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Time Domain Simulation of Wind Shear and Tower Shadow in Wind Turbines

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ABSTRACT

This paper presents an aerodynamic analysis of a three-bladed wind turbine using unsteady Blade Element Momentum (BEM) method. A MATLAB code has been written to perform the analysis in which a simulation model for a wind speed acting on a wind turbine rotor plane was used considering the effect of wind shear and tower shadow. Results obtained from the analysis have proved that tower shadow and wind shear contribute to periodic fluctuations in loads and mechanical power of a wind turbine .The frequency of the periodic fluctuations is *n* times the blade rotational frequency *p*, where *n* is the number of blades. For three- bladed wind turbine, this inherent characteristic is known as *3p* effect. Furthermore, as the aerodynamic loads change periodically due to wind shear and tower shadow, this may have a large effect on output power quality and fatigue life of the blade. Hence, the loads analysis in this paper may be applicable to the improving power quality and design analysis of the wind turbine.

Keywords: Wind turbines, Blade element momentum, Wind shear, Tower shadow.

محاكاة نطاق الزمن لتأثير القص ووجود البرج على توربينات الرياح

الخلاصة

يتناول البحث الحالي تحليلا للقوى الأيروديناميه لتوربينات الرياح ذات الثلاث شفرات بأستخدام برنامج (MATLAB) وأعتمادا على نظرية (Blade Element Momentum) . حيث تم أستخدام موديل رياضي لسرعة الرياح المؤثره على التوربين تحت تاثير القص ووجود البرج . أثبتت النتائج المستحصله من التحليل بأن تاثير القص والبرج على الرياح يسهم في التقلبات الدوريه للأحمال

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والقدره الميكانيكيه للتوربين، اذ تعد هذه التقلبات الدوريه ظاهره متأصله في توربينات الرياح و التي تعرف بتأثير (np) حيث n هي عدد الشفرات و p هي التردد الدوراني للشفره . وبذلك فأن هذا التأثير يدعى بتأثير 3p في التوربينات ذات الثلاث شفرات . وعلاوة على ذلك فأن التغير الدوري للأحمال الايروديناميه والقدره الميكانيكيه بفعل تأثير القص والبرج على سرعة الرياح قد يكون له تأثيرا كبيرا على نوعية القدره وعمر الكلال للشفرات. وبالتالي، فمن الممكن تطبيق التحليل الحالي للاحمال في تحسين نوعية القدره الخارجه وفي الحسابات التصميميه لعمر الكلال للشفرات.

INTRODUCTION

Growing energy demands and environmental concerns have increased the interest in the use of wind energy. However, there are numerous problems and limitations still exist and need to be resolved before wind energy can become a major source of energy [1].One such problem is that torque and power generated by a wind turbine experience fluctuations at *n* times the rotational frequency of the blades *p* or *np* fluctuations (frequency), where *n* is the number of blades. As wind turbines are connected to electrical grids, fluctuating output power causes rapid fluctuations of the supply voltage [2]. Recent studies have shown that in addition to the stochastic pulsations caused by wind, the sources of these power fluctuations are due to two effects known as wind shear and tower shadow [1-4]. Wind shear refers to variation of wind with height while tower shadow is used to describe the redirection in wind due to the obstruction presented by tower. These two effects are an inherent characteristic of any wind turbines. Thus *np* fluctuations are important to model since it could have large effects on power quality and in fatigue life analysis of wind turbine.

This paper focuses on modeling a three bladed-wind turbine based on Unsteady Blade Element Momentum method that includes the effects of wind shear and tower shadow. Furthermore, the dynamic stall and dynamic wake models are not considered in this paper. The present modeling can be used to improve power quality by reducing *np* fluctuations at design level and may be applicable to the design analysis of the wind turbine.

AERODYNAMICS MODELING

Although there are many advanced numerical methods based on Euler and Navier-Stokes equations, the unsteady Blade Element Momentum (BEM) method has been chosen to compute aerodynamic loads acting on the wind turbine blades because it is computationally cheap and thus very fast. Furthermore, it provides very satisfactory results provided that good airfoil data available for the lift and drag coefficients as a function of the angle of attack, [5].

Due to unsteadiness of wind seen by the wind turbine rotor caused by wind shear, and the presence of tower, it is necessary to use an unsteady BEM method to compute realistically the aerodynamic forces acting on the wind turbine blades [6]. BEM method is a combination of one dimensional momentum theory and blade element considerations. The method assumes that:

- The rotor is divided into sections and there is no interaction between each of the elements.

- The rotor has an infinite number of blades, in other words the force from the blades on the flow is constant in each section.

The latter assumption is corrected for a rotor with finite number of blades by introducing a correction called Prandtl’s tip loss factor. At a given radial section, a difference in the wind speed is generated from far upstream to deep in the wake. Hence, the result is a momentum loss due to axial loads produced locally by the flow passing the blades. This creates a pressure drop over the blades. The action of the axial loads generates induced velocity. The essence of BEM method is to calculate the induced velocity, relative velocity and aerodynamic loads at each time step, each blade station and for each blade.

Figures (1& 2) show a simple wind turbine model described by four coordinate systems. The fixed coordinate is placed at the bottom of the tower. Correct implementation of an unsteady BEM requires coordinates transformations between various turbine components. Using the transformation matrices given in [6, 7], the undisturbed incoming wind velocity can be obtained through the transformation from fixed coordinate system (1) to the blade coordinate system (4).

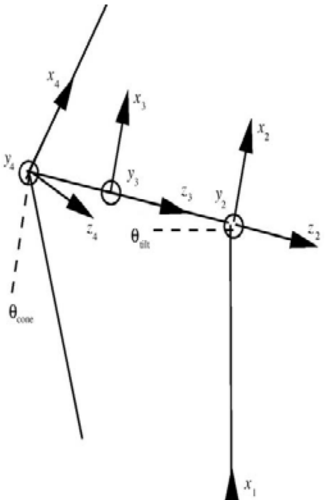

Figure (1) Four coordinate systems describing the wind turbines [6].

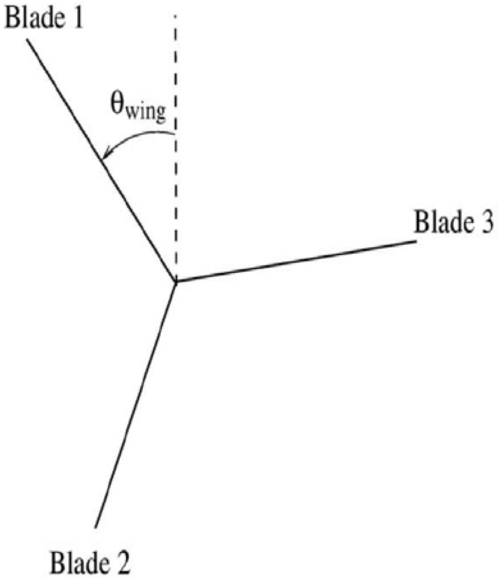

Figure (2) Rotor seen from downstream [6].

Figure (3) shows the velocity triangle seen locally on a blade element. The vector representation of relative velocity can be written as [6,7]:

$$\vec{V}_{rel} = \vec{V}_o + \vec{V}_{rot} + \vec{W} \quad \dots (1)$$

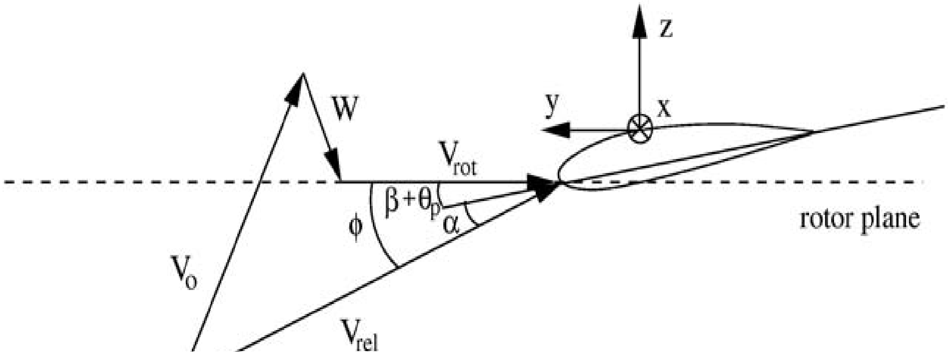

Figure (3) Velocity triangle seen locally on a blade [6].

From the velocity triangle, the angle of attack, α, can be computed if the induced velocity, W, is known:

$$\alpha = \phi - (\beta + \theta_p) \qquad \ldots (2)$$

Where $(\beta + \theta_p)$ is the pitch angle plus the twist of the blade at each station, and the flow angle, ϕ, is defined as:

$$\tan \emptyset = \frac{V_{rel,z}}{V_{rel,y}} \qquad \ldots (3)$$

Knowing α, the lift and drag coefficients can be looked up in airfoil data table. Hence, the main purpose of the BEM method is to determine the induced velocity W, and thus the local angles of attack. Unsteady BEM takes into account the deflection in the wake due to the induced velocity normal to the rotor plane which is caused by the thrust generated by the pressure drop across the rotor. The equations that are used in unsteady BEM model of the present work for normal and tangential induced velocities can be derived from Glauert's relation between thrust and induced velocity [5, 6].

$$W_z = \frac{-BL \cos \emptyset}{4\rho\pi r F |V_O + f_g . n(n.W)|} \qquad \ldots (4)$$

$$W_y = \frac{-BL \sin \emptyset}{4\rho\pi r F |V_O + f_g . n(n.W)|} \qquad \ldots (5)$$

Where *fg* refers to as the Glauert correction, is an empirical relation between the thrust coefficient and axial induction factor. It is assumed that the induction factor doesn't exceed 0.2 and hence f_g equals to 1, (refer to [6]).

DETERMINISTIC MODEL FOR WIND

Taking the unsteadiness in the wind field due to wind shear and tower shadow into account in calculating aerodynamic forces requires performing the following implementation:

Wind speed generally increases with height, see Figure (4). Therefore, a blade pointing upwards would encounter wind speeds greater than a blade pointing downwards. The wind shear is modeled by the widely used power law as [6, 7]:

$$V_O(X) = V_O(H) \left(\frac{X}{H}\right)^v \qquad \ldots (6)$$

Exponent v increases with the surface roughness. It is in the range between 0.1 and 0.25 [6].

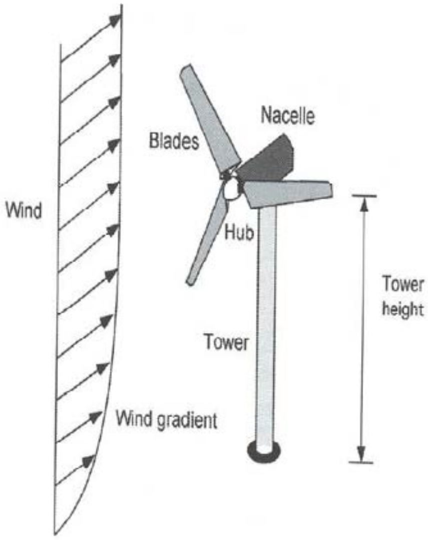

Figure (4) Wind shear model.

The distribution of wind is altered due to the presence of tower. For an upwind turbine, when the blade is directly in front of the tower, it experiences minimum wind. This effect is called tower shadow. A simple model for the influence of the tower is to assume a potential flow around a cylinder of a diameter 2a, see Figure (5).The radial and tangential velocity components V_θ and V_r around the tower are determined by the following equations [6,7]:

$$V_r = V_o \left(1 - (\frac{a}{r})^2\right) \cos\theta \quad \ldots (7)$$

$$V_\theta = -V_o \left(1 + (\frac{a}{r})^2\right) \sin\theta \quad \ldots (8)$$

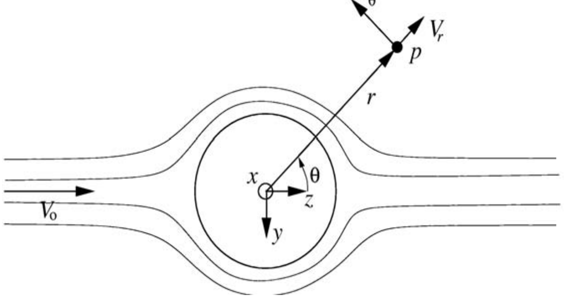

Figure (5) Tower effect model.

THRUST, MOMENT AND POWER CALCULATION

Once unsteady BEM algorithm is applied, the tangential P_T and normal P_N distribution of the loads acting on each blade at each radial position at each time step is computed from lift L and drag D forces resulting from the inflow on the blade using the relative velocity and angle of attack values as follows [6,7]:

$$L = \frac{1}{2}\rho|V_{rel}|^2 c\, C_l\,(\alpha) \qquad \dots\ (9)$$

$$D = \frac{1}{2}\rho|V_{rel}|^2 c\, C_d\,(\alpha) \qquad \dots\ (10)$$

Where C_l and C_d are obtained from a lookup airfoil data table depending on the angle of attack. The projection of the lift and drag forces to the normal to and tangential to the rotor plane, gives the forces into these directions, see Figure (6):

$$P_T = L \sin(\phi) - D \cos(\phi) \qquad \dots\ (11)$$

$$P_N = L \cos(\phi) + D \sin(\phi) \qquad \dots\ (12)$$

Thrust, shaft torque and power is computed by integrating P_T and P_N over the length of blade. It is important to note that the loading over the radial length is considered to be linearly varying between the points of computation.

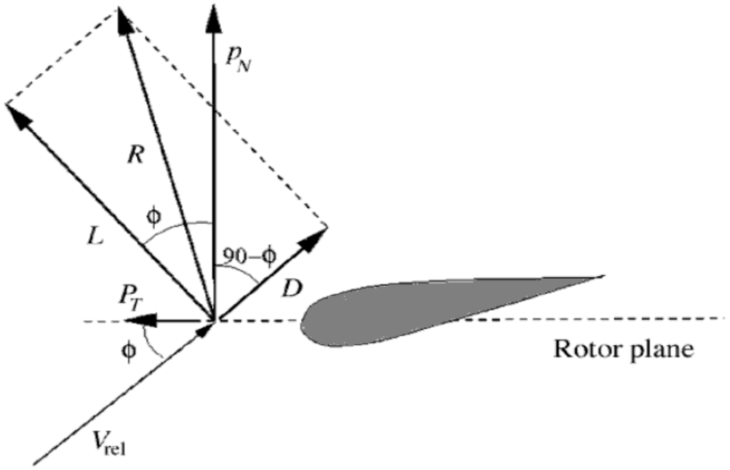

Figure (6) Local loads over airfoil [6].

In this paper, a MATLAB code based on an unsteady BEM method has been written to perform a time domain simulation for wind turbines. Unsteady BEM algorithm for computing wind loads at each time step, each blade station and for each blade can be summarized in ten steps as follows [6]:

1. Read geometry and operational parameters.
2. Initialize the position and velocity of blades.
3. Divide the blades into N elements.
4. Initialize the induced velocity for δ=1 to max. time step, for each blade and for each element 1 to N.
5. Compute the relative velocity to the blade element from eq. (1) using old values for the induced velocities.
6. Calculate the flow angle and thus the angle of attack from eqs. (2) and (3).
7. Read (interpolate) C_l and C_d from airfoil data table.
8. Calculate lift and drag forces from eqs. (9) and (10).
9. Compute the loads P_T and P_N using eqs. (11) and (12).
10. Compute new equilibrium values for the induced velocities using eqs. (4) and (5).

RESULTS AND DISCUSSION

In order to illustrate the influence of wind shear and tower shadow, an upwind 2MW Tjaerborg Wind Turbine [8] has been chosen to perform a time domain simulation. Some basic parameters and geometry of this turbine are listed in Table (1). A more detailed airfoil data of lift and drag coefficients as a function of the angle of attack is given in [8].In order to analyze the wind loads, a constant wind speed at hub V_h =10 m/s is assumed, wind profile exponent v is 0.2, and the diameter of the tower is assumed to be 4.5 m. The rotating speed of rotor is fairly constant speed of 20 rpm. Based on this information the rotor will make one complete revolution every 3 seconds, this means that a blade passes the tower every 1 second.

Table (1) Basic parameters and geometry of the 2MW Tjareborg turbine [8].

Rotor		**Blades**		**Tower**	
Number of blades	3	Blade length	29 m	Tower height	56 m
Rotor diameter	61.1 m	Root chord	3.3 m	Shape, upper half	conical
Hub height	61 m	Tip chord	0.9 m	Diameter at base	7.25 m
Rotor speed at rated power	22.36 rpm	Twist (linear)	0.333 deg./m	Diameter at h=28 m	4.75 m
Tilt	3 deg.	Blade profiles	NACA 4412 - 4443	Diameter at h=56 m	4.25 m

PERFORMANCE OF THE WIND TURBINE WITHOUT 3P EFFECT

The performance of the wind turbine without *3p* effect (tower shadow and wind shear model) is studied to determine the rated output power from the power curve for a set of wind speeds using steady BEM algorithm [6]. Figure (7) shows that the rated (steady) power is close to 0.8 MW when the wind turbine is subjected to rated wind speed V_h=10 m/s.

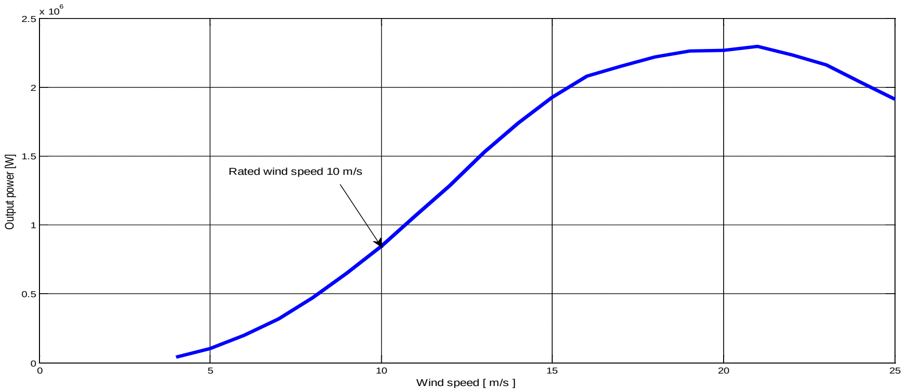

Figure (7) Power curve of a 2MW wind turbine model.

FACTORS AFFECTING THE WIND

Figure (8) shows the two wind speed components variation (in coordinate system1) due to the presence of tower and wind shear. The graphs show the wind speed seen by blade one, on a position situated 10 meters from the hub. The wind speed profile in the z-direction is symmetric and little increases in velocities are seen in the vicinity of the tower followed by drop at azimuth angle, θ=180°, where the blade is directly in front of the tower.

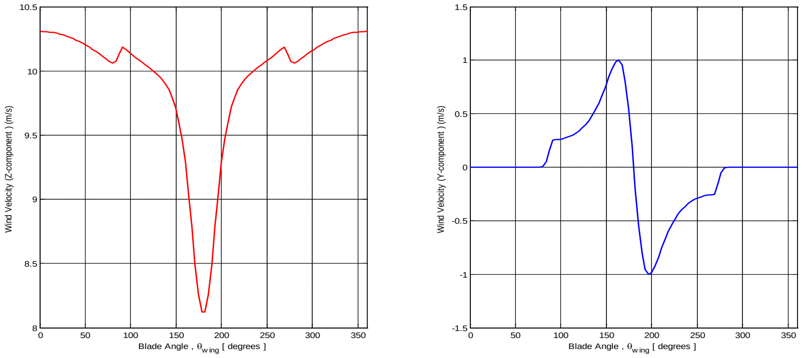

Figure (8) Effects of tower shadow and wind shear on wind speed at 10m from hub, showing the z and y components of wind speed for one revolution.

EFFECT OF WIND SHEAR AND TOWER SHADOW ON WIND LOAD AND OUTPUT POWER QUALITY

Due to the effects of both wind shear and tower shadow, each time the individual blade passes directly downwards, the wind load is minimum, while each time the individual blade passes directly upwards, the wind load is maximum. This will result in 3*p* torque and mechanical power fluctuations effect as shown in Figures (9). This effect may be important when it comes to the fatigue-life analysis and prediction for wind turbine blades. Figure (10) shows that during one revolution for the rotor, the mechanical power drop appears three times. Output power reaches minimum as any individual blade positioned directly downwards, while it is maximum as any individual blade positioned directly upwards. From this figure, it is concluded that the 3p fluctuations effect leads to the drop in the mechanical power can reach 10-12% of the rated (steady) power.

Figure (11) shows the time history of angle of attack, lift coefficient C_l and drag coefficient C_d of the individual blades at 50% of the radial length for each blade. The graphs show several dips. Each dip represents the instant that the individual blade passes the tower.

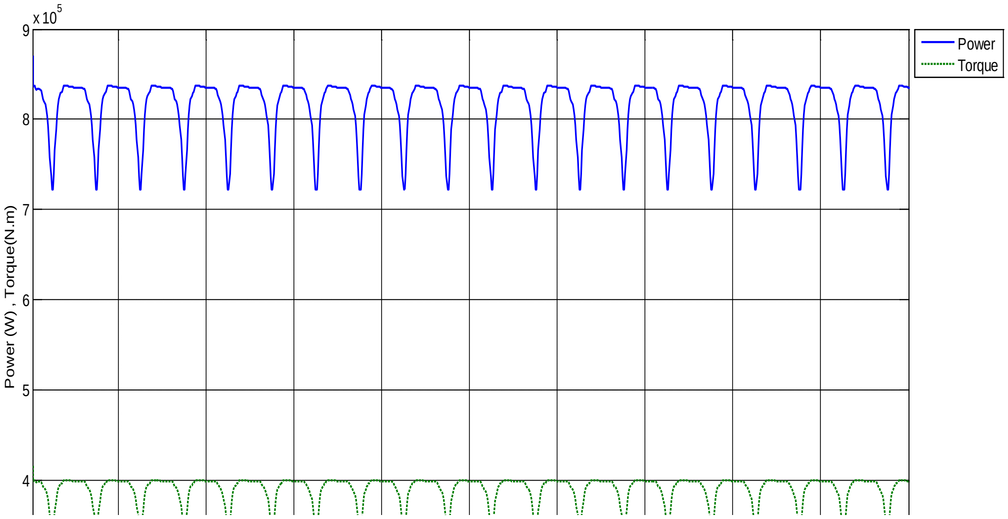

Figure (9) Effects of wind shear and tower shadow on torque and mechanical power.

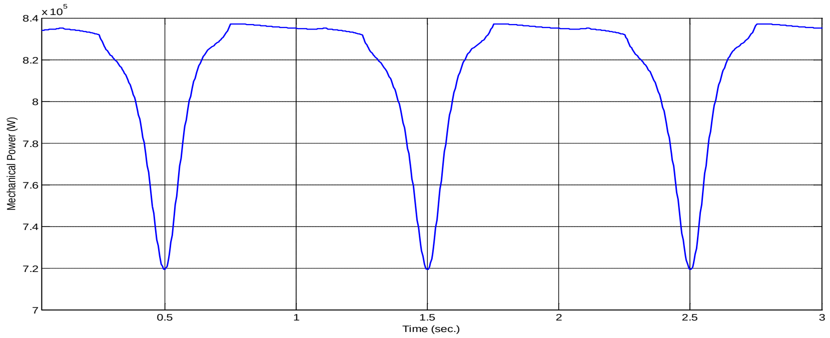

Figure (10) Effects of wind shear and tower shadow on mechanical power for one revolution.

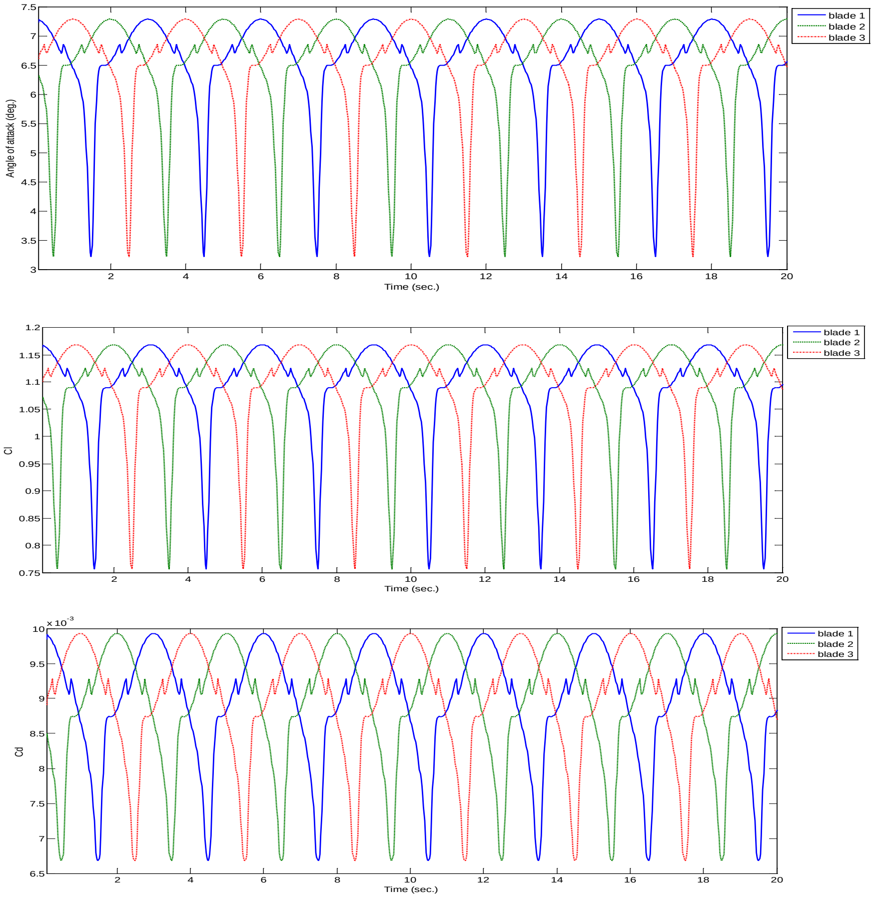

Figure (11) *3p* effect on angle of attack, lift coefficient, and drag coefficient for each blade at 50% of the radial length.

CONCLUSIONS

In this study, a time domain simulation has been performed by a MATLAB code for a three-bladed wind turbine using unsteady Blade Element Momentum (BEM) method. A mathematical model for tower shadow and wind shear has been used to show their effects on torque and output power. The simulation model proves the existence of tower shadow–wind shear induced *3p* fluctuations in torque and mechanical power. It can be concluded from the simulation results that improving the power quality and prolong the wind turbine life requires taking the effects of tower shadow and wind shear into consideration in wind turbine design.

NOMENCLATURE

a	radius of tower [m]
B	number of blades
C_l	lift coefficient
C_d	drag coefficient
c	length of chord
D	drag force [N]
F	Prandtl’s tip loss correction
f_g	Glauert correction
H	hub height [m]
L	lift force [m]
n	normal vector; number of blades
r	radial position [m]
$\vec{V_o}$	undisturbed wind velocity vector
$\vec{V}_{rot}$	rotational velocity vector
$\vec{V}_{rel}$	relative velocity vector
$\vec{W}$	induced velocity vector
X	distance from surface [m]
α	angle of attack [deg]
v	wind profile exponent
ρ	density of air [Kg/m^3]
ϕ	flow angle [deg]

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