



Fuzzy logic controller based MPPT Micro Wind Power Generation: A Case study on Debre Berhan University campus

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Abstract

Wind energy is considered to be one of the greatest sources of renewable energy. Before the implementation of micro wind power generation at the main campus of Debre Berhan University, a potential assessment for the feasibility study was done and it gave an attractive result. In this project micro wind power generation was conducted aiming to generate electricity from wind power at DBU main campus as a pilot project. From the simulation result, we have got the Brushless DC motor (BLDC) motor which has been selected as the best alternative for wind power generation. In this site, power is generated from a tower height of 13.5 meters and has five blades, which are able to power two 60-watt lamp and booting two 115watt desktop computer. Fuzzy logic controller is used to control the charging and discharging process as well as for maximum power extraction. The electrical circuit including battery, charge controller, inverter, and other accessories are properly installed in the powerhouse near the tower. Before implementing hardware, the proper operation of the system using fuzzy logic controller was tested by using MATLAB/SIMULINK software.

Keywords: BLDC Type Wind Generator, Fuzzy logic controller Abbreviations.

1. Introduction

Global electricity consumption is on an upward trend, with projections indicating a roughly 50% surge in world energy demand between 2018 and 2050 [1]. Currently, fossil fuels account for 85% of the world's energy use, making them the primary source of CO₂ emissions. The fossil fuel industry, as both a major energy producer and consumer, is a significant driver of climate change. Furthermore, petroleum-based fuels are finite resources that are steadily being depleted.

To address our growing energy needs, it's crucial to explore and adopt more environmentally friendly energy sources. Renewable energy offers a promising solution to meet this demand, given its abundance [2]. Among these, wind energy stands out as one of the world's most rapidly expanding energy sources, notable for its zero emissions and minimal pollution. Even though energy from wind has a lot of advantages, this technology is not sufficiently adopted in Ethiopia especially in North Shewa zone and people living here mainly use solid biomass as a fuel for cooking their food but using this has a lot of disadvantages. For example, as it produces a lot of smoke and soot that is bad for health, it results in deforestation and as a result

brings land degradation. Now a days, population is growing rapidly and the area is becoming smaller and smaller, so people may not have the capacity to get fuel wood in the future unless immediate alternative solution is found on biomass. For this, one alternative solution is wind powering because "It is a power source that renews itself, can be sustained long-term, and doesn't pollute, offering many advantages locally and internationally.". In this regard, as part of the country to support the work of low carbon development strategies n reducing greenhouse effect is essential. Hence the research project attempted to address how to generate controllable off-grid electricity using small scale wind generator to power the selected areas. The project was implemented on the main campus of Debre Berhan University, North Shewa zone, Ethiopia.

Moreover, this project work was implemented to show the visibility of wind power generation in selected site in DBU main campus. The project was implemented using available materials and based on the experience in our country. The design, modeling and manufacturing of wind tower structure, wind turbine blades and wind generator based on the available material was developed to provide 380W for demonstration and education purpose. It covered all stages of WECS at micro scale level.

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2. LITERATURE REVIEW

Wind turbines play a significant role in becoming another technology in the generation of electricity. Subsequently wind is clean and unbounded, wind energy is one of the greatest renewable sources of energy for the generation of electricity.

Environmentally-friendly renewable energy resources are wind, hydropower, solar, geothermal, etc. as a replacement for fossil fuels were used as energy security by reducing environmental pollution and global warming. Among those the first wind power which is developed by Chinese were found in the application of wind energy as a sail for their primitive travel from the raft, early about 4000 B.C. Therefore, wind energy presents a viable approach to mitigating global energy shortages exacerbated by climate change. Historically, this power source has been directly employed for tasks such as pumping water, milling grain, and propelling sailing vessels. Modern wind turbines, however, differ from traditional windmills in their primary function: they are specifically designed to transform the wind's mechanical force into electrical power. The pioneering automated wind turbine, constructed in 1888 by Charles Brush, featured 144 blades with a 17-meter rotating diameter. This innovative system had a total generating capacity of 12 kilowatts, primarily used for charging batteries that powered direct current (DC) equipment like lamps and electric motors [3]. Year to year, wind power generation technology is showing tremendous development, and the researchers' effort for designing and developing wind generator from traditional to recent becomes an advanced and shows good. In [4], the authors in this section present wind turbine generators based on advantages, classification upon the size, and drawbacks. So that synchronous machines, DC machines, and squirrel-cage induction machines are categorized under small scale power generator, while doubly-fed induction generator (DFIG), switched reluctance, permanent magnet (PM), and high temperature superconducting (HTS) are considered as medium and large wind turbines [4]. Controlling and monitoring wind turbine technology is a must as the wind has an intermittent nature, in [5] monitoring and controlling of wind power systems getting advanced in such a way that wireless sensors which were combined for electrical, mechanical, and environmental monitoring were developed and placed on wind turbine structure. These advanced sensor technologies are also currently improving the blade design efficiency.

A buck-type DC-DC converter control unit with a high-efficiency type equipped with an MPPT system driver is developed by applying mathematical modeling to drive BLDCM in the electric vehicle using wind energy, modeling and simulating which was

accomplished by using MATLAB/SIMULINK software [6].

Design of a brushless type DC permanent magnet generator for micro wind application is proposed to obtain the advantage of the lack of brush for the improvement of efficiency, for better reliability, less maintenance, for longer life, higher torque to weight ratio and for higher power density. A single optimization process based on modeling is done to calculate the performance of the generator [7]. The author in [8], discussed the optimal combination PV/Wind/Diesel Battery Hybrid Energy System for household energy requirement, under the climatic conditions in Jordan, the economic analysis and system modeling is checked using HOMER software. For the integration of the PV/wind and diesel system power system, power electronic devices are needed and such materials are costly and economic analysis of such hybrid system is not visible. If the average annual wind speed is capable for the production of electricity there is no need to combine them.

DFIG generator used in Off-Grid wind turbine and frequency and power fluctuation due to load mismatch is solved using mutual inductance change, and d-axis and q-axis current and pitch angle control was discussed in [9]. The DFIG as generator needs excitation in the rotor part to produce an electric field in the stator part. This is one of the difficulties of using this generator in an off-grid wind turbine system.

According to the Authors' study [1] of micro wind turbine fed by BLDC motor for electric vehicle drive application, BLDC motor is used as wind generator and maximum energy extraction is done by MPPT.

In a study [11], the authors used permanent magnet brushless dc motor as a generator and used buck-boost DC-DC converter for speed control of permanent magnet brushless DC (PMBLD) generator, and they have also used a control algorithm for monitoring a buck-boost converter to control over the PMBLDC generator power and to control of single-phase Voltage source inverter to regulate load voltage and frequency. In [12] the authors discussed the size of batteries based on wind speed rather than the demand of the load. But the author didn't explain the effect of the load demand on the batteries and, inverter sizing, charge controller, number of blades, and types of generator. In [13] the authors optimized the power loss of the wind energy system for long-term wind speed profile. However, the authors did not discuss the simulation result and checked it with experimentally

The advantage of the low-cost installation of micro wind turbine for the application of homes villages is briefly discussed [14]. In [14] the potential resource of wind power in Bangladesh is well described.

The proposed system was designed based on the wind power potential assessment data obtained in [15], and the recorded data using data logger from the site of this micro wind power generation, a potential assessment

of wind power was performed at Debre Berhan University of the main campus in [15].

In [16] the authors designed MPPT for a variable speed for small scale wind turbine system using fuzzy logic controller have been designed and simulated.

The change in mechanical power, change in rotor speed and sign of the ratio of mechanical power to rotor speed were considered as input variables and reference generator current was the output variable for fuzzy logic design.

The controller performance was analyzed and validated by digital simulations and the controller tracks the MPPT for variation of wind speed with respect to change in turbine parameters.

System Design and Concept Selection

Wind speed Data and Site Selection

The project site stated in Debre Berhan university compass is located at a latitude of N 9.664910 and longitude of E 39.622410 [16]. The site has an average wind speed of 7.78m/s for a hub height of 78m. The average hourly wind speed measurement at 10 meters above the ground was taken and it was extrapolated to the height of 13.5m for horizontal axis wind turbine. In addition to the above wind data, the measurement data from NASA Surface meteorology and solar energy database was used for comparison purpose.

On the specified site, the wind data has also been collected from the site since 2013 using the NRG data logger. The data indicate that the monthly average wind speed data ranges from 2.8m/s to 4.8m/s at 14 meters above the surface of the ground. The slowest average hourly wind speed experienced in August which has an average speed of 2.82m/s. Both data confirmed that it is feasible for electricity generation. In general, 3m/s is the typical cut-in speed so that the electric power can be produced from wind and if the speed is maximum, the power generation is also maximum as discussed in [17]. Based on Debre Berhan University's monthly average wind speed, the designed wind velocity is 4m/s. From these wind speed data analyses, it is clear that the turbine extracts a minimum of 39.2W/m² for 4m/s.

Load Estimation for Selected Site

The primary load input, which is taken as a sample is expected for modeling and analysis of micro wind system as shown Table 1 below. In this paper, the modeling of energy system must meet the load demand of 4 lamps of each has 9W, and for using of computer PC which is having 115W rating power.

Table. 1. Power demand and energy consumption for sample size

Electrical Loads	Rating (W)	Qty	Total (w)	Hourly used per day	Consumption (kWh/day)
Incandescent Lamp	9	4	36	12	0.432
Desktop Computer	115	2	230	18	4.14
Total power(w)			266		4.572

Design of a Wind Turbine

Micro wind turbines have great potential in developing countries but they have not been pursued. This is because it can be implemented in several circumstances which are great for the micro grid and off-grid implementations. In this paper, micro wind generation implementation real application was done in Debre Berhan University main campus. The site is located in Debre Berhan City which is approximately 130 km away from Addis Ababa, the capital city of Ethiopia.

Power generated by the wind power is directly proportional to the wind speed since there is no pitch control or turbine speed control technique. Due to this reason, the generated output voltage from a wind turbine is converted to DC using a rectifier, stored in a storage device (battery), and then converted to suitable AC voltage using an inverter. As soon as batteries are full, the extra power should be diverted to isolated load so that the wind turbines will not go into high-speed freewheeling in heavy winds. When a dump load (also called a divert load) comes in the MPPT charge controller will switch from battery charging to transfer power to the dump load to retain the wind turbine under load. If there is no using a reliable dump load, or no divert load at all, can cause heat build-up in the wind turbine generator which might ultimately cause the generator to overheat, conk out, and wear out the stator.

Overall, electrical circuit diagram of the system is composed of seven main components, shown in **Fig 1**.

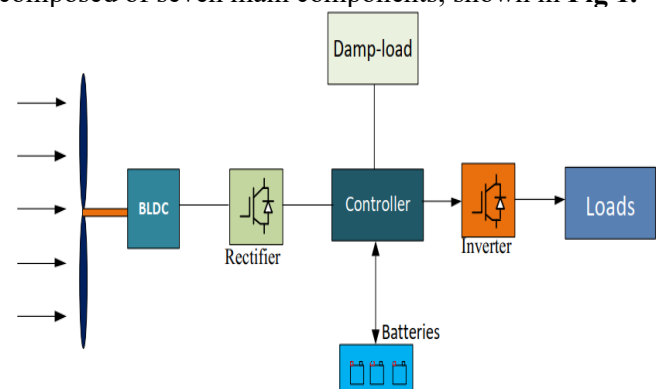


Fig. 1. Overall Electrical Circuit Diagram of Micro Wind Energy Conversion System

Design of wind turbine blades

"Contemporary wind turbines are generally classified into two primary designs: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs).

- i. HAWTs distinguish themselves from VAWTs by featuring their main rotor shaft positioned atop the tower, oriented perpendicularly to the ground. Their key advantages include a fully automated control system and highly efficient power utilization.
- ii. Conversely, VAWTs are designed with their main rotor shaft aligned transversely to the wind flow, with most of their essential components situated at the base of the turbine. Their vertically oriented blades allow them to capture wind effectively from any direction.

Considering a consistent wind speed, V , as it interacts with the turbine rotor, let V_1 represent the wind velocity upwind and V_2 the wind velocity downwind at a certain distance from the rotor. The rotor extracts mechanical energy by diminishing the kinetic energy of the air current as it moves from the upwind to the downwind side, essentially applying a decelerating force to the wind. This leads to the relationship:

$$V_1 < V_2 \quad (1)$$

As a result, the air stream cross-sectional area rises from upstream of the turbine to the downstream location:

$$S_1 > S_2 \quad (2)$$

If the air stream is considered as a case of incompressible flow, the conservation of mass or continuity equation can be written as:

$$\dot{m} = \rho SV \quad (3)$$

Equ.3 expresses the mass flow rate is persistent along the wind stream. Continuing with the derivation, Euler's Formula gives the force exerted by the wind on the rotor as:

$$F = \rho SV(V_2 - V_1) \quad (4)$$

Similarly, the incremental work in the wind stream yields the power content of the wind stream as:

$$P = \rho SV^2(V_1 - V_2) \quad (5)$$

The wind velocity at the rotor might be considered as the average of the upstream and downstream wind velocities. It indicates that the turbine must act as a brake, reducing the wind speed from V_1 to V_2 , but not reducing it to zero. At this point, the equation is invalid. To extract energy from the wind stream, its flow should be sustained and moving. One can write

the expression of force F and power P using upstream and downstream velocities by substituting for the value of V like:

$$F = 0.5\rho SV(V_2^2 - V_1^2) \quad (6)$$

$$P = 0.25\rho S(V_1^2 - V_2^2)(V_1 - V_2) \quad (7)$$

Where, b can be introduced as the ratio of the downstream speed V_2 to the upstream speed V_1 as:

$$b = \frac{V_2}{V_1} \quad (8)$$

From Eqn 6 and Equ 7 the force F and P can be further expressed as:

$$F = 0.5\rho SV_1^2(1 - b^2) \quad (9)$$

$$P = \rho SV^3(1 - b^2)(1 - b) \quad (10)$$

From Equation 10, it becomes clear that the amount of power recoverable from the wind is directly proportional to the cube of the upstream wind speed (V_1^3) and also depends on the interference factor ' b '.

The concept of power density (p) is then defined as:

$$p = \rho SV_1^3 \quad (11)$$

The kinetic energy inherent in the undisturbed wind stream upstream, with a velocity $V = V_1$ and spanning a cross-sectional area S , can be quantified as:

$$W = 0.5\rho SV_1^3 \quad (12)$$

The performance coefficient C_p is the dimensionless ratio of the extractable power P to the kinetic power W available in the undisturbed stream. It is defined as:

$$C_p = 0.5(1 - b^2)(1 + b) \quad (13)$$

If the interference factor, ' b ', equals 1, this implies that $V_1 = V_2$, signifying an undisturbed wind stream. In such a scenario, the performance coefficient consequently drops to zero. Conversely, when ' b ' is 0, and V_1 is also 0, the turbine effectively halts all airflow, resulting in a performance coefficient of 0.5. Notably, the performance coefficient achieves its peak value when ' b ' is precisely $1/3$, yielding a C_p of approximately 0.59259.

"In a real-world wind turbine setup, however, after accounting for various efficiencies lost in components like the gearbox, bearings, and generator, only about 10% to 30% of the wind's available power actually gets converted into usable electrical energy. This fundamental principle is known as the Betz Criterion, or more commonly, the Betz Limit, a concept first articulated in 1919. The actual power captured by the rotor blades can be mathematically expressed as follows [12], [17], [18]:"

$$P_T = 4a(1 - a)^2 \left[\frac{1}{2} \rho A U_o^2 \right] \quad (14)$$

In this context, ' a ' represents the axial induction factor (or perturbation factor), ρ denotes the air's density, A stands for the swept area covered by the blades, and U_o signifies the velocity of the upstream wind. The specific blade profile employed for this design has been selected based on the characteristics detailed in Table 2: Design Tip Speed Ratio and Blade Number Selection [19].

Design tip speed	ratio, λ_d Number of blades, B
1	6-20
2	4-12
3	3-6
4	2-4
5-8	2-3
8-15	1-2

The power coefficient varies with the tip speed ratio of the turbine. The tip speed ratio is defined as:

$$\lambda = \frac{\text{Blade tip speed}}{\text{wind speed}} = \frac{\omega_m r}{V_1} \quad (15)$$

The radius of wind Turbine is, $r = 4\text{m}/2 = 2\text{m}$, as the tip speed ratio-is $\frac{V_{tip}}{V_1}$ (Velocity at tip)/ (upwind velocity) = 2.09. Up wind velocity = $2/3 \times$ undisturbed wind velocity (V). Therefore, $V_{tip} = 2.09(2/3) V = (4.18/3) V$. Angular velocity of the wind turbine is related to velocity at the tip of the blade is $V_{tip} = \omega_m r$. The angular velocity at the cut in speed, $V_c = 3\text{m/s}$, $3(4.18/3) = 2\omega_m \Rightarrow \omega_m = 2\text{rad/sec}$. This is the minimum wind speed at which the turbine blades overcome friction and begin to rotate [20].

Table 3. Project Design specification.

Particularly, for this project, the tower height is 13.5m, the rotational wind speed in revolution per minute is 10rpm, the value of λ is 2.09. Using Table.2, the number of blade for our data can be selected from 4 to 12 blades. Therefore, consequently, five blades were chosen for this project. The power coefficient itself is influenced by profile drag, specifically through the ratio of the drag coefficient (C_d) to the lift coefficient (C_l). A reduction in the maximum achievable power coefficient is directly associated with both the tip speed ratio and the C_d/C_l ratio.

The wind turbine designed should be able to generate minimum electricity power of 284 welts at an average prevailing wind speed of 4m/s, the height of 13.5m, with 1.225kg/m³ density of air. Designing of a wind turbine was done based on the following parameters. The blade area was calculated by the following equations [21] and [22]

To extract 380W power from a wind turbine with an air density of 1.225kg/m³, $C_p = 0.59$, and overall turbine system efficiency of 0.8, requires a swept area of 15:3577m². This leads to a rotor radius of 2m.

From a physical perspective, solidity directly translates to the area blocked by the rotor's solid components.

Solidity is typically understood as a measure of the portion of the rotor's circumference obstructed by its blades. For a horizontal axis wind machine, solidity (σ) is precisely defined by Equation 16 as follows:

$$\beta C_\sigma = 2\pi R \quad (16)$$

In Fig 2.the relationship between the cord length and the ratio of blade radius with each airfoil radius is shown. This relation is used to design the airfoil structure of the blade.

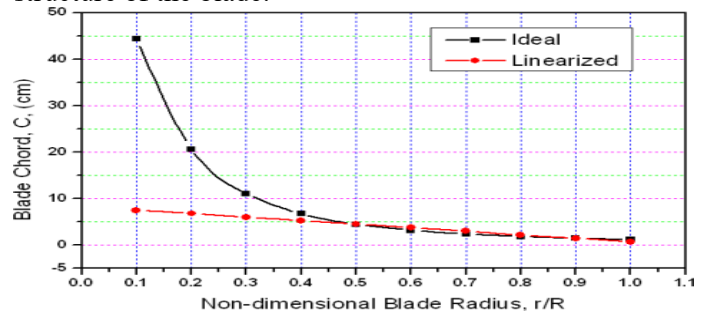


Fig. 2. Optimum and linearized blade chord distribution. As illustrated in Figure 2, 'B' denotes the number of blades, 'C' represents the blade chord, and 'R' signifies the rotor's radius. An increase in solidity generally leads to a higher starting torque, but typically results in a reduction in both RPM and the coefficient of performance. Solidity is directly proportional to the number of blades. Therefore, for the chosen operational site, the wind turbine incorporates five blades, yielding a solidity of 0.028 [20].

The condition of the blade surface is paramount for optimal performance; any degradation can cause a significant drop in shaft power. Consequently, the drag generated by friction on the blade surface is a very important consideration. The cost of the blade materials and their availability are also critical factors to determine the type of blade used for the given project works. In this consideration, Poly Vinyl Chloride

No	Item	Value
1	Tower Height	13.5 m
2	Rotational wind speed in revolution per minute	10rp m
3	Value of λ	0.29
4	Number of Blade	5
5	Expected power generated, P	284 Watts
6	The average prevailing wind speed, V	4m/s.
7	Density of the wind at height of the tower of 13.5m	$\rho = 1.22k$ g/m ³
8	Swept area	15.4 m ²
9	Radius of the rotor, r	2m

(PVC) maintains its surface highly finished and hence, selected for this work.

Tower design

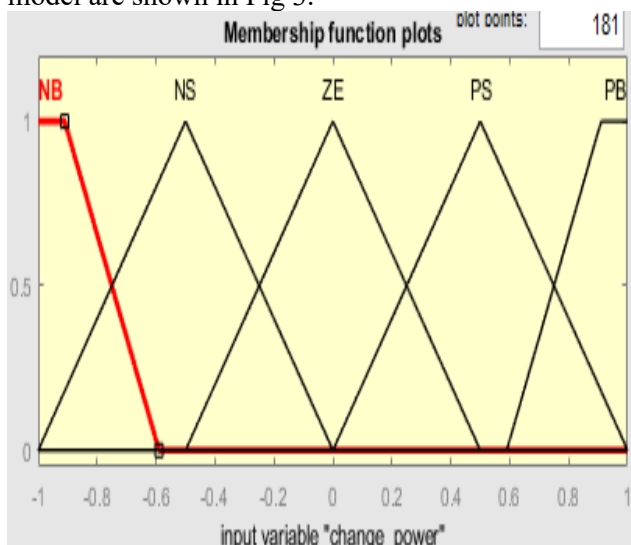
The turbine's supporting tower plays a crucial role in ensuring the system's stability and structural integrity throughout its operational lifespan. By keeping the turbine within a small-scale range, both the tower's construction cost and its visual presence in the area were minimized. This approach also considerably simplified the processes of installation and subsequent maintenance for the turbine. Taking into account the readily available materials and the necessity of positioning the turbine above the local coastal vegetation, metal poles were ultimately utilized, elevating the turbine to a height of 13.5 meters.

CONTROLLER DESIGN

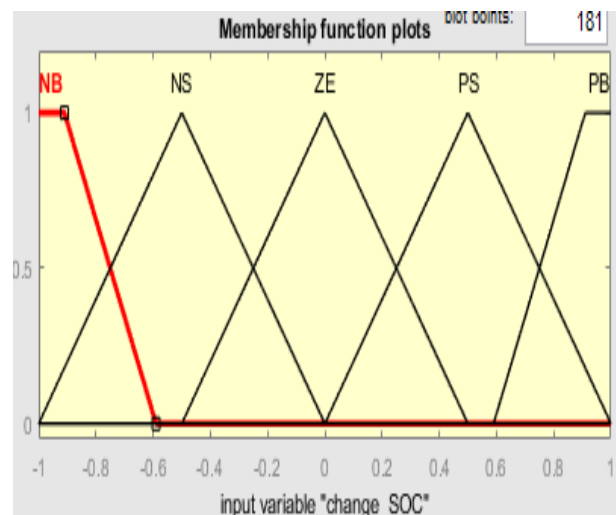
The selection and design of the controller for a wind turbine were based on the characteristics of wind speed variation during each season. For off-grid wind turbine generators, extracting the maximum power and storing energy is necessary.

Fuzzy based maximum power tracking

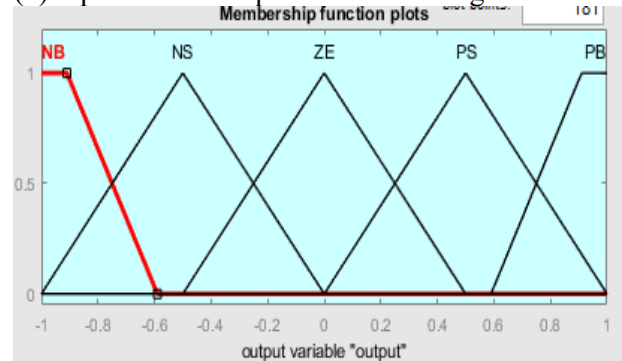
The power generated from the wind turbine varies during each time and season due to the high variation of wind speed, and even the variation of wind speed is not linearly determined. To extract the maximum power at each time, a nonlinear controller was designed. The fuzzy logic controller is one of the best controller selections for this type of system because the variation of the wind is not easily modeled mathematically. The voltage and current being sensed using the current and voltage sensor and calculating the power and change of power which is considered as an input to the fuzzy logic controller. The membership function, input and output function of Matlab Simulink model are shown in Fig 3.



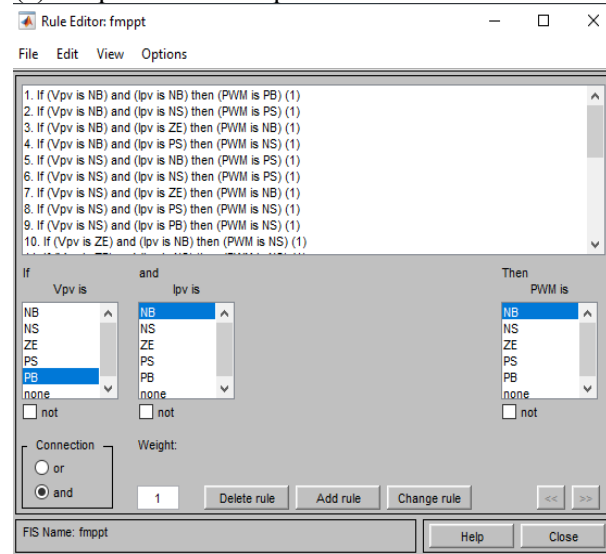
(a) Input membership function for change in voltage



(b) Input membership function of change of current



(c) Output membership function



(d) Fuzzy rules for maximum power tracking

Fig. 3 a,b,c,d fuzzy logic controller

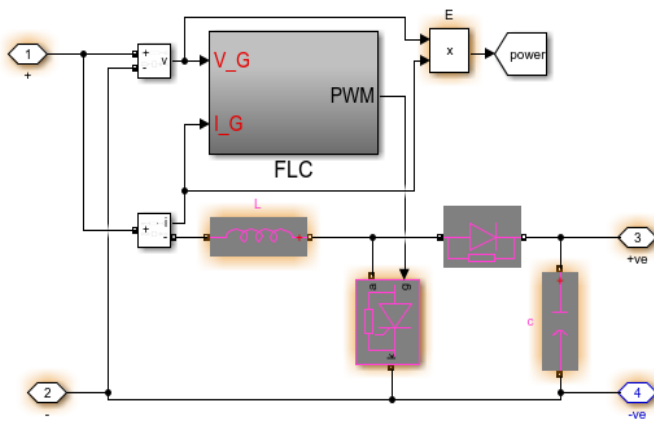


Figure 4 Maximum power point tracking by FLC

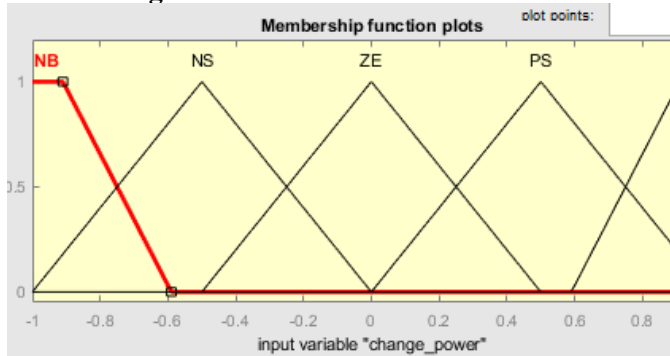
Battery management system

For off-grid system, the energy storage is a difficult work even if the wind power in Debre Berhan is visible for electrical energy production. Simulink model of the battery management system is shown in Fig 6. Lithium-ion battery is selected due to its performance. Due to nonlinear characteristics of charging and discharge behavior, fuzzy logic controller was used to the controller its charging and discharging rate. The power and state of charge were considered as an input to the fuzzy logic controller.

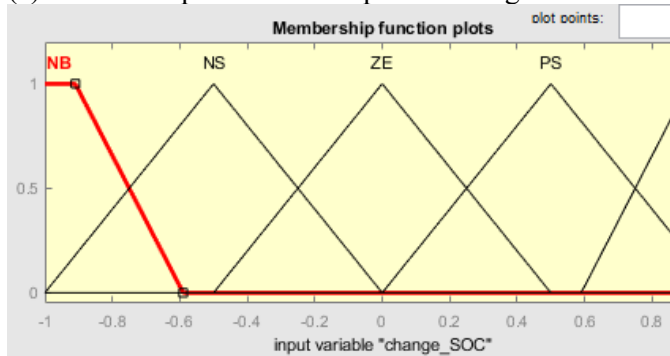
Change of power = load power - generated wind power

Change of state of charge (SOC) = command state of charge - new state of charge

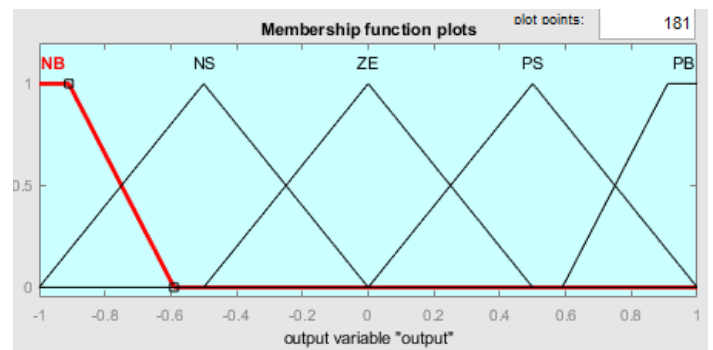
The input, output membership function and the rule based battery management of the wind turbine is shown in Fig.5.



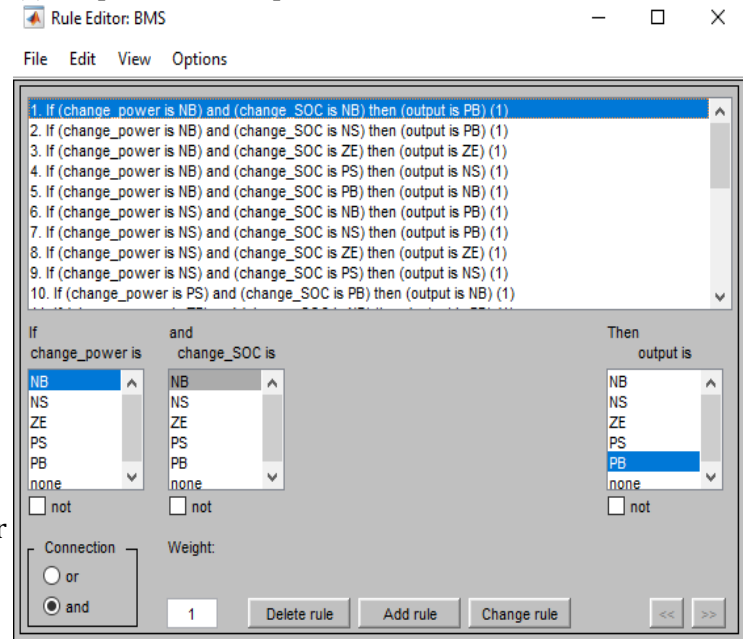
(a) Membership function of input for change in Power



(b) Membership function of input for change of SOC



(c) Output membership function



(d) Fuzzy rules for battery management system

Fig.5. a,b,c,d, Fuzzy logic controller of the battery management system

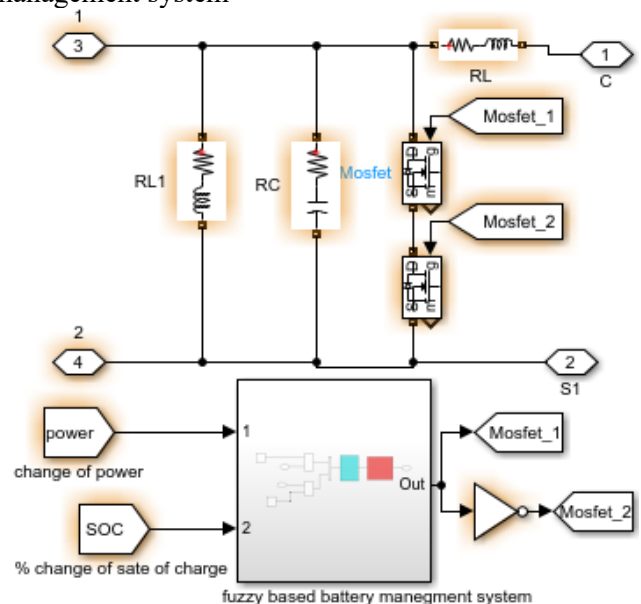


Fig.6. Simulink model of battery management system

AC-DC CONVERTER

Power converters may consist of the rectifier, boost converter, H-bridge converter [2]. Rectifiers are devices that convert AC into DC and the boost converter boosts up the voltage when there is a

decrease in wind energy to the required voltage which is constant. A boost converter generally functions as a voltage step-up power circuit, transforming a low input voltage into a higher output voltage [23]. This is a standard, fundamental DC/DC converter that achieves its operation using just a single switching component. The methodology presented in this paper employed a variable speed wind power system for the concurrent purposes of battery charging and alternating current (AC) load supply. The type of generator used in this research paper was 72V, 1000 W, 350 rpm brushless DC Electric Scooter Hub Motor (hub generator). The output dc voltage V_{dc} for a three-phase power rectifier was computed with RMS line to line source voltage, V_{LL} as follows:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} \quad (17)$$

The maximum ideal RMS line to line voltage and maximum phase voltage of the generator were 53.29V and 29.035V respectively. The diode should have a voltage rating of at least $2 \times V_{pn} = 60V$ and a current rating of at least $1.25 \times 1000W/72V \approx 17.36A = 20A$. the nominal frequency range is 0.24Hz with a ripple frequency of 1.444Hz and maximum frequency of 17.7Hz for the generated voltage can be determined from the cut-off wind speed and maximum rpm of the hub generator.

The required LC filter was designed for the converter to avoid harmonic. The L and C are computed as:

$$L = \frac{0.013V_{LL}}{2\pi f I_{cri}} \quad (18)$$

$$C = \frac{1}{4\pi^2 f_c^2 L} \quad (19)$$

where f is line frequency and I_{cri} is the value that the inductance is to maintain for continuous conduction mode till 20% of rated load current discussed in [24]. Replacing values $f_c = 50Hz$, $V = 220V$, and $S = 1000V A$, the capacitor capacitance is $3.29\mu F$.

As shown in Fig.7. LCL filters were specially designed to reduce harmonics of current absorbed by power converters, in [25] with a rectifier input stage mainly, the filter was completed of a parallel-series arrangement of reactors and capacitors. The design of the inverter and load side inductor is as follows: Inverter side inductor was determined using:

$$L_1 = \frac{V_{dc}}{4f_{sw}\Delta I_{ppmax}} \quad (20)$$

$$L_2 = \frac{0.1V^2}{2\pi f S} - L_1 \quad (21)$$

Where V_{dc} input dc voltage to the inverter, f_{sw} switching frequency of 1 kHz, considering 20% of maximum inverter current, I_{ppmax} is 3.928A. The value of the inverter side and load side inductor were 0.7637mH and 14.65mH respectively.

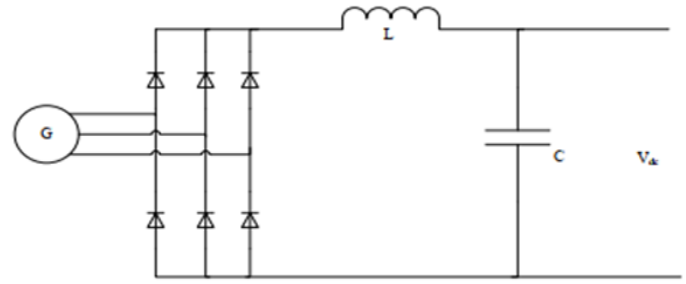


Fig.7. LCL filter topology for harmonic reduction

Sizing and selection of inverter

The size of the inverter was designed for the load power P_L and the inverter output $\eta_{inv} = 50\%$ is defined as:

$$P_{inv} = \frac{P_L}{\eta_{inv}} \quad (22)$$

The charge controller's current value is determined by the ratio of the inverter power, which is utilized by the wind power generation system, to the battery voltage:

$$I = I_{charge} + \frac{P_{inv}}{P_{battery}} \quad (23)$$

Sizing and selection of battery

Accumulators are used for surplus electric energy generated from wind turbines. The ratio of the electrical power produced by the wind turbine to the accumulator (battery) voltage quantifies the accumulator's capacity in ampere-hours [26], [27]. Furthermore, considering inverter efficiency of $\eta_{inv} = 80\%$, $WAhr = 284.5W \times 12hr = 4, 267.5Whr \eta_{inv}$. The battery bank capacity (KBatWhr) in Whr taking into account that the accumulators are discharged down to 20%, with one day of autonomy and 1.19 temperature multiplier for 24oC is 4, 062.66Whr, using equation $3.43 KBatWhr = PAhr \times Battery Temp. Multiplier \times Days of Autonomy \times Discharge limit$. The battery bank capacity (KBatWhr) in Ampere hour (Ahr) is 338.55Ahr using equation 24.

$$K_{BatAhr} = \frac{K_{BatWhr}}{V_{battery}} \quad (24)$$

It is advisable to use two parallel-connected battery strings. Given this configuration, the series-connected strings should collectively possess a maximum rating of 169.2775 Ahr.

$$N_{series} = \frac{K_{BatAhr}}{2} \quad (25)$$

3. Results and Discussion

In this paper, the power generated by the wind turbine system was analyzed by varying wind speed with constant blade radius and electronic converter. Based on our designed blade radius of the turbine was set and then the circuit was simulated using different wind velocities.

For this work, the blade's radius was two meters and varying the wind velocity from 3 m/s till 12 m/s was simulated. Then, the difference of power generated was calculated and analyzed.

Simulation Results

The simulation result of fuzzy-based MPPT boost converter of the wind turbine was carried out to assess its performance. Knowledge of generator parameters and design characteristics of the blade is important for this simulation, since the power generated is highly dependent on the wind speed variation. The effect of wind speed was tested based on the different conditions that were put on its effects on power generation robustness.

Wind Speed Characteristic Curve from MATLAB Simulation

The complete Simulink model, depicted in Figure 12, underwent simulation using a turbine model characterized by constant pitch and variable wind speed. The turbine's performance coefficient (C_p) is defined as the ratio of its mechanical output power to the available wind power. This coefficient is influenced by wind speed, rotational speed, and the pitch angle (β). Notably, C_p attains its peak value when the pitch angle (β) is zero. As the wind speed rises, the power generated by the turbine also increases, a trend clearly demonstrated in both Figure 8 and Figure 9.

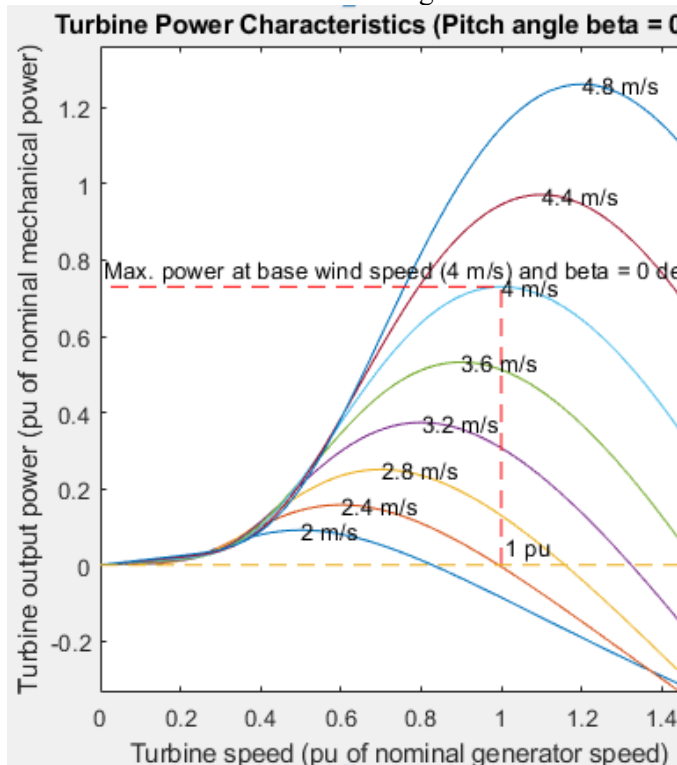


Fig.8. wind speed vs turbine power characteristics for base wind speed 4.5 m/s

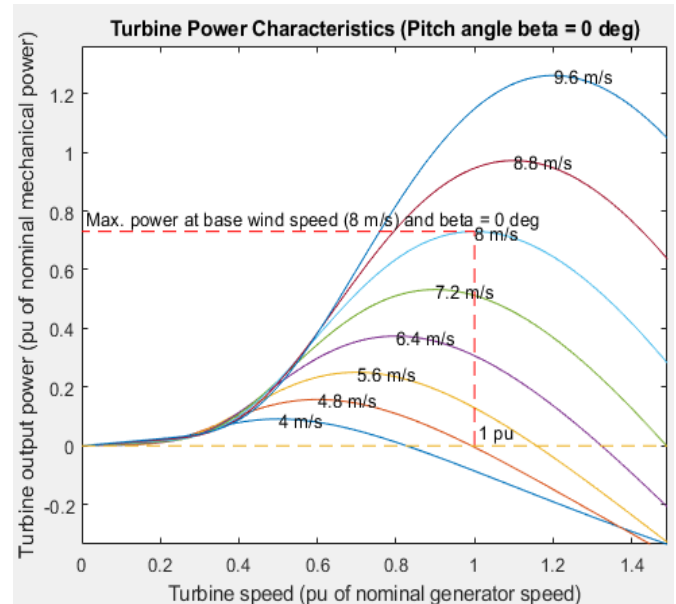


Fig.9. Wind speed vs turbine power characteristics for base wind speed 8m/s.

From Fig 8 and 9, we observed that the power generated from the wind speed increased as the wind speed increased till the turbine rated voltage achieved.

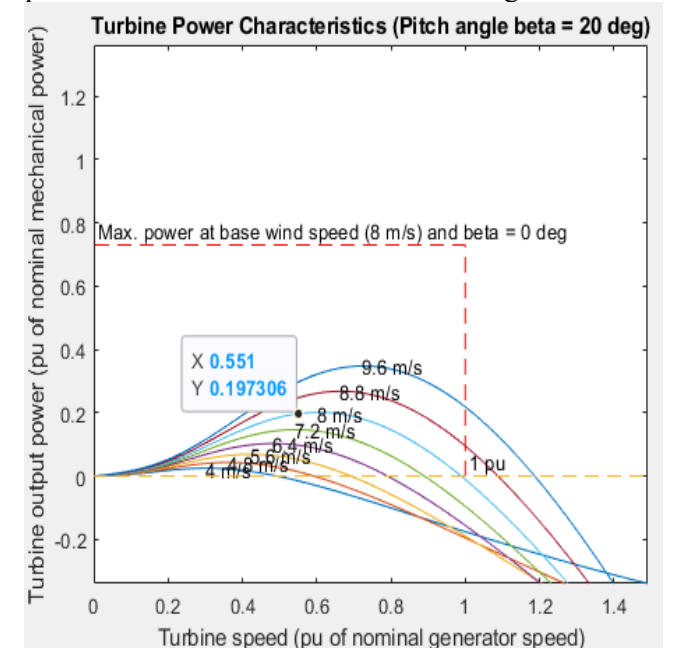


Fig.10. pitch angle vs turbine power characteristics

Fig 10. Illustrated that the pitch angle increased from zero degree to 20 degrees the power generated decreased from 0.73 to 0.1973 pu power. So for maximum power generation, the pitch angle was adjusted based on the wind speed variation to its minimum value using nonlinear control.

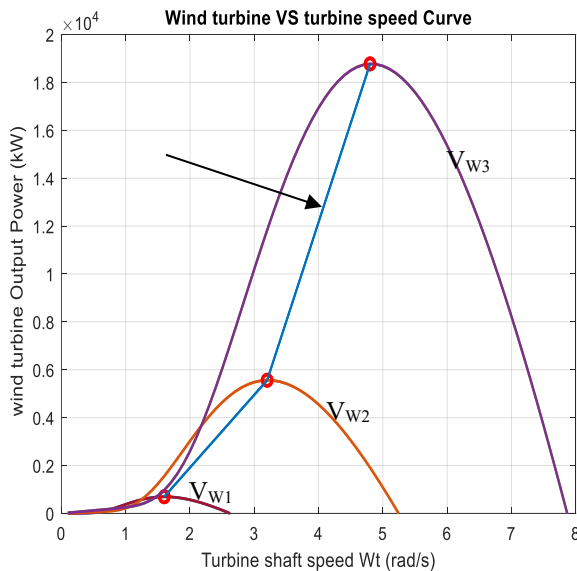


Fig.11. Mechanical power of turbine as a function of rotor speed for various wind speeds.

As shown in Fig 11, when the wind speed varies, the rotor speed and the power generated also vary. When the wind speed rises, the power captured increases for certain values, and there is a point when the maximum power is grasped at the optimal rotor speed which is illustrated in the Fig 9. For the different wind speeds, the maximum power is achieved at different rotor speeds.

AC output and battery characteristics of the wind turbine project

The general Matlab Simulink model for the proposed system is shown in Fig12, consisted of different blocks and is modeled based on the extraction of maximum power from variable wind speed.

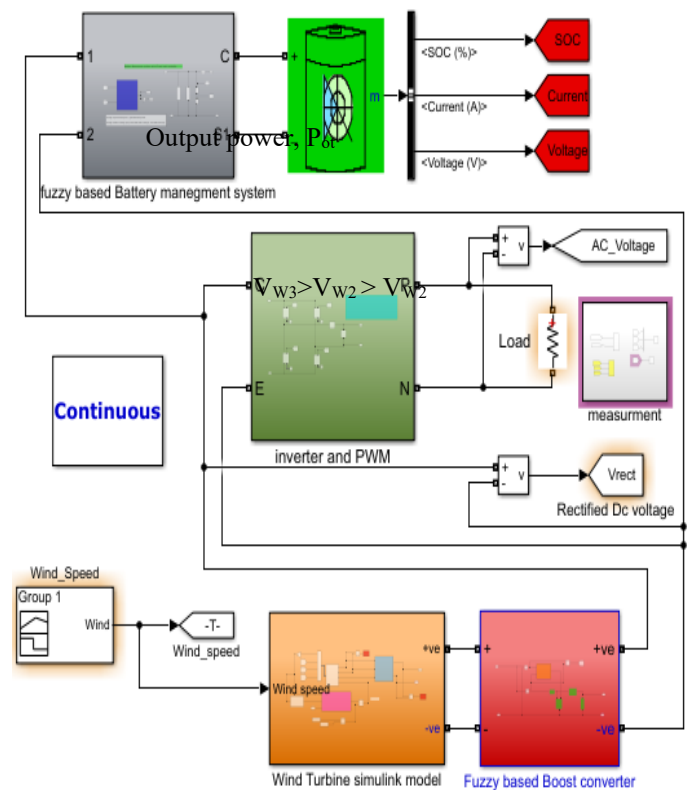


Fig. 12. General block diagram for this project

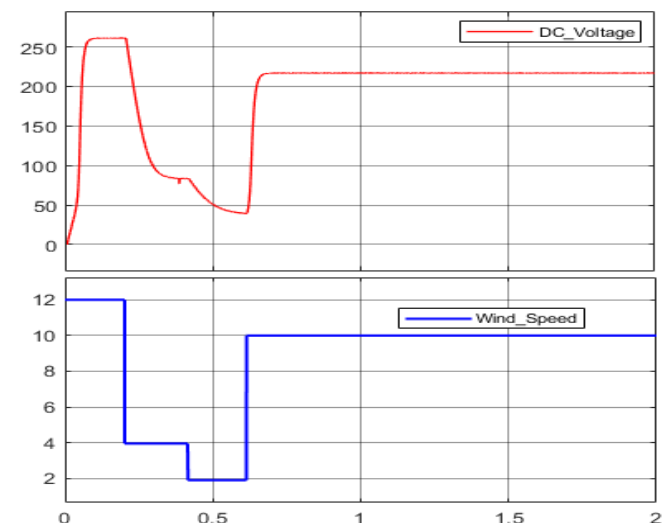


Fig. 13. Wind speed vs DC voltage generated

As shown in Fig 13, the voltage and wind speed are directly proportional. The rectified DC out voltage is shown in **Fig.14**.

As shown in **Fig.14**, the simulation result for the inverter output is stare case like fully square wave. To convert this in to fully sinusoidal at frequency of a 50 Hz, low passed filter was designed and the simulation result is shown in **Fig.15**.

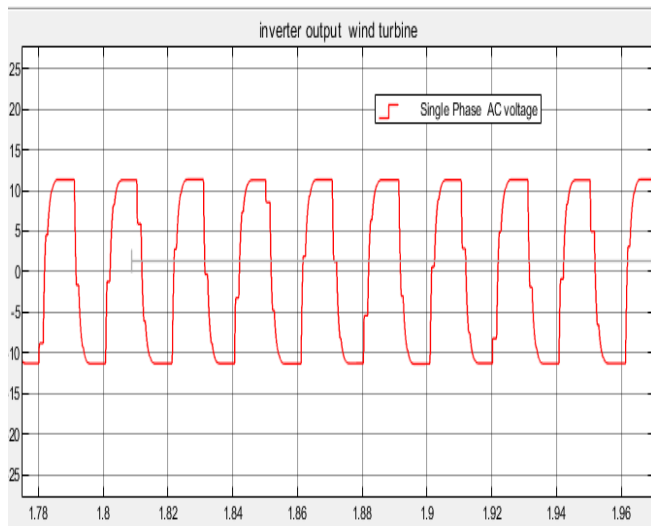


Fig.14 AC output from the inverter

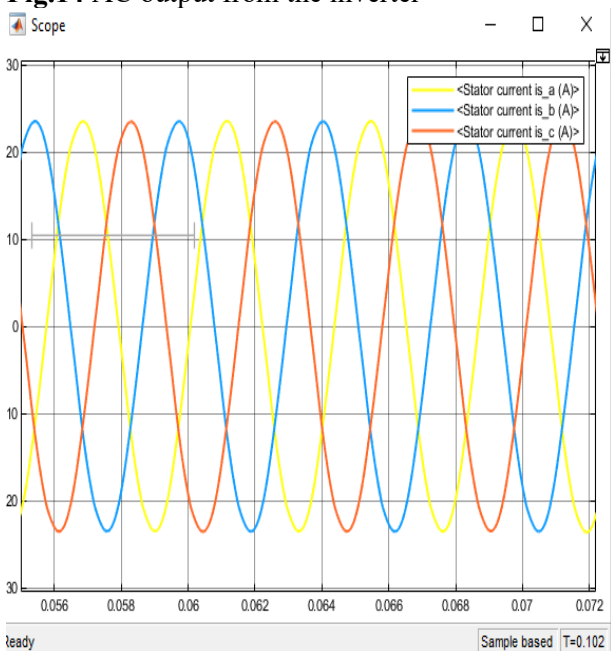


Figure 15 AC output from Low pass filter

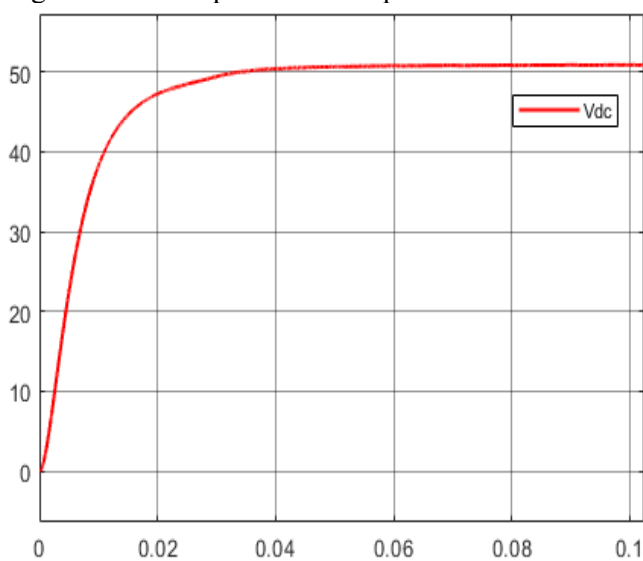


Fig.16. Rectified DC output Voltage at 6m/s
The simulation result for the battery charging and discharging was simulated on MATLAB/SIMULINK

by turning on the battery switch and turning off the battery switch respectively as shown in Fig 17.

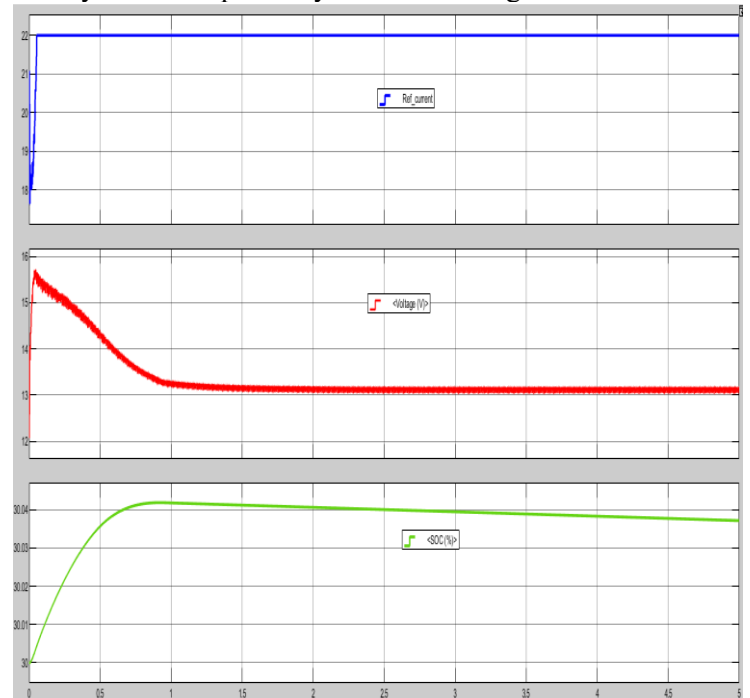


Fig.17 Battery characteristics

PWM maintains the inverter's output at a constant 220V AC, irrespective of the load. Conversely, a conventional inverter's output voltage shifts with load changes. The simulation result for PWM signal generator to turn on and turn off the inverter gate terminals for a duty cycle 95% as discussed in Fig 18.

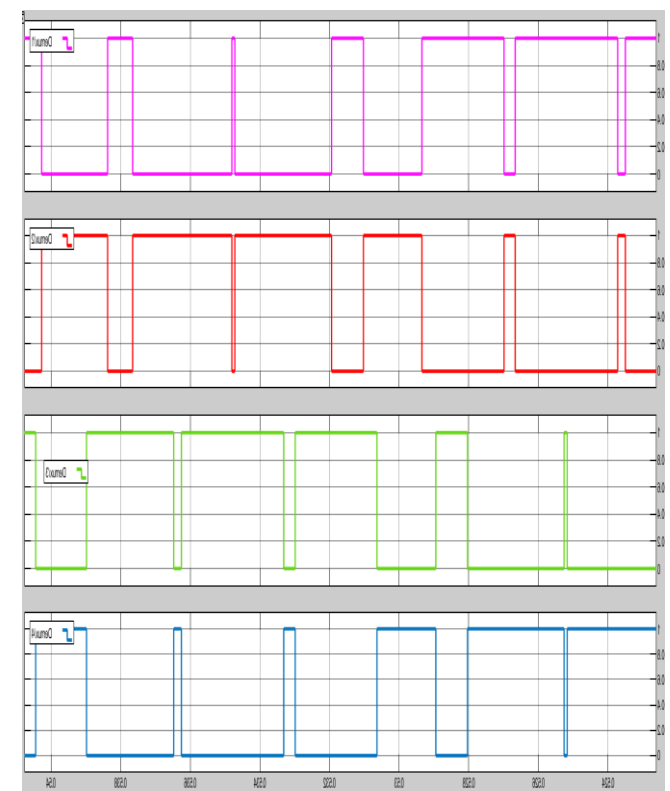


Figure 18 PWM Signal Generator

4. EXPERIMENTAL IMPLEMENTATION

The performance of the proposed scheme, experimental work was carried out using a BLDC motor with a horizontal axis wind turbine. For this experimental work, the wind turbine is directly coupled with the BLDC motor, there is no speed multiplication technique is used to multiply the speed of the BLDC motor.

The overall horizontal axis wind turbine system with BLDC generator with its control and protection circuitry developed is shown on the right side of Fig 19. The circuitry includes a protection fuse, AC to DC converter, filter circuit, generated voltage display unit, PWM voltage control, and an inverter and battery management system. To demonstrate that the system was working, two 60W lamp which had the power 115W desk top computer is connected as a load to the system as shown in left side Fig.18. To register the wind speed status, Symphonies' data logger was used to store data from wind vane, temperature sensor and anemometer

This system incorporated a Brushless DC (BLDC) generator paired with a horizontal axis wind turbine, functioning to transform mechanical energy into electrical voltage. The generator specifically produced a three-phase AC voltage. To ensure frequency stability, this three-phase AC voltage was subsequently rectified into DC using a three-phase full-wave rectifier. Both the amplitude and frequency of the generated voltage are directly influenced by the prevailing wind speed. To guarantee a continuous power supply to the load and regulate the delivered power, a battery bank was integrated for charge storage. A PWM charge controller managed the battery bank's charging and discharging cycles, reacting to both the battery's state of charge and the power output from the wind turbine generator. Finally, the power accumulated in the battery bank was then converted into single-phase AC power via an inverter to energize the connected AC loads.



Fig.19. Experimental setup of System Configuration After installing the experimental setup, the recorded data is shown in Table 4.

Table. 4. Experimental result of wind speed and output DC voltage

Wind Speed (m/s)	DC Output voltage (V)
2.33	6.3
2.99	7
4.14	7.27
4.43	8.2
4.52	9
4.9	9.9
5.2	10
5.6	11
5.66	13

5. CONCLUSION

A micro-horizontal wind turbine was designed and implemented with five blades inside the campus of Debre Berhan University. The wind turbine site was selected near the Electrical and Computer Engineering laboratory to utilize the generated power for experimental purposes. The initial wind turbine data were collected from the university using the installed Data Logger since 2013. Information pertinent to the wind turbine's design, such as wind speed, ambient temperature, and humidity, was acquired from the Symphonie data logger. A brushless DC motor (BLDC) was used as a wind generator in the modified version. The charging system used was a Pulse Width Modulation (PWM) charge controller and functioned as a 13.8 dc voltage regulator. There are four gel-type battery banks used to store generated voltage with a total capacity of 12 Volts 72 ampere-hour or 864 Watt-hours. The power inverter converts the 12 volts direct current to 220volts alternating current with a maximum load power capacity of 1000 watts. The maximum capacity of the wind generator is 1000 watts. The nominal speed of the BLDC motor is 350 rpm which is suitable for this wind speed without a gearbox. ~~Otherwise,~~ one can notice that gearbox design is mandatory for low-pole generators. The wind turbine can also scan the wind to self-rotate and align the blade to the best direction of the wind speed. The hub generator is a three-phase system with 72V line-to-line voltage. It gives ± 20 phase voltage at normal wind speed. This voltage is suitable and enough to operate low-voltage three-phase/single-phase loads in the electrical engineering laboratory.

The electromechanical, and power electronics conversion design and simulation were also analyzed

in the MATLAB Simulink toolbox. The input and output side of the pulse-width-modulation (PWM) converter was designed with considering 10% current harmonics distortion and 120% over current. Finally, from the experimental and simulation results, the researchers conclude the following points: The research site has wind potential to generate energy from wind for a selected load in the compass.

Low-speed BLDC is suitable for micro-wind generators to reduce the challenge of mechanical gearbox design and associated components. The selection of the wind turbine site can potentially affect the generation capacity.

The experimental and simulation verification indicate that the research can also be further extended in the next phase in the selected area of the university.

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