Power Prediction of a Fermeuse Newfoundland Wind Farm

Deepa Paga, Tariq Iqbal
Faculty of Engineering and Applied Science,
Memorial University of Newfoundland
dp5437@mun.ca , tariq@mun.ca

***Abstract*- Wind power forecasting within time intervals ranging from few minutes to hours is essential for utilities. Such information is required for planning operation and shut down of thermal units in the system. This research involves finding a simulation model and developing software that could be used for power prediction of Fermeuse wind farm. The model includes a simple individual wind turbine dynamic model, variation in wind speed with height, variation in wind speed over the site area and the wake interaction between wind turbines. Detailed Computational Fluid Dynamics (CFD) based flow models of a wind farm including dynamic model of a wind turbine are too complex and are not suitable for real time power prediction and need a supercomputer for calculation. Wind power physical model takes into account topographical map, a wind farm layout and the long term site wind and atmospheric data and uses this information to calculate wind speed at all wind turbines. Using the wind turbine physical model the output power of each individual turbine in a wind farm is established and the wake effects are calculated. The developed power model is applied to Fermeuse, Newfoundland 27MW wind farm and the results are presented in the paper.**

Index Terms—Wind Turbine, Power Prediction, Renewable energy, Wind farm.

I. INTRODUCTION

Wind Power is the conversion of wind energy to produce electricity using wind turbines and is the alternate source of renewable energy. Various physical factors are considered in estimating wind power of a wind turbine. The physical factors determine the wind power estimation in real time. In this paper, algorithm is designed considering the physical factors effecting wind power of the wind turbines in the wind farm and code is written in MATLAB to estimate the wind power in real time. The wind turbine manufacturer supplied power curve assumes ideal condition and in reality there is a variation in physical factors. Physical factors considered in this paper are vertical shear, turbulence intensity, turbulence adjusted speed, air density, pressure, and temperature to estimate wind power of a wind turbine. The wind farm consists of many wind turbines and wake model is incorporated to estimate wind farm power. Fermeuse wind farm is located in Newfoundland. The wind farm has nine wind turbines in operating condition. The wind turbines of Fermeuse wind farm are Vestas V90 3MW and the total capacity of the windfarm is 27MW. The main challenge for this work is to find a simple model that will take a topographical map, a wind farm layout and the long term site wind and atmospheric data and uses this information to calculate wind speed at all wind turbines. The designed algorithm estimates wind speed adjusted for shear and turbulence for the wind turbine rotor disc from lower rotor tip to upper rotor tip. The value estimated is effective wind speed and is assumed to be at the hub height. Air density is adjusted to predict wind power of each wind turbine. For estimating power for the wind farm, speed and height for each wind turbines varies and it depends on the distance between wind turbines and contour height and layout information. Wake model is incorporated when wind turbines are located less than four times the rotor diameter of upstream turbines and power of the wind farm is estimated. The resulting simple model of a wind farm will be used to develop a computer program that is fast and can be used in real time using a High Performance Computer Cluster (HPCC).

II. WIND TURBINE POWER ESTIMATION

The wind turbine manufacturer supplied power curve assumes ideal condition and in reality there is variation in physical parameters and variation in power. The wind turbine manufacturer supplied power curve is digitized by plotting power vs. speed characteristics. An eighth order polynomial is fitted in MATLAB for accurate estimation. Fermeuse wind farm has nine wind turbines; the height of wind turbine rotor disc is determined by considering its contour height, hub height and rotor diameter. The input wind speed and standard deviation values of wind data are given at known heights (sensors height). The input wind speed data should be known at lower rotor tip of wind turbine to upper tip. The input wind data at unknown heights is determined using the power law equation of shear. The input wind data is given in per second time series order. From the given input wind data, turbulence intensity, turbulence adjusted speed, wind shear exponent is determined at known heights. Turbulence intensity is determined from the average wind speed and standard deviation value of wind data. Turbulence adjusted wind speed is determined from the input wind speed and turbulence intensity at the known model levels or height which intersect wind turbine rotor disc. Wind shear exponent is calculated using the power law equation of shear from the turbulence adjusted wind speed data at known heights. Final disc wind speed which is adjusted for turbulence and vertical shear is evaluated for the entire rotor disc by numerically integrating wind speed values from lower rotor tip to upper rotor tip by solving the equation of disc speed. This value is assumed to be at the hub height. The uncorrected power is determined from the polyfit curve fitting equation of MATLAB. The disc speed is substituted in the uncorrected power curve equation and is subsequently adjusted for air density to estimate power of the wind turbine. Thus wind power is estimated for one wind turbine from the disc speed (adjusted for turbulence and vertical shear). Thus, the power is estimated for the wind turbine considering physical factors.

III. FERMEUSE WIND FARM POWER ESTIMATION

A. Layout of Fermeuse Windfarm

After site visit to Fermeuse windfarm and extensive research regarding the layout information as shown in Fig.1. assumptions are made to the windfarm layout data as it is commercially sensitive information.

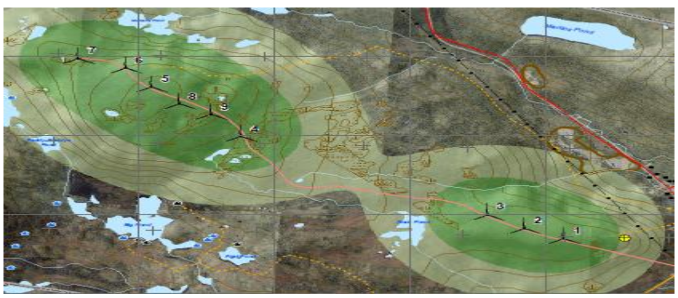

Fig.1. Fermeuse Windfarm Layout

Fermeuse wind farm has nine wind turbines in the wind farm. The wind turbine at Fermeuse site are Vestas V90, 3MW. After a site visit to the Fermeuse, the site information was collected through extensive research. It is concluded that wind farm has nine wind turbines in operating condition. The contour height of wind turbine is determined through its layout information and the horizontal distance between wind turbines is assumed. Using the similar approach of predicting wind power of a wind turbine, the power of each wind turbine in Fermeuse site using the physical factors is estimated, therefore wind power for all the nine wind turbines is predicted. The wake effect is considered for wind turbines for a particular wind direction in the wind farm. The wake effect arises when wind turbines are at a distance less than four times the rotor diameter. The speed of wind turbines operating in wake effect is reduced and therefore there is considerable reduction of wind power. At a particular wind direction, wind turbines operate in partial shadow or complete shadow of upstream or neighboring wind turbines and there is considerable reduction in wind power. The wake speed for all the wind turbines with wake effect is determined from the thrust coefficient of wind turbine and free disc speed and corresponding power is estimated for all the wind turbines. The wake power of each wind turbine in the wind farm is added to determine the total power of the wind farm. There is considerable reduction in wind power of downstream wind turbines operating with partial shadow or full shadow effect. At all the other wind direction there is no reduction of wind speed and the wind turbines operate at maximum power.

IV. DESIGNED ALGORITHM

B. Wind power of a wind turbine with no-wake effect

The manufacturer supplied power curve is digitized by plotting power vs. speed characteristics and uncorrected power curve is determined from the polyfit equation (1) of degree eight for accurate estimation [1]. In this equation variable x is replaced by wind turbine rotor disc speed ($\overline{U}_{Disk}$). The uncorrected power ($P1_{(uncorr)}$) is determined from disc speed.

$$P1_{(uncorr)} = q(9) + q(8) * x + q(7)*x^{2} + q(6)*x^{3} + q(5)*x^{4} + q(4)*x^{5} + q(3)*x^{6} + q(2)*x^{7} + q(1)* x^{8}. \quad (1)$$

Turbulence Intensity at known heights is calculated using equation (2) from the input wind speed is (U) and standard deviation data is (σ).

$$Iu = \sigma / U. \quad (2)$$

Turbulence adjusted wind speed ((U’ (TI)) is calculated [2] using equation (3) from input wind speed and turbulence intensity (Iu) at known heights.

$$U^{'}(TI) = \sqrt[3]{U^{3} * (1 + 3I_{U}^{2})}. \quad (3)$$

Wind shear exponent (α) is calculated [7] from the above turbulence adjusted wind speed data $U'2(TI)$ and $U'1(TI)$ at the given model level or known heights H_2 and H_1. It is given by power law equation of shear.

$$\alpha = \frac{\log\left(\frac{U'2(TI)}{U'1(TI)}\right)}{\log\left(\frac{H2}{H1}\right)}. \quad (4)$$

Wind velocity across wind turbine rotor disc [2] adjusted for turbulence and vertical shear is calculated using equation (5) from lower rotor tip (H-R) to upper rotor tip (H+R) where H is wind turbine hub height and R is radius of the wind turbine rotor disc and A is area of wind turbine rotor disc.

$$\overline{U}_{Disk} = \frac{2}{A}\int_{H-R}^{H+R} U_{Z}\sqrt{R^{2} - H^{2} + 2HZ - Z^{2}}\,dZ. \quad (5)$$

Actual air density (ρ) [1] correction is applied to the disc power from input pressure (P) and temperature (T) using equation (6)

$$\rho = 3.4837 * P / T. \quad (6)$$

Corrected power ($P1_{(corr)}$) of wind turbine [1] is determined from actual density, density at Standard Temperature Pressure (STP) and uncorrected power ($P1_{(uncorr)}$) from curve fitting equation of MATLAB using equation (7)

$$P1_{(corr)} = P1_{(uncorr)} * \rho \text{ / density at STP.} \qquad (7)$$

C. Wind power of a wind farm with no-wake effect

Below is the general equation to predict wind power of wind turbines with no-wake effect. For Fermeuse wind farm, detail study of wind farm layout, number of wind turbines, contour height of wind turbine and distance between wind turbines is studied. These values are considered to estimate power of wind turbines in the windfarm. At a particular wind direction, wake effect takes place when wind turbines are placed at a distance less than four times the rotor diameter. At all the other wind direction, the wind turbines operate in free wind speed. The wind turbines operate at maximum power and power of windfarm is determined by adding power of each wind turbine with no-wake effect. Fermeuse wind farm has nine wind turbines and total power of the windfarm is sum of the power of each wind turbine in the windfarm and is calculated using equation (8), where number of wind turbines is denoted by n. For Fermeuse windfarm, total number of wind turbines in windfarm are nine and power of windfarm with no-wake effect, $P_{(no\text{-}wake)}$ is calculated using equation (8).

$$P_{(no\text{-}wake)} = \sum_{n=1}^{n=n} P1_{(corr)}. \qquad (8)$$

D. Wind power of a wind turbine with wake effect

Below is the general equation to predict wind power of wind turbines with wake effect. For Fermeuse wind farm, detail study of wind farm layout, number of wind turbines, contour height of wind turbine and distance between wind turbines is studied. These values are considered to predict actual power of a wind turbine. At a particular wind direction, wake effect takes place when wind turbines are placed too close. With wake effect, the wind speed of downstream wind turbine reduces depending on the shadow area of rotor disc, radius of the shadow cone, thrust coefficient of wind turbine and correspondingly there is reduction in wind power. The wake speed of wind turbine is determined from the free disc speed at the rotor disc and correspondingly wake power is determined.
Depending on the distance between wind turbines (X), the radius of the shadow cone Rx [3] of upstream turbine is calculated using equation (9) from radius of rotor (R) and tana. The value of tana is 0.04 under free stream and 0.08 under wake stream.

$$Rx = R + X^* \text{ tana.} \qquad (9)$$

Thrust coefficient (Ct) of a wind turbine [4] is calculated from the disc speed adjusted for vertical shear and turbulence using equation (10) and is given below. The disc speed is assumed to be at hub height.

$$Ct = 3.5*[2*(\bar{U}_{Disk}) - 3.5] / (\bar{U}_{Disk})^2. \qquad (10)$$

Wake speed (U_{wake}) of a wind turbine [8] is calculated from disc speed, thrust coefficient, radius of rotor disc, radius of the shadow cone (Rx) of rotor disc, area of shadow region (AS) of rotor disc and area of the wind turbine rotor (A) using equation (11).

$$U_{wake} = \bar{U}_{Disk}*[1- \sqrt{(1-Ct)}*(R/Rx)^2 *(AS/A)]. \qquad (11)$$

The manufacturer supplied power curve is digitized by plotting power vs. speed characteristics and uncorrected power curve is determined from the polyfit equation of MATLAB and for accuracy eighth order polynomial is fitted using equation (1). The variable x is replaced by wake speed and uncorrected wake power $P2_{(uncorr)}$ of wind turbine is calculated using equation (12).

$$P2_{(uncorr)}=q(9)+q(8)*U_{wake}+q(7)*U^2_{wake}+q(6)*U^3_{wake}+q(5)*U^4_{wake}+q(4)*U^5_{wake}+q(3)*U^6_{wake}+q(2)*U^7_{wake}+q(1)*U^8_{wake}. \qquad (12)$$

Actual air density is determined from input pressure (P) and temperature (T) using equation (6). Air density correction is applied and corrected wake power, $P2_{(corr)}$ of wind turbine[1] with wake effect is determined from actual density, density at STP and uncorrected wake power from curve fitting equation of MATLAB using equation (13)

$$P2_{(corr)} = P2_{(uncorr)} * \text{ actual density / density at STP.} \qquad (13)$$

E. Wind power of a wind farm with wake effect

Fermeuse windfarm, there are nine wind turbines and corrected power ($P_{(wake)}$) of each wind turbine with wake effect is added using equation (14) and is the total power of the windfarm with wake effect. Table I gives the details of wind turbines of Fermeuse windfarm operating in wake effect and area of shadow region of rotor disc at a particular wind direction.

$$P_{(wake)} = \sum_{n=1}^{n=n} P2_{(corr)}. \qquad (14)$$

F. Wake coefficient of wind turbines in the windfarm

Wake coefficient (C_{wake}) [3] of wind turbines in the wind farm is calculated by the ratio of total output power of wind farm with wake effect to the total output power of windfarm neglecting wake effect.

$$Cwake = \frac{\Sigma P(wake)}{\Sigma P(nowake).} \qquad (15)$$

V. FERMEUSE WINDFARM DATA

Table I and II gives the details of layout data of wind turbines assumed in Fermeuse windfarm.

Table I

Fermeuse Windfarm Layout Data						
Number of Wind Turbines	Contour Height of Wind Turbine (m)	Lower Rotor Tip (m)	Upper Rotor Tip (m)	Hub Height (m)	Horizontal Distance Between Wind Turbines (m)	
WT1	95	35	125	80	WT1-WT2	250
WT2	95	35	125	80	WT2-WT3	250
WT3	95	35	125	80	WT3-WT4	1000
WT4	127	67	157	112	WT4-WT5	250
WT5	153	93	183	138	WT5-WT6	250
WT6	140	80	170	125	WT6-WT7	250
WT7	128	68	158	113	WT7-WT8	250
WT8	148	88	178	133	WT8-WT9	250
WT9	120	60	150	105		250

Table II

Area of Shadow Region and Wake Coefficient Data of Fermeuse Windfarm										
Wind Direction	WT1 (AS)	WT2 (AS)	WT3 (AS)	WT4 (AS)	WT5 (AS)	WT6 (AS)	WT7 (AS)	WT8 (AS)	WT9 (AS)	WC
40,220	3181	3181	0	3181	4772	3181	0	4772	3181	0.8
45,225	4772	4772	0	6362	4772	6362	0	6362	4772	0.6
50,230	3181	3181	0	3181	4772	3181	0	4772	3181	0.8
All Other Direction	0	0	0	0	0	0	0	0	0	1.0

VI. WINDFARM POWER RESULTS

G. Graph of Matlab Results from the deigned algorithm

Below are the results of designed algorithm implemented in MATLAB. The disc speed and power results of wind turbine and wind farm are shown.

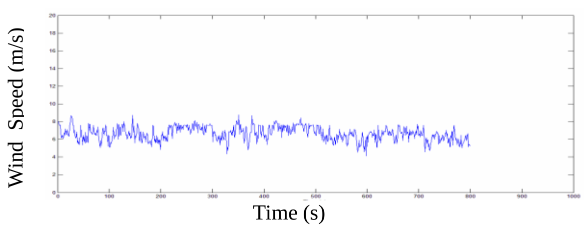

Fig.2. Input wind speed is plotted with respect to time in seconds for 800 input time series data.

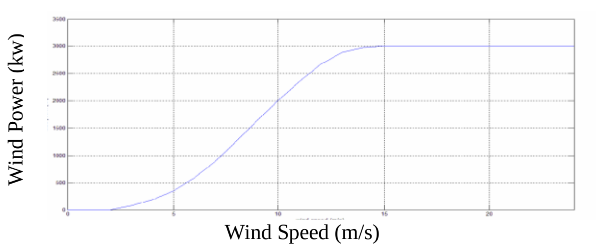

Fig.3. Power curve characteristics of manufacturer supplied Vestas 3MW wind turbine

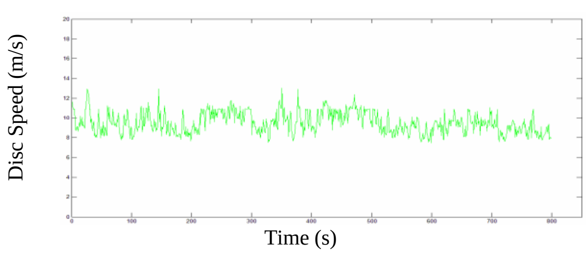

Fig.4. Disc speed (m/s) adjusted for turbulence and shear is plotted against time (s) for 800 input time series wind data.

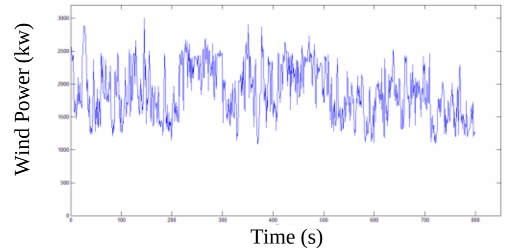

Fig.5. Wind power (kw) estimated from disc speed is plotted against time (s) for one wind turbine

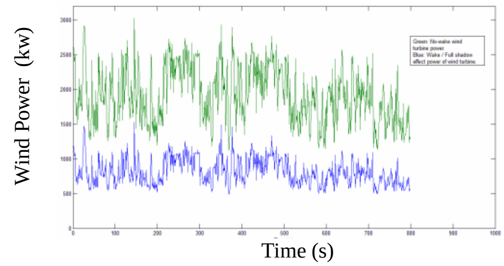

Fig.6. Comparision of wind turbine power (kw) with wake effect (blue) and without wake effect(green) and is plotted againt time(s) for 800 time series data.

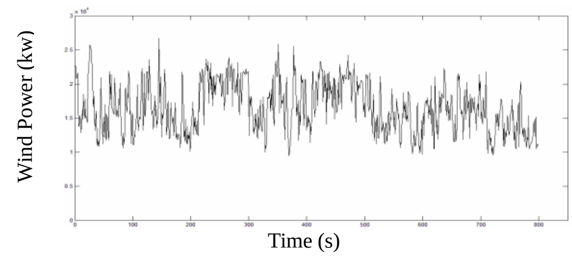

Fig.7. Plot of wind power (kw) of a windfarm with no-wake effect against time(s) for 800 time series data.

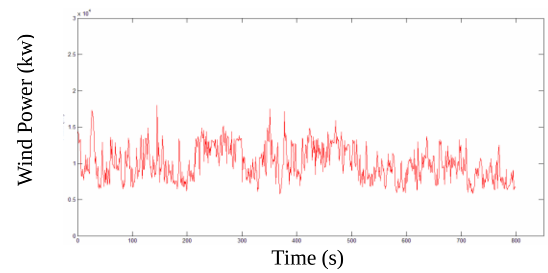

Fig.8. Plot of wind power (kw) of a windfarm with wake effect against time for 800 time series data.

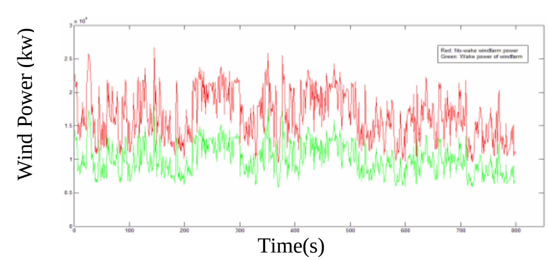

Fig.9. Comparision of windfarm power (kw), with wake effect (green) and without wake effect (red) against time (s) for 800 time series data.

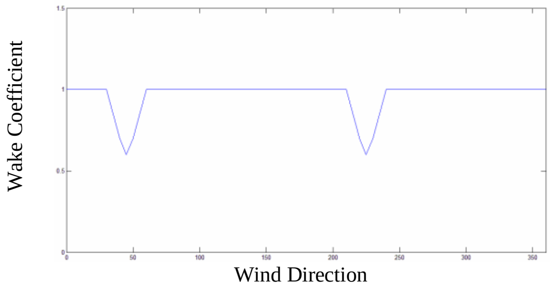

Fig.10. Wake coefficient is plotted against wind direction (°)

VII. CONCLUSION

The atmospheric parameters need to be considered in power estimation since the manufacturer supplied power curve assumes ideal condition. Any variation in the physical parameters leads to change in power production considerably.
From the Fermeuse layout information and designed algorithm implemented in MATLAB, the estimated results are presented. Fig.2. gives the input wind speed data in per second time series order for 800s measured at sensor height at a distance of 10m. Vestas 3MW wind turbine is plotted from power vs. speed characteristics [6] as shown in Fig.3. The disc speed, adjusted for turbulence and vertical shear is effective wind speed estimated for wind turbine from lower rotor tip to upper rotor tip and is shown in Fig.4. Wind power is estimated from the disc speed, adjusted with air density and is shown in Fig.5. The graph of wind turbine operating with wake effect (45^o) and without wake effect (20^o) is shown in Fig.6. and the reduction in power is compared and is plotted. Fig.7. and Fig.8. shows wind farm operating without wake effect and with wake effect respectively. At a wind direction of 45^o, 225^o wake effect takes place in wind farm and the graph shows wind farm operating in wake effect. The graph is plotted by comparing the reduction in power in wake effect and that when wind turbines operate under no wake effect at a wind direction of 20^o. This effect is shown in Fig.9. Wake coefficient is plotted against wind direction in Fig. 10. and shows the impact of wake effect on windfarm. A wake coefficient of 1 denotes the wind turbine operating at maximum power. From the results it is concluded that the wind speed estimated at the rotor disc is effective wind speed and covers the rotor disc and the power estimated is for the entire rotor disc and not at hub height. There is reduction in power in wake effect for the windfarm. The probability of wind turbine operating at the wake coefficient of 0.6 is very low. The deigned algorithm and implemented code in MATLAB works for any input time series wind data and correspondingly results are estimated.

ACKNOWLEDGMENT

Authors would like to thank AMEC Earth and Environment, St John's, NL for their guidance in this research work. The research is also supported and funded by AMEC Earth and Environment.

REFERENCE

[1] Renewable Energy System Course Work.
[2] Wharton, S., & Lundquist, J. (2010). Atmospheric Stability Impacts on Power Curves of Tall. Wind Turbines - An Analysis of a West Coast North American Wind Farm.
[3] F. Koch, M. Gresch, F. Shewarega, I. Erlich, Member, IEEE and U. Bachmann, Institute of Electrical Power Systems and Automation, University of Duisburg – Essen, Germany. - Consideration of Wind Farm Wake Effect in Power System Dynamic Simulation.
[4] Peter Frohboese, Christian Schmuck. Thrust Coefficients used for estimation of wake effects for fatigue load calculation- European Wind Energy Conference 2010, Warsaw , Poland.
[5] GL Garrad Hassan - Thrust coefficients used for estimation of wake effects for fatigue load calculation - European Wind Energy Conference 2010, Warsaw, Poland.
[6] www.vestas.com – power curve characteristics
[7] Giovanni Gualtieri a, Sauro Secci b. May 2010-Wind shear coefficients, roughness length and energy yield over coastal locations in Southern Italy.
[8] F. González-Longatt, P. Wall, V. Terzija.
August 2011-Wake effect in wind farm performance: Steady-state and dynamic behavior, September 2011.