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Design and Simulation of a Wind Turbine for Electricity Generation

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Abstract

This study is focuses on the design of a cost effective wind turbine for electricity generation using locally sourced materials. The design of the turbine takes into the reduction in the weight and size of the turbine thereby lowering production and installation costs. This increases the efficiency by increasing the resistance from dynamic loads and reduction of acoustic noise discharge. The locally sourced materials employed include the; blades, hub, a permanent magnet motor as generator, tower, electric starter and fan as well as a controller. The wind turbine designed as a power controlled, variable speed, 3-bladed horizontal axis upwind turbine. Its airfoil characteristics include maximum thickness 10.02% at 32.1% chord, maximum camber 5.5% at 49.7% chord. The blade design of the airfoil SG 6043 was performed in Q-blade software to generate the aerodynamic properties of SG 6043 while the control was simulated in the Matlab Simscape and Simulink 2017a environment. The aerodynamic properties include the angle of attack which is 2.2° and the maximum twist angle which is 25.66°. Aluminum was employed as the material for the blade for cost effectiveness and weight reduction. In addition, the choice of aluminum as the material for the blade results in considerable reduction in weight as opposed to carbon or other materials in existing design. This work also provides design data for the development of wind turbine system as well as a suitable template for scaling the future development of wind turbine system.

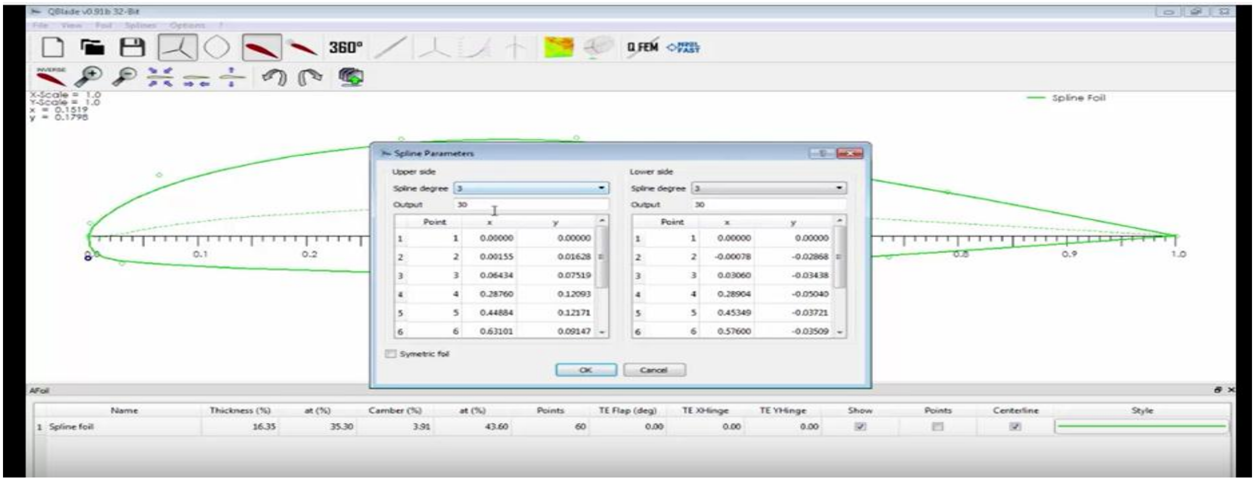
Keywords: Controller, Dynamic Loads, Electricity, Wind Turbine, Motor

1. INTRODUCTION

Wind energy or wind power involves the generation of mechanical power from wind (Amdi *et al.,* 2012; Devbratta and Jin, 2017). A wind turbine is a device that converts kinetic energy from the wind into electrical power (Wood, 2011; Kunduru *et al.,* 2015). Today, an ever increasing number of individuals are utilizing wind turbines to wring power from the breeze. Over the previous decade, wind turbine utilization has expanded at more than 25 percent a year (Sambo, 2008; Burton, 2011). Wind turbines work on a basic standard. The energy in the wind turns the blades fixed around a rotor, the rotor connected to the primary shaft also turns the generator to produce mechanical power (Kersten, 1998; Adrid, 2007). A quantitative measure of the wind energy accessible at any area is known as the Wind Power Density (WPD) (Gipe *et al.,* 2009). It is a calculation of the mean yearly power accessible per square meter of swept area of a turbine. The wind power density, measured in watts per square meter, shows how much energy is accessible at the site for transformation by a wind turbine Wind turbine can be vertical, horizontal upward or downward (; Gordan *et al.*, 2001; Gasch *et al.*, 2002; Horikiri, 2011). Aerodynamic lift is the force that overcomes gravity and is in a right angled direction to the wind flow. It occurs due to the uneven at pressure on the upper and lower aerofoil surfaces (Gosh, 2002) while aerodynamic drag force is parallel to the direction of oncoming wind motion (Dabiri, 2011). Drag occurs due to uneven pressure on the upper and lower aerofoil surfaces (Yurdusev, 2006; Dominy, 2007; Holdsworth, 2009; Navin *et al.,* 2014). According to Heier (1998), the use of wind power reduces the chances of environmental pollution. Also, in remote areas lacking purchased electricity, wind energy is the best alternative because it is a renewable resources (Okoro *et al.*, 2010). In addition, the use of wind energy will be suitable and cost effective for rural farming due to its location. (Amuna and Okoro, 2006). Many works have been reported on the modeling and simulation of wind turbine system for optimum generation of energy. For instance, Roshen and Mahdi (2017) used Matlab-Simulink for the modeling and simulation of turbine generator while Devbratta and Jin (2017) developed a wind turbine simulator for integration to a microgrid and Erchiqui *et al.* (2014), performed umerical investigation of vibration and dynamic pressure of a vertical axis wind turbine 421. These works provided modeling and simulation analysis for the developmental frame work of wind turbine system. This aim of this work is to design a cost effective wind turbine for energy generation using locally sourced materials. The design of the turbine takes into the reduction in the size of the turbine thereby lowering production and installation costs. This increases the efficiency by increasing the resistance from dynamic loads and reduction of acoustic noise discharge. The design, control and dynamic simulation of the wind turbine system using the combination of two versatile software namely Q-blade software and MATLAB Simulink has not been sufficiently reported in the existing literature.

2. METHODOLOGY

The Q blade software was employed for the model design of the blade and rotor as well as its simulation (Figure 1). This is because the software is very versatile as it shows the relationships of the design concepts and turbine performance. In addition, it can sufficiently carry out complex calculations as well as turbine blade design and optimization. Many calculations, design variables and relationship relating to the blade twist, blade chord, section airfoil performance, turbine control, power and load curves as well as the rotor simulation were obtained with the use of the software.



Spline Parameters

Upper side
Spline degree: 3
Output: 30

	Point	x	y
1	1	0.00000	0.00000
2	2	0.00155	0.01628
3	3	0.06434	0.07519
4	4	0.28760	0.12093
5	5	0.44884	0.12171
6	6	0.63101	0.09147

Lower side
Spline degree: 3
Output: 30

	Point	x	y
1	1	0.00000	0.00000
2	2	-0.00078	-0.02868
3	3	0.03060	-0.03438
4	4	0.28904	-0.05040
5	5	0.45349	-0.03721
6	6	0.57600	-0.03509

☐ Symetric foil

OK Cancel

	Name	Thickness (%)	at (%)	Camber (%)	at (%)	Points	TE Flap (deg)	TE XHinge	TE YHinge	Show	Points	Centerline	Style
1	Spline foil	16.35	35.30	3.91	43.60	60	0.00	0.00	0.00	☑	☐	☑	

Figure 1: Modelling the wind turbine system with the Q blade software

2.1 Design and Assembly of Turbine Components

For the wind turbine system, all the components which include the blades, the hub, the generator and the tower, the controller are individually designed and though in these parts selection, alternatives were available but after considering the cost, machinability and reliability. The following design specifications were realized.

2.1.1 Blade

The wind turbine is a power controlled, variable speed, 3-bladed horizontal axis upwind turbine (HAWT). Since this is a small turbine, a pitch direction framework would be too expensive and complex, yet a variable speed rotor is important to track ideal TSR for most extreme vitality catch of IEC Class III wind speeds. A 3-bladed rotor (shown in Figure 2) was chosen to reduce tower top wavering oscillation and blade length for easy movement. An upwind HAWT setup was chosen to provide the blades clean air and in light of the fact that it generally has more noteworthy efficiency over Vertical Axis Turbines which is basic for low wind speeds.

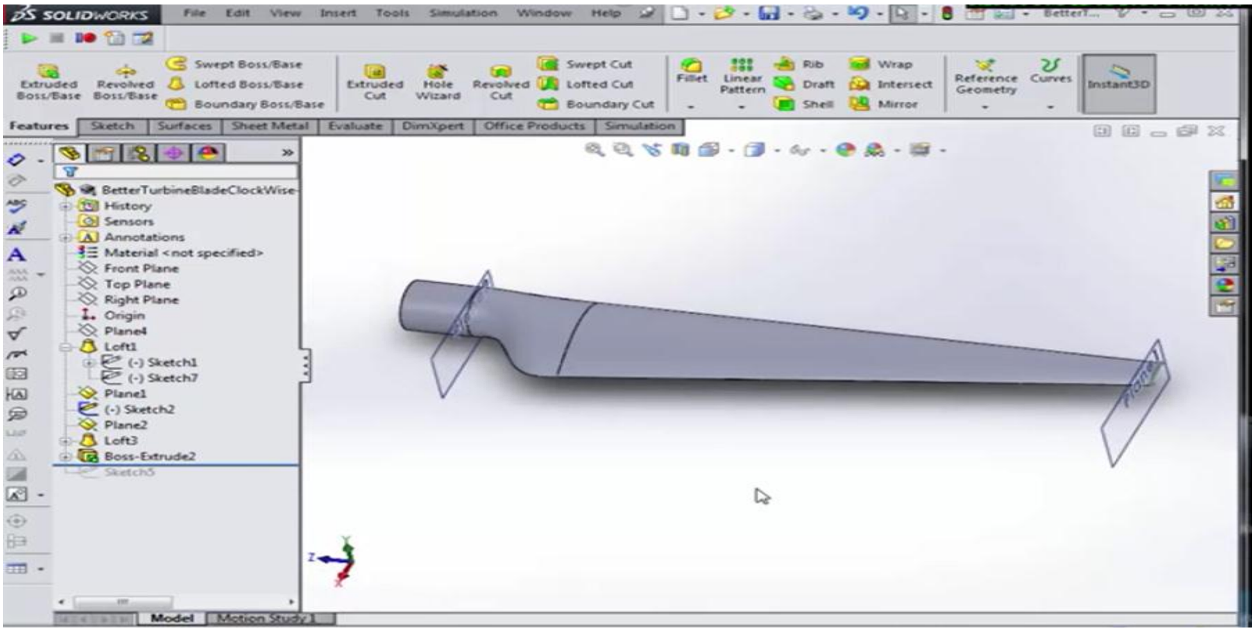


Figure 2: Blade rotor design

2.1.2 Materials

To assemble a solid blade material, for example, Pre-Preg carbon combines the merit of strength with stiffness more than the fiber glass but it is relatively costly. Therefore, aluminum is preferred for this small-scale wind turbine blade material because of its low weight and cost effectiveness in assembling contrasted with carbon

Design of the blades is aimed at achieving the best result when it comes to electricity generation at the most economic cost without compromising the standard. The blade is curved to allow lift forces at the tip of the blades causing them to move faster hence generating more power and higher efficiencies.

2.1.2 Hub design

The wind turbine system is designed to consist of three blades attached to the hub, the hub is also attached to the motor. The hub is also designed to have grooves to accommodate blade connection.

2.1.3 Generator

Ideally, a generator is meant for this designed but on the basis of economic concerns a motor is used. A generator produces either by using induction, excitation or permanent magnets, it is for this reason a permanent magnet motor is used. Inside a permanent magnet motor is a coil of wound copper encompassed by permanent magnets. These motors rotate utilizing electromagnetic induction, which implies electricity is provided to wound copper wire which makes a magnetic field. The magnetic field made by the electricity flowing through the copper wire restricts the permanent magnets in the motor housing. Thus, the copper wire that is joined to the pole of the motor tries "to propel" itself far from the permanent magnets thus rotation is achieved. Turning the copper wire by utilizing the energy from the breeze within the sight of the magnets makes a voltage distinction between the two closures of the copper wire. The distinction in voltage causes the electric charges (electrons) to stream in the copper wire, producing electric current.

Therefore, for this design, a tread mill motor is used as the generator because of its robustness and effective nature. They are durable, readily available and they meet the economic requirements of the wind turbine design. Also, they are permanent magnet motors thus, from the explanation previously stated, they can be used in place of generators when put in use and the output current can be used to charge batteries. The volts to rpm ratio is also considered in the design. The motor is to be of high voltage, low speed and high current so that the motor can produce a reasonable output after the shaft has undergone a considerable rotation. The blades are attached to the motor via the hub and then blades on the mounting that keeps it turned in the wind turbine. The generator is shown in the Figure 3.

Figure 3: DC motor with 12 V output

2.1.4 Nacelle and tower

The nacelle and tail are injection formed from a plastic from the rotor to keep up high generation runs and drivetrain security. The turbine is 5 long, 3 0.5 m in diameter with partially threaded 316 stainless steel rods and tie downs (Figure 4). The wind turbine will fuse a variable stature tower by utilizing commercial long, width, partially threaded stainless steel rods and tie downs. The wind turbine will incorporate a detached tail vane for tower top yawing to track the wind. This is regularly the best yawing system for little wind turbines because of the low torque required.

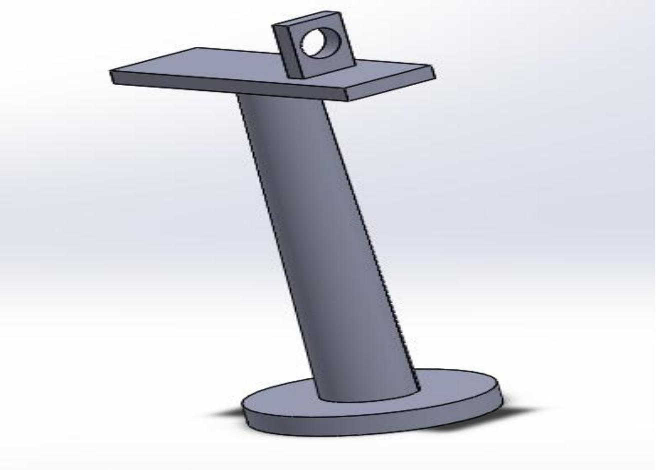


Figure 4: The model of the tower

2.1.5 Electric starter

An electric starter is a device that controls the use of electrical power to an equipment, usually a motor (see Figure 5). As the name implies, starters “start” motors. The starter is used to control fluctuating current from the electric motor to the load. The starter sends current to the load gradually to prevent breakdown either due to unstable power from the wind or overloading.

Figure 5: Electric starter

2.1.6 Electric fan

The fan consists of an arrangement of blades which rotates thereby acting on the fluid. The fan takes some of the output from the battery to provide power for itself. The fan shown in Figure 6 is used to check no-wind situation which can reduce the efficiency of the turbine.

Figure 6: Electric fan

2.1.7 Electronic control system

The controller is used to control the rotation along the longitudinal axis and to control the charge of the battery by displaying the voltage of the battery constantly. When the battery is below the discharge value, the turbine enters charging mode and when it reaches the discharge value, but still below terminal voltage battery, the turbine power with an automotive relay can be switched between charging mode or dumping mode (dumping the turbine power into a dummy load). When the battery reaches the full terminal voltage, the charging is cut off and current from the turbine is sent to the dummy load. A Light Emitting Diode (LED) is integrated into the design to facilitate indicating the charging mode and dumping mode. The circuit of the control system connected to a 12 V battery, relay and turbine is shown in Figure 7.

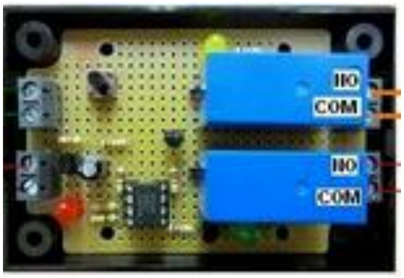


Figure 7: The Control circuit

2.2 Design calculations

2.2.1 Power

The kinetic energy E (Joule) of a mass of body in motion is obtained is expressed as Equation 1.

$$E = \frac{1}{2}mv^2 \qquad (1)$$

$where$; m is mass *(kg)*; v is velocity *(m/s)*

But the power is defined as the rate of change of energy, thus

$$P = \frac{dE}{dT} \qquad (2)$$

Where;

$\frac{dE}{dt}$ is the energy flow rate, (J/s)

If the kinetic energy of the wind is assumed to be of constant velocity, then the wind power can be calculated from Equation 3

$$P = \frac{1}{2}v^2\frac{dm}{dt} \qquad (3)$$

Where;

v =is wind speed, (m/s); $\frac{dm}{dt}$ is the mass flow rate, (kg/s).

Also the mass flow rate is expressed by Equation 4

$$\frac{dm}{dt} = \rho A\frac{dx}{dt} \qquad (4)$$

ρ is the density, (kg/m^3);A is the swept area, (m^2); $\frac{dx}{dt}$ is the rate of change of distance expressed by Equation 5.

$$\frac{dx}{dt} = v \qquad (5)$$

Therefore, substituting Equation 5 into 4;

$$\frac{dm}{dt} = \rho Av \qquad (6)$$

Hence, from the Equation 3 and 6, the power is expressed as Equation 7.

$$P = \frac{1}{2}\rho A v^3 \tag{7}$$

The equation of the area of circle is expressed by Equation 8

$$A = \pi r^2 \tag{8}$$

where; the radius r (m) is equal to the blade length

Considering the Betz limit, the theoretical maximum power efficiency for wind turbine system is 0.59 (In other words, close to 59% of the energy conveyed by the wind can be separated by a wind turbine). This is known as the "power coefficient" and is characterized as Equation 9.

$$C_{pmax} = 0.59 \tag{9}$$

The Cp value being a function of wind speed is exceptional to every types of wind turbine types. Consequently, the power coefficient is obtained from Equation 9, while the amount of power that can be generated from the wind is expressed by Equation 10.

$$P = \frac{1}{2}\rho A v^3 C_p \tag{10}$$

2.2.2 Wind speed

The wind speed is the average incident speed on the swept area by the blade and it is important in determining the value of the Reynold's number and is expressed by Equation 11.

$$Re = \frac{\rho u c}{\mu} \tag{11}$$

Where; ρ is the density (1.225 kg/m^3), u is the rated output wind velocity (18 m/s), c is the chord length of the blade (0.1 m) and μ is the dynamic viscosity of the air fluid (1.983×10^{-5} NS/m^2).

Reynolds number of the fluid flowing over the airfoil shape is calculated as follow;

$$Re = \frac{\rho u c}{\mu} = \frac{1.225 \times 18 \times 0.1}{1.983 \times 10^{-5}} = 111195.15$$

Since the value of the Reynolds number is greater than 4,000, the flow is said to be turbulent.

2.2.3 Angle of attack

The blade pitch is adjusted to control the angle of attack in amplifying the lift; however, a similar element can be utilized for safety purposes. Amid unfavorable climate condition, the blades' angle of attack can be lessened to zero with the goal that it creates no lift. A maximum angle of attack of 2^o was obtained from the simulation. An increase in the angle of attack beyond 2.2^o decreases the lift-drag ratio.

2.2.4 Power extracted

It is imperative to ascertain how much accessible power is removed by the turbine blade configuration in order to determine the efficiency of its operation. This is expressed by Equation 12.

$$P = T\omega \tag{12}$$

Where T is the torque (Nm) and ω is the angular velocity (rad/sec). Torque T is expressed by Equation 13.

$$T = Fr \tag{13}$$

Where F is the force (N) and r is the radius (m) from the center position.

Therefore, the efficiency of the wind turbine is as expressed by Equation 14.

$$C_p = \frac{P_R}{P} \tag{14}$$

Where;

P_R is the power extracted (Watt) and P is the power available (Watt)

The efficiency of the wind turbine system gives a smart thought the correct positioning of the turbine system. The correct positioning of the system increases the efficiency of its operation and vice versa. The wind turbine additionally winds up with some loss in efficiency to beat the frictional effects and some energy is lost in the process in the form of noise and heat.

Also, the torque obtained from the rotor is expressed by Equation 15.

$$T_r = \frac{\rho \pi r^3 V^2 C_p}{2} \tag{15}$$

The torque and the power coefficient C_p can be represented analytically as a function of the tip step ratio (λ) and pitch angle (β) as expressed by Equation 16.

$$C_p = k_1\left(\frac{k_2}{\lambda_1} - k_3\beta - k_4\beta^{k3} - k_6\right)\left(e^{\frac{k_2}{\lambda}}\right) \tag{16}$$

where; $\lambda_1 = \frac{1}{\lambda + k_8}$ (17)

2.2.5 The swept area

Rotor radius is the total sum of the hub radius and blade span calculated as 0.6 m

Using rotor radius 0.60 m, the value of the swept area A, is calculated as follow;

Thus we have;

$$A = \pi r^2 = \pi * 0.6^2 = 1.1311\, m^2$$

The plan form area is given by: $S = c \times b = 0.1 \times 0.3 = 0.03\, m^2$

Therefore, the Aspect Ratio is: $AR = \frac{b^2}{S} = \frac{0.3^2}{0.03} = 3$

The lift L is calculated as

$$L = \frac{1}{2}\rho v^2 C_l s = \frac{1}{2} \times 1.225 \times 18^2 \times 1.2 \times 0.5 = 119.07\, N$$

The C_d is calculated using airfoil lift value, hence

$$\frac{L}{D} = \frac{C_l}{C_d} \tag{18}$$

$$\frac{23.52}{1.2} = \frac{1.2}{C_d}$$

$$C_d = 0.061$$

2.2.6 Wind turbine power

At a wind speed V of 18 ms^{-1}, air density ρ of 1.225 kg/m^3 and rotor radius R of 0.60 m, the wind power is calculated using Equation 10.

$$Wind\ Power = \frac{1}{2}\rho A V^3 = \frac{1}{2} \times 1.225 \times 1.311 \times 8^3 = 4.683\ kW$$

But taking into account Betz limit and machine efficiencies, power to be generated can be derived from the Equation 19.

$$P = 0.6CpNAV^3 \qquad (20)$$

Where,

C_p is the power coefficient which is usually used as 0.4; N is the efficiency of driven machinery given as 0.7 and A is the swept rotor area which is 1.1311 m^2

Therefore, the power generated by the turbine is

$$P = 0.6CpNAV^3 = 0.6 \times 0.4 \times 0.7 \times 1.1311 \times 18^3 = 1.108\ kW$$

The dynamic pressure of the fluid is expressed by Equation 21.

$$P_d = \frac{\rho u^2}{2} \qquad (21)$$

Where; P_d is the dynamic pressure (Pa) and u is the fluid velocity (m/s).

$$P_d = \frac{1.225 \times 18^2}{2} = 198.45\ Pa$$

2.2.7 The rated revolution

Now at tip speed ratio TSR of 6, fitting the revolution to the wind speed and radius of rotor, the revolution per minute is calculated from Equation 22.

$$Revolution\ (rpm) = \frac{V\,TSR60}{6.28R} = \frac{18 \times 6 \times 60}{6.28 \times 0.6} = 1719.74\ rev/min$$

The power generated by the turbine is calculated as 1.108 kW at 1719.74 rev/min respectively.

The speed of the blade tip is expressed by Equation 22.

$$blade\ tip\ speed = TSR * wind\ speed \qquad (22)$$

$$blade\ tip\ speed = 6 * 18 = 108\ m/s$$

2.3 Design of control system for the wind turbine using MATLAB Simscape and Simulink

There is need for control so as to keep critical parameters that determines the efficiency of aerodynamics as well as the power extracted such as wind speed, yawing angle, blade pitch, pitch angle, angle of attack, torque etc. within the designed limits. Using the Matlab Simscape and simulink, the electrical connection and control are shown in Figures 8 and 9 respectively. Using the Proportional and Integral control (PI), the set point reference value of each measured parameter is compared with the actual value measured and the error is corrected by the actuator which changes the system to curb the effect of external disturbances. The proportional term (P) corrects the gross error while the integral term (I) eliminates the residual error by integrating it over a period of time (T).

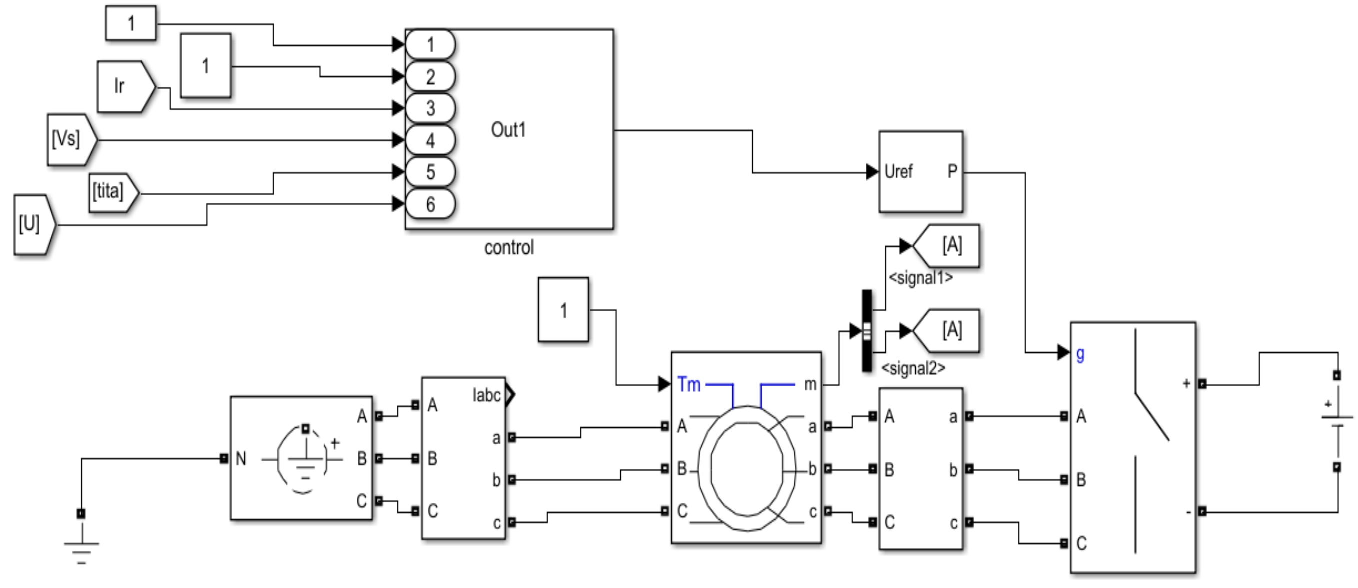


Figure 8: The electrical connection

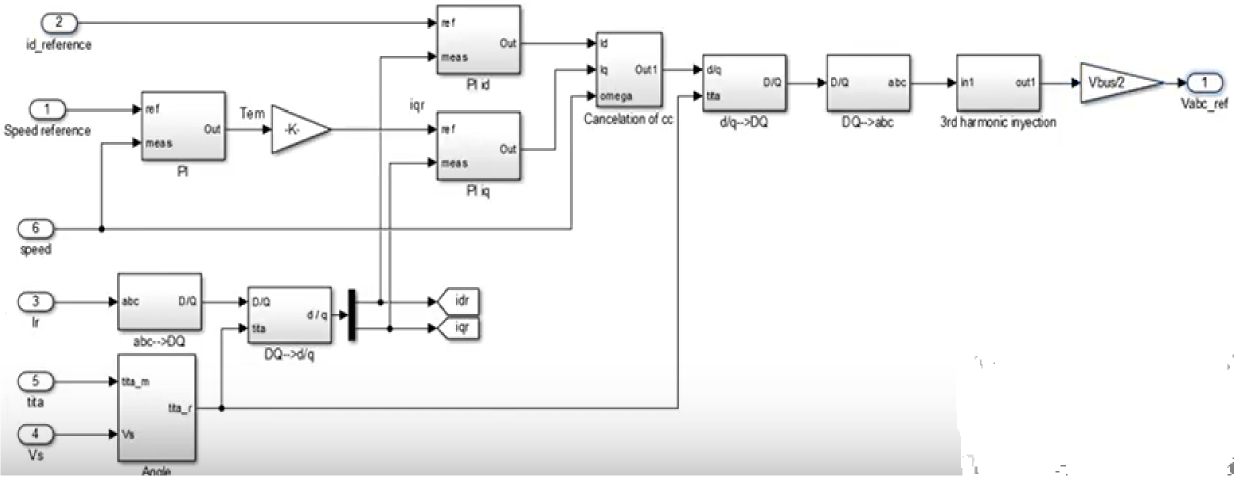


Figure 9: The Control system

3. RESULTS AND DISCUSSION

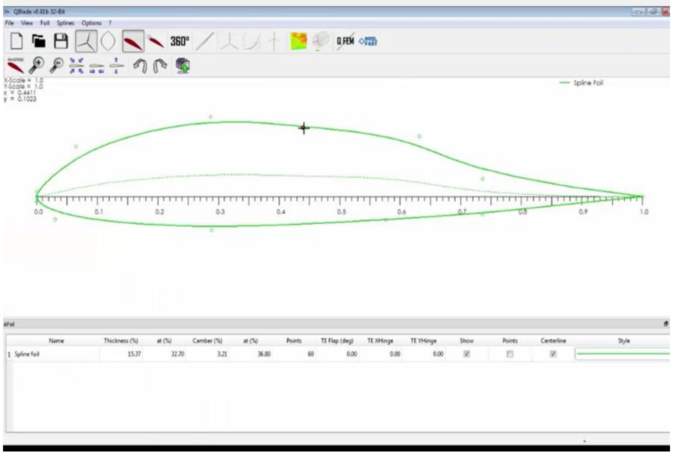
The main reason for the model design and simulation of the turbine blade and SG 6043 airfoil is to obtain maximum aerodynamics and power efficiency. From the simulation, the aerodynamics and power efficiencies increases by 3% as the number of blades increases from 2 to 3. Further increase in the numbers of blade from 3 to 4, results in marginal increase in the aerodynamics and power efficiencies by 0.5%. Hence, the optimum number of blades selected was 3, this is because increase in the numbers of blade beyond 3 results in marginal increase in the aerodynamics and power efficiencies coupled with the fact that the cost of the wind turbine system increases with increase in the number of blades. Also, the optimum blade length obtained was found to be 0.5 m. Further increase beyond this length will results in deflection of the blades and collision of the blades during operation with attendant decrease in the aerodynamics and power efficiencies. Since the fluid flows in different direction and with different velocity, a thin blade with thick root in shape and orientation was found to be sufficient to withstand axial wind load due to bending stresses. The design specifications obtained for design of the turbine blade and SG 6043 airfoil is presented in Table 1.

Table 1: Design of the turbine blade and SG 6043 airfoil

S/N	Parameter	Value
1.	Tip speed ratio	6
2.	Length of each blade	0.5 m
3.	Number of blade	3
3.	Hub radius	0.1 m
4.	Cut-in speed	3 m/s
5.	Rated output speed	18 m/s
6.	Cut-out speed	25 m/s
7.	Chord length	0.1 m
7.	Tower height	60.96 m

3.1 Airfoil selection

The wind turbine is intended to be capable of producing considerable power even at low wind speed. For this purpose, airfoil section chosen was the SG 6043 (see Figure 10) which was designed especially for small wind turbines. Its airfoil characteristics include maximum thickness 10.02% at 32.1% chord, maximum camber 5.5% at 49.7% chord. The blade design of the airfoil SG 6043 was performed in Q-blade software; it was used to generate the aerodynamic properties of SG 6043. The aerodynamic properties include the angle of attack at which the wind strikes the blade which is 2.2° and the maximum twist angle which is 25.66°.



X-Scale = 1.0
Y-Scale = 1.0
x = 0.4411
y = 0.1023

	Name	Thickness (%)	at (%)	Camber (%)	at (%)	Points	TE Flap (deg)	TE XHinge	TE YHinge	Show	Points	Centerline	Style
1	Spline foil	15.37	32.70	3.21	36.80	60	0.00	0.00	0.00	☑	☐	☑	

Figure 10: Airfoil SG 6043

3.2 Simulation of the SG 6043 airfoil

The simulation of the SG 6043 airfoil is shown in Figure 11. The dynamic pressure which is the kinetic energy per unit volume of the fluid is a function of the static and stagnation pressure as well velocity of the moving fluid. From Figure 11, the speed of the turbine reduces as the dynamic pressure increases thereby reducing the power extracted from the wind. This agrees with the Bernoulli's theorem and the law of conservation of energy. However, from simulation, a cut in speed of 3 m/s and a cut out speed of 25 m/s is sufficient for the required operation. At a cut in speed of 3 m/s, the torque produced by the wind is relatively insufficient for to make the blade rotate. An increase in speed beyond 3 m/s increases the blade rotation hence more electrical power is generated in the process. The power output reaches the limit the generator is capable of producing at an optimum speed 18 m/s, this is known as the rated output wind speed. Further increase beyond this speed up to the cut off speed (25 m/s) can damage the rotor hence the operation of the rotor can be halted via the use of a braking system. From simulation, the maximum and dynamic pressure was observed as 678.79 Pa and 239.00 Pa respectively while the minimum dynamic pressure from manual calculation gives 198.45 Pa.

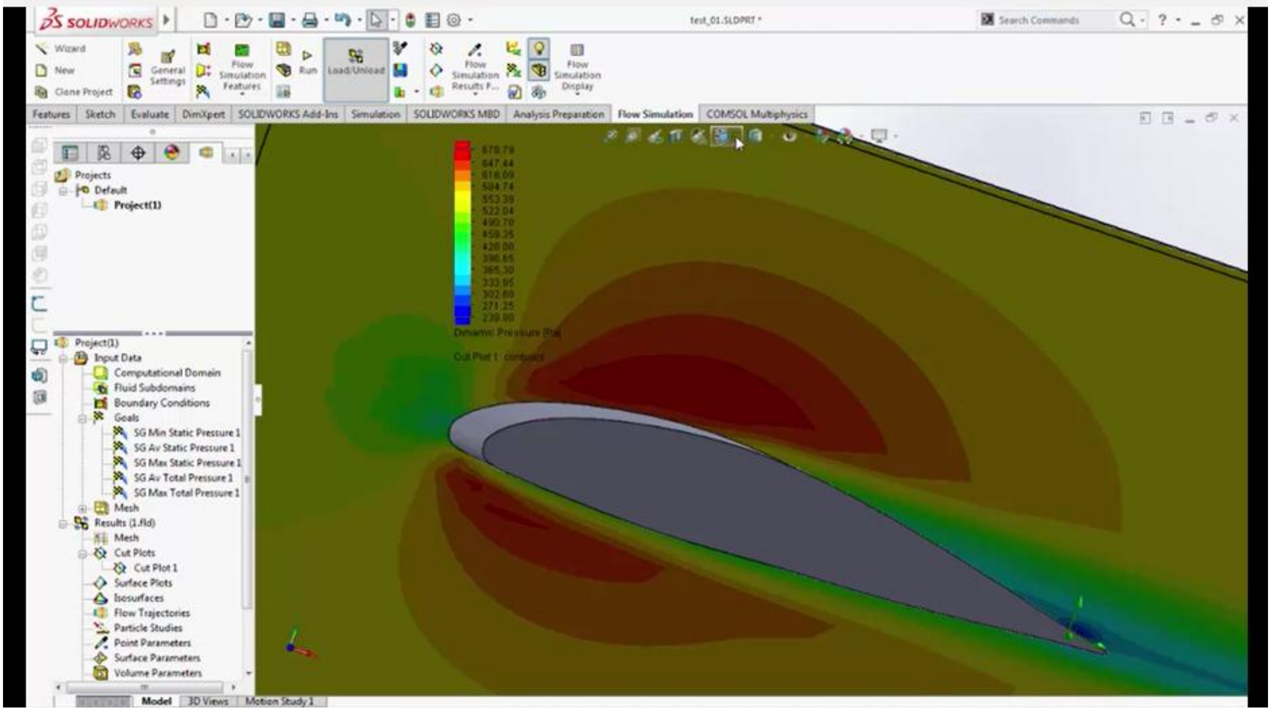


Figure 11: Simulation of the SG 6043 airfoil

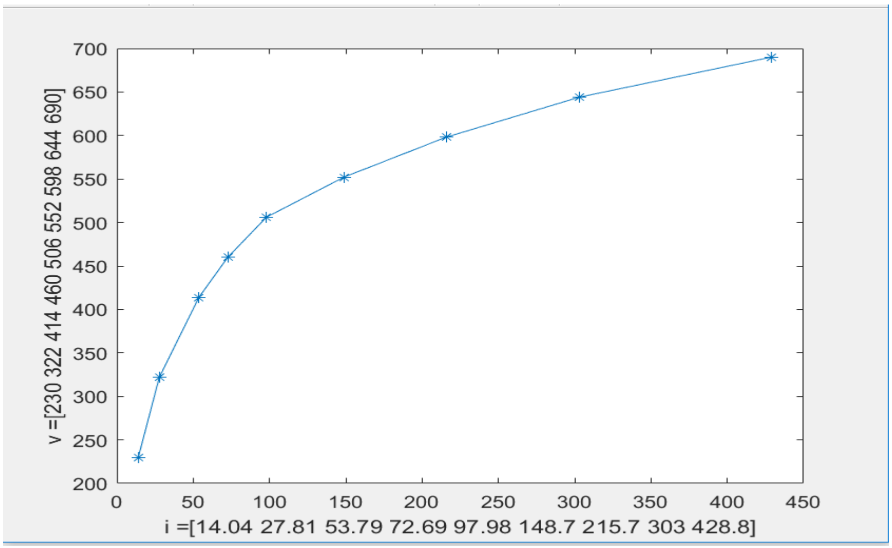


Figure 12: Plot of time varying voltage and current

Figure 12 shows the time varying sinusoidal voltages and currents. Increase in voltages leads to increase in the current in agreement with the Ohm's law.

4. CONCLUSION

The model design, control and simulation of the wind turbine system was carried out using the Q blade software and Matlab-Simscape and Simulink. The successful completion of this design provides design data for the development of a wind turbine system using locally sourced materials. The fact that most of the materials employed are locally sourced makes it cost effective. In addition, the choice of aluminum as the material for the blade results in considerable reduction in weight as opposed to carbon or other materials in existing design. The limitation of this work however lies in the fact that the work is under development but it has provided a suitable template for scaling the future development of wind turbine system.

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