The insight investigation on the performance affecting parameters of Micro wind turbines

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Abstract. The large to small wind turbines have been investigated for past few decades, but only a few have conducted the investigation on micro wind turbines, whose power rating and rotor diameters are less than 1 kW and 1.5 m respectively. The growing utilization of power electronic devices creates space for the development of micropower harvesting that could be used for standalone charging applications. The theoretical investigation is conducted on rotor diameter of 30 cm and which is targeted to operate at the cut in, rated and cut out wind speed of 4 ms⁻¹, 7 ms⁻¹ and 11 ms⁻¹ respectively with the rated tip speed ratio ranging from 2.5 to 4.

The airfoils SD7037, E193, RG15, SG6041, SG6051 and S7012 are shortlisted on the basis of the prior aerodynamic investigation, and this study aims to improve the performance of MWT rotor at 7 ms⁻¹. The different chord and twist equations are used to determine the optimum blade geometry with trade-offs between the better starting and maximum performance. The turbines with RG15 and SD7037 attains the maximum power of 2.3 W at a wind speed of 7 ms⁻¹ of wind speed and design TSR of 2.5 leading to better annual energy production.

1. Introduction

Wind is one of the widely available non-conventional energy sources and roughly 10million MW of energy existing on the earth surfaces. The energy harvesting from the wind based on the rotor swept area and availability of wind potential. The micro wind turbines(MWT) can be used to power up the stand-alone sensors for different activities such as weather monitoring, bridge structural and river level monitoring, surveillance that would create the extensive opportunities for the development and installation of power electronic devices and reduces the dependency of battery usages. Usually, conventional turbines are installed at the dedicated sites, having a high wind potential, but small and microturbines(SWT) are installed at places where power is required, irrespective of the average wind speed[1]. The SWT rotor is operating under the Re range of 0.35x10⁵–2x10⁶[2–4], at low Re, where the laminar separation bubble dominates the aerodynamic performance, to avoid this separation effect, some new airfoils were developed that showed the better performance at Low Re [5,6]. These turbine rotors are very short, and due to low inertia, they face starting problem which is one of the significant factors that affect the rotor performance and economic feasibility too[7–9]. To start rotating the rotor, more amounts of potential needs to flow across the swept area. Therefore, for better starting increasing the number of blades is advisable; moreover, it also increases the performances and cost of the system. The performance affecting parameters are associated with SWT can applicable to MWT due to shorter the rotor diameter and operating condition.

So far, the aerodynamic investigation conducted on the micro wind turbines with the rotor diameter of less than 50 cm are discussed: -The 3 bladed and 45 cm diameter rotor was designed...
using NACA 4415 airfoil for design wind speed 7 ms\(^{-1}\) and two numerical codes were developed for performance analysis that shows better prediction with wind tunnel tests that attains the Cp 0.35 and corresponding power of 22 Watts [10]. The 30 cm diameter almost constant chord and twist rotor with NACA4415 airfoil blade produced a better performance of 0.40 at the wind speed of 20 ms\(^{-1}\) for the 30-40% solidity among the different combinations considered [11]. Three bladed, 39.4cm diameter rotor developed with NACA0012 airfoil cross section produced the power of 0.87 W with Cp of 0.14 at the rated speed of 5 ms\(^{-1}\) [9]. In following study, conducted by the same author on 3 bladed constant chord and variable twist rotor is obtained the power coefficient of 32% at 4 ms\(^{-1}\) wind speed with the power output of 1 W that can produce till 2.2 W at 5.5 ms\(^{-1}\) which is one of the efficient turbines in Micro range[12]. The four-bladed, 7.5 cm diameter rotor produces the power of 8mW at the speed of 3.5 ms\(^{-1}\), and overall system efficiency reaches up to 7.5% at the wind speed of 6 ms\(^{-1}\). In the following study, with and without gear transmission system along with the effect of Buck-boost converter were investigated, without gear system produced a better performance for the wind speed ranges from 2-6 ms\(^{-1}\) and with gear transmission system operated well at speeds higher than 6 ms\(^{-1}\) [13,14]. The 2.6 cm diameter Swirl type micro wind turbine produces the power of 2.72 mW at the wind speed of 6.5 ms\(^{-1}\) that is equal to 3.42% of system efficiency[15]. Some studies were incorporated into the BEM method for MWT rotor design with conventional airfoils characteristics that produce better performances than fan blade configurations. The performance of microturbines ranges between 5-10% which is lesser than the cp of small, i.e. 0.31-0.40 and large scale turbines, i.e. 0.46-0.48 respectively [13–15].The deviation in performance occurs in MWT, due to use of fan blade configurations and eluding the standardized design methodologies as used in the large and small wind turbines. The primary objective of the study is to improve the aerodynamic performance of MWT rotor at a low wind speed of 7 ms\(^{-1}\) with the use of existing Low Re airfoils characteristics and incorporating BEM theory for rotor design.

2. Methodology for determining the operating parameters
The chord length and wind speed were determined considering density and viscosity of air as constants. The relative wind velocity is used to determine the Reynolds number, under which the aerodynamic performances of airfoils such as lift and drag characteristics were estimated using Xfoil. The relative wind speed is drawn from the velocity triangle that comprises the upstream velocity of air and rotor speed. The free stream wind velocities reflect the commonly available urban wind condition in India is in the range of 3-7 ms\(^{-1}\). Hence, the design wind speed is taken as 7 ms\(^{-1}\). The rotor’s rotation velocity was estimated for a mid-span MWT with the rotor diameter of 40cm and, \(\lambda\) of 2.90 at which a 3 bladed system gives maximum power coefficient, Cp [12,16]. The operating Reynolds number calculation is given below.

| \(V_x(\text{ms}^{-1})\) | \(V_{tan}(\text{ms}^{-1})\) | \(V_{ref}(\text{ms}^{-1})\) | Reynolds number \((c=0.033m @ 50\% )\) |
|-----------------|-----------------|-----------------|-----------------|
| 3               | 6               | 6.7             | 13416           |
| 4               | 8               | 8.9             | 17889           |
| 5               | 10              | 11.2            | 22361           |
| 6               | 12              | 13.5            | 26833           |
| 7               | 14              | 15.7            | 31305           |
| 8               | 16              | 17.9            | 35777           |
| 9               | 18              | 20.2            | 40249           |
| 10              | 20              | 22.4            | 44721           |

2.1 Selection of airfoils
As stated earlier, the airfoil is one of the essential elements in the WT rotor design and is chosen on the basis of aerodynamic performance and applications. The airfoils intended for SWT, UAV and
other Low Re applications were selected on the basis of their aerodynamic performance. The performance investigation is carried out on the airfoils at low operating Reynolds number that reflects the urban wind conditions in India and this study aims to identify the airfoils with highest \( C_p \).

### Table 2. Airfoil geometrical Information

| Airfoil | Camber, \( \% C \) | Camber location, \( \% C \) | Thickness, \( \% C \) | Thickness location, \( \% C \) | LE radius, \( \% C \) | Angle Degree |
|---------|------------------|----------------------|-------------------|-----------------|----------------|-----------------|
| RG15    | 1.76             | 39.9                 | 8.928             | 31.4            | 0.00512        | 5.07°           |
| S7012   | 2.02             | 36.2                 | 8.75              | 29.1            | 0.00542        | 1.94°           |
| SD7037  | 2.99             | 42.2                 | 9.2149            | 27.8            | 0.00983        | 3.22°           |
| E193    | 3.57             | 41.1                 | 10.22             | 32.2            | 0.00570        | 5.56°           |
| SG6051  | 3.2              | 46.8                 | 12                | 35.1            | 0.0078        | 3.87°           |
| Sg6041  | 2                | 38.9                 | 10                | 36.1            | 8.22           | 5.57°           |

### 3. Theoretical Modelling

The theoretical investigation is used to determine the high-performance airfoils at operating Reynolds number, i.e. airfoils having a high lift to drag ratio using Xfoil and design of MWT rotor diameter of 30 cm through Qblade. The aerodynamic parameters such as lift and drag coefficients are the functions of angle of attack (AoA) and Reynolds number \([1,17]\). Therefore, in this study, AoA is varied from \(-4°\) to \(12°\) for three different Reynolds numbers.

#### 3.1 Xfoil

Xfoil is the panel code method iterative based design and optimization tool for subsonic airfoils, which predicts the aerodynamic characteristics of airfoils such as lift and drag for viscous or inviscid flows and free or forced transitions. In order to predict the aerodynamic characteristics of the airfoils with an acceptable range of accuracy, the airfoils with 240-panel nodes and suitable \( N_{crt} \) value of 8.15 are taken.

#### 3.2 Theoretical modelling Using BEM method

The wind turbine design involves expensive CFD tools to carry out performance evaluation and optimization. The BEM method is very economical and takes less computational resources to determine the power coefficient and Annual Energy Production. The Qblade is a tool which follows the BEM theory that has good agreements with experimental results for the same range of turbines as explained by et al. \([18]\).

The blade is divided into 10 segments, and the blade shape is determined based on the BEM theory with the inclusion of Glauert assumption. The complicated iterative procedure integrated with the BEM method to calculate the optimum geometry of the blade is performed by Qblade which follows the standard assumptions made in the BEM theory.

### Table 3. Blade parameters.

| Parameter                             | Value          |
|---------------------------------------|----------------|
| The radius of the blade (m)           | 0.15           |
| Hub Radius \((R_h)\) (m)              | 0.02           |
| Number of Blades                      | 3              |
| Area of blade \((m^2)\)               | 0.070685835    |
| density of air \((kgm^{-3})\)         | 1.225          |
| wind velocity \((ms^{-1})\)           | 3-7            |
| \(C_p\)                               | 0.35           |
| Design power \((watts)\)              | 5.19           |
4. Result and discussion

4.1 Aerodynamic Performance of Airfoils

The aerodynamic investigation of the SD7037, E193, RG15, SG6041, SG6051 and S7012 airfoils was carried out for the Reynolds numbers of 13416, 31306 and 44721, which reflects the starting wind speed, design and cut out Reynolds numbers of micro wind turbines. The aerodynamic performance of airfoil such as \( C_L/C_D \) ratio increases with increasing Reynolds number and also with increasing Angle of Attack (AoA) till stalling condition is reached.

At Re of 13416, S7012, SD7037 and RG15 airfoils produce relatively better performance reaching the \( C_L/C_D \) max of more than 6 at 4° of Angle of Attack (AoA) and also operates for a broader range of AoA. At Re 31306, which represents the operating wind speed condition of the rotor, the SG6041 and RG15 airfoils produce the maximum \( C_L/C_D \) ratio of 25 at the AoA of 7° as shown in Figure 1 SD7037, and S7012 airfoils reach \( C_L/C_D \) max of 20 and 23 respectively at 8° AoA. They also operate for a broader range of angle of attack. Moreover, the RG15, SG6041, S7012 and SD7037 airfoils attain the \( C_L/C_D \) ratio of above 30 in the range from 6° to 8° of AoA at Reynolds number of 44721 that represents the cut-out wind speed of the turbine.

Comparing the performances of three different Roof 13416, 31306 and 44721, RG15 and SG6041 airfoils suitable for maximizing the performance at rated condition. Better starting characteristics can be achieved when using SD7037 and S7012 airfoils due to their wider operating range of AoA. The \( (C_L/C_D) \) ratio of the high thick airfoils such as SG6051 and E193 are affected by the LSB phenomena which results in low performance as compared to other airfoils shown in Figure 2.

![Figure 1. \( C_L/C_D \) vs AoA at Re 13416, 31306 and 44721 for six airfoils.](image1)

![Figure 2. \( C_L \) and \( C_D \) vs AoA for different airfoils at Re 31306](image2)
4.2 Chord and Twist distribution

The inverse relationship between the aerodynamic lift of the airfoils and rotor chord is established in BEM theory. Hence, the maximum lift coefficient is attained by SG6051 and E193 airfoils resulted in low chord values as shown in figure 3. But, relatively low drag and medium-lift coefficients occur for RG15, SG6041, SD7037 and S7012 airfoils leading to higher C_l/C_D ratio. The use of larger chord values at the root section of the rotor creates axial thrust force which might lead to permanent damage as well as the performance degradation. The MWT has a shorter rotor which needs to overcome the blade inertia at low wind speeds in order to produce power. Hence the trade-off between the rotor inertia and solidity avoids the issues related to low chord and low-speed performance. The chord distribution of airfoils decreases with increasing the design Tip Speed Ratio (TSR). The chord distribution for RG15 and SD7037 airfoils has lower value compared to SG6041 and higher when compared with E193 and SG6051 airfoils. The chord distribution and power generation are shown in figure 3 and figure 5. SD7037 and RG15 airfoils exhibit better performance with more optimum chord values as compared to the rest of the airfoils.

The twist angle of the rotor is the difference between the angle of attack at which the maximum C_l/C_D occurs and relative flow angle of the rotor, so that the airfoil produces maximum C_l/C_D ratio at higher AoA, leading to lower twist angle range over the span. The twist angle of all airfoils decreases with increasing design TSR from 2.5 to 4 as chord vs TSR varies in Fig 3. The higher twist at the root of the rotor leads to the better low wind starting and reducing the idling time of the rotor. The low twist angles at the root of E193 and SG6051 airfoils result due to the larger operating AoA. Moreover, the twist angle distribution of SG6041 and RG15 are almost constant and having larger twist angle values as compared to SD7037, S7012, E193 and SG6051 airfoils shown in figure 4.

The solidity effect influences the performance of MWT rotors; the low design Tip speed ratio rotor generates more power than high design tip speed rotors due to subsequent chord distribution changes with respect to design TSR. At TSR of 2.5 and 900 rpm, SD7037 and RG15 airfoil reach 2.3 W at 7 ms\(^{-1}\) wind speed and at 3 TSR; both airfoils attain the power of 2 W at a rated wind speed of 7 ms\(^{-1}\). The power generation further decreases at rated and cut out wind speed for higher design TSR values as shown in figure 5. The turbine reaches the maximum power output of 2.3 Watts, that is more than enough to power up the individual sensors whose power requirement lies in the range of 10-100 mW[15].

![Figure 3. Chord distribution for different design TSR for SD7037, E193, RG15, SG6041, SG6051 and S7012](image)

![Figure 4. Twist distribution along the span for different design TSR for SD7037, E193, RG15, SG6041, SG6051 and S7012](image)
5. Conclusion
The 30 cm MWT rotor is subjected to the performance investigation to maximize the power extraction using the E193, SG6051, SD7037, S7012, RG15 and SG6041 airfoil aerodynamic characteristics over the Reynolds number of 13416, 31306 and 44721. The MWT performance is primarily influenced by chord and twist distribution from root to tip, design tip speed ratio and the aerodynamic performance of airfoils. The maximum power generation occurs at the design TSR of 2.5 and 3; however, the RG15 and SD7037 airfoils produce the maximum power of 2.3 W at a wind speed of 7 m s⁻¹ of wind speed and design TSR of 2.5. It reaches the power coefficient of 32% which is relatively higher than the similar range of turbines.

References
[1] Karthikeyan N, Kalidasa Murugavel K, Arun Kumar S and Rajakumar S 2015 Review of aerodynamic developments on small horizontal axis wind turbine blade Renew. Sustain. Energy Rev. 42 801–22
[2] Karthikeyan N, Kalidasa Murugavel K, Arun Kumar S and Rajakumar S 2015 Review of aerodynamic developments on small horizontal axis wind turbine blade Renew. Sustain. Energy Rev. 42
[3] Giguère P and Selig M S 1998 New Airfoils for Small Horizontal Axis Wind Turbines J. Sol. Energy Eng. 120 108
[4] Natarajan K, Thomas S and Ramachadran B 2016 Numerical investigation of airfoils for small wind turbine applications Therm. Sci. 20 1091–8
[5] Singh R K, Ahmed M R, Zullah M A and Lee Y-H 2012 Design of a low Reynolds number airfoil for small horizontal axis wind turbines Renew. Energy 42 66–76
[6] Henriques J C C, Marques da Silva F, Estanqueiro A I and Gato L M C 2009 Design of a new urban wind turbine airfoil using a pressure-load inverse method Renew. Energy 34 2728–34
[7] Pourrajabian A, Mirzaei M, Ebrahimi R and Wood D 2014 Effect of air density on the performance of a small wind turbine blade: A case study in Iran J. Wind Eng. Ind. Aerodyn. 126 1–10
[8] Wood D H 2009 Dual Purpose Design of Small Wind Turbine Blades Wind Eng. 28 511–27
[9] Kishore R A, Coudron T and Priya S 2013 Small-scale wind energy portable turbine (SWEPT) J. Wind Eng. Ind. Aerodyn. 116 21–31
[10] Lanzafame R and Messina M 2010 Power curve control in micro wind turbine design Energy 35 556–61
[11] Chen T Y, Liao Y T and Cheng C C 2012 Development of small wind turbines for moving vehicles : Effects of flanged diffusers on rotor performance Exp. Therm. Fluid Sci. 42 136–42
[12] Anant Kishore R and Priya S 2013 Design and experimental verification of a high efficiency small wind energy portable turbine (SWEPT) J. Wind Eng. Ind. Aerodyn. 118 12–9
[13] Xu F J, Yuan F G, Hu J Z and Qiu Y P 2014 Miniature horizontal axis wind turbine system for multipurpose application Energy 75 216–24
[14] Xu F, Yuan F-G, Liu L, Hu J and Qiu Y 2013 Performance Prediction and Demonstration of a Miniature Horizontal Axis Wind Turbine J. Energy Eng. 139 143–52
[15] Zakaria M Y, Pereira D A and Hajj M R 2015 Experimental investigation and performance modeling of centimeter-scale micro-wind turbine energy harvesters J. Wind Eng. Ind. Aerodyn. 147 58–65
[16] Lanzafame R and Messina M 2007 Fluid dynamics wind turbine design: Critical analysis, optimization and application of BEM theory Renew. Energy 32 2291–305
[17] N Karthikeyan T S 2016 Computational studies on Small Wind Turbine performance characteristics
[18] Monteiro J P, Silvestre M R, Piggott H and André J C 2013 Wind tunnel testing of a horizontal axis wind turbine rotor and comparison with simulations from two Blade Element Momentum codes J. Wind Eng. Ind. Aerodyn. 123 99–106