Numerical Simulations of Effects of Faults in a Vertical Axis Wind Turbine's Performance

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ABSTRACT

Renewable sources of energy are being developed globally to overcome the present excessive dependence on fossil fuels. Wind energy is one of the important sources of renewable energy. Considerable amount of research is being carried out on the innovative designs for optimal performance of wind turbines. Furthermore a lot of research is being carried out on maintenance and condition monitoring of such systems. Torque output is one of the most important parameters in analysing the performance of a turbine; which in turn depends on a number of factors including the structural health and the performance of each blade. Cracks in a wind turbine blade affect the aerodynamic profile of the blade and consequently flow field around it, and may cause vibration in the blade further affecting its performance. In this paper Computational Fluid Dynamics (CFD) based technique has been used to study the effect of the presence of cracks in the blades on the torque output of Vertical axis wind turbine (VAWT). For this purpose, different cracks configurations have been simulated and results analysed which indicate variations in the amplitude of the torque output of the turbine due to the presence of cracks.

Keywords

Computational Fluid Dynamics, Vertical Axis Wind Turbine, Tip Speed Ratio, Torque, Power.

Nomenclature

r Radius of VAWT (m)
w Angular velocity (rads/sec)
v Linear velocity (m/sec)
P Power Output from VAWT (W)
T Torque Output from VAWT (N-m)

1. INTRODUCTION

Fossil fuels' depletion, rising cost of fuel prices, CO_2 emissions and nuclear disasters, such as the recent one in Japan, have made renewable energy sources increasingly important. Wind energy is being considered a potential candidate in present climate. The global investment in renewable energy is increasing exponentially. Total current installed wind capacity is nearly 238GW. In 2011 more than 40GW of wind energy systems were installed, with China and India leading the contribution by sharing 50% of the installed capacity. Europe installed wind energy systems worth 10GW in 2011 while UK installed nearly 1.3GW which is 3.2% of global installed capacity [4].In order to generate 15% of its energy from renewables by 2020, as required by the EU directive, the UK has set the target for wind energy to contribute in the range of 28 to 31GW of installed capacity [3].

Realising the potential and benefits of the wind energy, considerable amount of research is being carried out on the innovative designs for optimal performance of wind turbines with the focus on both centralized and decentralized harnessing of wind energy. Two most common designs being used are Horizontal axis wind turbines (HAWT) and Vertical axis wind turbines (VAWT). HAWT are more efficient as compared to VAWT but require good quality wind energy. In urban areas where wind is in-consistent and highly fluctuating, VAWT is more beneficial due to its low starting torque characteristics as well as other advantages like in-expensive to build and simple design [5][7].

The important performance parameters of VAWTs, as mentioned by Gareth et. al. [1], are the tip speed ratio (TSR) and the torque output. TSR is the ratio between the rotational speed of the tip of the blade and the actual velocity of the wind.

$$\lambda = \frac{r * w}{v} \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

where r is the radius of the VAWT, w is the angular velocity and v is the linear velocity. Torque output of the wind turbine has a significant impact on the total power output of the turbine.

$$P = w * T \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where P is the power and T is the torque output.

The overall output of the wind turbines depends on several geometric, flow and fluid parameters. The performance of each blade contributes towards the overall torque output of the turbine. In case the shape of the blades gets distorted, significant variations in the performance output of the VAWT could be expected. Cracks in wind turbine blades affect the aerodynamic profile of the blade and consequently flow field around it. In adverse conditions these cracks may cause vibration of the blade also, further affecting its performance. This study focuses on the investigation of performance characteristics of a wind turbine when one of its blades starts to get affected by initiation of a crack. Various operating conditions have been numerically simulated using computational fluid dynamics.

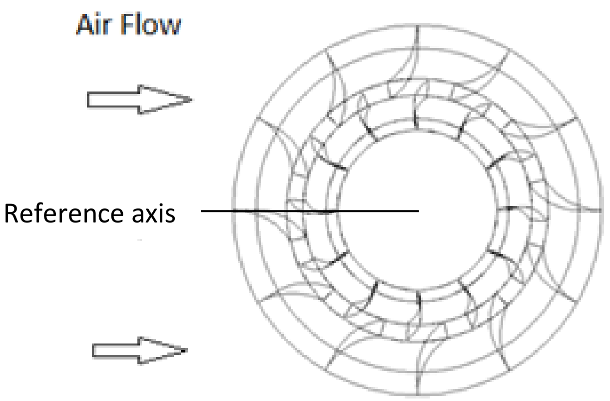


Figure 1. 3D model of the VAWT.

2. NUMERICAL MODELLING

The performance output of an in-house fabricated VAWT (shown in figure 1) has been numerically analysed for various faulty blade configurations. This VAWT has a diameter of 2m and a height of 1m. The geometry of the VAWT features 12 equally spaced rotor and stator blades respectively. Cracks of various sizes in one of the rotor blades have been generated in order to analyse the effect of the presence of faults in the VAWT on the overall performance output of the VAWT. The details of the faults have been summarised in table 1 while figure 2 shows the geometric models of the VAWTs with the faults.

Table 1. VAWT Configurations

Condition	Fault/Defect in the VAWT
Condition 1	Healthy (Non – defective)
Condition 2	25mm crack
Condition 3	50mm crack
Condition 4	100mm crack

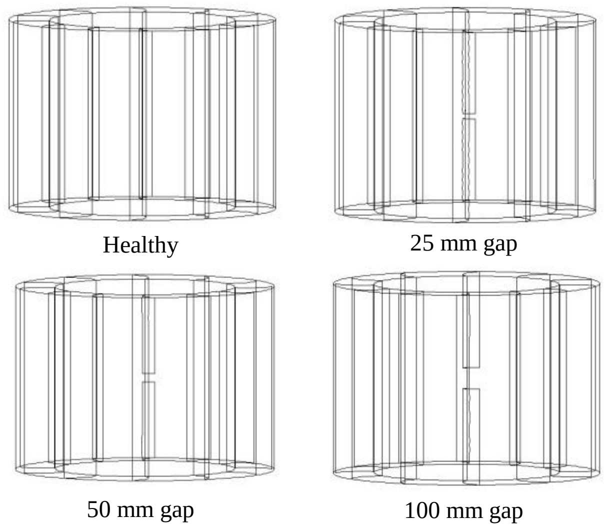


Figure 2.Various Rotor blades' configurations.

Commercial CFD package Ansys 13.0 has been used to numerically simulate the flow in the vicinity of the VAWT. The geometric details of the flow domain, encompassing the VAWT, have been shown in figure 3. 4 m/sec of air flow velocity has been specified at the inlet boundary of the domain whereas the outlet of the flow domain is assumed to be at the atmospheric pressure. The other sides of the flow domain have been specified as stationary walls with no-slip boundary conditions. k-ε turbulence model has been shown to resolve the steady-state turbulent parameters in the flow domain with reasonable accuracy [2] and hence has been chosen for analysis in the present study. Sliding mesh technique as mentioned by Park et. al [6] has been used to rotate the blades with respect to the central axis of the turbine at an angular velocity of 1.143 rads/sec such that the TSR of the VAWT is 0.2.

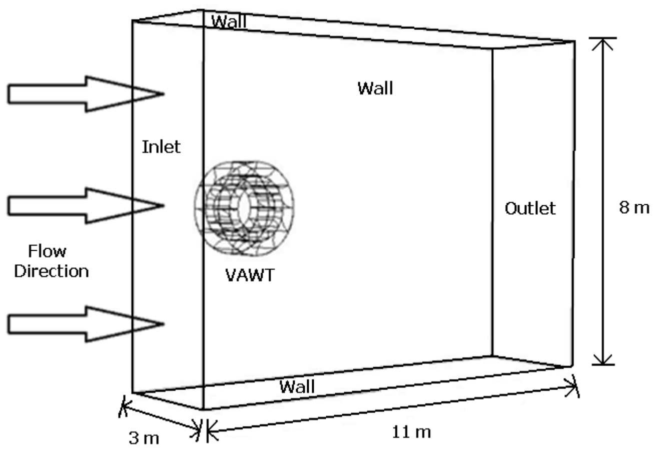


Figure 3. Flow domain encompassing the VAWT.

Three dimensional Navier Stokes equations have been numerically solved in an iterative manner to predict the flow structure in the vicinity of the VAWT for every 3^0 rotation of the rotor blades. During the initial revolutions of the VAWT, significant changes in the flow structure have been observed due to the numerical diffusion. The flow structure within the flow domain has been constantly monitored. The non-uniformities in the predicted flow fields die out from 4^{th} revolution onwards (see table 2) and hence the solution becomes statistically steady.

3. RESULTS AND ANALYSIS

Numerically converged solutions have been used to analyse the effect of various parameters on the output characteristics of the vertical axis wind turbine. To ensure that the results obtained are independent of the mesh being used for the analysis purposes, a mesh independence study has been conducted.

3.1 Mesh Independence

In order to capture the small scale features of the flow, the flow domain needs to be subdivided into small parts, known as mesh elements. To obtain fairly accurate results, the flow variables needs to be independent of the size of these mesh elements. In the present study, the flow domain has been subdivided into one and two million mesh elements respectively. The results for the average torque output, for each revolution of the VAWT having 25mm crack, have been summarised in table 2.

Table 2. Convergence and mesh independence for 25 mm crack condition

Revolution of VAWT	$1x10^6$ Mesh Elements		$2x10^6$ Mesh Elements	
	Average Torque (N-m)	Diff. (%)	Average Torque (N-m)	Diff. (%)
1st	10.545		11.051	
2nd	10.192	3.348	10.684	3.321
3rd	10.192	0.000	10.686	0.019
4th	10.193	0.010	10.687	0.009
5th	10.194	0.010	10.687	0.000

On average, the difference in the average torque output from the VAWT, for both the meshes being used, is 4.8%. The mesh with two million elements yields fairly accurate results and hence has been chosen for further analysis.

3.2 Healthy state VAWT

The results presented hereafter correspond to the 5th revolution of the VAWT as it has reached a statistically steady state. Figure 4 depicts the instantaneous torque output of the healthy state VAWT. The instantaneous torque has been normalised with the average torque for that revolution of the VAWT.

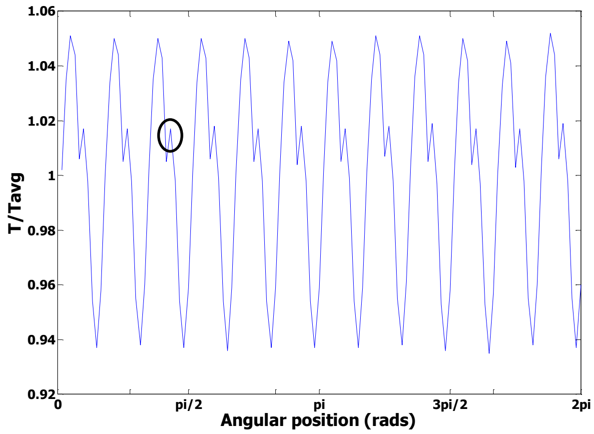


Figure 4. Instantaneous Torque output from Healthy VAWT.

It can be seen that the normalised average torque output during one revolution of the VAWT is cyclic. The average distribution of torque is same for all the blades. Highest peaks refer to the maximum torque output when the rotor blades are in line with the stator blades, making uniform passages for the flow of air. The maximum normalised average torque output is 1.051. The lower peaks (black circle in figure 4) correspond to that orientation of the VAWT when the rotor blades are in between the two stator blades, making two passages for the flow of air. The minimum values of the normalised average torque is 0.93 which corresponds to that orientation of the VAWT when the rotor and stator blades make non-uniform passages for the flow of air, hence blocking the flow and offering greater resistance.

3.3 Faulty VAWTs

In order to analyse the VAWT under various faulty conditions, three different crack configurations have been generated in one of the rotor blades. Detailed analyses of the performance output of the VAWT under these faulty conditions have been presented below.

3.3.1 25mm crack

Figure 5 depicts the variations in the normalised torque output for one complete revolution of the VAWT having a 25mm crack in one of its rotor blades. Although the torque variation is cyclic, the torque output values are considerably different from that observed for the healthy state.

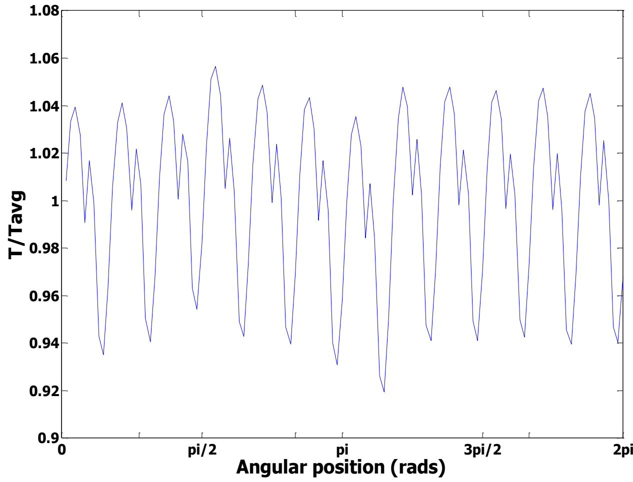


Figure 5. Instantaneous Torque output from VAWT with 25mm crack.

An increase of 0.44% in the maximum normalised torque output, compared to healthy state VAWT, has been noticed. The maximum normalised torque output is 1.056 when the cracked blade is positioned at 99^0 degrees from the reference position shown in figure 1. A decrease of 1.6% in the minimum normalised torque output, compared to healthy state VAWT, has been noticed. The minimum normalised torque output is 0.919 when the cracked blade is positioned at 207^0 from the reference position. The variations of the amplitude of the normalised torque output from the VAWT having a 25mm crack in one of its rotor blades is 17% higher compared to the healthy state VAWT. This variation in the amplitude of the normalised torque output leads to structural instabilities, such as vibrations, in the VAWT; hence degrading the performance output from the VAWT and adversely affecting its structural integrity and remaining useful life.

3.3.2 50mm crack

To investigate the effect of progressive increase in crack size within a blade, simulations have been carried out on a VAWT having a 50mm crack in one of its rotor blades. It is evident from figure 6 that the torque variations for 50mm wide crack are similar to that observed in 25mm crack case. However, the normalised torque values are significantly different. It can be clearly seen that the variations in the normalised torque output are higher as compared to 25mm crack.

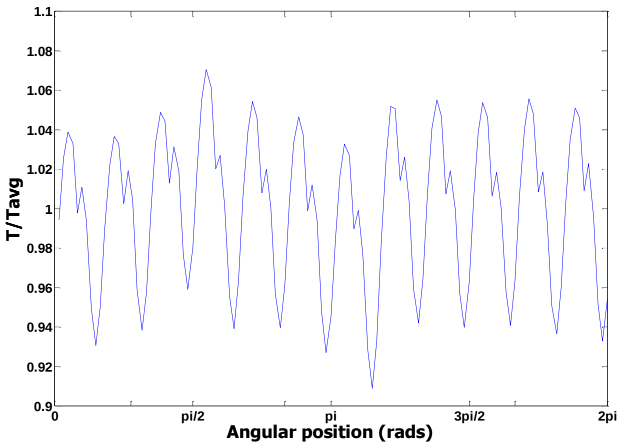


Figure 6. Instantaneous Torque output from VAWT with 50mm crack.

An increase of 1.79% in the maximum normalised torque output, compared to healthy state VAWT, has been noticed. The maximum normalised torque output of 1.07 occurs when the cracked blade is positioned at 99^0 degrees from the reference position shown in figure 1. A decrease of 2.77% in the minimum normalised torque output, compared to healthy state VAWT, has been noticed. The minimum normalised torque output of 0.908 occurs when the cracked blade is positioned at $207^0$from the reference position. The variations or the amplitude of the normalised torque output from the VAWT having a 50mm crack in one of its rotor blades is 38% higher compared to the healthy state VAWT.

3.3.3 100mm crack

To further quantify the effect of crack size, numerical simulation has been carried out with one of the blades of the VAWT having a crack of size 100mm. Figure 7 depicts the variations in the normalised torque output for one complete revolution of the VAWT having a 100mm crack.

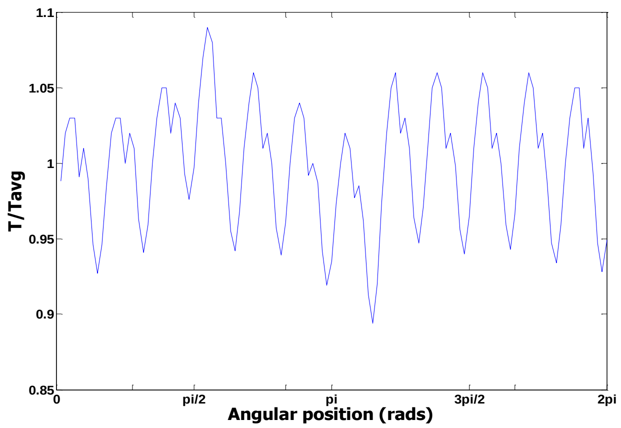


Figure 7. Instantaneous Torque output from VAWT with 100mm crack.

An increase of 3.31% in the maximum normalised torque output, compared to healthy state VAWT, has been noticed. The maximum normalised torque output of 1.086 is obtained when the cracked blade is positioned at 99^0 degrees from the reference position shown in figure 1. A decrease of 4.38% in the minimum normalised torque output, compared to healthy state VAWT, has been noticed. The minimum normalised torque output of 0.893 is obtained when the cracked blade is positioned at $207^0$from the reference position. The variations in the amplitude of the normalised torque output from the VAWT having a 50mm crack in one of its rotor blades is 64.8% higher compared to the healthy state VAWT.

The above discussion clearly indicates that the presence of a crack in the blade significantly affects the instantaneous torque output of the VAWT. The phenomenon is further depicted in figure 8 which shows the normalised torque output for each configuration of the VAWT during one complete revolution.

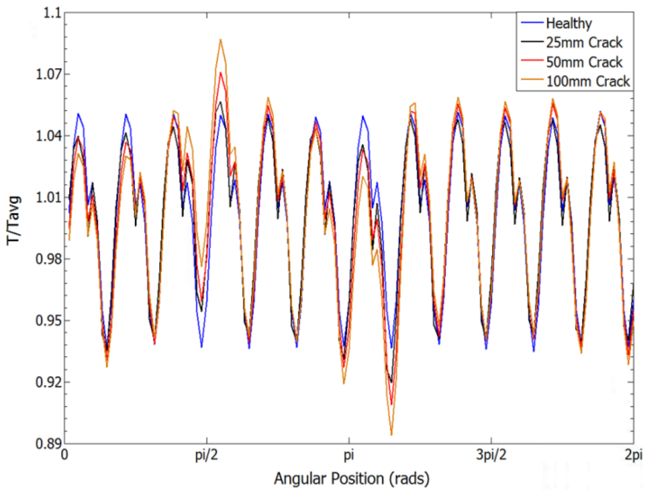


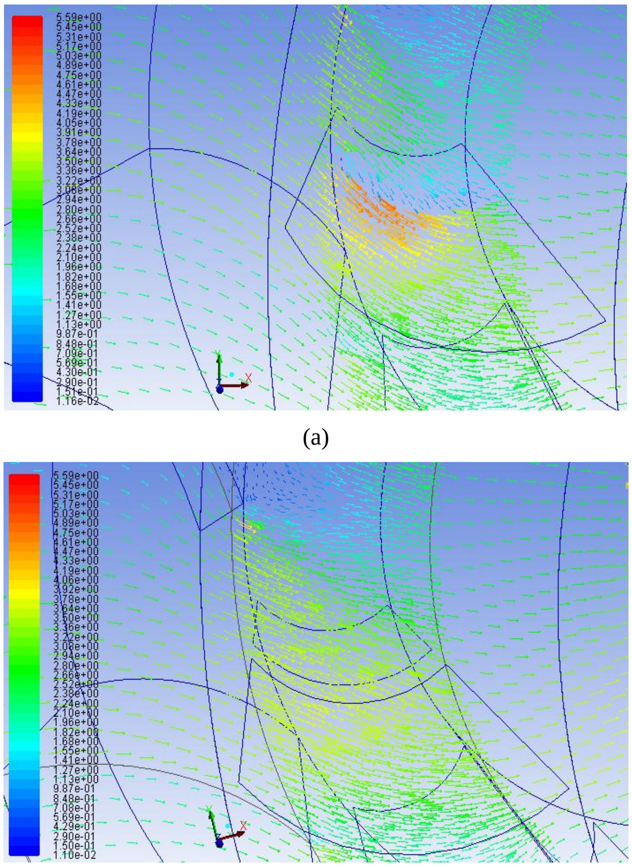
Figure 8. Instantaneous Normalised Torque outputs from various configurations of the VAWT.

Table 3 summarises the results presented here. Since average torque output obtained from the numerical for one complete revolution corresponding to each condition doesn't differ significantly, more information about the local flow field is required.

Table 3. Torque outputs from various configurations of the VAWT

Condition	Minimum Torque (Tmin) (N-m)	Maximum Torque (Tmin) (N-m)	Average Torque (Tavg) (N-m)
Healthy	0.934	1.051	1.000
25mm crack	0.919	1.056	1.000
50mm crack	0.908	1.070	1.000
100mm crack	0.893	1.086	1.000

To analyse the effects on flow field variables due to the presence of a crack in the blade, the velocity vectors have been shown in figure 9. It clearly shows that local velocities are much higher for healthy blade VAWT configuration as compared to the faulty blade VAWT configuration. The trend is the same for all the crack sizes.



(a)

(b)

Figure 9. Velocity vectors: (a) Healthy VAWT (b) VAWT with 100mm crack.

Table 4 shows a clear correlation between the gap size and the percentage increase in the difference between maximum and minimum torque values. It can be clearly seen that as the size of the crack in the blade increases, the difference between maximum and minimum torque values increases.

Table 4. Amplitude of Normalised Torque outputs

Condition	Tmax – Tmin (N-m)	Diff. w.r.t. Healthy VAWT (%)
Healthy	0.117	
25mm crack	0.137	17.09
50mm crack	0.161	38.25
100mm crack	0.192	64.85

The presence of a 25mm crack in one of the rotor blades increases the difference between maximum and minimum torque values by 17.09%. A further increase in the crack size to 50mm further increases the difference between maximum and minimum torque values by 17.51%. A crack size of 100mm further increases the difference between maximum and minimum torque values by 19.25%. On average, an increase of 18.38% has been observed as crack becomes double in size.

The above result highlights that increase in the value of Tmax – Tmin is an indication of increasing crack size in one of the blades of the turbine. This parameter can further be tuned to clearly isolate the crack related faults in a vertical axis wind turbine both qualitatively and quantitatively. This parameter can be embedded on any model based diagnostic system for continuous monitoring of wind turbine systems.

4. CONCLUSIONS

The paper clearly highlights usefulness of computational fluid dynamics in simulating fault related effects in wind turbines. For this purpose various wind turbine configurations have been studied and analysed to investigate the behaviour of the torque output for various crack sizes. It has been seen that during one complete revolution of the turbine, maximum torque is generated at a specific position of the rotor blade with respect to the axis of incoming air flow. The results indicate that there is a direct correlation between the gap size and the amplitude of the torque at specific orientations of the cracked blade. Furthermore crack size has a very small effect on the average overall torque output of the turbine. The difference between maximum and minimum torque values increases during one complete revolution of the turbine when the gap size increases. Hence, Tmax – Tmin can be used as a tool to diagnose the presence and size of cracks in the blade.

5. REFERENCES

[1] Colley, G. and Mishra, R. (2011). “Computational flow field analysis of a Vertical Axis Wind Turbine”, In proceedings of the International Conference on Renewable Energies and Power Quality, Las Palmas, Gran Canaria.

[2] Colley, G. and Mishra, R. (2010). “Effect of rotor blade position on Vertical Axis Wind Turbine performance”, In proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ’10) Granada, Spain.

[3] DECC (2011). *UK Renewable energy Roadmap*. Available at: http://www.decc.gov.uk/, accessed: 20 September 2012.

[4] GWEC (2011). *Global Wind Report*. Available at: http://www.gwec.net/, accessed: 28 September 2012.

[5] Manwell, J.F. Mcgowan, J.G. and Rogers, A.L. (2009). *Wind energy explained; theory, design and application*. Second edition, John Wiley & Sons Ltd., Chichester, UK.

[6] Park, K.S. Asim, T. and Mishra, R. (2012). “Computational Fluid Dynamics based fault simulations of a Vertical Axis Wind Turbine”. *Journal of Physics: Conference Series*, 364.

[7] Rohatgi, J. and Barbezier, G. (1999). “Wind turbulence and atmospheric stability – their effect on wind turbine output”. *Journal of Renewable Energy*, 16 (1-4), pp. 908-911.