Development of Power Simulation Model for Wind Energy Conversion Systems

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Abstract: The development of wind turbine simulation model is characterized in order to avoid expensive experiments with sophisticated instruments installed in windy outdoor locations. Two models of horizontal axis wind turbines were tested in the laboratory to develop their performance curves. Based on these test results, an electric motor was made to simulate similar performance pattern of the wind turbine. Preliminary test results have indicated that the simulated system worked well at different wind speeds. This was then verified by the experimental data taken from a model wind-driven water pumping system with a positive displacement pump.

Keywords: *WECS, Simulation model, HAWT, WPS, Overall performance.*

INTRODUCTION

As a result of worldwide energy crisis, research and development activities in the field of wind energy conversion systems (WECS) are gaining momentum for the last few years in many developing countries. These systems commonly employ electricity generators or water pumps coupled to wind turbines. Naturally, the engineering of such system involves a multitude of structural, aerodynamic, mechanical and electrical problems associated with individual system components. In fact, the complexity of input/output characteristics of typical wind turbines and the load suggests that the system engineering dependents on so many factors that it is not possible to provide a general solution. However, proper functioning of such systems mostly relies on how well the performance of the wind turbine is matched with the other counterpart equipment. Unfortunately in most cases this is ignored and the system installed with very high first cost ended in failure.

To overcome the problem of very expensive experiments with wind turbines and sophisticated instruments installed in windy outdoor locations, an electric motor was made to simulate wind turbine power. The main objective of this research is to replace the wind turbine portion of the WECS by this simulated system. At first, laboratory test results obtained by model wind turbines were used to determine power coefficient, torque coefficient and their variation with respect to tip speed ratio. Wind velocity was controlled by the butterfly valves of the wind tunnel and specially designed brakes controlled the rotational speed of the wind turbine. Based on these test data, the wind turbine was replaced by an electric motor whose performance was made to simulate the wind turbine power.
The kinetic energy of the moving air mass is converted to mechanical energy by a wind

turbine. This mechanical energy available from the rotation of the wind turbine rotor can be used directly by a mechanical device or can be used to produce electrical energy by coupling it to an electricity generator. Excluding the complicated details WECSs can be classified into 3 main groups as follows:

a. A wind turbine operating the load directly by mechanical transmission.
b. A wind turbine operating the load by electrical transmission.
c. A wind turbine operating the load by pneumatic transmission.

Mechanical transmission is by direct mechanical means such as crank, gear, chain or belt. Electrical transmission is by an electric generator and a motor. Pneumatic transmission is by a compressor and adequate pipelines. Obviously, the overall efficiency of the combined system depends on (among many other related factors) the performance characteristics of the individual machine and the appropriate matching between them. The simulated wind turbine model would replace the wind turbine part of all of the above categories.

BRIEF THEORY AND THE METHODOLOGY

At a particular wind speed V, the power extracted by the rotor of a wind turbine, W_T is a function of its rotational speed N. Also the power of a rotating machine is the product of its angular velocity Ω ($\Omega=2\pi N$) and its torque T. Therefore, the torque developed by the wind turbine can be represented as a function of its rotational speed [1]. Thus for each different wind speed, the power-speed characteristics, W_T - N and torque-speed characteristics, T - N can be drawn as shown in Figure 1. The power coefficient C_p, can be defined as the ratio of power extracted by the wind turbine, W_T to the total power available in the cross-sectional area A of the wind stream suspended by it. Also defining torque coefficient C_T and tip speed ratio λ, as follows, the following non-dimensional expressions can be made:

$$C_p = W_T / \frac{1}{2}\rho A V^3 \qquad (1)$$

$$C_T = T / \frac{1}{2}\rho A V^2 R \qquad (2)$$

$$\lambda = R\Omega / V \qquad (3)$$

where, ρ = density of air, V = wind velocity, R = rotor radius. The developed simulated systems should correspond to C_p - λ (power coefficient versus tip speed ratio) and C_T - λ (torque coefficient versus tip speed ratio) performance curves.

WIND TURBINE SELECTION

When a system is to be selected for a WECS for a specific purpose, the wind turbine counterpart has to be chosen from among the too many different kinds available. A wind turbine could either a lift or a drag device and its performance vary a lot, generally represented by characteristic curves in a C_p - λ plot. In fact, this non-dimensional presentation of C_p - λ curves permits the properties of geometrically similar wind turbines

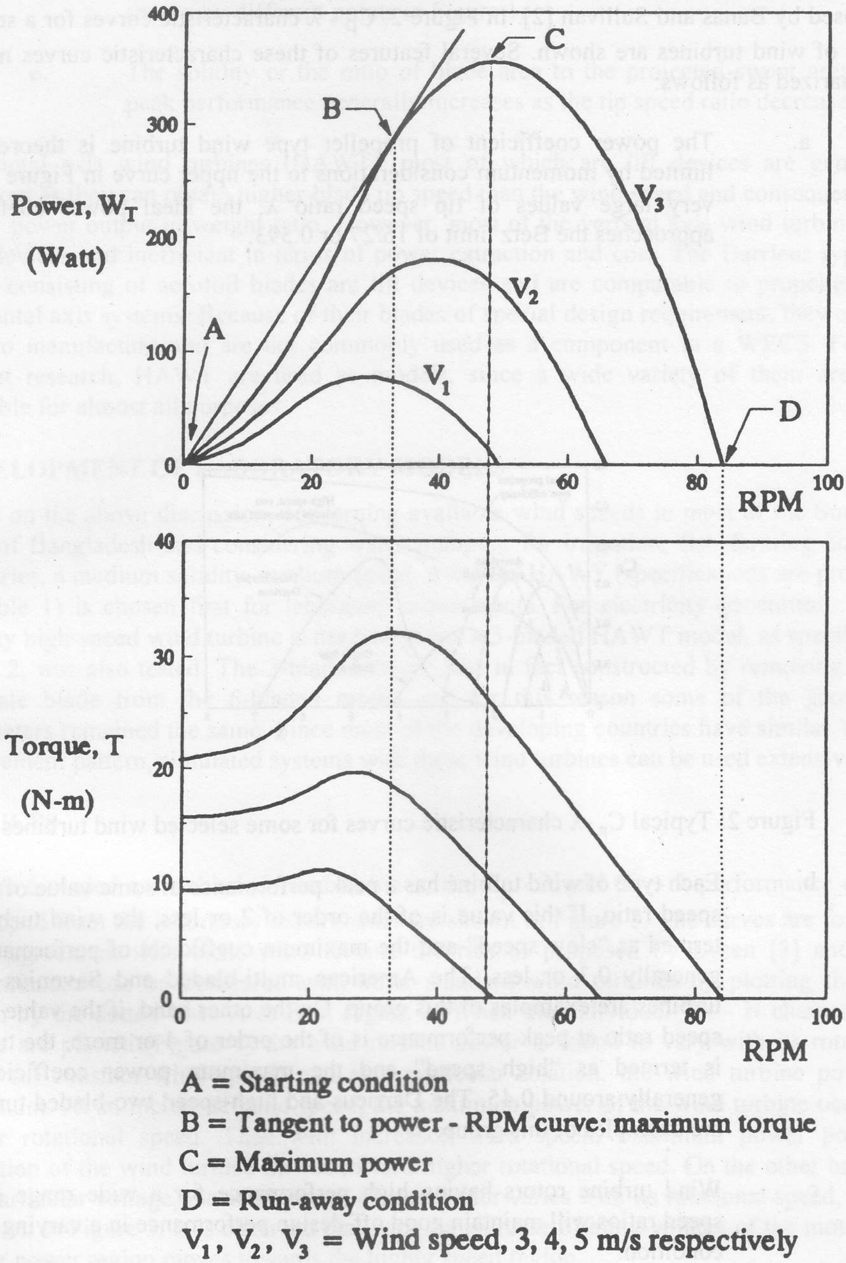

Figure 1: Typical W_T–N and T-N characteristic curves for a wind turbine as a function of wind speed

of the same family to be plotted as a single line assuming no Reynolds Number effect as proposed by Banas and Sullivan [2]. In Figure 2, C_p - λ characteristic curves for a selected range of wind turbines are shown. Several features of these characteristic curves may be summarized as follows:

a. The power coefficient of propeller type wind turbine is theoretically limited by momentum considerations to the upper curve in Figure 2. For very large values of tip speed ratio λ, the ideal power coefficient approaches the Betz limit of 16/27 or 0.593.

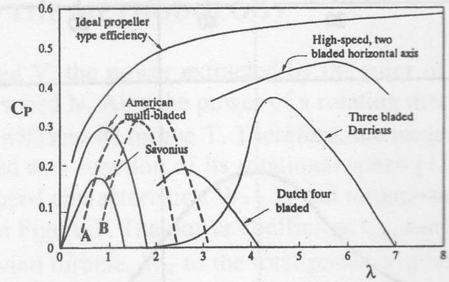

Figure 2: Typical C_p -λ characteristic curves for some selected wind turbines

b. Each type of wind turbine has a peak performance at some value of its tip speed ratio. If this value is of the order of 2 or less, the wind turbine is termed as "slow speed" and the maximum coefficient of performance is generally 0.3 or less. The American multi-bladed and Savonius wind turbines are examples of this group. On the other hand, if the value of tip speed ratio at peak performance is of the order of 4 or more, the turbine is termed as "high speed" and the maximum power coefficient is generally around 0.45. The Darrieus and high-speed two-bladed turbines are examples of this group.

c. Wind turbine rotors having high performance for a wide range of tip speed ratios will maintain good off-design performance in a varying wind condition.

d. Since the starting torque of a wind turbine is proportional to the slope of the performance curve at λ = 0, the comparative starting torque of various wind turbines can be predicted by comparing the slopes at zero tip speed ratio. The lower the slope, the lower the starting torque. This is shown by different points in Figure 1.

e. The solidity or the ratio of blade area to the projected swept area with peak performance generally increases as the tip speed ratio decreases.

Horizontal axis wind turbines (HAWT), most of which are lift devices are generally preferred as they can obtain higher blade tip speed than the wind speed and consequently, a higher power output to weight ratio. However, most of the vertical axis wind turbines are drag devices and inefficient in terms of power extraction and cost. The Darrieus types of rotors consisting of aerofoil blades are lift devices and are comparable to propeller type horizontal axis systems. Because of their blades of special design requirement, they are not easy to manufacture and are not commonly used as a component in a WECS. For the present research, HAWT are used as models, since a wide variety of them are now available for almost all purposes.

DEVELOPMENT OF LABORATORY MODELS

Based on the above discussion, concerning available wind speeds in most of the Southern zone of Bangladesh and considering water pumping for irrigation, fish farming and salt industries, a medium solidity, medium speed, 6-bladed HAWT (specifications are provided in Table 1) is chosen first for laboratory experiments. For electricity generation, a low solidity high-speed wind turbine is necessary. So, a 3-bladed HAWT model, as specified in Table 2, was also tested. The 3-bladed model was in fact constructed by removing every alternate blade from the 6-bladed model and for this reason some of the geometric parameters remained the same. Since most of the developing countries have similar WECS requirement pattern, simulated systems with these wind turbines can be used extensively.

RESULTS

For the 6-bladed and 3-bladed wind turbines, the C_P - λ and C_T - λ performance curves developed from the laboratory experiments are shown in Figure 3. The curves are found to be in agreement with basic wind turbine theories as proposed by Lysen [3] and their performances can be compared with other standard wind turbines by plotting them as shown by the dotted lines A & B in Figure 2. When the individual W_T - N characteristic curves are plotted (Figure 4) the wind turbine power is found to vary with its rotational speed (at constant wind speed) and at a particular rotation, the wind turbine power is maximum. At an increased wind speed, the maximum power of the wind turbine occurs at higher rotational speed. Thus with increased wind speed, maximum power point of operation of the wind turbine moves toward higher rotational speed. On the other hand, at any particular voltage, the shaft power of a dc motor varies with its rotational speed, which is shown in Figure 5. It is observed that with the increase of input voltage of the motor, the higher power region moves towards the higher speed region.

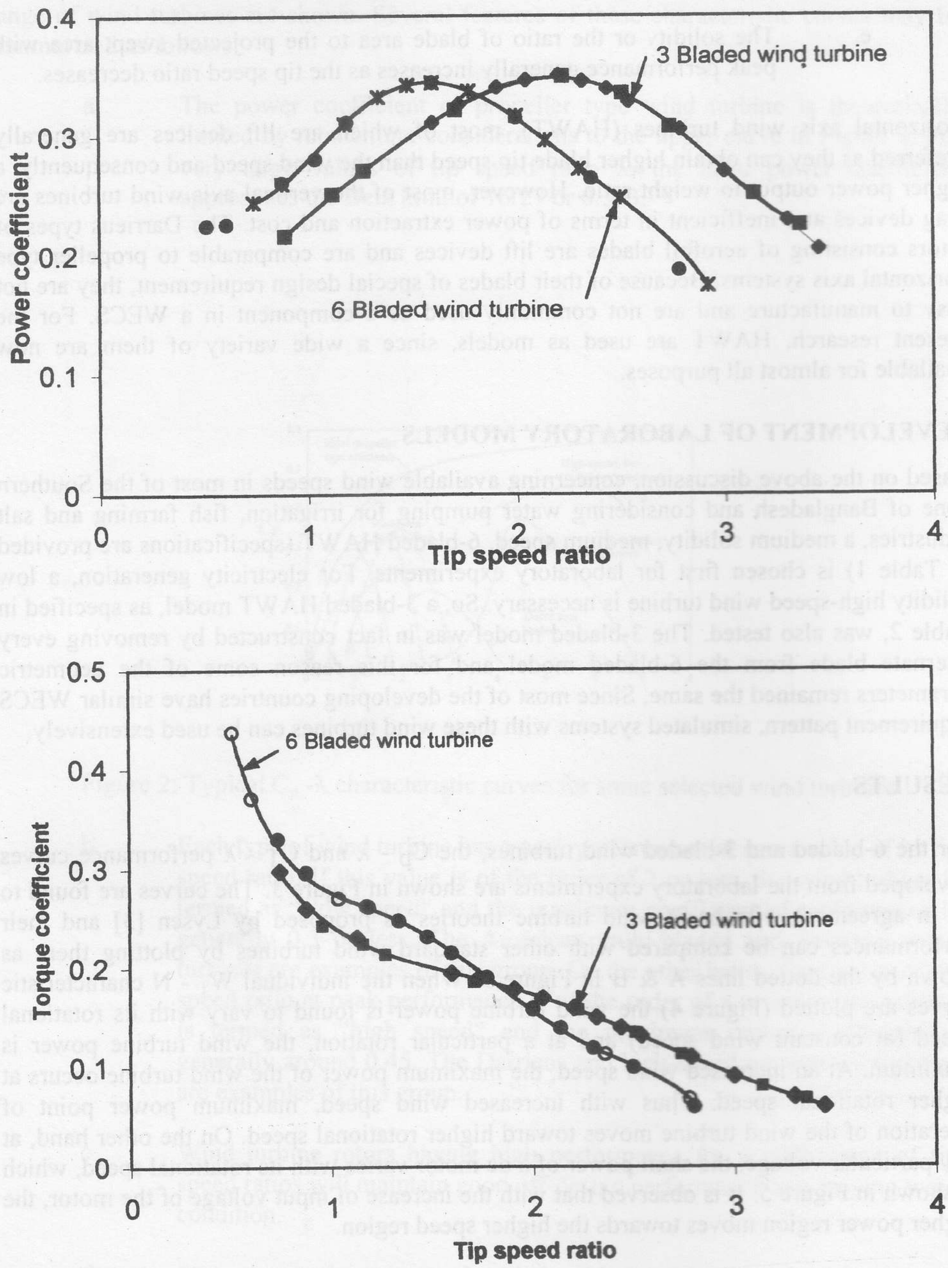

Figure 3: C_p -λ and C_T -λ characteristics of 3 and 6 bladed wind turbine models

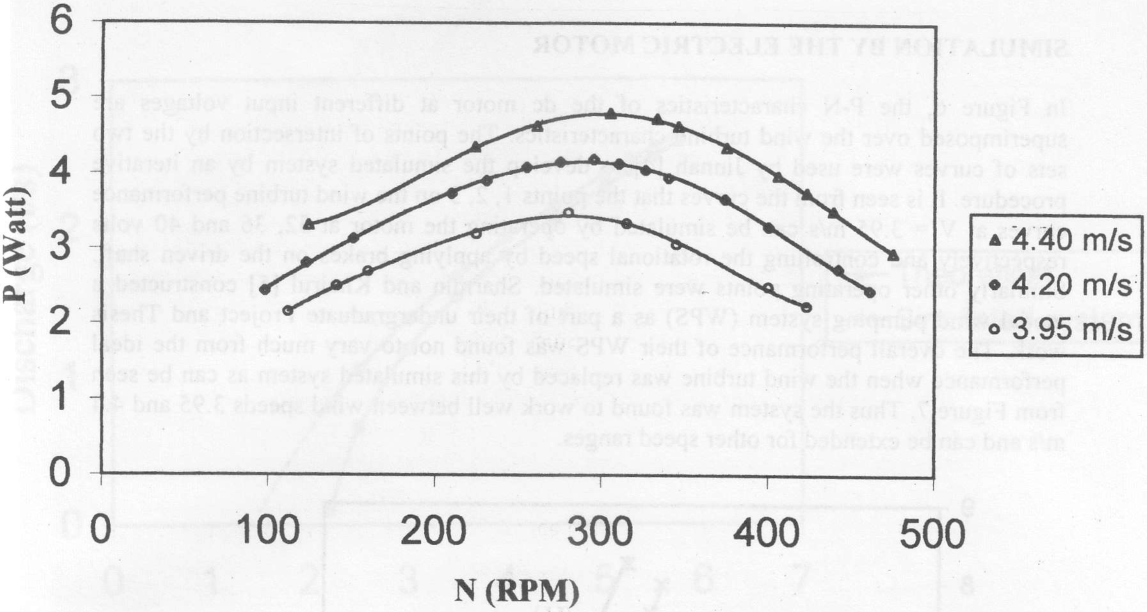

Figure 4: P-N characteristic curves for different wind speeds for a 3 bladed wind turbine

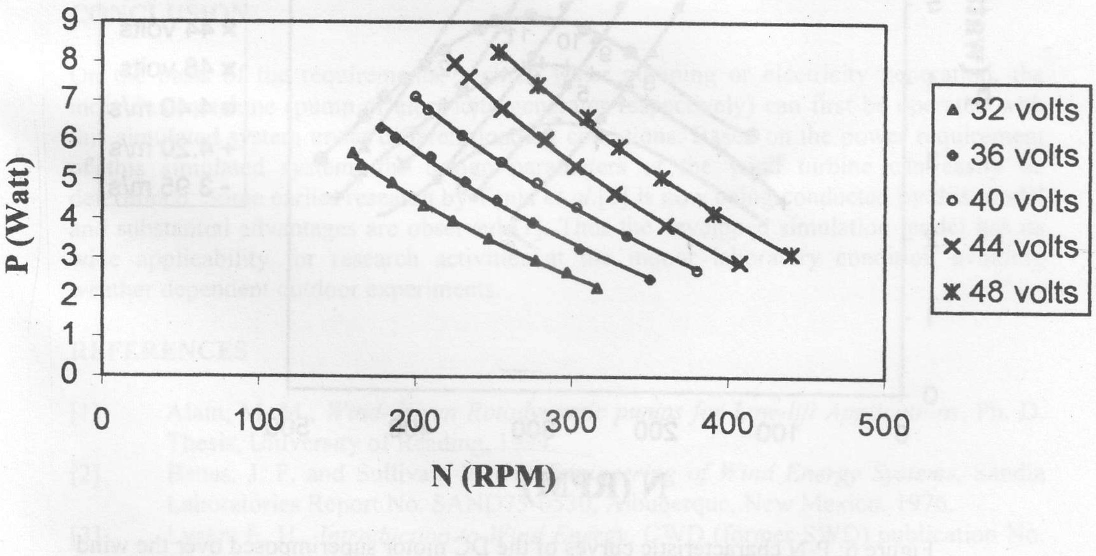

Figure 5: P-N characteristic curves for different voltages for the DC electric motor

SIMULATION BY THE ELECTRIC MOTOR

In Figure 6, the P-N characteristics of the dc motor at different input voltages are superimposed over the wind turbine characteristics. The points of intersection by the two sets of curves were used by Jinnah [4] to develop the simulated system by an iterative procedure. It is seen from the curves that the points 1, 2, 3 on the wind turbine performance curves at V = 3.95 m/s can be simulated by operating the motor at 32, 36 and 40 volts respectively and controlling the rotational speed by applying brakes on the driven shaft. Similarly other operating points were simulated. Sharmin and Khairul [5] constructed a model wind pumping system (WPS) as a part of their undergraduate Project and Thesis work. The overall performance of their WPS was found not to vary much from the ideal performance when the wind turbine was replaced by this simulated system as can be seen from Figure 7. Thus the system was found to work well between wind speeds 3.95 and 4.4 m/s and can be extended for other speed ranges.

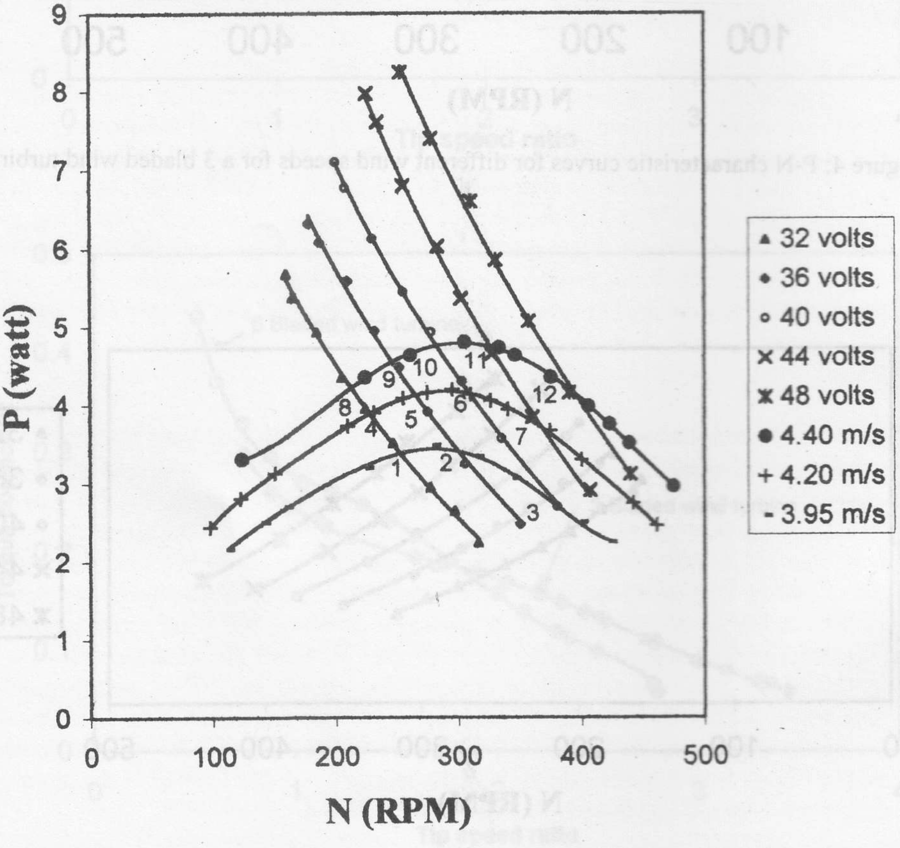

Figure 6: P-N characteristic curves of the DC motor superimposed over the wind turbine characteristic curve to develop the simulated system

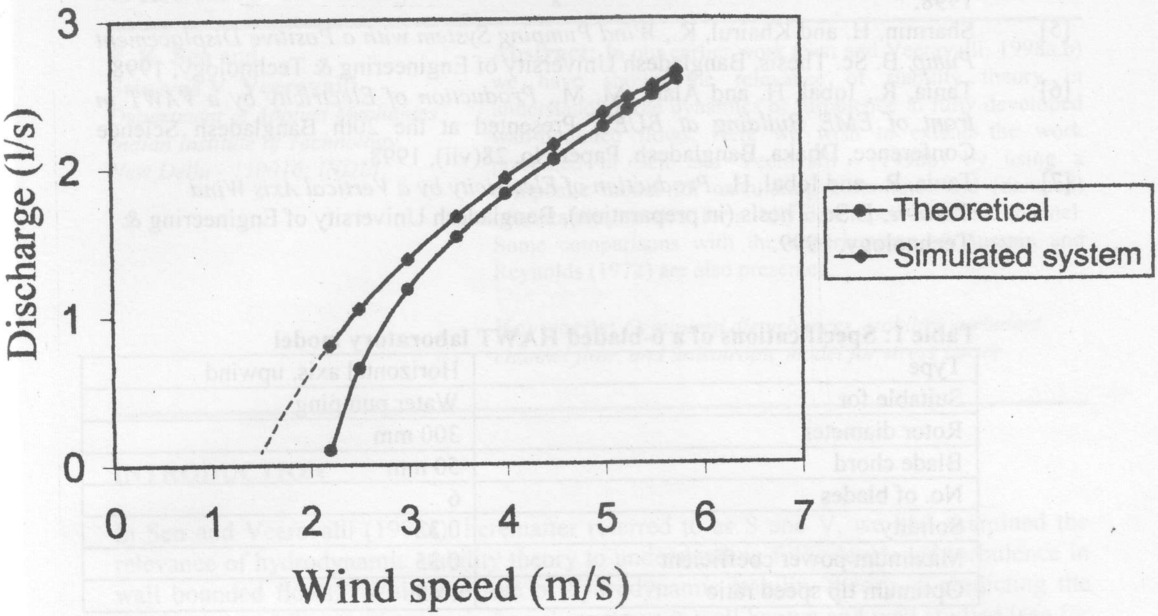

Figure 7: Overall Q-V performance curve for a WPS using the simulated system

CONCLUSION

On the basis of the requirements, such as water pumping or electricity generation, the individual machine (pump or electricity generator respectively) can first be operated with this simulated system under different loading conditions. Based on the power requirement of this simulated system, the design parameters of the wind turbine can easily be determined. Some earlier research by Tania *et al.*[6] is now being conducted by this model and substantial advantages are observed [7]. Thus the developed simulation model has its wide applicability for research activities at the indoor laboratory condition avoiding weather dependent outdoor experiments.

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Table 1: Specifications of a 6-bladed HAWT laboratory model

Type	Horizontal axis, upwind
Suitable for	Water pumping
Rotor diameter	300 mm
Blade chord	50 mm
No. of blades	6
Solidity	0.32
Maximum power coefficient	0.35
Optimum tip speed ratio	1.42

Table 2: Specifications of a 3-bladed HAWT laboratory model

Type	Horizontal axis, upwind
Suitable for	Electricity generation
Rotor diameter	300 mm
Blade chord	50 mm
No. of blades	3
Solidity	0.16
Maximum power coefficient	0.34
Optimum tip speed ratio	1.92