

Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.



15th International Conference
on Applied Mechanics and
Mechanical Engineering.

FAILURE ANALYSIS OF WIND TURBINES IN ZAFARANA WIND FARM, SUEZ GULF, EGYPT

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ABSTRACT

A detailed analysis of the recoded failure data of the wind turbines in Zafarana wind farm namely Site-3 has been introduced. The failure cost consequences of one of the main components of the wind turbine have been introduced for cost analysis and maintenance planning.

The effect of variation of the capacity factor and the down time on failure cost consequences is introduced. The down time has a significant effect on the failure cost consequences of wind turbine components. The failure recoded data have been illustrated for one year for the same site for different wind turbine components while the capacity factor has only effect on gearbox and blade failure cost.

For failure rate and reliability analysis, the Weibull distribution has been introduced, the modified maximum likelihood method has been used to evaluate the Weibull distribution parameters. The failure rate and reliability have been studied for different wind turbine components. The initial failure rate after one month (720 h) was 0.0026 while the failure rate was 0.0084 at the end of the year (8760h) for the generator critical components.

KEY WORDS

Failure analysis, Weibull distribution, reliability, failure rate.

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NOMENCLATURE

c	Weibull distribution scale parameter
c_f	Capacity factor
C_I	Cost of item
C_T	Cost of transportation
C_L	Cost of loading
C_{LO}	Cost of off loading
dv	Wind speed increment
E_f	Energy pattern factor
F(T)	Probability of failure
k0	Shape factor initial value
K	Dimensionless Weibull distribution shape parameter
N	Number of wind data points
NS	Time to supply materials (days)
Nhc	Time to hire a crane (days)
NRd	No of repair days
NL	No. of labors to replace components
Nd	No. of days required to replace components
LR	Labor rate per day
Nc	Cost of crane hire per day including driver
Ndy	No. of days
P (X)	Life time for which the unit will function successfully with a reliability of
$P_{out-wp-T}$	Total wind output power
Pout-wp	Wind output power based on the Weibull distribution directly
Pout-ws	Wind output power based on the wind speed modeling
R(TR).	Reliability of time TR
T	Time
T(R)	Reliable life
Vac	Actual wind speed data
VM	Modeled wind speed using
vmec	Maximum energy carrier
V_i	Wind speed in time step i
v_{mp}	Most Probable Wind Speed
\bar{v}	Average wind speed
WT	Wind power turbine rating

Greek

$\Gamma()$	Gamma function
$\lambda(T)$	Failure Rate
σ	Standard deviation

Abbreviations

FBM	Failure-Based Maintenance
GM	Graphical method
MMLM	Modified maximum likelihood method
MLM	Maximum likelihood method

MWS	Mean wind speed method
MTBF	The mean life or mean time of failure
NREA	New and Renewable Energy Authority
OEM	Original Equipment Manufacturers
PDM	Power density method
RMSE	Root mean square error
TBM	Time-Based Maintenance
TP	Total wind output power
WT-1	Wind turbine No.1
WT-2	Wind turbine No.2
WT-3	Wind turbine No.3

INTRODUCTION

Today, wind turbines have to compete with many other energy sources. It is therefore important that they be cost effective. They need to meet any load requirements and produce energy at a minimum cost for money investment. Performance characteristics such as wind power output versus wind speed or versus rotor angular velocity must be optimized in order to compete with other energy sources. Yearly energy production and its variation with annual wind statistics must be well known.

Although there are various comprehensive design tests for the various components of a wind turbine, it cannot accurately predict all the actual environmental factors which may vary from site to site or all possible causes of failure that may occur during the operating life of the wind turbine. The possible causes of a wind turbines components and subsystems failure are human error, design faults, components related failure and unknown causes.

Some researches have been highlighted as literature survey in the following; Celik (2003) studied the estimation of energy output for small-scale wind power generators. Monthly wind energy production was estimated using the Weibull-representative wind data for a total of 96 months, for five different locations in the world. The Weibull parameters were determined based on the wind distribution statistics calculated from the measured data, using the gamma function. It is shown that the Weibull-representative data estimate the wind energy output very accurately. The overall error in estimation of monthly energy outputs for the total 96 months is 2.79%.

Celik (2004) studied the developments of compressed wind speed data to be used in wind energy and performance calculations of stand alone or hybrid wind energy systems. The data were generated based on the Weibull wind speed distribution model. Two different sets of wind speed data are generated, three and four-day month, each month being represented by 72 and 96 h of wind speed, respectively. The most important finding is the overall error in the wind energy yield estimation is 3.67% for the three-day month and 3.21% for the four-day month and the three- and four-day month compressed wind speed data can be successfully used instead of the measured hourly time series data to calculate the wind energy yield over a certain period of time, monthly or yearly.

Toure (2005) applied a new method to identify the 2-parameter Weibull distribution. The differential equation was identified. Then the study disclosed a linear relationship with two Eigen-coordinates. The results showed a better reliability. The Eigen-coordinates method is applied to the 2-parameter Weibull distribution. The results were compared with those found by the regression method. The study disclosed a better reliability of the fitting by the Eigen-coordinates method.

Xiao et al. (2006) investigated the probability distributions of extreme wind speed and its occurrence interval based on extreme wind speed data recorded in Hong Kong. The three-parameter Weibull distribution and two-parameter Weibull distribution are adopted in this study to fit the wind speed data. It is found that the three-parameter Weibull distributions are more appropriate than the two-parameter Weibull distribution. It is also observed that the occurrence interval of a specified extreme wind speed is a random variable which follows the three-parameter or the two-parameter Weibull distribution, while the two-parameter Weibull model is a better choice.

Andrawus et al. (2008) analyzed the failure Modes and Effect Criticality Analysis (FMECA) techniques that permits qualitative evaluation of assets' functions to predict critical failure modes and the resultant consequences to determine appropriate maintenance tasks for the assets. The presented a hybrid of FMECA technique to assess the failure characteristics of a selected subsystems of a chosen wind turbine. Optimal inspection intervals for critical subsystems of the wind turbine are determined to minimize its total life-cycle cost. The FMECA approach was used to determine failure modes of the wind turbines. Failure consequences of critical subsystems were determined and expressed in financial terms. The costs of inspection and repair as well as the failure rate of the components of the subsystems were calculated.

Albadi (2009) analyzed recent wind speed measurements taken at the Duqm metrological station to obtain the annual and monthly wind probability distribution profiles represented by Weibull parameters. The monthly average mean wind speed ranges between 2.93 m/s in February and 9.76 m/s in July, with an annual average of 5.33 m/s. An annual capacity factor of 0.36 is expected. For the base-case assumptions, the cost of electricity is about \$0.05 and \$0.08 per kWh for discount rates of 5% and 10%, respectively.

Fyrippis (2010) investigated the wind power potential of Koronos village, a remote location in the northeastern part of Naxos Island, Greece, using real wind data. The obtained wind characteristics were statistically analyzed using the Weibull and Rayleigh distribution functions. From the statistical analysis of these results, it was revealed that the Weibull model fitted the actual data better. This remark was further enhanced by the evaluation of the performance of these two distributions. The Weibull parameters k and c were found to be 2.17 and 8.58 m/s, respectively. Weibull distribution represented the actual data better than the Rayleigh distribution.

Safari and Gasore (2010) studied the potential of wind resource in Rwanda and to constitute a database for the users of the wind power. A time series of hourly daily measured wind speed and wind direction for the period between 1974 and 1993 on

five main Rwandan meteorological stations was provided. Statistical methods applying Weibull and Rayleigh distribution were presented to evaluate the wind speed characteristics and the wind power potential at a height of 10 m above ground level using hourly monthly average data. The results gave a global picture of the distribution of the wind potential in different locations of Rwanda. The results from such investigations can further be used in the design and estimation of performance of the types of wind energy conversion systems to be used in Rwanda.

Herbert et al. (2010) investigated the performance, failure, reliability and the spare parts analysis for a wind farm, of 15 wind turbine generators, each is 225 kW capacities located in India. The performance parameters such as technical availability, real availability and capacity factor were calculated during the years 2000 to 2004. Also, the Weibull distribution was applied for the reliability study.

Islam et al. (2011) estimated the performance of a wind in a planning wind energy project. In their study, with the help of 2-parameter Weibull distribution, the assessment of wind energy potentiality at Kudat and Labuan in 2006-2008 was carried out. The monthly and yearly highest mean wind speeds were 4.76 m/s at Kudat and 3.39 m/s at Labuan respectively. They concluded that these sites are unsuitable for the large-scale wind energy generation.

Mostafaeipour et al. (2011) investigated the wind power potential of the city of Shahrabak in Kerman province in Iran. The potential of wind power generation was statistically analyzed. It was concluded that it costs 18 cents for 1 kWh which is 5 cents more than the marketprice. Each turbine of 10 kW can supply power for icebox, washer, water pump, TV, lighting, electrical fan, charger, and air conditioning units for small houses. An economic evaluation was done in order to show feasibility of installing small wind turbines.

In the present study, the failure data of wind turbines for one year in Zafarana wind farm, Site-3, have been analyzed statistically. Zafarana Site, located in Suez Gulf, is approx. 200 km south east Cairo at the southern border of N 27° 40' 5" and northern point of E 33° 11' 31.4" / N 28 ° 12' 1.5" as shown in Fig. 1.

The site consists of 8 wind farms of different power outputs of total 545 MW and with averaged wind speed of 9 m/s. The studied wind farm consists of 46 wind turbines (three-blade upwind machine with active yaw) of 660 KW with a total site power output of 30 MW. The wind turbines are of Vestas type, V47-660/200kW, of pitch control and the studied Site-3 has been commissioned with cooperation with DANIDA on November 2003.

The failure data were collected for one year from July 2010 to June 2011. The Weibull statistical distribution parameters have been estimated using the maximum likelihood method and the modified maximum likelihood method for maintenance strategy planning purposes.

This paper is organized as follows; the cost distribution for the wind turbine will be introduced in section two, the failure data for the studied wind turbine will be illustrated in section three. Reliability analysis will be presented in section four and the conclusions will be addressed in section five.

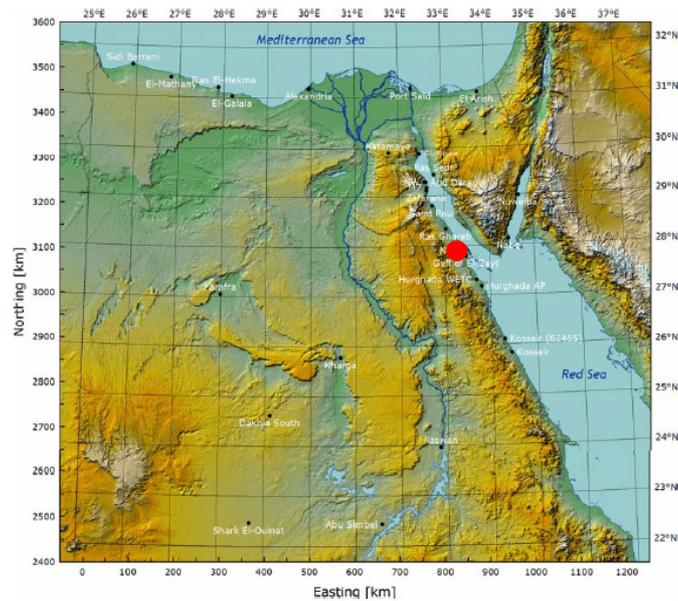


Fig.1. Map of Egypt and location of Zafarana wind farm in Suez Gulf.

COST DISTRIBUTION OF SIGNIFICANT ITEMS IN WIND TURBINE

The cost of the wind turbine will result in significant items is the wind turbine such as main drive and the generator which is about 56% of the total cost of a wind turbine. The rotor which comprises the blades, the hub and associated components is about 29%, and the tower is approximately 15%, as shown in Fig. 2.

A further breakdown of cost of components/subsystems within a nacelle of a wind turbine is shown in Fig. 3. The gearbox, converter and the generator have 33%, 17% and 13% respectively of the total cost of a nacelle. Thus, the gearbox, converter and the generator are the cost significant items within a wind turbine.

Cost of Generated Energy

When evaluating the design of a wind turbine, it is critical that the designer evaluate the impact of the design on the system cost and performance. The designer must consider several elements of this process: the initial capital cost, operations and maintenance and annual energy production. The initial capital cost is the sum of the turbine system cost neither cost includes construction financing or financing fees, because these are calculated and added separately through the fixed charge rate.

Annual operating expenses include land cost, Operation and maintenance, replacement/overhaul cost. The operation and maintenance cost normally covers the day-to-day scheduled and unscheduled maintenance and operations cost of running a wind farm such as labor, parts, and supplies for scheduled turbine maintenance and the labor for administration and support. The replacement/overhaul cost includes the cost of major replacements and overhauls over the life of the wind turbine.

Foundation cost is based on the diameter of the tower base. The road and civil works is assigned for roads and civil works were taken by logistics study including

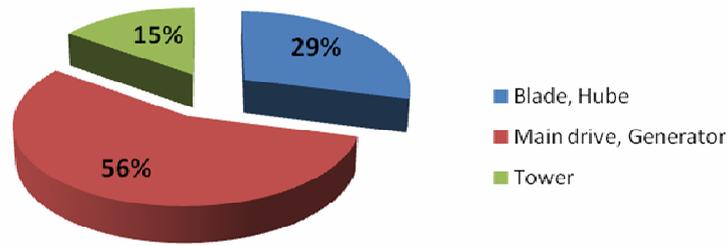


Fig.2. Percentage cost of Wind turbine items for WT-660 KW.

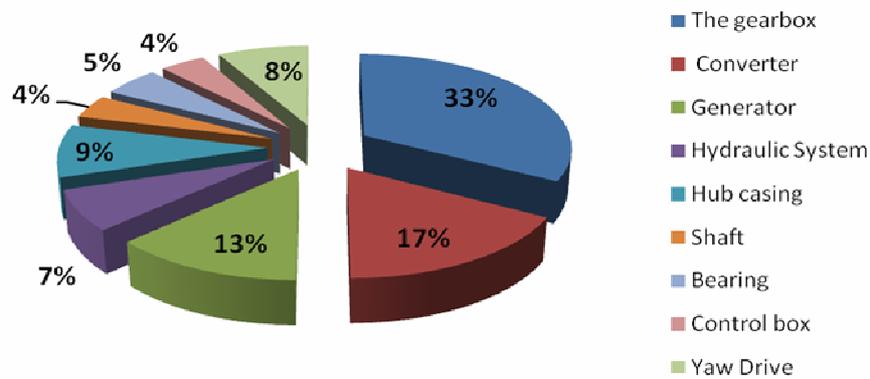


Fig.3. Percentage cost of Wind turbine main drive components for WT-660 KW.

modifications to road widths and crane pads to handle larger machines. Electrical interface covers the turbine transformer and the individual turbine’s share of cables to the substation.

For Site-3, the capital cost includes 1 million dollar for one wind turbine including the entire electrical interface with a total of 46 million dollars stands for 46 wind turbine in the farm. The maintenance cost includes five million Egyptian pounds and two hundreds thousands Euros per year. The total averaged life for the wind turbine is about 20 years of operation and the actual measured wind output energy for one year was 97809.2 MWhr.

$$\text{Unit Energy Cost} = \frac{(\text{Capital cost} + \text{Annual cost} + \text{Foundation /electric cost})}{(\text{total generated energy})} \quad (1)$$

Based on the rated power, the cost per MWhr should be calculated as follows:

$$\begin{aligned} \text{Unit Cost} &= (46 \cdot 1000000 \cdot 6 + 20 \cdot 5000000 \cdot 1.1 + 20 \cdot 200000 \cdot 8 \cdot 1.1) / (20 \cdot 46 \cdot 0.66 \cdot 8760) \\ \text{Unit Cost} &= 79.1 \text{ LE/MWhr} \end{aligned} \quad (2)$$

Based on the actual energy generated, the cost per MWh should be calculated as follows:

$$\text{Unit Cost} = (46 \times 1000000 \times 6 + 20 \times 5000000 + 20 \times 200000 \times 8) / (20 \times 97809.2)$$

$$\text{Unit Cost} = 161 \text{ LE/MWhr} \tag{3}$$

Cost Consequences of Significant Items Failure in Wind Turbine

The cost consequences of the wind turbine failure will result in significant financial loss is the wind turbine significant items such as main drive and the generator. Current market prices of major components of a 660kW wind turbine, including transportation cost to site, were obtained from NREA for a period of one year, from July 2010 to June 2011. The NREA Authority records failures and the date and time of failure occurrence. Labor requirements for replacements of these components as well as the access costs were obtained from the collaborating wind farm operators. Our analysis is based on the following equations, using functions given as follows:

Table 1: Failure cost consequences of significant components in Wind Turbine.

Item	Blade	Main Bearing	Main Shaft	Gearbox	Generator
Initial Cost:					
Cost of item (LE), C_i	280000	80000	90000	500000	200000
Cost of transportation (4% of the item cost), C_T	11200	3200	3600	20000	8000
Cost of loading (0.5% of the item cost), C_L	1400	400	450	2500	1000
Cost of off loading (0.5% of the item cost), C_{LO}	1400	400	450	2500	1000
Tax (12% of the item cost), Tax	12	12	12	12	12
Labour Replacement Cost:					
No. of labours to replace components, N_L	3	3	3	3	3
No. of days required to replace components, N_d	2	2	4	3	2
Labour rate per day, L_R	200	200	200	200	200
Crane Cost:					
Cost of crane hire per day including driver, N_c	10000	10000	10000	10000	10000
No. of days, N_{dy}	3	3	4	4	3
Time Loss Cost:					
Time to supply materials (days), N_s	180	21	30	120	60
Time to hire a crane (days), N_{hc}	2	2	2	2	2
No of repair days, N_{Rd}	3	3	4	4	4
Hours per day	24	24	24	24	24
Wind power turbine rating, WT	600	600	600	600	600
Capacity factor, c_f	40	40	40	40	40
Cost of energy per MWhr, Wp	79.1	79.1	79.1	79.1	79.1

$$C_{IT} = (C_i + C_T + C_L + C_{LO}) \left(1 + \frac{\text{Tax}}{100} \right) \tag{3}$$

$$C_{LB} = (N_L * N_d * L_R) \tag{4}$$

$$C_{CR} = (N_L * N_{dy}) \tag{5}$$

$$C_{SC} = (N_s + N_{hc} + N_{Rd}) * 24 * WT * Wp * \left(\frac{c_f}{100} \right) \tag{6}$$

$$FC_T = (C_{IT} + C_{LB} + C_{CR} + C_{SC}) \tag{7}$$

Table 2 shows the failure consequences of critical components of a 660kW wind turbine expressed in financial terms. The distribution of cost consequences between different factors have been illustrated in Fig. 4. The effect of the down time and capacity factor on the cost consequences have been illustrated in Fig. 5 and 6.

It has been noticed that the main cost of the wind turbine due to failure are in the gearbox failure and in the blade failure. In these cost consequences for the two main items, the big share of the cost is in the item cost itself.

Table 2: Failure cost consequences of the wind turbine critical components.

Item	Blade failure	Main Bearing Failure	Main shaft failure	Gearbox failure	Generator failure
Initial cost (LE)	329280	94080	105840	588000	235200
Labour cost (LE)	600	600	2400	1800	600
Crane cost (LE)	30000	30000	40000	40000	30000
Time loss cost (LE)	53280	7488	10368	36288	19008
Total cost (LE)	413160	132168	158608	666088	284808

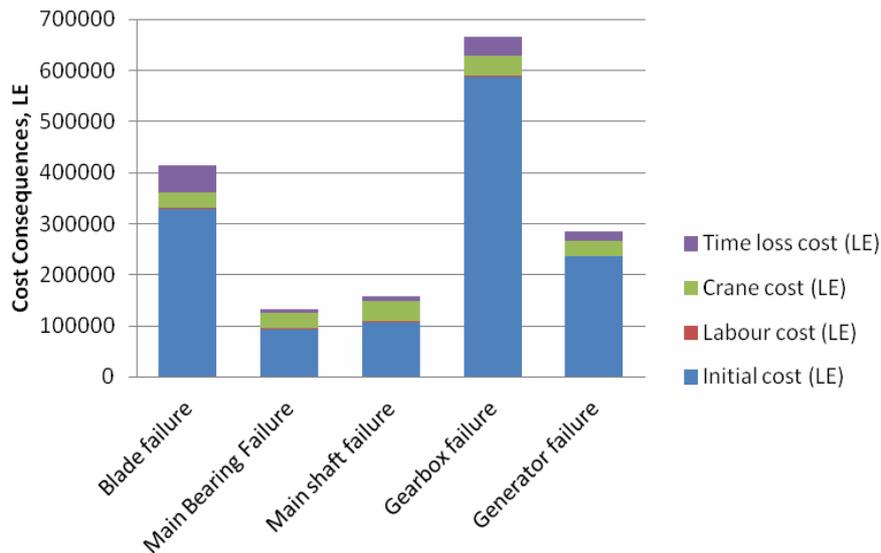


Fig. 4. Wind turbine failure cost consequences.

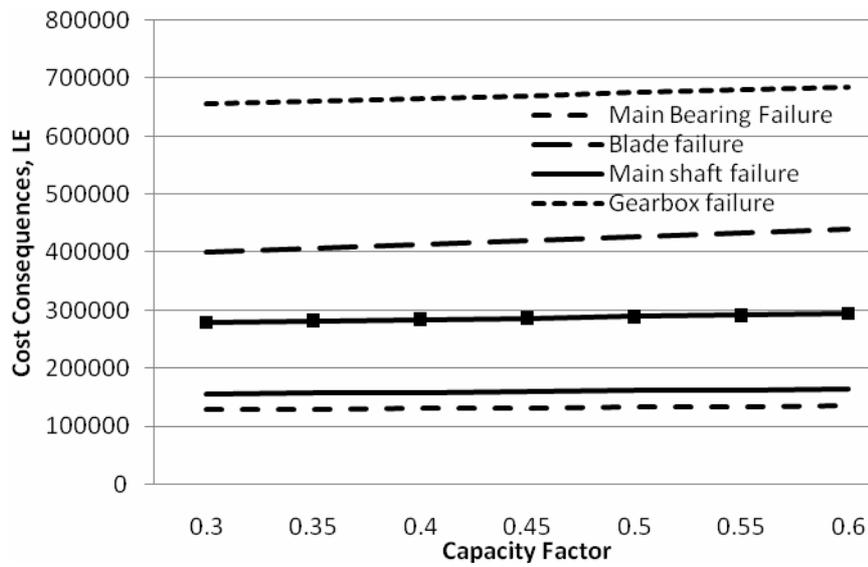


Fig.5. Variation of the total wind turbine failure cost consequences with the capacity factor.

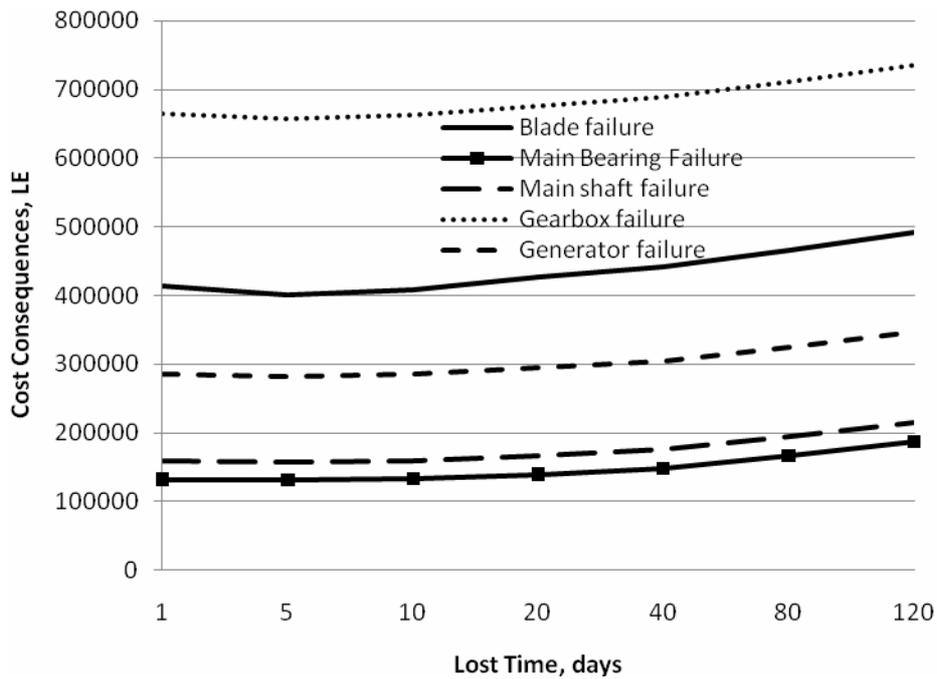


Fig.6. Variation of the total wind turbine failure cost consequences with the down time.

In the above figure, the increase of the lost days will increase the cost consequences of the item failure due to the generation loss from the wind turbine farms.

WIND FARM FAILURE DATA

Field failure data of horizontal axis wind turbines are collected from wind farms through NREA. The failure date is recorded for one year and the monthly distribution of this failure between the main components has been illustrated in Fig. 7 to 12. The failure time for each component on monthly basis is illustrated in Fig. 13 to 15.

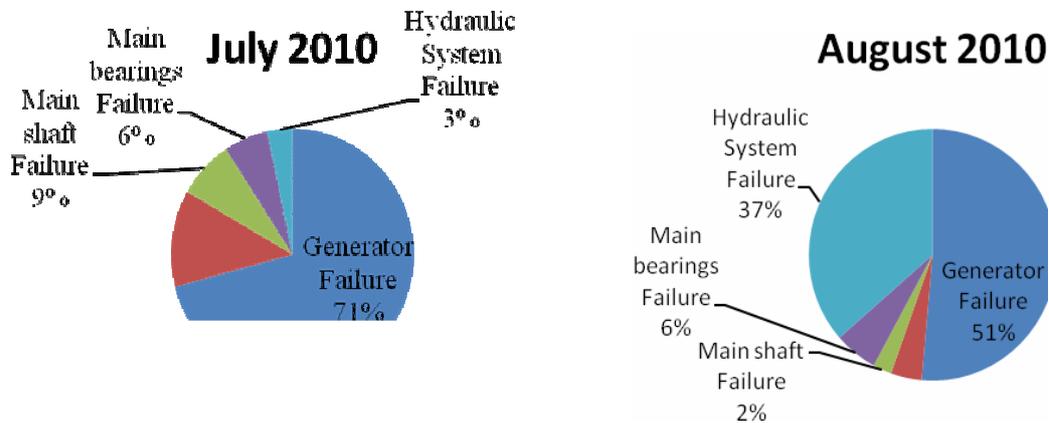


Fig.7. Percentage distribution of stoppage time in wind farm, July and August 2010.

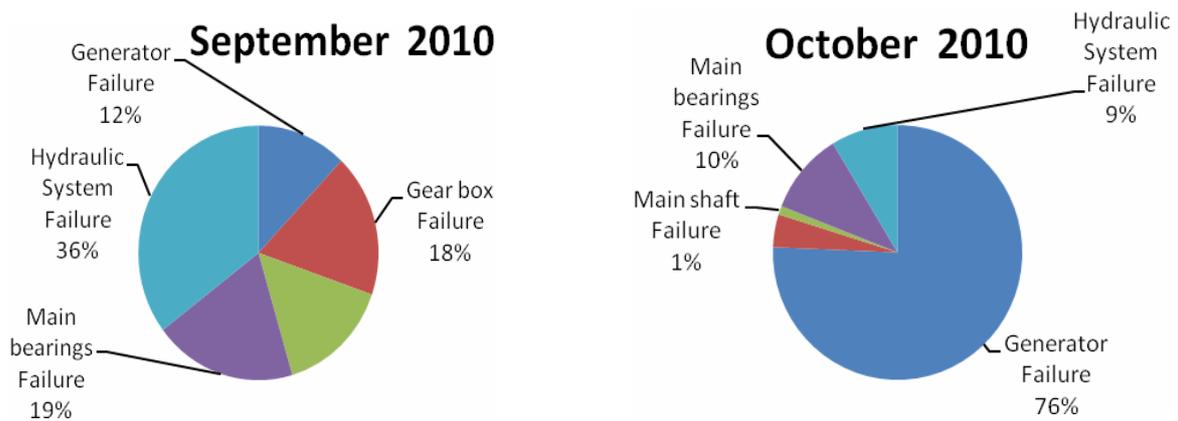


Fig.8. Percentage distribution of stoppage time in wind farm, September and October 2010.

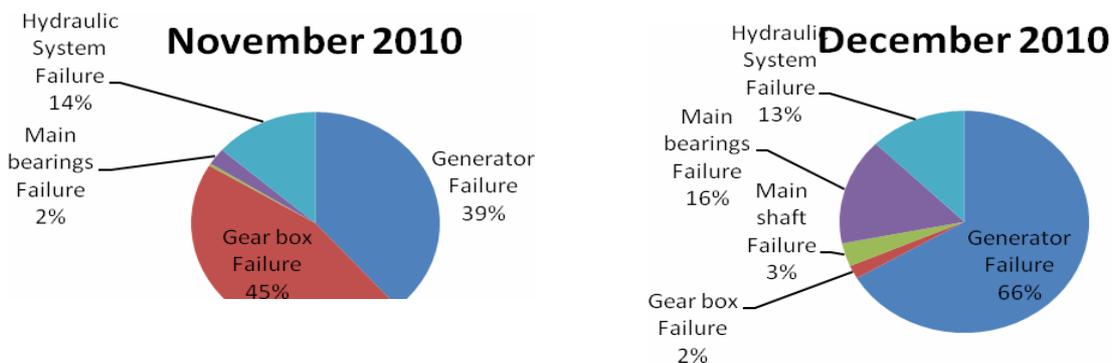


Fig.9. Percentage distribution of stoppage time in wind farm, November and December 2010.

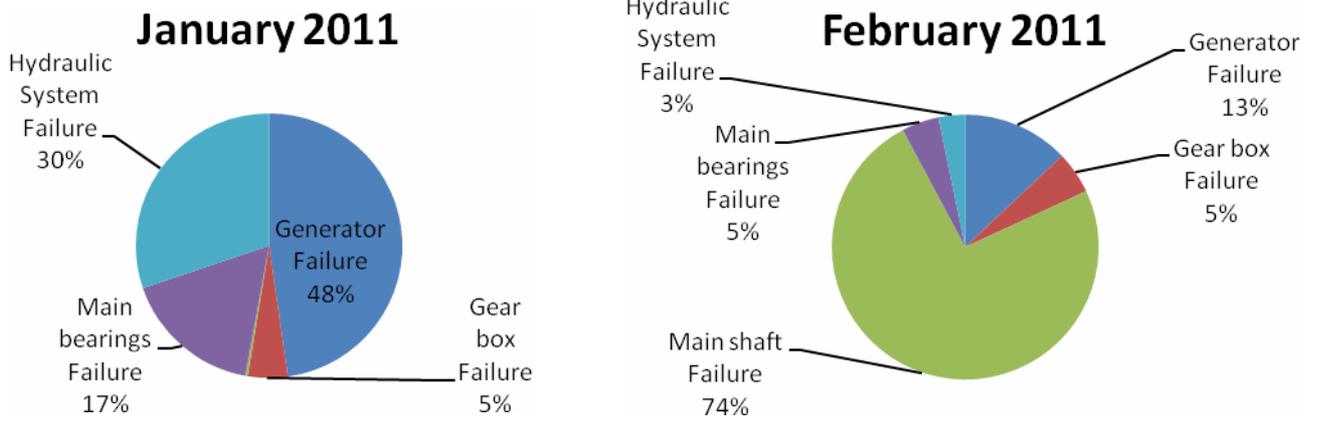


Fig.10. Percentage distribution of stoppage time in wind farm, January and February 2011.

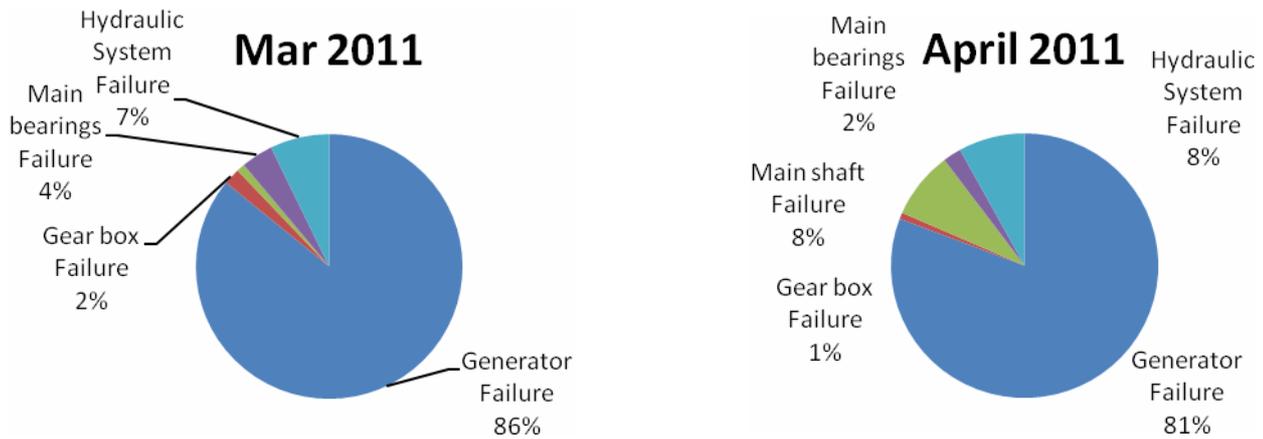


Fig.11. Percentage distribution of stoppage time in wind farm, March and April 2011.

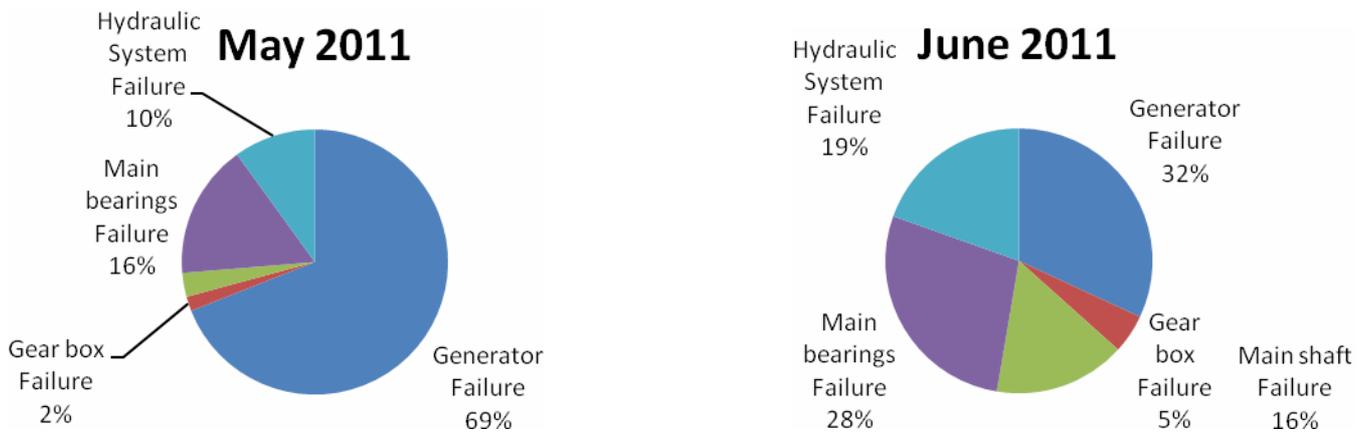


Fig.12. Percentage distribution of stoppage time in wind farm, May and June 2011.

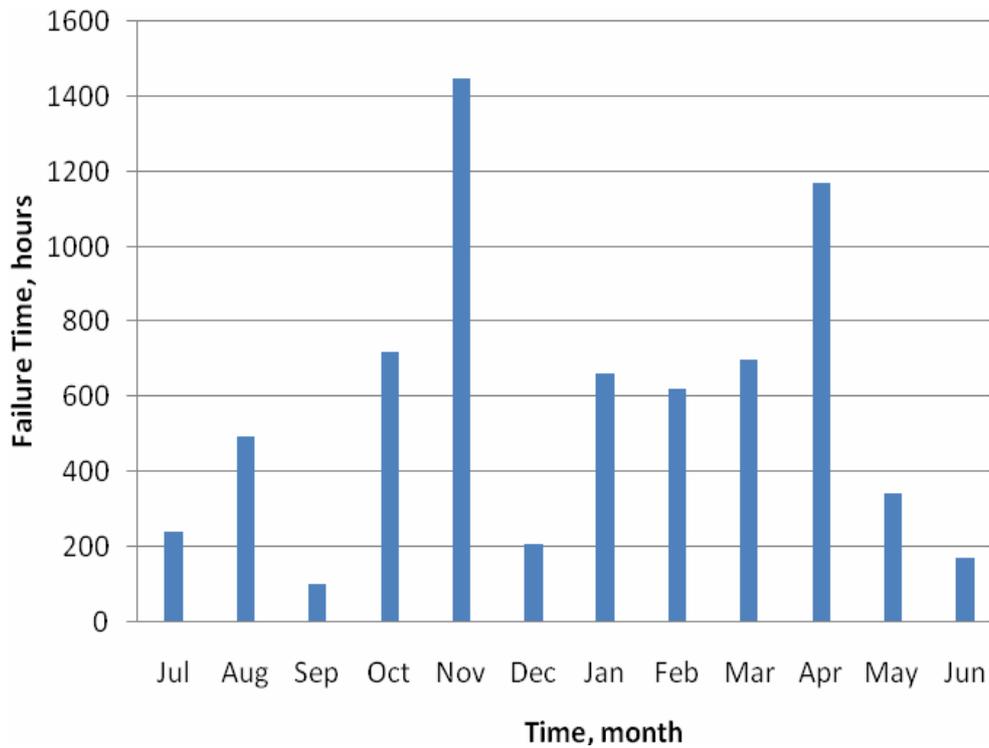


Fig.13. variation of failure time in hours through the whole year.

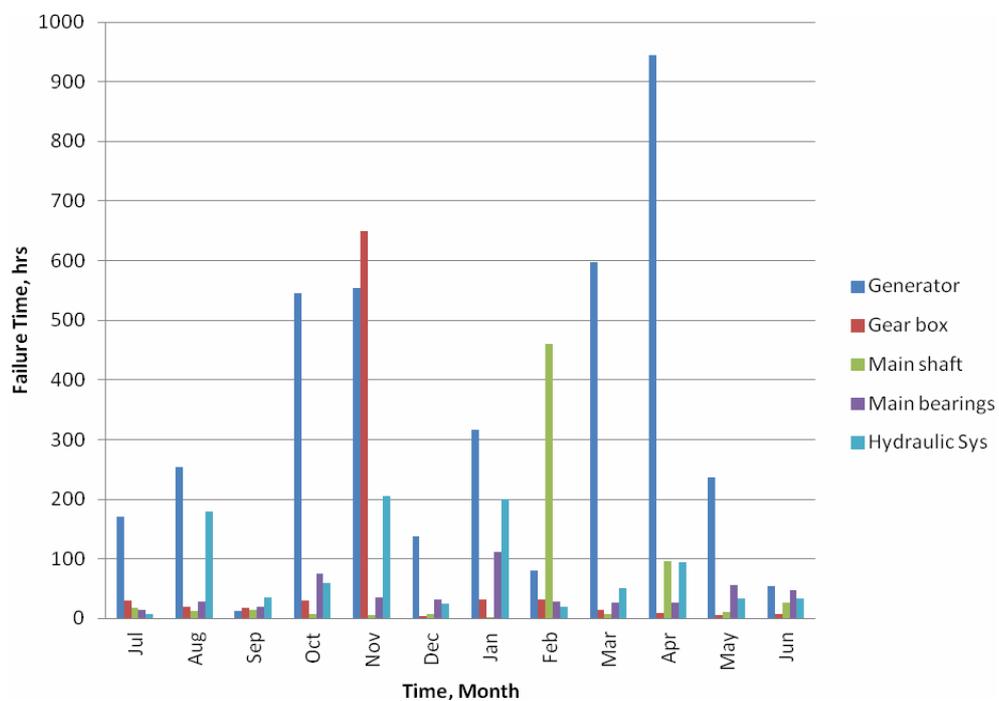


Fig.14. Variation of different component failure in hours through the whole year.

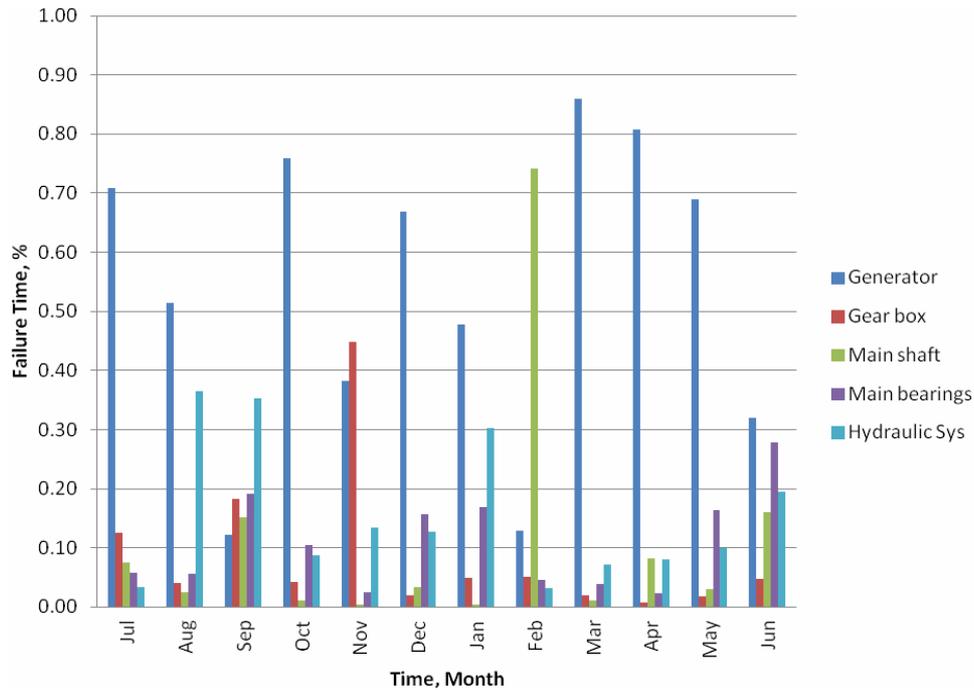


Fig.15. Variation of different component failure in percent through the whole year.

Based on Fig. 13 to 15, it has been shown that maximum failure time of the wind turbine is in winter season (in November) due to the environmental condition such as the dust in air and the main item that has been affected by this condition is the gearbox, while the generator failure time is maximum in summer season due to the hot weather in the wind farm location.

The down time is used to identify the current maintenance condition. Fig. 16 shows the annual percent of down time represented in each month. The stoppage time consists of stoppage due to low wind, grid failure, control panel fault, electrical and mechanical failures, and maintenance works. The average stoppage time due to preventive maintenance, electrical failure and control panel failures was 286.2 h.

The capacity factor and technical availability are computed and their variations in the one year of operation. The technical availability was almost steady throughout the period and its average value was 96.7%. It is possible to increase the technical availability by reducing technical failures of the wind farm. The real availability is presented where the turbine does not operate and is assigned for the total time due to grid failure time, turbine failure time and low wind speed (less than 4 m/s) time.

The wind farm had very low real availability to an increase in down time because of grid failure and low wind speed. By reducing the failures due to grid and components, the real availability can be increased and thereby the reliability factor can also be improved. The capacity factor was found to vary from 367%. The capacity factor could be calculated based on the rated energy as follows:

$$Cf = \frac{\text{actual energy}}{\text{rated energy}} = \frac{97809.2}{46 \times 0.66 \times 3760} = \frac{97809.2}{241776} = 0.367 \tag{8}$$

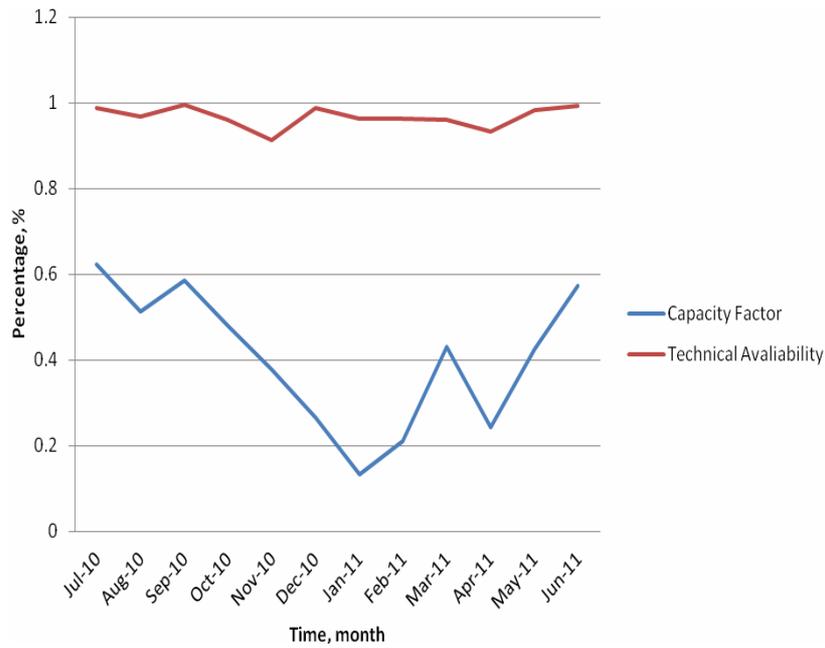


Fig.16. Variation of technical availability and the capacity factor throughout one year.

RELIABILITY ANALYSIS

The Wind Turbine has an impact on the performance of generating the required wind power. Consequently, a concern for the reliability of the wind turbine and better maintenance skills are required. Reliability estimation is highly desirable for such equipment and is directly related to their failure rate. For that purpose, a Weibull distribution technique is presented to study the reliability of the wind turbine critical components which believed to reflect the actual field failure rate and defect density. The Weibull analysis is a powerful technique for identifying the reliability characteristics of wind turbine components.

The estimation of the Weibull distribution parameters can be estimated by using different methods such as the graphically method, the maximum likelihood methods or the modified maximum likelihood methods. The two-parameter Weibull cumulative density function is given as below:

$$F(T) = 1 - \exp \left[- \left(\frac{T}{c} \right)^k \right] \tag{9}$$

where $F(T)$ is the probability of failure; t is time; k is the shape parameter; c is the scale parameter. Reliability is defined as the probability in which an item or an entity performs its intended function over a period of time under stated conditions. The reliability function for the two-parameter Weibull distribution is given as:

$$R(T) = \exp \left[- \left(\frac{T}{c} \right)^k \right] \tag{10}$$

The mean life or mean time of failure (MTTF or MTBF) is defined as the average time of failure-free operation up to a failure event calculated from a homogeneous lot of equipments under operation. The MTBF of the Weibull distribution is given as:

$$-T = c \Gamma\left(1 + \frac{1}{k}\right) \tag{11}$$

where

$\Gamma\left(1 + \frac{1}{k}\right)$ is the Gamma function.

Then the two-parameter probability density function f(t) is given as:

$$f(T) = \left(\frac{k}{c}\right) \left(\frac{T}{c}\right)^{k-1} \exp\left[-\left(\frac{T}{c}\right)^k\right] \tag{12}$$

The estimation of the Weibull distribution parameters, shape and scale parameters, for different critical components of the wind turbine have been determined using different methods such as the Maximum Likelihood Method, MLM, and the Modified Maximum Likelihood Method, MMLM, and the results are tabulated in Table 3. The MMLM method has been used to estimate the Weibull parameters as follows:

Table.3. Weibull distribution parameters.

WT Critical Component	MLM		MMLM	
	Shape factor	Scale factor	Shape factor	Scale factor
Generator	1.13	339.1	1.3730	384.1
Gearbox	1.63	80.2	1.82	82.3
Main Shaft	1.22	56.67	1.34	59.8
Main Bearing	1.71	47.1	1.82	48.3
Hydraulic System	1.14	82.73	1.36	84.5

Failure Rate and Reliability Factor

To calculate the wind failure rate for critical wind turbine components, the values of the Weibull distribution parameters, shape and scale parameters, have been used according to Equation 12 using a Matlab program for each critical component of the wind turbine components.

The Weibull failure rate function is defined as the number of failures per unit time that can be expected to occur for the product. It is given as:

$$\lambda(T) = \frac{f(T)}{R(T)} = \left(\frac{k}{c}\right) \left(\frac{T}{c}\right)^{k-1} \tag{13}$$

The median is defined as the failure density function equivalent to 50% probability. Mode is defined as maximum failure intensity of the probability density function.

Warranty time is defined as the estimated time when the reliability will be equal to a specified goal. The reliable life T(R) of a unit for a specified reliability is given by:

$$T(R) = k\{-\ln[R(T_R)]\}^{k-1} \tag{14}$$

This is the life time for which the unit will function successfully with a reliability of $R(T_R)$.

In Figs. 17 to 19, the failure rate of the generator item has been calculated using Weibull distribution, the estimation of the Weibull parameters are based on the actual data using MLM method. It has been shown that with the increase of the surface life of the item, the failure rate will be increased which reduce the reliability of that item, the rate of the failure after one year of the generator will be 0.0085, for the gearbox is 0.14 while for the main shaft is 0.05.

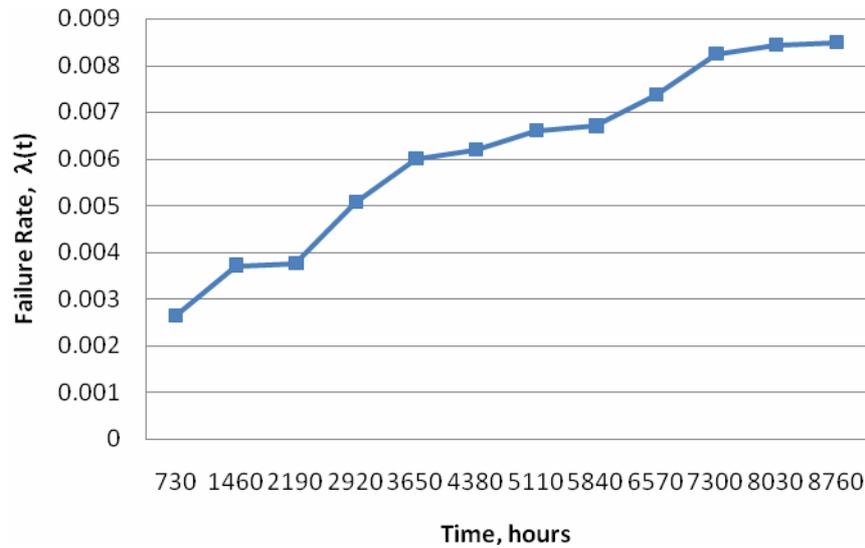


Fig.17. The failure rate of generator system failure.

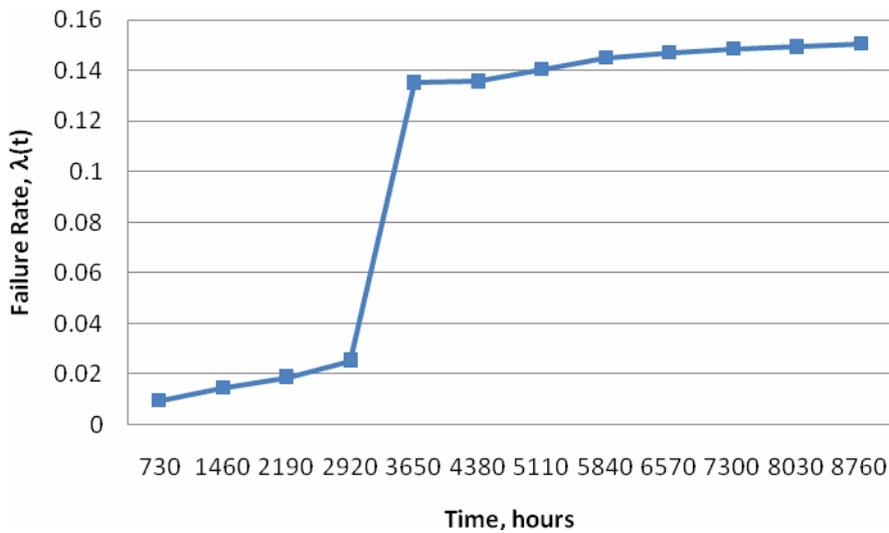


Fig.18. The failure rate of gearbox system failure.

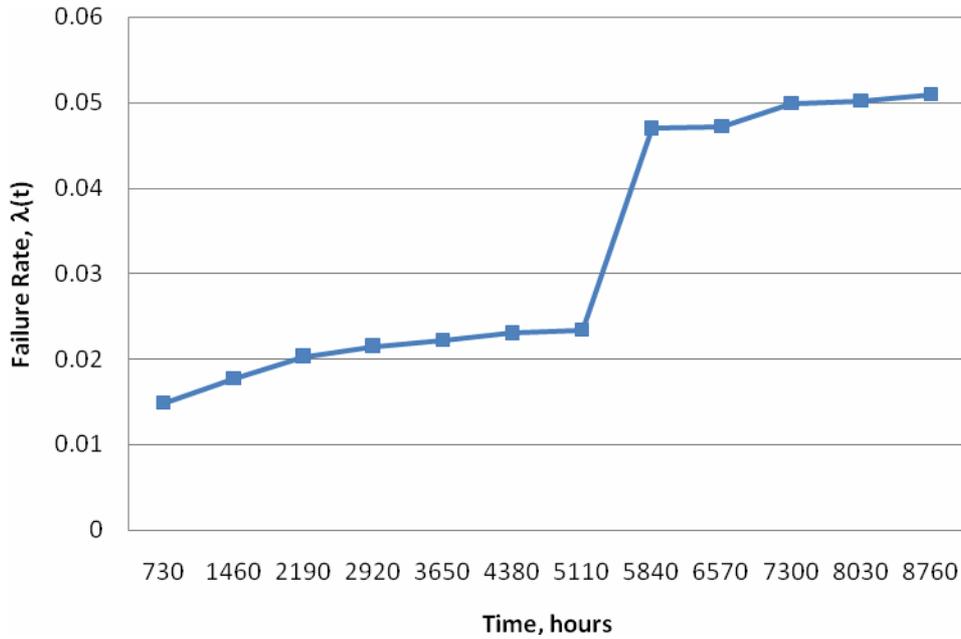


Fig.19. The failure rate of main shaft system failure.

Based on that, the higher failure rate which gives indication of the most critically component is belong to gearbox component, this result is consistent with the actual failure data measured for the wind farm which could be explained due to the sensitivity of this component to the environmental conditions.

Another way to have a look into these data is introduced in Figs. 20 and 21, in which the reliability have been plotted with time. Based on these plots, the reliability reduced with the time for the most critically component such as the gearbox and the generator.

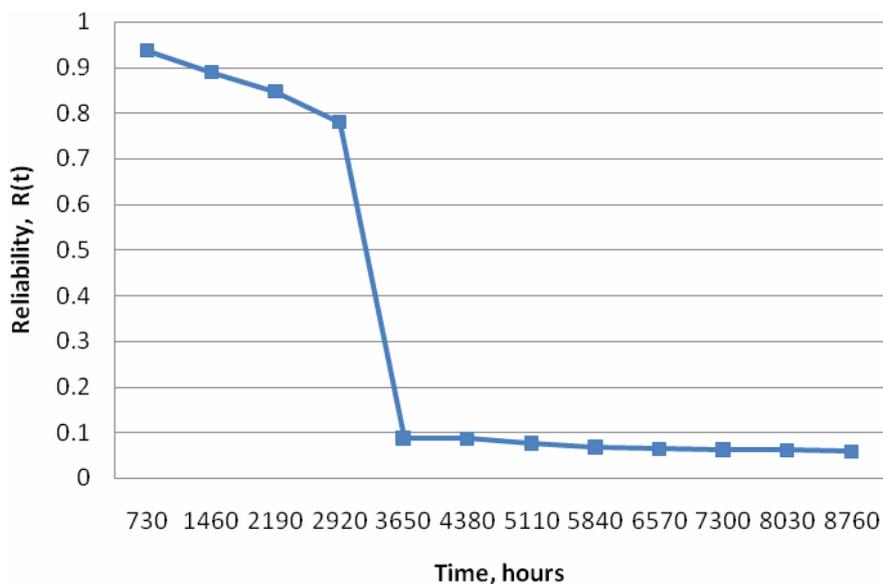


Fig.20. The Reliability of gearbox system.

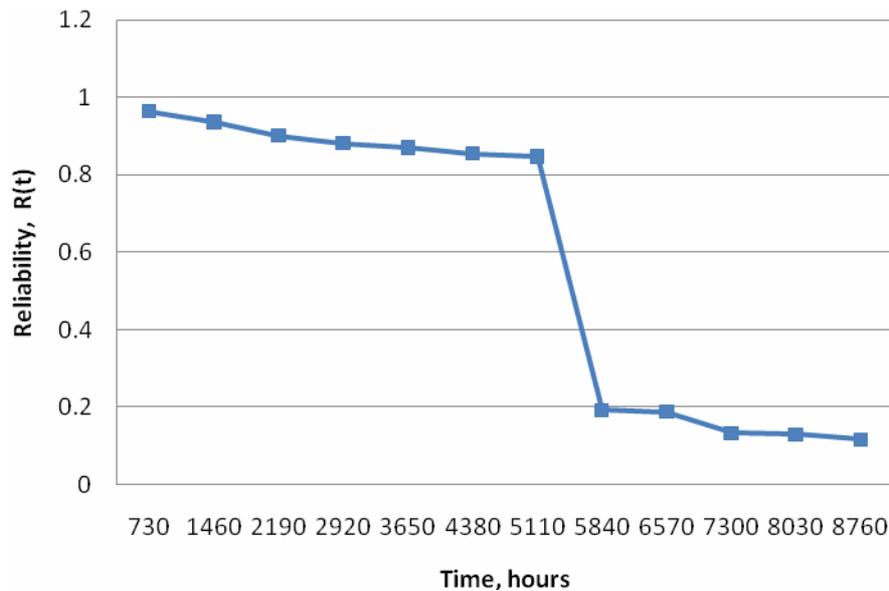


Fig.21. The Reliability of generator.

CONCLUSIONS

The data for failure of wind turbines components have been analyzed to achieve a good maintenance planning. The cost consequences of wind turbine failure have been also introduced for cost analysis. The statistical distribution, Weibull distribution, has been used to estimate the reliability and failure rate analysis, modified maximum likelihood method has been used for evaluation the Weibull parameters. The wind turbine reliability has been studied for different wind turbine components and the initial failure rate after one month (720 h) was 0.0026 while the failure rate was 0.0084 at the end of the year (8760h) for the generator critical components.

ACKNOWLEDGEMENT

The authors would like to thank the New and Renewable Energy Authority (NREA) in Egypt for their support and providing the necessary field measurement to complete this work which enrich and enhance the article.

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