Power Quality Estimation in a Remote Wind-Diesel Hybrid Power System in Cartwright, Labrador

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Abstract: *Generation of electricity using diesel is costly for small remote isolated communities. At remote location electricity generation from renewable energy such as wind can help reduce the overall operating costs by reducing the fuel costs. Siting of wind turbines connected to diesel in a remote location effects wind penetration and power quality. In this paper we study how the location of a wind turbine effects the voltage in a remote wind-diesel system. We selected an isolated diesel system in Cartwright, Labrador, Canada. Four possible sites for a wind turbine are selected and for all four cases we study the voltage and frequency variations in the system due to addition of a wind turbine. Hybrid power system modeling and simulation results are presented in the paper. Results will be used to finalize the most suitable location of the wind turbine.*
Keywords: *Hybrid, Attenuation.*

1. Introduction

Cartwright is an isolated community in Southern Labrador, Canada. It generates electricity using four diesel generators which consume more than 1.2 million liters of fuel per year. As fuel price is increasing and so the cost of electricity generation in Cartwright. By adding electricity generation from a wind turbine will reduce the diesel consumption in Cartwright. The utilization of wind energy is not a new technology but draws on the long tradition of wind power technology. Generation of electricity from wind is a fastest growing energy technology in the world. Figure 1 shows the topographical map of Cartwright, Labrador.

Figure 1. Topographical map of Cartwright, Labrador

Cartwright is situated on southern cost of Labrador. Community's main source of income is fishery. Diesel plant is located in the community. Wind turbine can be installed outside the community. To extract maximum power from wind, turbine can be placed on top of any of the hill in the area. Small circles in figure 1 represent the top of the hills. We have considered different lengths of transmission line for the wind turbine. Figure 2 shows the satellite image of a possible wind turbine location and distance from the diesel plant.
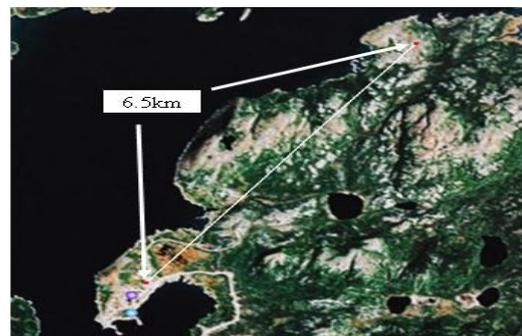
Figure 2. Wind turbine is placed 6.5km away from diesel plant

To study voltage fluctuations in the system for each possible wind turbine site we modeled diesel generators, transmission line and the wind energy conversion system, which includes wind turbine,

gearbox and induction generator. Generally there are two types of utility scale wind turbines, fixed speed and variable speed. Fixed speed wind turbines operate at a near constant rotor speed at all times which are directly connected to the grid. The fundamental frequency of the system determines the rotor speed. Variable speed wind turbines can operate at a wider range of speeds depending on the wind speed. A variable rotor speed can be achieved by varying the blade pitch angle and generator speed. In this case power converters are needed to interface the wind turbine to the power system. For this study we consider a 100kW fixed speed wind turbine. The MATLAB/SIMULINK modeling of a fixed speed wind turbine, diesel generator and transmission line are discussed in the following sections.

2. Wind turbine model

With the help of elementary momentum theory the typical output characteristic of a wind turbine is given by:

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

Here A (m2) is the rotor swept area and Cp is known as the performance co-efficient which can be expressed as a function of tip speed ratio (λ). The tip speed ratio (λ) is obtained from the quotient of the peripheral velocity Vu (rad/sec) to the undisturbed wind velocity V1 (m/s)

$$\lambda = \frac{V_u}{V_1} \qquad (2)$$

For a fixed blade pitch turbine Cp can be approximately expressed as [1]:

$$Cp = \frac{1}{2} \times \left(\frac{116}{\lambda_p} - 0.4 \times (\alpha - 5) \right) \exp^{\frac{-16.5}{\lambda_p}} \qquad (3)$$

Where

$$\lambda_p = \frac{1}{\dfrac{1}{(\lambda + 0.089)} - \dfrac{0.035}{\alpha^3 + 1}} \qquad (4)$$

And α is the blade pitch angle. A mid sized wind turbine with a rated power of 100kW at rated rotor

speed of 32 rpm and wind speed of 13m/s is used for the modeling. The blade pitch angle is assumed to be constant.

3. Gearbox Model

The drive power of a wind turbine engenders torque in its mechanical drive train or generator that is subject to fluctuation as a result of both periodic and aperiodic process, such as
i. change in wind speed
ii. tower-shadow or tower-occasioned upwind overpressure
iii. blade asymmetry
iv. blade bending and skewing and
v. tower oscillation

In addition, load moments in generator and converter due to static, dynamic and electromechanical disturbances also act on the wind turbine via the drive train [2]. A model of a wind turbine drive train is presented in figure 3. It includes turbine low speed shaft, gearbox and generator high speed shaft. Here aerodynamic torque (T_T) is counteracted by the electromechanical torque generated by the generator (Tg) through the gearbox.
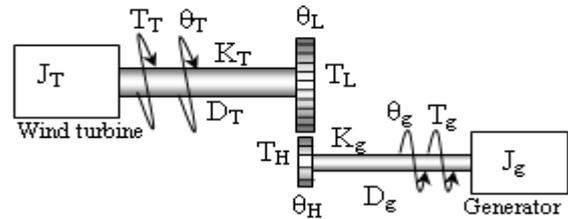
Figure 3. Two mass Model of the wind turbine drive train

The model can be reduced to a single mass model by considering high stiffness of wind turbine rotor and generator and also neglecting the moment of inertia, damping co-efficient and stiffness for the gear box as these are very small compared with the wind turbine rotor and generator[4]. The torque equation for this simplified model is given by-

$$T_g - T_T = J_{equ} \times \frac{d^2\theta_G}{dt^2} \qquad (5)$$

$$J_{equ} = J_G + \frac{J_T}{n_g^2} \qquad (6)$$

Here n_g is the gear ratio of the gearbox. Torque Equation is represented for induction machine as motor operation. For generator operation the only

change is instead of negative sign there will be a positive sign [5] in torque equation.

4. Induction Machine Model

The induction machines commonly used on fixed speed wind turbines are very similar to conventional industrial induction motors. The d-q or dynamic equivalent circuit of induction machine is shown in figure 4. There are numerous ways of formulating the equations of an induction machine for the purposes of computer simulation. One of the most popular induction motor models derived from this equivalent circuit is Krause's model [7]. The current equations which were used in this simulation are given below:

$$i_{qs} = \frac{1}{X_{ls}} \left(\varphi_{qs} - \varphi_{mq} \right) \tag{7}$$

$$i_{ds} = \frac{1}{X_{ls}} \left(\varphi_{ds} - \varphi_{md} \right) \tag{8}$$

$$i_{qr} = \frac{1}{X_{lr}} \left(\varphi_{qr} - \varphi_{mq} \right) \tag{9}$$

$$i_{dr} = \frac{1}{X_{lr}} \left(\varphi_{dr} - \varphi_{md} \right) \tag{10}$$

Here

$$\varphi_{mq} = X_m \left(i_{qs} + i'_{qr} \right)$$

$$\varphi_{md} = X_m \left(i_{ds} + i'_{dr} \right)$$
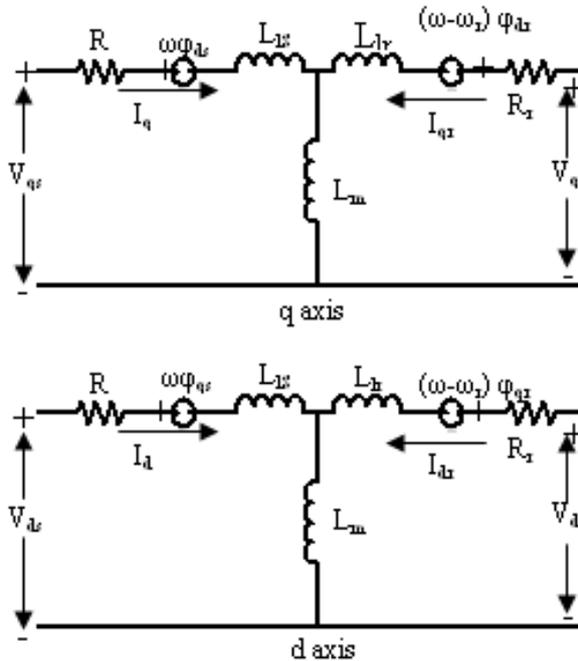
Figure 4. d-q axis equivalent circuit of a 3-phase induction machine.

And the flux linkage in terms of voltage quantities can be written as:

$$\varphi_{qs} = \omega_b \int \left[v_{qs} - \frac{\omega}{\omega_b} \varphi_{ds} + \frac{R_s}{X_{ls}} \left(\varphi_{mq} - \varphi_{qs} \right) \right] dt \tag{11}$$

$$\varphi_{ds} = \omega_b \int \left[v_{ds} + \frac{\omega}{\omega_b} \varphi_{qs} + \frac{R_s}{X_{ls}} \left(\varphi_{md} - \varphi_{ds} \right) \right] dt \tag{12}$$

$$\varphi'_{qr} = \omega_b \int \left[v'_{qr} - \frac{\omega - \omega_r}{\omega_b} \varphi'_{dr} + \frac{R'_r}{X'_{lr}} \left(\varphi_{mq} - \varphi'_{qr} \right) \right] dt \tag{13}$$

$$\varphi'_{dr} = \omega_b \int \left[v'_{dr} + \frac{\omega - \omega_r}{\omega_b} \varphi'_{qr} + \frac{R'_r}{X'_{lr}} \left(\varphi_{md} - \varphi'_{dr} \right) \right] dt \tag{14}$$

Since a squirrel cage induction machine is used, V'_{dr} and V'_{qr} in the above equations can be set to zero. So the magnetizing flux equation can be written as:

$$\varphi_{mq} = X_t \left(\frac{\varphi_{qs}}{X_{ls}} + \frac{\varphi'_{qr}}{X'_{lr}} \right) \tag{15}$$

$$\varphi_{md} = X_t \left(\frac{\varphi_{ds}}{X_{ls}} + \frac{\varphi'_{dr}}{X'_{lr}} \right) \text{Where} \tag{16}$$

$$X_t = \left(\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X'_{lr}} \right)^{-1} \tag{17}$$

The electromagnetic torque equation is given by

$$T_g = \frac{3P}{4\omega_b} \left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds} \right) \tag{18}$$

5. Diesel Generator

Diesel generator is equipped with diesel engine and a synchronous generator.

Diesel Engine: For modeling, diesel engine statistical data curves were used which are provided by the manufacturer is shown in figure 5.

By using the best fitting curve option in MATLAB a sixth order polynomial curve is derived for both engine speed vs. power and engine speed vs. fuel consumption curves. Output power is given by:

$$P = \left(5.1554 \times 10^{-8} \omega^6 \right) - \left(7.0552 \times 10^{-5} \omega^5 \right)$$
$$+ \left(0.037776 \omega^4 \right) - \left(10.241 \omega^3 \right) + \left(1485.8 \omega^2 \right)$$
$$- \left(1.0823 \times 10^5 \omega \right) + 3.1539 \times 10^6 \tag{19}$$
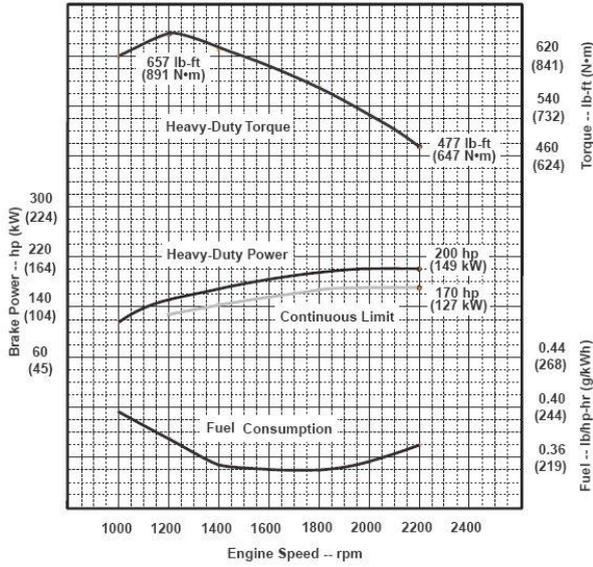
Figure 5. Diesel engine characteristic curves

Fuel consumption is given by:

$$F_c = 5.667 \times 10^{-11} \omega^6 - 6.6665 \times 10^{-8} \omega^5$$
$$+ 3.2056 \times 10^{-5} \omega^4 - 0.0080567 \omega^3$$
$$+ 1.1168 \omega^2 - 81.071 \omega + 2618.6 \quad (20)$$

Here ω is the engine speed (rad/sec), P is the engine power (kW) and F_c is the engine's fuel consumption (g/kWh).

    Synchronous generator: The d-q or dynamic equivalent circuit of a synchronous machine is shown in figure 6. The current equations expressed in rotor reference frame can be given by [7]:

$$i_{qs}^r = -\frac{1}{X_{ls}}\left(\varphi_{qs}^r - \varphi_{mq}^r\right) \quad (21)$$

$$i_{ds}^r = -\frac{1}{X_{ls}}\left(\varphi_{ds}^r - \varphi_{md}^r\right) \quad (22)$$

$$i_{kq1}^{/r} = -\frac{1}{X_{kq1}^{/}}\left(\varphi_{kq1}^{/r} - \varphi_{mq}^r\right) \quad (23)$$

$$i_{kq2}^{/r} = -\frac{1}{X_{kq2}^{/}}\left(\varphi_{kq2}^{/r} - \varphi_{mq}^r\right) \quad (24)$$

$$i_{fd}^{/r} = -\frac{1}{X_{lfd}^{/}}\left(\varphi_{fd}^{/r} - \varphi_{md}^r\right) \quad (25)$$

$$i_{kd}^{/r} = -\frac{1}{X_{lkd}^{/}}\left(\varphi_{kd}^{/r} - \varphi_{md}^r\right) \quad (26)$$

q axis

d axis
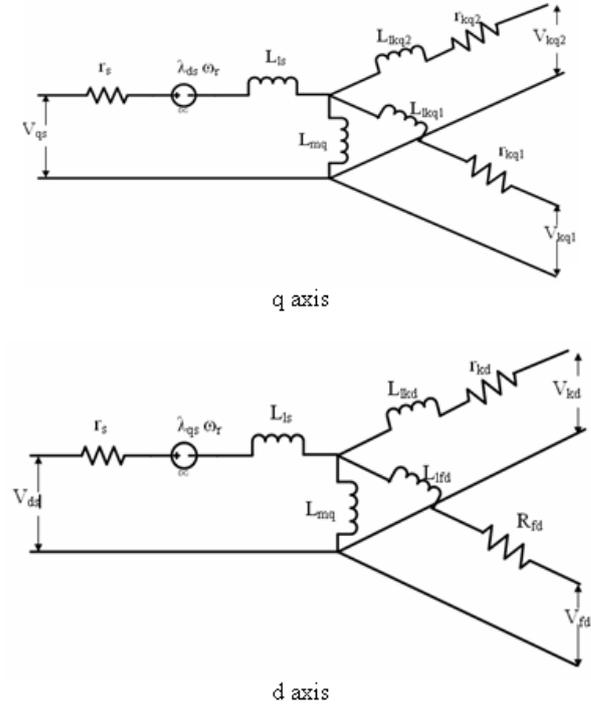
Figure 6. The d-q axis equivalent circuit of a 3-phase synchronous machine.

Flux linkage equations which were used in this simulation are given as follows:

$$\varphi_{qs}^r = \omega_b \int\left[v_{qs}^r - \frac{\omega_r}{\omega_b}\varphi_{ds}^r + \frac{r_s}{X_{ls}}\left(\varphi_{mq}^r - \varphi_{qs}^r\right)\right]dt \quad (27)$$

$$\varphi_{ds}^{/r} = \omega_b \int\left[v_{ds}^r + \frac{\omega_r}{\omega_b}\varphi_{qs}^r + \frac{r_s}{X_{ls}}\left(\varphi_{md}^r - \varphi_{ds}^r\right)\right]dt \quad (28)$$

$$\varphi_{kq1}^{/r} = \omega_b \int\left[v_{kq1}^{/r} + \frac{r_{kq1}^{/}}{X_{lkq1}}\left(\varphi_{mq}^r - \varphi_{kq1}^{/r}\right)\right]dt \quad (29)$$

$$\varphi_{kq2}^{/r} = \omega_b \int\left[v_{kq2}^{/r} + \frac{r_{kq2}^{/}}{X_{lkq2}}\left(\varphi_{mq}^r - \varphi_{kq2}^{/r}\right)\right]dt \quad (30)$$

$$\varphi_{fd}^{/r} = \omega_b \int\left[\frac{r_{fd}^{/}}{X_{md}}e_{xfd}^{/r} + \frac{r_{fd}^{/}}{X_{lfd}}\left(\varphi_{md}^r - \varphi_{fd}^{/r}\right)\right]dt \quad (31)$$

$$\varphi_{kd}^{/r} = \omega_b \int\left[v_{kd}^{/r} + \frac{r_{kd}^{/}}{X_{lkd}}\left(\varphi_{md}^r - \varphi_{kd}^{/r}\right)\right]dt \quad (32)$$

Magnetizing flux equation can be given by:

$$\varphi_{mq}^{r} = X_{aq}\left(\frac{\varphi_{qs}^{r}}{X_{ls}} + \frac{\varphi_{kq1}^{/r}}{X_{lkq1}^{/}} + \frac{\varphi_{kq2}^{/r}}{X_{lkq2}^{/}}\right) \qquad (33)$$

$$\varphi_{md}^{r} = X_{ad}\left(\frac{\varphi_{ds}^{r}}{X_{ls}} + \frac{\varphi_{fd}^{/r}}{X_{lfd}^{/}} + \frac{\varphi_{lkd}^{/r}}{X_{lkd}^{/}}\right) \qquad (34)$$

Where

$$X_{aq} = \left(\frac{1}{X_{mq}} + \frac{1}{X_{ls}} + \frac{1}{X_{lkq1}^{/}} + \frac{1}{X_{lkq2}^{/}}\right)^{-1} \qquad (35)$$

$$X_{ad} = \left(\frac{1}{X_{md}} + \frac{1}{X_{ls}} + \frac{1}{X_{lkd}^{/}} + \frac{1}{X_{lfd}^{/}}\right)^{-1} \qquad (36)$$

The electromagnetic torque equation can be given as follows:

$$T_{g} = \frac{3P}{4\omega_{b}}\left(\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds}\right) \qquad (37)$$

6. Transmission Line

For modeling transmission line a distributed parameter model is used [8]. Figure 7 shows a technique for implementing a transmission line using the single-phase circuit.
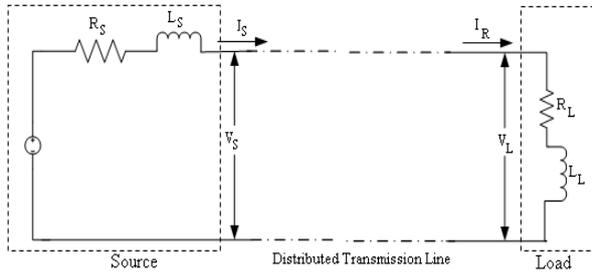
Figure 7. Single-phase line connecting a source to load.

Here at source end, the source end current can be calculated as:

$$I_{s} = \frac{1}{L_{s}}\int\left(e - V_{s} - R_{s}I_{s}\right)dt \qquad (38)$$

Source end voltage (Vs) can be calculated as:

$$V_{s} = Z_{C}\ I_{s} + 2V_{bs} \qquad (39)$$

V_{bs} is the backward voltage component at the sending end. At receiving end, the load current can be calculated by integrating the voltage equation for the load which is given as follows:

$$I_{R} = \frac{1}{L_{R}}\int\left(V_{R} - R_{L}I_{R}\right)dt \qquad (40)$$
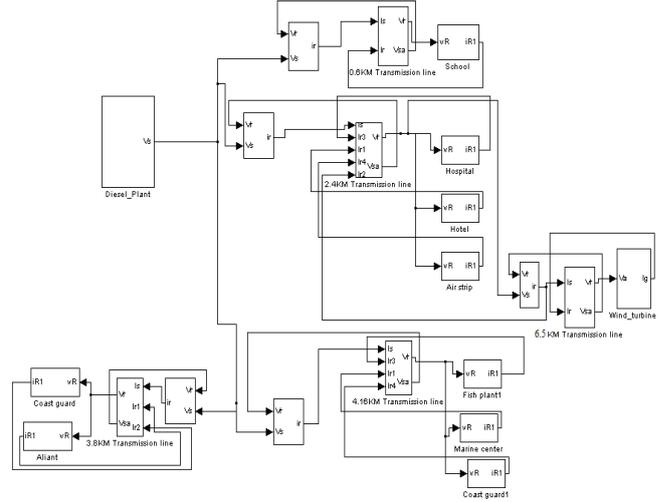
Figure 8. Model of the proposed Cartwright wind-diesel system in SIMULINK

If V_{fR} is the forward voltage component at the receiving end. Receiving end voltage (V_R) can be calculated as:

$$V_{R} = 2V_{fR} - Z_{C}I_{R} \qquad (41)$$

The characteristic impedance of the transmission line can be given by:

$$Z_{C} = \sqrt{\frac{L}{C}} \qquad (42)$$

The attenuation characteristic and transport delay of transmission line can be given as follows:

$$\text{Attenuation factor} = e^{-\frac{R}{2}\sqrt{\frac{C}{L}}x} \qquad (43)$$

$$\text{Transmission delay} = x\sqrt{LC} \qquad (44)$$

Here x is the length of transmission line.

7. Simulation Results and Discussion

All equations from (1) to equation (44) are used to develop a complete wind-diesel system model in SIMULINK as shown in the figure 8. For the simulation wind speed is input to the wind turbine and three phase voltage from diesel grid is applied to the induction machine through a 6.5km transmission line.

The following equations were used to generate wind field [9].

$$V_{w} = V_{t} + V_{a} \qquad (45)$$

$$\frac{dV_t}{dt} = -\frac{1}{T_v}V_t + m_w(t), \qquad T_v = \frac{10.5z}{V_o} \qquad (46)$$

Here V_w is the wind speed which is composed of average wind speed component (V_a) and turbulence component (V_t). The average wind speed value is chosen from table 1 for different season. The $m_w(t)$ is random white noise which is used to generate the turbulence component within the wind field. The z is the turbine height and V_0 is maiden wind speed. Figure 9 shows the wind speed data for Cartwright over a 20s time period. The simulation was performed for 20 second time interval and simulation integral and basic mathematical blocks are used instead of derivative term to avoid spikes in signals. All system parameters are provided in the appendix. Initial transients are also shown in the figures below.
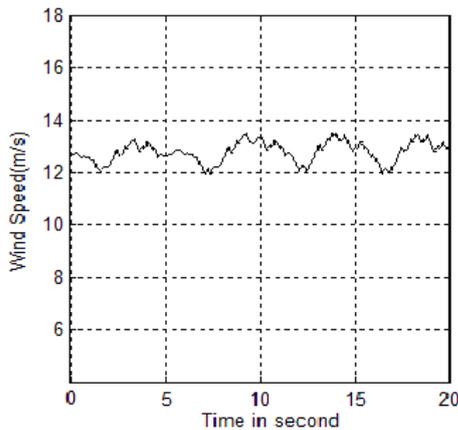
Figure 9. Wind speed (m/s)

With the wind speed data shown in figure 9 the system is simulated in Simulink. The simulation results i.e. wind turbine voltage, grid voltage and frequency variations are shown in the following Figures.
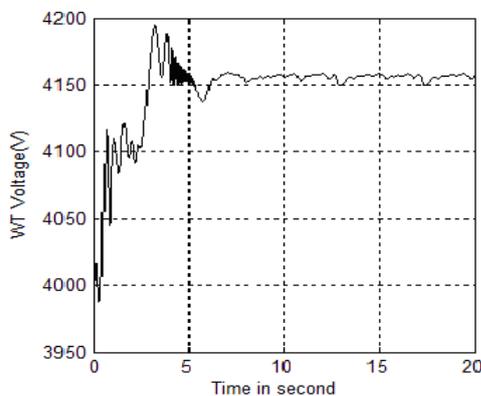
Figure 10. Variation of voltage at wind turbine

The variation of voltage at the wind turbine side is about 8.443V with the wind speed variation.
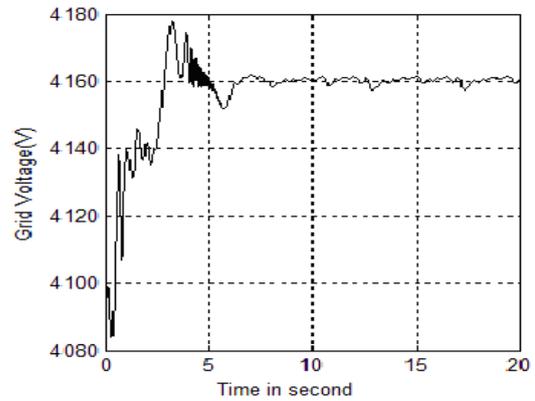
Figure 11. Variation of voltage at grid

The variation of voltage at the grid side is about 4.0784V due to the fluctuation of voltage generated from the wind turbine.
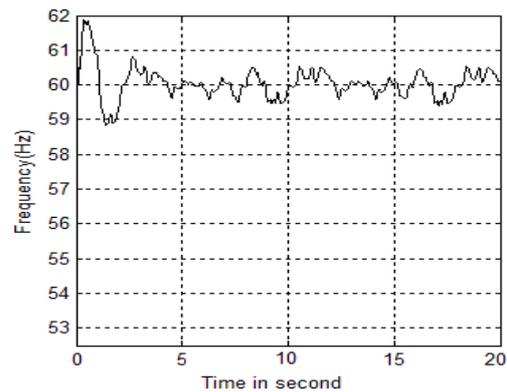
Figure 12. Variation of frequency

The frequency variation induced by the wind-diesel system is about 1.1Hz at the grid. As from figure 1 it can be seen that there are some hilly area outside the community of Cartwright. So during simulation we have also observed the voltage fluctuations and frequency variation considering different location of wind turbine in the community. The simulation results are given in the Table 1.

Table 1: Voltage and frequency fluctuation for different length of transmission lines

Wind turbine distances (km)	Voltage fluctuation at grid (V)	Voltage fluctuation at wind turbine (V)	Frequency Hz
8	4.03	8.1	0.97
10	3.91	7.5	0.85
13	3.5	7.2	0.801

The above table shows that with increasing the distance of wind turbine placement from the grid can reduce the voltage fluctuation and frequency variation. The variation of voltage at the customer's terminals under any condition must be within the limit of +10% of the nominal voltage [10]. Frequency variation for large power system is allowed to vary within the range of <1%. Small diesel generated power system and wind-diesel hybrid power system are allowed to operate within the variation of frequency is about +3% [10]. Our simulation results "Table 1" show that voltage and frequency variations for all three selected locations are well within the limit.

8. Conclusion

In this paper the impact of a 100kW wind turbine on a remote isolated diesel power system is observed. From above discussion it is found that a 100kW wind turbine can be installed outside the community which can bring benefit to the community from the available wind energy in this area. As wind energy is variable in its nature, so to avoid sudden variation of voltage at the grid terminal and load end, wind turbine can be placed at a suitable distance but it can't be placed far away from the diesel plant as attenuation characteristic of transmission line can reduce power flow to the system. A 100kW wind turbine can be placed outside Cartwright and voltage and frequency will be in the acceptable range.

9. Acknowledgement

10. List of Symbols and Parameters

Table A1: List of symbols and parameter values.

d	Direct axis
q	Quadrature axis
l	Leakage variable
s	Stator variable
r	Rotor variable
f	Field quantity
m	Magnetizing quantity
k	Damping variable
R	Resistance variable
I	Current variable
V	Voltage variable
ω	Stator angular electrical frequency
ω_b	Rotor angular electrical base frequency
ω_r	Rotor angular electrical speed
X	Reactance variable
L	Inductance variable
φ	Flux variable
λ	Flux linkage variable
p	d/dt
P	No of generator pole
T_g	Electromagnetic torque
T_T	Aerodynamic torque

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