Development of Wind Power System Simulation for the Use in Remote Areas of Developing Countries

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Wind Turbine  DC Motor  Tunnel Air  Water Pumping  Electricity Generation

ABSTRACT

In the present work, a study has been carried out to investigate performance characteristics of horizontal axis wind turbine. The wind turbine is tested using wind tunnel air at different velocities to determine power coefficients, torque coefficients and their variations with respect to tip speed ratios. Based on these test data, the wind turbine can be coupled with an electric motor whose performance is close to the wind turbine. Thus this development of the wind-power utilization systems can be removed the difficulties of the wind power utilization in the field of irrigation and electricity generation as well as for research activities at the indoor laboratory conditions. Various wind-powered models matched for water pumping or electricity generation can be developed without weather dependent outdoor experimentation.

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1. INTRODUCTION

Wind energy is now being considered as one of the cleanest renewable energies used throughout the world. Scope of utilization of wind powered equipment in Asia and Europe are various types such as lifting water from nearby river or sea for irrigation, salt farming, prawn farms and electricity generation for remote areas. In present world, energy crisis is a vital problem. There are many sources of energy, in them, wind energy is one of the cheapest source of energy. Wind energy can be converted into mechanical energy through wind turbine. Environmental pollution and public health hazard due to energy conversion may be avoided if we extract energy from wind. The success of wind energy as an alternative energy source is obviously a direct function of the economics of production of wind power machines. In this regard, the role of improved power output through the development of better aerodynamic performance offer some potential return. Various studies have indicated that wind energy has the potential to make significant contributions to the national needs. Therefore our nation is interested to new cheapest energy source and to justify their practicability.

The history of wind power utilization is very long. However its practical use has so far been almost neglected, mainly because of the instability of power supply for energy intensive modern society. Because of its small energy density and extreme fluctuation, wind cannot produce a constant power supply unless it has appropriate strength with proper controlling devices. The proverb saying that history repeats itself can be applied to the present worldwide energy situation as highlighted by the recent debate on the energy crisis. Recently wind power is being re-evaluated as a new potential source of power generation, irrigation and water supply.

Many different windmill designs have been constructed to extract power from the wind. The earliest known references to windmills related to a parsiann millwright in 644 A. D. and to windmills is seistan, Persia, in 915 A.D. [1]. These early windmills, which were used for moving water, consisted of several sails that rotate on a vertical axis. Later horizontal-axis windmills consisting of up to ten wooden booms, rigged with jib sails, were developed. Such primitive types of windmills are still found in use today in many Mediterranean regions. By the eleventh century A.D., windmills were in extensive use in the Middle East and were introduced to Europe in the thirteenth century by returning Crusaders. During that time in Europe, many horizontal axis windmills had been constructed for grinding grains and raising water.

In the fourteenth century, the Dutch had taken the lead in improving the design of windmills and they used them extensively for draining the marshes and lakes of Rhine river delta. The first oil mill was built in Holland in 1582 and in 1586 the first paper mill was constructed to the enormous demand for paper that resulted from the invention of the
introduced to process timber imported from the Baltic regions. By the Middle of the nineteenth century, some 9000 windmills were being used in the Netherlands for a wide variety of purposes. The Dutch introduced many improvements in the design of windmills and in particular, the rotors. With the introduction of the steam engine during the industrial revolution, the use of wind power in Holland started to decline and by the turn of the twentieth century, only about 2500 windmills were still in Netherland. By 1960, fewer than 1000 were still in working condition. Since the mid-nineteenth century, more than six-million small multi-bladed windmills, providing power outputs of less than 1 HP each in an average wind, had been built and used in the USA to pump water, generate electricity and perform similar functions. During the early part of the twentieth century, two quite different vertical designs were developed. One of the designs, known as the Savonius Rotor was form by cutting cylinder into two semi-cylindrical surfaces. The other vertical windmill design, patented in 1927 by George Darrieus consisted of two thin air foils with one end mounted on the lower end of a vertical shaft and the other end mounted on the upper end of the same shaft.

In Denmark, by the nineteenth century, there were about 2500 industrial windmills in operation, supplying a total of about 40,000 HP or 30 MW; i.e. about 25% of the total power available to Danish industry at that time [2]. In addition, approximately 4600 windmills were also being used on about 2% of the Danish for various applications, including threshing, milling of grains and water pumping. By the 1930’s the number of industrial windmills had declined about 1000 but the number of farm units had increased to about 1600. During World War I, the Danish developed and operated a number of various types of large scale wind machines for producing electricity. The number of these machines increased from 16 in the summer of 1940 to 88 by the beginning of 1944. After World War II, the number of operating machines started to decrease and at the end of 1947, the dropped to 57. The decrease continued in the 1950’s and by the end of that decade the production of electricity by wind machine was being conducted only on an experimental basis in Denmark. The 200 kW Gedser mill, which was the latest in this series, was operated until 1968. After the energy crunch of 1973, the 200 kW Gedser mill was refurbished, and in 1977 it was put back into service. In 1931, the Russians build an advanced 100 kW wind turbine near Yalta on the Black sea. The annual of this machine was found to be about 280,000 kWh per year.

For the design of horizontal axis wind turbines, it must be considered the structural efficiency and reliability together with minimal maintenance and weight in order to produce energy at a competitive cost. Major factors which dictate structural weight are the vibratory loads which act on the rotor and tower. For very large wind turbines vibratory stresses caused by dynamic loads will probably be the governing design consideration. An analysis was made by Putman [3] and his co-workers together with Von Karman on the 1250 kilowatt Smith- Putman wind power system, in an effort to minimize vibratory loads on the tower. Spera [4] analyzed the vibratory loads and stresses in the hingeless and teetered rotors for the NSF-NASA MOD-O wind power system. He concluded that the teetered rotor had substantial advantages over the hingeless rotor with respect to shank, stresses, fatigue life and power loading.

Glasgow [5] carried out tests on MOD-O wind turbines considering downwind and upwind wind directions. As a result of the tests, it was shown that while mean flatwise bending moments were unaffected by the placement of the rotor, cycle flatwise bending tended to increase with wind speed for the downwind rotor while remaining uniform with wind speed for the upwind rotor, reflecting the effecting the effects of increased flow disturbances for a downwind wind rotor. Linscott [6] has analyzed and measured the natural frequencies of MOD-O wind turbines. Good agreement between calculated and measured loads was obtained in analysis that included only two blades dynamic modes, first flap and first enplane and a blade quasi-steady mode. Miliborow [7] worked out in the field of rotor performance, blade loading, stresses and size limits of horizontal axis wind turbines. In order to indentify the variables which influence performance and blade loading, simplified methods of analysis had been developed and used to illustrate the process of rotor design. Spera and Janetzke [8] studied the effects of tower shadow on a downwind two-bladed horizontal axis wind turbine. A rotor aero-elastic simulation is used to predict the blade response to tower shadow and subsequently to estimate increased blade fatigue damage. He suggested reducing the effect of tower shadow by making the tower more aerodynamically smooth, thereby reducing the flow disturbance.

The present studies reported a procedure for the performance characteristics analysis of horizontal axis wind turbines. In the first part of the project, a wind turbine is tested by tunnel air. The wind turbine is tested at different air velocity to determine power coefficient, torque coefficient and their variations with tip speed ratio. Due to variation of wind velocity, the wind power fluctuates and this fluctuation of power can be removed by adding or subtracting power from external power source of electric motor whose performance is close to the wind turbine. By this simulated system, the wind power machine is developed to use in practical purposes. This development of the wind-power utilization systems can be removed the difficulties of the wind power utilization in the field of irrigation and electricity generation. In irrigation system wind-powered water pumps can be used where sufficient wind speed is available. Generation of electricity by wind turbine is also feasible in some rural area. The electric energy can be stored by storage device when a strong wind speed is available and the stored energy can be used for practical purpose when wind speed falls.
2. EXPERIMENTAL METHODOLOGY

The experiment on the wind turbine has been carried out with the help of air flow from the subsonic wind tunnel. The air velocity can be varying by ventilation which is placed inside the wind tunnel. The air velocities leaving from the wind tunnel are turbulent flow and these high velocities of air are considered as the natural air flow to rotate the wind turbine. There have many processes to measure the air velocity leaving from the wind tunnel. In the present experiment, the air velocities at the place of wind turbine are measured directly by anemometer. Different air velocities $V_1$, $V_2$ & $V_3$ are determined by these techniques. To determine the different characteristics of the wind turbine, a lever with brake is used to measure the shaft torque of the wind turbine and a tachometer is used to measure the revolution of the wind turbine shaft. The wind turbine is tested at different air velocities and at different rotational speeds of the turbine shaft to determine power coefficient ($C_p$), torque coefficient ($C_T$) and their characteristics curves with respect to tip speed ratios. From these tested data, the wind turbine can be coupled by an electric motor on suitable characteristics conditions.

To determine the characteristics curves of a DC electric motor (compound), a brake mechanism is used to measure torque and power at different input voltages. From these tested data, different Power-Speed curves at different input voltages are drawn. These characteristics curves are drawn in such a way that their power and speed limits are closed to the power and speed limits of the wind turbine. From such condition, the power from the electric motor can be transferred to the wind turbine shaft by suitable belt drive to remove fluctuating power of the turbine shaft.

In the present experiment, the following assumptions are underlying for the horizontal axis wind turbine:

i. The fluid is inviscid and incompressible.
ii. The flow velocity is constant at any point far ahead of the rotor blade.
iii. All blades are same size, shape and same angle of attack.
iv. Flow is entirely axial.
v. Thrust loading is uniform over the disc.
vii. The rotational speed of the rotor is uniform.

3. SIMULATION

A wind turbine shaft can extract power from the wind and the power extraction depends on the wind velocity and the applied torque on the turbine shaft. If the applied torque is zero then the turbine shaft obviously produces no power and at high rotational speeds the air is more or less blocked by the rotors and again no power is produced. In between these extremes, there is an optimal rotational speed where the power extraction is at a maximum. These are illustrated in Fig.1 and Fig.2.

It is often also interesting to know the Torque-Speed curve of a wind turbine shaft, when applying torque on the turbine shaft by a brake. The power $P$, the torque $T$ and the rotational speed, $\omega$ are related by a simple law:

$$ P = T\omega $$
It is observed that the maximum of the torque curve is reached at lower speeds than the maximum of the power curve. If the wind speed increases, power and torque increases, so far each wind speed a separate curve is to be drawn both for power and for torque.

The curves in Fig.3 and Fig.4 are established a relationship between shaft torque (T) and rotational speed (N) and it is observed that increasing the torque on turbine shaft decrease the shaft revolution for both three-bladed and six-bladed wind turbine. The parameters V, R, Cp, Cg and \( \lambda \) of the turbine make dimensionless expressions which are shown as below:

\[
\text{Power coefficient, } \quad \text{C}_p = \frac{P}{\frac{1}{2} \rho AV_n^3} \\
\text{Torque coefficient, } \quad \text{C}_t = \frac{T}{\frac{1}{2} \rho AV_n^2 R} \\
\text{Tip Speed ratio, } \quad \lambda = \frac{\omega R}{V_n}
\]

The immediate advantages are that the behavior of the turbine with different dimensions and at different wind speeds can be reduced to two curves: \( C_p - \lambda \) and \( C_t - \lambda \). One significant difference between six-bladed wind turbine and three-bladed wind turbine, as shown in Fig.5 and Fig.6, is that six-bladed turbine operates at low tip speed ratio and three-bladed turbine operates at high tip speed ratio. The advantages of increasing the number of blades are improved performance and lower torque variation due to wind shear. The maximum power coefficient is also affected by the number of blades because of the tip losses that occur at the tip of the blades. These losses depend on the number of blade and tip speed ratio. For the lower design tip speed ratio, generally a higher number of blades are chosen. This is done because the influence of number of blades on power coefficient is larger at lower tip speed ratios. For a high design tip speed ratio with a high number of blades will lead to very small and thin blades which results in manufacturing problems and a negative influence on the lift and drag properties of the blade.

From different characteristics curves, it is observed that the power of the wind turbine at any particular speed is depend on the wind velocity. Similarly the speed of the wind turbine at any particular power depends on the wind velocity. Again at any particular wind velocity, the power of the wind turbine varies with the change of turbine speed and at a particular turbine speed; the power of the wind turbine is maximum. Similarly at other wind velocity, the turbine speed at maximum turbine power changes to another value. So, in the \( P-N \) plot, as the increase of wind velocity, the turbine power move to maximum point with increasing the turbine shaft speed and after crossing the maximum power point, the shaft speed increases as decreasing the power. Again the relation between the turbine power and speed depends on the number of blades of the wind turbine. More the number of blades of the wind turbine, the shaft power will be high at low tip speed ratio. Further increasing the number of blades is increased the thrust on the blades due to higher solidity. The maximum power coefficient is also affected by the number of blades because of the higher thrust and tip losses that occur at the tip of the blades. For the lower design tip speed ratios, generally a higher number of blades are chosen. This is done because the influence of number of blades on power coefficient is larger at lower tip speed ratios. In the \( C_p - \lambda \) plot, the increase of number of blades shows that the region of higher power coefficient moves to the higher values of the tip speed ratio.

![Fig.4](image)

**Fig. 4.** The torque of six-bladed wind turbine as a function of rotational speed for different wind speeds.

![Fig.5](image)

**Fig. 5.** Power coefficient variations with respect to tip speed ratio for three-bladed and six-bladed wind turbine.

In the present experiment, a DC compound motor is tested at different input voltages and different applied torques exerted by a brake mechanism on the motor shaft. At a particular input voltage, the speed and the armature current of the motor vary with various applied torque on the motor shaft. By changing the input voltage, a set of \( P-N \) curves are obtained. The relation between power and speed of the motor are shown in Fig.7. The DC motor is tested in such power and speed ranges so that the characteristics curves of the motor can be compared to the characteristics curves of the wind turbine. From these characteristics comparison, the simulation system between the wind turbine and the DC motor are found.
1.0 watts due to increase in r and the speed of the wind turbine increase at constant torque as the wind velocity decreases. Similarly the power and the speed of the wind turbine fall as the wind velocity decreases. Similarly the power and the speed of the wind turbine increase at constant torque as the wind velocity increases. From Fig.1 if the constant torque on the wind turbine shaft is considered as $T=118.71 \text{ N-mm}$ then the power obtain from different wind velocities are given in Table 1.

Table 1. Power deviation for three-bladed wind turbine

<table>
<thead>
<tr>
<th>No of Observatio n</th>
<th>Wind velocity (m/s)</th>
<th>Constant torque, $T$ (N-mm)</th>
<th>Rotationa l Speed, $N$ (rpm)</th>
<th>Power, $P$ (watt)</th>
<th>Power deviation, $ΔP$ (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
<td>118.7</td>
<td>280</td>
<td>3.48</td>
<td>$-0.57$</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
<td>118.7</td>
<td>326</td>
<td>4.05</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>4.4</td>
<td>118.7</td>
<td>365</td>
<td>4.50</td>
<td>$+0.45$</td>
</tr>
</tbody>
</table>

Considering the speed, $N = 326 \text{ rpm}$ as the operating speed of the wind turbine for the constant applied torque, $T = 118.71 \text{ N-mm}$. From data Table-1, it is seen that when the wind velocity decreases from 4.2 m/s to 4.0 m/s, then the speed of the turbine decreases from 326 rpm to 280 rpm due to power fall from 4.05 watts to 3.48 watts. Similarly it is seen that when the wind velocity increases from 4.2 m/s to 4.4 m/s, then the speed of the turbine increases from 326 rpm to 365 rpm due to power rise from 4.05 watts to 4.5 watts. It is observed in Fig.8 that the reduction of power of the wind turbine, $ΔP = -0.57$ watts due to decrease of the wind velocity and it is possible to supply this amount of reduced power by the selected DC motor to restore the turbine operating speed. It is also observed in Fig.8 that the excess power of the wind turbine, $ΔP = +0.45$ watts due to increase of the wind velocity and it is possible to use this amount of excess power for other purposes through the selected DC motor to restore the three-bladed wind turbine operating speed.

From the $P-N$ characteristics curves as shown in Fig.2 for six-bladed wind turbine, it is shown that at the wind velocity, $V = 4.0 \text{ m/s}$, the maximum power, $P_{\text{max}} = 3.42 \text{ watts}$ is obtained with the turbine speed, $N = 200 \text{ rpm}$ when the exerted torque on the shaft is $T = 161.1 \text{ N-mm}$. If the applied torque, $T = 161.1 \text{ N-mm}$ on the shaft is constant, then the power and the speed of the wind turbine fall as the wind velocity decreases. Similarly the power and the speed of the wind turbine increase at constant torque as the wind velocity increases. From Fig.2, if the constant torque on the wind turbine shaft is considered as $T = 161.1 \text{ N-mm}$ then the power obtains from different wind velocities are given in Table 2.

Table 2. Power deviation for six-bladed wind turbine

<table>
<thead>
<tr>
<th>No of Observatio n</th>
<th>Wind velocity (m/s)</th>
<th>Constant torque, $T$ (N-mm)</th>
<th>Rotationa l Speed, $N$ (rpm)</th>
<th>Power, $P$ (watt)</th>
<th>Power deviation, $ΔP$ (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
<td>161.1</td>
<td>200</td>
<td>3.43</td>
<td>$-0.62$</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
<td>161.1</td>
<td>237</td>
<td>4.05</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>4.4</td>
<td>161.1</td>
<td>266</td>
<td>4.49</td>
<td>$+0.44$</td>
</tr>
</tbody>
</table>

Considering the speed, $N = 237 \text{ rpm}$ as the operating speed of the six-bladed wind turbine for the constant applied torque, $T = 161.1 \text{ N-mm}$. From data Table-2, it is seen that when the wind velocity decreases from 4.2 m/s to 4.0 m/s, then the speed of the turbine decreases from 237 rpm to 200 rpm due to power fall from 4.05 watts to 3.43 watts. Similarly it is seen that when the wind velocity increases from 4.2 m/s to 4.4 m/s, then the speed of the turbine increases from 237 rpm to 266 rpm due to power rise from 4.05 watts to 4.49 watts. It is observed in Fig.9 that the reduction of power of the wind turbine, $ΔP = -0.62$ watts due to decrease of the wind velocity and it is possible to supply this amount of reduced power by the selected DC motor to restore the turbine operating speed. It is also observed in Fig.9 that the excess power of the wind turbine, $ΔP = +0.44$ watts due to increase of the wind velocity and it is possible to use this amount of...
excess power for other purposes through the selected DC motor to restore the operating speed of the six-bladed wind turbine.

In the present simulation system, the addition of power from the motor shaft to the wind turbine shaft due to decrease of wind velocity can be measured experimentally by applying additional torque on the motor shaft. Similarly in this system, the reduction of power from the motor shaft due to increase of the wind velocity can be measured experimentally by subtracting the torque from the motor shaft. The system as developed by the DC motor is simulated as nearly as possible the characteristics found from the experimental results as mentioned earlier. Since the electric motor has different performance as shown in Fig. 7 and it is loaded by a brake to achieve a power variation curve whose image is similar to the power variation curve of the wind turbine due to variation of the wind velocity.

4. CONCLUSIONS

In the present work, a simulation system has been developed to use wind energy properly. The horizontal axis wind turbine extracts power from the wind because it slows down the wind-not too much not too little. At standstill, the turbine obviously produces no power and at very high rotational speeds, the air is more or less blocked by the turbine and again no power is produced. Our laboratory specimen, on the basis of the present experiment, the three-bladed wind turbine and six-bladed wind turbine were operated in between these two extremes so as to include the optimum values. The advantages of increasing the number of blade are improved performance and lower torque variation due to wind shear. It is also found that the tip losses and hub losses are influenced the performance of the turbine and these losses depend on the tip speed ratio. For the lower design tip speed ratios, generally a high number of blades are chosen. This is done because the influence of number of blades on power coefficient is larger at lower tip speed ratios. For a high design tip speed ratio with a high number of blades will lead a very small and thin blades which results in manufacturing problems and a negative influence on the lift and drag properties of the blades. From the result of our laboratory experiment, increase of number of blades increases the cost of blade manufacturing. Also increase of number of blade increase the solidity of the wind turbine. More the solidity of the wind turbine, the starting speed of the turbine will be less.

In the present simulation system, a DC motor has been selected to supply extra-power to the turbine shaft for avoiding power fluctuation at the turbine shaft. Because of the turbine power variation is the image of the motor power variation, so any power fall of the wind turbine due to decrease of the wind velocity can easily be compensated from the DC motor power or any power rise of the wind turbine due to increase of the wind velocity can easily be used through motor for further utilization. By this way, the simulation system of the wind power can be used for research activities at the indoor laboratory condition avoiding weather depended outdoor experimentation. For this purpose, an electric circuit can be developed to receive feedback signal from the wind turbine shaft and after getting such signal, the electric circuit can able to keep constant turbine torque by addition or subtraction of the motor power to the turbine shaft.

REFERENCES