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Effect of dust on the performance of wind turbines

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Abstract

An experimental investigation on the effect of blade surface roughness, due to dust accumulation, on the performance of wind turbines was performed. The development of the energy generating costs of wind turbines directly depends on the wind turbine output, which depends upon the characteristics of the turbine blades and their surface roughness. An important operating requirement that relates to a wind turbines airfoils are its ability to perform when the smoothness of its surface has been degraded by the dust. The effect of surface roughness of rotor blades due to accumulated dust on the blade surface of stall-regulated, horizontal axis 300 kW wind turbine was investigated. The mechanism of dust built up and accumulation on the blade surface of wind turbine was investigated, and the effect of operation period of wind turbine on the blade surface roughness intensity was investigated experimentally. Also, the quantity of dust accumulated on the blade leading edge; and the effect of changing dust area on blade surface were studied. Standard roughness in Hurghada site was chosen and put in various leading edge areas. The roughness area on blades was changed from 5 to 20% from the chord line towards the leading edge. The effect of dust on the performance of pitch-regulated 100 kW horizontal axis wind turbine was investigated. These results from pitch-regulated wind turbine were compared with 100 kW stall-regulated wind turbine.

Keywords: Wind turbine; Performance; Effect of dust; Pitch regulated; Stall regulated

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1. Introduction

The crucial to rotor design is the subject of airfoils. The most critical problem for wind turbine rotors is degradation of performance, and the unpredictability of stall due to dust accumulation on blade surface area. The objective of this work is to provide a better understanding for the effect of roughness due to dust accumulated on the blade surface on the performance of windmills, which erected in sandy sites. Field experience with big scale units of horizontal axis wind turbines (HAWTs) has indicated that very severe performance degradation can occur in these circumstances. The measured results show field tests power curves for some turbines

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in Hurghada wind farm with clean and dirty blades. The analysis of airfoil surface roughness has practical applications in addition to academic interest. The importance of the effect of dust on the roughness of airfoils in aviation is well realized. Surface roughness is a common feature of most operating airfoil surface. Roughness may arise from the manufacturing process, long period of service and natural accumulations as dust, ice, snow, frost, salt spray or any organic materials. For example, ice affects a plane's performance by hampering the wing's lift capacity. Even in cases where accumulation of ice is not severe, it still forces the aircraft toward more fuel consumption to compensate for the loss of the lift [1,2].

Generally, the roughness has a large effect on the fluid dynamic processes. [3,4]. Therefore, the stall-regulation phenomena in wind turbines is affected by a high degree due to increase the blade surface roughness. Despite some previous experimental and numerical work where surface roughness is involved, the information that has been obtained on this subject still remains far from complete. The processes of boundary-layer separation and stall phenomena, which occur on the blade of wind turbines in the presence of surface roughness of airfoils, are not fully understood. Many aerodynamic models of a horizontal axis wind turbines, which operate in cold (iced) places as European countries were performed by many researchers [5–7]. But it was noted that, the operation of HAWTs in dusty sites are not investigated yet. The sites of high rates of wind speeds in Egypt are very dusty, so it is important to suggest and verify some theoretical models to describe the effect of roughness, because the blade surface roughness play an important role on the aerodynamic load, power produced and lifetime of windmill. In Egypt, there is a growing and identified interest to erect more wind turbines in sites which affected even by heavy dust conditions like mountainous and desert regions. It is also noticed that dust even causes problems for wind turbines operating on traditional sites on the coastal areas like Hurghada and Zafarana sites, so, it is very important to study the effect of the dust accumulated on the rotor's blades surface on the performance of the wind turbines.

On the other hand, to enable wind turbine designers to predict loads and energy losses for wind turbines operating under dusting conditions, it is necessary to qualitatively and quantitatively know the change in the aerodynamic properties brought due to the dust collected on the surface of the blade's leading edge. With growing dust on the surface of blade the drag of the aerofoil increases, but the lift decreases. This lead to reduce the power output of the wind turbine. The dusting on the rotor's blades wind turbines may lead among others to long time stops without no production due to heavy accumulated dust, decreased power production.

2. Study procedure

The mainframe of this study included the following points:

2.1. Wind turbine operational periods

The effect of dust accumulated on the surface of rotor blades of Nordtank 300 kW wind turbine in Hurghada wind farm site was investigated experimentally. The measured data was taken from May 1999 to November 1999, where there is no any cleaning for blades in this interval. The measurements were carried out all time approximately except reappearing and maintenance periods. The aim from this part of investigation is to study the effect of operational periods of wind turbine without removing dust from blades on its power curve.

2.2. Site dust analysis

The actual dust accumulated on the blade of 300 kW wind turbine was analyzed experimentally.

The main aim from this part is investigating the process of building and accumulating the dust on the blade surface. The monthly blade roughness like dust area and size of particles were studied.

2.3. Dust simulator

Effect of dust accumulated on blades was investigated by making various dust simulators. Whereas the effect of blade surfaces roughness depends upon the size of dust grains, these dust grains were stuck on the of blade of the leading edge surface, and fixed as 10% from total area of blade approximately. The measurements were carried out in high and low ranges of wind speed. The aim from this part of study is to investigate the effect of dust size and dust blade areas on the power output losses of wind turbine. Standard roughness in Hurghada site was chosen and put in various leading edge areas. Also the effect of standard blade surface roughness on the power output of wind turbine was investigated.

2.4. Effect of dust the pitch-regulated HAWTs

The effect of dust on the performance of pitch-regulated 100 kW horizontal axis wind turbine was investigated. These results for the pitch-regulated wind turbine were compared with those for another 100 kW stall-regulated wind turbine.

3. Experimental set-up description

The main technical specifications of Nordtank 300 wind turbine are shown in Table 1. The wind turbine has three-bladed upwind, stall-regulated rotor. The gearbox is mounted on the main shaft behind the bearing and a torque stay is led to the machine foundation. The generator is induction type and mounted on the end of the nacelle. Yawing of the machine is carried out by an electric motor controlled by a wind vane mounted on the top of the nacelle.

Table 1
Main technical data of Nordtank 300 wind turbine

	Nominal rating
	300 kW
Swept area	755 m^2
Hub height	30.5 M
Number of blades	3
Diameter	31 m
Rotor speed (synchronous)	34 rpm

The wind turbine, during the measurement period, was in normal operation in accordance with the connected operation manual. The blade setting angles, the rotor rotational speed and the control strategy (settled values of the control system) or other essential parameters did not change during the measurement period. Also, the availability of wind turbine must be 100% during the operational periods. The measurement of the electrical power output by the turbine was carried out by three-current transformers, one for each phase. The current is measured with a separate current converter. The electrical power sensor measures the true RMS value of the active power. This sensor was mounted on the electric grid side of the wind turbine, so that it is only the net power of the wind turbine was measured. The wind speed was measured with a cup anemometer with three cups; the sensor was mounted at 1 m above hub height of the wind turbine. Also the wind direction was measured with a wind vane system with a cos/sin resolved. The wind vane sensor was used to sort out the data within the measurement sector. The sensor was mounted on a boom as close to the top of the mast as possible and with 1 m above the hub height of the turbine. Another sensor was used a reference one to measure the error in direction of the turbine. Ambient air temperature and barometric pressure were measured to be able to correct the air density to a standard condition. Barometer and temperature PT100 sensors were

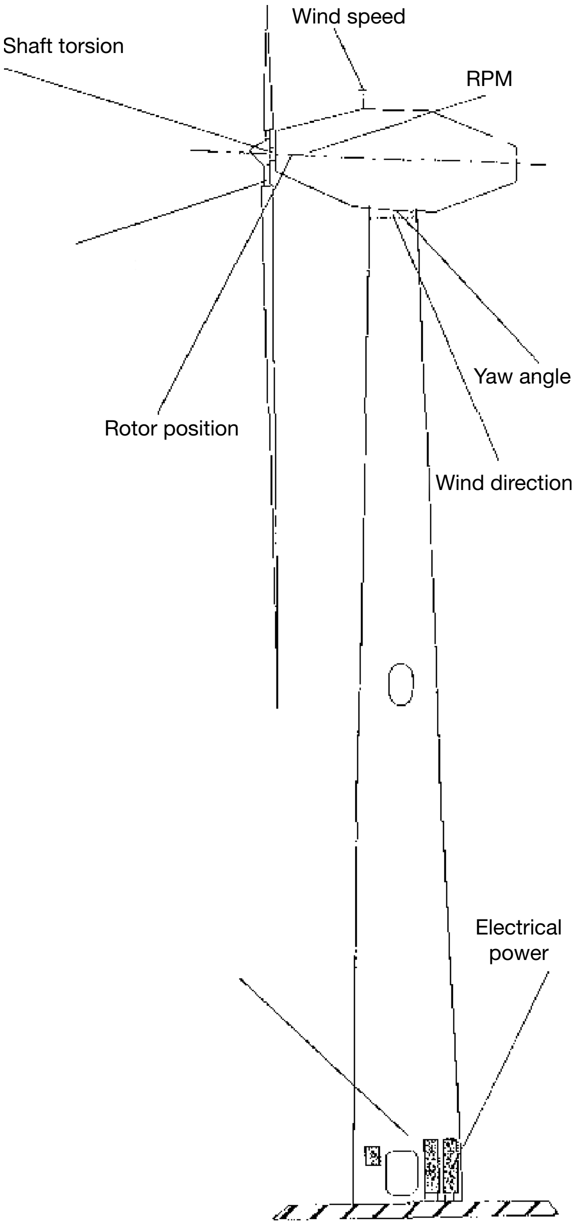

Fig. 1. Overall instrumentation at wind turbine.

mounted close to the hub height on the nacelle of the wind turbine. Fig. 1 shows the overall instrumentation of measurements on the nacelle of wind turbine.

All measuring sensors were connected with data acquisition system. Data was collected continuously during the whole measurement period in the operational range of the wind turbine. At the beginning of the measuring, all sensors were checked and calibrated. All of the stored data was averaged over 10 consecutive minutes. The study was carried out in Wind Energy Technology Centre, Hurghada wind farm, at 12.5 km north of Hurghada city. The site area is about 2.5 km times 1 km with the length parallel to the coastline. The wind condition in case of wind turbine operation is very important for the interpretation of the results of the measurement. The prevailing wind was westerly coming from the north. The ground is gently raised to an elevation of about (6 m) average at the stands. The surface consists mostly of sand roughness length 0.01 m approximately.

4. The results and discussions

During the rotation of the rotor blades in dusting weather conditions, the leading edge of rotor blades collects more and more dust around the stagnation points of aerofoils over the radius of blade. After that, due to increase of the air velocity along the radius of blade, the dust grains were built up more at the outer part of the blade with linear increase with radius approximately. The blade surface roughness depends on the amount of dust accumulated on the surface of blade area. Also, there is a relationship between the amount of dust collected on blade surface and wind turbine periods of operation. Fig. 2 shows the effect of dust on the power curve of Nordtank 300 kW wind turbine in various conditions of operations periods, 1 day, 1 week, 1 month, 3 months, 6 months, and 9 months. There was no cleaning of blades through each of these periods. Only the dust accumulated on the blade surface was removed at the first of each period. The wind speed ranges were different in all periods of operation,

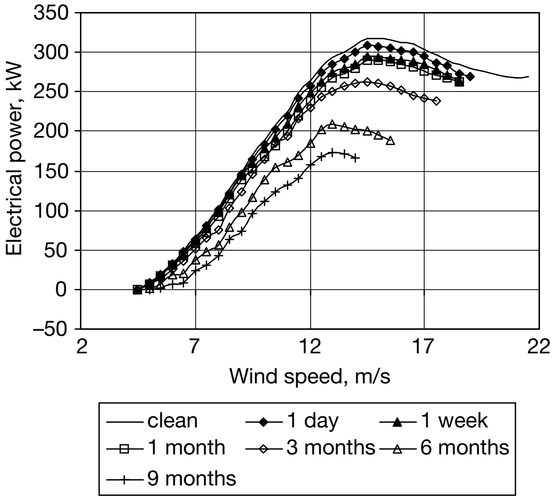

Fig. 2. Effect of dust for various operation periods on the power curve of turbine.

because this was depending upon the values of wind speed in site and non-controlled. The data was measured continuously except the time for stopping in cases of maintenance or repairs. During the measuring interval, there was not any rains condition or any methods for dust removing from the blade surface. The normal (clean) power curve was measured previously, whereas before the measurements the blade was washed very good by water and any cleaning material like detergents or liquid soap. It is shown from Fig. 2, by increasing the periods of operating wind turbine, the amount of dust accumulated on blade surfaces increased among all the measured time. From the results, the rate of variability of power curves compared to the normal one increased by increasing the time of operation without cleaning the rotor blades. So, it is very important to clean the blades of Nordtank 300 kW wind turbines after short intervals of operation.

The loss in power output of wind turbine increased by increasing the period of operation as shown in Fig. 2., also the mean power loss increased by increasing the operational periods without cleaning rotor blades. The data is fitted linearly as:

$$\text{MPL}\ (\%) \approx T/5 + 5, \qquad (1)$$

where MPL is the mean power loss (%) and T, the time by day, and must be >1.

This formula was checked with most wind turbines in Hurghada wind farm, it gave good. Results for all periods except period 1 day. It is noted that, the mean power loss (MPL) is the highest in the period 9 months which is about 57% approximately, but it is the smallest in period 1 day, it reached 2.5% as shown in Fig. 3. The experimental results in period (1 day) did not give the actual mean power loss, because this depends on the dust and wind speed range during that day. Therefore, the previous formula did not agree with 1-day operation period.

The study of dust specifications, which accumulated on the blade surface of wind turbines, is very important. The dust accumulated on blade surface of wind turbine was collected and removed continuously from the blade surface by using special tools. After that the dust particles and dust area on blade surface were measured during different months. The effect of wind turbine operational period without removing dust on blade surface roughness was investigated. The aim from this part of study was the investigation of how the process of dust built-up is going on and helping blade surface and helping

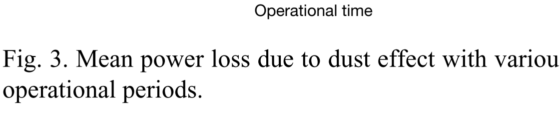

Fig. 3. Mean power loss due to dust effect with various operational periods.

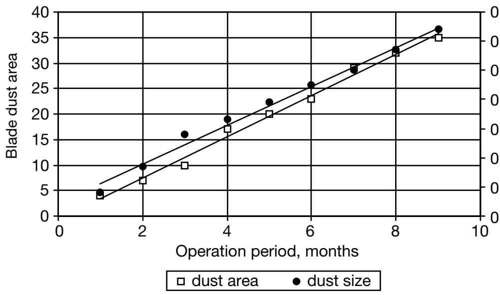

Fig. 4. Blade dust specification with operation period of turbine.

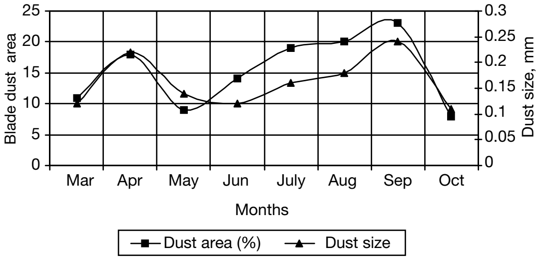

Fig. 5. Monthly blade surface roughness of turbine.

operation staffs in wind farm to select a suitable chemical material for cleaning the dust from blades efficiently without any harm to blade surface. The effect of long the operation period of wind turbine without removing dust on its size was shown in Fig. 4. The measured data is fitted linearly as following:

$$D_d = 0.08\,T + 0.02, \qquad (2)$$

where D_d is the dust size (diameter in mm) and T is length of operation period in months. Therefore, the built up of dust on the blade surface is proportional directly with the long of operation period without cleaning blades. The results show that the size of dust particle reached to 28 mm approximately after 3 months of operation. The blade dust area is defined as the area of blade, which was covered by dust particle. This area was measured from the leading edge side as a ratio of chord line over all length of blade. The blade dust area increased linearly approximately with increasing the long of operation period of turbine without removing dust.

The results was fitted mathematically as:

$$D_A = T/25, \qquad (3)$$

where, D_A is the dust area in percentage. Therefore, increasing of the wind turbine operation period without cleaning dust from blades surface lead to increase the blade surface roughness, and consequently, the loss in turbine power output increases.

Fig. 5 shows the actual measured dust size, which accumulated on wind turbine blade surface during various months. The data was measured in each month from March to October because in this interval, there is no any rains in Hurghada city approximately. The data was measured every month after cleaning the blades well. As shown in the figure the dust size was different from month to the other. This monthly blade roughness depends upon the average wind speed, prevailing wind direction and frequency of sandy storms in the each month. The maximum dust size reached 0.24 mm in month September and it reached its minimum value (0.11 mm) in month April approximately. Fig. 6 shows the size of dust accumulation and monthly average wind speed with various months. The wind speed values in site affect the built of dust on the wind turbine blades surface. Therefore, increase of wind speed in site leads to increase the size of dust accumulation.

There is a relative relationship between the behavior of dust size and wind speed in site in most periods of operation. In months June, July and August, despite, the wind speed is higher than other months approximately, the dust size is smaller, and, the rate of built of dust on blade surface is higher than the rate of increasing wind speed. Therefore, the mechanism of accumulating dust on blades surfaces of horizontal axis-stall regulated wind turbines depends on the other

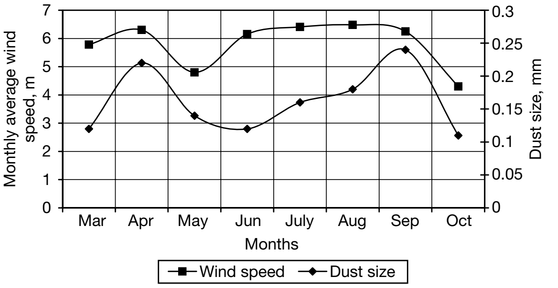

Fig. 6. Monthly mean wind speed and dust thickness (size) distributions.

factors in site like, sandy storm frequency, wind speed direction surface roughness of blades, topography of site, etc.

Fig. 7 shows the actual blade dusty area with monthly average wind speed in site during the all periods of operation. As shown the blade dust area affected by the monthly average wind speed in site. As an example in month October, while the average value of wind speed is the least; the blade dust area is the least too. Therefore, the covering and stacking the particle of dust on blade surface depends upon the site wind speed values. Also, it is shown that, the blade dust area is not fixed in all periods, but it is variable from month to another. The results show that, the maximum blade dust area occurred in month September (23%), but the minimum value occurred in month October (8%) approximately.

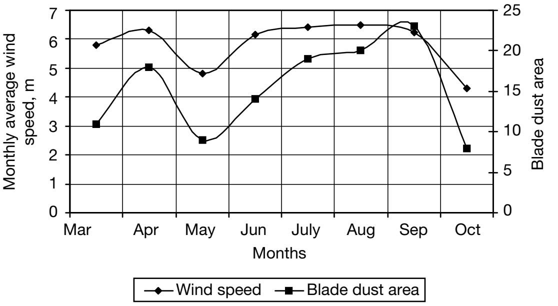

Fig. 7. Monthly blade dust area (%) with average wind speed.

The shape and size of dust particles, which accumulated on the blade surface specifies the degree of roughness of surface. Therefore, in this part a trial was carried out to use dust site models (dust simulators) using the previous results of dust analysis in Hurghada wind farm site. The effect of types of roughness of dust on the performance of Nordtank 300 wind turbine was investigated experimentally. The aim from this part is to know the behavior of the wind turbine power curve variability, when operating in various types of dust sites.

It was used three various types of dust particles with diameters 0.10, 0.20, and 0.30 mm as a dust simulators. And from the pervious part of study, it was noted that, the accumulated dust on the blade surface covered 10–20% from the blade surface area over leading edge in all periods of operation approximately. Therefore, the dust particles were stuck on blade surface whereas; the blade dust area is fixed at 10% only (10% from chord line in all sections of blade length). Also, during these measurements, it was assumed that, there is no any source of dust (from site) accumulated on blade surface except the dust, which was used in simulators. The data was measured in 1 day or over that according to the wind speed frequency during the time of experiments.

Fig. 8 shows the effect of various blade roughness due to changing dust index on the power curve of Nordtank 300 kW wind turbine. The power curve due to this roughness was compared with the clean one (normal power curve). As shown for the three cases of different dust sizes, the power curve variability increases as increasing the dust particles sizes. The reason of that, the increase of dust size on blade surface increases the blade surface roughness, and accordingly the loss in wind turbine power output increases due to probability of flow separation (quick stall) on the most of blade

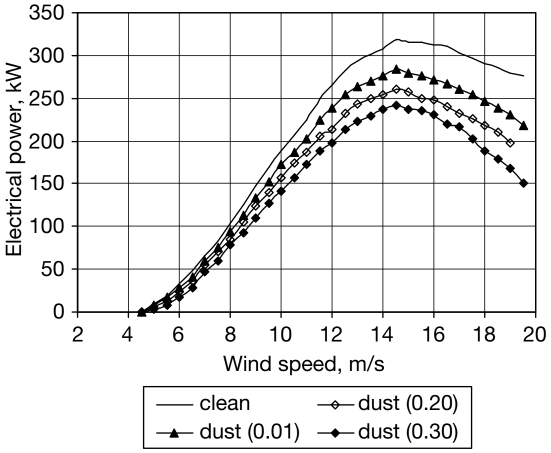

Fig. 8. Power curve variability due to various blade dust thickness.

span. Also the results show that, the losses in power output increases by increasing the wind speed in all three cases of dust models.

It is concluded that, when the blade surface roughness increased, the power curves variability increased. So, in the sandy wind farm sites which have big dust particles (high roughness index) and high values of the annual wind speed, it is recommended to clean dust from blade surface during short intervals to decrease the high reduction of output. Also, it is very important to choose very blade surface finishing (very low blade surface roughness) to decrease the wind turbine power curve variability due to dust effect. Actually these results were taken into consideration when selecting the Zafarana site wind farm and wind turbine types especially the surface roughness of blades because the Zafarana is very dusty and the annual wind speed is higher than Hurghada site wind farm where the annual mean wind speed is about 10.5 m/s.

It is known that, the dust, which accumulated on the blade surface, depends on the shape (profile) of blade designed. As an example, the blades, which have big leading edge area, collect more dust. So, it was important to investigate the effect of changing blade dust area on the power output loss of Nordtank 300 kW wind turbine. It is noted that the most size of dust accumulated in a period of 3 months was between 0.26 and 0.30 mm approximately, and also this size of dust index almost is constant each three operation months. Therefore, the standard size of dust in Hurghada site is considered as 0.28 mm. This roughness index may be fixed for each 3 months operational period of wind turbine without cleaning dust so, in this study, the 0.28 mm dust size was called as "Hurghada site standard roughness." But, the blade dust area in these measurements was changed from 5% to 20% of the total blade area.

Fig. 9 shows the measurements of power curve of Nordtank 300 kW wind turbines in cases of various dust blade areas, and constant 0.28 mm dust size (Hurghada site standard roughness). It is shown that, the loss in power output of turbine due to standard roughness increased as increasing the blade dust area. The power curve deviation in the case of (5%) blade dust area is less than other cases, therefore as shown in Fig. 9. The bigger blade dust areas lead to high variability in the wind turbine

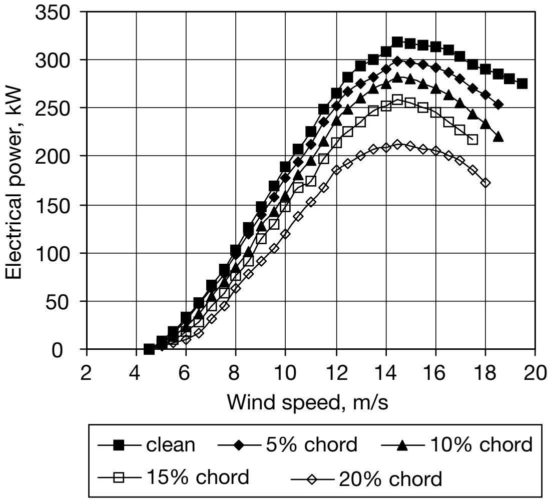

Fig. 9. Power curve variability due to various blade dust area.

power curve. The reason is due to increase the blade dust area, the surface roughness of blade increases after that, the losses in power output increases due to the high change in the aerodynamics performance of turbine. Whereas, by increasing the surface roughness of blade, the dynamic stall performance in HAWTs stall-regulated wind turbines decreases. It is concluded that, the blade dust area affects greatly the wind turbine power output, and it is important at design and manufacturing of the blades to take into consideration the shape of blade leading edge especially for turbines working in very dust sites. The big flat leading edge may collect more dust on blade surface, and as a result for that, the power curve variability increases, and the wind turbine ability to produce energy in dust site will be reduced very much.

As shown in pervious results, decreasing surface roughness of rotor blades is very important. The high blade surface finishing improves the aerodynamic performance of wind turbine especially the power output, and this is reflected upon the annual mean rated power and energy production. This discussion is very important for high dust sites, such as Hurghada wind farm in Egypt. The mean power loss due to blade roughness from dust accumulated on surface was calculated at different operations periods and also by using the actual site roughness during the measurements. Fig. 10 shows the effect of dust particles (dust size) on the mean power produced from the wind turbine. In these measurements, the dust blade area is fixed as 10% in all types of dust sizes. When, the size of dust particles increased, the mean power loss increased, this is due to the increase of the blade surface roughness. In case of 0.3 mm diameter of dust particles, the mean power loss reached to 38% approximately, but it reached to 6.5% in case of 0.05 mm diameter of dust grains. From these results, it is found that, the performance of horizontal axis wind turbines depends on the type of blade surface roughness. Also, there is a high loss in annual mean power produced by wind turbines in high surface roughness index (dust size) especially in site of high wind speed.

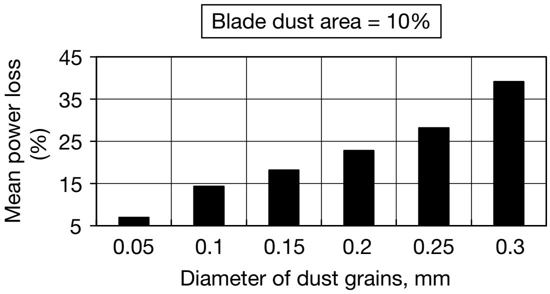

Fig. 10. Effect of various dust thickness on the mean power loss (%) of turbine.

The mathematical relationship between the mean power loss (MPL) and size of dust particles is formulated linearly as:

$$\text{MPL}\ (\%) = 125d, \tag{4}$$

where d is the diameter of dust particles in (mm) and the dust area (A_D) is fixed at 10%.

Fig. 11 shows the effect of standard roughness index in Hurghada site, where the specification of dust in site was 0.28 mm diameter of particles. In these measurements, the blade dust area was changed to 5%, 10%, 15%, and 20% from total surface area of blade. As shown in Fig. 11, the mean power loss increased as the blade dust area increased, whereas, the increase

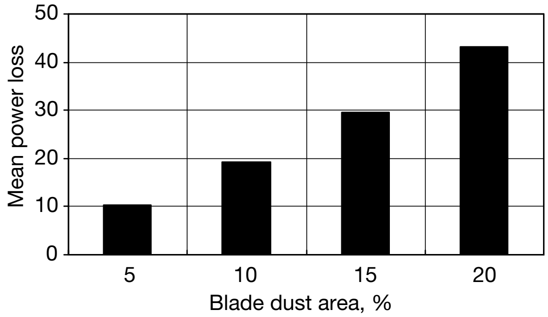

Fig. 11. Effect of standard dust thickness (0.28 mm) with various blade dust area on the turbine power loss.

of the blade dust area increases the blade surface roughness, and the aerodynamic sensitivity of blade decreases.

For case of standard roughness index (thickness, $d = 0.28$ mm), the mathematical relationship between the blade dust area and mean power loss is formulated linearly as following:

$$\text{MPL (\%)} = 2\,A_\text{D} - 1,$$

where A_D is the blade dust area in (%). This linear formula was expressed from dust simulators and checked with the actual results. The maximum numerical error is ±5%.

The effect of dust on the blade surface of 100 kW horizontal axis stall and pitch-regulated wind turbines was investigated experimentally. These turbines were installed in Hurghada wind farm in same site of Nordtank 300 kW stall-regulated wind turbine; they were manufactured by Wincon and Ventis companies. The specifications of stall-regulated turbine are: 100 kW rated power, 38 rpm, 24 m of nacelle altitude, and three blades in rotor, while the specifications of pitch-regulated turbine are: 100 kW rated power, 60 rpm, 39 m of nacelle altitude and two blades in rotor. Also, the two types have same blade profile, NACA design. In this part of study, the investigated is only the effect of operation period of turbine without cleaning dust from blade on the power output. These results are shown in Figs. 12 and 13, while the period of operation after cleaning rotor blades for the two types of turbines was changed from 1 day to 9 months after cleaning. As shown in figures the performance of pitch-regulated wind turbine (Ventis) is better than the stall-regulated turbine (Wincon turbine).

As shown in Fig. 13 the rate of power loss in stall type is higher than pitch type as the period of operation increases without cleaning dust from the blade surface. For pitch-regulated 100 kW wind turbine, the power loss relation can be expressed as:

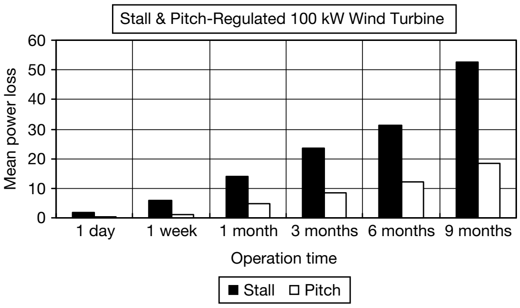

Fig. 12. Mean power loss (%) of stall and pitch-regulated 100 kW wind turbines.

$$\text{MPL} = T/20 + 2, \tag{5}$$

where T is the operation period in days. For stall-regulated 100 kW wind turbine, the power loss formula is: MPL = $T/5 + 5$, which is the same result as the 300 kW wind turbine.

Generally, the effect of dust accumulated on blade surface on the performance of horizontal axis wind turbines depends on the specification of the rotor turbine, speed of rotor, the altitude of rotor from the ground and the type of wind turbine regulation (stall or pitch). Also, the specification of wind farm site play an important role on the accumulation and built dust on blade surface of wind turbines. Whereas, the height of nacelle and rotor RPM in pitch regulated turbine

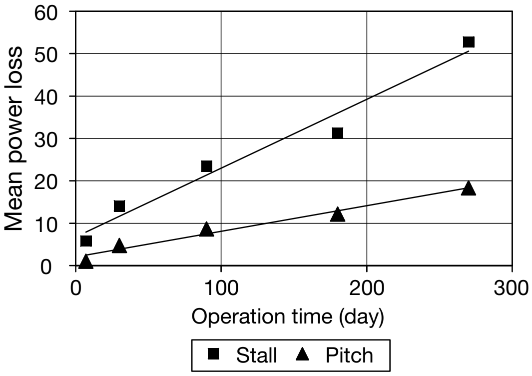

Fig. 13. Mean power loss (%) in stall and pitch-regulated wind turbines.

is higher than stall-regulated one, the effect of dust on the performance of pitch-regulated wind turbine is low. It is recommended to clean the dust from the blades in stall-regulated wind turbines in Hurghada wind farm within short periods with comparison to the pitch-regulated wind turbines.

Finally, the finding shows that the blade surface roughness reduces the effectiveness of the airfoil. By roughness, it means any protuberances or scratches on the airfoil's surface that can be felt by touch. The extent to which roughness affects airfoil performance is dependent on the nature of the roughness, its size relative to the boundary layer thickness, the Reynolds number and the airfoil type. The corresponding effects on airfoil lift and drag depend on the particular types of the pressure distributions developed by the airfoil. Boundary layer condition is more critical for airfoils, which utilize low pressure on the upper surface for lift. The surface roughness of the blade causes noticeable reductions in maximum lift coefficient and increases minimum drag coefficient.

5. Conclusion

It is concluded that, the effect of dust accumulated on blade surface on the performance of horizontal axis wind turbines depends on the specifications of the rotor turbine, speed of rotor, the altitude of nacelle from the ground and the type of power-regulation (pitch or stall). Also, the specifications of wind farm site play an important role on the accumulation and built-up of dust on the blade surface of wind turbines. Whereas, the height of nacelle and rotor RPM in pitch regulated turbine were higher than stall-regulated one, the effect of dust on the performance of pitch-regulated wind turbine is low.

With growing dust on the surface of wind turbine blades, the drag force of the airfoil increases, but the lift force decreases diminishing the power output of the turbine. Also, the dusting on the rotor's blades of horizontal axis stall-regulated wind turbines may lead among others to long time stops without no production due to heavy accumulated dust and safety demands, decreased power production and maintenance costs. The drag power loss in airfoils of wind turbines sections depends on the surface roughness of blade types of airflow, attack angle and geometry of blade airfoils. The blade surface roughness due to site dust depends upon the climate parameters as wind speed, number of sandy storms in each month, wind direction, relative humidity, and blade specifications. There are some factors that can not be controlled like climate factors, but other factors may be controlled as the blade surface roughness during manufacturing process and site surface roughness index. Also, some manufactured and petroleum vapors in near wind farm site especially in Zafarana may be affect the mechanism of accumulation of dust particles on wind turbines blades surface.

Generally, it is concluded that the blade surface roughness of wind turbines is increasing in desert sand roughness index sites due to accumulation of the dust. The blade surface roughness reduces the effectiveness of the airfoil to extract the useful power from wind and also leads to decreasing the power output of turbines. The extent to which roughness affects airfoil performance is dependent on the nature of the roughness, its size relative to the boundary layer thickness, the Reynolds number and the airfoil type.

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