



Identifying Factors Affecting the Efficiency and Increasing the Efficiency of Wind Turbines

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Abstract

The paper delves into the importance of wind energy as a clean and renewable source, emphasizing the need for efficient energy management to combat pollution and enhance electricity production. It identifies key factors influencing wind turbine efficiency, including dust accumulation on blades, blade damage, blade length, wind speed prediction using neural networks and turbine height. Various methods to improve efficiency are explored, such as automated blade cleaning, energy storage systems, remote monitoring and blade health diagnosis. The study utilizes a systematic literature review approach, referencing multiple scholarly works to support its findings. It concludes that implementing artificial intelligence technologies, energy storage solutions, remote monitoring systems and blade health detection mechanisms can significantly enhance wind turbine performance, leading to cost reduction and increased stability in wind energy resources. By leveraging these advanced technologies and methods, the efficiency and effectiveness of wind turbines can be optimized, contributing to a more sustainable and reliable energy generation system in the future.

Keywords: Wind turbines, renewable energy, energy management, electricity production efficiency.

Introduction

Wind power is considered as one of the cleanest, most environmentally friendly energy sources, and wind turbines have gained increased attention for the past few decades. Renewable energy plays a prominent role in combating climate change and reducing the risks of using technology. Wind energy can be contributory to generate a sustainable electricity generation system in the future. In wind energy conversion system the wind turbine captures the kinetic energy associate with the wind for the production of electricity with the help of generator. In this regard one of the ways undertaken by producers to reduce fossil energy consumption is energy management. Energy management can be done on two sides. First on the side of electricity generation or better known as the economy dispatch. Regulate the use of fossil energy to produce maximum electrical energy. Usually producers use intelligent algorithms to determine the scheduling of power plants [1-2]. Another method of energy management utilizing the battery beside the renewable energy sources decrease the dependence of the micro-grid on the upstream grid as well as reducing the pollutant gasses. Besides using energy management methods, another alternative is use renewable energy sources. Renewable energy including green energy is photovoltaic, wind power plant, hydropower, etc. The current obstacle is that the capacity of renewable energy plants that have been installed is still small, even though renewable energy sources are very much in the world. The available hardware is not yet able to help renewable energy power plants produce large amounts of power. For this reason, it is necessary to conduct researches that can increase the output power of renewable energy sources.

Several factors affect the power generation efficiency of wind energy extracted from wind turbines. One of them is dust accumulation resulting in roughness of the blade surface and resulting in power loss. To overcome this problem, wind turbine blades need to be cleaned frequently. There are some existing techniques of cleaning but not very efficient and economically viable.

Some factors affecting the efficiency of wind turbines

A. Non-stop automatic cleaning of wind turbine blades

In general, wind energy is readily available and is directly converted into electricity. However, there is a need of minimal maintenance and cost effective solutions for wind turbines. Stall is the loss of lift force on a blade due to changes in its aerodynamic behavior. With no stall, the power output (related to rotor speed) would increase with no limit, causing structural damage to the turbine. Double stall is a second and unpredicted aerodynamic loss in the blade that decreases the energy extracted from the wind. There are several factors that may cause double stall such as a malfunction in the yaw system, a faulty blade design or the accumulation of insects, ice, oil, dust or salt on the blade[4]-[6]. Dust deposition on the blade surfaces reduce the lift coefficient thereby causing an average power loss of up to 10% in a year. Studies have concluded that the efficiency of wind turbines reduce depending on roughness introduced by dust based on geographical location and atmospheric conditions. Khalfallaha and Koliubb surveyed Hurghada (Egypt) wind farm situated in an arid zone, and tested dust effect on a 300 kW wind turbine for various operation durations of power production without any cleaning of blades. They concluded that wind farm site plays important role in accumulation and build-up of dust on blade surface of wind turbine and blade roughness reduces effectiveness of the airfoil to extract power from wind thereby reducing power generation. Several kinds of dust having different physical properties were used and experiments were performed using a wind simulator which determined factors such as the principal dust material, the size of dust particles and dust deposition density[13]. Sagola et. al have also reviewed the effects of surface roughness due to accumulation of dust, dirt, ice and even insects on wind turbine blades which generate roughness of varying degrees and affect. These elements, depending on their size, location, and density, reduce the power produced by the machine[20]. In the cases of dust accumulation, the obvious solution is to clean the blades with water and labor. Some semiautomatic cleaning solution are also available in literature but these too require water and labor. This task is expensive, especially in areas with water shortage. A major drawback of these cleaning systems is that the turbines need to be stopped resulting in power generation loss in the slack period. M. Jeon et. al proposed a mechanized solution for cleaning the blades of wind turbine which goes up by dropping 4 ropes from nacelle down the power generator and connecting them to wire rope holder. In order to accomplish the task, trained professionals need to be operate the levers of a pick up truck. The robot sprays water using water-jet such that the brush can clean the surface and takes 60–90 minutes to clean a blade. The system is composed of side brush frame, camera, water tank, water jet, wire rope holder, roller shock absorber and brush. [12]. Manual cleaning is done by stopping the turbine when the wind speed is less than 3 m/s and it takes a minimum of 4 hrs (per blade of utility scale) with 2-3 qualified operators working on the blades with specialized equipment. There is physical contact with moving parts of the turbine if a lifting device needs to be installed, otherwise a crane is needed. The entire operation is high risk to the operator because of working at a high altitude and is also risky for the safety of the blade. The operation is

also expensive and leads to prospective power losses. There are many other drawbacks of manual cleaning like requiring a large amount of water. Additionally, regular inspections of rotor blades are indispensable for reliable operation and cost effective production without longer downtimes. Elkmann et al. have utilized a cleaning robot by fastening it to the blade surface and moving it using wires[7]. In this paper, a suitable solution for cleaning wind turbine blades in the form of a fully automatic robot that performs the cleaning operation in the working conditions of the wind turbine, which is shown in Figure 1. It reduces additional losses that would have been incurred due to the turbine downtime, while effectively removing accumulated dust. This system is composed of a light weight body and an efficient cleaning process. It includes three robots of similar shape and weight, and so there is no shift of center of gravity and moment of inertia. The robots can clean each blade in a harmonious and parallel activity. Such a mechanized system would allow for uninterrupted power generation from the turbine while the cleaning process goes on unabated. Imbalance in moment of Inertia can also result in damage to the blades which is avoided in this case. Guide-wheels smoothen the robot's movement on the asymmetric blade and govern its motion by guiding it along the blade. Brush is made of cloth microfiber which rotates in all three directions of robot with the help of conveyor shaft. This is a durable and soft material which causes no structural harm to the blade while efficiently cleaning the blade surface. Body frame of robot is made of light weight fibre reinforced plastic (FRP), which cause no significant amount of additional weight to the blade. the dust thickness measuring sensor measures the thickness of dust and according to that reading, the robot will decide the speed it should declare for brush rotation. For an expected condition of dust accumulation, the desired speed of brush motion will be known beforehand. However, if the dust thickness is much greater then the expected thickness then the speed of the brush will be increased up to a maximum allowable speed. If dust thickness is much less than the expected level, then the speed of brush will be slightly reduced. All the robots will individually have this facility and decide the threshold value for such actions of increase or decrease of brush speed.

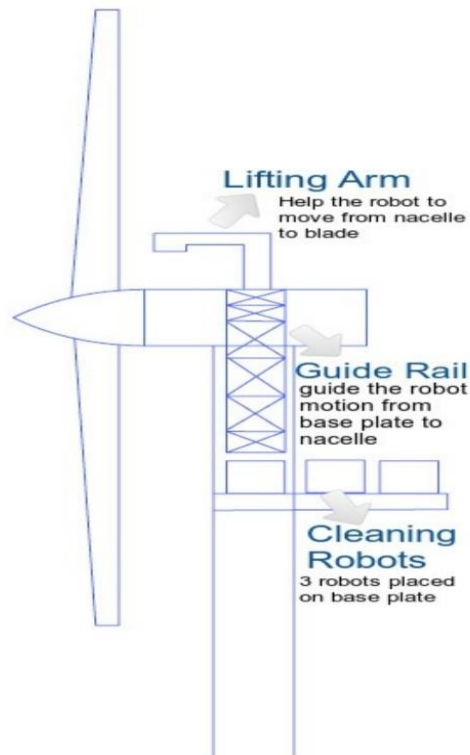


Fig. 1. Automated Blade Cleaning System.

B. Using energy storage

Utilizing the battery beside the renewable energy sources decrease the dependence of the micro-grid on the upstream grid as well as reducing the pollutant gasses. Indeed, the extra produced power of the distributed generation units can be stored in the battery when the demand is low and the stored energy can be used when the generated power of the renewable units is lower than the load of the micro-grid [9]. Of course, the demand response programs can be applied to the micro-grid for better matching the production pattern and load one. In the demand response program, the incentive of the consumers to control their demand is increased using variable electricity prices. Although the demand response is a new concept for the residential consumers, the industrial and commercial units always manage their load profile due to the economic issues [10]. Most of used small wind system should include a storage system. The storage

system can be charged or discharged based on the power captured from the wind. This would result in increasing efficiency of the overall WECS in compare to the conventional rectification circuits [18]. This storage system is based on battery pack and so battery becomes one from the main important items in the small wind system. As cleared, the operating temperature is a major factor in the determination of lead – acid battery’s service life. Heat will be generated within the battery due to exothermic electrochemical reactions within the cells and currents, both dc and ac, passing through the resistive components of the cells (I^2R). Chemical reactions internal to the battery are driven either by voltage or temperature. The hotter the battery, the faster chemical reactions will occur. High temperatures can thus provide increased performance, but at the same time the rate of the unwanted chemical reactions such as passivation of the electrodes, corrosion and gassing will increase resulting in a corresponding loss of battery life that lead to less running cost [26]. So, the valve regulated lead acid batteries (VRLAB) require very low voltage and current ripples to avoid the rise in temperature of the battery and get longer battery lifetime. Battery heating is caused by current ripple and so rise in temperature. Also it is well known that battery lifetime decreases as temperature increases. One of the major parameters that affect the service life of battery systems is ripple voltage and current. Among other parameters that can affect the health of battery systems include charge voltage, charge current, discharge events (frequency and duration of discharge), temperature, internal ohmic values (impedance, resistance, and conductance) connection integrity, and quality and design of batteries [23]. The complete control circuit guarantees converting the variable voltage and variable frequency to constant voltage and constant frequency at the load terminal using the dc/ac inverter using hybrid pulse width modulation (HPWM) controller [14]. Finally, a battery power flow controller is used to balance the load power as the wind power changes [16]. The bi-directional converter connected to the dc-link is controlled to adjust the power flow to/from the battery pack. When the wind power is larger than the load power, the buck switch S11 is activated to charge the battery pack. On contrary, when the wind power is smaller than the load power the boost switch S12 is activated to discharge the battery pack [17]. The power flow controller determines which switch buck switch S11 or boost switch S12 should be activated to achieve the power balance between the wind power and the load power. The control circuit should guarantee that the two switches don’t operate simultaneously.

C. Using neural network in wind speed prediction

Usually, a typical wind turbine system cannot generate electricity power consistently, because the power outputs are heavily depended on wind speed. However, terrain, temperature, humidity and other factors can also affect wind speed. Therefore, wind power forecasting is a complex, multi-dimensional, and highly non-linear system. Neural network is able to learn the relationship between system inputs and outputs without mathematical conversion, and perform complex non-linear mapping, data classification, knowledge processing, and so forth. In addition, neural network also has the ability of parallel processing to reduce computing time, so it is suitable for wind power forecasting. Certainly, if wind speed can’t be exactly predicted, the power generating capacity won’t be able to estimate previously. This causes power system unstable and difficult to dispatch electricity and increase operation cost [17]. Terrain, temperature, pressure, latitude and other factors also influence wind speed, there is a very complex and highly non-linear relationship. It is very difficult to forecast by using tradition physical mode or statistic method, especially in long term forecasting. However, neural network has the ability to learn the relationship between system inputs and outputs, and to set up mathematical model like wind system, dynamic physical system, and so forth [15]. In addition, neural network has the ability of parallel processing, so computation time can be reduced and multi-models instantaneously forecasting can also be achieved [22].

D. The effect of blade length on wind turbine output power and torque.

The higher the rotation speed, the greater the turbine torque. High-torque wind turbines can generally produce high power too. Besides that, there are circumstances where the higher the rotation speed, the smaller the torque. That is the cause of wind turbine power to fall when the rotation speed is getting higher. Changes in wind turbine torque to changes in wind turbine rotation speed are presented in Figure 2 [8].

$$A = \pi \cdot r^2 \quad (1)$$

$$P_{wind} = \frac{1}{2} \rho A v^3 \quad (2)$$

$$P = C_p \cdot P_{wind} = C_p \frac{1}{2} \rho A v^3 \quad (3)$$

Wind energy can be contributory to generate a sustainable electricity generation system in the future. Power is affected by wind speed. This effect is normally measured as a cubic function, which means the power increases eight times when speed is doubled. Turbines at a site where the wind speed averages 8 m/s produce around 75-100% more electricity than those where the average wind speed is 6 m/s. Based on the torque curve, the longer the turbine blade, the higher the maximum torque. At blade length of 2 m, it has maximum torque of 552.94 N.m at rotational speed of 20 rpm. Whereas at blade length of 5 m, it has a maximum torque of 66.9 kN.m at rotational speed of 12 rpm. Control of the turbine rotation speed can also determine the amount of turbine torque to get more power. The length of the turbine blade has affect the area of the circle and automatically makes the turbine even bigger. This case also affects the amount of torque in the wind turbine.

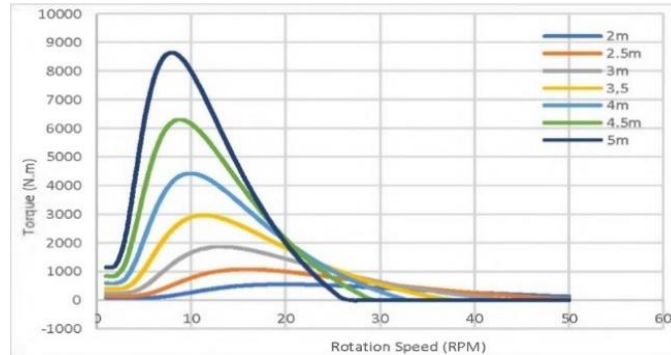


Fig 2. Change of Wind Turbine Torque to Rotation Speed.

E. Wind turbine height

As we all know, higher altitude has higher wind flow rate, and higher wind flow rate brings higher wind kinetic power. To match the industrial electricity generation requirements, the wind turbine towers for industrial wind farm must has a certain height. So one common thing for all the wind farms is they use tall wind turbine towers. In the following, the wind data and the height of the wind turbine tower are shown in Table 1.

$$E_p = m g h \quad (4)$$

$$E_k = \frac{1}{2} m v^2 \quad (5)$$

$$E_m = E_p + E_k \quad (6)$$

During the last 20 years, the height of industrial wind turbine towers keep increasing constantly. Take some European countries as an example, in 2000, the average wind turbine tower height is 60m in France, Netherlands and Belgium. But in recent years, the average height of wind turbine towers in France, Netherlands and Belgium is 120m. In 2013, three quarters of the industrial wind turbine systems that installed in Belgium adopts the wind turbine towers with a height that over 100 meters. The same thing happens in 70% of the wind energy generation systems in France. This trend is definitely mean to happen as people would certainly expect larger wind energy production with the constantly developed technologies. Moreover, as the size of wind turbine rotors keep increasing, and the clearance between ground and the rotor must keep in a certain rate, so the height of wind turbine towers also need to grow. As the wind turbine tower height keep increasing, the stiffness of wind turbine towers over 100m is a main focus. From the design point of view, as the height of the wind turbine towers increases, the design technology changes to make the wind turbine tower cost effectively. Moreover, onshore wind turbine towers suffer more restrictions than offshore wind turbine towers. For onshore wind turbine towers, the complete transportation is on road, and there are regulation about maximum production weight and dimension to transport. For example, if the wind turbine tower sections need to go through a tunnel, the wind turbine tower diameter must under 4 or 5 meters, or it can not pass the tunnel. But as we all know, when the wind turbine tower height increased, the diameter of wind turbine tower will also increase, so that the wind turbine tower can keep its stiffness. But with the restriction of transportation, the only solution is to reduce

the thickness of steel to keep the wind turbine tower diameter. And for the over 100 meters wind turbine tower project, the wind farm owners can still choose a steel and concrete hybrid tower to reduce the construction input.

Table 1. Wind data and wind turbine tower height.[27]

Height above ground	Mean wind speed	vref	Tower height as number of turbine diameters		Annual production MWh	
m	m/s	m/s	100m	126m	3MW	5MW
80	5.67	28.4	0.8	0.6	5000	7,945
100	6.20	31.0	1.0	0.8	6328	10,070
125	6.75	33.8	1.3	1.0	7770	12,392
150	7.22	36.1	1.5	1.2	9016	14,411
175	7.64	38.2	1.8	1.4	10100	16,178

F. Remote monitoring and blade health diagnosis

Rotor blade damage and/or failure is a common occurrence in wind turbines that is very costly and can lead to substantial downtime. If a remote monitoring technology is developed, it can give an early warning about blade anomalies before catastrophic failures occur, maintenance process can be largely improved, and downtime and losses can be minimized. Rotor blade damage and/or failure is a common occurrence in wind turbines that is very costly and can lead to substantial downtime. According to [24] annual blade failures are estimated at around 3800, and blade failures are the primary cause of insurance claims in the US onshore market; they account for over 40% of claims, ahead of gearboxes (35%) and generators (10%). Some of the most typical blade defects includes blade icing, blade delamination, blade cracks, and blade imbalance. In [25], massive ice is accumulated on wind turbine blades and cause additional operational stress to energy conversion system in cold weather. In [24], a catastrophic blade failure occurs, and the entire blade need to be replaced. In addition, blade damage can also result in tower damage or destruction, leading to even more repair costs and downtime. Currently-used market technology focuses on blade inspection, such as image capturing [28] and drone inspection to detect blade damage. Such methods, however, cannot be used to detect hidden blade cracks. Other methods for monitoring and detecting blade damage may include vibration analysis [11-۳], strain sensor analysis [19], acoustic emission analysis [21], or Doppler Radar technology [۶], but such instrument systems are very costly, very challenging to install on existing fleets, and present additional reliability risks.

Method

The article utilized a systematic literature review method to identify and analyze the factors influencing the efficiency and effectiveness of wind turbines. This involved a comprehensive examination of existing scholarly works, including books, articles, and research papers, within the domain of renewable energies. The review process involved the extraction of relevant information from these sources, which was subsequently synthesized and discussed to draw conclusions regarding the impact of various factors on wind turbine performance. Furthermore, the article employed a scholarly approach by referencing and citing numerous studies and research papers to substantiate its findings. This academic rigor enhanced the credibility of the article's analysis and conclusions. The methodological approach of the article aligns with established academic practices for conducting literature reviews and synthesizing scholarly knowledge to contribute to the body of research in the field of renewable energy and wind turbine technology.

Findings

This paper is about identifying the factors that affect the efficiency and effectiveness of wind turbines. Also, several methods have been investigated to improve the performance and efficiency of wind turbines. The article first deals with the importance of wind energy as a renewable energy source and its effect on reducing pollution and increasing the efficiency of the electricity production system. Also, the article deals with the importance of energy management and the use of renewable energy sources. Further, the article deals with identifying various factors that affect the efficiency of wind energy production from wind turbines. These factors include the accumulation of dust on the surface of the blades, damage or failure of the blades, the length of the blades and the prediction of wind speed using neural networks. Also, another one of these factors is the height of the wind turbine. The high height of the wind turbines increases the wind speed and thus increases the production power. Then it refers to the different methods used for energy management. This includes the use of battery-based energy storage systems, wind speed prediction using neural networks, and the use of remote monitoring and blade health detection technology. In this paper, various methods for cleaning wind turbine blades are also reviewed. This includes the use of robots and automated systems to clean the blades while running. Finally, the paper discusses the importance of using artificial intelligence technology, energy storage, remote monitoring and health detection to improve the performance and efficiency of wind turbines. Finally, the article has used various sources to present its findings, including scientific and internet articles. These sources include scientific articles from various magazines and internet resources from various websites.

Conclusions

Given the importance of wind energy as a renewable source, managing energy resources and achieving higher efficiency in wind turbines is of great importance. Further research into improving wind power generation technologies and using smart algorithms can help reduce costs and increase the efficiency of this energy source. Automatically cleaning wind turbine blades is an important method for improving their performance and efficiency. Blade pollution can lead to reduced efficiency and increased maintenance costs. For this purpose, automated cleaning systems using mechanical methods or robots can be used to remove pollution from the blades. Energy storage can be used to store energy generated during low demand periods and use it during high demand periods. This approach can help improve energy management and reduce costs associated with wind turbines. Using neural networks to predict wind speed and the impact of blade length on wind turbine power and torque output can also help improve the performance and efficiency of wind turbines. By using wind speed data and turbine technical characteristics, neural networks can identify complex patterns and provide more accurate predictions of energy production. Remote monitoring and blade health detection are also of great importance. Remote monitoring systems can actively monitor turbine performance in real time and quickly respond to identified issues. Furthermore, sensor technologies and artificial intelligence algorithms can be used to detect blade health and respond to turbine performance when necessary. On the other hand, the height of the wind turbine can have a positive effect on the production of wind energy. The higher height of the turbines leads to higher wind speed and thus more energy production. This can lead to an increase in the efficiency and effectiveness of wind turbines. In other words, the use of wind turbines with a higher height can help increase energy production and improve the performance of these energy sources. Given the above, the use of artificial intelligence technologies, energy storage, remote monitoring, and health detection systems can help improve the performance and efficiency of wind turbines. These methods can contribute to reducing costs and increasing the stability and efficiency of wind energy resources.

For this article, you may consider the following research suggestions:

1. Investigating the effect of different atmospheric conditions on the performance of piezo sensors and their accuracy in assessing the health of wind structures.
2. Evaluation of the effect of temperature and humidity changes on the performance of health monitoring systems of wind structures.
3. Providing methods to improve the accuracy and efficiency of health monitoring systems of wind structures using artificial intelligence algorithms.
4. Investigating the effect of changes in wind frequency and intensity on the performance of health monitoring systems of wind structures.

These suggestions can help you find the best way to start your research in this field.

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