On the need for the development of low wind speed turbine generator system

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Abstract. The study focused on the need for the development of a low cut-in wind speed turbine system with a view to challenge for concerted efforts towards improvement in design in such a way that favours operation at wind speeds as low as 1.5 to 2.0 m/s. It reviewed some existing reports on rotor designs with major focus on improved blade design for enhanced turbine performance and structural integrity. It found that despite the advances in turbine blade designs, there is the need to further the design to include those that can drive generators not just for small wind turbine applications but also for operation under lower cut-in speeds (less than 2.0 m/s). It further demonstrated the need to have improvement in wind turbine generator design that eliminates/reduce lubrication parts and possibly employ electro-magneto-mechanical principles for operation.

Key words: Wind Power, Rotor Design, Wind Turbine, Turbine Blade Design, Generator

1. Introduction

Wind power technology has over the years gone through several developmental changes. From the use of wind energy as windmills over 2000 years ago, it has grown to become pivotal in the power sector and engaged for the production of gigawatts of electricity across the globe. Today, wind power technology is one of the growing electricity resource technology in China, the United States of America and Europe. Global cumulative installed wind power capacity has constantly increased over the last two decades. Fig. 1 displays the trend of increase. It shows that there is a polynomial increase in the additions of new turbine plants to wind energy markets per year. Further analyses show that the annual growth in capacity averages about 22% within the last two decades while it is likely that the cumulative increase will exceed one terawatts (i.e. 1.0 TW) in the next three to five years. Based on this, some countries have contributed tremendously to this achievement. For instance, in the whole of Europe, five countries accounted for 68% of cumulative installed wind power capacity as at the year 2018. Germany, Spain and the United
Kingdom (UK) are the first three nations with 59,311 MW, 23,494 MW and 20,970 MW respectively, while France (with 15,309 MW) and Italy (with 9,958 MW) are the fourth and fifth in the rank [1]. Of this lot, Germany and Spain’s percentage contribution to Europe’s wind power capacity as at 2018 accounted for 31% and 12% respectively. The total for Europe was 189,229 MW in 2018. However, of this total capacity, onshore wind installations dominate across Europe. The percentage contribution of onshore wind turbine capacity for electricity generation is 99.1% [1]. This shows that adoption of offshore installations still has a long way ahead to further its development.

China, the United States of America (USA), India, Brazil and Canada are other five leading nations, outside the top five of Europe, that are making good contributions to global wind power capacity. For example, China’s total installed wind power capacity as at the year 2017 stood at 188,232 MW. This figure competes closely with that of the whole of Europe. USA on the other hand, has total installed capacity that is far above that of the best of Europe. Its value as at 2017 was 89,077 MW. Fig. 2 shows the contribution of the top five countries outside Europe and reveal that the values for the rest of the world excluding the top ten countries enumerated above was 83,008 MW as at 2017. Other nations are equally making developmental progress towards the adoption of wind energy utilities for power generation.

![Figure 1: Global cumulative installed wind power capacity [2]](image)
Fig. 2: Cumulative installed wind power capacities of top five countries outside Europe [2]

2. Advances in wind turbine design and development

Despite the progress in wind power industry, there are limiting factors, which have slowed/hindered a heightened growth of the wind energy market. These factors include high initial costs of hardware and installation. A few years ago, precisely between 2001 and 2012, a 1 MW wind turbine cost a little over US $ 1 million and today, the cost has not fared significantly better. This high cost of installed wind turbine may be a major hindrance to poorer nations adopting the technology of wind energy for electricity production. Based on this, research efforts focusing on hardware improvement are ongoing to bring down prices and reduce the cost of energy around the world. One major route adopted was to develop small wind turbine machines capable of producing few kilowatts (kW) of wind power either as standalone, embedded generation or for domestic use. Other arguments that have favoured development of small scale wind turbines is the fact that large wind farm operation may lead to climate changes which include increased average temperature and precipitation [3-4]. Hence, Tummala et al. [5] suggested that large-scale wind turbine farms may not be a sustainable viable option at the long run. Consequently, several researches have focused on small-scale wind turbine development. Part of these includes the various initiatives that range from using natural materials, like timber [6-7] as turbine rotor material to aero-structural design of the rotor/blade [8]. Thus, promoting the technology of small wind turbine system. The part that the shape and design of turbine rotors play in the magnitude of its performance, energy yield and aeroacoustics characteristics cannot be overemphasized. The design usually focus among other things on the interplay that occurs between the two most important forces that act on the airfoil. These forces are the lift and drag,
and the ratio of their coefficients is a very important parameter in the design process. Fig. 3 show the directions of the lift and drag forces along the line of airflow.

![Fig. 3: Schematics of airfoil showing the lift and drag forces in their direction of impact along the airflow direction](image)

Based on this, several studies have looked into the impact of rotor designs on the performance of wind turbines. For instance, [9] developed shrouded-twin-rotor turbine design to enhance the performance and power generation from a wind turbine. Elsakka et al. [10] studied the influence of the angle of attack of a vertical axis wind turbine’s rotor on power generation and the aerodynamic forces using computational fluid dynamics (CFD) analysis technique. It demonstrated that the sinusoidal variable pitch configuration has effect on the performance of the turbine. Hosseini and Goudarzi [11] developed and investigated the performance of a hybrid vertical axis wind turbine (VAWT) in order to obtain an extended operational range and enhance self-starting ability. A combined 2-bladed modified Savonius batch-type and 3-bladed Darrieus rotors were employed for the hybrid system’s design and CFD analysis. The results demonstrated that the design gave an improved efficiency with an operable tip speed ratio of between 2.5 and 4.5, and maximum coefficient of performance of 41.4%. Rezaei et al. [12] studied the effect of aeroelasticity and its corresponding dynamics as it relates to wind turbine rotor’s geometric nonlinearities, which originates from the blade deformation under cyclic loading. It developed a multi-flexible-body model for the aeroelastic analysis on the 3-bladed turbine assembly. The results were compared with those of a single-blade model, and found that the single-blade model gave the behavioural understanding of a wind turbine. However, the study asserted that employing the entire system model for analysis is necessary for complete dynamic performance or stability analysis. Lositano et al. [13] demonstrated the effect of cambered tubercle leading edge (TLE) blades on the performance, under steady conditions, of a 5 kW 3-bladed H-rotor Darrieus VAWT. It showed that the LTE had a negative impact on the performance of the rotors.

In the same vein, Wang and Zou [14] demonstrated a method to analyse the impact of geometric variations on the aerodynamic performance of a wind turbine rotor. Genç et al. [15] studied the impact of the pre-stall flow control on the lift and drag coefficients of a wind turbine airfoil. It found that, introduction of a roughness element improves the aerodynamic performance of the blades. Menon and Ponta [16] investigated how pitch control contributes to the mitigation of fatigue damage of turbine rotors. It used rapid pitch control to regulate short-term fluctuations in load and wind conditions. Other studies include Hua et al. [17], Manganhar et al. [18], Sengupta
et al. [19] and Yang et al. [20]. Each of the studies focused on improved blade design for enhanced turbine performance and structural integrity.

However, despite the advances in turbine blade designs, there is the need to further the design to include those that can drive generators not just for small wind turbine applications but also for operation under very low cut-in speeds (less than 2.0 m/s). This may require that the rotor is designed in such a way that the desire is to have an optimised chord and twist distribution with airfoils having glide ratio that is high at a range of angles of attack. When this is achieved and operated successfully, several low wind speed regions across the globe may be able to take advantage and adopt wind energy technology for power generation.

3. Cut-in wind speed as a limiting factor to popular turbine models

In addition to the limiting factors of large wind turbine models, another issue of importance is the fact that majority of the commercial megawatt (MW) turbine models have their cut-in wind speeds from 3.0 m/s (see Table 1 for instance). Table 1 displays that none of the popular wind turbine models has the cut-in wind speed below 3.0 m/s. This is in addition to the height requirement, which has made the large turbines unsuitable for application in residential and commercial areas.

| S/N | Turbine Model | Cut-in speed (m/s) | Cut-out speed (m/s) | Rated speed (m/s) | Power rating (kW) | Hub height (m) |
|-----|---------------|-------------------|-------------------|------------------|-------------------|---------------|
| 1   | PGE 20/25     | 3.5               | 25                | 9.0              | 25                | 24/30/36      |
| 2   | Enercon       | 3.0               | 25                | 12.0             | 3000              | 120/135       |
| 3   | GE 1.5 sle    | 3.5               | 25                | 14.0             | 1500              | 65/80         |
| 4   | G.E 1.5 xle   | 3.5               | 20                | 11.5             | 1500              | 80            |
| 5   | AV 927        | 3.0               | 25                | 13.1             | 3300              | 60-80         |
| 6   | AV 928        | 3.0               | 25                | 11.6             | 2500              | 80            |
| 7   | V 90          | 4.0               | 25                | 15.0             | 3000              | 80            |
| 8   | SWT-3.6-107   | 3.0               | 25                | 13.0             | 3600              | 80            |

This speed requirement is a major shortcoming when consideration is given to the fact that several potential sites, especially across the sub-Saharan Africa (SSA) region, have average surface wind speed below this value.

Moreover, the cut-in wind speed is a very important technical parameter. This is because it is related to the magnitude of the initial torque that the turbine rotor shaft is required to overcome to produce an output. The relationship between the torque and the wind speed is given as equation (1):

\[ \tau = \left( \frac{1}{2} rAP \right) C_T v^2 \]

where: \( r = \) rotor radius, \( A = \) swept area, \( \rho = \) air density, \( v = \) wind speed, \( C_T = \) torque coefficient

Based on equation (1), the torque is proportional to the square of the wind speed. Thus, suggesting that whatever can be done to reduce the initial torque will also have an impact on the cut-in wind speed. Another important parameter is the tip speed ratio (TSR) (\( \lambda \)). This is equally related to the wind speed (\( v \)) and rotor speed (\( u \)) as:
\[ \lambda = \frac{\Omega}{v} = \frac{\pi DN}{60v} \]  \hspace{1cm} (2)

where: \( N \) is the number of rotation of the blade per minute, \( D \) is the rotor diameter

However, it has been shown empirically that the optimum TSR for maximum power output, depending on the number of blades (n), occurs at [26]:

\[ \lambda_{\text{max, power}} = \frac{4\pi}{n} \]  \hspace{1cm} (3)

Relating equation (2) to (3) gives that:

\[ \frac{nDN}{240} = v \]  \hspace{1cm} (4)

This also suggests that the wind speed required at optimum TSR for maximum power output is related to the number of revolution per minute (N). Hence, maximum power can be achieved with few revolutions, if the cut-in wind speed can be reduced.

4. Wind turbine generator technologies

Moreover, aside the reduction of cut-in wind speed, another possible means of achieving output at reduced torque is to eliminate/reduce the lubricating parts. This is because the lubricating parts introduces mechanical losses into the system. Thus, efforts tailored towards achieving these sets of targets may require appropriate generator design. However, there are different types of wind turbine generators that have been the focus of previous studies. The aim of such studies is on criteria that include power quality, size, cost, weight and speed range [27]. Another factor of design is the determination of the operating principle of the generator, whether synchronous or induction (asynchronous) and may be multi-phase or single phase, direct current (DC) or alternating current (AC). The general differences in wind turbine generator models are summarised with Fig. 4. It shows that whatever the AC generator type, it either operates by squirrel-cage, permanent magnet, wound rotor or high temperature superconductor (HTS). According to Cao et al. [28], small-scale wind turbines generators use either DC machines, squirrel-cage induction machines or synchronous machines, while the medium to large-scale turbines employs doubly-fed induction generator (DFIG), permanent magnet, switched reluctance and HTS.

4.1. Synchronous Generator

This kind of electrical machines function to convert mechanical energy from prime mover to electrical energy at fixed frequency or voltage. Its name was derived from the fact that the machine moves with constant speed termed synchronous speed. It operates by electromagnetic induction as a result of relative motion between the magnetic field flux and the conductor, thereby generating induced electromotive force in the conductor. It is an efficient generator system. The make-up consist of two parts namely the stator, which is made up of the (stationary) armature coils (or conductor windings), and the rotor that consist of the (permanent) magnetic field windings. Fig. 5 is a schematic representation of a synchronous generator, while Fig. 6 shows the schematics of the utilisation of the synchronous generator (SG) in a wind turbine.
Fig. 4: Division wind turbine generator system

Fig. 5: Schematic representation of a synchronous generator
Synchronous generators are commonly employed in gas, steam, hydro and reciprocating turbines as well as in wind turbines. Its use in variable speed wind turbines is due to the turbines’ low rotational speed [29]. Worth noting is the fact that the frequency ($f$) of the induced voltage in the armature conductor is proportional to the rotation speed ($N$) of the rotor. This is given as:

$$f \propto N$$

(5)

$$f = kN = \frac{p}{120}N$$

(6)

where: $k$ is the constant of proportionality given as $\frac{p}{120}$, $p$ is the number of magnetic poles.

Hence, going by equation (6), for a constant frequency of 50 or 60 Hz, the revolution per minutes will be inversely proportional to the number of poles. A 2-poles and 50 Hz system will rotate at 3000 rpm while 8-poles, 50 Hz will rotate at 750 rpm. However, power in the prime mover (turbine blades) is related to the torque ($\tau$) and rotation (or synchronous) speed ($N$) as:

$$P = \tau \times N$$

(7)

Worth noting therefore is the fact that the cut-in wind speed (related from equations (1) to (7)) is a very important design criterion that affects the generator performance. Hence, the need to consider the design of wind turbine generators in such a way that the power requirement to overcome the initial torque will be achieved possibly at lower speeds that 3.0 m/s. When this is achieved, sites with low wind speed profiles will benefit from the adoption of wind turbine for electricity generation. This may require the use of magneto-electromechanical system as speed booster. Further to this, a major disadvantage of the SG is that maximum power output occurs at the optimum tip speed ratio. Thus, at the TSR, the rotational speed is low and this will require a high number of poles, which could make the system bulky, expensive and may require speed limiter or continuous variable transmission in order to regulate the speed when the turbine is a direct drive machine. This shows that there is still the need to further the synchronous generator design for small scale wind turbine power generation, in order to have a system that is compact and capable of operating at very low wind speed.
4.2. Asynchronous Generator

This type of generators use a principle similar to that of the induction motor in which a 3-phase set of voltage, applied to a stator winding, produces magnetic field in the opposite (anticlockwise) direction. In this type of generator however, the rotor moves faster than the synchronous speed. In this case, producing negative torque. Moreover, just like the synchronous type generators, it has a fixed stator winding in which rotating magnetic field produces induced voltage. The construction is usually based on the squirrel-cage induction machine. One major advantage of this type of generator is the fact that it can produce electricity at the frequency and voltage of the grid system, thus, requires no inverter or rectifier. Further to this, when it is connected to a 3-phase mains supply, it can produce electricity without a voltage controller or exciter, which could make it require additional circuitry. However, operating it, as a standalone facility, usually requires the addition of capacitors connected to its windings for self-excitation. This is its major disadvantage. The capacitors function to supply reactive power (which would have been supplied by the grid, if connected to it) to the generator. Fig. 7 is a schematic representation of an asynchronous generator.

Hence, based on the aforementioned, for both synchronous and asynchronous generators, the magnitude of the torque plays an important role in the power generation, hence the need for designs that is capable of generation at low wind speeds.

Conclusion

The study explored the various efforts at the development of wind turbines systems. It reviewed some of the existing reports on turbine rotor designs and also considered associated generators that are employed with wind turbine system for power generation. The outcome showed that, despite the progress in the design of wind turbine rotors and generators, there is still the need to further the designs towards the development of lower cut-in wind speed turbine system that is capable of generating power below 2.0 m/s. If this is achieved, several sites with low wind speed regimes across the globe will be able to employ wind turbine models for power generation. To achieve this will require:

- Improved rotor design with a focus on lower cut-in wind speed below 2.0 m/s
- Concerted research efforts to have the rotor designed in such a way that the chord and twist distribution will be optimised and the airfoil will have high glide ratio at a range of angles of attack instead of at single peak angle or few angles.
- Improvement in wind turbine generator design that eliminates or reduce lubrication parts and possibly engage electro-magneto-mechanical principle of operation.

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