Reliability Analysis of a Horizontal Axis Wind Turbine

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Abstract

Wind is one of the cheapest and cleanest sources of energy. However, large and frequent fluctuations in wind intensity and directions cause serious problems in harvesting this energy. Wind turbines are subjected to many limiting conditions, which lead to their failure or degraded performance. Therefore, reliability is a very important parameter that governs the overall performance of wind energy system. This paper describes a methodology for the reliability and availability analysis of a horizontal axis wind turbine. The discussed methodology is used to conduct reliability and availability analysis of AOC15/50 wind turbine, which is widely used in Atlantic Canada and USA.

The methodology comprises of four steps. First step involves assessment of failure modes using Failure Mode and Effect Analysis (FMEA) approach. Subsequently interrelationship among different components is deduced and represented using event tree analysis technique. Later based on operational characteristics, environmental condition (load), and failure characteristics reliability of each individual component is computed. Finally, Knowing the interrelationship and reliability of each components, reliability of complete system is assessed using fault tree analysis. Having maintainability characteristics known this procedure is repeated to calculate availability. Paper also includes discussion on 3 state Markov analyses for wind turbine system. It helps modeling degrading and total failure scenarios leading to better estimation of overall availability of the system round the year or during lifetime of system.

Keywords: Wind turbines, renewable energy, reliability analysis, failure analysis, reliability engineering.

1. Introduction.

Due to a rapid increase in wind energy use and related industrial activities, demands for introducing a easy to understand reliability assessment method for small and large wind turbines have increased. Wind turbines are designed in accordance with the deterministic design rules. These rule concern the design of main components e.g. blade, tower, hub and controller system. Some time the operating conditions are harsh due to external working environment (high wind etc). These increased loads have a significant impact on the system reliability as whole. The reduced reliability of the system after sustaining a storm can lead to sever damages during normal operating conditions in future. AOC 15/50 have been used in areas of Atlantic Canada where high winds are a regular phenomenon.

The objective of this paper is to present and describe a computational method for the reliability assessment of major components of AOC 15/50. The methodology applied in this study can be used in further studies to perform a similar analysis for a complicated wind turbine system. The analysis will be performed for both normal operating conditions as well as for sever weather condition keeping in consideration the weather profile of one specific area i.e. Newfoundland. Both qualitative and quantitative analysis will be performed, the first one is also known as FMEA, which will determine the cause and severity of a component failure. Task of quantitative analysis is strictly based on the operating conditions, loads, lifetimes and operating time of those specific components and can give beforehand information on the reliability and availability during the life of system. This method is compatible with existing international safety and reliability standards IEC 61400 and is frequently used by designers, manufacturers and certification institutes for wind turbine systems.

2. Reliability in Wind Engineering.

Methods of reliability engineering for wind technology are same as in any other process industry, however the approach presented by every researcher is always different with regards of work and scope of study. Study by A. J Seebregts et.al [1] develops an approach towards the collection of data from field and then implementing a block diagram model for normal working conditions and emergency situations. The emphasis is laid on event tree analysis keeping in view specific events that will contribute to potential failure scenarios. That Paper established the Mean Value Approach (MVA) toward the study and collection of all the parameter especially the stochastic variables like wind and lift coefficients. Keeping all the parameters mutually independent, reliability integral function was established which has a normal distribution. The stochastic variables and their effects on MVA are analyzed in depth and hence sampling patterns of data are brought under discussion. Assessment and reliability analysis of protection and control system of wind turbine is presented by D. Michos et.al [2]. Paper establishes a general definition of control and protection system and how it is integrated into different components like sensor, relays and break assembly itself. Event tree analysis is being done and a reduced version is presented in paper in order to give a clear sequence of events that will lead to an eventual failure of over-speed protection system. Other studies in this area also present similar kind of works, but in a perspective of a whole wind farm and its power production.

The focus of the current study is to explore the applications of reliability analysis of a wind turbine system on a component basis, which so far has not been researched in detailed. Reliability estimation approach is discussed with different assessment criteria for various components depending upon their working environment. Emphasis is on developing a generic reliability model for a simple wind turbine system like AOC15/50 hence providing hands on approach to researchers and manufacturers for assessment of a lifetime of a stand-alone system with minimum available data. Fault tree analysis and Markov analysis is performed for modeling the degraded performance if a certain component fails. All the data used is acquired directly from the literature from different source.

3. AOC 15/50 - System description.

The 50-kW AOC 15/50 is an improved and simplified version of the Enertech 44/60 wind turbine developed in the United States in the early 1980s. The downwind, stall-regulated, three-bladed turbine features passive yaw control, wood epoxy composite blades incorporating NREL-designed airfoils, aerodynamic tip brakes, an electrodynamics brake, and an integrated drive train. This turbine is well suited for remote, stand-alone applications, village power systems, and small wind power plants.

The AOC 15/50's integrated drive train eliminates many critical bolted joints found in conventional turbine designs and creates an efficient load path from the rotor to the tower top. A cast-steel, tower-top plate further improves the efficiency of the load path. The new drive train design weighs less than conventional drive trains and eliminates maintenance-prone couplings between the gearbox and the generator. Other design features include tip brakes and an optional yaw damper. The optional yaw damper, a passive hydraulic system that limits yaw rates (and gyroscopic loads), is available for turbulent wind sites. A system diagram from manual is as follows:

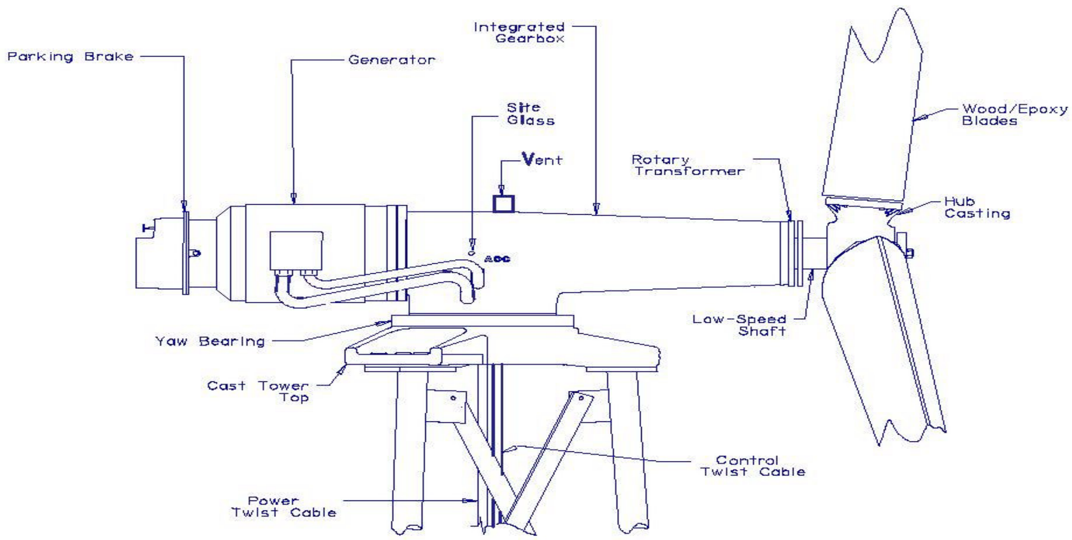


Fig-1: AOC 15/50. (et a [3] AOC15/50 Manual)

Components crucial to the system integrity are selected, for which the reliability analysis will be performed Fig-2. The following diagram also clarifies the interrelationship of the components and how they contribute towards the proper functioning of the system.

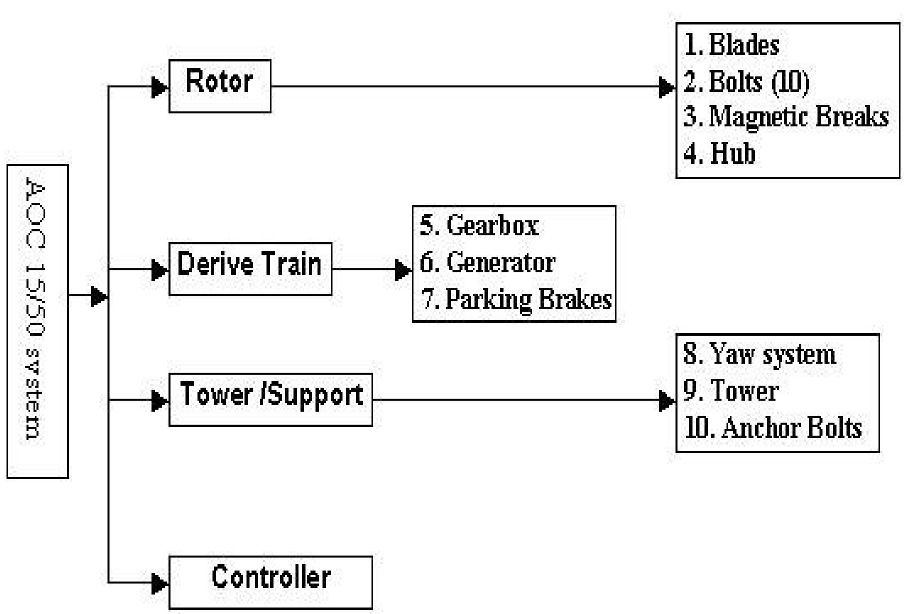


Fig-3: System block diagram

4. Methodology.

Methodology adopted for this study is underlined in a flow chart Fig-3. Methodology comprise of four main steps which are conducted in sequence shown in figure-3. Further details of these steps and results are discussed in subsequent section of this paper.

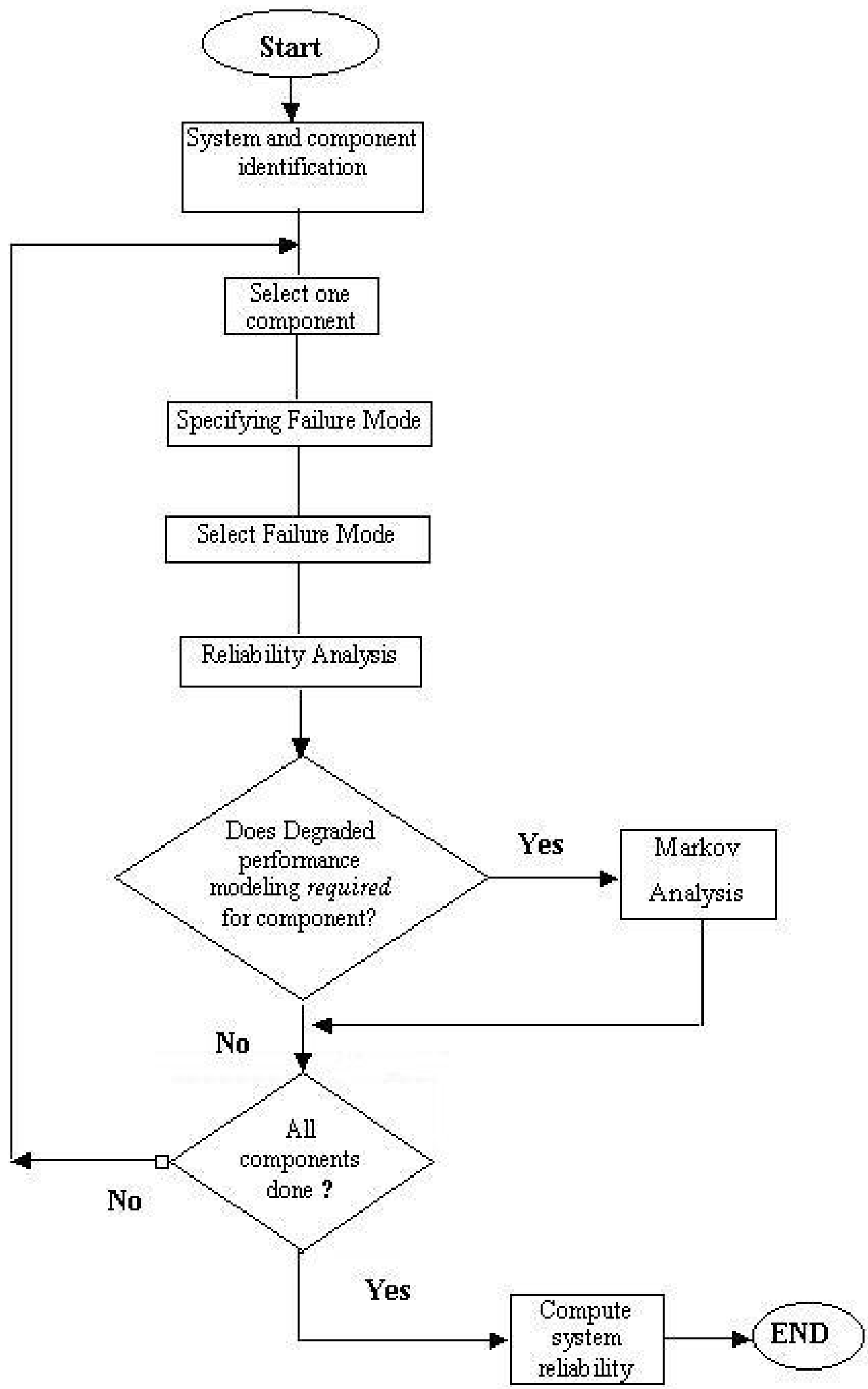


Fig-3: Flow Chart of tasks.

5. Reliability Models.

5-a: Component identification.

The very first step in the reliability assessment is the identification of failure modes of the system. Wind turbine system under consideration can be divided into many components for analysis. The basic problem is to define a level of sub-dividing a system into a finite number of elements. The increased number of elements will pose more problems in terms of collection of real data and some assumptions have to be made. Assumptions in case of parameters such as ***mean time to fail (MTTF)*** can easily create undesirable and misleading results, which will lead to a false reliability calculation. To keep the analysis accurate, the system is divided into the following basic components. Sub division of these components further is possible but not adopted due to unavailability of data. The relationship (series or parallel) between these components will affect the reliability of the entire system. Four basic structural areas are specified and components in that area are listed in figure –2 are as under:

- i) Blades.
- ii) Bolts.
- iii) Magnetic/Aerodynamic breaks
- iv) Hub.
- v) Gearbox.
- vi) Generator.
- vii) Parking Breaks.
- viii) Yaw Bearing.
- ix) Tower.
- x) Anchor Bolts.
- xi) Controller and Constituent components.

A single AOC15/50 turbine unit consists of above listed ***major*** components considered for this study. Providing redundant components sometime enhances system inherent reliability. However in case of wind turbines in general, due to the limitations of cost and space it is not possible. The only component that is redundant is the blade, but here blade redundancy is not related to reliability rather it behave as a separate component. Table –1 will outline a Failure Mode Effect Analysis of the whole system, describing component's mode, cause and effects of failure.

5-b: FMEA.

Table –1: Failure modes, Causes and consequences

No.	Component	Failure Modes	Causes	Consequences
1	Blades.	Fatigue failure	Overloading due to wind load.	If any of blades fail, whole system will fail.
2	Gearbox.	Random failure /Over- speed	Increased wind speed.	Complete failure or the system will result in failure of this component.
3	Generator.	Random failure/ Over speed.	Over speed due to disconnection from Grid. (No Load)	No generator, no electricity. So it will be a complete failure.
4	Brakes (parking)	Fatigue failure	Continuous usage to stop.	If Breaks are unable to perform, a serious damage can happen in emergency situations when turbine is needed to be parked.
5	Breaks (Aerodynamic)	Fatigue.	Magnet failure, DC voltage failure or	Failure can cause two problems, if open during

			controller relay failure.	normal operation during normal speed; the system will deliver a degraded performance. If didn't work in over-speed conditions, can cause blades to brake or serious structural damage to blades due to high speed.
6	Tower.	Fatigue	High-speed winds fatigue or over speed of rotor can cause excessive thrust on tower.	Total collapse of structure and hence failure.
7	Yaw Bearing.	Fatigue.	Roller bearing problems or lubrication maintenance.	Degraded performance as the angle of attack for wind will not be correct, Nacelle can fall down if alignment is lost.
8	Bolts (Hub – blade) 10 each.	Shear failure.	Increased wind speed during operation or parking can cause excessive shear on any of bolts.	Systemic degradation of support of blade that later can cause detachment during operation.
9	Hub	Fatigue	Constant stress on flanges can result in a crack.	Will result in detachment of blade if operation continues.
10	Controller.	Random failure	Any of components may fail at any time.	PLC failure will result in no monitoring and can be catastrophic if not checked; Failure of circuit bakers can result in disruption of power supply to and from the system.

5-c: Failure Models.

Reliability analysis of any component can be done once data is known. However to select a failure model is in itself a task. Here due to different individual working environment, the components are analyzed considering their working environment. For some components working loads and conditions remains the same no matter how much they work and hence are governed ***Random failures***. Three main components modeled on random failure basis are generator, gearbox and controller. However some components, as they start their life in service start constantly wearing out. Such components have to be modeled on basis of time dependent failure data.

There are two most commonly used time dependent distributions that can be used that are ***Lognormal*** and ***Wiebull***. Both are characterized by the same principles but have different distribution parameters. Wiebull model is more appropriate then the lognormal model because its ability to address most of the failure and fatigue data distribution.

The two parameters in Wiebull distribution are β and θ, the ***shape parameter*** and ***characteristic life*** or ***scale parameter*** respectively. Shape parameter by its name defines the shape of the distribution should be 1<β<3. 1>β>3 are not desirable as the first signifies significant improvement in reliability with time (infant mortality) and the second as normal distribution, which are not desirable to analyze a physical system. For the intermediate values of β the distribution is positively skewed. Almost all components in industry follow a positively skewed distribution function for the reason that they survive a viable lifetime before they fail. If they follow a normal probability density function half of them will fail and half will not, as normal distribution is symmetric about the mean value. The ***scale parameter*** on the other hand influences both the mean and the spread/ dispersion of the distribution function. As θ increases the reliability increases at a given point in time or visa versa. This method is used for parking breaks; tip breaks and yaw bearing in this study. For better understanding the behaviors is explained in following table;

Table-2: Wiebull Shape Parameter *β*

Values	**Property**
0<β<1	Decreasing Failure rate DFR
β =1	Exponential Model or Random Failures
1<β<2	***Increasing Failure rate IFR***
β=2	Linear Failure: Rayleigh Distribution Model
β>2	***Increasing Failure rate IFR***
3≤β≤4	FR Values approach Normal distribution

Components, which are not governed by either of the above distributions and are subjected to excessive stress, are analyzed by physical reliability model involving static reliability at any instant of time. These static values are then modeled for periodic loads for dynamic reliability of the component. This method is very effective and important for accessing structural components under constant load and can be applied in this case to blades, blots connecting blades, Hub, tower and anchor bolts. For modeling the ***load*** and stress on these components the load distribution is taken to be lognormal.

5-d: Bathtub Curve.

The bathtub curve is a result of composition of several different distribution patterns as can be seen from the following diagram:

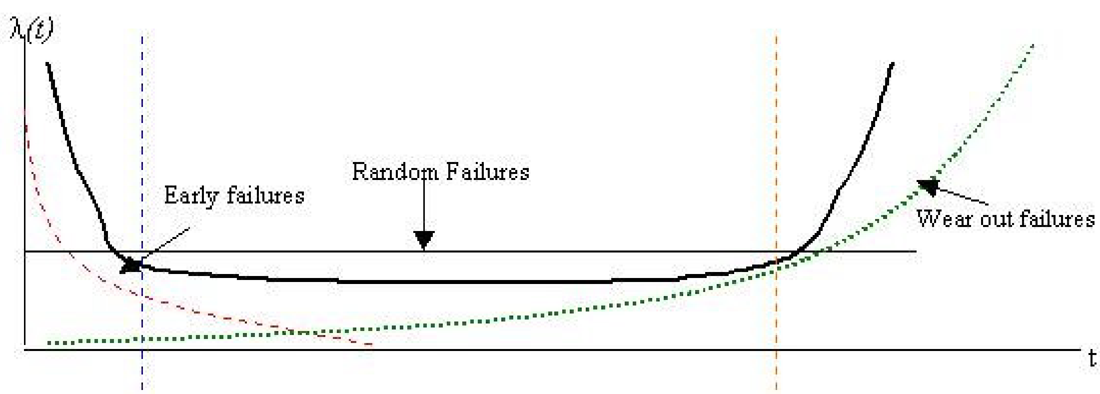


Fig –4: Bathtub curve and failure regions.

The red colored pattern in Fig-4 above depicts an infant mortality of components, black straight line indicate a constant failure rate when the component have crossed the early life stage and finally the green the wear out period of life. Early or burn in failures are not of interest as the components have to be tested for that time in industry and haven't failed, however the rest of two patterns will be useful. As discussed above the not all components are in the same working environment and do not follow a same failure pattern, some fail randomly and some are in wear out region since their first installation. Similarly some components may follow a random failure while other a wear out failure pattern. As wear out is time dependent so it will be modeled using a Wiebull failure distribution while random failures will be as exponential distribution. Based on discussion in Table-1, the distribution model to be used for each component is as under:

Table-3: Reliability models used for components.

No	Component	Failure Mode	Reliability Analysis method.
1	Blade	Fatigue	Physical Reliability models
2	Gearbox	Random	Random failure model
3	Generator	Random	-do-
4	Brakes (Parking).	Fatigue	Wiebull reliability model
5	Breaks (Aerodynamic)	Fatigue	-do-
6	Tower	Fatigue	Physical Reliability models
7	Yaw bearing	Fatigue	Wiebull reliability model
8	Bolts 10/blade	Fatigue	Physical Reliability models
9	Hub	Fatigue	-do-
10	Controller	Random	Random Failure model.

6. Reliability Analysis.

***6-a: Reliability Model Block Diagram*.**

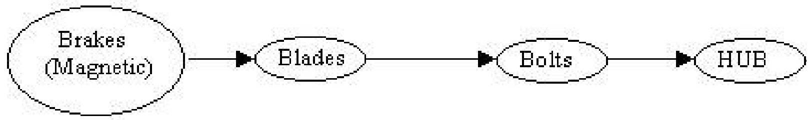
As per description of the system components, it is clear that no component is redundant. This will imply that all components are in series configuration, signifying that failure of a single component will lead to a complete failure of the whole system or will result in a degraded performance. However the system can be divided into four major areas for the ease of analysis.

i) Blade Assembly.
ii) Derive train.
iii) Tower and supports.
iv) Controller.

We can take the subcomponents of these three areas and put them in a block diagram according to reliability modeling principles.

i) **Blades Assembly**:

Blade assembly can be put into three for four different parts, Blade, Aerodynamic Breaks, Bolts and Nuts, and pitch mechanism if any. Now failure of any of these components will completely or partially fail the whole system.



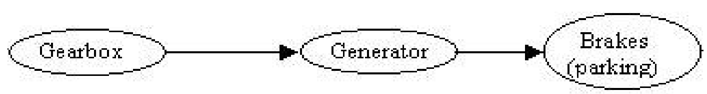
$$R_{Rotor} = R_{brake\text{-}Mag} \times R_{blade} \times R_{bolts} R_{HUB}$$

Fig –5: Rotor components in Series.

There are 10 bolts in total on one blade and 3 blades. All of the blades will be considered as separate components in series as failure of one will result in the failure of whole system, however two different systems of 5 bolts can be considered for bolts are parallel or load sharing system.

ii) **Derive Train**.

Derive train is custom build by AOC however the components are from different manufacturers, Generator is made by **Elliot MagneTek, California**, it has a two stage planetary gear system custom made by **Fairfield manufacturing Co.**, brakes are from standard product line of **Stearns 81000 series** disk/parking brakes. This part contributes to the center of all generation and transmission activity and can play crucial role in the system reliability. There is no redundancy in this sub-section so all of the component will be in series.

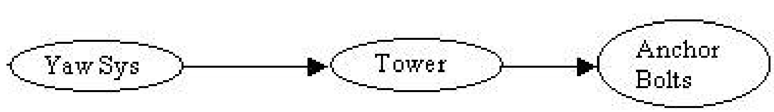


$$R_{D\_train} = R_{Gearbox} \times R_{Generator} \times R_{Brakes\ Assembly}$$

Fig-6: Drive Train in series.

iii) **Tower and Support**.

Tower and support include two different components, Yaw baring mechanism and tower components. It is one big roller bearing, which is fixed with tower top. This mechanism is passive in nature and is not driven or control by any motor, so that the turbine will automatically orient itself in the direction if wind. Tower is of Galvanized steel with three legs and certain number of Truss-members on each section. There are 4 sections of tower 6 meter each and 900Kg/section. However given the structure of tower and time limits forces on each and every member cannot be analyzed, as it will out of the scope of this study however it can be accomplished by a detail ***finite element analysis*** of the whole tower. Tower is considered as one component, yaw mechanism as one and support that will include system of anchor bolts. Anchor bolts will themselves be a system of 3 series system components as failure of one-leg can induce vibrations and that can lead to toppling of the whole structure in high winds only.



$$R_{Support} = R_{Yaw\_sys} \times R_{Tower} \times R_{Anchor\text{-}Bolts}$$

Fig-7: Tower and Support components in series.

Failure tower can also be represented as a common mode failure to the whole system as failure of tower will be failure of the whole system. After looking into the reliability block model of these sub-systems we can now compute the whole reliability block diagram of the system as follows.

$$R_{SYS} = R_{Rotor} \times R_{D\_Train} \times R_{Support} \times R_{Controller}$$

6-b: Reliability Model of Components.

Reliability can be defined in many ways, the simplest definition would be the probability that a component or a system will function over some period of time *t* when used under stated condition. If T be the continuous random variable to be the time to failure of the system (component); $T \geq 0$. Then reliability can be expressed as follows;

$$R(t) = \Pr\{T \geq t\} \qquad \text{(i)}$$

For a given value of ***t***, R(T) is the probability that the time to failure is greater or equal to ***t*** also known as *Reliability function*. If we define F(t) as follows, then F(t) is the probability that the failure will occur before time ***t*** it is also called *cumulative distribution function*.

$$F(t) = 1 - R(t) = \Pr(T < t) \qquad \text{(ii)}$$

Another function that describes the shape of the failure distribution is knows as *probability density function* is specified by the following relationship.

$$f(t) = \frac{dF(t)}{dt} \qquad \text{(iii)}$$

In addition to the reliability function defined as above, there is another function that plays an important role in analysis and often available as a numeric value for different components. From figure –4 we can see the transition effect on failure rate with time in the life of a system (component).

$$\lambda(t) = \frac{f(t)}{R(t)} \qquad \text{(iv)}$$

As discussed in Table –1 & 2, the specified reliability models will be used for the reliability computation from the available data (failure rate or available parameter values) for different reliability models. As the first step the components assessed are governed by the Random failure model.

i) Random Failure Model.

As discussed previously that random failure model have been used for only those components that are not affected by workload and environment in which they are working and failure is due to completely random or chance events. This model is also referred to as CFR (constant failure rate) or exponential model. In this study this model is applied to the analysis of three major components Generator, Gearbox and Controller (PLC). Failure rate for these components are used from reliability date book et al [5].

- ***Generator.***

Failure rate = $\lambda(t)$ = $\mathbf{0.796 \times 10^{-6}}$ **/ hr**.

Estimating the reliability using CFR for; t = 1 yr => 8760 hrs.

$$R(t) = e^{-\lambda t} \qquad \text{(v)}$$

$$R(t) = 0.99305$$

- ***Gearbox.***

Failure rate = $\lambda(t)$ = **0.63 x 10 $^{-6}$ / hr**.

Similarly; t=1 year => 8760hrs. Using (v)

R(t) = 0.9944

- ***Controller.***

Failure rate = $\lambda(t)$ = 0.25/ year provided in Lees [11];

$\lambda(t)$ =2.85 x 10^{-5}/hr. t=8760 hrs

R (t) = 0.77906

ii) Time dependant Reliability Model.

Time Dependent reliability model used is Wiebull distribution model. The calculation of reliability for this model depends on availability of two model parameters as stated in the discussion above, θ and β. This model is applied to three components, which are Yaw bearing, Parking breaks and aerodynamic magnetic brakes. In case of yaw bearing the parameter values are given in a separate reliability database et.al [4]. These values are used in conformity with the working condition of yaw bearing.

- ***Yaw Bearing*.**

Data available for Roller bearing (yaw bearing et al [4]):

β = 1.3.

θ = 50,000 hrs.

The hours of operation account for continuous working of any component, the Wiebull reliability model used for analysis;

$$R(t) = \exp -(\frac{t}{\theta})^{\beta} \qquad \text{(vi)}$$

For t = 1 yr = 8760 hrs

R (8760) = 0.9013

The ideal values of reliability for a given time can be seen from the following table.

Table –3: Yaw bearing R (t)

t (yrs)	R
30	0.000017
10	0.1258
5	0.438
3	0.6438
2	0.77428
1.5	0.8386

- ***Aerodynamic Tip Breaks.***

The parameters for the yaw bearing were known and used directly as they were provided, however in the case of breaks (parking and aerodynamic) this is not the case. The data provided is the failure rate and one of the parameters has to be assumed on the basis of discussion made in section of 5-c of this paper. In following it is shown how the available data (failure rate) is manipulated in to required parameters for the next two components.

The failure rate is provided by RAC- NERPD-95 [5]

$\lambda(t)$ = 100.00 x 10 $^{-6}$ /hr.

$$\text{MTTF} = \frac{1}{\lambda} \qquad \text{(vii)}$$

MTTF = 10,000 hrs

For Wiebull reliability model, relationship given by et.al [6] is as under, where MTTF is Mean Time to Failure for any given component;

$$\text{MTTF} = \theta\,\Gamma(1 + \frac{1}{\beta}) \qquad \text{(viii)}$$

With reference to the discussion in section 5-c and from the table-2 provided in et.al [6], a suitable value of β will be selected for both remaining components.

A suitable value range from 1.1 to 2.9 ***excluding*** β ***=2*** for an increasing failure rate; value chosen for Aerodynamic break is $\beta = 1.85$.

From (viii) computing the value of θ; when Γ(x) provided in the tables in et.al [6],

$$\theta = 11258.99 \text{ hrs} \cong 11260 \text{ hrs (approx).}$$

Wiebull reliability model from (vi) gives the reliability t = 8760 (1 year).

$$R(8760) = 0.5334$$

- ***Parking Break***

The analysis for parking break will proceed in the same fashion as above. FR is used from the same resource.

$$\lambda(t) = 2.10 \times 10^{-6} \text{/hr.}$$

$$\text{MTTF} = \frac{1}{\lambda} \qquad \text{from Eq. vii}$$

$$\text{MTTF} = 429.962 \times 10^3 \text{ hrs}$$

Assuming $\beta = 2.2$ as IFR, using Eq. (viii), $\theta = 537688.756$ hrs. A 1-year reliability estimate will yield;

R (t) given; t = 8760.

$$R(t) = 0.999$$

iii) Physical reliability Models.

In many situations it is not appropriate to assume that the reliability is merely a function of time as in the case of all remaining components under discussion. These components experience unusual stress during normal operation and their proper functioning and life depends on their periodic loading. Development of a *static model* from the available distributions will be the first task as stated in et.al [6]. These static models find the point reliability at any instant of time under stress; afterwards this model is subjected to periodic loading, which is described in reliability literature as *dynamic modeling.* Model used in this study for static modeling is know as " Constant Strength and Random Stress" model. In a simplistic way this model can be stated as under as given in [6];

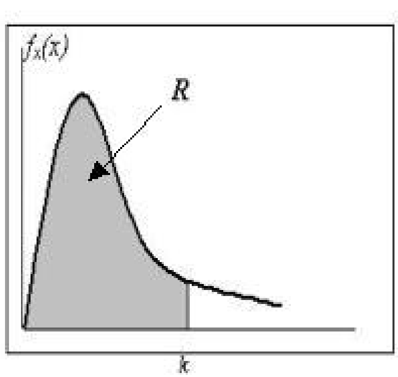


Fig – 8: Reliability of a component under a random load with fixed strength

If the system/component strength is a known constant ***k***, and stress is a random variable with PDF as defined under, then the system's static reliability can be defined as *the probability that stress does not exceed strength value k*. That is;

$$R = \int_0^k f_x(x)\,dx = \boldsymbol{F}_x(k) \qquad \text{(ix)}$$

Specific stress distribution is required for static reliability modeling. In this paper all the stress are taken to be lognormally distributed, as given in [6] by the following expression:

$$R = \phi\left(\frac{1}{s}\ ln\ \frac{k}{x_{med}}\right) \qquad \text{(x)}$$

Where *s* is shape parameter taken to be ***s = 0.1*** in all cases. Additional relation ship that will help in the analysis is given in [6] as;

$$x_{mode} = x_{med} / \exp(s^2) \tag{xi}$$

Where x_{mode} is the mode value of load acting most of the time for a specific situation (normal operation or in a storm conditions). In the following the analysis is performed for blade, bolts, hub, tower and anchor bolts.

- ***Blades.***

Moments on blade can only be found out from the total thrust produced by the rotor disk J.F Manwell [7]. The thrust on the disk is given as;

$$T = C_T \frac{1}{2} \rho \pi R^2 U^2 \tag{xii}$$

Where;

C_T = Thrust coefficient (8/9 for rigid rotor assumption)

ρ = Density of Air.

R = Radius of Rotor.

U = Free Stream Wind Speed.

There are two kind of moments that will primarily act on the blade, flapwise and Edgewise moments. Edgewise moment is responsible for the lift of the blade and hence will not be considered. The Flapwise moment will be responsible for failure due to fatigue during normal operation or increased stress during high winds when turbine is parked. The Axial forces and moments on the blade can be found by model provided in [7] which is;

$$M_\beta = \frac{1}{B} \int_0^R r\, [1/2\, \rho\pi\, 8/9 U^2\, 2r]\, dr \tag{xiii}$$

Where:

M_β = Flapwise bending moment on one blade root.

r = instantaneous radius.

B = No of blades. (3)

R = outer radius.

Computing the integral for eq.(xiii); we have

$$M_\beta = [\frac{\rho\pi 8U^2}{2B9}] \int_0^R 2r^2 dr$$

Subsisting from (xii) when C_T = 8/9; $\boldsymbol{2T = 8/9\, \rho\pi R^2 U^2}$ we have;

$$M_\beta = \frac{2T}{3B} R \tag{xiv}$$

This moment value can be translated into maximum instantaneous Stress as follows;

$$\sigma_{max} = M_\beta . \frac{C}{I_b} \tag{xv}$$

Where;

σ_{max} = Maximum Stress.

C = Distance to neutral axis of force.

I or I_b = Blade root moment of inertia.

The moment calculated and discussed is on the blade root and the reason of that being the root is directly attached to hub via 10 bolts / blade. Root will be experiencing the affect of all the moments on the blade eventually

Model Equation (xii) and (xiv) are used to for peak values of input variables like cutout *wind speed = 23 m/sec, Radius = 7.2 m;* $\rho = 1.29\ Kg/m^3$ to calculate moment on one blade root.

$$T = 49.3945 \times 10^3\ N$$

$$M_\beta = 79.031 \times 10^3\ N.m$$

In Eq. (xv) the value of I_b is unknown, the root section is assumed to be rectangular in this case and on basis of data provided from manufacturer the dimensions of the cross-section of root are ***l*** or Chord Length = 451 mm, ***t*** thickness = 281mm. Moment of inertia is given by;

$$I_b = \frac{l}{12} t^3 \qquad \text{(xvi)}$$

$$I_b = 8.977 \times 10^{-4}\ m^4$$

Eq- (xv) will provide with max stress on the root with C = ***t***/2 being flapwise neutral axis.

$$\sigma_{max} = 12.677\ MPa$$

Static Reliability Model:

From analysis we have established maximum value of bending stress on the blade root. Using the static models discussed in (x) and (xi), and taking $\sigma_{max} = x_{mode}$, material strength of (wood epoxy) ***k*** *(range of values)* = ***49 –125 MPa*** for different resins. Assuming the lowest value of strength being conservative in analysis, static reliability is;

$$x_{med} = 12.794\ \text{MPa.}$$

$$R = \theta(14.069)$$

$$R = 0.9997$$

From et.al [6] $\theta(x)$; where x>4 implies R= 0.9997 however when ever ***x>>4*** we take R = 0.999...97

Dynamic reliability Model (periodic loading):

Dynamic reliability model as stated in et.al [6] is given as ;

$$\boldsymbol{R} = \exp^{-(1-R)\,\alpha\, t} \qquad \text{(xvii-a)}$$

Where α is defined as Load cycles. For a wind turbine blade and related components the cyclic loading phenomenon is described in detail in et.al [7] as under;

$$\eta_L = 60\ K\ \boldsymbol{n}_{rotor}\ H_{op}\ Y \qquad \text{(xviii)}$$

Where**:** η_L = cyclic loads ***same*** *as* α in (xvii), K = number of cyclic event *bending in this case*=1 (minimum), $\boldsymbol{n}_{rotor}$ = rotational speed of rotor (62 rpm top speed for AOC15/50), H_{op} hours of operation/year (8760 hours / year) and, Y = number of years same as t in (xvii).

For a 1-year reliability estimate (Y =1) assuming round the clock operation without any maintenance; we have;

$$\boldsymbol{R} = \exp^{-(1-R)\,\eta L} \qquad \text{(xvii –b)}$$

$$\boldsymbol{R} = 0.9068$$

This will value will further reduce, as there are three blades in series configuration according to reliability block model, more over if the period of operation is increased the reliability will further decrease as shown under; $H_{op} = 4000\ hrs$ and Y= 20 yrs.

$$\boldsymbol{R} = 0.4095$$

$$R_{blades} = [\boldsymbol{R}]^{3}$$

These values corresponds to a 20 year continuous operation for almost 6 moths a year; 4000 x 20 = 80,000 hours of operation at peak operating speed of 23 m/s (worst case scenario). Due to variation in speed these operating hours can go up because the resulting load and stress on blade will be less in those conditions and will provide a longer life.

- ***Bolts.***

The failure of bolts, which connect blade to the hub, is associated with shear forces that can cause the bolt to break away. Once a rotation every blade will be faced downward, during that position, the component of thrust acting down and the weight of blade will be the worst load case for bolts as they will be experiencing a maximum shear at that time. Assuming that blade will bend at root a total of 10' (max), we have the following results for maximum load on one of hub tubes. Forces on hub will be combined result of that component of thrust plus weight and centrifugal force on hub.

$$T_y = T \sin \varphi$$

$$F_{hub} = 8.57k + 1.470k + 3.992k = 14.036 \text{ K N}$$

$$f_{bolt} = 11.936 \text{ K.N} /10. = 1.403 \text{ K.N}$$

Shear Stress experienced by one bolt is given as;

$$\tau = F/A = f/\pi r^2$$

Bolts specification listed in et.al [3] and A193 heavy hex bolts series governed by ASME; we have diameter = 0.625" = 0.0163068m; r = 8.1534×10^{-3}.

$$\tau = 6.718 \text{ MPa}$$

Static and Dynamic Reliability Model.

Ultimate strength of Grade –8 Steel bolt used here is =640 M.Pa. Using (x) and (xi) for the analysis;

$$x_{mode} = 6.718 \text{ MPa.}; \ \boldsymbol{k} = 640 \ M \ Pa.$$

$$R = \theta(45);\ x >>> 4$$

The value imply the same results as observed in Blade with R = 0.999. For the periodic loading 8760 hours of operation using (xvii) and (xviii);

$$\boldsymbol{R} = 0.9068$$

$$R_{bolts} = [0.9068]^{10}$$

This will compute the reliability if 10 bolts per blade however a degrading analysis will be performed in Markov analysis.

- ***Hub.***

Failure of hub can be a result of two distinct events; crack in the hub branch to which blade is connected, or crack of flange to which blade is bolted on the hub-branch. Worst case of loading will be 90' angle will vertical axis of blade when it will behave momentarily as a cantilever beam. The following analysis is performed for finding the bending moments on the Hub branch.

$$M = F.\ L/2. \qquad \text{(xix)}$$

Where L = 0.3 meters

$$F = ?$$

$$\text{Force} = \text{Weight} + \text{Force due to Torque.}$$

$$\textbf{Force} = \textbf{W} + \textbf{F'} \qquad \text{(xx)}$$

Force due to torque can be calculated using the following model given in et.al [8].

$$\text{Power} = \frac{TN}{9550}$$

Where: T = torque, N= RPM, P = Power (K Watts)

$$T = \frac{9550}{62} \text{ x } 50$$

$$T = 17701 \text{ N.m}$$

$$\text{Torque} = \text{Force (F') x distance(s)}$$

$$F' = \frac{T}{S} = \frac{7701}{0.1524} = 50.53 \text{ K.N}$$

Using (xx) we have Force = 52.005 K.N; the moment on hub branch;

$$M = 3.962 \text{ x } 10^3 \text{ N.m}$$

With dimension of the Hub Branch known; width = 0.231775 m; Height = 0.1501 m and using (xv) and (xvi) we can have the σ max = 4.553596 M.Pa.

Static and dynamic Reliability Model.

Following the same procedure and analyzing using (x) and (xi) with x_{mode} = 4.55 M.Pa. R= 0.999...97,the reliability for 20 year period with 4000 hours of operation per year using (xvii) and (xviii);

$$\boldsymbol{R} = 0.9068$$

$$R_{hub} = [\boldsymbol{R}]^3$$

$$R_{hub} = [0.9068]^3 = 0.7456$$

- ***Anchor Bolts and Tower.***

The guidelines for analysis of tower are followed directly from et.al [9]. This provides a useful and easy approach to a number of transmission structures. However same approach is used for Wind Turbine tower keeping in consideration the environment and terrain requirements. A summarized version of the analysis is presented in this paper to save time and space. The wind force acting on a tower or transmission component as state in et.al [9] is given by;

$$F = Q\,(Z_v\, V)^2\, G\, C_f\, A \qquad \text{(xxi)}$$

Where:

Q = Air density factor [0'F = -17.7C $\cong 0.00289$] specified by elevation above sea level.
Zv = Terrain factor [open land = 1.14, open shore =1.29 @ 80ft.]
V = wind speed =51mph = 22.5 m/sec (peak speed of operation).
G = G_t = Gust response factor for tower only.

G_t can be calculated by direction and tables given in et.al [9].
C_f = force coefficient value.
A = Projected area of tower in ft².
Using the appropriate parameters for the above equation all selected from et.al [9], the analysis is as follows;

Area of projected tower face.

Face of tower experiencing the winds will be the most crucial case of loading, face of tower if observed have a trapezoidal face with dimensions; h = 80 feet, b_1 = 10.75 feet, b_2 = 2.75 feet. A = ½ (b1 + b2) h =>A = 540 ft². *Assuming* a solidity factor of 30% effective area = 162 ft². Force coefficient given for 30% solidity in et.al [9] is 3.75. Putting everything in (xxi) we has;

$$F = 7.0856 \times 10^3 \text{ Kip}$$

1 Kip = weight of 1000 pound

1 Kip = 4.448 KN.

$F = 31.517 \times 10^6$ N = 31.517 MN. Forward thrust produced by the rotor disk in the direction of wind will also be added to this force value;

$$F = 31.517 \text{ MN} + 49.39454 \times 10^3 \text{ N} = 31.566 \text{ MN}.$$

If it is assumed that tower behaves as a cantilever beam, with forces on tower known it is possible to compute maximum stress, however moment of inertia has to be known for that computation. That is not possible in a simplistic way as tower is lattice bolted and a truss structure. In et.al [10] a similar analysis is presented for a telecommunication tower for a service life of 30 years, the author of that paper have presented upper and lower bound values of probability of failure taking in consideration different wind speed and ice loading scenario. Keeping in view a large number of values presented in the paper and our computational limit of nine significant figure we take a failure probability as $F(t) = 0.33 \text{x} 10^{-9}$ corresponding to the lower bound group with ice thickness $\leq$35mm and wind speeds of $\leq$ 150km/h. Using (ii) we have

$$R(t) = 0.99997$$

With this value of reliability of tower under winds up to 150km/h, there is no possible cause of failure for anchor bolts. The specification of bolts also rule out such a failure possibility due to their extraordinary tensile strength, stainless steel material and the fact that they are bolted to foundation and supporting a heavy structure not allowing it to vibrate/topple with wind gusts.

7. Markov Analysis.

Markov analysis looks at the system as being in one of several states. States are defined as total operation or degraded states. Every degraded state differs from the other depending upon which component has failed and what effect will it have on the overall performance and production level. For this study the components that may leads the system to a degraded performance OR a sequential failure scenario are bolts, tip breaks and yaw bearing implying that the total number of states will be 5. The fundamental assumption in a Markov process is that the probability that system will undergo a transition from one state to another depends only on the current state of the system and not on any previous state system may have experienced.

In other words this property is equivalent to the memorylessness of exponential distribution and it is not surprising that exponential time to failure satisfy markovian property. From the discussion regarding reliability analysis failure rate of most of components are known, however for those they are not know will be calculated in this section.

Conditions.

As there are total of 30 bolts (connecting 3 blades to hub), failure of any of two bolts on one blade will be considered as system failure as continuous operation at that point can cause sever damage. Mean time to failure can be found out from the following expression provided in et.al [6];

$$\text{MTTF} = \int_0^\infty R(t)\,dt \qquad \text{(xxii)}$$

Where R (t) is taken from (xvii-a) and (xvii-b) for the components analyzed by physical reliability model. In those equations if the variable time are ignored we will be left with the following form of equation;

$$\boldsymbol{R}\ (\boldsymbol{t}) = \exp^{-(1-0.99999997)\,(60\text{x } 1 \text{ x } 62)\ t} \qquad \text{(xvii - c)}$$

Using the above two relations, the MTTF can be computed for components who have a static reliability of R=0.9997 and will be the same for all those components. The failure rate in /hrs can hence be computed as follows; here λ_1 is for bolts only.

$$\text{MTTF} = 89605 \text{ hrs} \cong 89600 \text{ hrs}$$

$$\lambda_1 = \frac{1}{MTTF} = 1.116 \text{ x } 10^{-5} \text{ /hr}$$

In case of yaw bearing the failure rate λ_3 has to be deduced from Wiebull failure model given as under;

$$\lambda(t) = \frac{\beta}{\theta}\{\frac{t}{\theta}\}^{\beta-1} \qquad \text{(xxiii)}$$

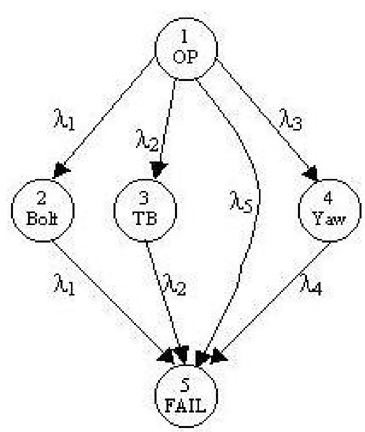


Fig-9: 5-Stage Markov Model.

Yaw failure Scenario:

In case of yaw bearing the failure will cause system to go in a degraded state-4, from that state the system will go to a complete fail state and the failure rate from that stage to stage-5 will be the combine FR of all the remaining components λ_4. Wiebull FR for yaw bearing for an operating period of 1 yrs (8760 hrs) using (xxiii) is;

$$\lambda_3 = 1.15 \times 10^{-5}$$

λ_4 according to above discussion can be calculated as follows:

$$\lambda 4 = \lambda 1 + \lambda 2 + \lambda 5 \quad \text{(xxiv)}$$

FR (tip break) provided in ***section –6 b*** of this paper;

$$\lambda_2 = 100.00 \times 10^{-6}$$

There can be a scenario in which the system will directly to a failure state with out going in a degraded operation mode as shown in figure –9. For such a case the failure rates will be the combined rate (λ_5) of all components failing randomly. Model equation for different states provided in et.al [6] will be used to model the probability of being in total operational state over a period of time.

$$\lambda_5 = \sum \lambda \boldsymbol{i}$$

Where i =3 in this case for generator, gearbox and controller.

Transition for State –1:

$\boldsymbol{P_i\ (t)}$ is the probability if system staying in stage-***i*** at time t, where i = 1,2,3,4,5; where $P_1\ (t)$ that is complete operational stage and can be modeled as follows general from of model provide in [6];

$$P_1\ (t) = e^{-(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 5)\, t} \quad \text{(xxv-a)}$$

Transition of system from state-1 to any of the degraded state or failure state is hence the result of combined failure rate of bolt, tip break, yaw bearing and components failing randomly. The first step in the analysis will be performed for t = 8760 hrs. For the ease of analysis we can consult the following table for transition failure rates.

Table –4: Transition Failure Rates for Markov analysis

S.No	Transition	Failure rate	Effective FR
1	State 1-2 & State 2-5	λ_1	$\lambda_1 = 1.116 \times 10^{-5}$
2	State 1-3 & Sate 3-5	λ_2	$\lambda_2 = 100.0 \times 10^{-6}$
3	State 1-4	λ_3	$\lambda_3 = 1.15 \times 10^{-5}$
4	State 4-5	λ_4	$\lambda_1 + \lambda_2 + \lambda_5 = 1.041 \times 10^{-6}$
5	State 1-5	λ_5	$(0.796 + 0.63 + 28.5) \times 10^{-6} = 2.99 \times 10^{-6}$

The failure probabilities for being in each state is provide in Ebling [6] as follows and will be used to conduct the further analysis.

$$P_4\ (t) = e^{-\lambda 3t} - e^{-(\lambda 3 + \lambda 4)\, t} \quad \text{(xxvi)}$$

The probabilities for state-2 and 3 are provided in a different manner then given in et.al [6]. The transition *from* state-2 and -3 to state-5 is the result of the failure of same type of components that brought the system *to* state 2 and 3.

$$P_2\ (t) = \boldsymbol{e}^{-\lambda 2t} - \boldsymbol{e}^{-(\lambda 2 + \lambda 2)\, t} \quad \text{(xxvii-a)}$$

$$P_2\ (t) = \boldsymbol{e}^{-\lambda 3t} - \boldsymbol{e}^{-(\lambda 3 + \lambda 3)\, t} \quad \text{(xxvii-b)}$$

Since total reliability is equal to 1. We have the following relationship for state-5.

$$\boldsymbol{P_5\ (t) = 1 - P_2\ (t) - P_3\ (t) - P_4\ (t) - P_1\ (t)} \quad \text{(xxviii)}$$

The above relation will provide the Markov analysis results presented in following table for 1 and 2 yr operation. However the probability that the system will make a transition from state-1 to any of the degraded states can be determined ($\boldsymbol{1 - P_{1\text{-}a}\ (t)}$) given by amendment in xxv-a as follows;

$$P_{1-a}(t) = e^{-(\lambda 1 + \lambda 2 + \lambda 3)t} \qquad \text{(xxv-b)}$$

Table-5: Markov Analysis Results for States 1-5

S.No	State of System	Probability @ t = 8076	Probability @ t = 8076 x2
1	P_1 (t)	0.3632	0.1106
2	P_2 (t)	0.2425	0.1433
3	P_3 (t)	0.0856	0.14916
4	P_4 (t)	0.008139	0.014
5	P_5 (t)	0.299	0.58294

The values of ***P_1 (t)*** and ***P_5 (t)*** can give us a good idea about system availability in completely operational states and complete failure possibility.

8. Fault Tree Analysis.

Fault tree is a standard reliability analysis procedure for a multiple component system. It gives a better understanding or the failure scenarios and contribution of different components toward total failure of system. In the following it is presented.

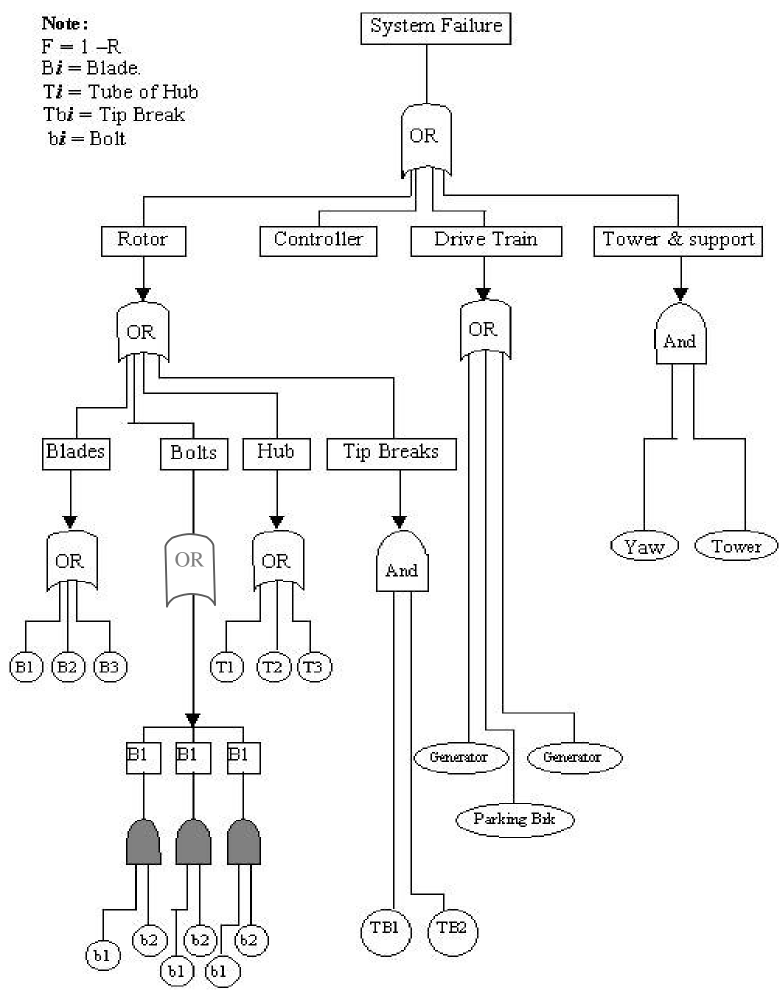


Fig-10: Fault tree Representation.

The analysis of the tree can follow as follows by deducing the Failure probability F(t) form the preceding sections of paper. The basic analysis will follow as under where P(T) is the probability of top event;

$$P\ (T) = F_{rotor} \cup F_{\ controller} \cup F_{derive\ train} \cup F_{tower\ support} \quad \text{(xxix)}$$

$$P\ (T) = [F_{blades} \cup F_{bolts} \cup F_{Hub} \cup F_{tipbrk}] \cup [F_{Controller}] \cup [F_{generator} \cup F_{gearbox} \cup F_{parkingbrk}] \cup [F_{yaw} \cap F_{tower}]$$

Following the rules of binary algebra and sets described in [6] eliminating redundant events we have;

$$P\ (T) = 0.0932 + 0.44667 + 0.2209+0.00695+ 0.0056+0.0001+(0.0987 \times 0.3 \times 10^{-9}) = 0.768$$

The above value is very high for system failure but if tip break whose failure is discussed markov analysis, is excluded the value drops to P (T) = 0.3218. This observation emphasize on the periodic inspection of tip break for enhanced probability.

$$F\ (T) = 0.3218$$
$$R\ (T) = 0.67819$$

Conclusion

Paper describes a computational method to perform the reliability analysis of a wind turbine system. All the integral components were taken in to account. Based on analysis, assumptions and availability of relevant date it can be seen that some component play vital role in decreasing system inherent reliability. Tip break and yaw bearing are proven to be most vulnerable to failure due to their environment and loads. PLC failure can also occur if the system is not inspected for a longer period of time. A strategy need to be established with in the wind engineering practice to collect all available data for all relevant components moreover an online monitoring methodology should be adopted even for small systems like AOC15/50. Reason for developing remote monitoring system is to avoid any major damages to the systems in larger wind farms and a better maintenance can be kept using a monitoring system of that kind. There is still room for further work and analysis in the field of reliability in Wind engineering Technology.

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