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The Dynamic Behaviour of the Conventional Power Transmission Mechanism in Horizontal Axis Wind Turbines

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Keywords：wind energy, wind turbine, power transmission, dynamic analysis, theoretical model.

ABSTRACT

This study aims to theoretically investigate the dynamic behavior of the conventional power transmission mechanism in horizontal-axis wind turbines. For this purpose, a new theoretical model was developed by evaluating the non-dimensional design parameters described. With this model, different non-dimensional parameters called the generator torque (T_G) and the coefficient of effectiveness (K_t) were defined for the purpose of estimating the power transmitted to the generator.

INTRODUCTION

Wind power is one of the most advanced and suitable sources of renewable energy. It has many advantages, such as low cost, cleanliness, and abundance in everywhere in the world. It is also known as an environmentally-friendly energy source (Ilkilic, 2012).

Wind turbines are used to generate electrical energy from wind power. Kinetic energy in wind turbine blades is converted into mechanical energy via power transmission systems, then, electrical energy is obtained from generator. They are classified as either horizontal axis or vertical axis, according to the axis of rotation. The typical structure of a horizontal axis wind turbine mainly consists of blades, a tower, a nacelle, a low-speed shaft, a high-speed shaft, a gearbox, a generator, a clutch, an anemometer, a wind vane, a yaw mechanism, pitch system, and controller (Senel, 2012, Burton, 2001).

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In the horizontal axis wind turbines, various power transmission mechanisms have been developed in order to obtain torque and power. These are direct drive, integrated and conventional power transmission mechanisms. In a direct drive type, the torque and power are transmitted into the generator through a rotor. In an integrated type, a gearbox and rotor are both used. Finally, the most commonly used power transmission mechanism is a conventional power transmission mechanism. This mechanism is demonstrated in Fig. 1 (Cokunlu, 2007).

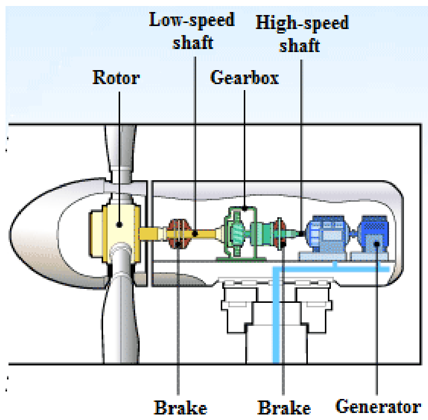


Fig. 1. Conventional power transmission mechanism in horizontal-axis wind turbines (Senel, 2012).

The blades on horizontal axis wind turbines are designed with selected aerodynamic geometry in order to take advantage of the wind. The most important function of the blades is to create a torque, and hence, a power transmitted with minimum loss. Special blade profiles have been developed, which are described as aerofoils. In aerofoils, the upper section has more curves than the lower ones. This means that different fluid velocity is generated on both curves, causing a pressure difference between the upper and bottom surfaces. Air movement creates a lifting force, moving it from high to low pressure. The most important parameters are the lifting force, drag force, and angle of attack in aerofoils. The force acting on the blades is the lifting force (F_L). This force is horizontal to the direction of wind speed (V). The other force acting on the blades is the drag force (F_D) which is vertical to the direction of the wind speed also. Finally, the angle between the reference axis and wind direction is the angle of attack (α) (Manwell et al., 2002; Hau, 2006; Hansen, 2008).

Several aerodynamic theories examine the wind effect on the forces, torque, and power exited on horizontal axis wind turbines. There are three main aerodynamic theories; namely, the one-dimensional momentum theory, the actuator disc momentum theory, and the blade element theory relating to wind turbine aerodynamics. The one-dimensional momentum theory examines the force on the disc in the air flow tube. It is assumed that the disc consists of an infinite number of blades. The maximum power coefficient is limited to 0.593 based on Betz' Law. It is the highest ratio of power that can be transmitted to the blades by the wind. The actuator disc momentum theory is very similar to the one-dimensional momentum theory. The most important difference is the interaction between the air and rotating disc. The actuator disc momentum theory assumes that the disc consists of an infinite number of blades. Additionally, the friction caused by the blade is neglected, but the vortex effect of the flow is considered. The blade element theory is widely used to determine the forces and torques acting on the aerofoil. The amount of torque acting on the blades can easily be determined via the amount of torque acting on the aerofoil being integrated along the blades. In this study, two different aerodynamic theories such as actuator disc momentum theory and blade element theory are examined in order to define the magnitude of torque affecting the blades (Manwell et al., 2002; Hau, 2006).

Many studies in the literature have concentrated on wind turbine design and the aerodynamic performance of the wind turbines. Bansal et al. (2002) examined some design aspects of wind energy conversion systems. These design aspects included factors that affected wind power, the placement of wind turbines, the network connections, the material selection of the wind turbines and generators, the design criteria of the wind turbines, the choice of generator, the gear box and two or three-bladed rotors, the weight and size criteria, and environmental factors. Maalawi et al. (2001) also discussed the aerodynamic performance of horizontal axis wind turbines using both the direct and Glaurent iteration methods. It was determined that the direct method provided an advantage regarding computational time. Ozgener (2006) analyzed the aerodynamic performance of the small wind turbine system application. The 1.5 kW small wind turbine system was designed to ensure a power supply for the need of Solar Energy Institute buildings and surroundings. The experimental results indicated that the system could be used for producing electricity in the Aegean region of Turkey. Vardar et al. (2008) examined the effects of the National Advisory Committee of Aeronautics (NACA) profiles on wind turbine aerodynamic performance. In this study, 180 various combinations of rotor blades were obtained and tested in a wind tunnel. According to their studies, the highest power coefficient has been evaluated using NACA 4415 profiles with 0° twisting angle, 18° blade angle and 4 blades. Morcos et al. (1994) investigated the wind energy potential of Egypt and the aerodynamic performance of horizontal axis wind turbines. In this research, three different blade profiles - flat, symmetrical, and circular plates were studied. It was concluded that the flat and symmetrical aerofoils were preferable for circular aerofoils. Bofares et al. (2014) investigated the design and performance of horizontal axis wind turbine by developing a model based on blade element momentum theory. Mohamad et al. (2015) discussed the effects of aerodynamic parameters (the type of aerofoils, tip speed ratio etc.) on power output in horizontal axis wind turbines. Pinto et. al. (2017) examined a revised theoretical analysis of aerodynamic optimization of horizontal-axis wind turbines, including drag effects, based on Blade-Element Momentum theory. It is shown that horizontal axis wind turbines can never reach Betz limit, even absence of drag effects.

In the present study,_a new theoretical model was designed based on the energy conversion for the basic dynamic behaviour of horizontal axis wind turbines. It was assessed by evaluating design parameters, and the geometrical and physical sizes of the blades in accordance with torque equations. With this model, non-dimensional parameters such as the generator torque, the coefficient of effectiveness were developed in order to estimate the amount of wind power transmitted to the generator.

POWER TRANSMISSION AND DESIGN PRINCIPLES OF WIND TURBINES

The torque and power transmission in a typical wind turbine is created by various wind turbine elements such as the blades, gearbox, bearings, couplings, and shafts. Bearings, flexible couplings, and planetary gear systems are widely used elements in horizontal axis wind turbines. There are many advantages using planetary gear systems for wind turbines. The small size of the planetary gear systems and the high gear ratio are the most important advantages of this system. Gear ratio in single-stage planetary gears is up to 1:12 while it is up to 1:5 in single-stage spur gears (Hau, 2006; Emniyetli, 2007).

Wind power (N) indicates the variation of wind energy per unit of time at wind speed (V). Parameters (wind speed (V), air density (ρ) and blade radius (R)) that affect wind power are shown in Fig. 2. This model includes three blades, a two-stage spur gearbox, bearings, and a generator. In this model, the high torque and low rotation velocity of the blades are converted into low torque and high rotation velocity of the generator via the gearbox. The other design parameters (i.e. ω, ω_G, i, z, T_R, T_G, V_{tip}) are given in the figure.

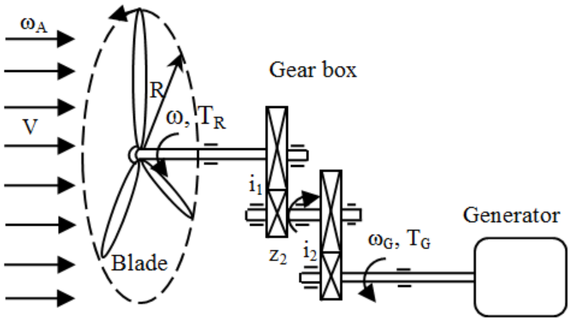


Fig. 2. Transmitted power/torque in horizontal axis wind turbines.

Considering the kinetic energy of air with the mass of m and the velocity of V, wind power (N) can be obtained in terms of the mass flow rate of air ($\dot{m}$), air density (ρ), wind speed (V), and the cross-sectional area of blades (A) as given below.

$$N = 0.5\dot{m}V^2 = 0.5(\rho AV)V^2 = 0.5\rho AV^3. \qquad (1)$$

In order to achieve an optimally-designed wind turbine, design parameters should be analyzed. Torque, taken from blades, (T_R) is determined by wind speed (V), the power coefficient (C_P), the tip-speed ratio (λ), blade angle (θ), and the angular speed of blades (ω).

The main design parameter in wind turbines is the tip-speed ratio which is expressed as the ratio of the blade tip-speed (V_{tip}) to wind speed (V) as given in Equation (2), and depends on parameters such as blade radius (R), angular speed (ω), and wind speed (V).

$$\lambda = V_{tip}/V = \omega R/V. \qquad (2)$$

This non-dimensional parameter takes the values between 6 and 20 for single-bladed horizontal axis wind turbines. However, it is between 5 and 9 for those with three-blades (Hau, 2006).

The other design parameter is power coefficient (C_P). This parameter is obtained to determine the wind power that is transmitted to the blades and is denoted as C_P being defined as the ratio of the power obtained from the wind (N_R) to the related wind power (N).

$$C_P = N_R/N = N_R/(0.5\rho\pi R^2V^3). \qquad (3)$$

This non-dimensional parameter depends on wind speed (V), density of the air (ρ), and blade radius (R). The maximum power coefficient does not exceed the Betz limit (C_{Pmax}=0.593). It is approximately 0.40-0.45 when losses are considered in horizontal axis wind turbines.

The other design parameters such as axial induction factor (a), angular induction factor (a'), torque coefficient (C_Q), and gear ratio (i) are given in Table 1.

Table 1. Design parameters defined for wind turbines (Hansen, 2008).

Parameter	**Expression**	**Explanation**
Axial induction	$a = (V - V_2)/V$	Based on one-dimensional linear momentum theory V: Wind speed far away from the blades V_2: Wind speed at the blades
Angular induction factor	$a' = \Omega/(2\omega)$	Based on momentum theory for rotating disc Ω: Angular velocity of wind ω: Angular velocity of blades
Torque coefficient	$C_Q = C_P/\lambda$	C_P: Power coefficient λ: Tip-speed ratio
Gear ratio	$i = \omega_G/\omega$ $i = \alpha_G/\alpha_R$	ω and ω_G: Angular velocity of low and high-speed shaft α_R and α_G: Angular acceleration of low and high-speed shaft

WIND TURBINE DYNAMIC ANALYSIS AND THEORETICAL MODEL

For this study, a new theoretical model was designed based on the energy conversion and basic dynamic behavior of three-bladed horizontal axis wind turbines and a typical transmission system with single-stage spur gears is given in Fig. 3. The main elements of this theoretical model are a low-speed shaft, gearbox (three-stage spur gear systems), high-speed shaft, and generator. The mass moment of the inertia of the low-speed shaft (I_1), high-speed shaft (I_4) and gears (I_2 and I_3) are assumed to be less than the mass moment of the inertia of the blades (I_R). Therefore, I_1, I_2, I_3 and I_4 are neglected in this model. This theoretical approach has been modeled by dividing the whole system into two sections - namely System 1 and System 2. Hence, the power and torque calculations can be performed as illustrated below in order to estimate the generator power of the wind turbines (Senel et al. 2013).

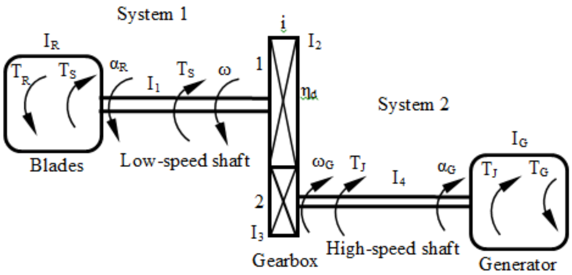


Fig. 3. Wind turbine theoretical model.

The theoretical model has been based on dividing the whole system into two sections namely System 1 and System 2. The main parameters for system 1 are the torque taken from blades (T_R), the torque at the entrance of the gearbox (T_S), the mass moment of inertia of blades (I_R), angular speed of blades (ω), gear efficiency (η_d), gear ratio (i), and angular acceleration of blades (α_R). With these parameters, the torque equivalence for system 1 can be expressed as follows:

$$T_R - T_S = I_R \alpha_R. \tag{4}$$

The torque equation for system 2 can also be written as:

$$T_J - T_G = I_G \alpha_G. \tag{5}$$

The main parameters for system 2 are sequentially torque on the exit of the gearbox (T_J), generator torque (T_G), mass moment of the inertia of the generator (I_G), angular speed of the high-speed shaft (ω_G), and angular acceleration of the high-speed shaft (α_G).

According to the model developed, there is a relationship between T_J and T_S as $T_J = T_S \eta_d / i$. Hence, generator torque (T_G) can be obtained by evaluating system 1 and system 2 together as

$$T_G = T_R \eta_d / i - I_{eq} \alpha_G, \tag{6}$$

where equivalent mass moment of inertia (I_{eq}) is defined as $Ieq = (I_R \eta_d / i^2) + I_G$. Gear efficiency can be expressed as $\eta_d = I_G i^2 / I_R$. The magnitude of the mass moment of the inertia of blades (I_R) can be written as $I_R = m_R R^2$. If the mass of one blade is m_R', the total mass of the blades will be $m_R = 3m_R'$. The distance from the blades' centre of gravity to the hub (R_{eq}) is nearly one-third of blade radius ($R/3$) (Morren et al., 2006). Hence, the mass moment of the inertia of blades (I_R) can be expressed as $I_R = m_R R^2 / 9$. Considering η_d and I_R expressions, and the simplifying the results, the equivalent mass moment of inertia can be re-defined as

$$I_{eq} = (2 m_R R^2 \eta_d)/(9 i^2). \tag{7}$$

Using non-dimensional parameters offers various design options within a wide range. Hence, the dimensional parameters (I_{eq}, T_R, N_G etc.) were converted into the non-dimensional forms.

Generator power (N_G) can be obtained by multiplying the generator torque (T_G) with the angular speed of the high-speed shaft (ω_G). Hence, the generator power (N_{G1}) based on blade element theory was defined as (Hansen, 2008),

$$N_{G1} = \frac{R^2 \eta_d \omega_G}{18 i} \left(9 \rho \pi R V^2 C_Q - \frac{4 m_R \alpha_G}{i} \right). \tag{8}$$

The non-dimensional torque taken from blades ($\bar{T}_{R1}$) based on the blade element theory has been obtained in this theoretical model as,

$$\bar{T}_{R1} = 0.5 \pi C_P / \lambda, \tag{9}$$

where the left hand side was defined as $\bar{T}_{R1} = T_{R1} / (\rho V^2 R^3)$.

Having defined the following non-dimensional parameters, the generator power (N_G) was obtained in the non-dimensional form as illustrated below.

$$\bar{R} = (\rho V^2 R)/(m_R \alpha_G), \tag{10}$$
$$\bar{I}_{eq} = I_{eq} / (m_R R^2), \tag{11}$$
$$\bar{\omega}_G = \omega_G R / V, \tag{12}$$

where $\bar{R}$ is the non-dimensional blade radius, $\bar{I}eq$ is the non-dimensional equivalent mass of inertia, and $\bar{\omega}_G$ is the non-dimensional angular velocity of the high-speed shaft.

Considering $\bar{I}_{eq}$, $\bar{\omega}_G$, $\bar{R}$, and $\bar{T}_{R1}$, the generator power given in Eq. (8) was non-dimensionalized as,

$$\bar{N}_{G1} = \left((C_P \pi \eta_d \bar{R})/(2 \lambda i) - \bar{I}_{eq} \right) \bar{\omega}_G, \tag{13}$$

here again the non-dimensional generator power can be expressed as $\bar{N}_{G1} = N_{G1} / (m_R R V \alpha_G)$.

The generator power based on the actuator disc momentum theory denoted as N_{G2} can be determined by multiplying T_{G2} and ω_G and hence (Hansen, 2008),

$$N_{G2} = \frac{R^2 \eta_d \omega_G}{i} \left(\mathrm{a}'(1-\mathrm{a}) \rho V \omega R^2 \pi - \frac{2 m_R \alpha_G}{9 i} \right). \tag{14}$$

Based on the same recommended theory, the non-dimensional torque taken from blades denoted as $\bar{T}_{R2}$ was developed as

$$\bar{T}_{R2} = a'(1-a) \lambda \pi, \tag{15}$$

where a is the axial induction factor, a' is angular induction factor, and the non-dimensional torque taken from the blades was again expressed as $\bar{T}_{R2} = T_{R2} / (\rho V^2 R^3)$. In a similar way, the generator power (N_{G2}) can be shown non-dimensionality by using $\bar{I}eq$, $\bar{\omega}_G$, $\bar{R}$, and $\bar{T}_{R2}$ as

$$\bar{N}_{G2} = \left(a'(1-a)\lambda\pi\eta_d\bar{R}/i - \bar{I}_{eq}\right)\bar{\omega}_G, \tag{16}$$

where the non-dimensional generator power was defined as $\bar{N}_{G2} = N_{G2}/(m_R R V \alpha_G)$.

The coefficient of effectiveness (K_t) can be found in order to determine the magnitude of the transmitted power to the generator by wind. In this section, different approaches have been attempted to define different coefficients of the effectiveness denoted as K_{t1} and K_{t2} by using the generator power expressions given above. Based on the blade element theory, the coefficient of effectiveness (K_{t1}) can be obtained with the definition of $K_{t1}=N_{G1}/N$ as follows

$$K_{t1} = \left(\frac{RC_P}{\lambda} - \frac{4m_R\alpha_G}{9\rho\pi V^2 i}\right) \times \left(\frac{\eta_d\omega_G}{Vi}\right), \tag{17}$$

where K_{t1} is a non-dimensional parameter which is determined depending on R, C_P, λ, m_R, α_G, ρ, V, i, ω_G, and η_d. With K_t expressions, both aerodynamic efficiency and mechanical efficiency together were evaluated in the horizontal axis wind turbines, whereas only the aerodynamic efficiency of the wind turbines can be determined with power coefficient (C_P). In this theoretical model, the coefficient of effectiveness (K_t) was expected to take the values lower than those of the C_P values.

Similarly, based on the actuator disc momentum theory, K_{t2} can be expressed as below with the definition of $K_{t2}=N_{G2}/N$.

$$K_{t2} = \left(2a'(1-a)\lambda R - \frac{4m_R\alpha_G}{9\rho\pi V^2 i}\right) \times \left(\frac{\eta_d\omega_G}{Vi}\right). \tag{18}$$

THEORETICAL RESULTS AND DISCUSSION

Within this theoretical approach outlined above, the dynamic behavior of conventional power transmission mechanisms in horizontal axis wind turbines has been examined, and the results obtained are discussed below.

Power taken from generator

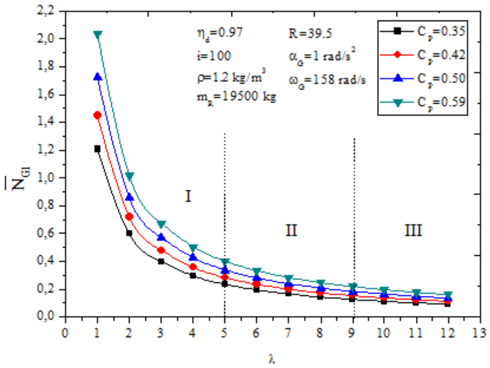
The non-dimensional generator power denoted as $\bar{N}_{G1}$ based on the blade element theory was obtained in terms of C_P, η_d, λ, i, $\bar{R}$, $\bar{I}_{eq}$, and $\bar{\omega}_G$. The variation of the non-dimensional generator power ($\bar{N}_{G1}$) with the tip-speed ratio (λ) for different power coefficient (C_P) values is illustrated in Fig. 4.

Although it may have different values in some applications, the gear ratio (i) was maintained at 100, the gear efficiency (η_d) was selected as 0.97, whereas λ varied from 1 to 12, and C_P changed from 0.35 to 0.59 (Fig. 4a). Due to the definition of the non-dimensional blade radius ($\bar{R}$), the non-dimensional equivalent mass moment of inertia ($\bar{I}_{eq}$) and the non-dimensional angular velocity of generator ($\bar{\omega}_G$),$\bar{R}$, $\bar{I}_{eq}$ and $\bar{\omega}_G$ were calculated as 0.55, 0.0000216 and 0.693, respectively by taking η_d=0.97, i=100, m_R=19500 kg, R=39.5 m, ω_G=158 rad/s, ρ=1.2 kg/m^3, V=15 m/s, and α_G=1 rad/s^2. By using these values as compatible with the results of the other researchers optimum parameters such as tip-speed ratio (λ), power coefficient (C_P), the axial induction factor (a), the angular induction factor (a'), and the corresponding non-dimensional power ($\bar{N}_{G1}$ and $\bar{N}_{G1}$) can be predicted in order to generate 2 MW nominal power of the wind turbine (Hau, 2006). It can be illustrated that increasing the tip-speed ratio (λ) decreases the non-dimensional power taken from generator ($\bar{N}_{G1}$) in all power coefficient (C_P) values. With the small λ values, approximately less than 5, there was a sharp drop in $\bar{N}_{G1}$ observed with the increase in λ, whereas with the high λ values, a slight drop was observed as λ is increased from 5 to 9.

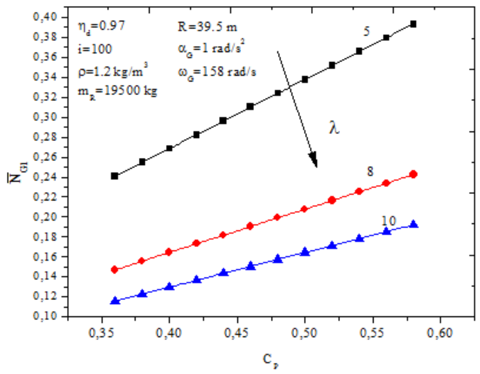
It can also be seen that there are three different modes of operation in power variation determining the design and operation limits of the system. These are marked as region I, II, and III in the figure. In the first mode (region I) relatively high non-dimensional generator power ($\bar{N}_{G1}$) was obtained. In the second mode (region II) slowly decreased power values to certain maximum points for λ were detected as shown within the dashed lines. This region may be considered as the transitional region. In region III, the model gives relatively minimum power values, and the curves tend to be almost constant; and increasing λ seems to cause a small decrease in power values for all fixed C_P values. Due to the definition, an increase in the angular speed of blades (ω) results in an increased λ when wind speed (V) is fixed, whereas with a certain blade radius (R), an increase in wind speed (V) means decreasing λ and hence, an increased $\bar{N}_{G1}$ (Region I). At the beginning of the wind turbine operation, a rapid decrease in $\bar{N}_{G1}$ was observed due to the instability of the wind turbine system at this stage. Therefore, the operation of wind turbines with λ values lower than 5 is not suggested, and the first mode is not eligible for wind turbine designers.

In region III, $\bar{N}_{G1}$ is between 0.10 and 0.20, and this region is not appropriate for designers because of the high angular speed of blades (λ>9) causing damage to the system. The speeds arising in this region should be controlled by the controller unit in the wind turbines.

In region II, it varies from 0.2 to 0.35, and this transitional mode may be selected as the advised design region. It appears that increasing power coefficient (C_P) results in increased $\bar{N}_{G1}$ for fixed λ. It may be concluded that the tip-speed ratio should be selected in region II, which coincides with the findings of other researchers (Hansen, 2008; Bansal et al., 2002).



(a)



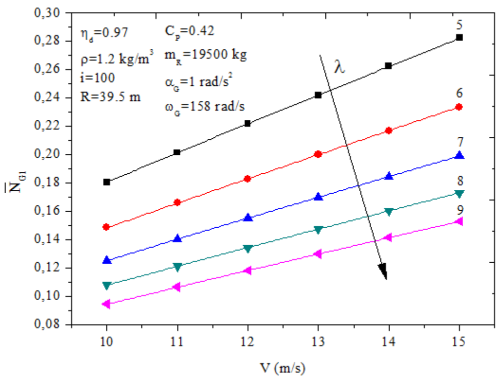
(b)

Fig. 4. The variation of non-dimensional power taken from generator ($\overline{N}_{G1}$) with λ and C_P.

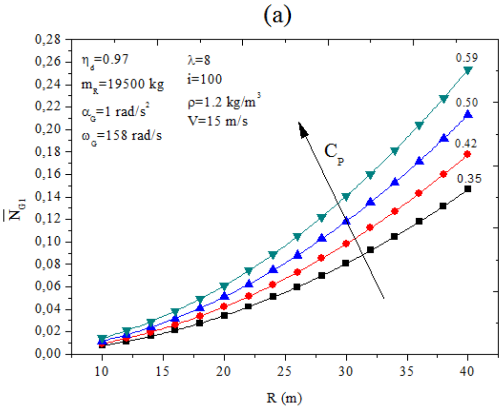
The magnitudes of dimensional generator powers such as N_{G1} and N_{G2} may be determined from the non-dimensional generator powers obtained from the model developed by using the referenced wind turbine parameters (m_R, R, i, η_d, V, α_G). For this reason, the magnitudes of the wind turbine geometrical and operating parameters were taken from the relevant manufacturer catalogues for comparison.

It can be noted from Fig. 4b that $\overline{N}_{G1}$, in general, increased as C_P increased for all λ values. Here, the rapid increase in $\overline{N}_{G1}$ with the increasing C_P is clear for λ=5 curve and the non-dimensional power varies between 0.11 and 0.40. As indicated in the figure, the other parameters ($\eta_{d,}$ i, ρ, and ω_G) are taken as constant. Selecting λ=8 and C_P=0.42, the corresponding $\overline{N}_{G1}$ is obtained as 0.173, when the referenced wind turbine parameters are taken as m_R=19500 kg, R=39.5 m, V=15 m/s, and α_G=1 rad/s^2 which in turn corresponded to the dimensional generator power of N_{G1}=1.99 MW. The nominal power of the referenced wind turbine in operation is found as 2 MW for the same R and m_R values. As a result, it can be seen that the generator power obtained from the model developed is very close or coincident to the referenced wind turbine power and hence, with this model, the generator power can confidently be predicted for different operating and geometrical parameters of turbine.

In application, tip-speed ratio generally varies from 5 to 9 and the nominal wind speed (V) commonly changes between 10 and 15 for the three-bladed horizontal axis wind turbines. The cut-in speed of the wind turbines is lower than 4 m/s and the cut-out speed is higher than 20 m/s, and hence, $\overline{N}_{G1}$ was investigated under the velocity values between 10 and 15 (Fig. 5). The non-dimensional generator power denoted as $\overline{N}_{G1}$, in general, appears to be improved with an increased wind speed (V) for fixed λ values**,** whereas $\overline{N}_{G1}$ decreases with increased λ when the specific parameters such as η_d, ρ, i, R, C_P, m_R, α_G, and ω_G are taken as constant (Fig. 5a). From the figure, $\overline{N}_{G1}$ the variation is more marked for λ=5 and 6. With these selected parameters (λ and V), N_{G1} may be determined as very close to the referenced wind turbine power (2 MW). The non-dimensional generator power ($\overline{N}_{G1}$), in general, rapidly increases with increased blade radius (R) between 10 m and 40 m for various C_P values and the increase in N_{G1} is clearer for the higher blade radius (Fig. 5b). In application, the blade radius (R) commonly varies from 35 m to 40 m for the wind turbines with 2 MW nominal power as given in the manufacturers' catalogues and C_P is changed from 0.35 and 0.59. The maximum value of C_P was taken as 0.59 because of the Betz limit recommended, and the minimum value of C_P was limited as compatible with the results of other researchers (Hansen, 2008).



(a)



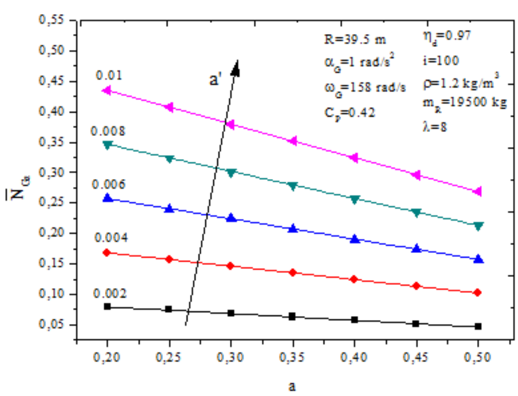
(b)

Fig. 5. The variation of non-dimensional power taken from generator ($\overline{N}_{G1}$) with V and R.

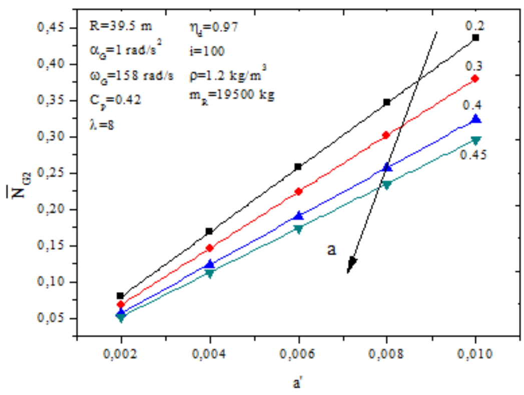
The effect of the induction factors on the non-dimensional generator power ($\overline{N}_{G2}$) can be seen in Fig.

6. In the analysis, the gear ratio (i) and tip-speed ratio (λ) were kept at 100 and 8, respectively, the axial induction factor (a) varied from 0.2 to 0.5, and the angular induction factor (a') changed from 0.002 to 0.01. The other parameters such as η_d, i, ρ, V, R, m_R, α_G, ω_G, λ, and C_P were selected as constant, which is compatible with the results of other researchers (Hansen, 2008; Bansal et al. 2002). With the fixed angular induction factor (a'), the increasing axial induction factor (a) decreases $\overline{N}_{G2}$ and this decrease effect is faster than the others for a'=0.01 and 0.008 curves (Fig. 6a). Due to the definition of the axial induction factor ($a=(V-V_2)/V$), increasing wind speed at the blades (V_2) decreases the axial induction factor (a) for the fixed wind speed far from the blades (V), resulting in an increased $\overline{N}_{G2}$. This means that increasing the wind speed at the blades (V_2) appears to increase the non-dimensional power ($\overline{N}_{G2}$) for constant V as expected.

In order to investigate the relationship between the non-dimensional generator power ($\overline{N}_{G2}$) and the angular induction factor (a') for different axial induction factors (a), Fig. 6b was obtained. For the fixed axial induction factor (a), any rise in the angular induction factor (a') results increased $\overline{N}_{G2}$. Similarly, owing to the definition of the angular induction factor ($a'=\Omega/(2\omega)$), an increase in angular speed of wind (Ω) increases a' for the constant angular speed of the blades (ω) and consequently, increases $\overline{N}_{G2}$. Selecting a=0.45 and a'= 0.006, the corresponding non-dimensional power $\overline{N}_{G2}$ is predicted as 0.174, which in turn corresponds to the dimensional generator power of N_{G2}=2.01 MW by taking m_R=19500 kg, R=39.5 m, V=15 m/s, and α_G=1 rad/s^2. Therefore, it is recommended to any corresponding designers that a and a' values should be taken as 0.45 and 0.006 for horizontal axis wind turbines with a 2 MW power capacity. Hence, with the model developed, the dimensional generator power of the wind turbines may easily be predicted under varying operating conditions.



(a)



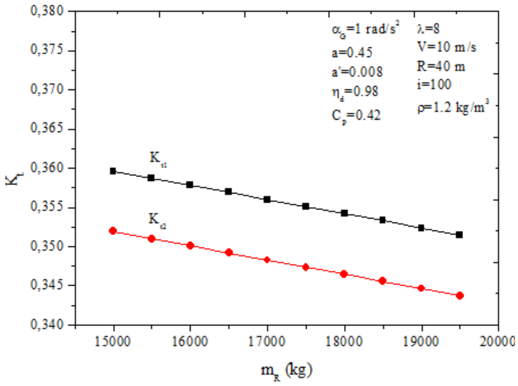
(b)

Fig. 6. The variation of non-dimensional power taken from generator ($\overline{N}_{G2}$) with a and a'.

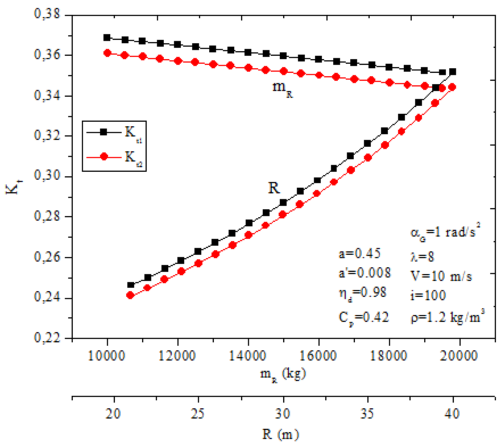
The Coefficient of Effectiveness

In the present investigation, the coefficient of the effectiveness (K_t) was developed in order to estimate the magnitude of the transmitted wind power to the generator. The coefficients, K_t based on the blade element theory and actuator disc momentum theory may be proposed depending on the geometrical and operating parameters such as R, m_R, λ, and C_P etc. Fig. 7 represents the variation of the both coefficient of effectiveness (K_{t1}, K_{t2}) with the mass of the blades (m_R) and blade radius (R). Both K_{t1} and K_{t2} are inversely proportional to m_R changing from 15000 kg to 19500 kg due to the increase of the mass moment of the inertia of blades (Fig. 7a). It was observed that K_{t1} values were slightly greater than K_{t2} values with the specific parameters given in the figure. With m_R=15000 kg, K_{t1} and K_{t2} were obtained as 0.360 and 0.352 being very close to each other, respectively. It is clear that the mass of the blades (m_R) should be selected to be as low as possible in order to obtain the higher relevant K_t values.

The variation of K_t with both R and m_R with constant parameters is illustrated more clearly in Fig. 7b. It can be seen that the coefficient of effectiveness (K_{t1}, K_{t2}) is directly proportional to blade radius (R) whereas, it is inversely proportional to m_R. R varied from 20 m to 40 m and m_R changed from 10000 kg to 20000 kg. It was detected that R and m_R curves intersected at the values of m_R=19500 kg and R=39.5 m giving optimum K_t values under these conditions. On the curve, taking R=39.5 m, the corresponding K_{t1} and K_{t2} were found to be 0.348 and 0.343, respectively when the other parameters were taken as constant. In applications, the blade radius (R) should be selected as high as possible in order to generate the maximum generator power.



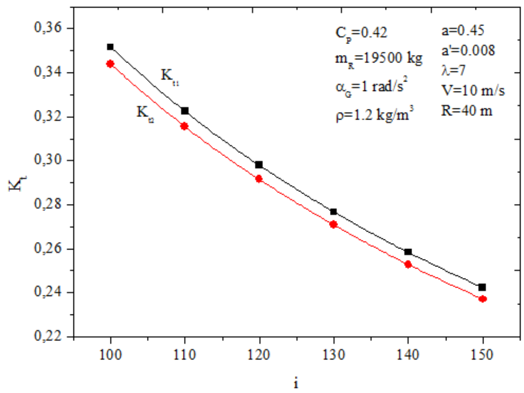
(a)



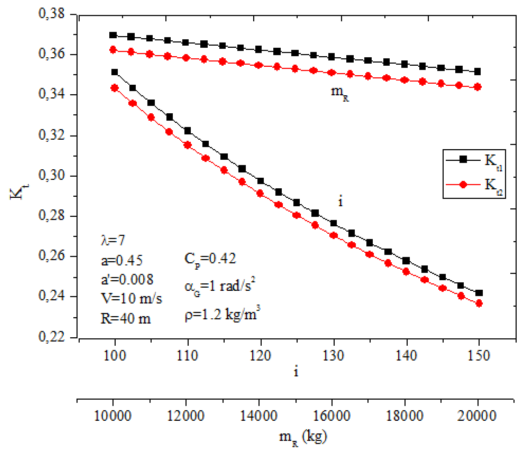
(b)

Fig. 7. The both coefficient of effectiveness (K_{t1} and K_{t2}) variations with m_R and R.

It can be noted from Fig. 8 that K_{t1} and K_{t2}, in general, decrease as gear ratio (i) is increased. In this figure, gear ratio was changed from 100 to 150 and the other specific parameters were indicated on the figure. The lower gear ratio (i) corresponded to the higher coefficient of effectiveness, for instance, for the minimum gear ratio (i=100), the corresponding K_{t1} and K_{t2} were found as 0.352 and 0.344, respectively (Fig. 8a). That is to say, 35% of wind power was approximately transmitted to the generator. The increase in the gear ratio (i) results in an increased number of gear stages meaning decreased gear efficiency, consequently, decreased K_t values are detected. In other words, decreasing K_t is attributed to the increasing number of gear stages. The effect of the gear ratio on the coefficient of effectiveness (K_t) is more marked than the effect of the mass of blades on K_t (Fig. 8b). It is apparent that the mass of blades and gear ratio should be selected as 19500 kg and 100, respectively for wind turbine with 2 MW nominal power. In this analysis, it is advised that gear ratio (i) should be preferred as 100 in order to generate 2 MW nominal power in horizontal axis wind turbines from the design point of view.



(a)



(b)

Fig. 8. The both coefficient of effectiveness (K_{t1} and K_{t2}) variations with i and m_R.

In this theoretical approach, the coefficient of effectiveness (K_t) obtained from the model given may be compared with the power coefficient (C_P) obtained from the results of the other research workers for the same specific parameters of λ, V, R, i, α_G, η_d, ω_G, m_R, and ρ. The values of C_P were varied between 0.40 and 0.44 for the same specific parameters in horizontal axis wind turbines (Hansen, 2008; Bansal et al. 2002). By taking m_R=19500 kg, R=39.5 m, i=100, and λ=8, the corresponding K_{t1} and K_{t2} were predicted as 0.38 and 0.37, respectively. In other words, 38% of wind power was nearly transmitted to the generator in horizontal axis wind turbines with 2 MW nominal power which is the most important conclusion arising from this theoretical study.

CONCLUSIONS

As a result of theoretical investigations on the conventional power transmission mechanisms in horizontal axis wind turbines, the important points determined are summarized as below:

(1) The dimensional parameters (I_{eq}, T_R, N_G etc.) were converted into the non-dimensional forms. Using

the non-dimensional parameters defined, it is always easy and useful to determine the dimensional parameters by taking into account the different geometrical and operating parameters. With this model developed, different non-dimensional parameters are the generator torque and the coefficient of effectiveness (Kt) were defined for the purpose of estimating the power transmitted to the generator.

(2) According to the results, it was clear that the higher the coefficient of effectiveness (K_t) values obtained the higher the generator power (N_G).

(3) From the theoretical analysis adopted, it was possible to estimate the blade radius, mass of blades (m_R), tip-speed ratio (λ), and gear ratio (i) for horizontal axis wind turbines. Consequently, the blade radius, mass of blades, tip-speed ratio, and gear ratio were predicted as R=40 m, m_R=19500 kg, λ=8, and i=100, respectively in order to generate 2 MW nominal power in wind turbine.

(4) In this model, it was recommended to the relevant designers that gear ratio (i) and the mass of the blades (m_R) should be selected as low as possible in order for a higher generator power to be attained.

(5) From the theoretical model proposed, it was possible to estimate the coefficient of effectiveness. K_t values could be found as 0.38 when the wind turbine parameters were taken as m_R=19500 kg, R=39.5 m, i=100, and η_d=0.98 in horizontal axis wind turbines with 2 MW power capacity. In other words, it was determined that 38% of wind power was transmitted to the generator. The power coefficient (C_P) varied from 0.40 to 0.44 taken from the results of other researchers. It was concluded that, due to the definition, C_P values were higher than K_t values defined in this model, as expected.

(6) Considering the remarks outlined in this paper regarding the dynamic behavior of the conventional power transmission mechanisms in horizontal axis wind turbines, this theoretical approach can be considered as a tool for designers. However, further experimental substantiation of the results predicted from the model should be carried out.

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BIOGRAPHICAL NOTES

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