Implementation and Evaluation of a Low Speed and Self-Regulating Small Wind Turbine for Urban Areas in South Africa

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ABSTRACT

A low-cost small 500W wind generator was used as a basis for the prototype development. The research was primarily focused on the determination of the type of aerofoil for improved rotor blades and pitch angle, and for adapting the number of blades in order to optimize the power output from the prototype, for low wind-speed inland conditions in Soweto. NACA-4412 type aerofoil was chosen as a departure point for the blade design, and a variation of the maximum pitch angle of 6°, 10°, and 12° at an optimum angle of attack of 5°, 7°, and 9° were implemented respectively for Designs 1, 2 and 3. With the Soweto area having an average wind speed of 2.3m/s (8.28km/h), 3-, 5-, and 7-blade sets were subsequently developed, implemented, and tested. Prototype 1 produced a maximum output power of 8.2W at 4.2km/h wind speed. Prototype 2 yielded a maximum output power of 12.5W at 4.2km/h, and Prototype 3, generated a very useful power output of 39.5W during testing. The maximum power output was achieved at an average wind speed of 1.17m/s (4.2km/h). Moreover, the developed prototype designs were also tested for self-regulation in case of high-speed gust conditions. Prototype 3, with a 12° maximum pitch angle during operation in high gust conditions, had its blades control high speed. A drawback pressure occurred on the back side of the blades and tangent drag was developed normally to the blade rotation direction, consequently limiting the maximum speed of the rotor and acting as a self-regulation mechanism with regard to maximum achievable speed. The other two designs suffered from over-speeding tendencies in high gust speed conditions, also causing noise and turbulence.

Keywords-SWT design prototypes; self regulation; experimental results

I. INTRODUCTION

Population and technology use growth result in increased energy consumption and increased emissions of Greenhouse Gases (GHGs). The use of fossil fuels in the generation of electricity contributes significantly to GHG emissions, which contribute to climate change [1, 2]. Utilizing renewable energy as an alternative energy source will reduce environmental problems, essentially GHG emissions and air pollution [3]. Wind energy has seen a dramatic increase in development during the last 20 years [4]. This development occurred especially in the implementation of small-scale wind farms at households and business premises in urban areas, and in huger large-scale wind turbines in far off rural areas, where high wind speeds prevail. Large scale wind turbine systems are complex and expensive technology and energy has to be transported over large distances, while small scale wind turbines in urban areas can be implemented in an autonomous and low-cost basis. A preliminary review on recent designs and developments on Horizontal Axis Wind Turbines (HAWTs) will be discussed below.

Small wind turbines are characterized as having an output power of less than 50kW and operating at low wind speeds and low Reynolds numbers, which is common in the industry. The rotor blades are considered as the most critical component, as their aerodynamic efficiency has a direct effect on the turbine system's overall performance [5]. The blade design is influenced by various parameters, the most important of which is the aerofoil, which dictates the cross-sectional geometry of the blade. Numerous aerofoils have been designed expressly for small wind power generation [6-8]. Numerous methods and techniques have been developed over the last few years to increase the efficiency (performance) of wind turbines. These methods and techniques were supported by the empirical analysis and optimization of the wind turbine blade design characteristics. Blade Element Momentum (BEM) theory is a critical method for simulating and optimizing the performance of wind turbine blades [9].

A small wind turbine blade was designed and optimized to maximize blade number and tip speed ratio for solidity in [10]. In [11], a variety of BEM parameters for the design and optimization of small (less than 1kW) wind turbine blades at rated wind speed of 8.4m/s, was simulated in QBlade, and plots of CP and power versus tip speed ratio were shown. The SG6043 airfoil was selected because it had the maximum lift coefficient of 1.63. QBlade was used to simulate a 1.2m blade length. Authors in [12] investigated the performance of the rotor blade (horizontal axis) of a small wind turbine. The wind turbine was considered to operate ideally at low wind speeds and low Reynolds number (5×10^5). The rotor had a 2m diameter and 3 blades. The blade model was built utilizing 3 aerofoils (DU86-084, E387, and SD2030) with a tip speed ratio of 7. E387 outperformed the other two simulated aerofoils.

It is necessary to ensure that the turbine's protection is not compromised by turbulence and vibration effects. Thus, a critical feature of a wind turbine is power control, which prevents the wind turbine from being damaged at extremely high wind speeds [13].

In this article, the results of the undertaken work on the low cost mechanically self-regulating HAWTs, that were optimally designed and eventually implemented and tested in a residential area in Soweto, Johannesburg, South Africa, is presented. These test prototypes can be implemented at large volumes in middle-income households and can make a significant contribution to the generation of clean energy in South Africa.

II. METHODS

The methodologies applied in this project considered different perspectives and routes. The plan of action was eventually taken after a thorough literature review. Basic design choices would be made based on known considerations [13, 14].

A. BEM Theory Considerations [12]

In this analysis, the theoretically inter-relationships between pitch angle, blade solidity, maximum power coefficient, and tip speed ratio were studied. The study was conducted using the following theoretical considerations: a fixed experimental design route was chosen and implemented and predictive data were derived. One twisted blade design, fixed chords and varying number of blades (3, 5, and 7) mounted on a rotor diameter of 0.95m, were considered. The derived conclusion was that the optimum power coefficient is mainly dependent on pitch angle and tip speed ratio for the dimensions chosen in our design.

B. Chosen Design Procedure

The basic design choices considering low wind speed operating conditions were [15]:

- Not too large rotor diameter since noise, turbulence, and vibration, would be the primary functions of blade radius size.
- High pitch angle of the blades near the hub region of the blade. This approach would maximize the torque on the rotor axis at low wind speeds, while it would not cause an excessive apparent wind on the outer edges of the rotor. The optimum power coefficient is mainly dependent on the pitch angle and tip speed ratio.
- Since many physical and dynamic parameters, such as apparent wind speeds, apparent wind directions, and stall speeds are quite difficult to derive theoretically, it was decided to primary focus on designing and investigating the effect of (i) the number of blades and (ii) the pitch angle of the blade and the variation of these along the blade radius as a primary variation parameter. Increasing the radius and number of blades on the rotor, would increase the total wind capture area of the blades and the total power transfer.
- After reviewing the published specifications of commercially available wind turbines on the market, it was decided to implement a known and proven design within the NACA 44 family, and then vary the blade radius and the attack angle along the radius of the blade, and adapt these to the specific conditions in Soweto.
- Using the BEM theory and blade specifications of the NACA 44 family, it was derived that the electrical power output goal of about 380, 420, and 430W could be a reasonable output choice for a 3-, 5-, and 7-bladed, 1m radius systems, respectively.

These power levels seemed to be enough to generate and store a few kWh per day and power basic essential appliances in a medium scale house for a day or two.

C. Flow Chart of the Proposed Research

The flowchart of the undertaken research can be seen in Figure 1.

III. EXPERIMENTS AND RESULTS

The Soweto Small Wind Turbine (SWT) set contained a three-phase 500W synchronous generator which was used as a basis for optimizing the power output of the designed blades (3, 5, 7). The performance testing steps of the rotor-blade prototypes required the assembly of the following equipment associated with the wind turbine:

- Charge controller
- Two 12V batteries connected in series
- An off-grid inverter

- Output load
- Unit-B anemometer and power wattmeter

These components were coupled to the designed prototypes that were implemented. Figure 2 shows a block setup test diagram for the Soweto project.

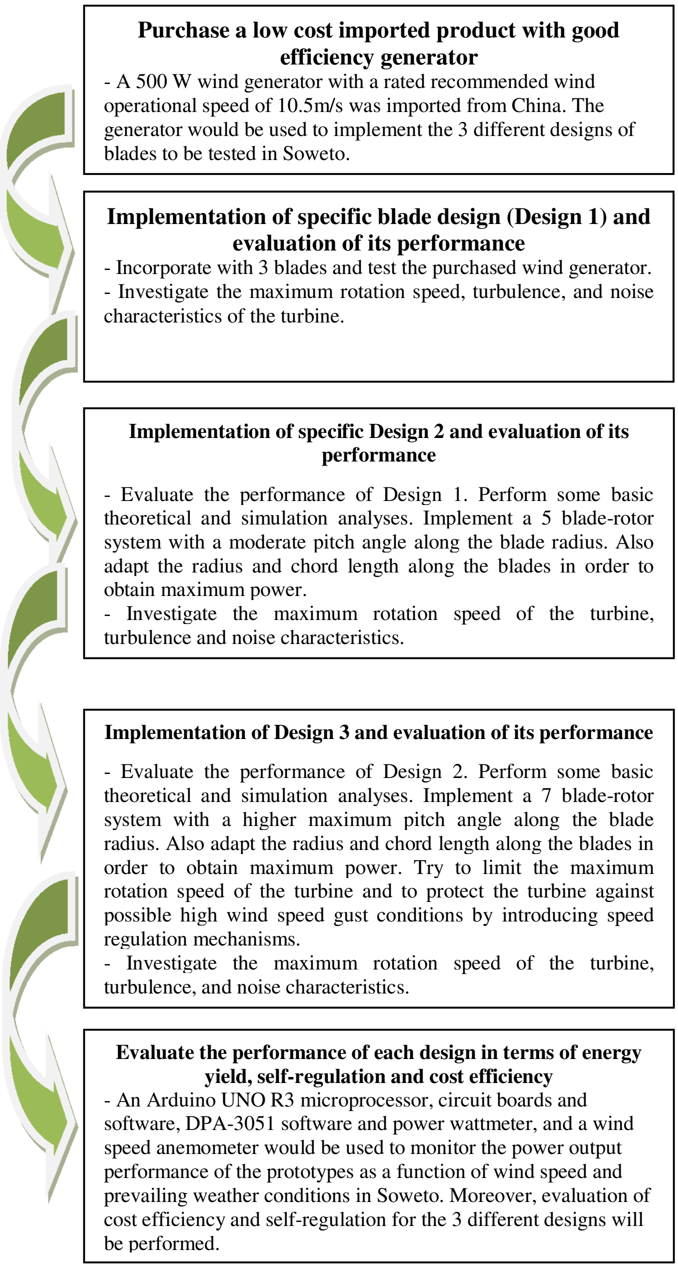

Fig. 1. The flowchart of the followed methodolody.

The prototypes were tested under conditions of full load (discharged batteries) and the experimental data were collected. All the tests were done at output voltage of approximately 19.0V, corresponding with a charger state of approximately 70% of the storage batteries. The same reference voltage of 19.0V was used at the start of each test. Appliances (LCD TV, sound equipment, DSTV decoder, and camera) were connected to the storage batteries, output controller, and off-grid inverter, especially during non-charging periods. Load conditions varied with power usage during the day and the passive resistive load was added. The tests were always initiated in early afternoon when wind speeds were picking up in Soweto. These provided the most practical conditions for testing and were nearest to true operational conditions. The 3-blade wind turbine system (Prototype 1) was implemented, as shown in Figure 3 and the experimental data shown in Table I were collected.

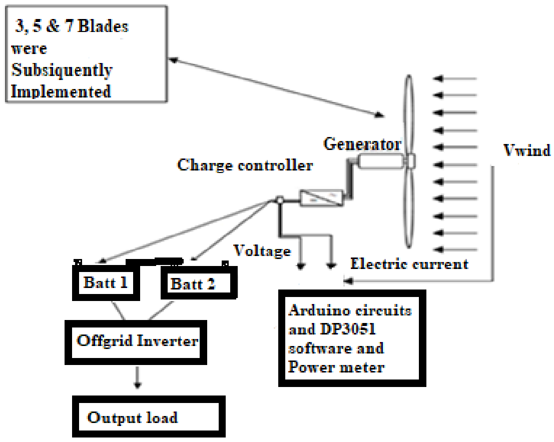

Fig. 2. Block setup test diagram for the Soweto project.

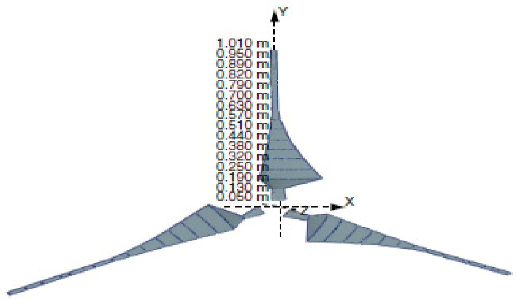

Fig. 3. 3-bladed system design view with maximum blade pitch angle of 6°.

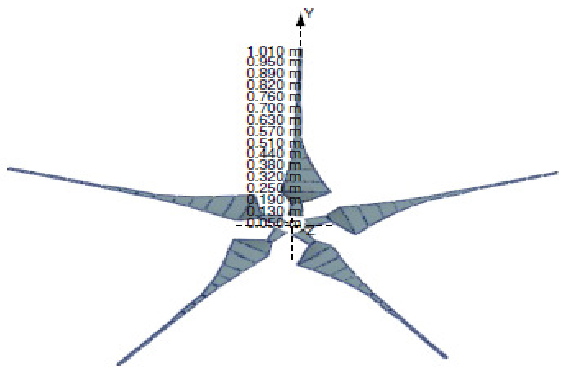

Fig. 4. 5-bladed system design view with maximum blade pitch angle of 10°.

TABLE I. EXPERIMENTAL DATA FOR PROTOTYPE 1

Wind speed (km/h)	Measured current (A)	Turbine speed (rpm)	Measured Voltage (V)	Real Power (W)	Calculated Power (W)
1.2	0.069	61	19.3	1.33	0.049
1.4	0.072	72	19.4	1.4	0.051
0.9	0.015	35	19.0	0.285	0.009
2.8	0.15	85	19.2	2.88	0.12
1.9	0.1	75	19.0	1.9	0.065
0.8	0.016	34	18.9	0.302	0.008
3.1	0.2	142	19.3	3.86	0.19
2.9	0.16	86	19.3	3.088	0.13
1.5	0.073	73	19.5	1.42	0.052
3.2	0.21	141	19.3	4.05	0.2
1.5	0.073	73	19.4	1.41	0.053
2.0	0.11	76	19.1	2.10	0.075
0.9	0.017	35	19	0.323	0.009
1.6	0.074	74	19.6	1.45	0.053
4.2	0.41	165	19.8	8.2	6.42
2.1	0.12	77	19.2	2.31	0.085
1.6	0.074	74	19.4	1.44	0.053
1.4	0.072	72	19.4	1.4	0.051
0.9	0.015	35	19.0	0.285	0.009
0.8	0.016	34	18.9	0.302	0.008
1.2	0.069	61	19.3	1.33	0.049
1.6	0.074	74	19.6	1.45	0.053
1.7	0.075	75	19.5	1.46	0.054
1.9	0.1	75	19.0	1.9	0.067
1.5	0.073	73	19.5	1.42	0.053

Figure 4 illustrates the 5-Blade wind turbine system (Prototype 2) implementation. Table II provides the experimental data collected for Prototype 2. Figure 5 illustrates the implementation of Prototype 3 (7-blade wind turbine system) and Table II shows the collected experimental data.

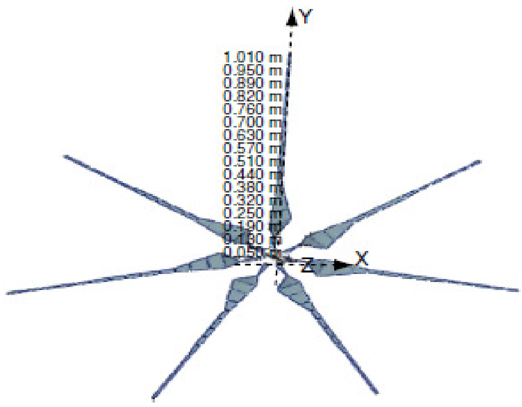

Fig. 5. 7-bladed system design view with maximum blade pitch angle of 12°.

A. Power Performance Comparison

During the design of the wind turbine blade for Prototype 3, it was predicted that the rated output should be 40W at rated Soweto wind speed of 2.3m/s (8.28km/h) [15]. As can be seen in Figure 6, during the comparison of the three prototypes, 40W was achieved at an average wind speed of 1.17m/s (4.2km/h).

TABLE II. EXPERIMENTAL DATA FOR PROTOTYPE 2

Wind speed (km/h)	Measured current (A)	Turbine speed (rpm)	Measured Voltage (V)	Real Power (W)	Calculated Power (W)
1.2	0.085	55	19.7	1.67	0.221
1.4	0.095	99	19.5	0.175	0.212
0.9	0.019	66	19.2	0.36	0.009
2.8	0.19	45	19.5	3.70	0.102
1.9	0.098	135	19.7	1.93	0.27
0.8	0.058	125	19.9	1.15	0.068
3.1	0.24	85	19.8	4.75	0.75
2.9	0.15	98	19	2.85	0.36
1.5	0.096	89	19.1	1.83	0.145
3.2	0.23	141	19.4	4.46	0.68
1.5	0.096	89	19.1	1.83	0.155
2.0	0.099	136	19.8	1.96	0.27
0.9	0.019	25	19	0.361	0.015
1.6	0.1	90	19.7	1.97	0.156
4.2	0.64	179	19.6	12.5	9.25
2.1	0.12	114	19.2	2.30	0.28
1.6	0.1	85	19.3	1.93	0.156
1.4	0.095	35	19.5	1.85	0.154
0.9	0.057	65	19.7	1.123	0.067
0.8	0.056	45	19.4	1.08	0.066
1.2	0.069	141	19.7	1.35	0.221
1.6	0.1	129	19.4	1.94	0.156
1.7	0.187	102	19	3.55	0.157
1.9	0.196	35	19.9	3.9	0.27
1.5	0.152	45	19.5	2.96	0.155

TABLE III. EXPERIMENTAL DATA FOR PROTOTYPE 3

Wind speed (km/h)	Measured current (A)	Turbine speed (rpm)	Measured Voltage (V)	Real Power (W)	Calculated Power (W)
1.2	0.14	141	19.7	2.75	1.25
1.4	0.12	99	19.5	2.34	1.58
0.9	0.1	121	19.2	1.92	0.089
2.8	0.15	123	19.5	2.93	1.36
1.9	0.13	101	19.7	2.56	1.58
0.8	0.09	112	19.9	1.79	1.989
3.1	0.43	85	19.8	8.55	1.997
2.9	0.33	99	19	6.9	1.37
1.5	0.28	102	19.1	5.5	1.57
3.2	0.39	141	19.4	7.58	1.898
1.5	0.27	126	19.4	5.3	1.58
2.0	0.36	123	19.2	6.9	1.59
0.9	0.16	99	19	3.2	0.088
1.6	0.31	75	19.7	6.1	1.55
4.2	0.98	225	19.6	39.5	28.5
2.1	0.37	110	19.2	7.2	1.61
1.6	0.28	99	19.9	5.6	1.59
1.4	0.26	141	19.5	5.2	1.58
0.9	0.16	121	19.7	3.2	0.089
0.8	0.16	113	19.4	3.1	0.090
1.2	0.21	121	19.7	4.2	1.25
1.6	0.31	99	19.4	6.1	1.55

Figures 7-9 illustrate the delivered output power observed at different pitch angles as implemented in the prototype designs. Prototypes 1, 2 and 3 were respectively implemented with a maximum pitch angle of 6°, 10°, and 12° near the rotor of the turbine and were tested for wind speed values of 0, 0.4, 0.8, 1.2, 1.6, 2, 2.4, 2.8, 3.2, 3.6, 4, and 4.2km/h. It can be seen in Figure 9, that Prototype 3, which was designed for a 12° pitch angle, generated a maximum power output of 39.5W when compared with Prototype 2 (Figure 8), which was designed for pitch angle of 10°, whereas maximum power output of 12.5W was observed. For Prototype 1 (Figure 6), which was designed for pitch angle of 6°, the maximum power output was only 8.2W.

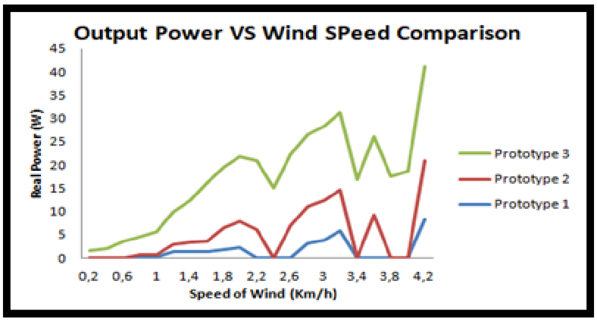

Fig. 6. Wind speed vs. real power.

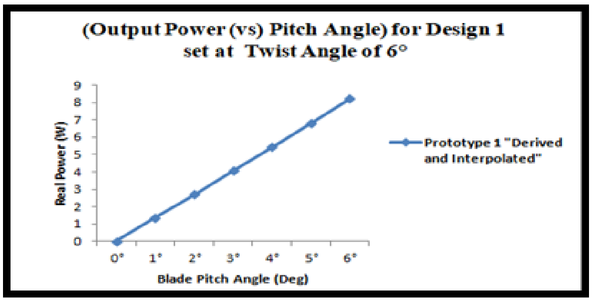

Fig. 7. Prototype 1, delivered power vs variation of maximum pitch angle.

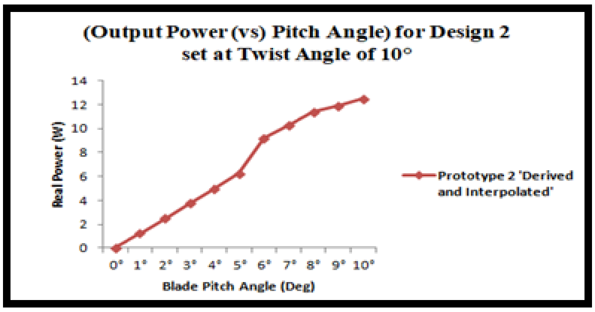

Fig. 8. Prototype 2, delivered power vs variation of maximum pitch angle.

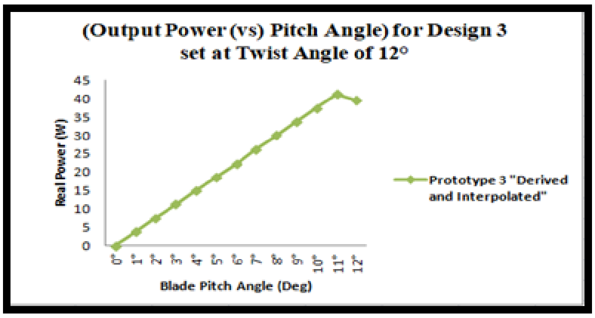

Fig. 9. Prototype 3, delivered power vs variation of maximum pitch angle.

The results shown here are of course also dependent on the number of the blades. Nevertheless, a deduction can be made that the high pitch angle setting in Prototype 3 had a substantial impact on the higher power delivery observed in Figure 9.

A. Prototype Energy Delivered versus Time of day/month

Figure 10 shows the delivered energy versus time for a 24-hour period. It can be seen that Prototype 3's performance significantly outclassed those of Prototypes 2 and 1 during the day as there was a consistent generation of energy. Figure 11, shows the energy production of Prototypes 1, 2 and 3 per month during operation at Soweto. It can be seen that Prototype 3 outclassed Prototype 1 and 2 in terms of energy generated per month. Prototype 3 achieved 39.5W output for a wind speed of 1.17m/s and was predicated to generate a maximum 40 kWh per month.

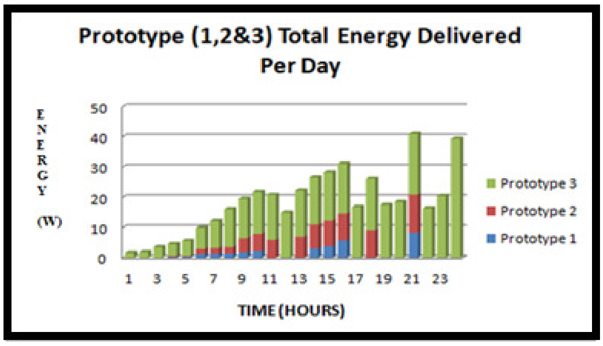

Fig. 10. Delivered power vs time per day.

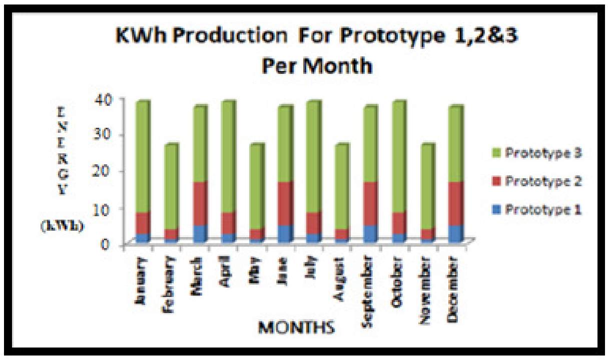

Fig. 11. Predicted total energy delivered per month in Soweto.

IV. DISCUSSION

The results showed that a Prototype 3 with a 7-blade design and with a maximum pitch angle of 12° produced maximum output power of 39.5W during testing, achieved at about 1.17m/s (4.2Km/h) wind speed**.** The Prototype 2, with a 5-blade design and blade pitch angle of 10°, produced maximum output power of 12.5W at 4.2km/h wind speed**,** and Prototype 1 with a 3-blade design and a pitch angle of 6°, produced a maximum power output of 8.2W at 4.2km/h wind speed**.** The results, furthermore, confirm that increasing the pitch angle from the standard 6° used for NACA 4412 specifications to 10° and 12° near the hub and tapering/twisting to lower angles of the tip of the blade, and optimizing the attack angle to about 5, 7, and 9° along the section of the blade radius for 1, 2, and 3 designs, respectively, definitely increased the power delivery and the total energy capture of the rotor. These settings were derived from the available specifications and the published literature. The 7-blade prototype with NACA-4412 blade design is an original implementation in Soweto, Johannesburg environment. Derivation of the results and predictions for other areas in South Africa (specifically, Soweto and Port-Elizabeth) [16], contributed to new knowledge created within the field of the study.

V. CONCLUSIONS

The current study is primarily focused on determining and adapting low-cost technologies applicable to South African conditions. This included the choice of the type of aerofoil, the number of blades, and optimizing the pitch angle along the blade radius in order to maximize the power output for low wind speed conditions in Soweto. The main conclusions derived from the current study are:

- In Soweto area, having an average wind speed of 2.3m/s (8.28km/h), 3-, 5-, and 7-blade sets were developed and tested. The obtained results definitely indicate that for very low wind speed conditions, the implementation of more blades on single rotor/hub increased the captured power and energy significantly.

- Moreover, the developed prototype designs were also tested for self-regulation in case of high speed gust conditions. The results showed that the blades of Prototype 3, with 12° maximum pitch angle during operation in high gust conditions, would control high speed, then cause a drawback pressure on the back side of the blades and tangent drag developed normally to the blade rotation direction, consequently limiting the maximum speed of the rotor and acting as a self-regulation mechanism of the maximum achievable speed. The other two designs suffered from over-speeding tendencies in high gust speed conditions, also causing noise and turbulence.

- Finally, it can be deduced that the power derived from the 7-blade system would be close to the expected optimum power that would be delivered for the designed 1m blade rotor system. Any implementation of a higher pitch angle along the blades would, according to the theoretical considerations, probably lead towards an excessive angle of attack.

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