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An experimental design of 3 kW variable speed wind turbine with doubly-fed induction generator for standalone applications

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ABSTRACT

Variable speed wind turbines are suitable for isolated populations, island communities or usages in which the charge of electric lines beats the connection and upkeep charge of wind turbine. This research builds wind turbine which working over variable velocity of wind. The proposed construct incorporates three-bladed aerofoil rotor, gear box with ratio 1:8, three-phase doubly-fed induction generator, automatic voltage regulator and tower. Results verify efficacy of this installed structure at wind speed of 7.0-8.2 m/s. The proposed design generates power output at 3 kW, voltage per phase between 220 V, and frequency of 50 Hz; and exhibits noise just around 60-70 dB which is below the permissible noise threshold of 85 dB.

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1. INTRODUCTION

The significant increase of responsiveness to the growth of ecologically clean power sources, namely wind, solar, biomass, and hydroelectric, as a replacement for fossil fuel energy has come from an escalating attention regarding global climate change, environmental contamination, and security of energy supply [1]. Destructive emissions, such as CO_2, SO_2, and further toxic litter as in out-of-date coal-fuel power plants could be eliminated through using wind power plants [2]. As the mainly to ensure renewable energy sources, wind power is decidedly projected to lay hold of a greater number in electric power generation in the years to come.

Small scale wind power turbines propose a fascinating clean energy resource for isolated areas or island communities. At low wind speeds, power can be harvested by wind turbines and had better be visually well-suited by the milieu and ought to perform including small noise. Enclosed by defining installed sites of wind power turbines applied around populated areas, atmospheric instability perhaps reduced to give consideration toward surrounding structures. Installation difficulties must be carried away to take electric power from wind farms to populated locations, where it is taken to come across demand [3]. Notwithstanding the aforesaid challenges, on the spot continues growing interest as to rooftop wind turbines [4], [5].

Many studies came to be conveyed upon modest scale wind turbines. For instance, Chaudhary *et al.* [6] studied the design of a small-sized horizontal-axis wind turbine. The aerofoil SG6043 was exposed; through the distributions of blade twist and chord, the performance improving was achieved. The highest power quantity of 0.4 is made by blades at tip speed ratio (TSR) 6 conforming toward a pitch angle of 0º. At another time, Suresh and Rajakumar in [7] create a 2-kW horizontal axis wind turbine through rotor diameter of 3.6 m and of TSR 6 to perform at small wind velocity for country operations. Streamlined examination stayed on 10 aerofoil to evaluate lift constant and lift to drag the ratio concerning dissimilar angles of attack. The result notes that SD7080 is an appropriate air foil for generating great power in a small velocity valuation. Then, Abo-Serie and Oran in [8] propose a scheme of a tiny wind turbine. A structure is based over permanent magnets impeded toward a cloak which clutches rotor-blades. The scheme is based on direct coupling for electric generation. Outcomes exhibited that power could be took out of turbine assuming the size of blade chord growth on layer site and declines on the hub for small TSR at the range around 1.5-3.

Among essential factors about wind turbine is blade. The working of turbine blade principally relies on the streamlined shape and the blades angle together with substances [9]. Turbine blades were covered towards various operational conditions, namely dirt and gleaming milieu, hard shower, extreme gust speeds in rough landscape, radical fluctuations in the term of heat, humidity, and electromagnetic contamination. Then, turbine blades are exposed to extreme weakness. This develops in fracture construction and spreading. Centrifugal forces in turbines are major cause. Moreover, a turbine blades brings up extra weakness cycles by way of a revolving speediness purpose. Physical blade had greater strength and toughness, great strength to mass proportion, hostility to weakness loss and ecological burden, and less cost.

An extensive over substances is obtainable aimed at blades of turbine blade. Here assortment comprises wood, alloys, and composites matter such as glass fibre strengthened polymers, carbon fibre strengthened polymers, and natural fibre strengthened polymers. Every substance owns this encouraged and repellent features [10]. In strength experimental design of the blades, it is significant to regard the explicit forte and detailed toughness of ingredients. Wood becomes an ordinary compound fabricated of fibre and cellulose. Wood is special damping materials. This has great toughness to mass proportion. Conversely, wood usage in blade fabricating could be restricted due to this minor confrontation to ecological deprivation and extreme effect on the ecosystem. In contrast to a ligneous substance, traditional irons possess high stiffness to weight ratio and better resistance to environmental degradation. Galvanized steel is used instead of wood. Later aluminum and its derivatives such as galvalume is castoff for fabricating turbine blades as a result of lesser denseness which considerably reduces blade weight. Lastly, a compound matter is mixture of many synthetically different elements. This improves required features of the castoff elements. It remunerates drawback of earliest ingredients. These materials which contains lengthy fibres giving extensive strong degree and rigorousness, and resin medium expands crack durability and delamination toughness.

Variable speed operation as to small scale and single wind turbine have been succeeded with a doubly-fed Induction or with permanent magnet synchronous generators. Nevertheless, recently doubly-fed induction generator becomes more broadly utilized since owns more benefits including slighter dimensions, minor charge, and negligible maintenance [11], [12]. Furthermore, a doubly-fed induction generator is offered since this can manage both frequency and voltage accordingly of variable gust velocity. Similarly, this adaptable-speed capacity owns bigger energy efficiency, enhanced power excellence, and act similar step out related many notices, with the aim of convertor has not been categorized to topped up grading [13].

Variable speed control systems aim to improve the energy grabbing after gust; nevertheless, output voltage concerning doubly-fed induction generator varies with its angular speed [14]. For an ac supply, the voltage and frequency have to be held unchanged. The add-on of electronic converters regarding conversion of frequency and voltage can control both real and reactive power concerning a good compromise among performances concerning wind turbines and those of the electrical generator, namely boost the energy losses [15], [16].

The weight of the doubly-fed induction generator is quite heavy then if its placement is parallel to turbine blades, it will require a very large and strong tower. On the other hand, it also has to pay attention to the height and strength of the tower which has to provide an appropriate flounced area of the turbine and could withstand weight of blades. One solution to decrease the magnitude and heaviness regarding tower is to place the induction generator separately from blades. The blades can be placed at head of the tower while generator is positioned at tower groundwork. Therefore, the blades and generator are connected utilizing a gearbox system that uses a vertical shaft.

Net loads on the tower derived as of tower head assembly. Those weight stand conveyed to groundwork through tower. Essential load covering rotor creates foremost load on tower. Vigorous loading is produced through gust turbulence of blade-tower collaboration. Additional innervation frequency is occurred because of obvious mass inequity in the revolving portions. The elementary strategy viewpoint is circumventing reverberating singularities and refers to turbine mounting [17].

Turbine blades are in general attached to the turbine rotor or hub by means of numerous methods, namely welding, bolting, or by the way of specialized blade root designs that fit into slots on the rotor. Welding is not possible as blade and rotor are of different materials. The type of root fixed by bolting is secured by lock nuts. These attachment methods are guaranteed secure fixation while allowing the blades to withstand the high rotational forces and heats experienced during working [18]. Rotating in high speeds, the centrifugal force on the blade is so high a loose fix can dart it out similar to a bullet from the rotor.

This paper describes establishment of an endurable wind energy transformation scheme have been utilized by means of electric generator toward urban and single applications. The design incorporates three bladed rotor, gear box, doubly-fed induction generator, and tower. Blades angle can be adjusted so pitch arrangement can control how many energies are able to be taking out. The design was operative forerunner of the hub and rotor representing the efficacy of the power taking-out structure. The turbine construct was graded by way of output power of 3 kW and used for 220 V per phase loading circuit. The paper is organized as follows: first, the variable speed wind turbine with doubly-fed induction generator models is developed. Then, the complete designs are tested based on real parameters. Next section elucidates result and analysis. Conclusions of research are defined.

2. VARIABLE SPEED WIND TURBINES SYSTEM

The wind velocity at the site of a planned setting-up is amongst the foremost influential aspects as to that kind of wind turbine is going to be planned, such as horizontal center-line, blade configuration, blade type, gearbox type, and generator type. Wind velocity diverges through altitude and could be rationally approached.

$$u = V\, ln((z - d)/z_o) \tag{1}$$

Where u, z, z_0, d, and V denote horizontal velocity, height, roughness length, a zero-plane height, and characteristic velocity, respectively. Within the zone at which wind velocity is small, bladed rotor may be implemented because of the blade's well running at a lesser tip velocity proportion. Velocity varies with height.

Seeing adapted size for a turbine rotor, the number of forces performing on the flowing is as (2).

$$\sum F_x = \int_{CS} u\rho\bar{u}\, \overline{dA} = \dot{m}(u_2 - u_0) \tag{2}$$

Where ρ, u_2, and u_0 denote fluid density, downstream velocity, and upstream velocity, correspondingly. The energy exhibited by a blade is the total dynamic power given as (3).

$$P = \tfrac{1}{2} m(V_1^2 - V_2^2) \tag{3}$$

With P, m, V_1, and V_2 denote kinetic energy generated by a wind turbine, a mass flow rate on gust, an initial air velocity, and an air velocity of the turbine, respectively. The rate of wind mass flow bent on the blend about density, turbine rotor sweeping range, and velocity regarding to act toward air is as (4).

$$m = \rho A V_a \tag{4}$$

With ρ, A, and V_a are air density, an area that sweeps turbine rotor, and speed approached by air, respectively. By put on turbine rotor stands the typical velocity among inlet and outlet where $V_a = \tfrac{1}{2}(V_1 + V_2)$ then given as (5).

$$P = \tfrac{1}{4}\rho A[1 - (V_2/V_1)^3 - (V_2/V_1)^2 + (V_2/V_1)] \tag{5}$$

The all-out energy taken out over rotor is $dP/dV_2 = 0$. Over mathematical manipulation, it will be found as (6).

$$P = (0.5925)\, \tfrac{1}{2}\rho A V_1^3 \tag{6}$$

Where the fraction of 0.5925 is coefficient of Beth or C_v.

Each configuration of rotor remains the mainly numerical portion of turbine construct. Rotors utilize streamlined elevate offering rotating gravity and therefore intake torque toward the gearbox. At that point exist numerous homogeneous airfoil shapes different in fragmentary side view that are able to be categorized identifiably through their camber, width, and chord dimension, as seen in Figure 1. The design of the proposed blades in this study will be depend on the Betz and blade section concept which be sure of two essential postulations, namely in view are no aeromechanical relations among distinct blade components and pressure on blade parts are merely created in elevate and drag quantities. Furthermore, blade form can be determined through its outline, its quantity, aerofoils outline, and tip velocity proportion.

This aerofoil profiles shown in Figure 2 are nearly all usual aerofoil fragmentary which is used on wind turbines. National advisory committee for aeronautics (NACA) constructs aerofoils for airplane wings, numerous which get usage by way of suitable turbine rotor fragmentary. The NACA four-digit enumeration scheme is procedure on categorizing an aerofoil outline in regard to its camber, chord and width. NACA 4412 takes highest camber of 4% at a span of 40% of the chord distance from leading edge by highest width of 12% of the chord. The geometry of NACA 4412 is seen at Table 1.

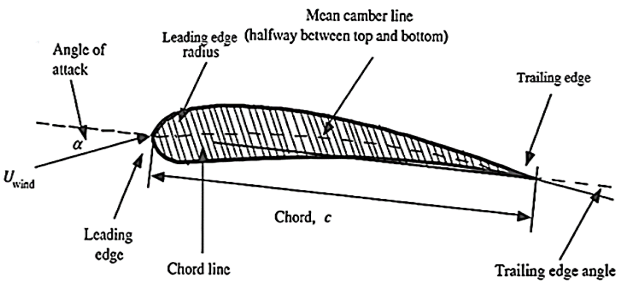

Figure 1. Aerofoil nomenclature [19]

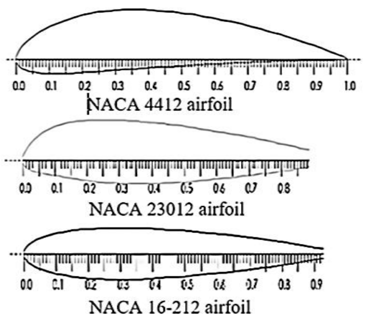

Figure 2. Ordinary aerofoil cross sections [20]

Table 1. Determination of NACA 4412 blade geometry [21]

Blade's shape	C_L/C_D	α	C_L	TSR	Number of blades
Taper	133.6	6	1.14	7	3

Horizontal wind turbines have a propeller-like perception, everyplace the rotor revolves touching straight center-line and is practically aligned to gust stream [22]. Horizontal wind turbine has many benefits, namely quite great power quantity grade, rotor velocity and output energy are able to be regulated in governing pitch angle on the blades. Moreover, blades shape can be streamlined improved and the most efficiency condition can be reached after streamline lift going to its highest value.

A proposed structure of an adjustable velocity wind turbine is described at Figure 3. Wind turbines can be received maximum power transfer value through wide area of wind velocity. The turbines are able to unchangingly adapt its revolving velocity transferring into a wind velocity. That system is built on doubly-fed induction generator concerning the blades, drivetrain, and tower. Constructed for conversion of voltage and frequency, generator output is AC voltage by means of the amplitude gain and frequency of the networks.

2.1. Blade design

Aerofoils which are fragmental framework of blades are foundation of turbine blade structure, shown in Figure 4. The blade design is relatively complex, with several different components. The perfect structure of blade is aerofoils kind since the profile can captivate dynamic energy. It has also undertaken a collection of existences with difference of materials, measurements, aerofoil forms, and the quantity of blades.

Tip velocity proportion could be identified as association both rotor blades and relative wind speeds; and becomes greatest important factor within entirely additional optimal dimensions of rotor are evaluated.

$$\lambda = (\Omega\, r)/\, V \quad (7)$$

Where Ω, r, and V denote rotational speed of blade, length of rotor blade, and, wind speed respectively. Straight center-line of wind turbine containing three of blades takes the all-out energy constant value and tip velocity proportion in comparison with other forms [23].

Referring to the Betz method, the shape structure and blades quantities devotes elementary shape of the modern turbine blades [24]. Then as given in (8).

$$C = (\, 2\pi r 8 U_{wd}\,)/(\, n 9 C_l\, \lambda\, V_r\,) \quad (8)$$

Where r, U_{wd}, C_l denote radius of the blade, speed of wind design and coefficient of the elevator, respectively. Then, V_r is the total wind speed $V_r = \sqrt{U^2 - V^2}$. The perfect shape of propeller is the aerofoil structure which can convert dynamic energy of wind trust within highest revolving energy. Each aerofoil comprises average camber line, leading edge, trailing edge, chord line, camber, thickness and angle of attack [25].

All-out energy removal happens at the best tip velocity proportion of the bar is 59% or also called the Betz coefficient. Uncaptured wind power consists of rubbing shortfalls, limited wing dimensions, and turbine structure drop, adding by means of the circumstance that turbine cannot work at ideal tip velocity proportion across its operating range of wind speed. By allowing the primary efficiency of blades and all of energy components are previously recognized, proficiency of the wind turbine is able to be evaluated through (9).

$$K = \eta_{blade}\,\eta_{trans}\,\eta_{gen}\,\eta_{cont} \tag{9}$$

Where K is the system efficiency, η_{blade} , η_{trans}, η_{gen}, and η_{cont} are the efficiency of blade, transmission, generator, and controller, respectively. If both efficiency and energy production have been obtained as (10).

$$P_a = P_e/K = {}^1\!/_2\,\eta\,A\,V_{max}^3 \tag{10}$$

Where P_a, P_e, η, A, V_{max} denote wind power capacity, electric power capacity, air density, area of sweeping, and maximum wind speed, respectively. The radius of the blade can be found as $R = \sqrt{A/3.14}$.

Another geometric parameter of the blades which needs to be determined is value of the partial radius.

$$r = r_0 + [(R - r_0)/n] \times \text{elements} \tag{11}$$

Where r, r_0, R, and n are partial radius, partial radius of the initial blade confirmation, radius of the blade, and the quantity of parts, respectively. Within development of aerofoil blades, as is required facing settle on the twist (β) in clarifying flow angle (φ) and angle on attack (α) of the blade. The flow angle can be calculated using (12).

$$\phi = \tfrac{2}{3}\tan^{-1}(1/\lambda_r) \tag{12}$$

Where λ_r is the value of partial speed ratio tip at each element. The λ_r and β values are able to evaluate $\lambda_r = (r/R)\lambda$ and $\beta = -\alpha$. The width of the blades can be specified on every element is as (13).

$$C_r = \big(16\,\pi\,R\,(R/r)\big)/(9\,\lambda^2 B C_l) \tag{13}$$

Where C_l and λ are lift coefficient and tip speed ratio.

Figure 3. Variable speed wind turbine

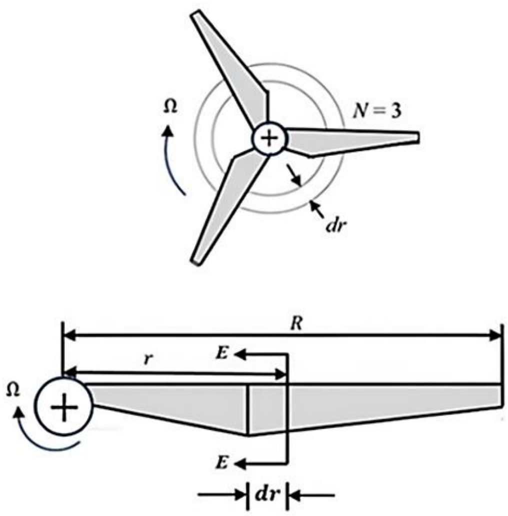

Figure 4. The blade of wind turbine

Among focusing the assignment is to construct turbine blade that is relatively easy to shape and corrosive resistant. Zinc galvalume sheet became a substantial that were moderately often utilized inside blade assembly. Various zinc galvalume kinds become trialed in blade usage and confirmed positive outcomes. Over proposed outline, blade form is tailored own equal effects just when the improved NACA 4412 aerofoil, shown in Figure 5. Since the arrange of aerofoil data, as is crucial detecting certain attack angle regarding lift; drag may perhaps be maximized in order for having highest potential mining of force.

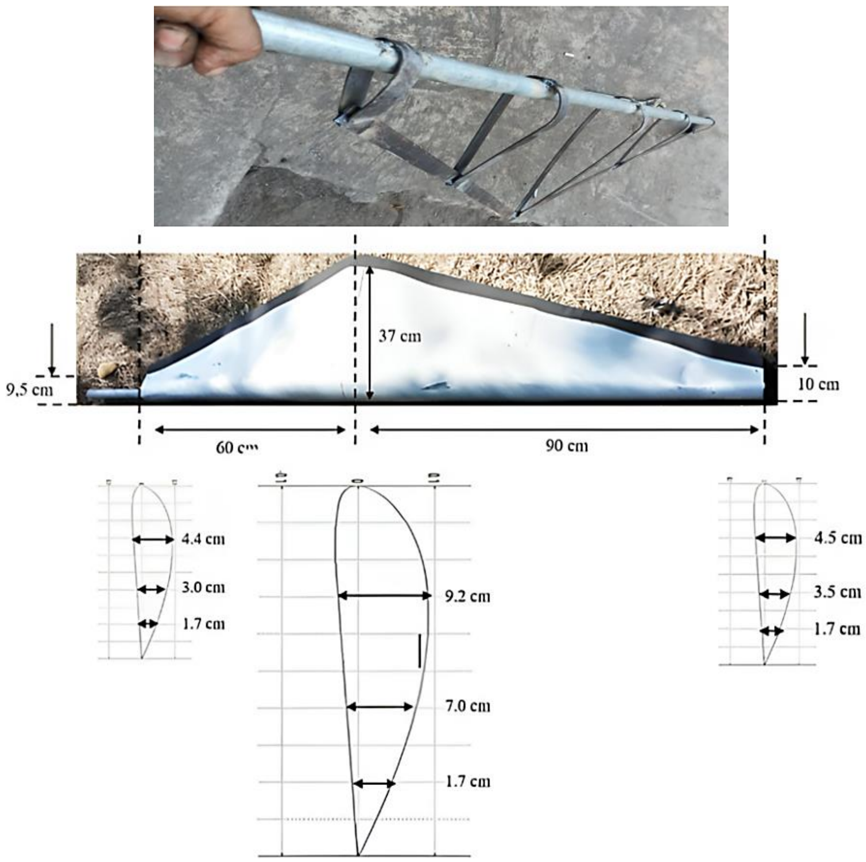

Figure 5. Top view of aerofoil's profile of proposed blade

2.2. Gearbox design

The turbine gearbox transforms a great torque on primary shaft to lesser torque on the high-velocity shaft encounter electro-mechanical needs of generator. Drivetrain malfunction became the main instigate of many problems for the wind turbine. Even supposing wavering in turbine powertrains was known a noteworthy consideration as of researchers, the vital disaster means is incomplete identified because of very complex character. Drivetrain is a complex geometric structure acquiring highly complex loading conditions. Operating torque is steered through rotor blades under wavering wind, and fluctuating charge exist in a whole drivetrain. The debility of drivetrain is much concerned.

The bevel gearbox model shown in Figure 6, the ratio is 1:8 which increasing the speed of the driven gears. Streamlined charge are mostly absorbed through primary shaft bearings, and could not impact on the gear teeth excluding aimed at forcing torque. Input charge of the archetypal is restricted near rotational force load only, and supposed to be used clearly toward gearboxes, which conveys the charge to generator rotor. A bevel gearbox is applied to transmit force at steady velocity proportion among two shafts which the axes cross at a quantified angle. Drivetrain are able to deliver great power and appropriate to less center length of shafts because of both great effectiveness and compact layout. Bevel gears between distinctive gears are used for delivering force through crossing shafts in similar position. Mating gear teeth functioning against the whole lot generating rotating movements possibly equate relate toward cam and follower. In place of two gears mesh, besides propensity for undesirable noise chosen produced. Xie [26] obtained which exact tooth overlay and great outward condition are crucial achieving silent bevel powertrain drives.

Lewis, Buckingham, and Tregold method is operated to shape the tooth shape, beveling aspect, tooth shape aspect and static dilution [27]. Stationary dilution of bevel gear is attained through resolving constraints namely speed factor, equal number of teeth, tooth shape aspect, bevel factor, and lateral tooth charge, shown in Table 2. Meanwhile, v, σ_{01}, and σ_{02} denote speed of pinion or gear, acceptable stationary strain of pinion wheel, acceptable standing stress of gear wheel; and θ_{p1}, θ_{p2}, T_1 and T_2 are pitch angle for pinion wheel (°), pitch angle for gear wheel, quantity of teeth in pinion and wheel, respectively.

Wind turbines take large inertia. Yet, in wind turbine drivetrains, the shift ratio of the machinery reduced the inertia faced at the generator. Restoring this inertia needs a direct joining of a large flywheel to the rotor of the generator. Flywheel, weighty wheel tied to revolving shaft in the role of smoothing out delivery of power from a wind turbine to a generator, displayed in Figure 7. This flywheel apathy competes with and regulates oscillations in the velocity of the turbines and also keeps surplus energy aimed at sporadic operate.

Figure 6. Gearbox system, gear ratio of 1:8

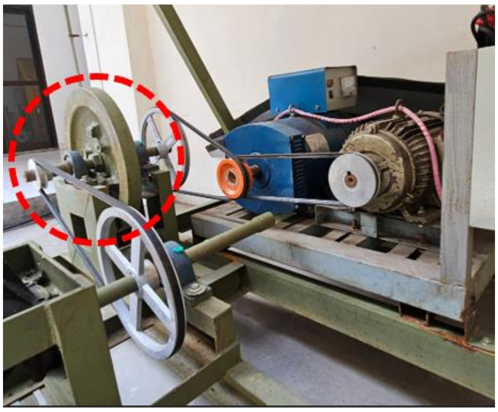
Figure 7. Flywheel

Table 2. Parameter and its equation regarding the bevel gearbox

Parameter	Equation	
Velocity factor	$C_v = 3/(3+v)$	
Teeth equivalent number	$T_{E1} = T_1 \sec\theta_{p1}$(pinion)	$T_{E2} = T_2 \sec\theta_{p2}$ (gear)
Tooth form factor	$Y_1' = 0.154 - 0.912/T_{E1}$ (pinion 1)	$Y_2' = 0.154 - 0.912/T_{E2}$ (pinion 2)
Bevel factor	$BF = (L-b)/L$	$b = L/3$
Load of tangential tooth	$W_{T1} = \sigma_{01}\, C_v\, b\, mY_1'\, BF$	$W_{T2} = \sigma_{02}\, C_v\, b\, mY_1'\, BF$

2.3. Turbine tower design

Owing into fairly big dimensions of the turbine, the problem must stand placed in a special location, namely tower. The objective of a tower is offering blades a headroom as of the floor location of turbine into continuous flow subway, shown in Figure 8. Small scale and stand-alone wind turbines are generally mounted on structural towers and are relatively low-priced.

The tower used in this particular design was selected to locate doubly-fed induction generator that could be mounted into a foundation rather than on to head of the structure. The substance is selected by way of glazed steel as a result of the ingredients obtainability and moderately bargain. its glazing makes is weather resistant and possess mechanical properties to support turbine even under extreme charging conditions.

Another problem related to tower design is dynamic loading, the main cause of which is wind turbulence blade-tower interaction. Another excitation frequency happens as a result of inevitable physique inequity in revolving fragments. To avoid resonance phenomena, the turbine blades must be tightly attached to the hub and the hub must also be firmly connected to the rotor, as seen in Figure 9. The proposed hub is specifically designed so that the turbine blades are installed strongly but also the pitch angle of the blades are able to be accustomed beforehand.

2.4. Doubly-fed induction generator design

Both DC and synchronous machines could be utilized by way of any generators or motors, exactly alike induction motors became working as induction generator. For now, the energy catastrophe of the 1970's, researchers were established using induction motors as generators, mostly in wind energy transformer by means of an appropriate device for altering mechanical energy entering electrical energy. The induction generators are as well denoted to as asynchronous generators do not work at synchronous velocity.

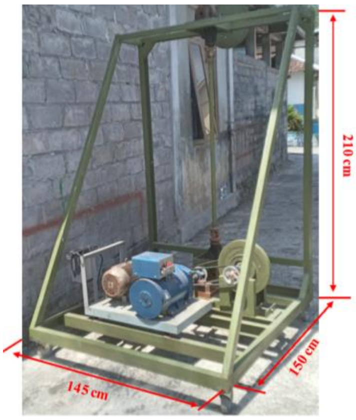

Figure 8. Turbine tower

Figure 9. Turbine blade mounting

Once a voltage is operated to stator coiling of motor, current devised of two apparatuses drifts toward it, namely magnetizing and real power elements. Magnetizing element delays a used voltage by 90° and charging aimed at generating magnetic field or revolving flux. The real section is in phase with working voltage and delivers real power to induction motor. That element therefore induces revolution towards the shaft of motor and accountable for machine-like output and inner losses. Provided active load is detached from the structure, the motor remains bringing in similar induction current. Though active current grows into tiny. On condition that machine-like power is combined towards the shaft producing supplementary revolving and upsurge within velocity to a quantity where this revolving over synchronous velocity; on one occasion induction motor became induction generator.

During transformation, the slip rate develops a negative quantity. Rotor electrodes are move about at a velocity greater than that of the revolving flux; connotation that the movement on rotor conductors respective near the flux set to switch in route. Therefore, the direction of the rotor current is going to modify triggering a setback in the magnetlike flux exhibited in stator coiling. Such implies that electric power is going now drift out of stator coiling similar to generator.

The machine ensures though endure to describe similar exciting current as of AC supply grid by way of induction generator is no self-exciting and spinning flux needs uniform source. Once present inner losses of induction motor are now provided through the prime mover which is the revolution given by means of wind turbine. The frequency of produced stator voltage is relied on rotating velocity of magnetic flux and thus will be of the similar frequency in place of operated exciting stator voltage [28].

An induction generator is fabricated of stator and rotor. Stator is a motionless sequences of coated steel sheets installed on a structure that eventually develops the cage that is inside diameter of casing fabrication. Laminations of the stator are fitted on the interior body as it were that they create slots similar to a synchronous machine. Rotor could originate either in the wound-rotor kind or cage kind. A wound-rotor type, also recognized as slip ring-rotor, is an induction generator kind where the rotor coiling is linked over slip-rings to outer resistance. Correcting the resistance permits regulate on velocity and force features of generator. Wound-rotor generator is able to be fired up with small inflow current, through implanting excessive resistance into a rotor unit; as the generator increase speed, resistance is able to be reduced.

Doubly-fed induction generators is like to coiled-rotor generator, then has added structures that let them to work at velocity somewhat upper or lesser its ordinary synchronous velocity as shown in Figure 10. The basis of the doubly-fed is that stator own three-phase coiling is linked toward grid, then over AC-DC-AC driven form voltage source bidirectional converter, rotor output is coupled. Upfront linking to grid is aimed at stator flux designates permanently synchronous to system frequency. Rotor takes alike three phase coiling in excess of stator rotations which are pinched over electromechanical tool named slip rings. Rotor-linked scheme and converter receives variable frequency power built on wind velocity changing and alters to DC form that is gained by way of linking voltage and reverses to AC form at an expected line phase. Gearbox is employed taking a greater slip power [29].

Rotor proceeds power beginning at the line in sub-synchronous way and distributes power toward the line during super-synchronous way [30], [31]. Motorized power took out as of accessible wind velocity in turbine. The generator output is gained by the consequence of efficiency and the input mechanical power from the wind turbine. Generator output is comparable to the sum of both stator power and rotor power. As slip is adverse, power in rotor is positive. The powers of the stator can be regulated through the internal transient electromotive force.

By synchronous velocity in valuation on rotating random orientation frame, d-axis current is able to control DC network voltage and q-axis current takes reactive power regulate capacity [32], [33]. All over making for constant rotating velocity over synchronous velocity, motorized torque T_m is positive. The electro-magnetic torque is as (14).

$$T_e = \frac{3P}{2}\left[I_{\alpha s}\left(L_m I_{\beta s} + L_r I_{\beta r}\right) - I_{\beta r}\left(L_m I_{\alpha s} + L_r I_{\alpha r}\right)\right] \quad (14)$$

Notations of $i_{\alpha s}$ and $i_{\beta s}$ are α and β axis stator currents; $i_{\alpha r}$ and $i_{\beta r}$ are α axis and β axis rotor currents [34].

2.5. Automatic voltage regulator

Automatic voltage regulator is an equipment utilized within induction generator to exhibit automatically regulating voltage, which denotes which can turn changeable voltage degrees through constant voltage quantities. It works in steadying output voltage on induction generator at adjustable charges, yet can split too the reactive charge among generators which was working in parallel and helps react to overloads. Solving the problematic into output voltage fluctuation of induction generator, an appropriate quantity of reactive power was required preserving steady terminal voltage. Static capacitor-thyristor controlled reactor can be utilized controlling generator terminal voltage over fluctuating charging conditions. The reactor comprises static capacitor linked in parallel by grouping of two antiparallel thyristors coupled within sequence with reactor as seen in Figure 11. This feedback control is able to regulate firing angles of antiparallel thyristor and windingly control reactive power inject facing network through regulating current across apparatus.

The compensator of fixed VAR is controlling susceptance on every phase through adjusting firing angles of thyristor-controlled reactor [35], [36] this compensator is frequently utilized over sinusoidal voltage settings, signal of controlled current exhibit excessive harmonic substance [37]. Reactor is taken within transmission by consecutive function on gate pulses into forward biased thyristor around every half-cycle. That one will hinder instantly later AC current intersects zero, except gate signal is reutilized. Current around reactor are able to be regulated since maximum toward zero through process of activating angle dictate. Thyristor activation was delayed as highest of used voltage during every half-cycle, then interval of the current conduction period was regulated. On the designed wind turbine, automatic voltage regulator is a tool utilized in doubly-fed induction generator through the role of automatically regulating voltage, denoting that the subject will turn changeable voltage degrees into constant voltage degrees. The type of AVR is static tap switching. AVR is located in the alternators terminal box, seen in Figure 12.

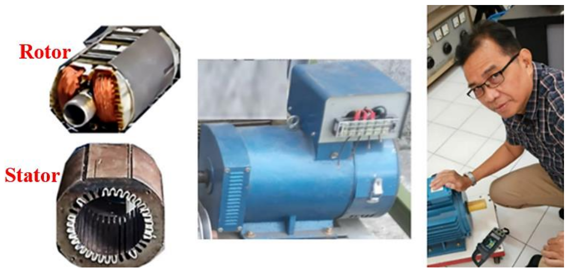

Figure 10. Doubly-fed induction generator

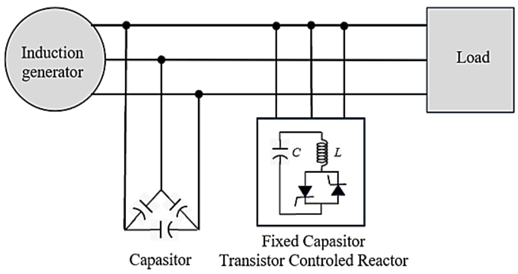

Figure 11. Schematic of induction generator with automatic voltage regulator

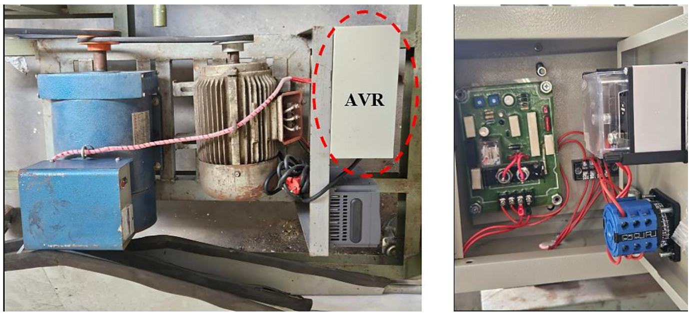

Figure 12. AVR installed in the wind turbine design

3. RESULTS AND DISCUSSION

Construction about designed 3 kW variable speed wind power plant has several important parts. Apart from electronic components, this system also has several parts that support optimizing the performance of the instrument. Among them are blade, gearboxes, and tower. These four parts have important functions because the functions of the four are very closely related, shown in Figure 13. The construction of the wind power plant was taken to a location in Glagah Beach, Temon, Kulon Progo, Yogyakarta on daytime assessing to deal with pitch angle at certain wind velocity immediately for the purpose of reaching 150 rpm of shaft of blade.

3.1. Testing of turbine blade

Wind generating station project result is then led an experimental to clarify the work of turbine blade. The assessments were taken on September 12, 2024 located at Glagah Beach, in Figure 14. On schedule the assessment happens, conditions in Glagah Beach location were clear by heat was around 31 °C. Wind speeds and rotating speed of wind turbine shaft are shown in Table 3. Table 3 displays rotating velocity of turbine shaft reaches 142-150 rpm at 7.8-8.2 m/s of wind speed; the torque generated during this rotation will be able to rotate the generator at a rotor speed of 1,450-1,500 rpm.

Figure 13. The construction of 3 kW variable speed wind power plant

Figure 14. Testing of proposed wind turbine blade

Table 3. Wind and rotating speeds of turbine shaft

Wind speed (m/s)	Shaft speed of turbine (rpm)	Rotor speed of generator (rpm)
5.3	68	703
6.0	92	900
6.5	105	1,002
6.8	113	1,100
7.0	119	1,205
7.5	131	1,310
7.8	142	1,403
8.2	150	1,504

3.2. Testing of doubly-fed induction generator

In a wind turbine, generator is functioned as mechanical-electrical converter. Generator is attached straight into shaft input or shaft output of drivetrain conditional on revolving velocity needed by generator for producing that one valued power output. The 3 kW doubly-fed induction generator was sourced and assessed to evaluate the conducting of induction generator at fluctuate revolving speeds.

In order to verify conversion system, the test is accomplished in seeing that doubly-fed induction generator that owns main governor emulating the torque supplied through turbine machine-driven unit. Figure 15 shows the test scheme. Doubly-fed induction generator is coupled with inductor motor through V-belt. Results are seen in Tables 4 and 5. The subject is clear from Tables 4 and 5 that utilizing automatic voltage regulator is going to alter instable rotor of levels into constant voltage degrees. Output voltage around 220 V and approximately 50 Hz are achieved on rotor speed of 1,350-1,500 rpm.

3.3. Testing of complete system

The individual designs presented in section 2 are assembled as seen in Figure 16. Simulating the fulfilled wind turbine system some remarks, need to be done. For instance, the different special treatments are required in a wind turbine system, namely pitch, voltage unbalance and frequency. Results are displayed in Tables 6 and 7. As seen on Table 6, generator speed of 1,200 to 1,500 rpm is created during wind velocity in a variety of 7.0-8.2 m/sec. Under these conditions, the output voltage of the induction generator reaches 220 V per phase with a frequency of around 50 Hz. Whereas Table 7 displays the performance of wind turbine that induction generator does not use automatic voltage regulator. It is seen that although the generator output voltage reaches around 220 V, the frequency varies between 47 Hz and 51 Hz.

Figure 15. Doubly-fed induction generator connected to an induction motor

Figure 16. Complete system of 3 kW variable speed wind turbine

Table 4. Rotor speed and stator voltage of generator without automatic voltage regulator

Rotor speed (rpm)	Output voltage of doubly-fed induction generator			Unbalance U_{unb} (%)	Frequency (Hz)
	R phase (Volt)	*S* phase (Volt)	*T* phase (Volt)		
1,515	227	227	227	1.7 – 1.9	50.0
1,453	188	188	190	12.9 -16.0	50.0
1,486	202	201	203	12.0 – 15.0	50.0
1,400	160	162	165	0.4 – 2.4	50.0
1,307	73	73	74	8.0 – 19.0	50.0
1,253	50	50	50	0.6 – 1.5	50.0
1,210	35.8	36.2	36.5	2.2 – 4.1	49.8

Table 5. Rotor speed and stator voltage of generator with automatic voltage regulator

Rotor speed (rpm)	Output voltage of doubly-fed induction generator			Unbalance U_{unb} (%)	Frequency (Hz)
	R phase (Volt)	*S* phase (Volt)	*T* phase (Volt)		
1,588	221	219	226	1.4 – 2.0	49.9
1,458	219	218	223	16.0 -19.0	52.4
1,411	220.6	219	224	0.7 – 3.8	50.7
1,348	220	222	221	1.2 – 3.6	49.1
1,200	223	224	223	3.0 – 4.0	44.0
1,067	225	226	225	16.0 – 20.0	37.9

Table 6. Performance complete system with automatic voltage control

Wind speed (RPM)	Turbine speed (RPM)	Generator speed (RPM)	Output voltage (V)			Frequency (Hz)	Excitation current (A)	Sound (dB)
			R	S	T			
5.3	68	705	159	160	166	22	47	
6.0	92	903	189	200	201	26	56	
6.8	113	1,100	231	236	234	37	59	
7.0	119	1,203	220	220	221	49	59	60-70
7.5	131	1,304	221	220	220	49	69	
7.8	142	1,401	220	221	220	49	20	
8.2	150	1,504	223	223	220	50	17	

Table 7. Performance complete system without automatic voltage control

Wind speed (RPM)	Turbine speed (RPM)	Generator speed (RPM)	Output voltage (V)			Frequency (Hz)	Excitation current (A)	Sound (dB)
			R	S	T			
7.0	119	1,201	56	55	54	41.0	5	
7.5	131	1,311	86	85	84	44.8	7	
7.8	142	1,409	160	158	159	47.7	13	60-70
8.2	150	1,501	210	207	209	51.2	17	
8.3	154	1,519	222	219	220	51.5	17	

4. CONCLUSION

The study describes experimental design about 3 kW variable speed wind turbine through doubly-fed induction generator which is considered to be used at wind speed of 7.0–8.2 m/s. A 3 kW wind turbine has been successfully implemented under 8.2 m/s wind speed condition which produce turbine speed of 150 RPM, generator speed of 1,500 RPM, and excitation current of 17 A. This wind turbine also generates voltage per phase between 220-223 V and the frequency of 50 Hz. Last but not least, the proposed wind turbine generates only around 60-70 dB which is still below the permissible noise threshold of 85 dB. Future works should be investigating the implementation of wind turbine blade which is lighter but still strong so it can drive the generator at wind speeds below 5 m/s. These future works could also make allowance for a broader range of input variables, such as pitch angle and loading effect.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors whose names are listed directly below certify that they have no affiliations with or involvement in any organization or entity with any financial interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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