Performance, reliability and failure analysis of wind farm in a developing Country

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A B S T R A C T
In this paper, an analysis of the performance, failure and reliability, as well as a spare parts analysis have been conducted for a wind farm, which has 15 wind turbine generators (WTGs), each of 225 kW capacity. This wind farm is located at Muppandal, Tamil Nadu, South India. The average value of performance parameters such as technical availability, real availability and capacity factor for the wind farm were 94%, 82.88% and 24.9% respectively during the years 2000–2004. This paper also deals with Pareto analysis to find out the reduction in problems, when one problem is tackled partly and completely. The Weibull technique was also used for the reliability analysis. The reliability factor in the initial period after one year seems to be good as the wind farm has a lower failure rate of 0.000019. As a supplemental activity, spare parts optimization was also carried out for a few vital components of this wind farm and the results are presented. The failure and its financial implications are also analyzed in this paper.

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1. Introduction

Wind energy is one of the vital inputs for the social and economic development of any nation. It supplies affordable, inexhaustible energy to the economy. It is an alternative clean energy source and has been the world’s fastest growing renewable energy source with a growth rate of 28% in the last decade. Technological improvements over the last 5 years have placed wind energy in a stable position to compete with conventional power generation technologies. Due to the impending exhaustion of fossil fuels, it is crucial to develop clean wind energy as an alternative source of energy. Wind energy is eco-friendly and does not pollute the atmosphere like thermal power plants. It is to be noted that a 225 kW wind turbine installed in a moderately high wind area, generates about 600 MWh per year. The same amount of energy, when generated in a thermal power plant, consumes about 250 tonnes of coal and emits 800 tonnes of CO2 and other poisonous gases into the atmosphere.

Carbon dioxide build up in the atmosphere is the single biggest contributor to global warming. The total CO2 emission from all the coal-fired power plants in India is 1.1 million tonnes per day with an annual emission computed to be 395 million metric tons. Coal fired plants cause diverse public health and environmental problems. To address the problems of global warming and environmental degradation, steps need to be taken to slash the amount of CO2 that various power plants emit. The replacement of traditional fossil fuel-based energy with wind energy offers great opportunities for the reduction of CO2 emission.

Enormous power can be generated by the selection of suitable wind farm sites with suitable WTGs, improved maintenance procedure, better policies from the Government and advanced technologies of wind turbines. A literature survey was conducted to review the performance and failures of WTGs in different parts of the world. Mejia et al. [1] analyzed the performance of a wind turbine generator by studying its capacity factor. Ben Amar et al. [2] calculated the monthly and annual values of capacity factor and energies of the first wind farm section of Sidi Daoud, Tunisia. Zekai Sen [3] analyzed statistical behaviour of wind energy within the northeastern part of Turkey by employing the Chebyschev’s inequality to approximate the probability distribution function of the wind energy. It provided a basis for assessing the risk and reliability of wind energy. Chi-ming Lai and Ta-hui Lin [4] analyzed wind power potential, described the practical installation, measured the actual energy output, verified the reliability of the energy output for a land aqua-farm in Taiwan and introduced the relationship between the actual energy generated and the wind speed characteristics. Dokopoulos et al. [5] proposed a Monte Carlo based method for predicting the performance of energy systems consisting of diesel generators and WTGs to eliminate problems associated with wind intermittency and to provide a source of electrical energy. Paul Denholm [6] proposed the technical,
environmental and social performance of wind energy systems using biomass-based energy storage.

Sorensen et al. [7] studied wind farms connected to weak grids in India and found that variations in grid voltage and frequency have a considerable impact on the operation of wind turbines. Jang et al. [8] described a simulation model and a case study for analyzing the probability of power supply failure in hybrid photo-voltaic-wind power generation systems incorporating a storage battery bank and also analyzed the reliability of the system on the islands surrounding Hong Kong. Danmi et al. [9] suggested the stall-delay phenomenon for horizontal axis wind turbine in order to accurately predict the loading and performance of WTGs operating in stall. Thomsen et al. [10] found that the difference in energy production could be more than 50% between MW sized wind turbines installed at different sites. Peter Fuglsang and Kenneth Thomesen [11] had compared a 1.5 MW stall regulated wind turbine in normal onshore flat terrain and in offshore wind farm and showed a potential increase in energy production of 28%.

Kathleen O’Dell [12] investigated new materials and new manufacturing processes to increase the performance of WTGs. Idriss Ammara et al. [13] had found that the inefficient spacing between the turbines reduced the performance associated with the wake effect. Energy is lost due to wake interactions and in electrical losses. Suu-yuan Hu and Jung-ho Cheng [14] evaluated performance of pairing between sites and wind generators and estimated energy output performance. Bhatt and Jothibasu [15] studied the prediction and enhancement of the performance of wind farm in India and found that there was scope for improving the grid and WTG availability. This paper is an attempt to study the performance, reliability and failure analysis of wind farm located at Muppandal (South India).

2. Wind energy programme in India

India is endowed with an abundance of natural wind energy resources, which can supply the energy needed even in remote areas. Considerable efforts have been made for the sustainable development of wind energy in India. The wind power programme in India is promoted and coordinated by the Ministry of New and Renewable Energy (MNRE), Government of India. The MNRE has issued guidelines to all the States on the general policies and the facilities to be offered for wheeling, banking and purchase of power from such projects. The Indian Renewable Energy Development agency (IREDA) plays a significant role in promoting wind energy projects in India.

Wind power generation has grown at an alarming rate in the past decade because of the advancement in power electronic technology. Wind power installations worldwide have reached 159,213 MW producing more than 340 TWh of electricity annually. The wind power programme in India was initiated towards the end of the 6th plan in 1983—1984. The Government of India established four demonstration wind farms in the year 1985 at Tuticorin (Tamil Nadu), Okha (Gujarat), Pur (Orissa) and Deogarh (Maharashtra). A detailed study of the establishment of wind farms on a scientific basis was started in the year 1986. The major demonstration wind farms in India were established by MNRE with the assistance of the Danish International Development Agency in the year 1989—1990. The installation of private wind farms was started in 1991 and more than 95% investment is made by the private sector. India has earned recognition as a new ‘Wind Super Power’ as per the 1998 World Watch Institute’s Report. The growth of the wind energy scenario accelerated from 1999 because of technological maturity, the introduction of machines suitable for Indian conditions and the Government’s declaration of incentives to private entrepreneurs, concessional import duty on specified wind turbine parts, a five-year income tax holiday and sales tax and excise tax relief.

India’s preliminary gross estimated potential stands at 45,195 MW, but recent scientific surveys re-assessed it as 60,000 MW. The State-wise capacity addition during the first half of the year 2007—2008 was 566 MW. In the last 10 years, wind power development in India has been promoted through Research and Development (R&D) support, policy support and development of infrastructure capability. The fiscal year 2006—2007 was a landmark year for the wind sector in India with a capacity addition of 1771.5 MW and this was higher than the last year’s installed capacity of 1746.3 MW. The installed capacity of wind power in India has reached 10,925 MW till December 2009 with more than 10,000 numbers of WTGs of different capacities. About 33.5 billion kWh of electricity have been fed to the grid so far. The percentage contribution of wind energy installed capacity is 5.82% of the all-India total installed capacity (134717 MW) of power. Since 1980, advances in aerodynamics, structural dynamics, and “micrometeorology” have contributed to a 5% annual increase in the energy yield of the turbines. Current research techniques have led to the production of stronger, lighter and more efficient blades for the turbines. These costs are expected to decline as profitability increases with technology improvements. Wind energy has been proven as a reliable and cost effective energy source and it is expected to create maximum impact in the production of electricity. The rapid increase of wind capacity in India is likely to continue, and is expected to reach a cumulative installed capacity of 18,028 MW by 2011.

A diagram of WTG is illustrated in Fig. 1 to identify the technology. A modern WTG is composed of five basic subsystems, 1) The rotor consists of blades mounted on a hub and includes aerodynamic braking systems and pitch control. 2) The drive train including gearbox, hydraulic systems, shafts, braking systems and nacelle, encases the actual turbine. 3) The yaw system positions the rotor perpendicular to the wind stream. 4) Electrical and Electronic systems include the generator, relays, circuit breakers, wiring, controls and electronic sensors and 5) The tower.

3. Performance analysis

The performance of the wind farm was analyzed to rectify the failures and improve the reliability of the system. The performance of the wind turbine is proportional to Wind Power Density (WPD). The pattern of monthly variation in WPD of the Muppandal wind farm is shown in Fig. 2. This curve indicates the maximum WPD of 723.3 W/m² in the month of June. The annual average WPD in this wind farm is 361 W/m². High WPD was recorded from April to September. Low WPD was recorded during the monsoon (October—December). The wind power density varies with different locations. The maximum extrapolated mean annual WPD of a site (Perambukettimedu, Kerala) at a 50 m height amongst the MNRE sites is 721 W/m². The number of wind monitoring stations in India with an annual WPD of more than 200 W/m² at a 50 m height is 212.

The monthly generation curve for one WTG of 225 kW for the period from April 2002 to March 2003 is shown in Fig. 3. It is found that the energy generation varies due to wind speed and technical factors. From April to July, it shows an upward trend and afterwards it shows a declining trend. The upward and downward trends are caused by a monthly variation in wind power density. The power generation curve is correlated with the wind power density curve. The WTGs should be properly maintained for sustained operation and generation of optimum power. To ensure optimum power generation, an undisturbed flow of air is required by the wind turbine.
The most important performance criterion is the power curve. The power curve is the official certificate of performance of a WTG. On the basis of the power curve the annual energy output can be calculated for a given site. The determination of the power curve is connected with both the technical properties of the turbine and the wind data on which the WTG design is based. The first factor determining the performance of the WTG is the aerodynamic characteristic of the rotor. The power curve for a stall regulated 225 kW capacity WTG is shown in Fig. 4. The International Electro technical Commission standard, IEC 61400-12, specifies the procedure for measuring the power performance characteristics of WTG systems. These performance characteristics are defined by the measured power curve and the estimated annual energy production. The technical specifications of this WTG are 3 blades, 29.8 m rotor diameter, 45 m hub height, stall regulation, tubular tower, asynchronous dual speed generator coupled with gear, rated power of 225 kW and rated wind speed of 15 m/s. The cut-in speed is 4 m/s and the cut-out speed is 25 m/s. The turbine is designed to operate between the cut-in speed and cut-out speed.

The performance data of a wind farm was collected from the Moppandal wind farm, in South India. This wind farm has a cluster of 15 identical wind turbine generators. The data pertaining to power generation, machine failure, grid failure, wind speed and maintenance were collected for 5 years from 2000 to 2004. The total installed capacity of this wind farm is 3375 kW i.e., \((15 \times 225 \text{ kW})\). The annual wind power generation is shown in Fig. 5. It is found that there is a fluctuation of generation from year to year due to climatic and technical factors. The generation reached a maximum (7480 MWh) in the year 2002 because of higher turbine availability. The annual average generation was 7370 MWh. There was minimum generation (7215 MWh) in the year 2001 because of increased break down and maintenance time. The accumulated dirt, grime, and insect deposits on the blade slightly impaired and reduced the power generation of WTGs.
blades should be periodically cleaned with a silicon-based solution to decrease bug accumulation.

The capacity factor, real availability and technical availability are computed and their variations in the five years of operation are shown in Fig. 6. The technical availability was almost steady throughout the period and its average value was 94%. It is possible to increase the technical availability by reducing technical failures of the wind farm. It is observed that the average real availability was 82.88%, because the turbine does not operate 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 in the year 2003 due 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 24.41% in 2001–25.3% in 2002. The average capacity factor for five years was 24.9%. There is scope for improvement in the performance of the WTG by improving the grid availability and turbine availability. The availability of the WTGs can be increased by proper maintenance procedure.

The down time is used to identify the current maintenance condition. Table 1 shows the annual comparison of total time, generation time and stoppage time for the wind farm. The summation of total generation time and stoppage time gives the total time. The total time, generation time and stoppage time for the five years of operation were 657,720 h, 517,394 h, and 140,326 h respectively. The stoppage time consists of stoppage due to low wind, grid failure, control panel fault, electrical and mechanical failures, and maintenance works.

Performance data of 3.735 MW wind farm is given in Table 2. It is observed that the down time due to low wind (100,887 h) was higher than the down time due to grid failure. Turbine fault time and maintenance time were less than the grid failure time. The low wind time (23,408 h) was more in the year 2003 due to climatic variation in the atmosphere. The average stoppage time due to low wind, grid failure and mechanical failure were 20,177, 5813 and 1011 h respectively. Overall, 21% of total time, wind farm was stopped. The average stoppage time due to preventive maintenance, electrical failure and control panel failures were 522, 470 and 72 h respectively. The percentage distribution of total stoppage
is shown in Fig. 7. The stoppage time due to mechanical failure is high in 2001 (8%) as well as in 2004 (7%).

It has been noted that the average time taken for replacement of electronic components is much less than the time taken for replacement of mechanical components. The wind farm was stopped for 4%, 2% and 21% of total stoppage time due to mechanical failure, electrical failure and grid failure respectively during the five years of operation. Grid drop, frequency fault, asymmetric current, overvoltage and low voltage are major causes of grid failure. Wind power generation can be increased through better operation and maintenance activities.

4. Reliability analysis

The Wind Turbine Generator (WTG) has a different impact on the reliable performance of a generating system. Concern for the reliability of the wind turbine with its complexity has grown, and this requires better maintenance skills. Reliability estimation is highly desirable for such equipment and is directly related to their failure rate. In this section, a Weibull distribution technique is presented to study the reliability of the wind farm.

4.1. Estimation of properties of Weibull distribution

The reliability estimation methodology reflects the actual field failure rate and defect density. It can be a good indicator of field reliability. For the reliability analysis of WTGs, the Weibull model is chosen. The Weibull analysis is a powerful technique for identifying the reliability characteristics of WTGs. The estimation of the parameters of the Weibull distribution can be done graphically via probability plotting or analytically, using least square or maximum likelihood methods. In this study an analytical method is used to determine the Weibull parameters. The Weibull methodology is a general purpose reliability-engineering model, which depending on the shape parameters, assumes exponential, normal as well as other types of distribution. The properties of the Weibull distribution are as follows.

The two-parameter Weibull cumulative density function is given as below:
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 MTTF or MTBF of the Weibull pdf is given as

\[
R(T) = e^{-\left(\frac{T}{\eta}\right)^{\beta}}
\]

where

\[
\Gamma\left(\frac{1}{\beta} + 1\right)
\]

is called gamma function.

The two-parameter Weibull probability density function \(f(t)\) is given as,

\[
f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{4}\]

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,

\[
\lambda(T) = \frac{f(T)}{R(T)} = \frac{\beta}{\eta} \left(\frac{T}{\eta}\right)^{\beta-1} \tag{5}\]

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. For Weibull the median and mode are given as

\[
\text{Median} = \eta + (\ln 2)^{1/\beta} \tag{6}\]

\[
\text{Mode} = \eta \left(1 - \frac{1}{\beta}\right)^{1/\beta} \tag{7}\]

Warranty time is defined as the estimated time when the probability of failure will reach a specified percentage point (X %). To be specific, in the bearing industry, it is the normal practice to check for the life deterioration of 10% of bearings and a check is kept on the time at which this occurs. This duration of the failure of 10% of bearings is normally termed as the warranty time for 90% reliability, i.e., 10% of the products are expected to fail within a specified time.

\[
B(X) = \frac{1}{\lambda(T)} = \frac{\eta}{\beta} \left(\frac{T}{\eta}\right)^{\beta} \tag{8}\]

B(X) life is defined as the estimated time when the probability of failure will reach a specified percentage point (X %). The warranty time can be given for more than one year for a reliability factor of 0.9. Preventive maintenance is to be carried out by trained employees to prevent failures and increase the life of the wind turbine generators. By reducing the failure rate, the warranty time can be increased further; thereby, customer satisfaction and continuous improvement can be obtained. The B(X) life information gives the time in hours for different percentages of failure. In this wind farm, the percentage of failure varies from 1% to 30%. For example, 10% of failures occur at 9710 h.

### 5. Failure analysis

Failure is an event in which an item does not perform its required functions within the specified limits under specified conditions. Failure analysis is an attempt to determine the causes of failure. The number of failures over the years is shown in Fig. 10. In the year 2000, the frequency of failure is 6 which is low for a five year period. The failures in the year 2003 were 3.83 times more than in the year 2000. The higher frequency of failures in the year 2004 was due to blade failure. The number of failures in each year is not constant because of variation in external load conditions. These failures reduced the overall generation and caused excessive stoppage time.

Failures due to the blades, gearbox, hydraulic unit, yaw unit and brake pad are considered as mechanical component failures and those of the control panel, capacitor panel and generator failures are considered as electrical and electronic component failures. Failures due to mechanical components are 79% and failures due to electrical and electronic components are only 21%. It is inferred that
Table 2
Performance data of 3.735 MW wind farm.

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation (kWh)</td>
<td>7,246,119 (19.7%)</td>
<td>7,215,905 (19.6%)</td>
<td>7,480,740 (20.3%)</td>
<td>7,430,162 (20.2%)</td>
<td>7,480,229 (20.3%)</td>
<td>36,853,155</td>
</tr>
<tr>
<td>Generation Time (hrs.)</td>
<td>103,943 (20.1%)</td>
<td>101,625 (19.6%)</td>
<td>106,558 (20.6%)</td>
<td>100,694 (19.5%)</td>
<td>104,574 (20.2%)</td>
<td>517,394</td>
</tr>
<tr>
<td>Grid Failure Time (hrs.)</td>
<td>5924 (20.4%)</td>
<td>5963 (20.5%)</td>
<td>4796 (16.5%)</td>
<td>6165 (21.2%)</td>
<td>6216 (21.4%)</td>
<td>29,065</td>
</tr>
<tr>
<td>Low Wind Time (hrs.)</td>
<td>20,188 (20.0%)</td>
<td>20,126 (19.9%)</td>
<td>19,179 (19.0%)</td>
<td>23,409 (23.2%)</td>
<td>17,986 (17.8%)</td>
<td>100,887</td>
</tr>
<tr>
<td>Control panel failure Time (hrs.)</td>
<td>39 (10.9%)</td>
<td>91 (25.4%)</td>
<td>63 (17.0%)</td>
<td>107 (29.9%)</td>
<td>59 (16.5%)</td>
<td>358</td>
</tr>
<tr>
<td>Mechanical Failure Time (hrs.)</td>
<td>736 (31.3%)</td>
<td>634 (27.0%)</td>
<td>233 (9.9%)</td>
<td>268 (11.4%)</td>
<td>477 (20.3%)</td>
<td>2349</td>
</tr>
<tr>
<td>Preventive Maint. Time (hrs.)</td>
<td>547 (21.0%)</td>
<td>679 (26.0%)</td>
<td>354 (13.6%)</td>
<td>404 (15.5%)</td>
<td>621 (23.8%)</td>
<td>2607</td>
</tr>
</tbody>
</table>

Fig. 7. Percentage distribution of stoppage time in wind farm.
a wind farm experiences more failures due to mechanical components than electrical and electronic components. Reliable components and effective preventive maintenance procedure can reduce failures.

The percentage distribution of failures of mechanical and electrical and electronic components from the year 2000 to 2004 is shown in Fig. 11. The inflexibility of the blade rope and improper crimping, rubbing of the blade rope against its support and lack of lubrication of the rope resulting in its erosion, are the main causes of blade rope failure. Proper heat treatment of the blade rope will strengthen it. The force at a right angle to the plane of rotation, attempts to bend the blade back against the tower. The clearance between the rotor and tower depends on the distance between the blade tip and the tower at no load condition. Due to wind force, creep, shrinkage and temperature deformation cause the blade to bend backward over time. Tip deflection is caused by the interaction of dynamic loading and structural response. Care should be taken during designing, to avoid gearbox failure. The dynamic loading on gear teeth due to frequent interruptions of grid supply should be reduced. The high temperature developed in the gearbox, can be avoided by using good lubricants, and by adequately cooling the gearbox oil. Adequate stock of high quality gear oil should always be maintained for periodical replacement of the old oil. The nature of blade failures was blade tip failure, blade rope failure and blade cylinder failure. Inflexibility of blade rope and bending of
blade at high speed thus hit the tower are the causes of blade failure. It is suggested that manufacturers should take necessary steps to improve the design.

Sufficient cooling and constant air gap between the stator and rotor and proper alignment of the driver and driven shaft, and grid supply without tripping will reduce generator failure. By providing sufficient cooling and protection to electronic components, the life of the components can be increased. The yaw unit of wind turbines is subjected to dynamic load and fatigue load. The yaw unit is subjected to loads which can be eliminated by means of an extra set of bearings, so that all the radial loads are led directly to the nacelle frame. The life of the WTGs can be increased by proper maintenance and good controls.

6. Pareto analysis

The Pareto diagram is one of the seven quality circle tools used to solve problems, to classify data, and to rank categories in the descending order of occurrence to separate significant categories from trivial ones. It helps in prioritising the different categories taken into account for analysis. This also helps in identifying the minimum number of factors required to fulfill a function from a lot. An added advantage is, getting the percentage reduction in the overall scenario when reduction is carried out in one or two of the factors. Even though one may want to solve all the problems, it may not be possible in reality. Hence, prioritisation is essential. All the problems identified have to be categorized in terms of the extent of damage they cause to the system. The percentage values can be used to find out the percentage reduction in the overall problems, when one or two of the prioritised problems are solved.

Pareto analysis has been carried out in this study to prioritise the vital factors which caused failures in the system. This analysis was extended to find out the reduction in problems, when one problem is tackled partially or completely. These failures reduce considerably, the availability of the wind farm and its generation. By tackling a few vital failures, failure time can be minimized to a great extent. Pareto analysis has been done for four vital components of WTGs such as the blade, gearbox, hydraulic unit and yaw unit, and the frequency of failures is shown in Fig. 12. It reveals that in five years of operation, the frequency of failure of these components was 26.92%, 25%, 25% and 23.08%, respectively. Among these mechanical components, the frequency of blade failure is high during the five years of operation. The Pareto diagrams of the condition, after 50% of the problem is solved, are shown in Fig. 12b–e. If 50% of blade, gearbox, hydraulic unit and yaw unit failures are removed, the overall reduction in failure will be 13.46%, 12.5%, 12.5% and 11.54% respectively, which is quite significant.

7. Spare parts analysis

Scientific spare parts management is of vital importance in wind turbine maintenance, where huge investments are made on spare parts. Any delay in replacement of failed components will result in a huge loss of power generation. By maintaining an optimum number of spares, the availability of the wind farm can be improved. So, a scientific spare parts optimization study was undertaken, and is presented in this section.

The spare parts optimization technique helps us to arrive at the optimum number of spare parts, by striking a compromise between over-stocking of spare parts involving heavy expenditure and under-stocking of spare parts, running the risk of non-availability of spare parts. The spares optimization of wind turbine generators is very essential for ensuring high operational readiness. With an increase in the basic quality level of the components, the repair rate can be reduced considerably.

Based on the collected data it was understood that certain policy decisions have to be taken to arrive at the various factors, viz. risk, replacement period and inventory procedure, that were required for the analysis. The failure rate is the main driver for the spare parts analysis. The failure rate was calculated using Weibull software for four vital mechanical units of WTGs and finally converted into failure per million hours for easy compatibility with the software calculation. For this study the software package on spare parts optimization, “Spare” was utilized. Inputs like failure rate, risk, unsupported period, and average utilization were fed into the spare software and the number of required spare parts was obtained. The spare parts analysis has been done for four vital units of the wind farm such as the blade, gearbox, yaw and hydraulic units.

7.1. Risk % analysis

A major risk in stocking spare parts is an insufficient spare parts during the unsupported period to meet the demands due to component failure. This risk is fixed by engineering judgment based on previous experience and non-availability of components. Taking
the following factors into account, the probability of risk can be assessed.

1) The cost of items going down while more spare parts are procured.
2) The possible long delay if more spare parts have to be procured (specialized spare parts may be unobtainable after an initial production run).
3) The importance of maintaining good customer relationship.

The spare holding is determined for three different risks individually, for comparison and better understanding. A single risk cannot be decisive as it involves many policy decisions to be taken at various management levels of the wind energy industry. Hence the risks of 90%, 80% and 70% are chosen to arrive at the results with marked differences in the total spare parts requirements, so that comparison can be easily made between the various risks.

7.2. Unsupported period (days)

This is the expected operational period of wind farms during which no replenishment of spare parts is needed. In other words, it is the period starting right from initiating the indent of requirement of a spare, to the actual time of receipt of the spare parts from a source. This has a direct bearing on the total number of spare parts required. As the unsupported period increases, the spare parts requirement also increases. The unsupported period can be between 1 and 999 days. In this study it is taken as 45 days, based on previous experience.

7.3. Average utilization (%)

This is the average percentage of time for which the wind farm is operational. The average utilization percentage is taken as 100% as
there is always a demand for continuous power generation from wind farms.

7.4. Spare parts requirement

An optimized spare parts requirement is essential for quick replacement of failed components to avoid loss of power generation. The optimization is done for 45 days of unsupported period and 100% average utilization. The risks on the operation of wind farms have been considered at three levels of 90%, 80% and 70% and spare parts requirements have been determined. The required number of spare parts for 15 WTGs is shown in Table 3.

In the case of 90%, 80% and 70% risk, the spare parts requirement was 10, 8 and 5 respectively. It was found that the requirement of gearbox bearing was the highest in comparison with the requirement of other sub-components. It was observed that when risk decreases, the requirement of spare parts also decreases. In order to increase wind farm availability, necessary steps are to be taken for
optimum periodical maintenance. In this spare parts analysis the optimum number of spare parts required was determined to maintain minimum shutdown period and to increase power generation. This spare parts analysis will be very useful for the effective maintenance of a wind farm.

8. Financial implications on failures

The failure and its financial implication are analyzed to determine the loss of power generation, consequential cost of failure, repair cost and return on investment. This wind farm is operated for 79% of total time and produced 36.8 million kWh during five years. The total stoppage time due to various failures including low wind speed period is 140,326 h during five years of operation. The low wind speed is considered as one of the critical stoppage parameters of the wind farm. Due to low wind, the loss of power generation was 7.2 million kWh and its consequential financial loss was Rs. 33 million. It is an indication that the wind speed plays a vital role in the selection of right location. It is recommended that the periodical maintenance can be arranged during the periods of low wind. The critical stoppage parameters, stoppage time, loss of power generation due to repair are depicted in Table 5. The repair time caused generation loss of 0.111 million kWh which also led to revenue loss to an extent of Rs.0.51 million. In the case of blade failure, if the blade failure is eliminated completely, the power generation can be improved to an extent of 0.21% and the return on investment will also be increased.

Table 4
Loss of power generation and consequential cost due to stoppage.

<table>
<thead>
<tr>
<th>Critical Stoppages parameters</th>
<th>Stoppage time in five years of operation (h)</th>
<th>Loss of power generation in million (kWh)</th>
<th>Consequential cost of failure in million Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low wind</td>
<td>100887.90</td>
<td>7.2</td>
<td>33.0</td>
</tr>
<tr>
<td>Grid failure</td>
<td>23065.01</td>
<td>2.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Control panel failure</td>
<td>358.00</td>
<td>0.025</td>
<td>0.11</td>
</tr>
<tr>
<td>Electrical failure</td>
<td>2349.78</td>
<td>0.17</td>
<td>0.77</td>
</tr>
<tr>
<td>Mechanical failure</td>
<td>5056.73</td>
<td>0.36</td>
<td>1.66</td>
</tr>
<tr>
<td>Preventive maintenance</td>
<td>2607.64</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>140326</td>
<td>10.045</td>
<td>45.9</td>
</tr>
</tbody>
</table>

[Note: 1 USD = Rs. 48.00].

Table 5
Loss of power generation and consequential cost due to repairs.

<table>
<thead>
<tr>
<th>Critical mechanical component</th>
<th>Repair time/repair in five years of operation (h)</th>
<th>No. of repairs</th>
<th>Loss of power generation due to repair in million (kWh)</th>
<th>Consequential cost due to repair in million Rupees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade cylinder</td>
<td>72</td>
<td>10</td>
<td>0.051</td>
<td>0.24</td>
</tr>
<tr>
<td>Bearing</td>
<td></td>
<td></td>
<td>0.021</td>
<td>0.09</td>
</tr>
<tr>
<td>Gear box bearing</td>
<td>25</td>
<td>6</td>
<td>0.011</td>
<td>0.05</td>
</tr>
<tr>
<td>Hydraulic spring</td>
<td>50</td>
<td>8</td>
<td>0.028</td>
<td>0.13</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>0.111</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 6
Components failure and replacement cost for 15 wind turbine generators.

<table>
<thead>
<tr>
<th>Components</th>
<th>Sub-components</th>
<th>No. of failures</th>
<th>Total replacement cost Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade</td>
<td>Blade up</td>
<td>2</td>
<td>3,800,000</td>
</tr>
<tr>
<td></td>
<td>Blade rope</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Blade cylinder</td>
<td>10</td>
<td>300,000</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>14</td>
<td>4,102,000</td>
</tr>
<tr>
<td>Gear box</td>
<td>Shrink disc</td>
<td>2</td>
<td>36,358</td>
</tr>
<tr>
<td></td>
<td>Gearbox shaft</td>
<td>1</td>
<td>31,949</td>
</tr>
<tr>
<td></td>
<td>Gearbox support</td>
<td>1</td>
<td>4900</td>
</tr>
<tr>
<td></td>
<td>Pinion</td>
<td>1</td>
<td>13,000</td>
</tr>
<tr>
<td></td>
<td>Bearing</td>
<td>6</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td>Fan cooling</td>
<td>1</td>
<td>475</td>
</tr>
<tr>
<td></td>
<td>Gear oil seal</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>13</td>
<td>102,182</td>
</tr>
<tr>
<td>Yaw unit</td>
<td>Spring</td>
<td>1</td>
<td>365</td>
</tr>
<tr>
<td></td>
<td>Bearings</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Pinion</td>
<td>5</td>
<td>60,000</td>
</tr>
<tr>
<td></td>
<td>Look screw</td>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Bed Bolt</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>12</td>
<td>62,665</td>
</tr>
<tr>
<td>Hydraulic unit</td>
<td>Damper bush</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Filter</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Burst disc</td>
<td>1</td>
<td>5500</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>8</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>Accumulator</td>
<td>2</td>
<td>30,000</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>13</td>
<td>37,290</td>
</tr>
<tr>
<td>Others</td>
<td>Brake pad</td>
<td>8</td>
<td>32,000</td>
</tr>
<tr>
<td></td>
<td>Control panel (MCCB)</td>
<td>6</td>
<td>106,800</td>
</tr>
<tr>
<td></td>
<td>Capacitor panel</td>
<td>3</td>
<td>22,500</td>
</tr>
<tr>
<td></td>
<td>Generator</td>
<td>5</td>
<td>62,500</td>
</tr>
<tr>
<td></td>
<td>Anemometer</td>
<td>2</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>24</td>
<td>233,800</td>
</tr>
<tr>
<td></td>
<td>Over all failures</td>
<td>76</td>
<td>4,537,937</td>
</tr>
</tbody>
</table>

Source: Log book maintained at Muppandal wind farm in Tamil Nadu.
increased to an extent of 0.28%. The components failure and replacement cost for 15 wind turbine generators are represented in Table 6. The total replacement cost for 76 failures of 15 WTGs is Rs. 4,537,937. About 80% wind turbine components are used by indigenous components such as anemometer, gear box, yaw unit and control card. The turbine requires periodic attention and proper maintenance for trouble free operation. By improving the electricity network and adopting planned maintenance during periods of low wind could reduce tremendous amount of loss of energy and cost.

9. Conclusion

The performance, reliability, failure and spare parts analysis of a wind farm were carried out in this paper. An effort was made in the present study to estimate the reliability of a wind farm using Weibull distribution as a measure of performance. The different types of failure and the causes of failure were determined. In order to increase the availability of wind turbine generators, spare parts analysis was also done to determine the optimum number of spare parts required at the wind farms. Important conclusions drawn from the present analysis are as follows.

- The performance analysis reveals that the technical availability was found to be 94%, real availability was 82.88%, and the capacity factor was 24.9%.
- The reliability analysis reveals that the reliability of this wind farm was high during the first year of operation and with time it decreases drastically beyond economical viability and is reduced to 13% at the end of the fifth year of operation.
- Pareto analysis reveals that if blade unit problems are solved completely, 26.92% of the total problems will be reduced and if 50% of blade failure, gearbox failure, hydraulic unit problems and yaw unit failures are removed, the overall reduction in failure will be 13.46%, 12.5%, 12.5% and 11.54% respectively.
- In this spare parts optimization study it was found that at 90%, 80% and 70% risk, the number of spare parts required for a wind farm was 10, 8 and 5 for an unsupported period of 45 days. It is hoped that these studies will be useful for WTG manufacturers and policy makers for the sustainable development of wind energy in India.
- The failure and its financial implication revealed that if blade failure is eliminated the power generation will be improved to an extent of 0.21% and the increase in return on the investment will be 0.28%.

References