 volt,

Total 16 points

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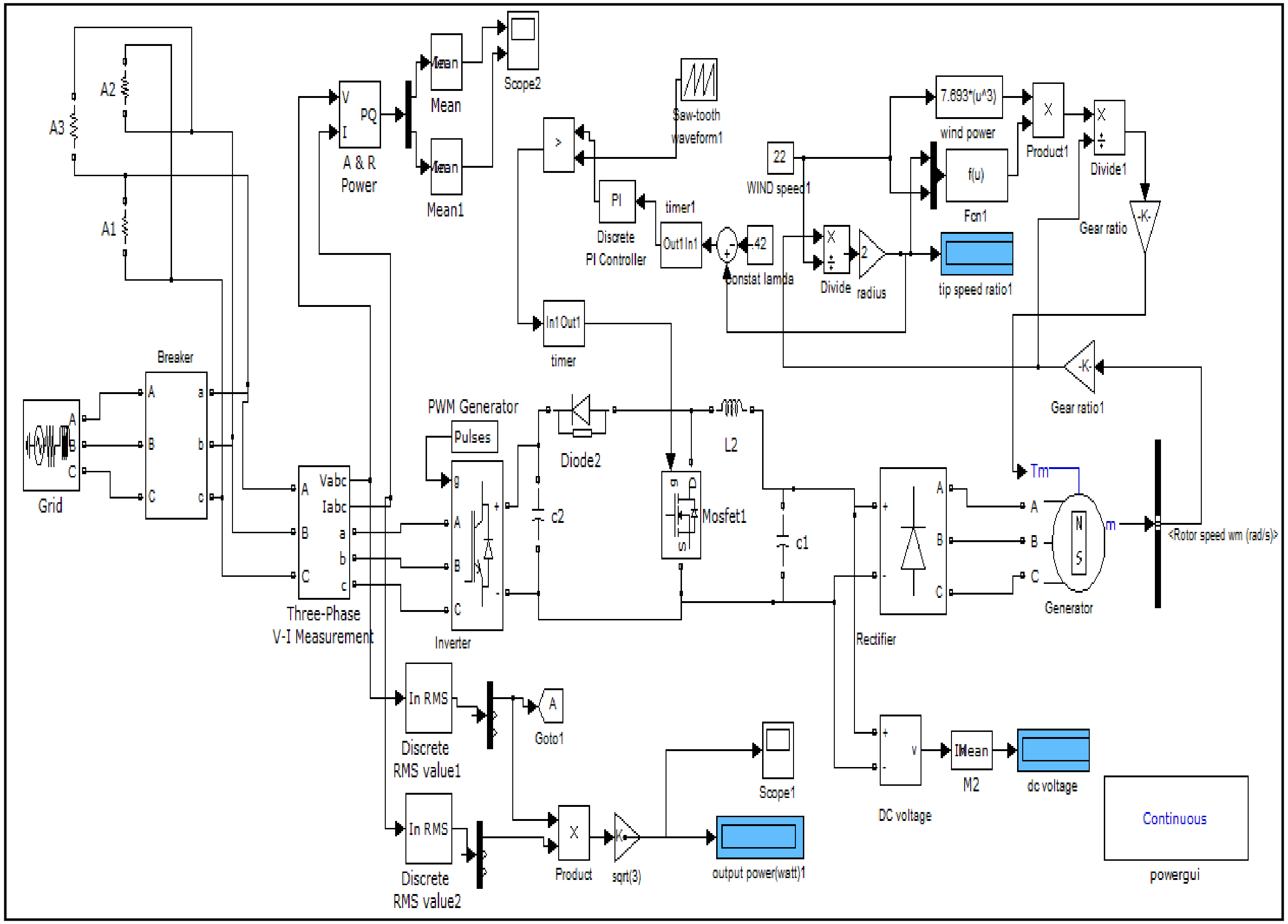
Simulation model of the VAWT to verify MPPT



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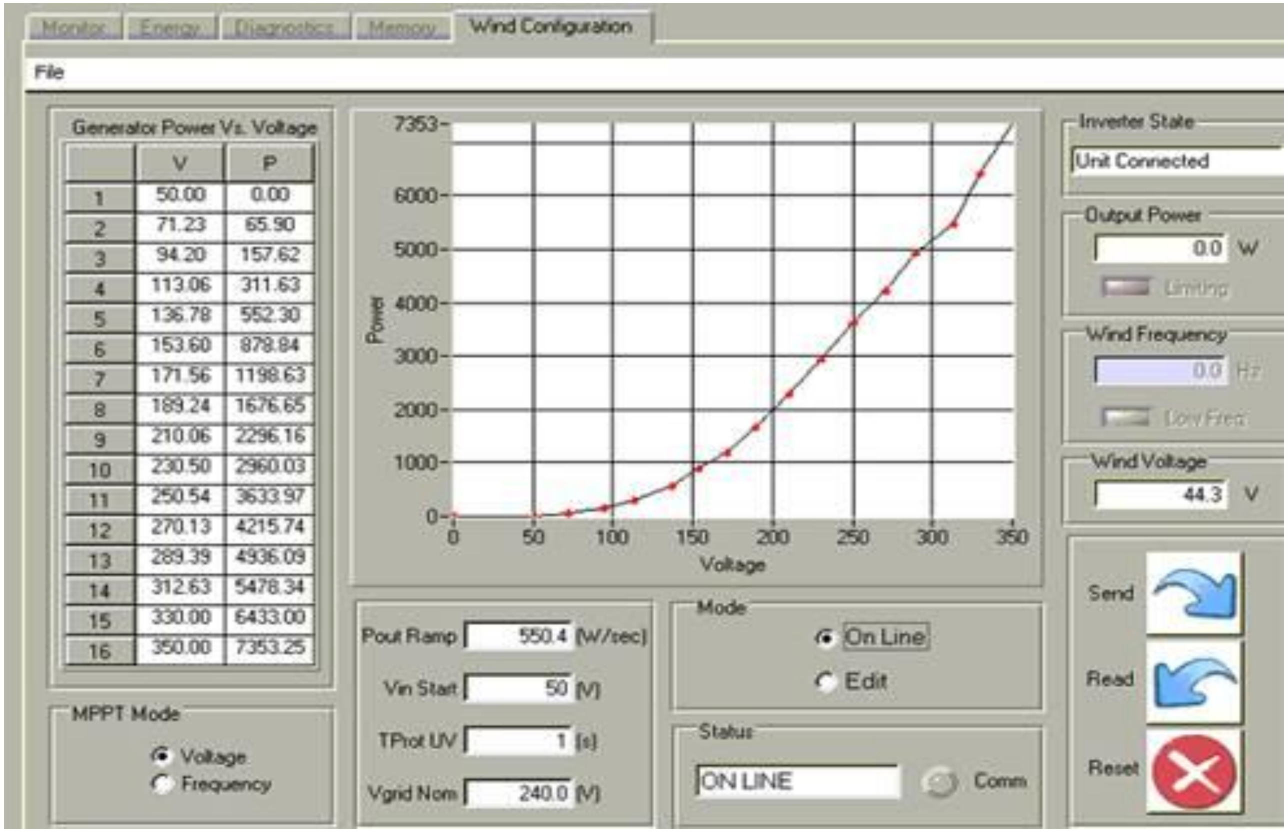
Derived MPPT verified in Simulink

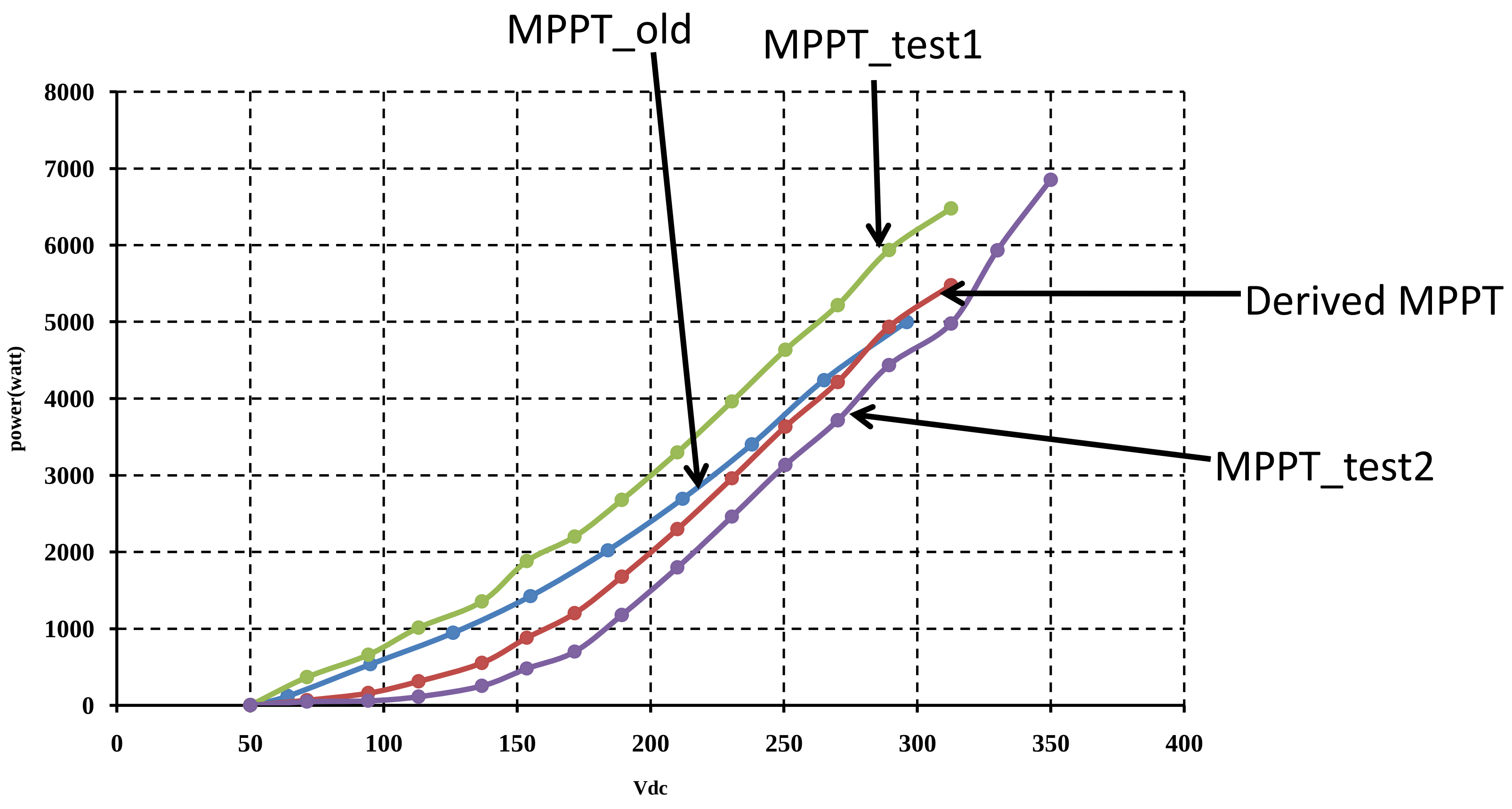
	Calculation from data sheet		Simulation result data		
Wind speed	Voltage	Power (watt)	Voltage	Power	Tip speed
2	24.36	4	15	4.1	0.26
4	48.58	19.65	39	31	0.35
6	72.39	65.9	66	88	0.39
8	95.72	157.62	92	173	0.4
10	114.87	311.63	118	288	0.417
12	138.95	552.3	144	442	0.424
14	156.01	878.84	168	640	0.427
16	174.23	1198.63	186	909	0.424
18	192.16	1676.65	204	1373	0.42
20	213.26	2296.16	224	1875	0.425
22	233.98	2960.03	241	2498	0.425
24	254.28	3633.97	258	3290	0.427
26	274.12	4215.74	275	4014	0.422
28	293.59	4936.09	311	4881	0.434

Power optimization…..

MPPT table programmed in inverter

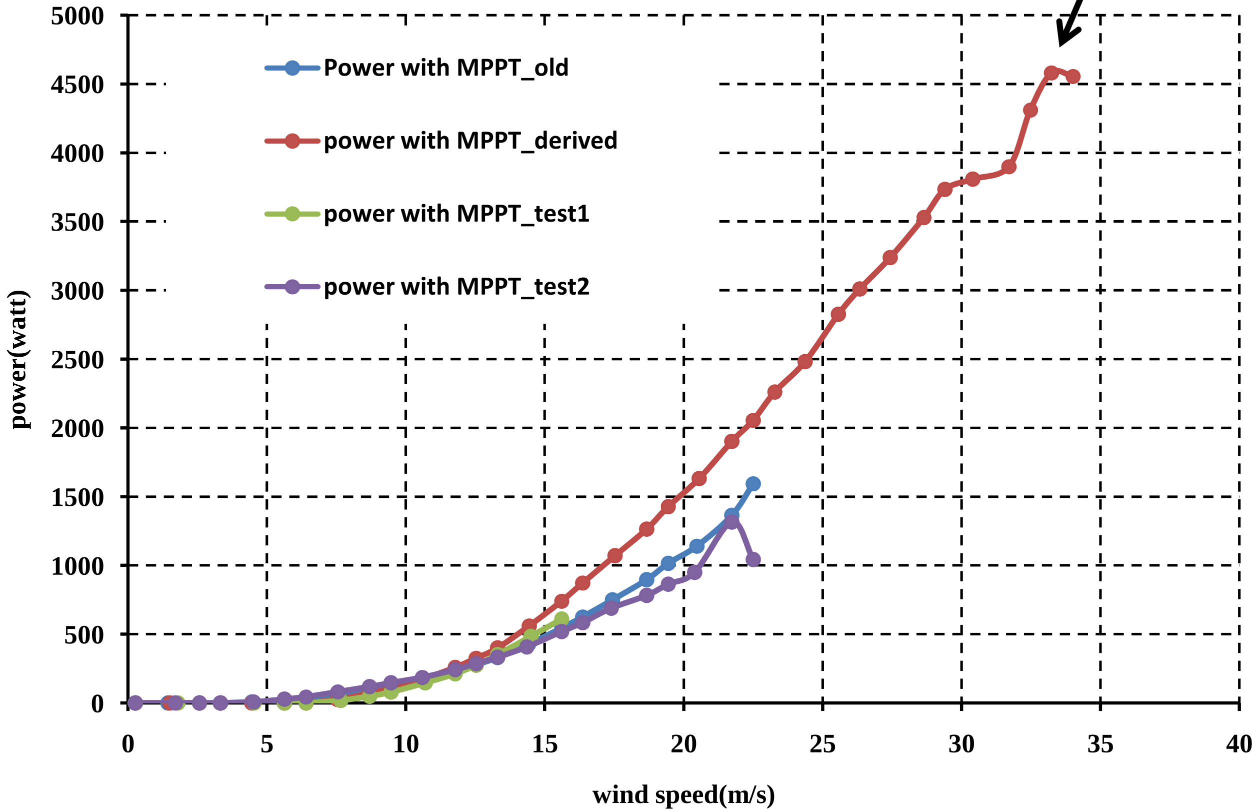


Other MPPT tables tested



Power performance with various MPPT tables

Best power performance with derived MPPT



Control System Design for Active and Reactive Power Control of a Grid Connected Small Wind Turbine

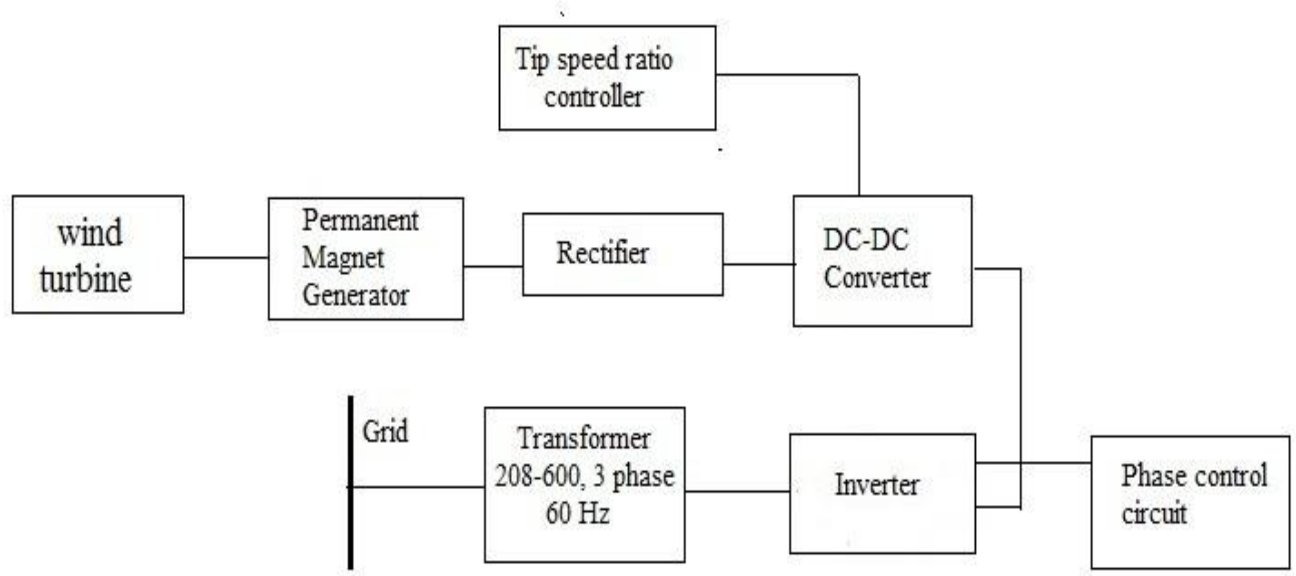
Objectives:

- Extract maximum power
- Provide required reactive power to local load

Design for:

- 1.1 KW small wind turbine
- Grid connected small WT
- The wind turbine has PMG
- Power coefficient is 0.5
- Tip Speed ratio is 6
- Load is connected between wind turbine and grid

Small Wind Turbine Configuration for this Research

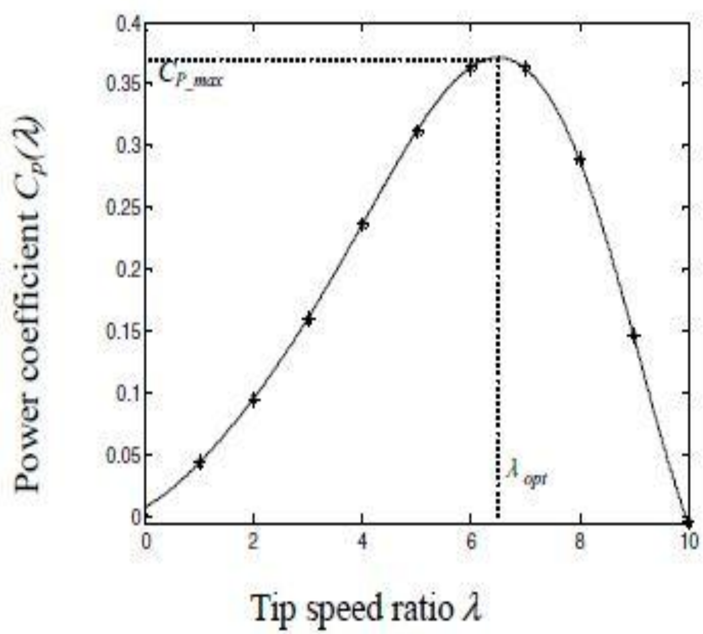


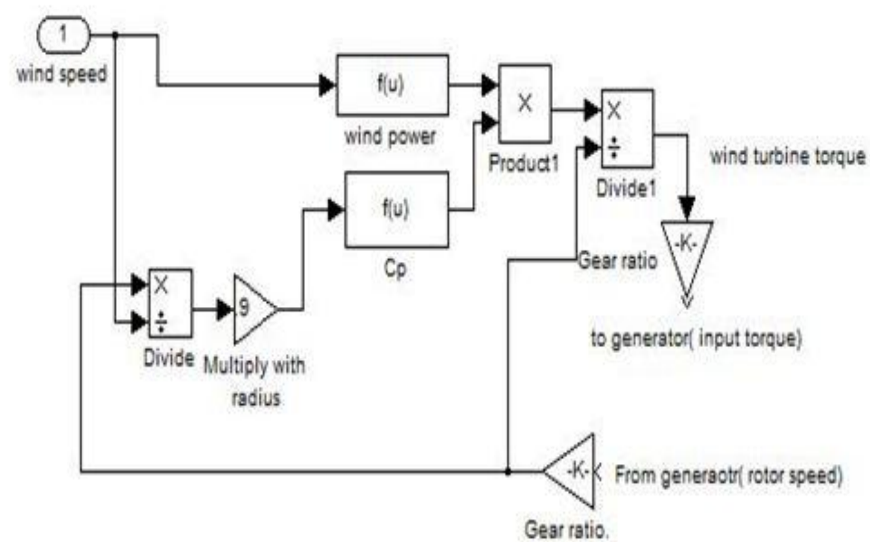
Control System Design……

System Modeling: Wind turbine

$$P = .5\rho A V^3 C_p$$
$$C_p = f(\lambda)$$
$$\lambda = \omega \frac{r}{V}$$

ρ = air density,
A = rotor blade area,
V = wind speed,
C_p = Power Coefficient=0.5,
λ = Tip speed ratio=6,
ω = rotor blade rotation,
r= blade radius=0.9m





Permanent magnet generator

$$\frac{d}{dt} i_d = \frac{v_d}{L_d} - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q$$

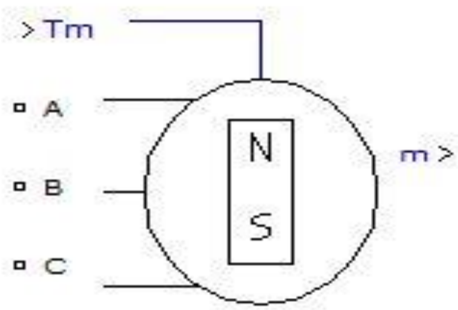
$$\frac{d}{dt} i_q = \frac{v_q}{L_q} - \frac{R}{L_q} i_q + \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda_a p\omega_r}{L_q}$$

$$T_e = 1.5p\left[\lambda_a i_q + (L_d - L_q) i_d i_q\right]$$

L_q, L_d = q and d axis inductances
R = Resistance of the stator windings
i_q, i_d = q and d axis current
V_q, V_d = q and d axis voltage
ω_r = angular velocity of the rotor
λ_a = Amplitude of the flux
p = pole pairs number
T_e = Electromagnetic torque

- The generator is 1.4 kW, 2 pole machine.

- Simulation block parameters are changed to match with a practical generator.



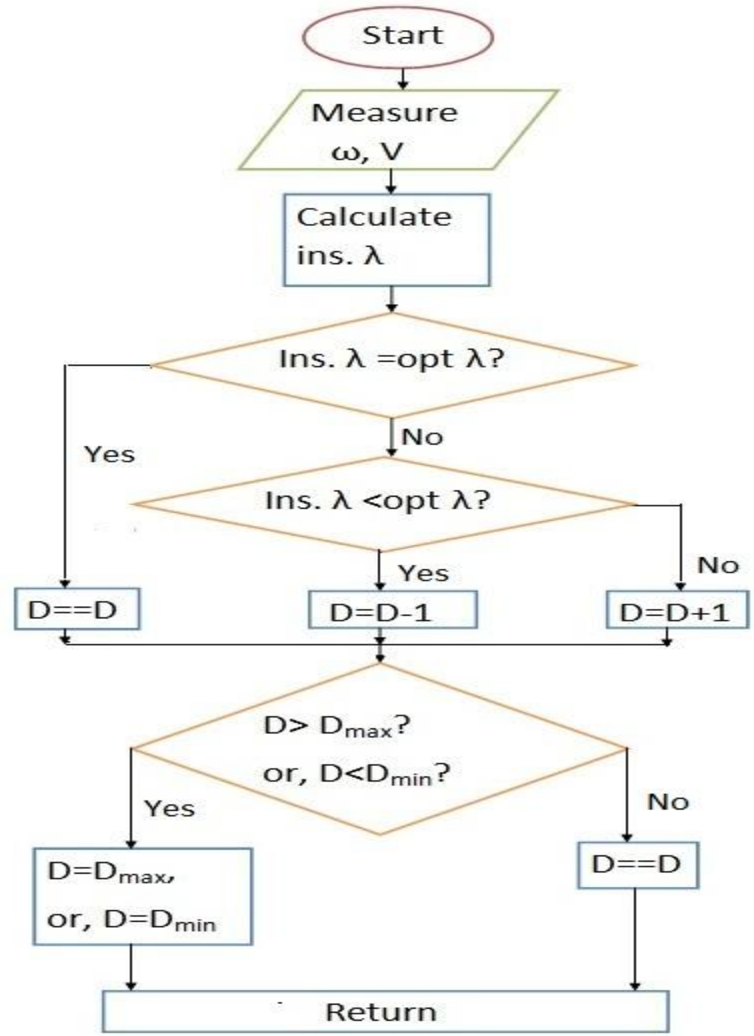
Power electronics

- Rectifier, Inverter ⟶ Simulink power system block-set
- Active power control circuit ⟶ PI Control block, saw tooth wave generator block, comparator and DC-DC boost converter.
- Reactive power control circuit ⟶ Proportional control block, Memory block, Plush width modulation generator
- Transformer ⟶ 1.5kVA (208V to 600V, 3 phase)
- Grid ⟶ AC voltage source

Active power control system

- Objective : Maintain a TSR equal to 6.
- From instantaneous TSR and optimal TSR, error is calculated.
- PI controller is used to correct the error in TSR.
- Output signal of the PI controller is compared with a triangular wave and a gate signal is generated for the DC-DC boost converter switch .
- DC current from the generator to load is controlled ⟶ Generator rpm is controlled ⟶ Turbine speed is control .

Flow chart for active power control

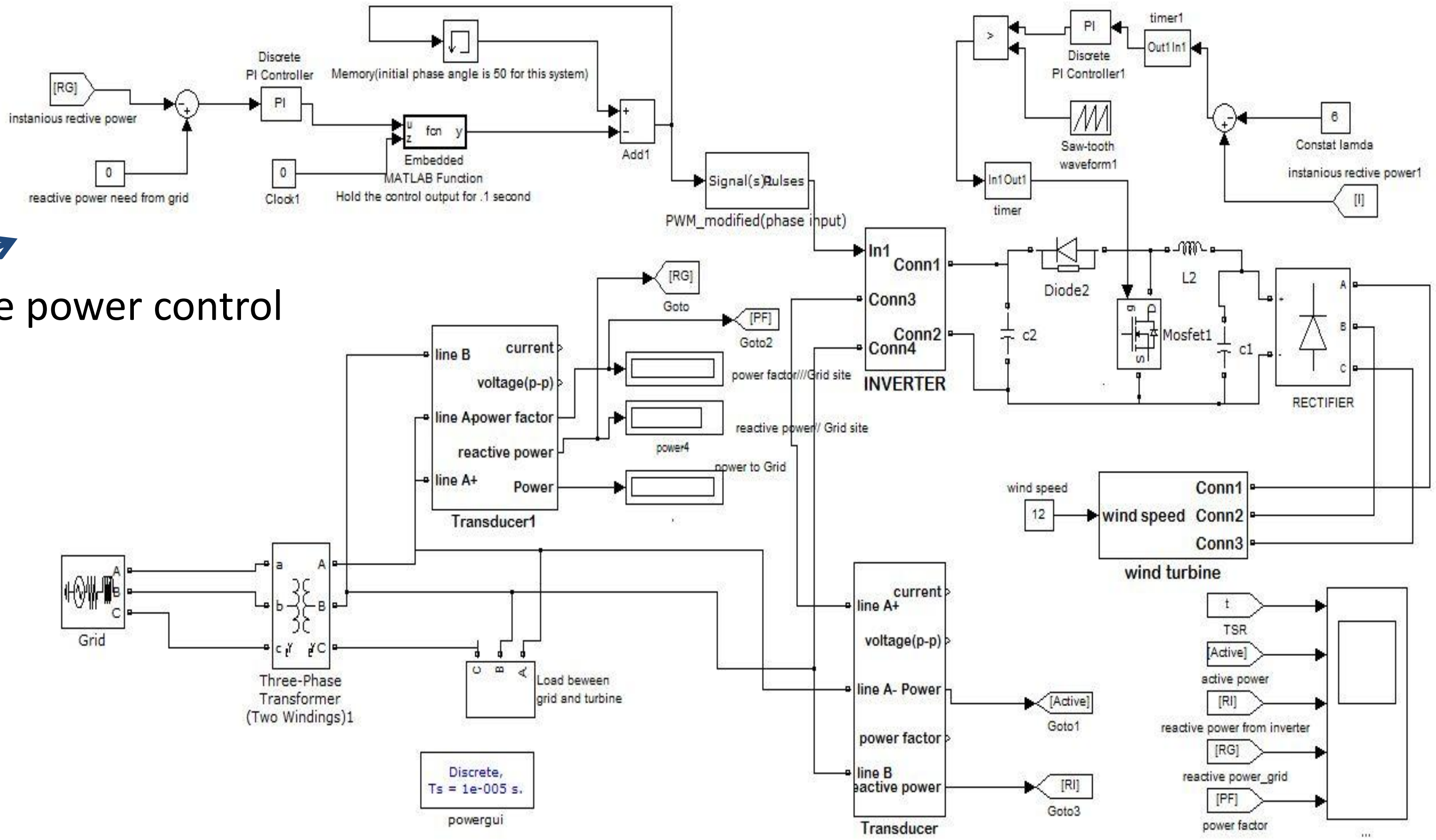


Reactive power control system

- Objective: Produce required reactive power for local load and exchange zero reactive power with grid.
- Reactive power error is the difference between the reactive power required by the local load and the reactive power supplied by the inverter.
- A proportional controller creates signal to minimize the error .
- By using previous time step output from memory block and controller signal, a new phase angle is generated for PWM generator input.

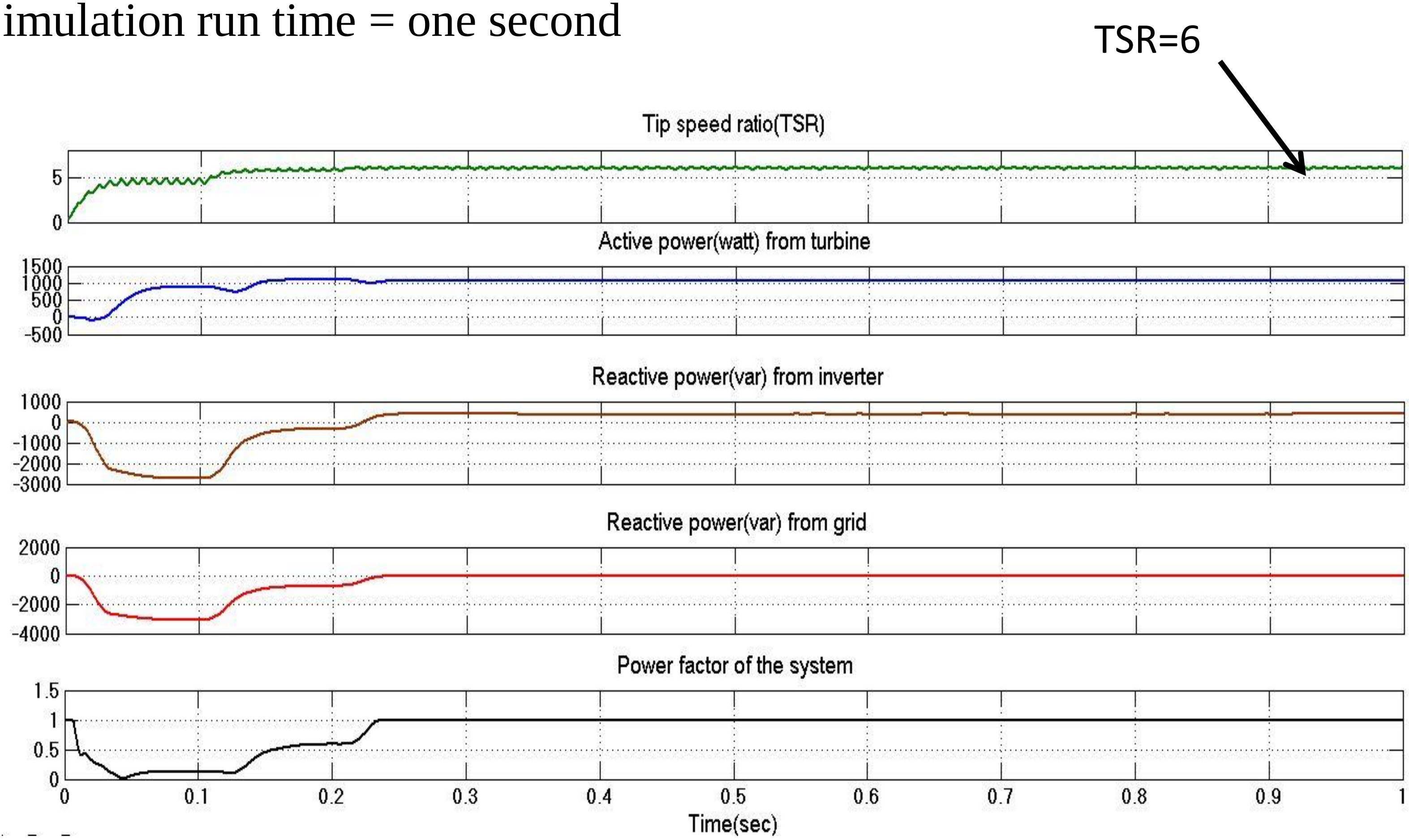
Simulink modeling

Active power control



Reactive power control

Case study 1: Condition: Wind speed=12.5m/s, Load=purely resistive load, Simulation run time = one second



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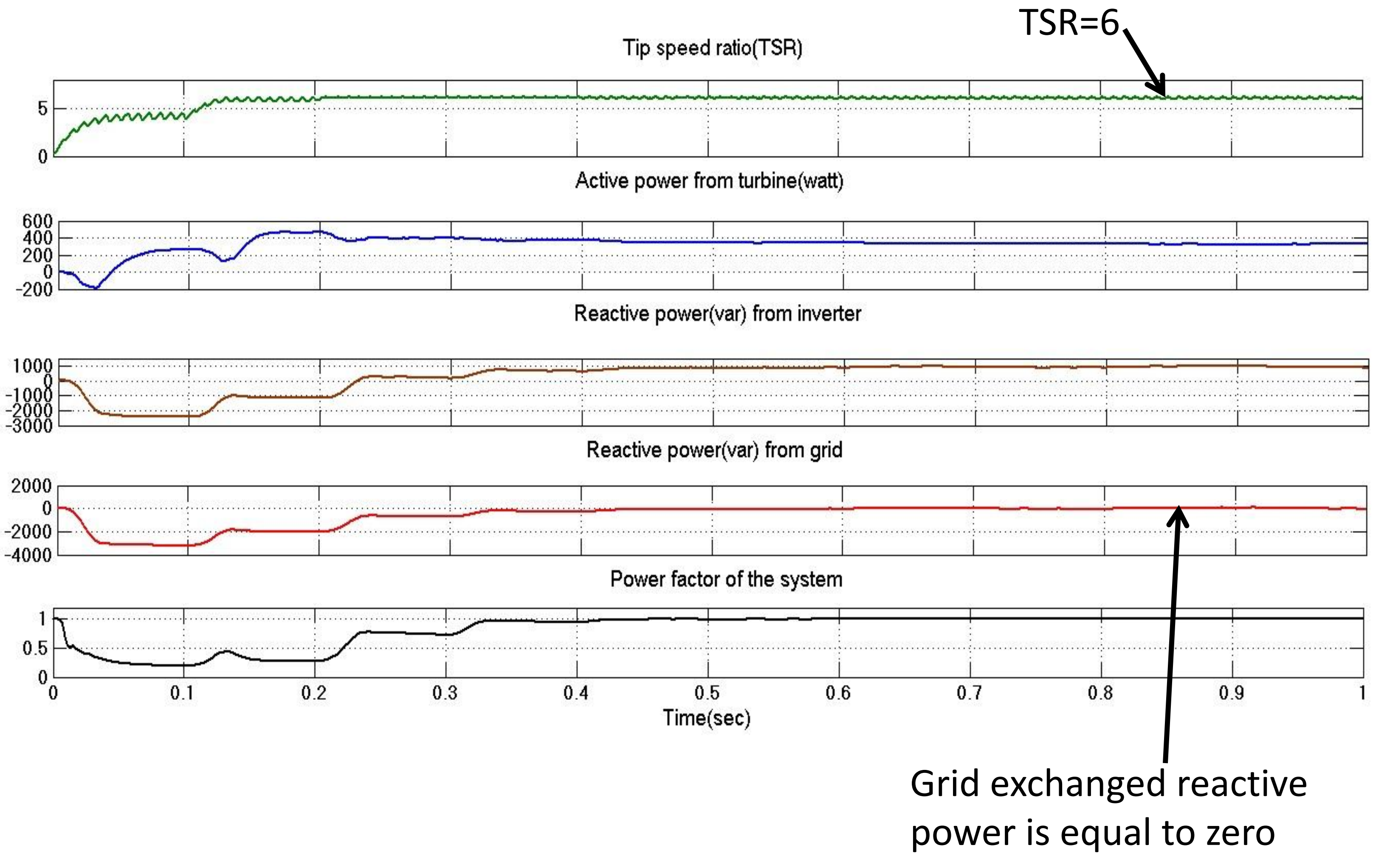
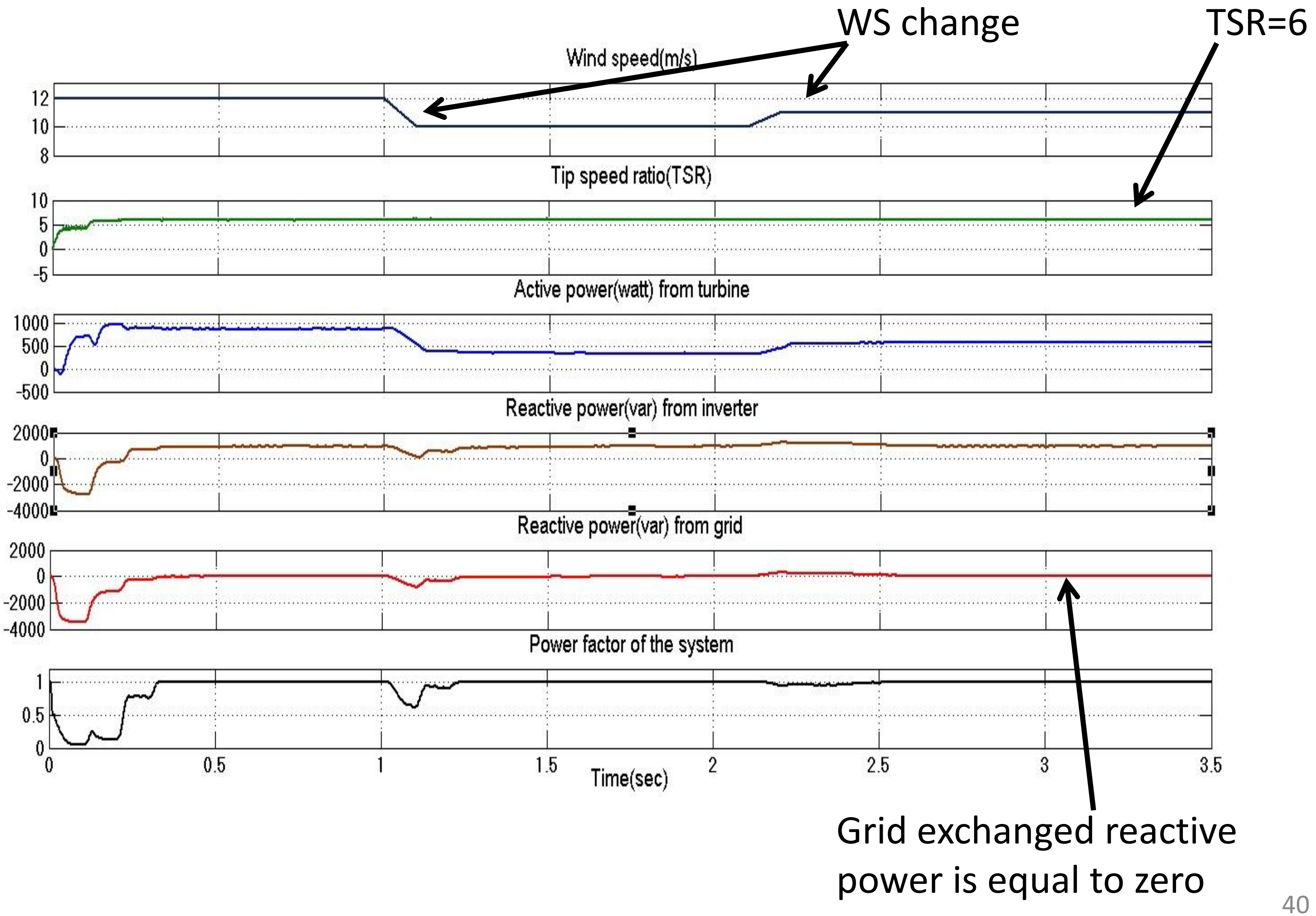
Case study 2: Condition: Wind speed=10m/s, Load=resistive and reactive load, Simulation run time = one second



Case study 3: Conditions: Wind speed= variable, Load=resistive and reactive load, Simulation run time=3.5 second



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Conclusion

The conclusions of the experiments are:

- Commercially available small wind turbine power performance is not affected by the local loads.
- Small wind turbine inverters need to be configured to maintain power factor of the whole system close to one.
- Small wind turbine inverters are unable to provide reactive power to load.

Conclusion……

The research contributions are as below:

- Determine grid-connected small wind turbine's behavior under variable local loads and proposed improvements.

- Development of a methodology to find an optimum MPPT table for small vertical axis wind turbine and field trials of MPPT table.

- Design and simulate a control system for active and reactive power control for a grid-connected small wind turbine.

Future work

- The MPPT table for the VAWT was derived by using the manufacturer provided data. In future, wind turbine system's experimental data (at least one year log) should be used to determine the MPPT table.
- Data collection for a long time is highly recommended.
- For future work a control system using only the PWM generator to control both the active and the reactive power is highly recommended.
- Full details of a real power system should be included in the Simulink model.

Acknowledgment

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- National Science and Engineering Research Council (NSERC)
- Wind Energy Strategic Network (WESNET)
- School of Graduate Studies (SGS) of Memorial University
- Wind Energy Institute of Canada (WEICan)
- Sugen Research

Publications

- **Paper 1**: Md. Alimuzzaman, M.T. Iqbal, "Dynamic modeling and simulation of a 1kW wind turbine based water pumping system", presented at *20th IEEE, NECEC*, 2011.

- **Paper 2**: Md. Alimuzzaman, M.T. Iqbal, Gerald Giroux, "An Investigation of Power Performance of Small Grid Connected Wind Turbines under Variable Electrical Loads" *International Journal of Energy Science, Vol. 2, Iss. 6*, December 2012.

- **Paper 3**: Md. Alimuzzaman, M.T. Iqbal, "Design of a Control System for Active and Reactive Power Control of a Small Grid Connected Wind Turbine" have submitted for review at *International Journal of Energy Science*.

- **Paper 4**: Md. Alimuzzaman, M.T. Iqbal. "Power performance of two small grid connected wind turbines" presented at *WESNet Student Poster Session and Competition*, October 18, 2012, Toronto, Ottawa, Canada.

- **Paper 5**: Md. Alimuzzaman, M.T. Iqbal "Dynamic Modeling, simulation and optimization of a novel 5kW grid connected vertical axis wind turbine system" presented at *21st IEEE, NECEC*, 2012.

Thank You!

Question?