Energy Gathering by Micro Turbines for Low Voltage Appliances

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***Abstract*—In a city environment, the wind is often less predictable and can be re-directed in many different ways by all kind of obstacles. Therefore large size wind turbines would not work effectively, not to mention the requirement for planning permission related to their installation. In an attempt to overcome these problems, this paper looks at the designing of 3 vertical micro turbines with a maximum diameter of 30cm, which generate electric power for low voltage DC loads. The paper looks at the design, simulation and building of a combination of Savonius-type, H-type and Darrieus type blade turbines. The results indicate that the most efficient turbine combines the principles of different blade designs, resulting in a power coefficient of 42%, an average total efficiency of about 32% leading to a high electric power output, a good self-starting characteristic, and low starting and cut-in wind speeds of 2.25m/s and 2.75m/s respectively. On top of that, the turbine has a simple mechanical structure and a can be produced cheaply.**

I. Introduction

Many countries around the globe have already invested significantly in large wind farms, either in the country side, off-shore, in the mountains or at the sea-side. The energy gathered in these wind farms can fairly easily be predicted and calculated, since wind speed and direction are well known and there are few factors that will influence them [1]. In a build up environment, however, the wind speed and especially direction are far from predictable since they are influenced by all kind of obstacles such as skyscrapers, apartment blocks, etc. In spite of this problem, there are still several locations within the city where there is nearly always going to be a sufficient amount of wind to provide a continuous energy supply. The market already comprises a variety of small-scale wind turbines, but on average they have a diameter of 50cm and above and require planning permission before being put up in these surroundings. As will be shown in section two, their size inherently implies a certain requirement on the amount of wind needed for them to generate energy. In order to generate energy at lower windspeeds, the turbine size should be reduced, which would possibly also overcome the planning permission requirement. Hence, this paper looks at several different designs of micro turbines with a diameter of 30cm. This diameter size was chosen as a fair compromise between size and energy generation. After the theoretical section, the paper will discuss the three different turbines for which prototypes were developed. The paper then moves onto the actual results for each of the turbines and compares them to determine the most efficient design, after which the paper concludes.

II. Theoretical Study

Before starting the design of the turbines, this research looked at the potential energy that could be gathered from the wind. This calculation assumes that there is no change of air density or possible climate changes. One futher assumes that the generated power will be directly proportional to the contact surface area of the turbine blades as well as the wind velocity.

$$P = C_P \lambda \frac{1}{2} \rho A V^3 \quad (1)$$

In the above equation P, the total mechanical power of the turbine, depends on ρ, the air density, A, the swept area, V, the average wind speed and $C_P \lambda$, power coefficient of the turbine blades. The latter of which has a maximum value of 59.3% [2], and is generally referred to as the power coefficient, which also means that the maximum theoretical power of the turbine is limited to this power coefficient. Commonly, this power coefficient is much lower and lies within the range of 0.35 to 0.45. Several parameters influence this power coefficient,

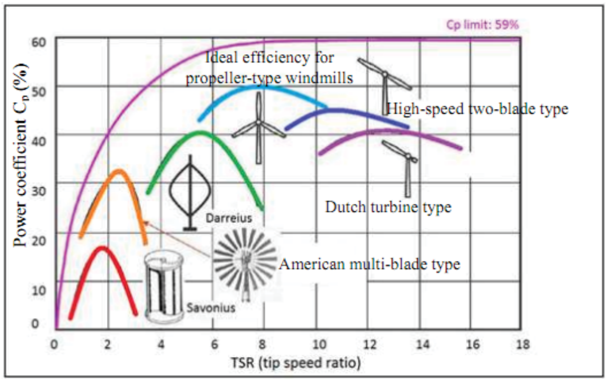

Fig. 1. Power Coefficient vs Tip Speed Ratio for different types of Turbines [2]

including: average wind speed, rotational speed of the turbine, and pitch angle. Consequently, depending on the type of turbine blades, the ratio of blade tip speed to wind speed will be different as is shown in Figure 1.

It will clearly be highly important to consider the position of the turbine. Considering the environment in which it will be used, the wind can actually come from any direction, which make a Vertical turbine more suitable, although these turbines have a slightly lower efficiency [1]. Independent of the type of turbine, the positioning on or around the building would also play a significant factor [3].

III. Turbine design

The purpose of the turbines being designed in this project was to start from the known types, namely: Savonius-type, H-type and Darrieus-type turbines, and build a small Vertical Axis Wind Turbine (VAWT) which has high self-starting ability and total efficiency, while remaining simple and cheap.

A. Turbine blade design

Taking into account that H-type turbine blades have an equal radius through the whole length of the blade, the swept area will be constant, consequently resulting in a constant power in the case of a constant wind speed. This is a result of the fact that the output power is generated over the complete length of the blade. On top of that, H-type blades are known to have a higher efficiency and rotation speed in comparison to other turbine blades for the same wind speed, but they have a poor self-starting ability.

On the other hand, Savonius-type blades have better self-starting characteristic than Darrieus or H-type blades. This is due to the large amount of surface area against the wind direction [6], resulting in the blades dispersing the momental forces on the axis with a larger angle. Consequently a combination of these two turbine types is considered.

The first turbine is a four blade Savonius-type combined with four windshields, which are actually H-type blades. The windshields were added to optimise the airflow impacting the S-type turbine blades. A small gap between the windshields and four turbine blades is created to disperse the airflow easily and reduce the negative torque affecting the turbine shaft. The size of the designed prototype is 30cm x 40cm, with an internal radius of 30mm for the S-type blades and 30cm being the outside diameter of the setup. The angle between the windshields and X-axis was determined to be optimal at 30°. A picture of this turbine can be seen in Figure 2 (a).

The second turbine is a Savonius-type with three blades combined with three H-type blades (See Figure 2 (b)). The use of the S-type blades enhances the dynamic torque performance of the VAWT at high rotation, while it will also reduce the dynamic torque performance at low tip speed ratio. Combining the S-type with an H-type will allow for an overall better performance. It should be mentioned that the angle of attack of each H-type blade on the prototype could be adjusted, but also that their configurations are different from that in turbine 1. The chord length of the H-blade is longer, but also the acute angle created by the chord of the H-blade and the X-axis at about 4045° is larger in comparison with the configuration of Turbine 1 (30°). The 45° includes a pitch angle of 15° and an optimal angle of attack of 30°. Additionally, the diameter of the three S-type blades is about 60mm to enhance the self-starting time in conditions with frequent wind speed changes. It should further be mentioned that the number of blades in this case is limited to 3 blades to avoid them obstructing each other for different wind directions.

Additionally, as a third turbine a Darrieus-type turbine with three blades was tested (See Figure 2 (c)). This lift-type turbine is appropriate for both low wind speed and frequent wind direction changes. On top of that, it is also highly efficient [9] and is well known for its smooth operation, minimal vibrations and reduction in acoustic noise. In relation to the mechanical structure, this turbine is designed with a small pitch angle of about 30°. However, this value can again be changed in the designed prototype. It is well known that a Darrius turbine operates well with a diameter above 50cm [7], [8], but their characteristics for a diameter below 50cm are not that highly spoken from, hence, this turbine was

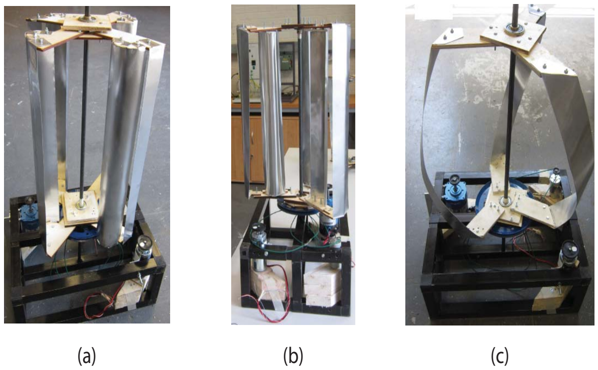

Fig. 2. Different Turbine Designs: (a) Four Blade Savonious with windshields; (b) 3 blade Savonious with H-type blades; (c) Darrieus type with 3 blades

included as a comparison.

B. Overall Efficiency

In order to obtain an overall high efficiency, one does not only need to consider the actual turbine, but also the efficiency of the generator, and the DC/DC convertor. The latter is required as a buffer to deal with the fluctuations of the wind speed and consequently the output of the generator and the constant demand from either the load or temporary energy storage.

The conversion from mechanical energy into electrical energy performed by a DC generator generally causes significant energy losses. With the rotational speed of the turbine blades being rather low, it is essential to use a drive system to increase this speed before it reaches the generator. A drive system will however introduce an average efficiency of 80% - 98% depending on the drive ratio. In this specific design a simple drive system with belts and pulleys is used due to its high efficiency and low investment. Besides the drive system efficiency, one also needs to consider the efficiency of the DC generators which is usually between 80% - 95% [4]. Therefore, the efficiency from mechanical energy into electrical energy (C1) is between 0.64 and 0.93.

To ensure a constant output voltage, a DC generator is required, which also has a certain efficiency. Depending on technical properties, and design parameters, the efficiency of this convertion (C2) can be between 90% - 96% [5]. Finally, the output power may be stored in batteries through a battery charger. The efficiency of chargers is generally very high, so it can be ignored. Consequently, the total efficiency of the system during the conversion from kinetic energy in the wind into electrical energy should be between 20% and 40%.

C. Electrical Design

To test the influence of the generator, a set of different generators were used, including a 12V & 10W, a 24V & 19W and a 12V & 30W DC generator. On the other hand, the DC/DC conversion was done using a single boost converter, with a 1.5V 28V input, a 24V output at a max of 3A and with a total efficiency of 94%. The output of this converter was connected to a set of NiMH batteries, that functioned as a load and storage system. NiMH batteries were chosen for their high power densities, environmental friendliness [10] and the fact that they are not prone to memory effect making them perfectly suitable for this application. More specifically, this design used four 12V, 2Ah packs that were combined per two to provide 24V storage and output and then in parallel to increase the output current capability. The choise for this kind of setup also allowed for 12V output to be provided by the system.

IV. Test Results, Analysis and Discussion

This section provides the measured data for the different combinations of turbines and generators, and will more specifically look at the following factors, namely: total efficiency, electric power output, self-starting ability, power coefficient, and the simplicity of the mechanical structure. The measured parameters are: current (I_{DC}), voltage (V_{DC}) generated from DC generators with respect to different loads and wind speeds; rotational speed (n) and self-starting time (t). From these measured parameters, the following parameters were calculated: mechanical output power (P), and electric output power of the DC generators (P_e); torque produced from turbine blades (T_m); power coefficient (C_p); and total efficiency (η_{total}) of the micro VAWT system.

A. Turbine 1

Figure 3 showns the electrical power output and total efficiency when linking different generators to turbine 1. From the graphs, it can be seen that the total efficiency of the 24V & 19W DC generator increases strongly between a wind speed of 3m/s to 7m/s, and reaches its highest percentage of 32.8% in comparison to the other generators from wind speeds above 7m/s. Although the electric power produced by the 12V & 30W generator is higher than that of the 24V & 19W generator, the cut-in wind speed when using this 12V & 30W generator is much higher (at 5m/s in comparison to 3m/s for the turbine using the 12V & 19W generator). The latter is probably due to the larger electrical power output specification for this generator, which would mean that

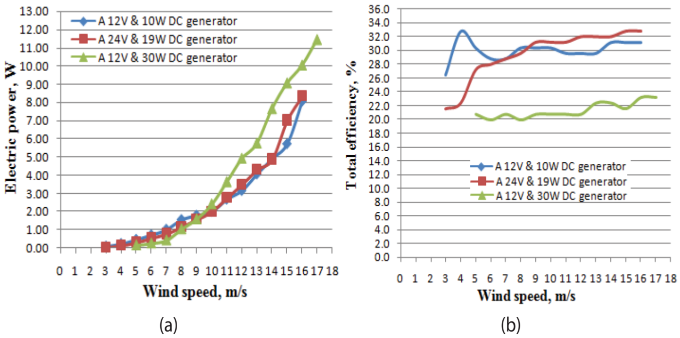

Fig. 3. Electric power output (a) and total efficiency (b) with respect to wind speeds for three different DC generators in Turbine 1

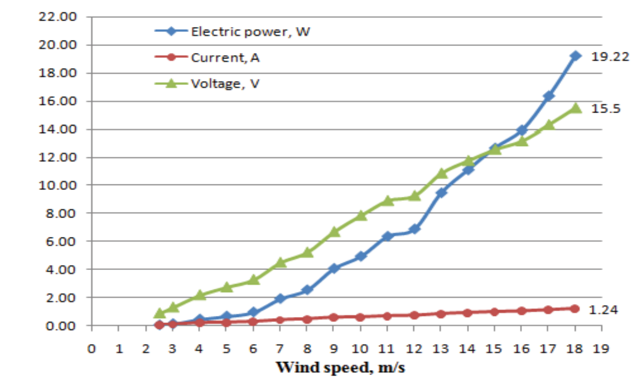

Fig. 4. Variations of electric power, voltage, and current for Turbine 1

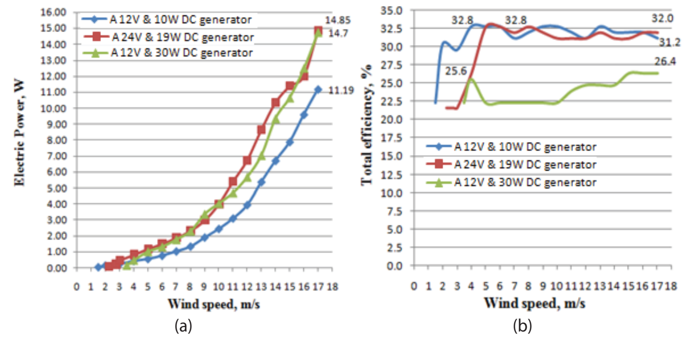

Fig. 5. Electric power output (a) and total efficiency (b) with respect to wind speeds for three different DC generators in Turbine 2

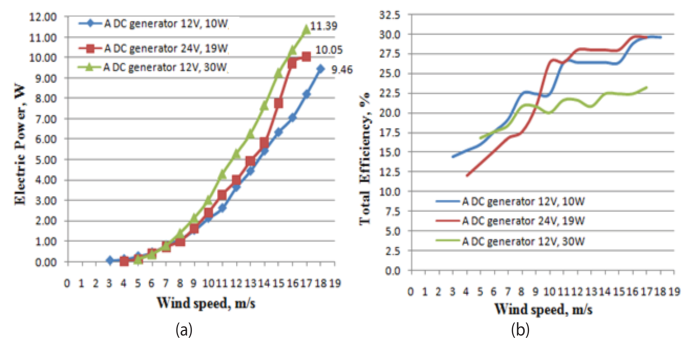

Fig. 6. Electric power output (a) and total efficiency (b) with respect to wind speeds for three different DC generators in Turbine 3

higher kinetic energy is required to start rotating the generator.

The variations of electric power, output voltage and current of Turbine 1 using the 24V & 19W DC generator are shown in Figure 4. The changes of current are insignificant when the output of the 24V & 19W generator is connected to a load in response to different wind speeds (from 0.07A at 2.5m/s to 1.24A at 18m/s). The output voltage strongly rises in correspondence to the change of wind speeds (from 0.89V at 2.5m/s to 15.5V at 18m/s). Additionally, electric power generated from turbine 1 at 2.5m/s is only 0.06W, whereas for an average wind speed of 8m/s, it is 2.57W. For an average wind speed of 18m/s, the electric power is 19.22W.

B. Turbine 2

Similar to Turbine 1, the comparison between the different generators for Turbine 2 is shown in Figure 5. A similar trend can be seen in relation to total efficiency, where the 24V & 19W generator now seems to compete more closely with the 12V & 10W generator. When considering the electrical power, it is again the generators with the higher power output specification that provide higher output. In overall, one can again see that the 24V & 19W generator forms the better solution when combined with this turbine.

C. Turbine 3

In contrast to the results for the first two turbines, when considering the different generators this turbine provides slightly different results, as shown in Figure 6. In combination with this turbine, the 24V & 19W DC generator is not feasible due to the high starting and cut-in wind speeds as well as the small voltage and electric power as shown in Table I. Additionally, one can also notice that the 12V & 30W generator is not suitable in combination with this turbine, and this from the aspect of total efficiency as well as starting and cut in wind speeds. This is largely due to the fact that this turbine does not extract much energy from the wind and hence does not reach very high rotational speeds, which can then not be converted into electrical energy. Therefore, in this case the lower specification generator is more efficient.

D. Comparison of the different turbines

When considering the electrical power generated, as shown in Figure 7 (a), one can notice that Turbine 3

TABLE I
MEASURED PARAMETERS FOR THREE DIFFERENT GENERATORS

GENERATOR	12V & 10W	24V & 19W	12V & 30W
Starting Wind Speed	$2.75m/s$	$3.5m/s$	$4.5m/s$
Cut-in Wind Speed	$3.5m/s$	$4.5m/s$	$5.5m/s$
Safe Wind Speed	$17m/s$	$17m/s$	$17m/s$
Self-Starting Time	$30s$	$38s$	$45s$

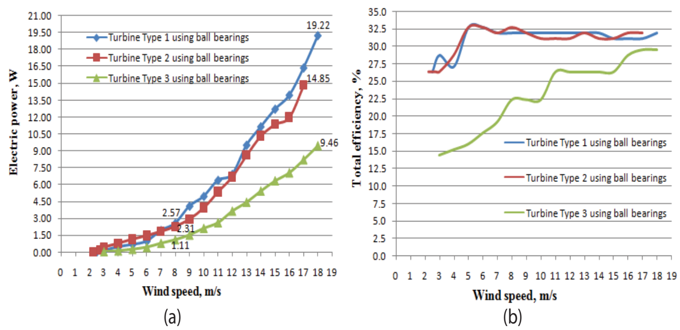

Fig. 7. Electric power output (a) and total efficiency (b) for the three different turbines

has the lowest produced electric power in comparison with Turbines 1 and 2. While Turbine 2 produces a higher electrical power for wind speeds below 8m/s, from wind speeds of 8m/s and above Turbine 1 generates more electrical power. This benefit towards Turbine 2 is related to its lower overall weight, which is with 592g for Turbine 2 versus 630g for Turbine 1 an advantage in particular for lower wind speeds. Considering the use of these turbines in a city environment with low wind speeds, turbine 2 has to be seen as the better solution in relation to generating electrical power.

A second factor of comparison is the total efficiency as indicated in Figure 7 (b) for each of the turbines. The graph clearly shows that Turbine 3 has the lowest total efficiency. When comparing Turbines 1 and 2, then the differences are only marginal, since for a wind speed of 2m/s to 5m/s, the total efficiency increases from 26.4% to 32.8% before remaining stable at a range of 31.2% to 32%. Hence, further parameters are required to determine the most efficient turbine constructed.

TABLE II
SELF STARTING ABILITY FOR THREE DIFFERENT TURBINES

	Turbine 1	Turbine 2	Turbine 3
Starting Wind Speed (m/s)	2.5	2.25	2.75
Self-Starting Time (s)	10	10	20
Rotational Speed (rpm) at 8 m/s when not connected to a DC generator	395	400	305
Weight (gram)	630	592	482

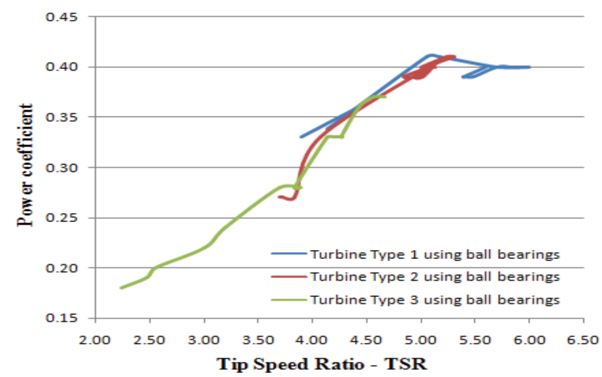

Fig. 8. Power Efficiency for the three different turbines

Table II showns the starting and cut-in wind speeds and self-starting time with respect to the three experimental turbines. Again, Turbines 1 and 2 are very close to one another, especially when it comes to starting wind speed at 2.5m/s and 2.25m/s respectively, the self-starting time at 10s, and the rotational speed of turbine blades without connecting to DC generators at 395rpm and 400rpm respectively for 8 m/s wind speed. Besides that, the weight of Turbine 1 is 630g while that of Turbine 2 is 592g. Although Turbine 3 has an advantage in rlation to weight, due to its design it does not get good performance on the self starting and rotational speeds.

A further factor to compare is the power coefficient of the three turbines, for which the results are shown in Figure 8. Again one can notice that Turbine 3 is not performing particularly well in comparison with Turbines 1 and 2. When comparing Turbine 1 and 2 with one another, then one can notice that Turbine 1 has a slightly higher power coefficient in comparison to Turbine 2. As a result, based on the power coefficient, both Turbine 1 and Turbine 2 are again both suitable for building micro VAWTs to operate in low wind conditions.

With regards to the mechanical components to construct the Turbines, the construction of Turbine 2 is slightly more complex due to the shape of the three H-type blades. However due to the fact that Turbine 2 only has 3 blades, it turns out slightly lighter than Turbine 1. Turbine 3 on the other hand is the most complex turbine to construct.

Hence, Table III summarizes all different parameters considered for the different turbines. Based on all parameters, one can conclude that Turbine 2 is the most efficient turbine to use in a build up area. The main advantages of this turbine lies in the fact that it produces the highest electric power at low wind speeds and it also has the lowest starting wind speed of all turbines. The

TABLE III
COMPARISON OF ALL FACTORS FOR THE THREE DIFFERENT TURBINES

Evaluation factor	Turbine 1	Turbine 2	Turbine 3
Electric power produced by each VAWT in low wind conditions	High	Highest	Low
Total Efficiency	High	High	Low
Cut in Wind speed and self starting time	Low	Low	High
Starting wind speed and weigth	Low	Lowest	High
Power coefficient and rotational speed	High	High	Low
Mechanical construction complexity	Simplest	Simple	Complex

total efficiency, cut-in wind speed, and self-starting time, power coefficient and the rotational speed of turbine 2 are then again similar to those of Turbine 1. In spite of the mechanical structure, modern machines should not have any problems to construct Turbine 2 easily and cheaply.

V. CONCLUSION

This paper considered several turbine designs for micro wind turbines to be used in built up areas with low windspeeds that can also quickly change direction. The turbines had a maximum diameter of 30 cm and are designed to power low voltage DC appliances. Vertical Axis Wind Turbines were selected because they can easily deal with the change of wind direction. A variety of different prototypes that combine different type of blades, including Savonious, H-type and Darrieus, were tested. The Savonious and H-type were combined with windshields and S-type blades respectively to enhance their performance. The paper also investigated the overall performance of the system and tested different generators in combination with each of the turbines.

Among the tested prototypes, the 3 blade S-type combined with H-type blades is considered the most optimal design to be used in city environments. The overall efficiency of this turbine is 31.2%, with a power coefficient of (0.42), which is above average considering that the total efficiency can be within the range of 20 to 40%. Additionally, the turbine has a low starting and cut-in wind speed at 2.25m/s and 2.75m/s respectively and a low starting time of 10s. This turbine, when combined with a 24V & 19W DC generator could provide energy via a DC/DC converter to a DC storage system that can then provide output at 12 and 24V as required by the appliances. The electrical power output of this turbine is about 15W, hence a multitude of turbines might be required, depending on the power demands of low voltage devices, like: laptops, LED-lights, and the like.

ALthough the overall output of the presented micro turbines is small, the paper shows that these turbines might provide an alternative source of energy that can be used in city environments and therefore deserve further research. Considering that the combining of different turbine types as presented in this paper results in overall better turbines, other combinations of existing turbines types will be investigated in the future to determine their suitability as micro turbines for city environments.

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