Grid Impact of Wind Energy on Isolated and Remote Power System

Graduate Student Seminar : Master of Engineering

July 31, 2009

Sheikh Mominul Islam
si6028@mun.ca
Faculty of Engineering & Applied Science
Electrical Engineering

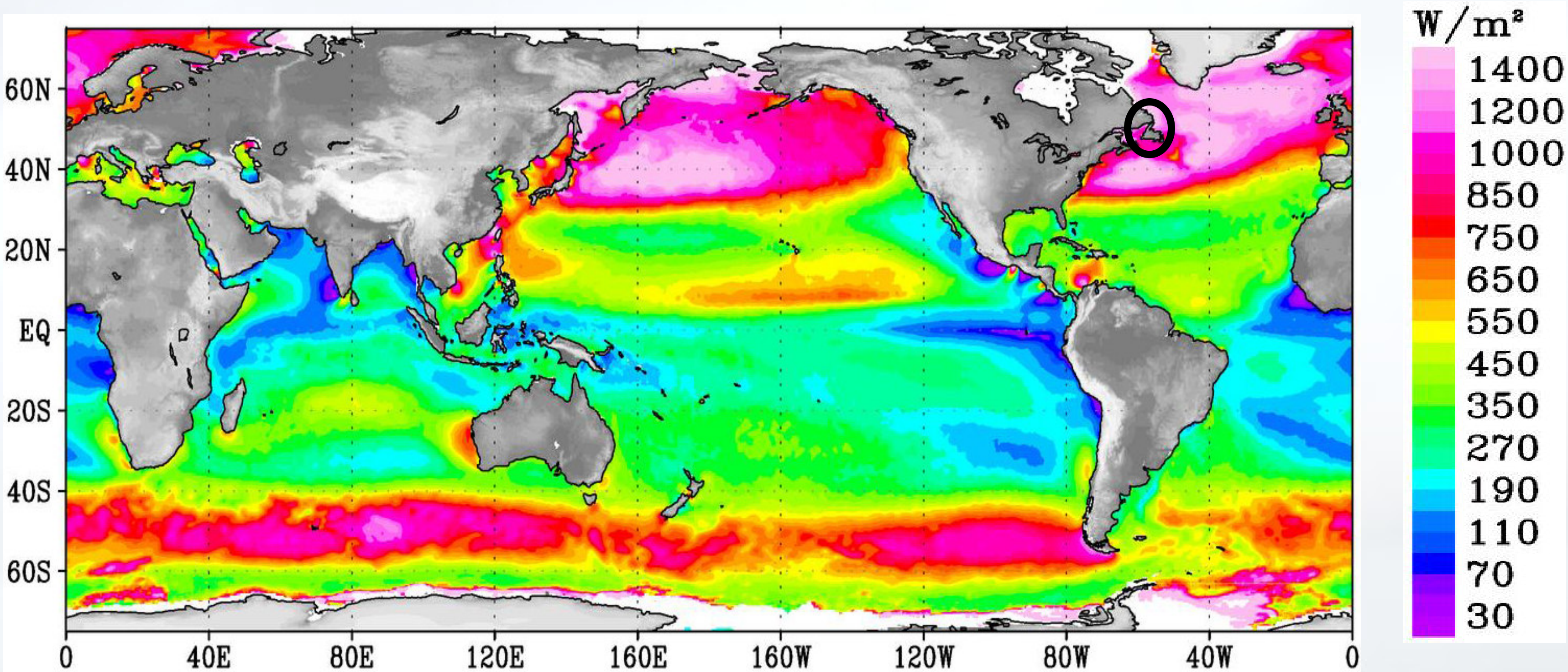
Outline

- Introduction
- Motivation
- Wind-Diesel System in Cartwright, Labrador
  - Model Formulation
  - Simulation Results
- Grid connected wind farm in St. Anthony, Newfoundland
  - Sizing of Wind Farm
  - Simulation Results
- Conclusion
- Future Recommendations

Why Wind Energy?

- Clean source of renewable energy
- Efficient and reliable
- Cost competitive to other fuel sources in large scale production
- Great resource to generate energy in remote locations
- No damaging affect on the environment

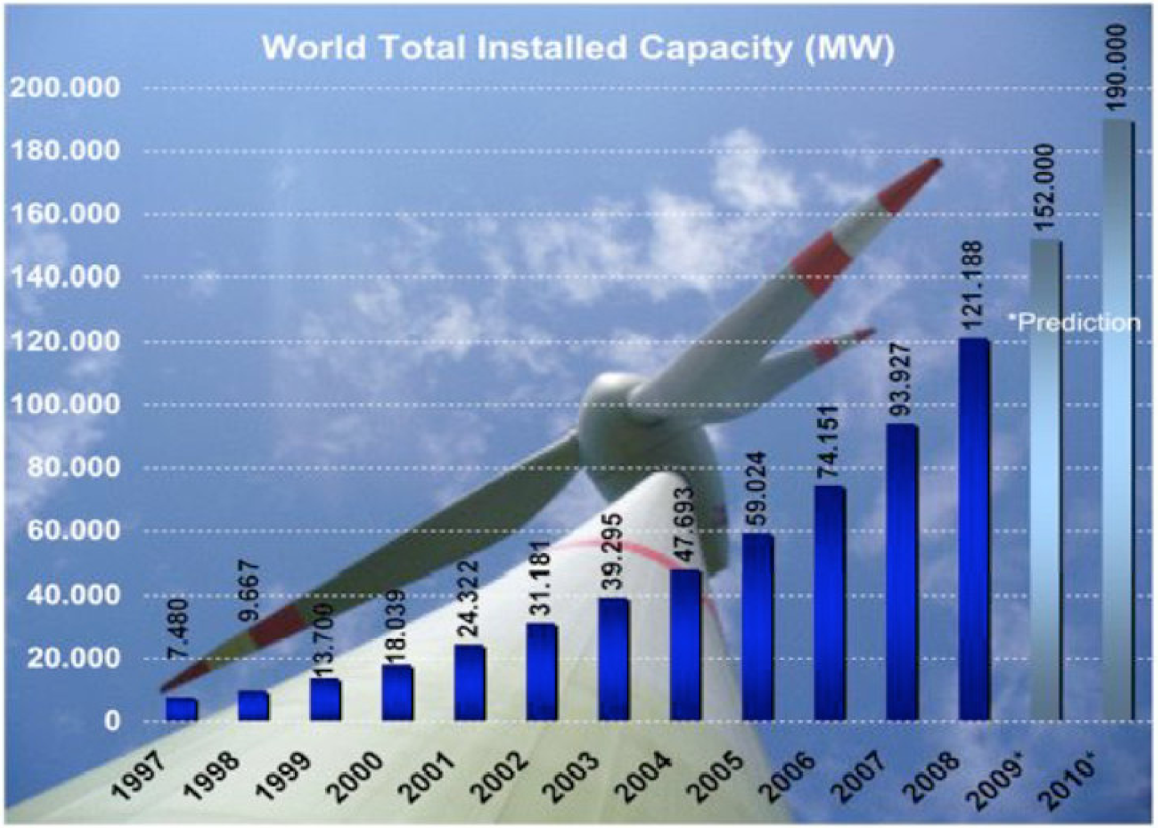
Available Wind Energy in the World



Source: National Aeronautics and Space Administration (NASA)

- Vast amount of wind energy is available in the world
- NL lies in one of the highest wind energy region

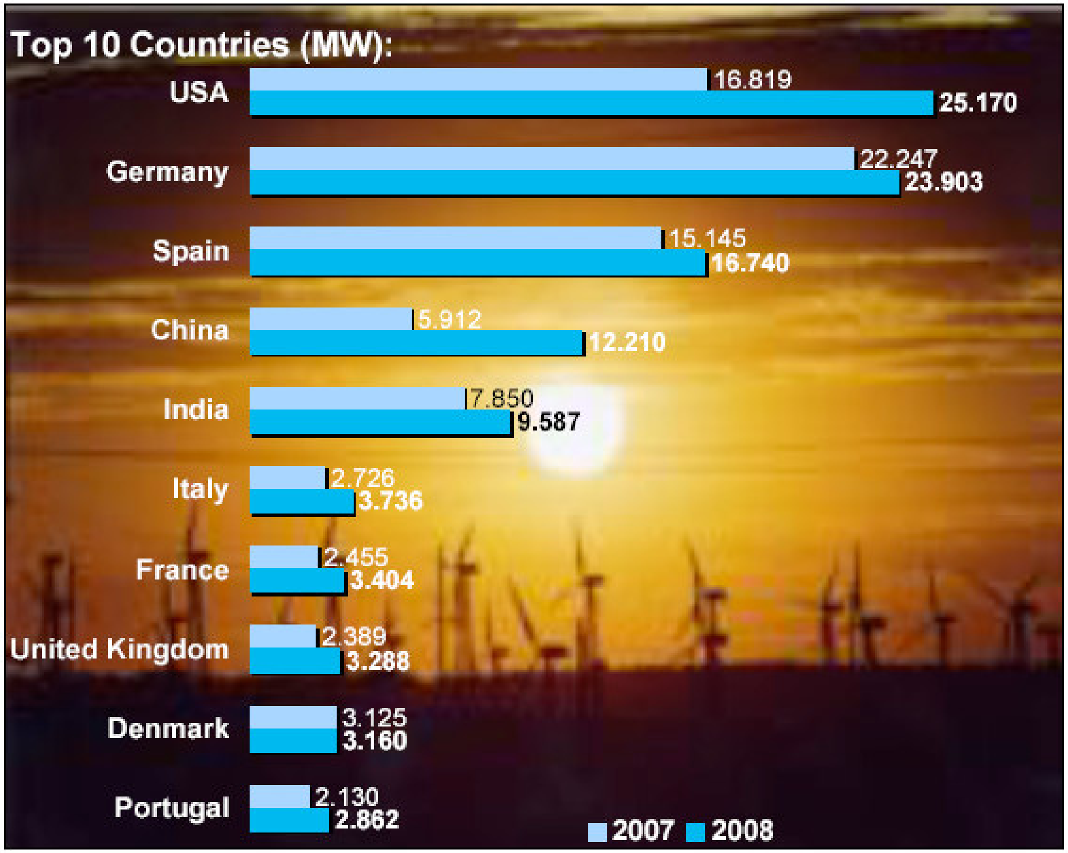
Global Wind Energy Scenario



Source: World Wind Energy Association

- The Increased growth rate in 2008 is about 29%
- Total energy produced from all wind turbines is about 250TWh
- Only 1.5% of global energy consumption demand are met

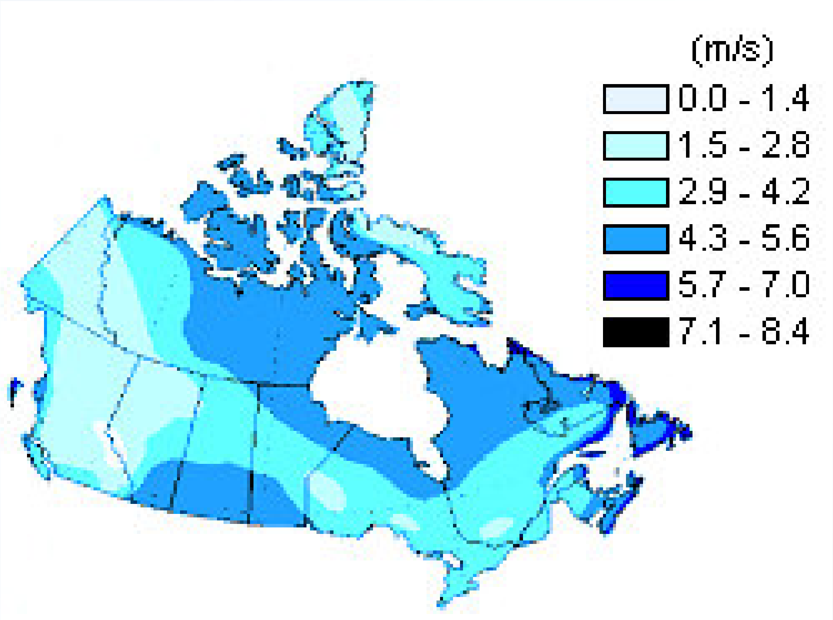
Global Wind Energy Scenario



Source: World Wind Energy Association

- Canada ranks 11th in the world with a total wind power capacity of 2,775 MW in 2008

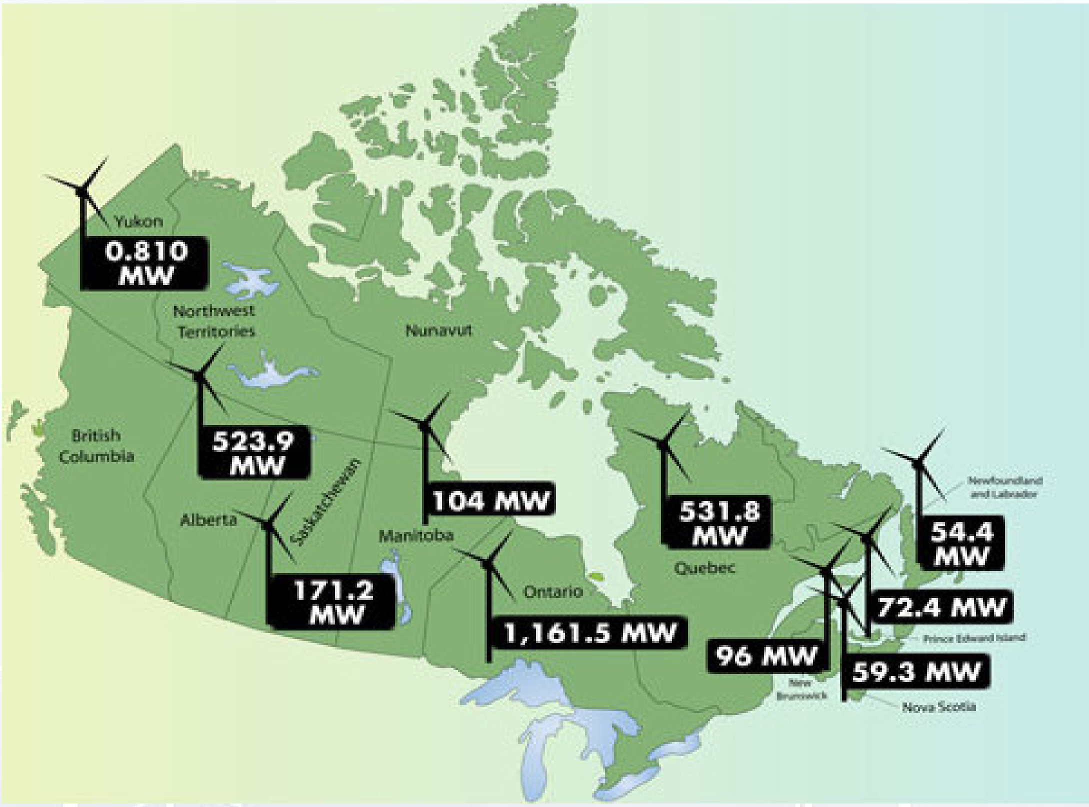
Wind Energy Scenario in Canada



Source: Natural Resources Canada

- **Only 1% of Canada's electricity demand met by presently installed wind capacity**
- **Plenty of wind energy potential is still unexplored.**

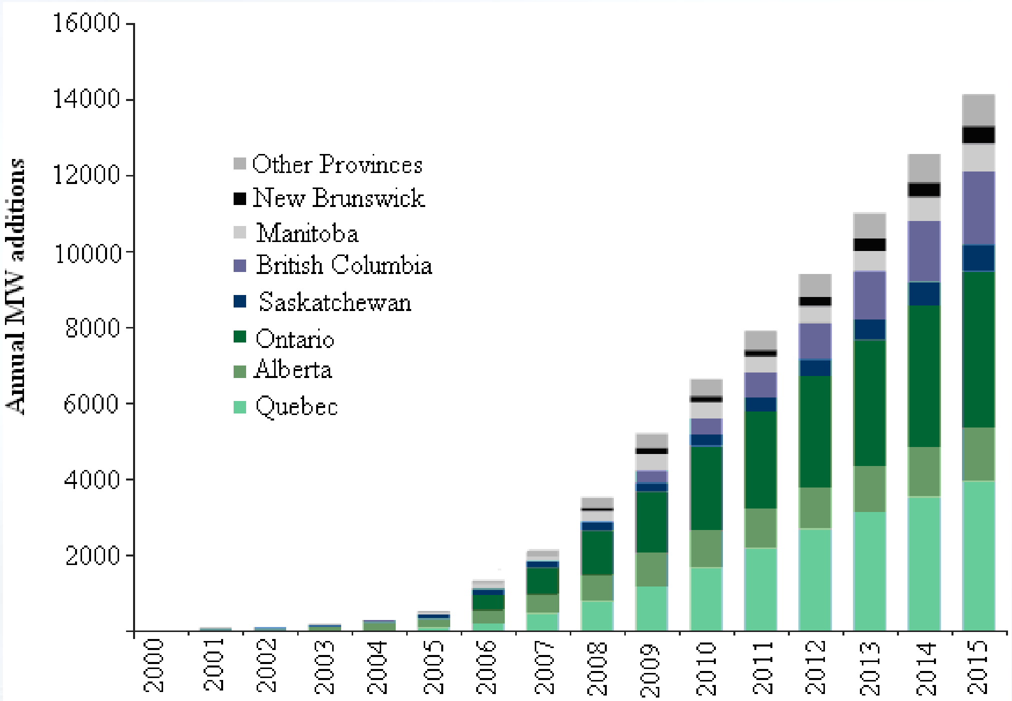
Wind Energy Scenario in Canada



Source: Canadian Wind Energy Association

- **87 wind farms with 1,400 wind turbines are currently operating in Canada**
- **Total installed capacity of 2,775MW – enough to power 840,000 homes in Canada**

Motivation



Source: Global Wind Energy Council

- **A minimum combined of 12,000 MW installed wind power capacity by 2015**
- **Wind Vision 2025 – Powering Canada's Future plan argues that Canada must ensure wind energy supplies 20% of the country's electricity demand by 2025,**

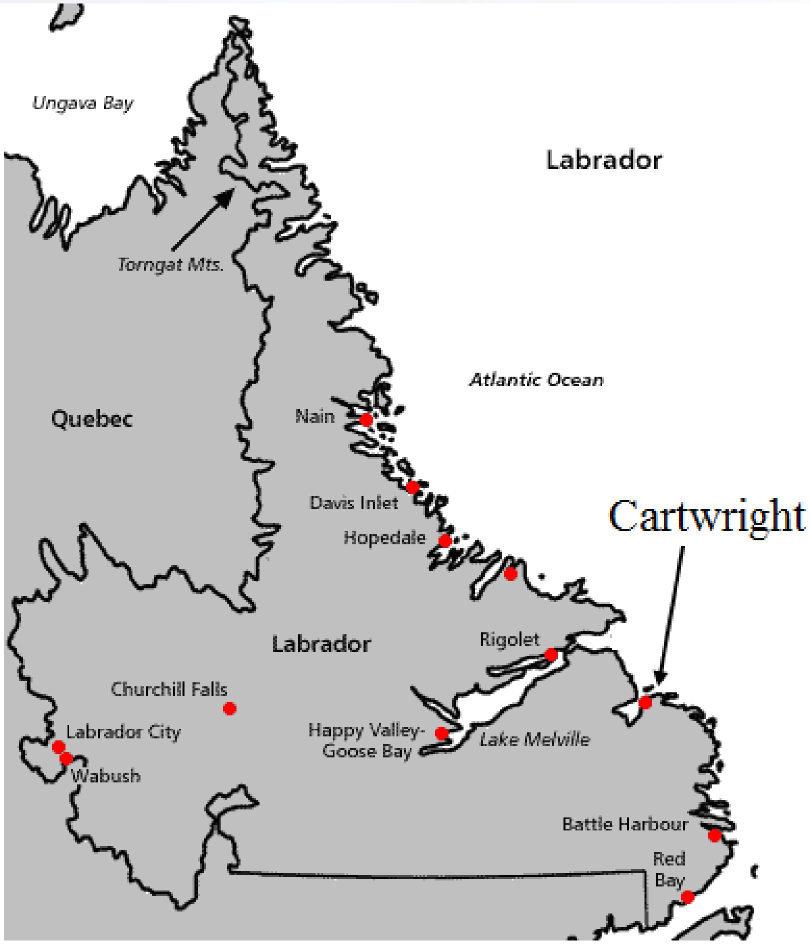
Scope of the Research

- **Most of the researches were done to control of wind-diesel system, flicker emission, wind diesel storage system, power quality from a wind farm etc.**
- **No research has been done the simulation of a community size wind-diesel system to study voltage and frequency fluctuations**
- **None studied the impact of wind power addition on local load in a community connected to the grid through a long transmission line.**

Scope of the Research

- **Two remote communities in Newfoundland and Labrador are identified to carry out the research**
- **Cartwright is in Labrador, which is an isolated community and is now being supplied by a diesel plant.**
- **St. Anthony in Newfoundland where the community is now supplied by a central power grid through a long transmission line.**
- **The objective is to identify the potential wind resource and to determine the voltage and frequency variation**

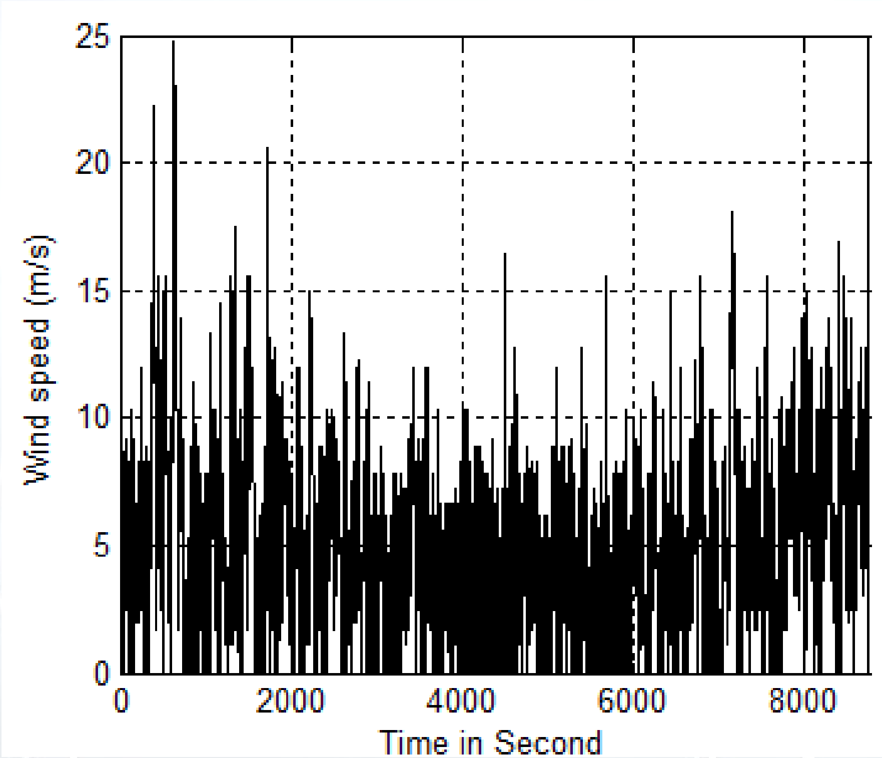
Wind-Diesel System in Cartwright, Labrador



- Cartwright is an isolated community in Southern Labrador
- Community's main source of income is fishery
- Diesel plant is the main source of generation of electricity
- Four diesel generators with the total capacity of 2150kW are operating to supply electricity
- The total diesel consumption by this diesel plant is about 1.2 million liters per year
- A wind-diesel hybrid system can help to reduce the overall electricity generation cost.

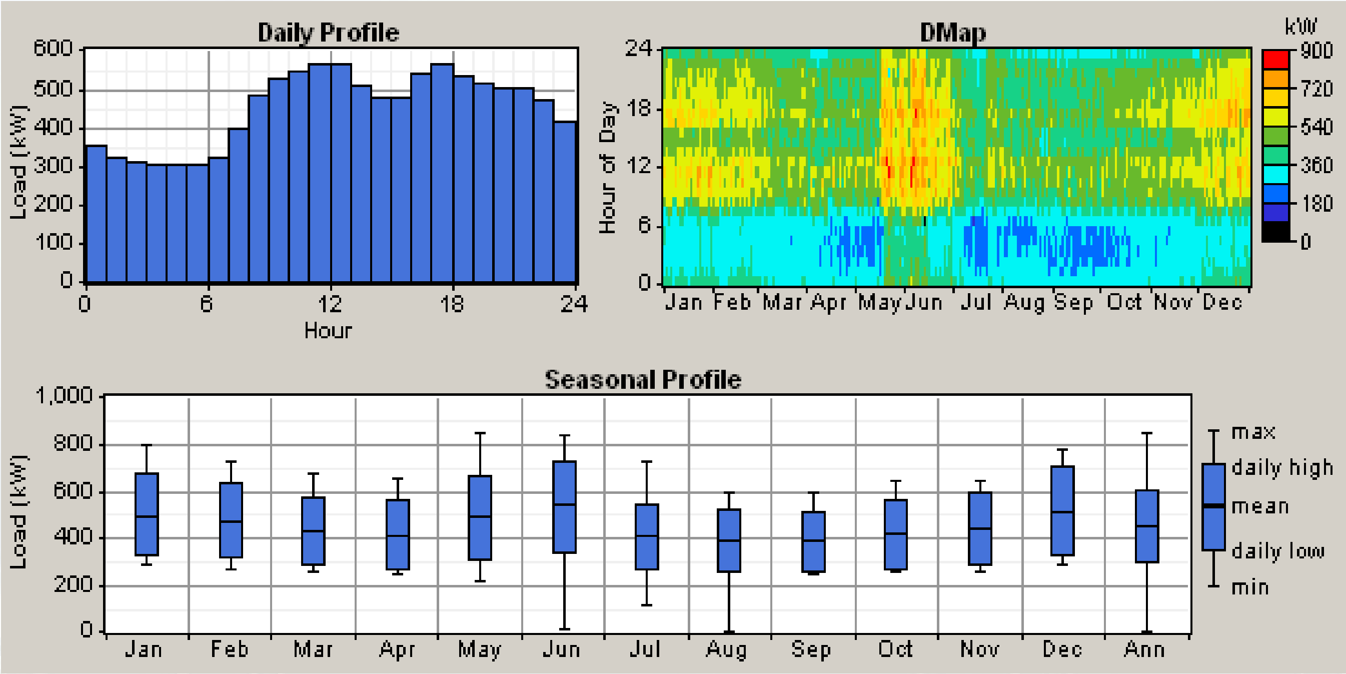
MEMORIAL UNIVERSITY

Wind Energy Resources in Cartwright



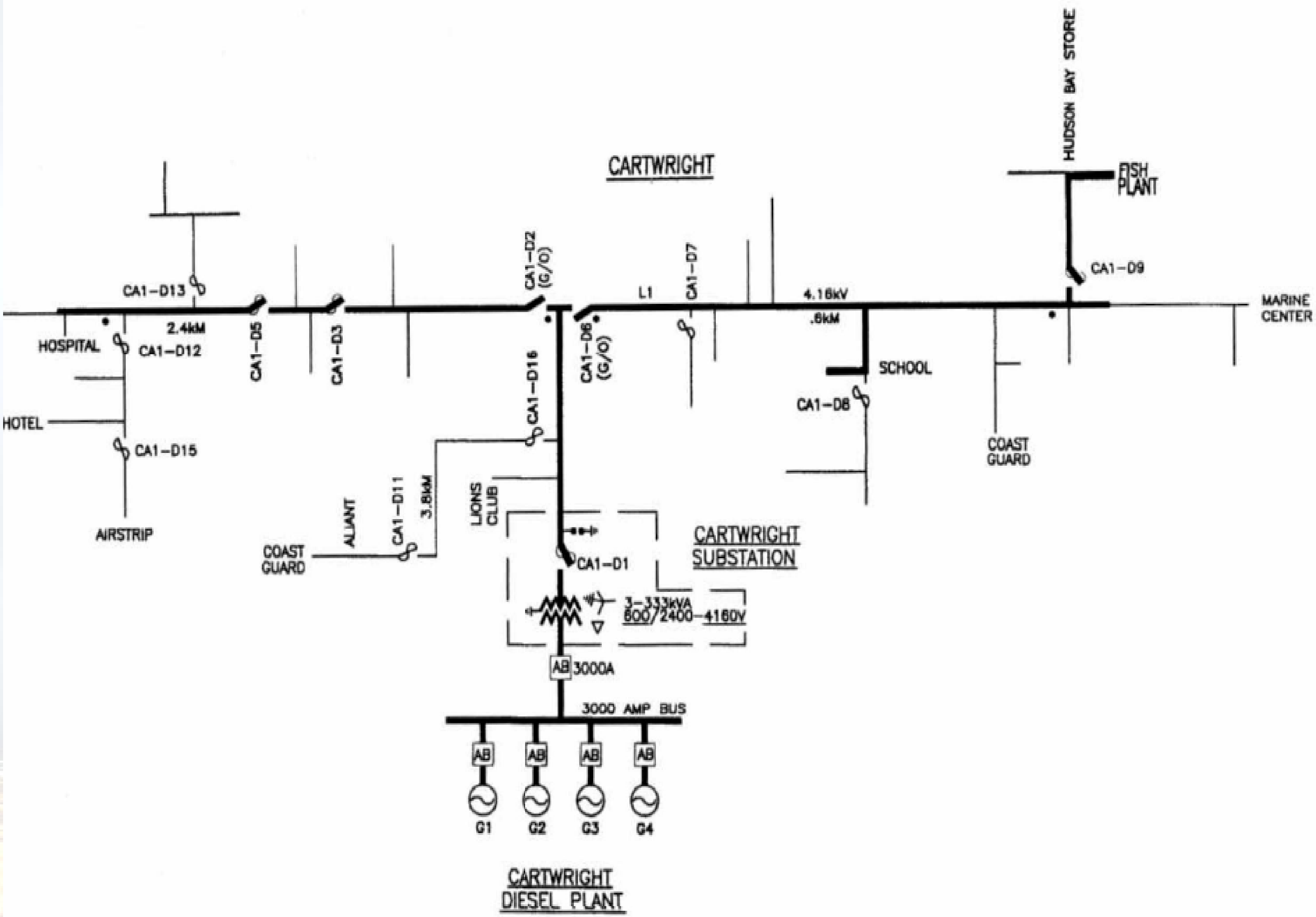
- **Annual average wind speed is 5.02m/s at 10m anemometer height.**

Load demand in Cartwright



- **Daily load profile varies from about 300kW to 550kW**
- **During summer load demand goes to its peak point about 850kW**

Existing power system in Cartwright

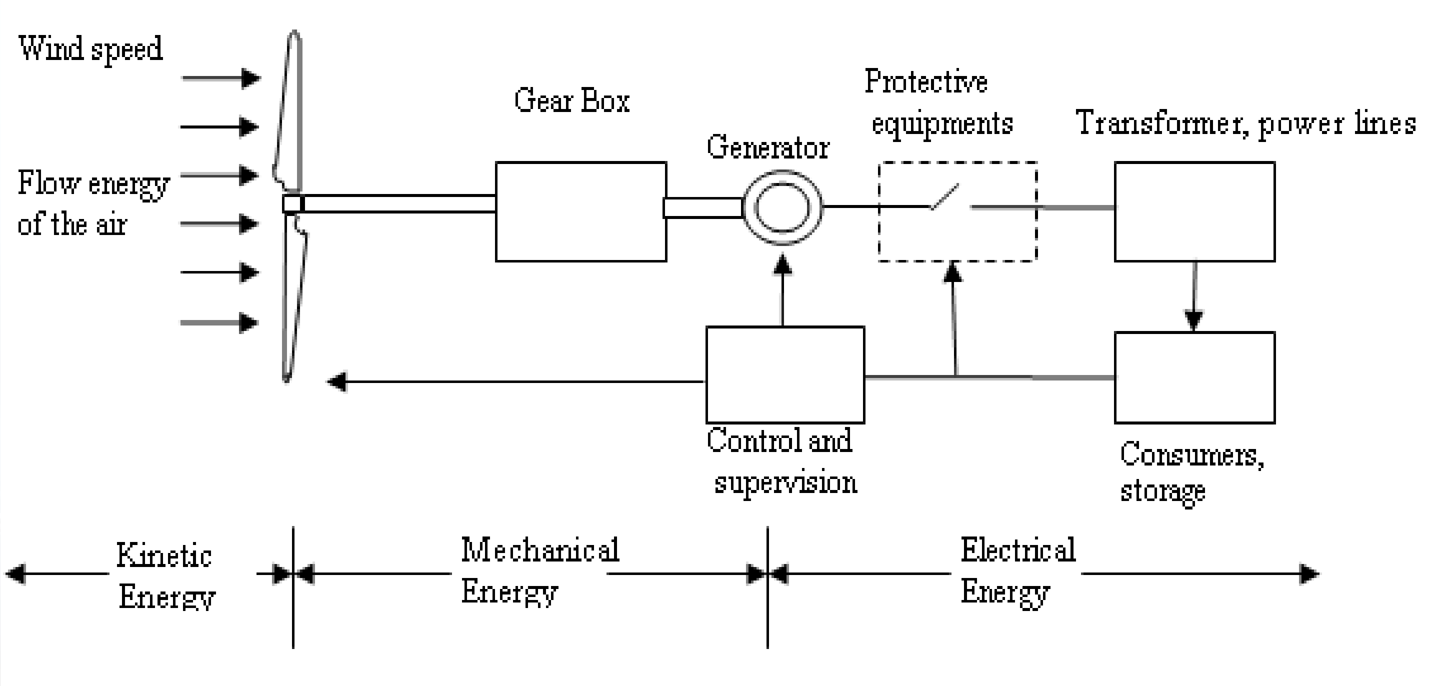


Existing power system in Cartwright

- Grid voltage level of 4.16kV is used to supply electricity to the community
- Two diesel generators can run at one time
- Diesel generators require a major overhaul after 15000hrs of operation
- The major load on diesel plant is fish plant
- Diesel plant has its own diesel storage tank which is maintained by local oil supplier
- Most of the residents of this community heat up their houses by using wood or furnace oil
- Total electricity production was 3953885kWhr in 2006

Model Formulation

Wind Energy Conversion system



Model Formulation

Wind turbine Model

Mechanical power output from a wind turbine

$$P = \frac{1}{2} C_p(\lambda, \alpha) \rho v^3 A \ \text{(W)}$$

Tip speed ratio of a wind turbine can be expressed as

$$\lambda_p = \frac{1}{\frac{1}{(\lambda + 0.089)} - \frac{0.035}{\alpha^3 + 1}}$$

Power Co-efficient of wind turbine can be given by

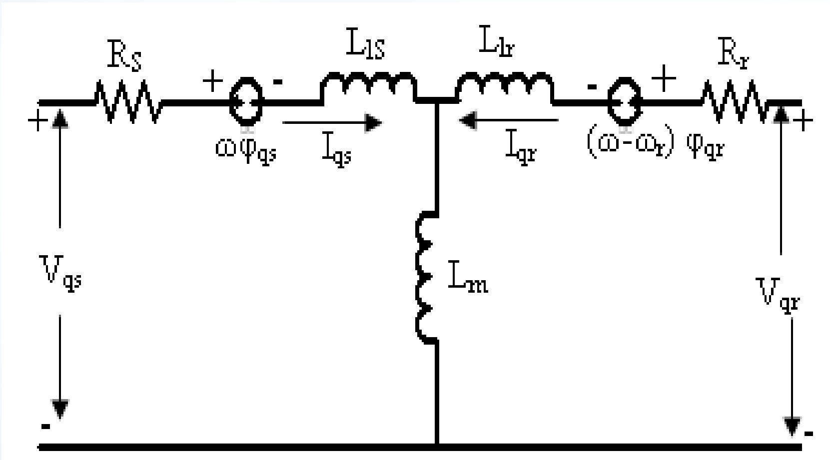
$$Cp = \frac{1}{2} \times \left(\frac{116}{\lambda_p} - 0.4 \times (\alpha - 5) \right) \exp^{\frac{-16.5}{\lambda_p}}$$

Mechanical torque output from wind turbine

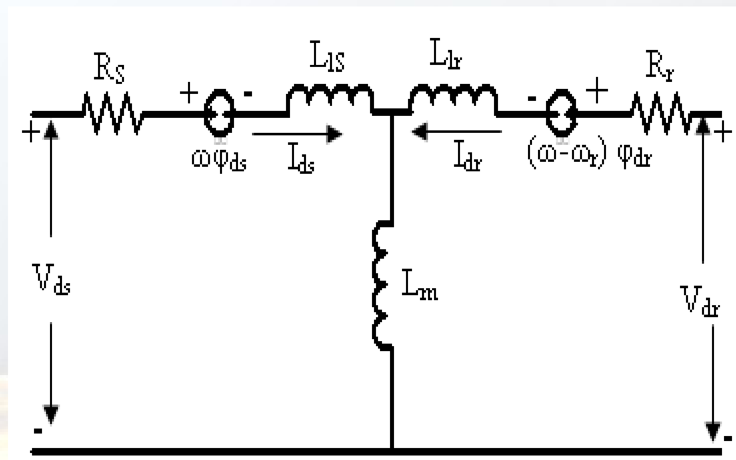
$$T_t = \frac{P_t}{\omega_t}$$

Model Formulation

Induction Machine Model



q axis



d axis

Model Formulation

Induction Machine Model

q-axis stator voltage $v_{qs} = R_s i_{qs} + \frac{\omega}{\omega_b}\varphi_{ds} + \frac{p}{\omega_b}\varphi_{qs}$

d-axis stator voltage $v_{ds} = R_s i_{ds} - \frac{\omega}{\omega_b}\varphi_{qs} + \frac{p}{\omega_b}\varphi_{ds}$

q-axis rotor voltage $v'_{qr} = R'_r i'_{qr} + \left(\frac{\omega - \omega_r}{\omega_b}\right)\varphi'_{dr} + \frac{p}{\omega_b}\varphi'_{qr}$

d-axis rotor voltage $v'_{dr} = R'_r i'_{dr} - \left(\frac{\omega - \omega_r}{\omega_b}\right)\varphi'_{qr} + \frac{p}{\omega_b}\varphi'_{dr}$

Model Formulation

Induction Machine Model

q-axis stator flux

$$\varphi_{qs} = \omega_b \int \left[v_{qs} - \frac{\omega}{\omega_b}\varphi_{ds} + \frac{R_s}{X_{ls}}\left(\varphi_{mq} - \varphi_{qs}\right) \right] dt$$

d-axis stator flux

$$\varphi_{ds} = \omega_b \int \left[v_{ds} + \frac{\omega}{\omega_b}\varphi_{qs} + \frac{R_s}{X_{ls}}\left(\varphi_{md} - \varphi_{ds}\right) \right] dt$$

q-axis rotor flux

$$\varphi'_{qr} = \omega_b \int \left[v'_{qr} - \frac{\omega - \omega_r}{\omega_b}\varphi'_{dr} + \frac{R'_r}{X'_{lr}}\left(\varphi_{mq} - \varphi'_{qr}\right) \right] dt$$

d-axis rotor flux

$$\varphi'_{dr} = \omega_b \int \left[v'_{dr} + \frac{\omega - \omega_r}{\omega_b}\varphi'_{qr} + \frac{R'_r}{X'_{lr}}\left(\varphi_{md} - \varphi'_{dr}\right) \right] dt$$

q-axis mutual flux

$$\varphi_{mq} = X_t \left(\frac{\varphi_{qs}}{X_{ls}} + \frac{\varphi'_{qr}}{X'_{lr}} \right)$$

d-axis mutual flux

$$\varphi_{md} = X_t \left(\frac{\varphi_{ds}}{X_{ls}} + \frac{\varphi'_{dr}}{X'_{lr}} \right)$$

Model Formulation

Induction Machine Model

q-axis stator current $$i_{qs} = \frac{1}{X_{ls}}\left(\varphi_{qs} - \varphi_{mq}\right)$$

d-axis stator current $$i_{ds} = \frac{1}{X_{ls}}\left(\varphi_{ds} - \varphi_{md}\right)$$

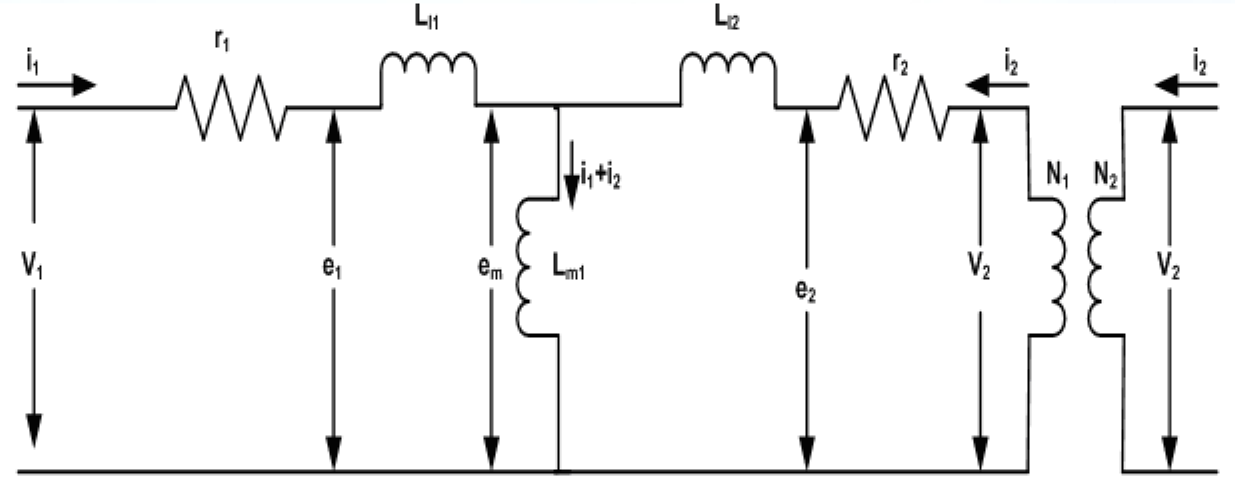
q-axis rotor current $$i_{qr} = \frac{1}{X_{lr}}\left(\varphi_{qr} - \varphi_{mq}\right)$$

d-axis rotor current $$i_{dr} = \frac{1}{X_{lr}}\left(\varphi_{dr} - \varphi_{md}\right)$$

Electromagnetic torque $$T_{g} = \frac{3P}{4\omega_{b}}\left(\varphi_{ds} i_{qs} - \varphi_{qr} i_{dr}\right)$$

Model Formulation

Transformer Model



- It is assumed that the windings have zero resistance
- The core reluctance is neglected

Model Formulation

Transformer Model

Primary winding induced voltage $V_1 = i_1 R_1 + \frac{1}{\omega_b}\frac{d\varphi_1}{dt}$

Secondary winding induced voltage $V_2' = i_2' R_2' + \frac{1}{\omega_b}\frac{d\varphi_2'}{dt}$

Primary winding induced flux $\varphi_1 = \omega_b \int \left[V_1 - R_1 \left(\frac{\varphi_1 - \varphi_m}{X_{l_1}} \right) \right] dt$

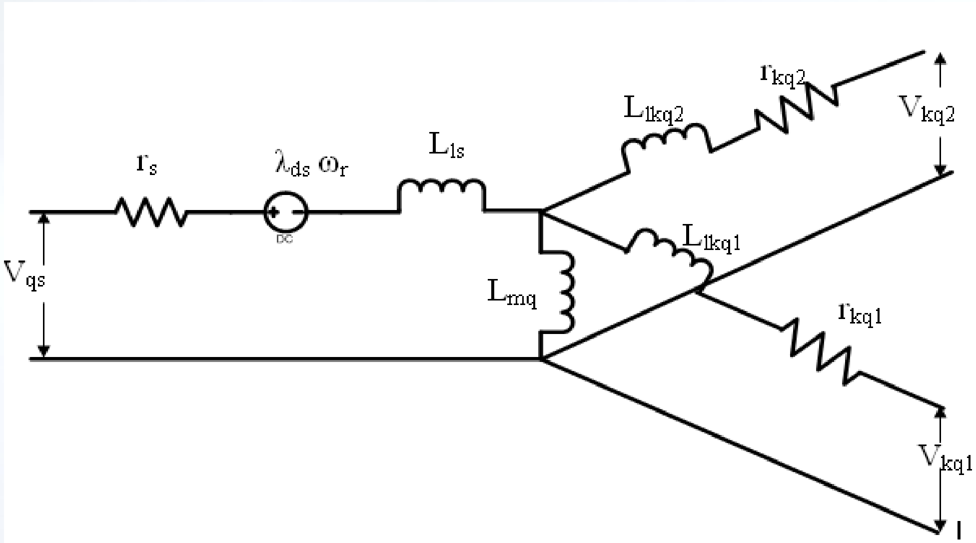
Primary winding induced flux $\varphi_2 = \omega_b \int \left[V_2' - R_2' \left(\frac{\varphi_2' - \varphi_m}{X_{l_2}'} \right) \right] dt$

Primary winding current $i_1 = \frac{\varphi_1 - \varphi_m}{X_{l_1}}$

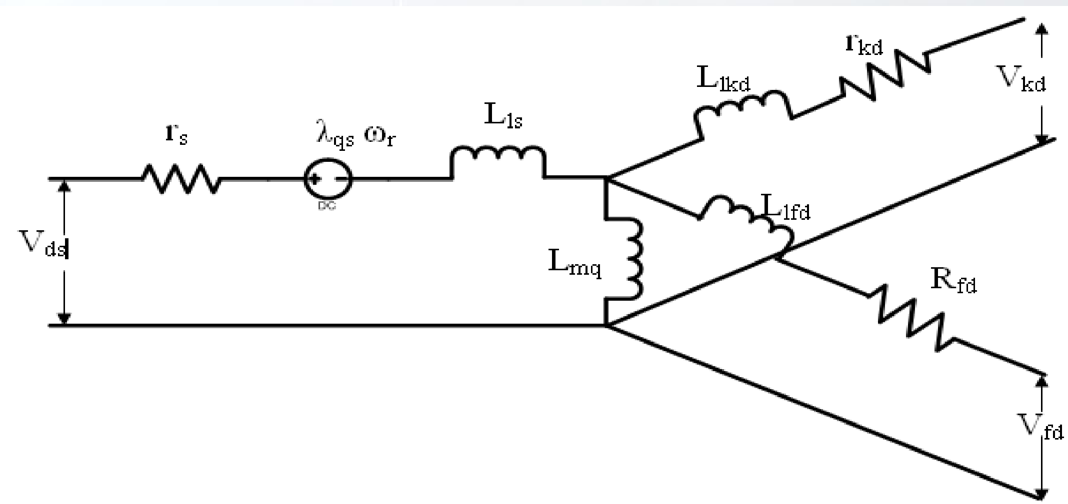
Secondary winding current $i_2' = \frac{\varphi_2' - \varphi_m}{X_{l_2}'}$

Model Formulation

Synchronous Generator Model



q axis



d axis

Model Formulation

Synchronous Generator Model

q-axis stator voltage

$$v_{qs}^{r} = -R_s i_{qs}^{r} + \frac{\omega_r}{\omega_b}\varphi_{ds}^{r} + \frac{p}{\omega_b}\varphi_{qs}^{r}$$

d-axis stator voltage

$$v_{ds}^{r} = -R_s i_{ds}^{r} - \frac{\omega_r}{\omega_b}\varphi_{qs}^{r} + \frac{p}{\omega_b}\varphi_{ds}^{r}$$

q-axis damping winding 1 voltage

$$v'^{r}_{kq1} = R_{kq1} i'^{r}_{kq1} + \frac{p}{\omega_b}\varphi'^{r}_{kq1}$$

q-axis damping winding 2 voltage

$$v'^{r}_{kq2} = R_{kq2} i'^{r}_{kq2} + \frac{p}{\omega_b}\varphi'^{r}_{kq2}$$

d-axis field winding voltage

$$v'^{r}_{fd} = R_{fd} i'^{r}_{fd} + \frac{p}{\omega_b}\varphi'^{r}_{fd}$$

d-axis damping winding voltage

$$v'^{r}_{kd} = R_{kd} i'^{r}_{kd} + \frac{p}{\omega_b}\varphi'^{r}_{kd}$$

Model Formulation

Synchronous Generator Model

q-axis stator flux
$$\varphi^{r}_{qs} = \omega_b \int \left[v^{r}_{qs} - \frac{\omega_r}{\omega_b}\varphi^{r}_{ds} + \frac{R_s}{X_{ls}}\left(\varphi^{r}_{mq} - \varphi^{r}_{qs}\right) \right] dt$$

d-axis stator flux
$$\varphi'^{r}_{ds} = \omega_b \int \left[v^{r}_{ds} + \frac{\omega_r}{\omega_b}\varphi^{r}_{qs} + \frac{R_s}{X_{ls}}\left(\varphi^{r}_{md} - \varphi^{r}_{ds}\right) \right] dt$$

q-axis damping winding 1 flux
$$\varphi'^{r}_{kq1} = \omega_b \int \left[v'^{r}_{kq1} + \frac{R'_{kq1}}{X_{lkq1}}\left(\varphi^{r}_{mq} - \varphi'^{r}_{kq1}\right) \right] dt$$

q-axis damping winding 2 flux
$$\varphi'^{r}_{kq2} = \omega_b \int \left[v'^{r}_{kq2} + \frac{R'_{kq2}}{X_{lkq2}}\left(\varphi^{r}_{mq} - \varphi'^{r}_{kq2}\right) \right] dt$$

d-axis field winding flux
$$\varphi'^{r}_{fd} = \omega_b \int \left[\frac{R'_{fd}}{X_{md}} e'^{r}_{xfd} + \frac{R'_{fd}}{X_{lfd}}\left(\varphi^{r}_{md} - \varphi'^{r}_{fd}\right) \right] dt$$

d-axis damping winding flux
$$\varphi'^{r}_{kd} = \omega_b \int \left[v'^{r}_{kd} + \frac{R'_{kd}}{X_{lkd}}\left(\varphi^{r}_{md} - \varphi'^{r}_{kd}\right) \right] dt$$

Model Formulation

Synchronous Generator Model

q-axis mutual flux

$$\varphi^{r}_{mq} = X_{aq}\left(\frac{\varphi^{r}_{qs}}{X_{ls}} + \frac{\varphi'^{r}_{kq1}}{X'_{lkq1}} + \frac{\varphi'^{r}_{kq2}}{X'_{lkq2}}\right)$$

d-axis mutual flux

$$\varphi^{r}_{md} = X_{ad}\left(\frac{\varphi^{r}_{ds}}{X_{ls}} + \frac{\varphi'^{r}_{fd}}{X'_{lfd}} + \frac{\varphi'^{r}_{lkd}}{X'_{lkd}}\right)$$

q-axis stator current

$$i^{r}_{qs} = -\frac{1}{X_{ls}}\left(\varphi^{r}_{qs} - \varphi^{r}_{mq}\right)$$

d-axis stator current

$$i^{r}_{ds} = -\frac{1}{X_{ls}}\left(\varphi^{r}_{ds} - \varphi^{r}_{md}\right)$$

q-axis damping 1 winding current

$$i'^{r}_{kq1} = -\frac{1}{X'_{kq1}}\left(\varphi'^{r}_{kq1} - \varphi^{r}_{mq}\right)$$

q-axis damping 2 winding current

$$i'^{r}_{kq2} = -\frac{1}{X'_{kq2}}\left(\varphi'^{r}_{kq2} - \varphi^{r}_{mq}\right)$$

Model Formulation

Synchronous Generator Model

d-axis field current

$$i'^{r}_{fd} = -\frac{1}{X'_{lfd}}\left(\varphi'^{r}_{fd} - \varphi^{r}_{md}\right)$$

d-axis current in damper winding

$$i'^{r}_{kd} = -\frac{1}{X'_{lkd}}\left(\varphi'^{r}_{kd} - \varphi^{r}_{md}\right)$$

Electromagnetic torque

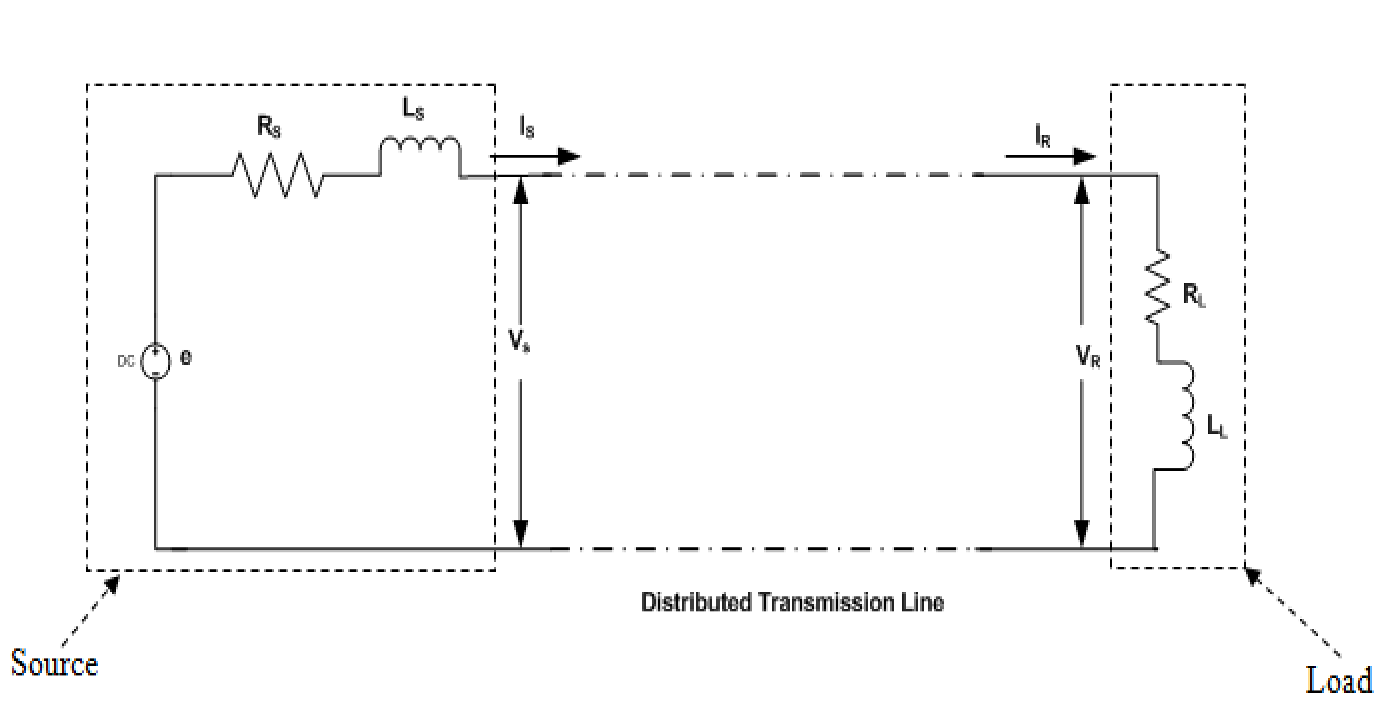
$$T_{g} = \frac{3P}{4\omega_{b}}\left(\varphi_{ds} i_{qs} - \varphi_{qr} i_{dr}\right)$$

Synchronous rotor speed

$$\omega_{r} = -\frac{\omega_{b}}{2J}\int\left(T_{g} - T_{m}\right)dt$$

Model Formulation

Transmission Line Model



Model Formulation

Transmission Line Model

Propagation Constant $$\gamma = \frac{R}{2}\sqrt{\frac{C}{L}} + s\sqrt{LC}$$

Transmission line characteristic impedance $$Z_c = \sqrt{\frac{(R+sL)}{(G+sC)}}$$

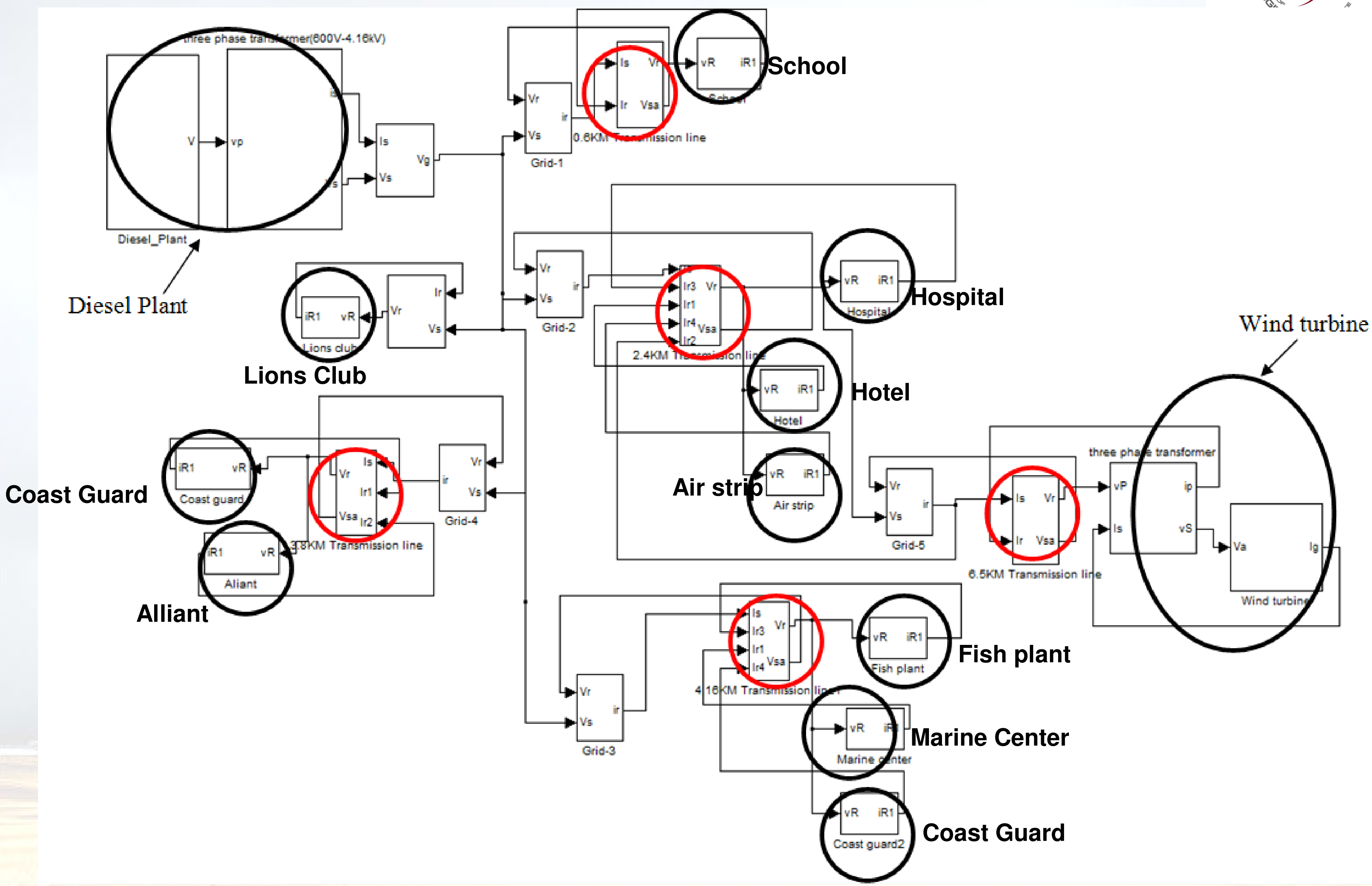
Sending end current $$I_s = \frac{1}{L_s}\int (e - V_s - R_s I_s)dt$$

Receiving end current $$I_R = \frac{1}{L_L}\int (V_R - R_L I_R)dt$$

Sending end voltage $$V_s = Z_c I_s + 2V_{bs}$$

Receiving end voltage $$V_R = 2V_{fR} - I_{fR} Z_c$$

MATLAB-Simulink® Simulation

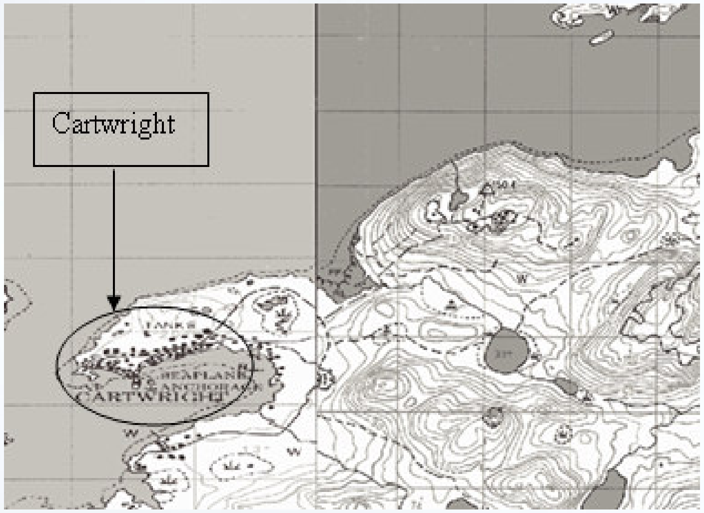


Wind-Diesel System in Cartwright, Labrador cont.

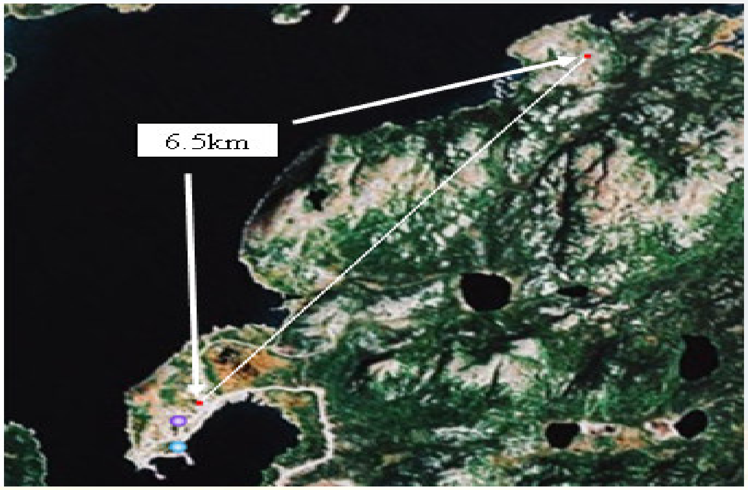
Simulation

- Simulation time 20 seconds
- Fixed load was considered
- The model is solved with ‘Variable Step/ode-45(Domand-Prince)’ method
- The relative and absolute tolerance was taken as 1e-3 and 1e-6 respectively

Simulation

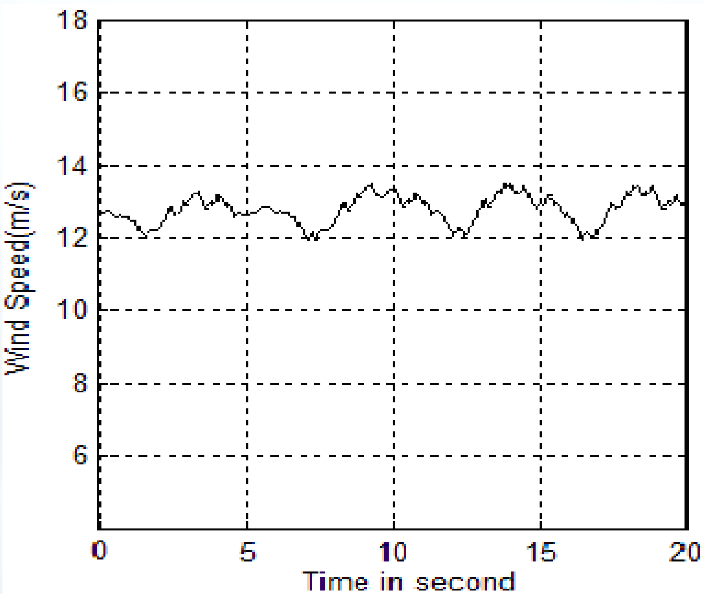


Topographical location of Cartwright

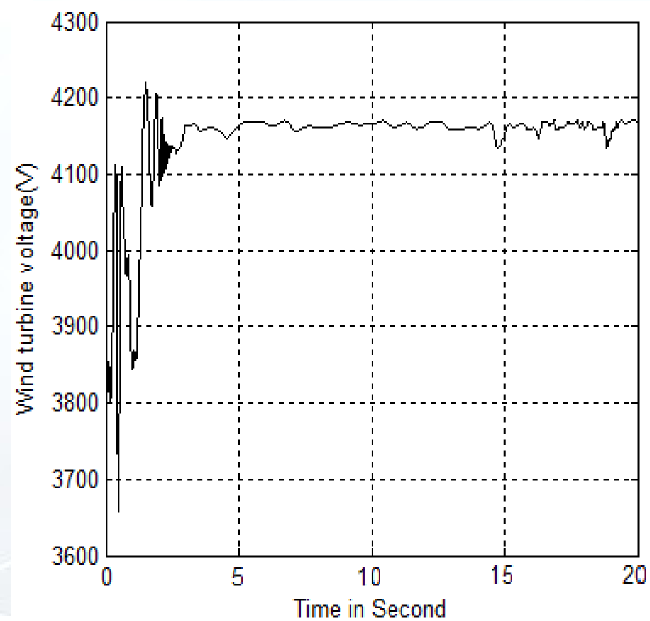


Satellite image of wind turbine placement

Simulation results

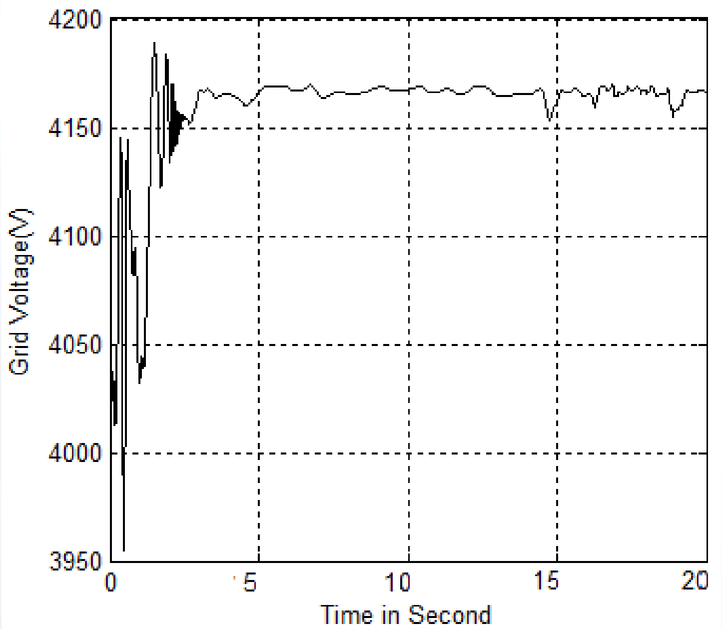


Wind speed

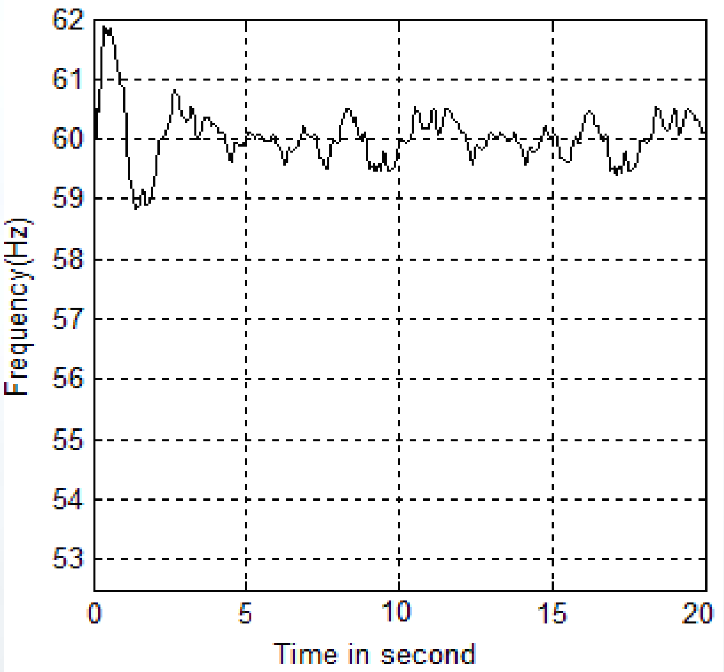


Wind Turbine Voltage variation

Simulation results



Grid Voltage variation



Frequency variation

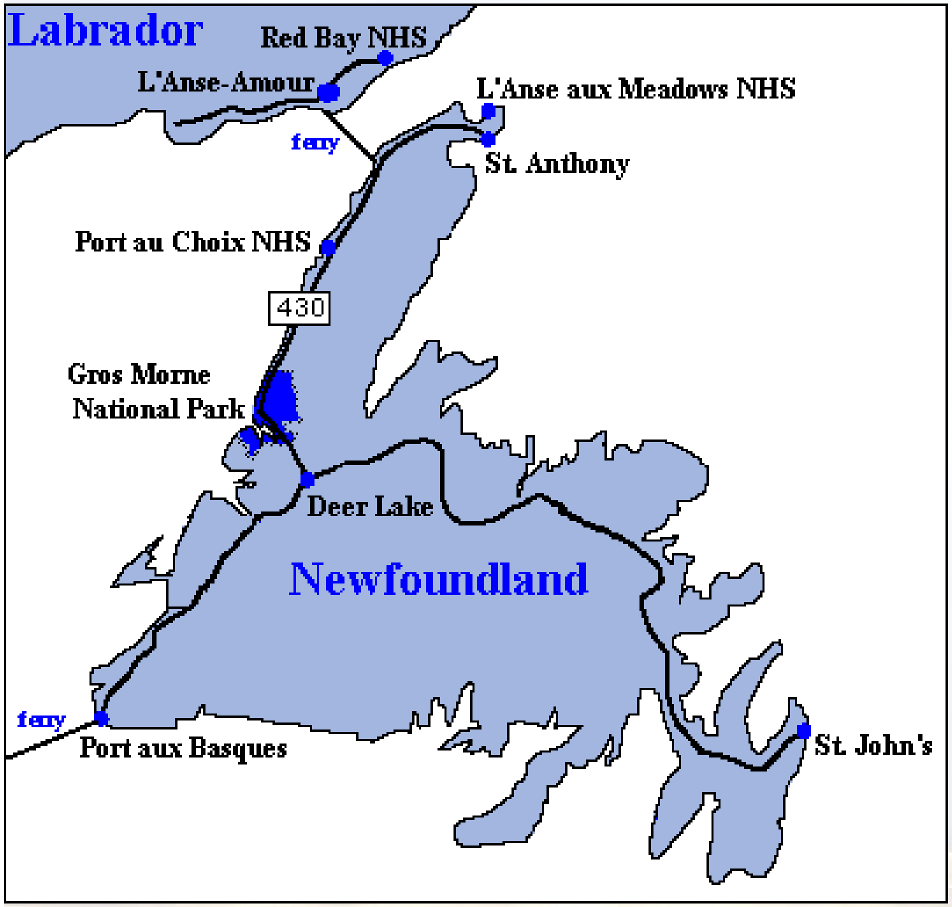
Simulation results

Wind turbine distances (km)	Voltage fluctuation at grid (V)	Voltage fluctuation at wind turbine (V)	Frequency Hz
6.5	**12.178**	**16.149**	**1.1**
8	**8.103**	**11.1**	**0.97**
10	**5.71**	**9.65**	**0.85**
13	**4.95**	**8.22**	**0.801**

- The frequency variation in a small wind-diesel hybrid power system is allowed to change within ±3%
- The voltage variation is allowed to change within ±10%

Grid connected wind farm in St. Anthony, Newfoundland

Introduction



- St. Anthony is a town with a population of 2730 on the northern peninsula of Newfoundland
- The economy is based mainly on three sectors, namely the fishery, institutions and retail/service industries
- A 6000kW diesel generating plant is installed to supply power to the town in case of emergency
- The electrical power is delivered from the Newfoundland central grid through a 248km transmission line

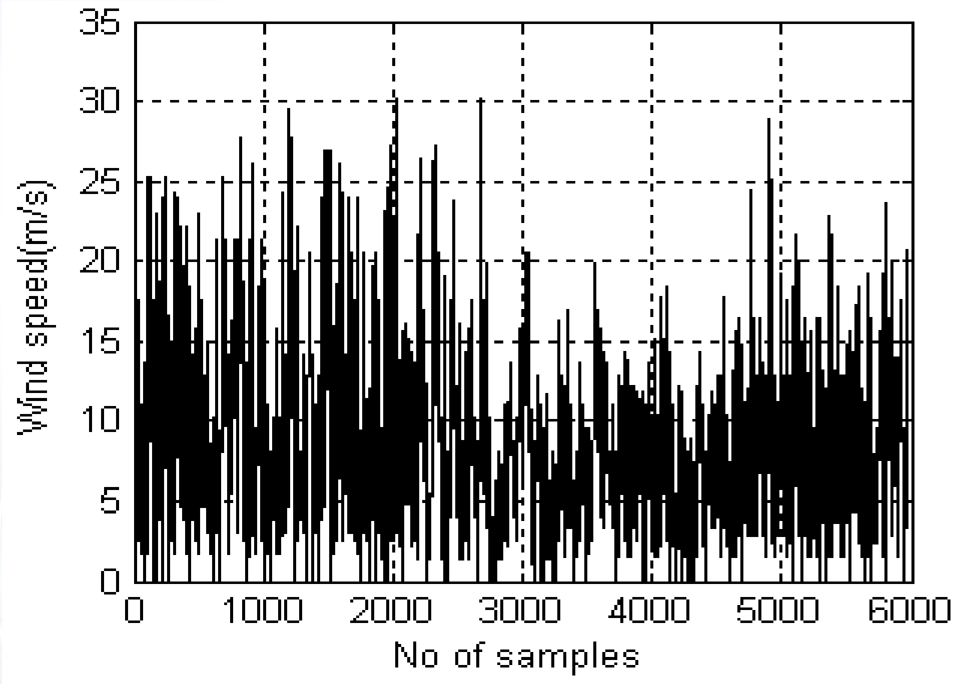
MEMORIAL UNIVERSITY

Introduction

Ranking	Community	Score
1	Cape Norman	155
2	Cook's Harbour	150
3	St. Anthony	145
4	L' Anse aux Meadows	130
5	Ship cove	115
6	St. Carrol's	110
7	White cape	110
8	Goose cove#2	105
9	Cape raven	105
10	Goose cove#1	100

Source: Fenco Newfoundland Limited

Introduction



- Annual average wind speed is about 8.85m/s at 32.9m height.

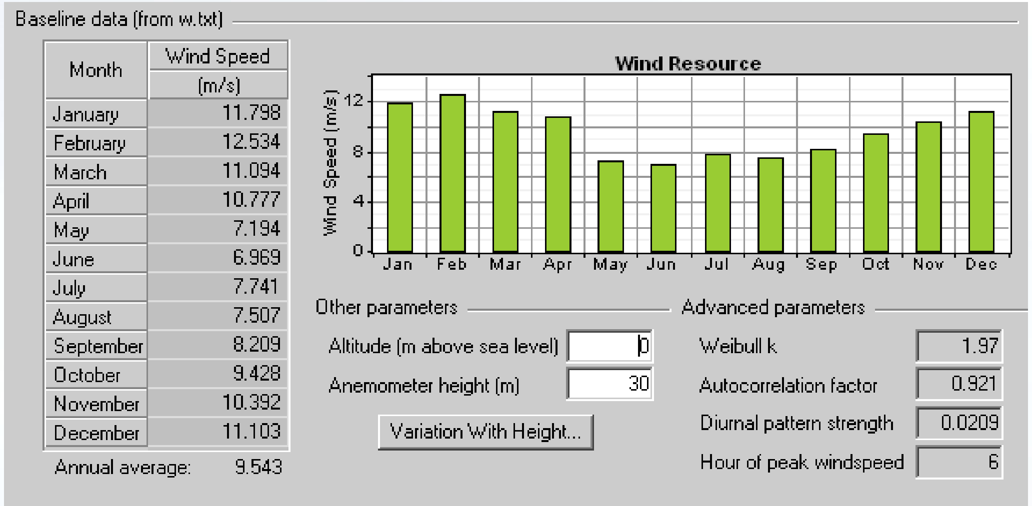
Sizing of wind farm

Scaling the St. Anthony wind data, seasonal mean wind speed value for Cape Norman is calculated

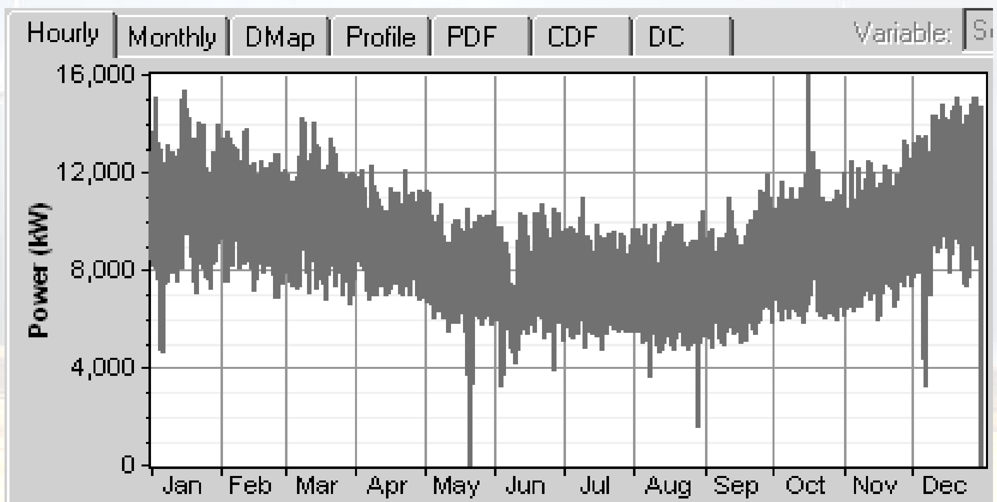
Period	Months	Mean Wind Speed
Winter	December/January/February (DJF)	11.81 m/s
Spring	March/April/May (MAM)	9.83 m/s
Summer	June/July/August (JJA)	7.15 m/s
Fall	September/October/November (SON)	9.12 m/s
Annual		9.46 m/s

The annual average wind speed for Cape Norman is 9.46m/s at 30m elevation.

Sizing of wind farm



Scaled wind speed data at Cape Norman



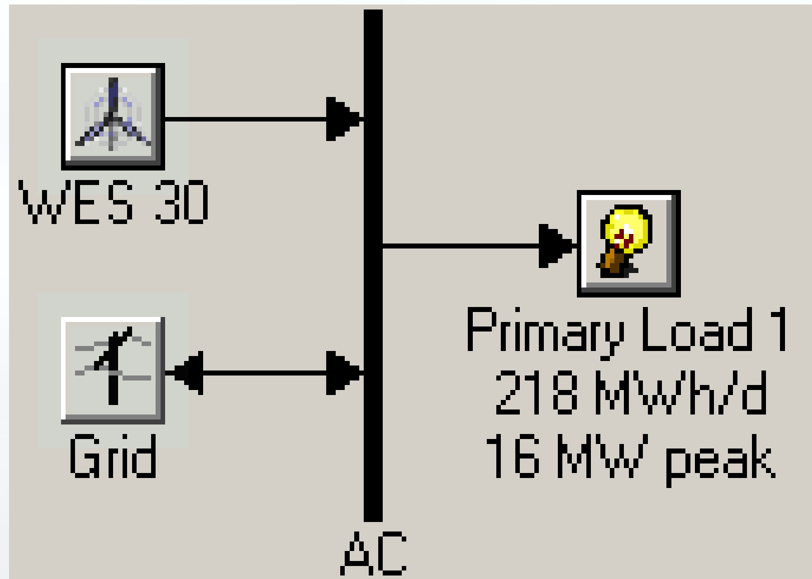
St. Anthony Load data

MEMORIAL UNIVERSITY

Grid connected wind farm in St. Anthony, Newfoundland cont.

Sizing of wind farm

Geographical location of St. Anthony



Proposed hybrid system

Sizing of wind farm

		WES30	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
		21	14400	$ 14,332,499	6,081,211	$ 79,248,056	0.093	0.27
		20	14400	$ 13,649,999	6,169,798	$ 79,511,208	0.094	0.26
		19	14400	$ 12,967,500	6,258,384	$ 79,774,344	0.094	0.24
		17	14400	$ 11,602,500	6,435,557	$ 80,300,632	0.095	0.22
		15	14400	$ 10,237,500	6,612,725	$ 80,826,856	0.095	0.19
		14	14400	$ 9,555,000	6,701,311	$ 81,090,000	0.096	0.18

Homer optimized results

Sizing of wind farm

Simulation Results

System Architecture: 14,400 kW Grid
21 WES 30 (10)

Total NPC: $ 79,248,056
Levelized COE: $ 0.093/kWh
Operating Cost: $ 6,081,211/yr

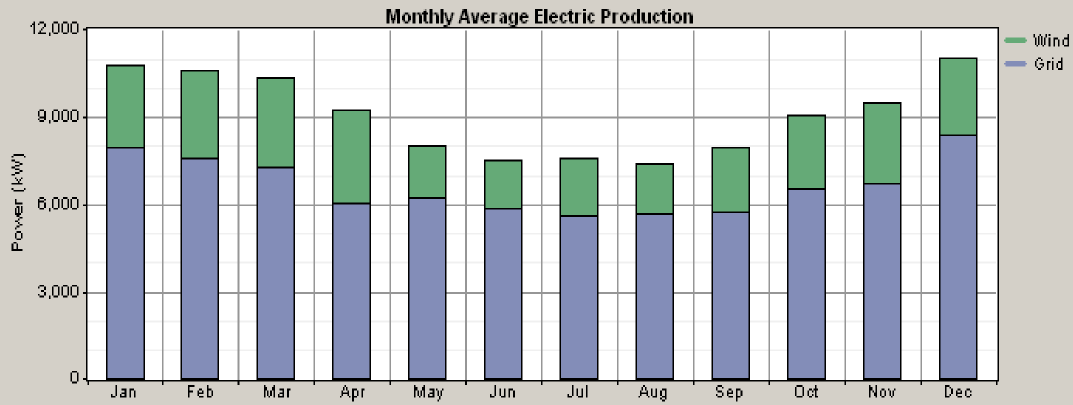
Cost Summary | Cash Flow | Electrical | WES30 | Grid | Emissions | Hourly Data

Production	kWh/yr	%
Wind turbines	21,468,268	27
Grid purchases	57,978,124	73
Total	79,446,392	100

Consumption	kWh/yr	%
AC primary load	79,410,336	100
Grid sales	36,181	0
Total	79,446,520	100

Quantity	kWh/yr	%
Excess electricity	0.186	0.0000
Unmet electric load	1,637	0.0021
Capacity shortage	64,474	0.0812

Quantity	Value
Renewable fraction	0.270



XML Report | HTML Report | Help | Close

Electrical performance of proposed hybrid system

Grid connected wind farm in St. Anthony, Newfoundland cont.

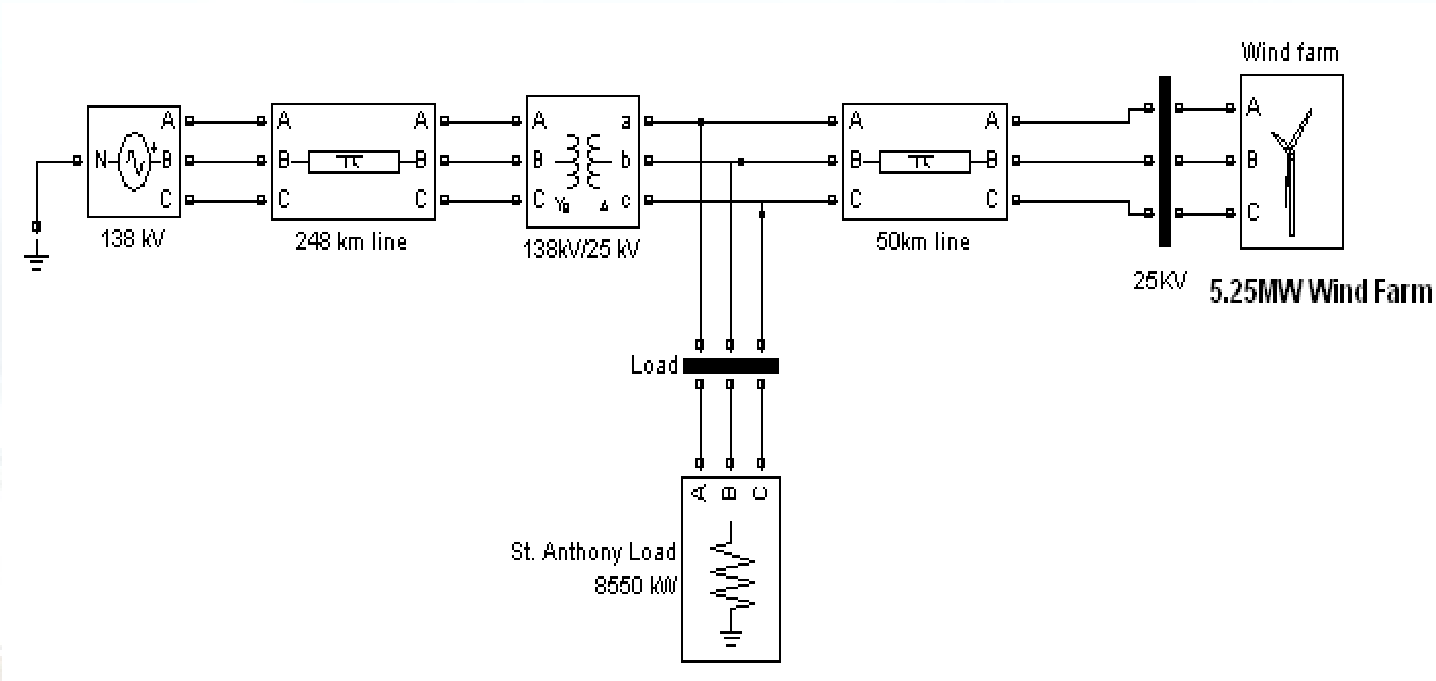
Wind turbine output

Period	Months	Power output	Energy output	Capacity factor
Winter	December/January/February (DJF)	109.77KW	240.42MWh/period	43.91%
Spring	March/April/May (MAM)	87.43KW	191.48MWh/period	34.97%
Summer	June/July/August (JJA)	61.65KW	135.03MWh/period	24.66%
Fall	September/October/November (SON)	69.7KW	152.66MWh/period	27.88%
Annual		80.97KW	709.36MWh/year	32.39%

Grid connected wind farm in St. Anthony, Newfoundland cont.

Dynamic simulation of grid connected wind farm

Wind speed within the farm $$U_x = U_o \times \left\{ 1 - \frac{1-\sqrt{1-C_T}}{\left(1 + 2K\frac{x}{D}\right)^2} \right\}$$

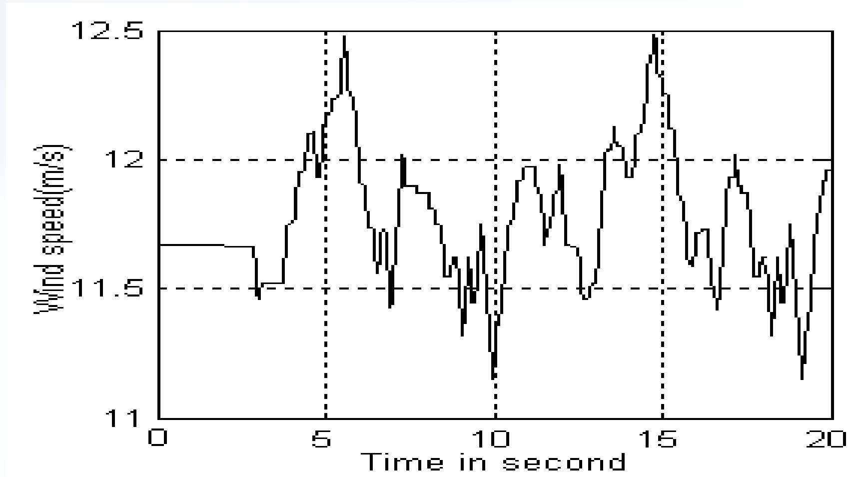


Proposed hybrid system in SIMULINK

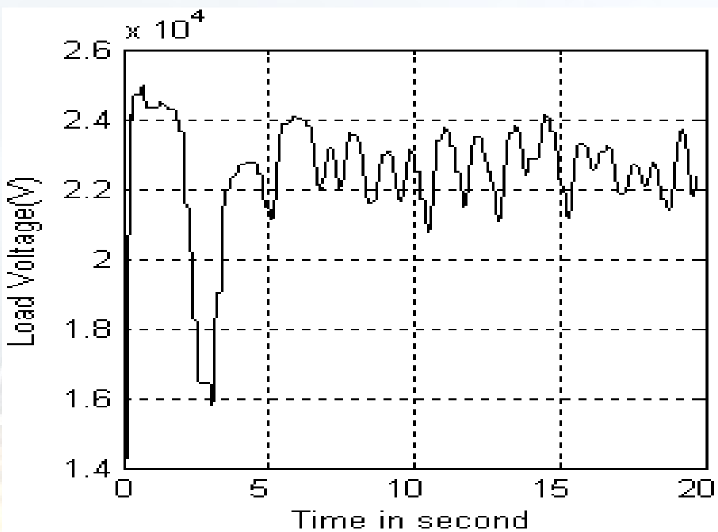
Simulation

- Simulation time 20 seconds
- Fixed load was considered
- The model is solved with ‘Variable Step/ode-45(Domand-Prince)’ method
- The relative and absolute tolerance was taken as 1e-3 and 1e-5 respectively

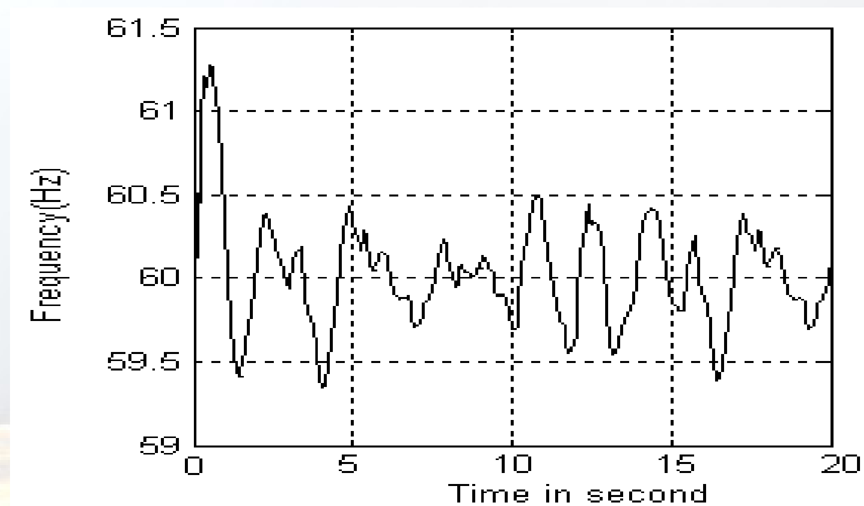
Simulation results



Wind speed



Load voltage variation



Frequency variation

Simulation results

Period	Voltage Variation	Frequency Variation
Winter (DJF)	1975V (7.9%)	0.942Hz
Spring (MAM)	1860V (7.48%)	0.789Hz
Summer (JJA)	1620V (6.5%)	0.652Hz
Fall (SON)	1570V (6.28%)	0.608Hz

- Maximum voltage variation about 7.9% will occur during winter
- Minimum variation will occur during the fall, which is about 6.28%
- Frequency variation is within $\pm$3%

Conclusions

- Variation of voltage and frequency are within limits in both cases.

- A 250kW wind turbine can be installed in Cartwright, Labrador diesel power system.

- A 5.25MW grid connected wind farm can be installed in Cape Norman to serve the community in St. Anthony.

Recommendations

For wind-diesel system

- Study of harmonics that is generated by variable speed wind turbine’s power electronics in an isolated wind-diesel grid is recommended
- Different types of long term and short term storage systems can be used with the proposed wind-diesel system to store excess electricity at minimum load.
- Dump load can be incorporated into the wind-diesel system to dissipate excess energy produced by wind turbine which can not be stored .
- Variable load can be considered.

Recommendations

For wind farm

- Variable speed wind turbine with voltage controller can be used to reduce voltage variation
- To reduce transmission loss HVDC system can be used to transmit power from wind farm to local power grid .
- Soft starters can be used to integrate wind farm with the power grid.
- Variable load can be considered.

Papers related to research

Conference papers

1. M. T. Iqbal, S. Mominul Islam, and John E. Quaicoe, Grid Impact of a 5.25MW Wind Farm Near St. Anthony, Newfoundland, Accepted for presentation at CanWEA 2009 conference to be held in Toronto Ontario, September 20-23, 2009.
2. Sheikh Mominul Islam, M. T. Iqbal, J. E. Quaicoe, Voltage fluctuations in a remote wind diesel hybrid power system, presented at ICECE 2008 on 20-22 December 2008 in Dhaka Bangladesh

Journal papers

1. Sheikh Mominul Islam, M. T. Iqbal and John E. Quaicoe, Grid Impact of a 5.25MW Wind Farm Near St. Anthony, Newfoundland, submitted to Wind Engineering Journal.
2. Sheikh Mominul Islam, M. T. Iqbal, Power Quality Estimation in a Remote Wind-Diesel Hybrid Power System in Cartwright, Labrador, submitted to Open Renewable Energy Journal

MEMORIAL UNIVERSITY

Acknowledgement

- Dr. M. T. Iqbal. And Dr. John E. Quaicoe
- Faculty of Engineering & Applied Science, MUN.
- School of Graduate Studies, MUN.
- NSERC

Other

- Md. Arifuzzaman
- Dr. Glyn George
- Dr. Benjamin Jeyasurya
- Ms Moya Crocker

Thank You

For your attention & presence

Questions/Comments