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Calculate the Wake Effect of a Wind Turbine for Power Generation Using FAST Tool

Mohammad Asif Sazzad*,
*(Ford Motor Company, Dearborn, Michigan, USA
Email: sazzad.me06@gmail.com)

Abstract:

The inspiration behind simulation of wind turbines is self-evident: wind turbines are substantial, costly machines. It would be restrictively expensive and risky to test new thoughts on real wind turbines. Even a moderate PC can resemble different parts of them. However, simulations help in testing and designing of numerous aspects of wind turbines, including the control frameworks and power electronics.
Getting prior idea of power rating along with the effect of atmospheric boundary layer (ABL) [1]- [4]. before the production of the real Wind Turbines are very important information. It can help to accommodate necessary change before the final production. This study was done utilizing the data from Large Eddy Simulation where ABL was accounted for both neutral and convective condition. We have focused how Turbulent Kinetic Energy (TKE), Wind velocity and deficit affect the power generation of the WTs.

Keywords —Wind Turbine, Wake, ABL, Power Calculation, FAST, Renewable Energy.

I. INTRODUCTION

Significant research has been done on the demonstrating and control of wind turbines [5]–[10]. The greater part of this research, in any case, has been done utilizing straightforward mechanical and aerodynamic models of wind turbines that disregard various noteworthy qualities. However, simulation packages FAST, Turbsim and Simulink can be utilized to design electrical and mechanical of features of a wind turbine in precisely. Yolanda Vidal et al. [11] used FAST to propose some controllers which are efficient for regulating power and manifest high performances for all other state variables. David G. Wilson et al. [12] tested for the trailing edge flaps as active load control device on wind turbine which allows increased blade length resulting in larger swept rotor area. They used FAST for their simulation purpose. Alexander J. Coulling et al. [13] built a model with 1/50th scaling of National Renewable Energy Laboratory (NREL) floating wind turbine simulator FAST. Results suggested that FAST delivers many of the appropriate physics for coupled floating WT problem. Jacob Aho et al. [14] focused on building a controller for WT which can vary the turbine's power output depending on receiving de-rated power set-point commands, manual commands and automatic frequency response commands to fulfill the system requirements in below rated and above rated wind speeds. Nevertheless, they used FAST code to make the controller [16]. Our purpose in this thesis is to simulate wind data from LES to get the corresponding power curve. Since, LES data have never been used with FAST before; it will be interesting to see how power curve comes out. We both generated for ideal constant wind field and LES data. Currently standard way of measuring power curve is described by IEC 61400-12-1 [15]. They use 10 minute mean data to produce the power performance curve. However, hub height velocity is used to generate the curves. We will demonstrate that wind power is directly correlated with the averaged profile velocity. Power curve of 10 min will be presented for both wake and without wake effect.

II. POWER SIMULATION USING FAST

FAST is an openly accessible aeroelastic simulator system for two or three bladed HAWTs. Aeroelastic fundamentally implies it simulates the communications of (wind) with mechanical bodies (tower, nacelle, rotor, and so forth). FAST, in its present structure, had its beginning in 2002 from the mix of two unique codes for demonstrating two and three bladed wind turbines [17]. FAST is frequently contrasted with, and confirmed against, a business program called ADAMS that can be utilized to reenact wind turbines. Actually, FAST can be utilized to create information for use in ADAMS simulations. FAST and ADAMS, alongside AeroDyn, were resolved appropriate for "the calculation of onshore wind turbine loads for design and certification"[18].

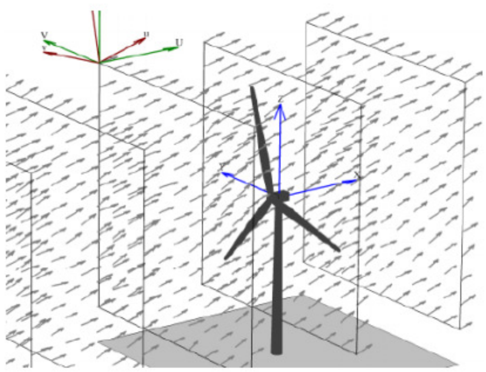

Fig. 1 Wind Data Files Used with AeroDyn

FAST is composed in FORTRAN 90, however a dynamic connected library (DLL) is accessible with the goal that FAST might be utilized as a part of MATLAB® Simulink® simulations as a S-function block. FAST is entangled programming and it is outside the extent of this postulation to totally clarify how it functions. Rather, a brief diagram of the hypothesis behind the product and how to utilize it as a feature of Simulink simulations will be given. FAST has twenty four degrees of flexibility (DOF) for a three-bladed wind turbine [19]. Twenty two of the twenty four DOF are outlined perfectly in Fig. 26.

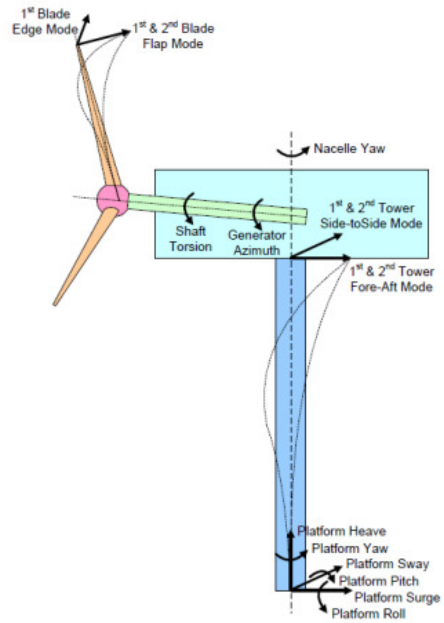

Fig. 26 FAST Degrees of Freedom

The two not demonstrated are rotor-roll pivot and tail-fold pivot. However, for offshore turbine simulations six DOF for the platform are used. Both multi-body and modal dynamics are used for derivation of FAST [19]. The subsequent nonlinear equations of motions are ordinary differential equations (ODE's) and they are settled utilizing the fourth order Adams-Bashforth-Adams-Moulton (ABAM) predictor-corrector fixed-step-size explicit integration scheme [20]. The platform motions expect small angles yet all other DOF motions might be substantial and exactness is held [20].

Some of the coordinate systems used for FAST are stated below:

Inertial Frame Coordinate System, Tower-Base Coordinate System, Tower-Top/Base-Plate Coordinate System, Nacelle/Yaw Coordinate System, Shaft Coordinate System, Azimuth Coordinate System, Hub Coordinate System, Coned Coordinate Systems, Blade Coordinate Systems etc. Coordinate systems t, n, h, and b comply to the International Electrotechnical Commission (IEC) standard for wind turbines [21]. Further coordinate systems i, p, a, s, and c are needed for depicting some of the output parameters. FAST also uses few coordinate systems internally which vary from these. Transformations of these systems are taken care of by FAST for the user [22].

Here, there is a table which is containing the information about turbine specification we have simulated.

Table1: Specification of the NREL wind turbine

Rating	5MW
Rotor Orientation	Upwind
Control	Variable Speed
Rotor Diameter/ Hub Diameter	126m / 3m
Cut-In, Maximum Rotor Speed	6.9 rpm, 12.1 rpm
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Maximum Tip Speed	80m/s
Hub Height	90m
Rotor Mass	110,000kg
Nacelle Mass	240,000kg
Tower Mass	347,460kg
Tip Speed Ration at Peak Power Coefficient	7.55
Peak Power Coefficient	0.482
Rated Mechanical Power	5.296610 MW

III. METHODOLOGY

For getting the power out of the wind field using FAST we had process a lot of files prior to simulation. We had to run LES simulation to get the wind data. However, to sort and process the large amount of time files we came up with a python script which processed all the .vtk files generated through simulation. To run and process all the files we needed to use multiple cores in Texas Advance Computing Center (TACC). We ran our python script through ParaView which is visualization software. For convenience python script is given in Appendix II. When we processed our .vtk files to .csv files with our required dimension, then files were downloaded to the local drive.

FAST requires wind field velocity data in .wnd format. It then takes aerodynamic properties from different subroutine to run the simulation. To process .wnd and .sum file we used a MATLAB code, which is able to read all the .csv files. Furthermore, FAST can be executed from MATLAB too. Hence, after processing the .wnd and .sum file where the velocity component in the three direction (x,y,z) along with turbulence intensity are stored. The size of the wind field is 160m × 160m. When FAST is executed, it reads aerodynamic property from aerodynsubrountine along with the .wnd and .sum files. Then it simulates power for 600 seconds. However, for about first 20 to 30 seconds the output fluctuates and then it delivers the actual power. In **Error! Reference source not found.** the whole process from processing LES file to simulate power is presented using a flowchart. There is a MATLAB code in Appendix III which does all the processes after the python script is run to generate .csv files. Besides, doing FAST simulation for LES data, we did generate one set of plot using constant profile data with and without wake effect. In order to calculate the velocity in the wake we used correlation of type given below:

$$\frac{\Delta V}{V_{hub}} = A\left(\frac{D}{x}\right)^n$$

Where, V_{hub} is the velocity at hub height, x is the downstream distance, D is the wind turbine radius, and A and n are constants. These constants are in the range $1<A<3$, and $0.75<n<1.25$ respectively.

Most of the time it is of designers concern to have an analytical expression which can evaluate the order of magnitude. To describe single wake behavior equation 3.1 is usually of the type regression or correlation obtained by different authors [22-27]. We used A=2 and n=1.2 for our simulation purpose. Hub velocity was 8 m/s and wake velocity we got 6.9905 m/s at x= 630m. Since, at 630m we collected wake data for LES, we calculated wake velocity for ideal case at the same downstream location. Below is the figure of the vorticity field of the LES simulation for two turbines.

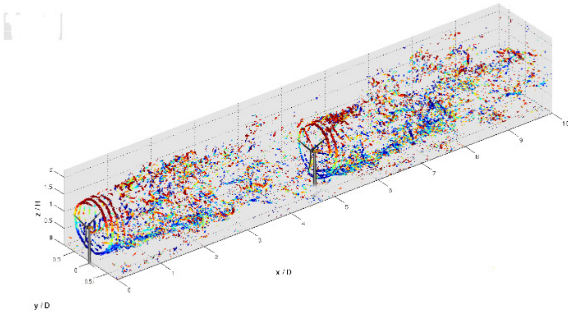

Fig. 3 Vorticity Field for Two Wind Turbine

IV. RESULT

The present form of the IEC technique uses 10 averages for wind speed at hub and electrical power generation. The wind speed and power estimations are initially filtered to expel periods where the turbine is not working properly, and periods where the measurement tower is in the wake of any neighboring wind turbine. These averaged 10 minute data points of wind speed and power are then assembled into "bins" in light of the wind speed estimations. The width of the wind speed bin is 0.5 m/s. The revised 10 minute normal wind speed and power estimations for a given bin are then averaged to get the corresponding wind speed and power for the respective bin. Therefore, to get the estimated steady state power curve data are plotted for the corresponding wind speed and power for a specific bin.

We presented the power vs. time of 10 min for constant velocity profile with and without wake effect against time. However, to calculate deficit we picked x=630m where we have taken the wake data for LES. The deficit we gotten from the formula is low compared to the LES data. However, from this kind of information we cannot produce any power curve which does not vary with time. To construct a power curve we need wind data which varying over the time.

We generated plot for corresponding TKE, velocity and power for both CABL and NABL with and without wake effect from Fig. 5 to Fig. 8. From all the plots it was evident that power is not correlated with the instantaneous TKE. Nevertheless, TKE has direct impact to the recovery of the velocity in the wake of a wind turbine. However, we can clearly see that the averaged wind profile velocity has a correlation with the power. Although, different profile having same hub velocity in we have a plot with different shear with same hub velocity **Error! Reference source not found.**, more power is yielded by the high averaged profile velocity **Error! Reference source not found.**. Hence, constructing power curve considering only the hub height would neglect the effect of shear.

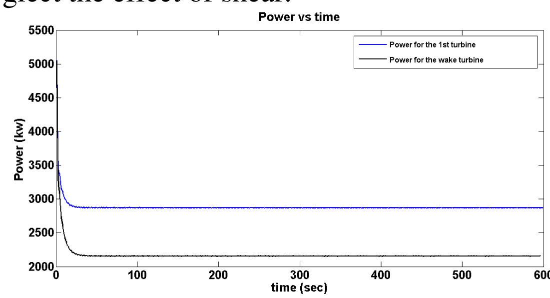

Fig. 4Power for the First Turbine and Second Turbine Using Constant Wind Velocity

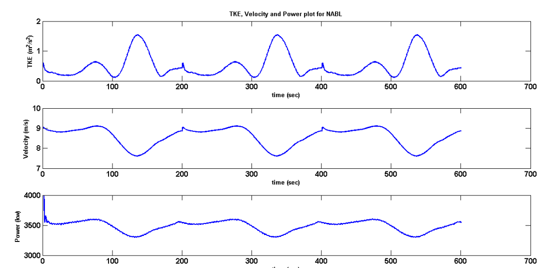

Fig. 5TKE, Velocity and Power Plot for NABL for 1st turbine

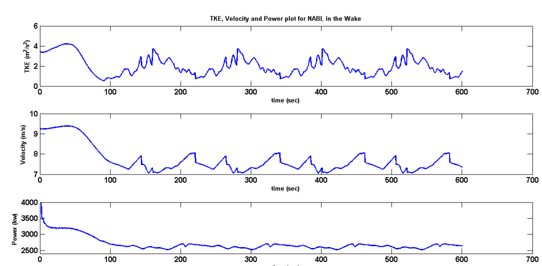

Fig. 6TKE, Velocity and Power Plot for NABL for 2nd turbine

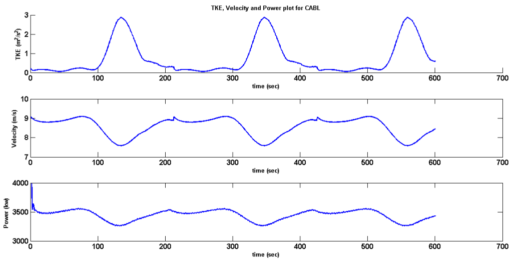

Fig. 7TKE, Velocity and Power Plot for CABL for 1st turbine

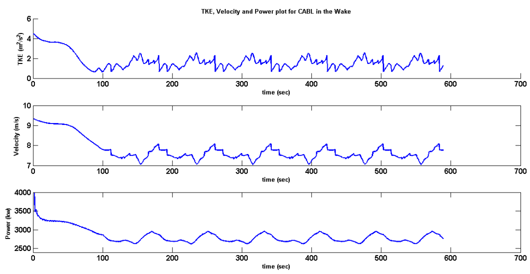

Fig. 8TKE, Velocity and Power Plot for CABL for 2nd turbine

Lower portion of the ABL is interacted by the earth's surface resulting in a turbulent boundary layer. Wind turbines are delivering power from this turbulent wind. This turbulence implies that the driving wind velocity is always fluctuating, creating the wind turbine's power generation to always vary. Furthermore, the power generation of a wind turbine can't react immediately to changes in wind speed. Due to some inertia power generation responds to the wind speed with a time delay. These, power vs. time curves will give us the information for different ABL condition that how the power is responding to the wind speed. Therefore, it will help to construct a power curve where velocity will be profile averaged. Power vs. time curve for first turbine and second turbine for both NABL and CABL are presented in **Error! Reference source not found.**. 9 and **Error! Reference source not found.**. 10. Although, hub velocity was different, the profile averaged velocities were very close for NABL and CABL. We can see comparatively power loss was more in NABL than CABL. CABL has higher wind shear at the lower portion of the turbine which contributes in addition to ABL turbulence intensity to create more turbulence in the wake. Hence, due to turbulent mixing wake recovery happens faster in CABL. So, the overall profile averaged velocity in the wake was higher in CABL than in NABL. [28] separated the wind velocity into different groups to discuss the impact of wind shear to the generation of power in different stability condition. However, it is clear from our study whenever turbine is facing maximum flow across its rotor it will yield maximum power.

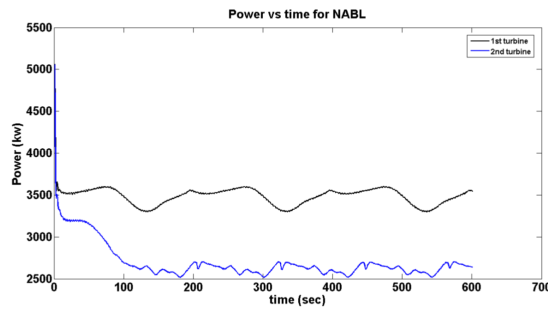

Fig. 9Power for the First Turbine and Second Turbine in NABL

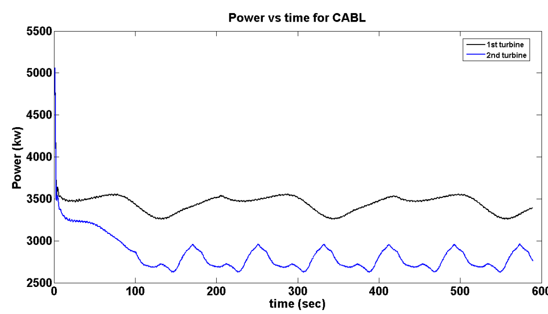

Fig. 10Power for the First Turbine and SecondTurbine in CABL

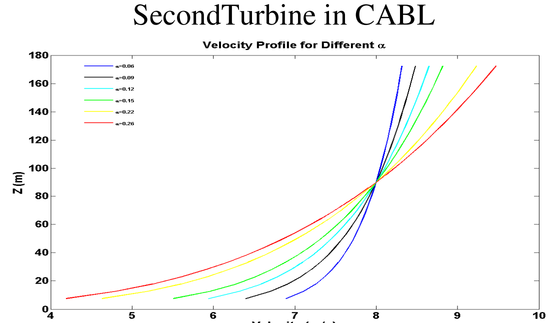

Fig. 11Velocity Profile for with different Wind Shear Coefficient

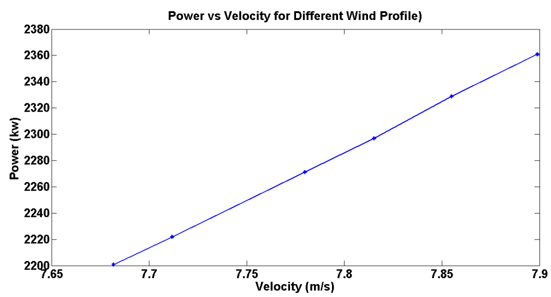

Fig. 12Power vs Velocity for Different Wind Shear Profile with Same Hub Velocity

V. CONCLUSIONS

This is the first study to use LES data by FAST. It can be very helpful to generate power curve which can get rid of the errors associated with the shear coefficient. Besides, it will help us to have the power information over the averaged velocity profile turbine facing. Another important finding from the study was instantaneous TKE had no correlation with the power. From other studies we know that TKE helps faster recovery of wake. It was evident from our study that power loss was less in CABL in comparison to NABL.

However, future work includes verify our turbulent scale coefficients with the experimental data. We didn't study how the coefficients come for stable ABL, since we only had data for NABL and CABL. To simulate power using FAST we did analyze for one specific temperature and air density. We can extend our study how much temperature and air density can impact the power output.

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My master's thesis paper was used to write this paper.

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