A Proposal of Implementation of Ducted Wind Turbine Integrated with Solar System for Reliable Power Generation in Bangladesh

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Received: 09.05.2012 Accepted:19.06.2012

Abstract-Exploiting the wind energy at low wind velocities is a major predicament in creating a sustainable energy resource for a country with inauspicious forthcoming energy crisis. Thus researching new and innovative systems to improve the efficiency of the wind turbines is an indispensable prerequisite. The scope of this paper concentrates on an approach to harness wind power by installing a conical shaped duct in front of the conventional turbine which is coupled with a generator. A solar panel has also been installed with the purpose of acquiring additional power supply. The reason for which a conical shaped duct is preferred is to get added wind velocity at the turbine inlet. The electrical power, obtained from the generator and solar panel are fed to the national grid. With the integration of solar panel and wind turbine more electrical power could be gained. A CFD simulation, utilizing ANSYS-CFX software, was eventually carried out to investigate the velocity profile at the inlet and outlet of the duct. The results obtained from the simulation could be employed to devise the conical shaped duct at the turbine inlet coupled with generator and solar photovoltaic cells.

Keywords-Wind energy, Solar energy, CFD.

1. Introduction

It is well known that the main drawback of wind power is the inherent variable behaviour. Significant research has been carried out to improve the performance of the wind turbines and establish the power system stability. Novel and significant designs of the wind turbines were developed during last few years. From the scientific literature survey it was found that a wind turbine system was developed which consists of a diffuser shroud with a broad-ring flange at the exit periphery and a wind turbine inside it for obtaining a higher power output [1]. Also for the optimization of the wind turbine energy as well as power factor an evolutionary computation algorithm was established. This evolutionary strategy algorithm solves the data-derived optimization model and also determines optimal control settings for the wind turbine [2]. To obtain a reliable and steady output of power, wind turbines are generally integrated with conventional solar panel or biomass energy or hydro power systems. From the previous research works hybrid photovoltaic wind energy system was analyzed to provide better electricity output to the grid [3]. From the literature survey it was also found that the Hybrid Solar-Wind System Optimization Sizing (HSWSO) model was developed to optimize the capacity sizes of different components of hybrid solar-wind power generation systems that employ a battery bank. A case study was reported in that paper to show the importance of the HSWSO model for sizing the capacities of wind turbines, PV panel and battery banks of a hybrid solar-wind renewable energy system [4]. Wind power was also complemented by hydropower to obtain firm power output. For getting constant power output in a hybrid power station without the intermittent fluctuations inherent when using wind power a conceptual framework was provided [5]. Wind power could be also integrated with bio energy.

An innovative system combining a biomass gasification power plant, a gas storage system and stand-by generators to stabilize a generic 40 MW wind park was proposed and evaluated with real data [6]. In this current study, a design is proposed to enhance the wind power. A conical shaped duct in front of the wind turbine could be installed in order to obtain additional wind velocity at the turbine inlet. Additionally a solar panel could also be incorporated with the purpose of obtaining more electrical power. The power obtained both from wind turbine and solar panel is stored in a battery which can be fed to the national grid. This design mainly encompasses the scenario where the wind speed fluctuates in a significant manner. For example, the prospect for wind energy in Bangladesh is not at satisfactory level due to low average wind velocities at different regions of the country. However, there are some places in Bangladesh like coastal areas where wind speed is relatively higher for harnessing power but is not constant for all the time during power extraction. In this paper, an approach is shown with clear description to enhance the wind power and simulation of the velocity profile through a conical shaped duct is also provided. Finally a comparative feasibility analysis of the modified system with the conventional wind turbine is given with elaborate mathematical explanations.

The following table gives information about the monthly variation of wind speed in some places of Bangladesh. It is clear that the wind speed is not constant for power extraction at promising level during a certain year, rather, it fluctuates in a significant manner. It shows that during few months for certain regions in the country power extraction from the wind turbine is not at all possible. Bangladesh Centre for Advanced Studies (BCAS) with the assistance from Overseas Development Administration (ODA) of UK launched the Wind Energy Study (WEST) Project in October 1995. They collected and analyzed wind speed data at seven areas of Bangladesh. The locations are widely dispersed along the vast coastline in the district of Cox's Bazar, Chittagong, Noakhali, Bhola and Patuakhali. The average wind speed of those locations is shown in Table 1 below.

Table 1. Average Wind Speed (m/s) at 20 Meters Height at Different Locations in Bangladesh [7].

Location	MONTHS												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN
Barisal	2.90	2.57	2.57	3.59	3.23	2.96	2.71	2.64	2.57	2.11	2.07	2.05	2.66
Bogra	1.95	2.20	3.05	4.03	4.15	3.66	3.42	3.05	2.56	2.20	1.83	1.71	2.82
Chittagong	3.64	2.88	4.95	5.01	5.51	6.89	7.09	6.83	4.64	2.82	3.39	3.20	4.65
Comilla	2.26	2.70	2.57	5.45	3.83	3.20	2.88	2.95	1.82	2.38	1.63	2.95	2.78
Cox'sbazar	3.76	3.83	4.91	5.58	6.33	4.14	3.83	3.95	3.20	3.26	2.57	2.44	3.81
Dhaka	3.39	3.26	4.39	5.77	2.93	5.71	6.01	5.89	4.39	3.45	2.64	2.57	4.52
Dinajpur	2.68	2.44	4.88	2.44	4.82	2.68	2.56	2.44	2.14	3.54	2.44	3.20	2.83
Hatya	3.04	2.64	4.16	3.97	8.34	6.47	5.75	2.64	2.96	2.77	3.09	2.57	3.74
Jessore	2.88	2.95	4.95	8.34	5.83	6.27	6.15	4.95	4.33	3.45	3.32	2.38	4.93
Khepupara	4.20	4.39	3.83	7.09	4.16	4.71	4.14	3.95	3.57	3.70	2.95	1.29	4.24
Khulna	2.96	1.65	3.04	3.05	2.77	3.89	3.31	2.44	2.51	1.98	3.31	1.01	2.89
Kutubdia	1.77	1.85	2.32	2.70	2.92	3.65	3.61	3.14	2.11	1.45	1.19	1.59	3.32
Mongla	1.07	1.25	1.72	2.51	2.11	2.63	2.48	2.35	1.83	1.27	1.02	1.70	2.20
Rangamati	1.35	1.65	4.42	3.10	2.44	3.23	1.72	2.24	1.45	1.45	1.39	1.83	2.15
Sondip	2.43	3.02	3.20	4.83	2.44	3.83	3.32	2.70	2.32	1.63	1.70	1.76	2.76
Sylhet	2.20	2.93	3.29	3.17	3.32	2.68	2.44	2.07	1.71	1.94	1.89	1.65	2.38
Teknaf	3.70	4.22	4.39	4.01	8.47	3.89	3.83	2.88	2.44	5.22	1.57	5.91	3.17
Patenga	6.22	6.22	7.37	7.92	6.11	8.69	9.20	8.54	7.48	6.93	6.71	2.86	7.48
Shatkhira	4.21	4.40	3.84	7.10	3.87	4.76	4.27	4.03	3.62	3.78	3.54	2.81	4.37
Thakurgaon	4.15	5.60	7.93	8.43	8.66	8.05	7.93	6.59	6.34	5.98	5.25	4.76	6.59

In Fig 1, wind speed data of 25m height at various locations in Bangladesh are shown and in Fig 2, Diurnal Variation of Wind Speed in Some Places of Bangladesh is also shown.

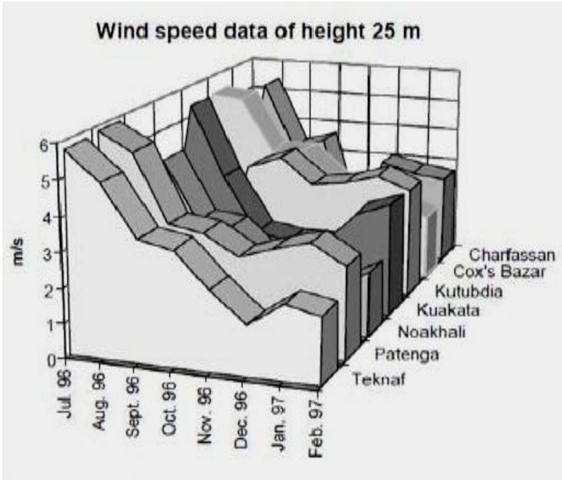

Fig 1. Wind speed data of 25m height at various locations in Bangladesh [8].

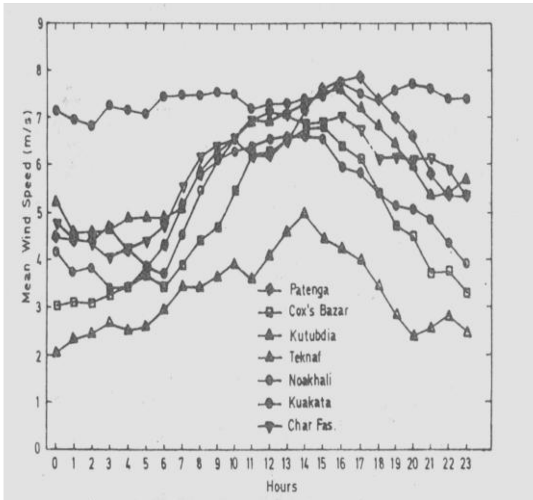

Fig. 2. Diurnal Variation of Wind Speed in Some Places of Bangladesh [9].

A promising technology that may play a part in the development of this new paradigm is the ducted wind turbine (DWT) [10]. Up to this point, wind energy has not played a major role in embedded generation for the built environment. However, the development of these small micro turbines that can be integrated into the building fabric opens up the possibility of exploiting the differential pressures that occur due to airflow around buildings for the purpose of local power production [11]. The ducted wind turbine (DWT) [12] is an emerging micro-grid technology; this is a small, wind energy conversion device that can be integrated into the facade of a building [13] and may be a useful means of producing power in areas with windier climates. The ducted wind turbine overcomes many of the problems associated with the use of conventional wind turbines in an urban environment, which are hampered by high levels of turbulence in the air stream, and are also constrained by concerns over visual impact, noise and public safety.

Researches on ducted wind turbines were carried out by Sheila Widnall [14] on Potential Flow calculations of axisymmetric ducted wind turbines. An incompressible potential-flow vortex method has been constructed to analyze the flow field of a ducted wind turbine following that outlined by Lewis [15]. Attention is paid to balancing the momentum change in the flow to the total longitudinal forces acting on the duct-turbine combination. Werle and Presz [16] were the first to point out that the increased power from a ducted wind turbine as compared to the Betz model implied a force acting on the duct in the flow direction.

2. Basic Theory of Wind Turbine

W. J. M. Rankine and W. E. Froude established the simple momentum theory for application in the ship's propeller. Later, A. Betz of the Institute of Gotingen used their concept to the windmill [9].

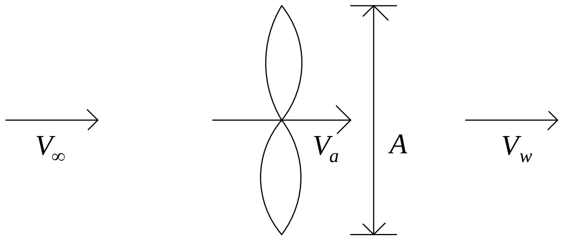

Fig 3. Flow velocities through a windmill [9].

Table 2. List of Symbols used

Symbol	Meaning	Unit
m	Mass flow rate of air	(Kg/s)
V_w	Wake velocity	(m/s)
V_∞	Free stream velocity	(m/s)
V_a	Induced velocity	(m/s)
P_{max}	Power	(Watt)
A	Swept area of rotor	(m^2)
K.E	Kinetic energy	(J)
Voc	Open circuit voltage	(V)
Isc	Open circuit current	(A)
D	Diameter of the wind turbine	(m)

As shown in the Fig.3, the symbols V_∞, V_a and V_w respectively are the free stream wind velocity, induced velocity and wake velocity. When the flow occurs through the windmill, the flow is retarded and it is further retarded in the downstream side of the windmill. The flow velocity through the windmill is usually called the induced velocity, while the flow velocity in the downstream side is called the wake velocity because wake is formed there. According to the Newton's Second law of motion the thrust developed in the axial direction of the rotor is equal to the rate of change of momentum i.e.

$$\text{Axial Thrust} = m(V_\infty - V_w) \quad (1)$$

Where m is the mass of air flowing through the rotor in unit time.

Therefore, the power produced is given by,

$$P = m(V_\infty - V_w)V_a \quad (2)$$

The rate of kinetic energy change in the wind is,

$$\Delta K.E/\sec = \frac{1}{2}m(V_\infty^2 - V_w^2) \quad (3)$$

Now balancing the equations (2) and (3),

$$m(V_\infty - V_w)V_a = \frac{1}{2}m(V_\infty^2 - V_w^2) \quad (4)$$

After simplifying the equation (4), one obtains

$$V_a = \frac{V_\infty + V_w}{2} \quad (5)$$

Glauert determined the identical expression in his actuator disc theory. Here the flow is assumed to occur along the axial direction of the rotor and the velocity is uniform over the swept area, A of the rotor. Since $m=\rho A V_\infty$ from the equation (2), one finds the expression of power extraction through the rotor,

$$P = \rho A V_a (V_\infty - V_w)V_a \quad (6)$$

Where, ρ is the density of air. Substituting the value of V_a from the equation (5) in the equation (6),

$$P = \rho A V_a^2 (V_\infty - V_w) = \rho A(\frac{V_\infty + V_w}{2})^2 (V_\infty - V_w)$$

Which can be rewritten as,

$$P = \frac{\rho A V_\infty^3}{4}(1 + \frac{V_w}{V_\infty})[1 - (\frac{V_w}{V_\infty})^2] \quad (7)$$

Inserting $x = V_w / V_\infty$ in the equation (7),

$$P = \frac{\rho A V_\infty^3}{4}(1+x)(1-x^2) \quad (8)$$

Now differentiating P of the equation (8) with respect to x and setting it to zero for maximum power, one obtains,

$$x = \frac{V_w}{V_\infty} = \frac{1}{3} \quad (9)$$

By simplifying, the expression of maximum power extraction is obtained as,

$$P_{\max} = \frac{8}{27}\rho A V_\infty^3 \quad (10)$$

The available energy in the wind is the kinetic energy per unit time,

$$K.E/\sec = \frac{1}{2}m_i V_\infty^2 = \frac{1}{2}\rho A V_\infty^3 \quad (11)$$

Here mass of air m_i flowing through the rotor has been considered to be ideal.

3. Schematic Diagram of the Proposed Model

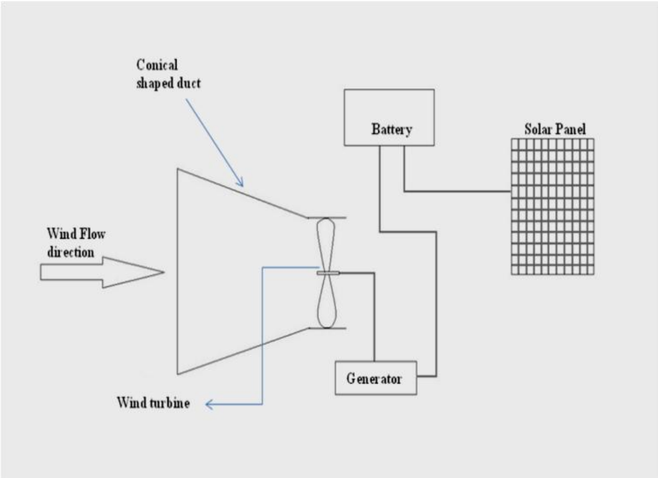

Fig 4. Schematic diagram of proposed model

When the wind speed would reach the desired level for power extraction the turbine would start to rotate and would give a certain power output. The converging section of the conduit is helpful in increasing the air velocity that could be utilized to run the wind turbine effectively. In order to maintain the continuity the air velocity in the converging section increases by an appreciable amount. So with additional wind velocity a significant amount of power can be extracted from the wind turbine with this proposed design (Fig 4). A solar panel has been installed which is integrated with the wind turbine. The overall power extraction as well as system efficiency is enhanced with the help of this proposed design. The ducted wind turbine overcomes many of the problems associated with the use of conventional wind turbines in an urban environment, which are hampered by high levels of turbulence in the air stream, and are also constrained by concerns over visual impact, noise and public safety. In contrast DWT units are purposely designed for attachment to buildings and are both robust and unobtrusive. In the next two sections the feasibility of this proposed system is justified with simulation and mathematical calculations.

4. Simulation Results

ANSYS FLOTRAN simulations were carried out with steady state, standard κ-ε turbulent model for varying downstream diameters of the conduit with varying pressure differences. From the simulations results depicted in fig.5, downstream diameter of 0.6 meter with upstream and downstream pressure difference of 30 Pa was selected to be the preferred parameters. Fig.6 depicts the air velocity profile with the selected parameters.

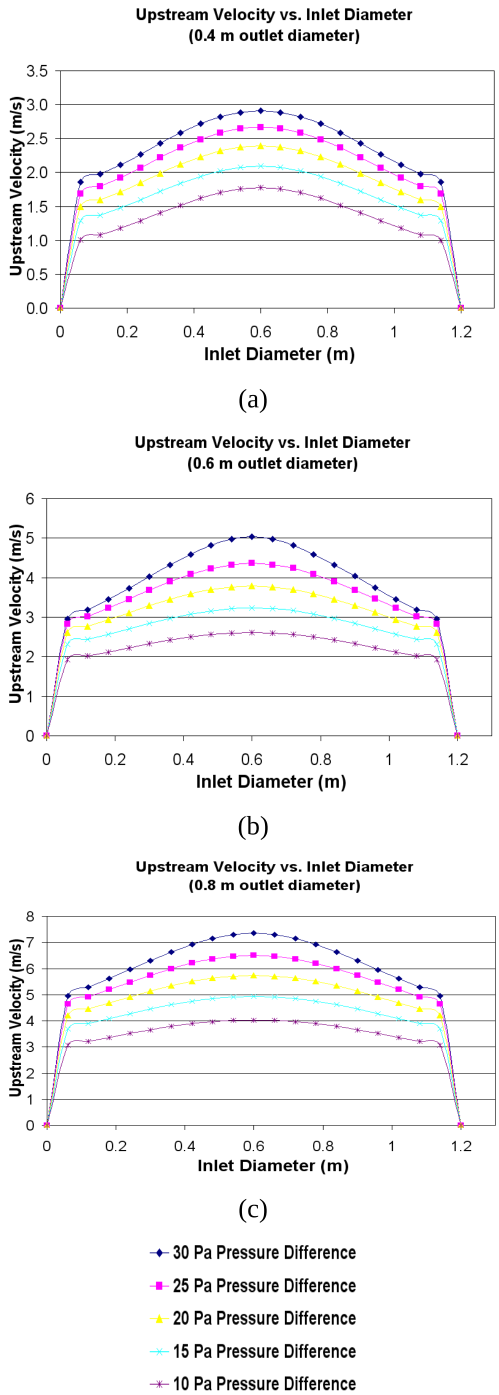

Fig 5. Upstream velocity vs. inlet diameter of the conduit for the outlet diameter of (a) 0.4m, (b) 0.6m, and (c) 0.8m

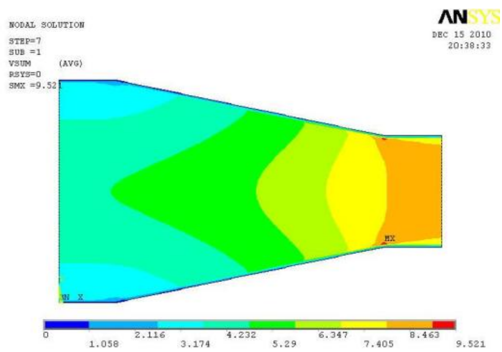

Fig 6. Velocity profile of air through the conduit

From simulation result Fig 6, it is observed that at the inlet of the duct wind speed is approximately 2 m/s where as at the outlet the wind speed is 8 m/s.The simulation was carried out to investigate the velocity profile through the conduit and without the wind turbine. So by the implementation of this conduit more wind energy could be harnessed.

5. A Survey on Practical Implementation of the Ducted Wind turbine

In 1972 Dr. James T. Yen invented the concept of the Tornado Wind Energy Conversion System (TWECS) [17]. The TWECS captures the wind stream and guides it into a cylindrical tower which entrains it into a tornado-like vortex. The vortex creates a column of very low pressure within its core; the bottom of which interacts with the floor of the tower. This is where a horizontal (vertical-axis) turbine is placed. The low pressure above (behind) the turbine acts as a powerful exhaust reservoir to draw air through the turbine. As long as the wind into the tower is sufficient, the vortex is self-sustaining. The TWECS tower concentrates the wind stream in much the same way as a convex lens concentrates sunlight, enabling it to do more work.

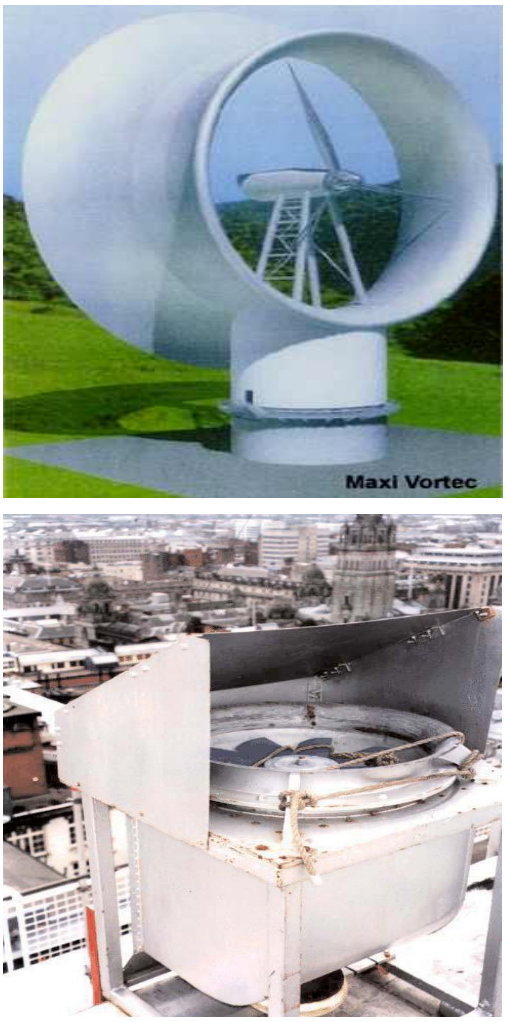

Fig 7. A ducted wind turbine [17]

The enclosing the turbine's rotor blades in a shroud or duct significantly increases efficiency. Technically, this duct is called a convergent-divergent diffuser (Fig 7) and the whole system is usually called a Diffuser-Augmented Wind Turbine (DAWT) or simply a Ducted Wind Turbine (DWT). The DAWT captures the kinetic energy of the wind as well as capturing a certain percentage of the flow-pressure energy of the wind and it can extract usable energy from both low speed and high speed winds more efficiently. Researches were carried out by C J Lawn on Optimization of the power output from ducted turbines[18]. Recently, researchers at the University of Rijeka in Croatia [19] have claimed that a shrouded turbine will produce 3 times more energy than a conventional machine. Vortec Energy Limited of New Zealand had intended to commercialize the world's first ever diffuser-augmented wind turbine, having constructed a prototype on the Waikato coastline in 1998 [20]. Kogan and Nissim [21] and Kogan and Seginer [22] first referred to the wind turbine with convergent entrance and divergent exit that could reduce the cut-in speed. Grassmann and Bet [23] used the numerical simulation to compare the pressure distribution between the non-ducted and ducted wind turbine. The result showed that the power of a wind turbine was increased by a factor of 2.0 by means of wing structure placed at some distance around the turbine. Frankovic and Vrsalovic [24] estimated that the efficiency of the ducted wind turbine could be raised 3.5 times while the area of the inlet was 3 times of the minimum section. Andy Grant and Nick Kelly [25] described the integration of a simple DWT model into a building simulation tool. There are several practical advantages in placing the turbine in a duct which are given as follows.

(a) In areas where there is a danger of divers and/or floating debris being drawn into the turbine, a grid could be placed on the upstream opening, thus reducing danger to life and danger of damaging or clogging the turbine.

(b) The duct shades the turbine itself from direct sunlight, and weed growth will thereby be reduced. Along with floating debris, this was one of the major problems experienced by Swenson in his work on tidal turbines in tropical waters near Darwin [26].

(c) A large duct made of low cost materials can be designed so the downstream side acts as a diffuser and reduces the downstream pressure, thereby increasing the available pressure drop, drawing in more flow and increasing the power output of a given sized turbine. Put another way, large flow area containing a large amount of energy is concentrated into a smaller area so that a smaller, lower cost turbine can be used for a given power output. Because a smaller turbine in a faster flow spins faster, the torque for a given power output is less and a smaller, lower cost gearbox can be used. This is a highly significant factor since flow velocities and hence turbine speeds are low and very large torque is required to produce useful amounts of power.

(d) The duct eliminates tip losses on axial flow turbine blades, improving efficiency [27].

(e) A rotating rim could be provided flush with the static duct, joining the blade tips of an axial flow turbine, with a belt or geared drive on its outside, thereby eliminating torque on the main turbine shaft.

(f) This idea has been taken a step further in the Tocardo turbine, with magnets incorporated in the blades and stator windings in the duct so that the turbine rotor also functions as the rotor of a permanent magnet generator, thereby eliminating gearing as well as torque on the main turbine shaft [28].

Some of the design features of the ducted wind turbines are given below

- Duct shaped to intercept upward air flow on the windward face of the building.
- Low-pressure region behind the angled PV panel at duct exit enhances flow.
- Unobtrusive shrouded rotor; small visual impact.
- Efficient axial-flow rotor with shaft drive to generator.
- Modular design for ease of handling.
- Power coefficient around 0.3, maintained over a ±30° range of wind direction.
- Output up to 180W per square meter of rotor area, for a wind speed of 10 m/s.

6. Feasibility Analysis of the Modified System

The feasibility analysis of the modified system is based on theoretical calculations. Here all conditions are assumed ideal.

6.1. Wind Power Calculation:

The specification of one of the wind turbine model no. D400 has been considered for theoretical power calculation. The noise and vibration usually associated with small wind turbines have been designed out of the D400. The D400 utilizes a 12-pole, 3 phase axial field alternator of very high efficiency. The specification is given below:

- Diameter of the wind turbine, D=1.1 m
- Cut-in speed for 1.1m diameter turbine = 2.5m/s
- Assumptions:
- Velocity at entrance of the conical shaped duct, V= 2.5 m / s
- Velocity at exit of the conical shaped duct that is entrance velocity for wind turbine from simulation, V_∞= 8 m / s
- The velocity variations were considered from the simulation results.

When wind speed is at the cut-in speed the energy output from the wind turbine is (V_∞= 8 m/s)

$$P_{\max} = \frac{8}{27}\rho A V_\infty^3 \text{ = 173 Watt}$$

Without installing conical shaped duct the extracted power from the wind turbine (V=2.5 m/s)

$$P_{\max} = \frac{8}{27}\rho A V_\infty^3 \text{ =5.28 Watt}$$

Additional power output = (173-5.28) =167.72 Watt

So by using conical shaped duct in front of the conventional wind turbine considerable amount of electrical power could be extracted which could easily satisfy the daily demand in houses, offices, industries etc to run the basic appliance.

6.2. Solar Power Calculation:

In our proposed model solar panel has been introduced along with wind turbine in order to generate Hybrid Photovoltaic-Wind Power for reliable power generation. For theoretical solar power calculation the one of the specifications of BP solar panel has been used.

Model: BP350J
Product of India, SO 9001 certified
Electrical ratings: At STC (1000 w/m^2, AM 1.5 Spectrum, Cell temp:25^{0}C)
Peak power = 50 W
Voltage, Vmp = 17.5 V
Current, Imp = 2.9 A
Open circuit voltage, Voc = 21.8 V
Open circuit current, Isc = 3.2 A
Minimum bypass diode = 9 A
Maximum Series fuse = 20 A
Total output from the proposed model = 167.72 +50
= 217.72 Watt

The overall feasibility of the proposed model was carried out based on theoretical calculation. Practically the ouput by this integrated system would be less but still it would be well enough to provide additional electrical energy to the remote areas or the areas with no access of electricity.

7. Conclusion

Being a tropical country, Bangladesh does have wind flow throughout the year. However, the prospect for wind energy in Bangladesh is not at satisfactory level due to low average wind velocities at different regions of the country. Nevertheless, the coastal areas of the country possess somewhat better prospects for harnessing wind power as the average wind velocity is comparatively higher in those particular regions. The field survey data indicated that the wind velocities are relatively higher from the month of May to August, whereas, it is not so for the rest of the year. Still, the average velocity of wind at prospective places like coastal areas is under the desired level to run the wind turbine effectively.

The theoretical analysis presented in this research paper shows that it is possible to ensure continuous availability feature of firm power by means of Implementing Hybrid Photovoltaic-Wind Power plant to provide electricity in rural areas or the areas with no admittance to electricity. Wind power could be enhanced by a certain amount by implementing this modified design. This feasible design could be implemented where wind speed is not at satisfactory level like Bangladesh. It would be beneficial if energy of the wind can be extracted at relatively low speed. Further research is currently being held regarding the prototype manufacturing and testing. Subsequently, the economical viability of the overall system would also be analyzed.

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