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Failure and reliability evaluation of turbines used in Nigerian thermal plant

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ABSTRACT

Failure and reliability evaluation of turbines used in Nigerian thermal plant has been undertaken. Data were obtained directly from the operational department of the stations log-book, which were records of the station's plant generation from each of the operational power generating units. The exponential and Weibull density models were used to evaluate the reliability of six turbines as an individual component in the station. Mean time to failure (MTBF), Mean time to repair (MTTR) and failure rate (λ) are evaluated from the maintenance record book of Sapele thermal power station and used to evaluate the distribution and reliabilities of system components. Each Weibull curve compressed on both axes and the vertical axis showed the density of stretchiness of the reliability of both turbines while the horizontal axis showed the minimum life of turbine or the aging condition in hours. The reliability of ST01 and aging condition of unit drop by 3.5% in every 77 hours from the year 2003 to 2012. ST02 reliability, 3% in 68 hours; ST06 reliability, 3.5% in 76 hour; GT01 reliability 3% in 75 hours; and GT02 reliability 3% in 84 hour. For a power generating station to be reliability the failure rate index must be reduced from unity to 0 as availability is directly proportional to reliability.

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I. Introduction

Reliability is the probability that a system, component or device will perform without failure for a specified period of time under specified operating condition. The discipline of reliability engineering

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adopted in this study targets the causes, distribution and prediction of failure of steam and gas turbines installed in the power plant, submitted to same commissioning process and starting to function at the same time. Zungeru et al. (2012) upheld that reliability assessment of a generating system is fundamentally concerned with predicting if the system can meet its load demand adequately for the period of time intended. Improving the availability of existing units is as important as improving the reliability expectation of units during the planning phase. The two are mutually supportive; design reliability impacts major changes in existing units, and information about operating availability is important to the system designers in both developing and developed countries (Oyedepo et al., 2015)

A widely used measure of product reliability is Mean Time Between Failure (MTBF). Before making a purchase decision for manufacturing equipment or other items, customers frequently require the supplier to provide an MTBF. Improper MTBF calculations used in head-to-head product comparisons can result in sales lost to competitors, higher procurement and maintenance costs, and customer dissatisfaction with product experience. In general terms, if the number of failures is unpredictably high in number, the equipment is said to be unreliable and its market value is reduced. On the other hand, if the number of failures is less, the equipment is reliable and its market value is high (Mishra, 2008).

The performance of a system can be defined in two ways, firstly the required performance which indicates what a system is supposed to do under all environmental conditions; secondly the achieved performance which the system will likely do under all environmental conditions (Mishra, 2008). Reliability analysis has been gradually accepted as a standard tool for planning, designing, operation and maintenance of electric power systems. In fact, the characteristic of reliability is usually used to describe some functions or tasks or in widest sense it may be said to be a measure of performance. The growing awareness of reliability arises from the fact that there is need for efficient, economic and continuous running of equipment in any organization for achieving the production target at a minimum cost and to measure with present competitive world (Mishra, 2008)

To know the real scope of reliability, it is required to highlight some technological system, which needs high reliability. The first on this class is aerospace system mainly aircrafts. It is known that capital investment in case of aircraft is very high and also human lives are at risk, therefore, the system used must be highly reliable. The other area where high reliability is required is the nuclear power plants. If such is not available for power production, they incur heavy loss per hour as well as the good will of the concerned people (Mishra, 2008).

According to Gavrilov and Gavrilova (2001), reliability theory describes the probability of a system completing its expected function during an interval of time. It is the basis of reliability engineering, which is an area of study focused on optimizing the reliability, or probability of successful functioning, of systems, such as airplanes, linear accelerators, and any other product. It developed apart from the mainstream of probability and statistics. It was originally a tool to help nineteenth century maritime insurance and life insurance companies compute fair-value rates to charge their customers. Even today, the terms "failure rate" and "hazard rate" are often used interchangeably. The failure of mechanical devices such as ships, trains, and cars, is similar in many ways to the life or death of biological organisms. Statistical models appropriate for any of these topics are generically called "time-to-event" models. Death or failure is called an "event", and the goal is to project or forecast the rate of events for a given population or the probability of an event for an individual.

According to Barringer (2004) evaluation of reliability of production systems begins with management and how they communicate the need for a failure free environment to mobilize actions to preserve production systems and processes. The need for reliability considers cost of alternatives to prevent or mitigate failures, which require knowledge about times to failure, and failure modes which are found by reliability technology. Justification for reliability improvements requires knowing: (a) when things fail, (b) how things fail, and (c) conversions of failures into time and money.

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Jibril and Ekundayo (2013) assessed the reliability performance of the 33kV Kaduna Electricity Distribution Feeders, Northern Region, Nigeria. Asis et al. (2012) carried out reliability assessment of Rukhia Gas Turbine Power Plant in Tripura. Adefarati et al. (2014) carried out reliability assessment of electrical power system by using some reliability indicators. Alwan et al. (2013) proposed a methodology for assessing the reliability of 33/11 Kilovolt high-power stations based on average time between failures. Zungeru et al. (2012) evaluated the reliability of Kainji Hydro-Electric Power Station in Nigeria. Sulaiman (2015) surveys the performance of gas-turbine plants in Egbin Thermal Power Station and evaluate the effect of planned preventive maintenance on the performance of Egbin thermal power station. Obodeh and Esabunor (2011) analyzed the reliability indices of the turbines based on a six-year failure database. They estimated such reliability indices as failure rate (I), repair rate (μ) and mean time to repair (z).

In general, the Nigerian power generation capability has nosedived to an abysmal level, particularly at the generation stations due to unavailability occasioned by many factors. Unplanned downtime has resulted in lost electricity-generation and requires resources to be diverted to get the system running again, i.e., lower profitability occurred. This has affected many sectors of the economy with the commercial sector being the most affected. The rising demand of this commodity from generating power stations cannot be over emphasized. The need to assess the reliability of these stations to ascertain if they are economically viable is therefore necessary. The aim of this study therefore is to carry out reliability evaluation of steam and gas turbines system components using exponential and Weibull density models.

II. Materials and Methods

Data were obtained from a thermal power station in Nigeria. These raw data were extracted from the operation department, which represents records of plant generation capabilities as well as other inherent daily conditions that will enhance the success of this study. From the records obtained, daily, monthly and yearly data of power generated were computed. In addition, during the process of gathering data on this research work, both junior and senior staffs of the technical department of the plant operation unit of the thermal power station were interviewed to get some other relevant information which was of a great assistance to the success of this work.

The analysis of reliability of a system begins with a plot of failure or hazard rate with time to establish the distribution pattern. Classical studies show three phases of distribution of hazard rate with time as debugging period characterized with the initial decreasing rate of failure with time, the next or second phase is characterized by a relatively constant chance failure rate period, which is the effective life of the system. This is followed with the next last phase, a period of increasing failure rate which indicates the beginning of wear-out failures in the population. The probability models for these three phases are commonly referred to as the DFR (decreasing failure rate), CFR (constant failure rate), and IFR (increasing failure rate) models, respectively. This combined graph can be shown in the form of hazard function, in which case it is called the bathtub curve graph shown in figure 01.

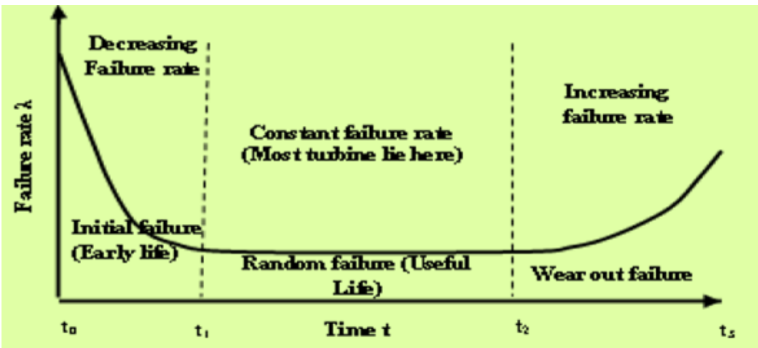

Figure 01. Three-stage (bath–tub) curve for complex product.

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Scholars have tried to establish some approximate models to analyze some distributions such as Weibull distribution, Gamma distribution, exponential distribution and normal distribution to characterize DFR, CFR and IFR of distribution. Hansen and Ghare (1987) and Dieter and Schmidt (2009) recommended these models for the analysis of reliabilities of serving systems.

Reliability analysis: If $R(t)$ is the reliability of the turbine with respect to time t, then $F(t)$ is the unreliability (probability of turbine failure) in the same time t. Since turbine failure and no turbine failure are mutually exclusive events then,

$$R(t) + F(t) = 1 \quad (1)$$

If N_o turbines are put on test, the number surviving to or at time t is $N_s(t)$ and the number of turbines that failed between t = 0 and t = t is $N_f(t)$.

$$N_s(t) + N_f(t) = N_o (2)$$

From the definition of reliability

$$R(t) = \frac{N_s(t)}{N_o} = 1 - \frac{N_f(t)}{N_o} (3)$$

The hazard rate or instantaneous failure rate or expected number of failure is the number of failures per unit time per the number of turbines exposed for the same time.

$$\lambda(t) = \frac{dN_f(t)}{dt}\frac{1}{N_s(t)} (4)$$

In more statistical term Shooman (1968) defined the expected number of failure $\lambda(t)$ as the probability that any of the turbines will fail between $t_1$and $t_1 + dt_1$, when it already has survived to t_1.

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{1 - \int_0^t f(t)dt} = P\left(t_1 \le t \le t_1 + \frac{dt}{t} \ge t_1\right) (5)$$

Where

$\lambda(t)$ = the distribution parameter (i.e., turbine hazard rate or instantaneous failure rate or expected number of failure or time t dependent failure rate)

$f(t)$ = Turbine failure density function (i.e., probability density function)

$F(t)$= Cumulative distribution function (i.e., probability of turbine failure at time t or unreliability)

Meanwhile, the denominator of equation (5) can be expressed as follows:

$$R(t) = 1 - \int_0^t f(t)\,dt (6)$$

Differentiating equation (6) with respect to t, we get

$$\frac{dR(t)}{dt} = -f(t) (7)$$

Combining equation (7) with equation (5) yields

$$\lambda(t) = -\frac{1}{R(t)} \cdot \frac{dR(t)}{dt} (8)$$

Equation (8) is quite useful to obtain hazard rate when the turbine's reliability function is known.

General reliability function: The general turbine reliability function can be obtained by rearranging equation (8) as follows:

$$\lambda(t)dt = -\frac{1}{R(t)} . dR(t) (9)$$

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Integrating both sides of equation (9) over the time interval [0, t], we get

$$-\int_0^t \lambda(t)dt = \int_1^{R(t)} \frac{1}{R(t)}.dR(t)\ (10)$$

Since at t=0, R (t) = 1.
Evaluating the right-hand side of equation (10) and rearranging the resulting expression yields

$$lnR(t) = -\int_0^t \lambda(t)dt\ (11)$$

$$R(t) = e^{-\int_0^t \lambda(t)dt}(12)$$

Equation (12) is the general expression for the reliability function. It can be used to obtain reliability function of an item when the item's hazard rate is defined by any probability distribution.

Exponential failure density model

Failure rate for exponential distribution: The turbine failure density function of the exponential distribution is defined according to Hansen and Ghare (1987) as,

$$f(t) = \lambda e^{-\lambda t}, \quad \text{when } t \geq 0, \lambda > 0 \qquad (13)$$

Inserting equation (13) into equation (5) we get the following expression for exponential distribution's hazard rate.

$$\lambda(t) = \frac{f(t)}{1-\int_0^t f(t)} = \frac{\lambda e^{-\lambda t}}{1-\int_0^t \lambda e^{-\lambda t}dt} = \lambda(14)$$

The right–hand side of equation (14) is independent of time t. thus λ is called constant failure rate. It simply means that when a turbine's time to failure is exponentially distributed, its failure rate is automatically constant.

Reliability function for exponential distribution: Substituting equation (14) into equation (12) we get the following expression for exponential distribution's reliability function:

$$R(t) = e^{-\int_0^t \lambda(t)dt}(15)$$

$$R(t) = e^{-\int_0^t \lambda dt}(16)$$

$$R(t) = e^{-\lambda t}(17)$$

Where, $\lambda(meantimetofailure) = \frac{\left(\frac{Totalnumberoffailure}{Turbinepopulation}\right)}{Operatingperiods(years)}(18)$

Weibull failure density model

Failure rate for Weibull distribution: The failure density function of the Weibull distribution is defined according to Shooman (1968) as

$$f(t) = \frac{\beta t^{\beta-1}}{\eta^\beta} e^{-\left(t/\eta\right)^\beta}, \quad \text{when } t \geq 0, \eta > 0, \beta > 0 \qquad (19)$$

Using equation (19) in equation (5) yields the following expression for Weibull distribution's hazard rate:

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$$\lambda(t) = \frac{f(t)}{1 - \int_0^t f(t)dt} (20)$$

$$\lambda(t) = \frac{\frac{\beta t^{\beta-1}}{\eta^\beta} e^{-\left({t}/{\eta}\right)^\beta}}{1 - \int_0^t \frac{\beta t^{\beta-1}}{\eta^\beta} e^{-\left({t}/{\eta}\right)^\beta} dt} (21)$$

$$\lambda(t) = \frac{\beta}{\eta^\beta} t^{\beta-1} (22)$$

The expected number of failure or hazard rate is given in terns like 1 percent per 1000h or 10^{-5} per hour (Dieter and Schmidt, 2009). It follows that any turbines in the range of hazard rate of 10^{-5}- 10^{-7} per hour exhibit a good commercial level of reliability.

Reliability function for Weibull distribution: The reliability distributions are evaluated based on failure database. In case of wear-out or fatigue failures of the system, the Weibull distribution parameters (Weibull distribution shape parameter and Weibull distribution characteristic life) are obtained by using equation (22) in equation (12) thus:

$$R(t) = e^{-\int_0^t \left(\frac{\beta}{\eta^\beta} t^{\beta-1}\right) dt} (23)$$

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} (24)$$

Where,

$R(t)$= Reliability at time t, t= time period (hours), β = Weibull distribution shape parameter, η = Weibull distribution characteristic life (hours)

III. Results and Discussion

Curve fitting and establishment of reliability function with time response of system components

Mean time to failure (MTBF), Mean time to repair (MTTR) and failure rate (λ) are evaluated from the maintenance record book of Sapele thermal power station and used to evaluate the distribution and reliabilities of system components as presented in tables 01-05 and figures 02-04.The first best practice in the analysis of the system is to understand the response of the failure rate with time. In this study failure rate of system components are plotted against the operation period as depicted in figures 02-04, it shows the three phases of distribution of failure rate with time as debugging period characterized with the initial decreasing rate of failure with time, and the second phase is characterized by a relatively constant chance failure rate period, which is the effective life of the system. This is followed with the next last phase, a period of increasing failure rate which indicates the beginning of wear-out failures in the population.

These graphics of figures 02-04 show the DFR (decreasing failure rate), CFR (constant failure rate), and IFR (increasing failure rate) failure phase models of the turbines. The hazard rate after the constant rate period increases with time.

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Table 01. Parameter computation for steam turbine 01

Year	No. of failure per year	Total operating time between maintenance in the year (hours)	Expected number of failure	Mean time to failure (MTBF) (hour)	Total outage hours per year	Mean time to repair(MTTR) (hours)	Expected repair rate	Specific period of failure free operation (hours)	Reliability
	Φ_n	β_t	$\lambda=\frac{\Phi n}{\beta t}$	$m=\frac{1}{\lambda}$	ψ_i	$\varsigma=\frac{\psi i}{\Phi n}$	$\mu=\frac{1}{\varsigma}$	T	$R(t) = e^{-\lambda t}$
2003	4	7020	0.00057	1755	720	180	0.0055	787	0.6385
2004	2	7776	0.00026	3888	864	432	0.0023	3847	0.3679
2005	1	8544	0.00012	8544	96	96	0.0104	8327	0.3672
2006	1	8616	0.00012	8616	24	24	0.0417	4761	0.3679
2007	3	7824	0.00038	2608	816	305,3	0.003	1907	0.5032
2008	3	8112	0.00037	2704	528	176	0.006	2700	0.3679
2009	4	8424	0.00048	2106	216	54	0.019	2722	0.2706
2010	3	8400	0.00036	2800	240	80	0.013	1907	0.5032
2011	5	8328	0.0006	1665.6	312	62.4	0.016	427	0.7738
2012	2	8400	0.00024	4200	240	120	0.0083	1280	0.7358

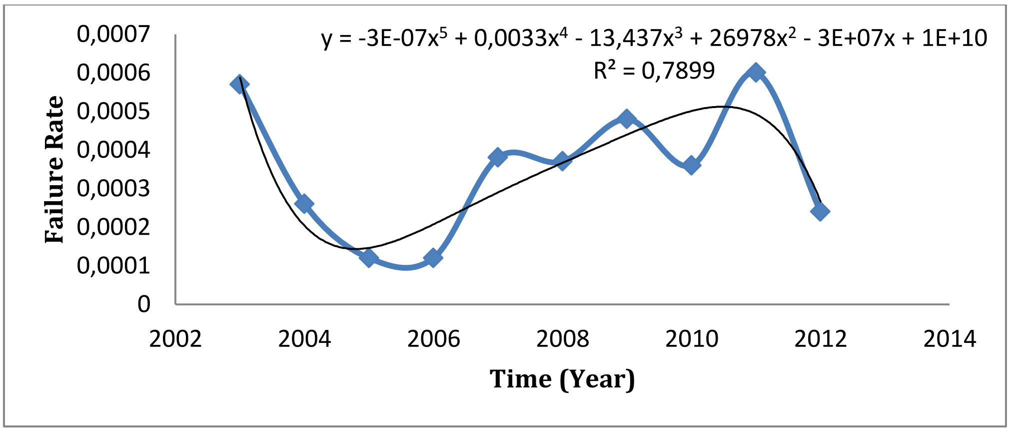

Figure 02. Depiction of Failure rate for steam turbine 01.

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Table 02. Parameter computation for steam turbine 02

Year	No. of failure per year	Total operating time between maintenance in the year (hours)	Expected number of failure	Mean time to failure (MTBF) (hour)	Total outage hours per year	Mean time to repair(MTTR) (hours)	Expected repair rate	Specific period of failure free operation (hours)	Reliability
	Φ_n	β_t	$\lambda=\frac{\Phi n}{\beta t}$	$m=\frac{1}{\lambda}$	ψ_i	$\varsigma=\frac{\psi i}{\Phi n}$	$\mu=\frac{1}{\varsigma}$	T	$R(t) = e^{-\lambda t}$
2003	5	7440	0.00067	1488	1200	240	0.0042	720	.6172
2004	1	8016	0.00015	8016	624	624	0.0016	6668	.7358
2005	2	8424	0.00024	4212	216	108	0.0093	1280	.7358
2006	2	7800	0.00026	3900	840	420	0.0024	1180	.7385
2007	3	8448	0.00036	2816	192	64	0.015	-	-
2011	2	8592	0.00023	4296	48	24	0.042	4349	.3679

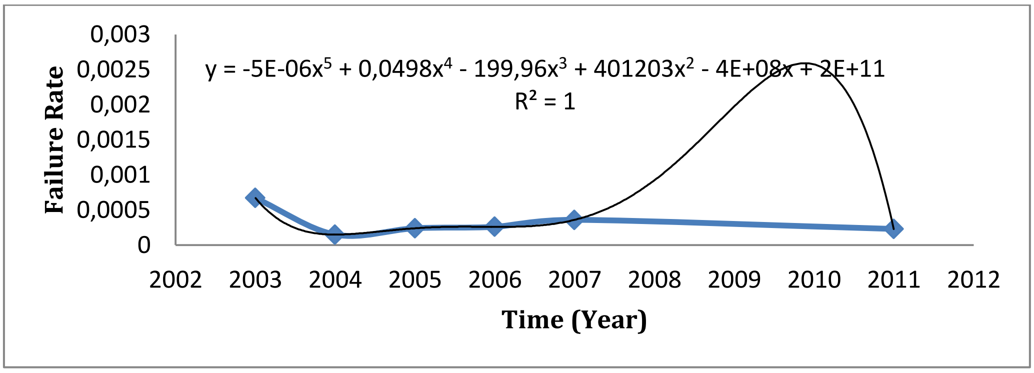

Figure 03. Depiction of Failure rate for steam turbine 02.

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Table 03. Parameter computation for steam turbine 06

Year	No. of failure per year	Total operating time between maintenance in the year (hours)	Expected number of failure	Mean time to failure (MTBF) (hour)	Total outage hours per year	Mean time to repair(MTTR) (hours)	Expected repair rate	Specific period of failure free operation (hours)	Reliability
	Φ_n	β_t	$\lambda=\frac{\Phi n}{\beta t}$	$m=\frac{1}{\lambda}$	ψ_i	$\varsigma=\frac{\psi i}{\Phi n}$	$\mu=\frac{1}{\varsigma}$	T	$R(t) = e^{-\lambda t}$
2003	6	1872	0.00321	312	6768	1128	0.00089	43	.8711
2004	2	1560	0.00128	780	7080	3540	0.00028	778	.3679
2005	6	1152	0.00531	182	7488	1248	0.0008	179	.3862
2006	3	1368	0.00219	456	7272	808	0.00124	205	.6385
2007	5	528	0.00947	1056	8112	1622.4	0.00062	32	.7358
2008	2	72	0.02777	36	8568	4284	0.00023	11	.7358
2009	3	768	0.0039	256	7872	2624	0.00038	78	1.472
2010	3	768	0.00391	256	7872	2624	0.00038	334	.2706
2012	3	840	0.00357	280	7800	2600	0.00039	380	.3679

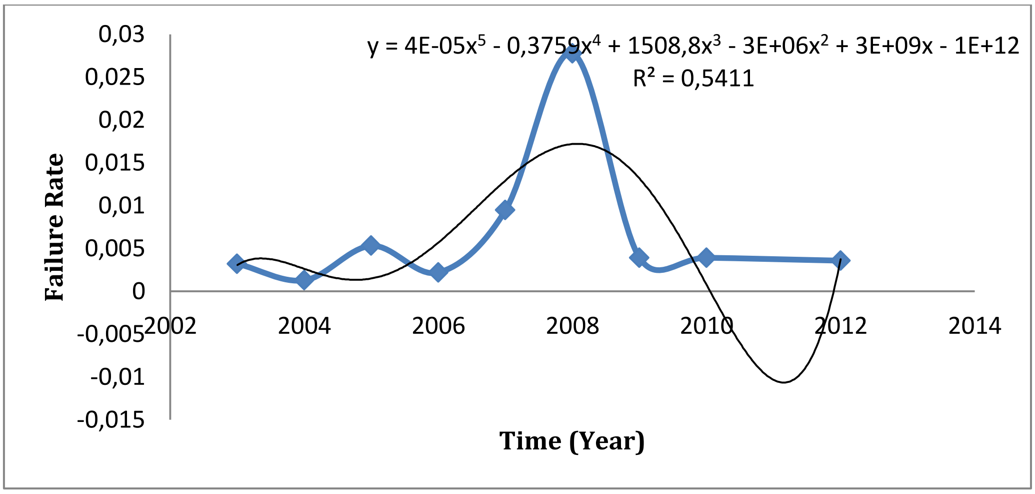

Figure 04. Depiction of Failure rate for steam turbine 06.

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Table 04. Parameter computation for gas turbine 01

Year	No. of failure per year	Total operating time between maintenance in the year (hours)	Expected number of failure	Mean time to failure (MTBF) (hour)	Total outage hours per year	Mean time to repair(MTTR) (hours)	Expected repair rate	Specific period of failure free operation (hours)	Reliability
	Φ_n	β_t	$\lambda=\frac{\Phi n}{\beta t}$	$m=\frac{1}{\lambda}$	ψ_i	$\varsigma=\frac{\psi i}{\Phi n}$	$\mu=\frac{1}{\varsigma}$	T	$R(t) = e^{-\lambda t}$
2003	1	1320	0.00076	1320	7320	7320	0.00014	5265	.0183
2004	6	2500	0.0024	414.7	6140	1023	0.00098	417	.3679

Table 05. Parameter computation for gas turbine 02

year	No. of failure per year	Total operating time between maintenance in the year (hours)	Expected number of failure	Mean time to failure (MTBF) (hour)	Total outage hours per year	Mean time to repair(MTTR) (hours)	Expected repair rate	Specific period of failure free operation (hours)	Reliability
	Φ_n	β_t	$\lambda=\frac{\Phi n}{\beta t}$	$m=\frac{1}{\lambda}$	ψ_i	$\varsigma=\frac{\psi i}{\Phi n}$	$\mu=\frac{1}{\varsigma}$	T	$R(t) = e^{-\lambda t}$
2003	2	336	0.00595	168	8304	4152	0.00024	339	.1353
2004	9	3072	0.00297	341.3	5568	618.7	0.0019	1580	0.0009
2008	4	888	0.00451	222	7752	1938	0.00052	222	.3679

Evaluation of steam and gas turbines system components

Reliability of equipment depends on prompt maintenance of equipment; when the interval period between first maintenance and sub- time of system maintenance becomes farther the reliability figure dropped from unity to zero. Equipment poor performance is likely to occur which will pave way to low power generations from the affected unit.

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Table 06. Weibull Distribution Parameters for Reliability of Steam and Gas turbines

Years			2003	2004	2005	2006	2007
Reliability R(t) & t	ST01	R(t)	0.6385	0.3679	0.3672	0.3679	0.5032
		t	787	3847	8327	4761	1907
	ST02	R(t)	0.6172	0.7359	0.7358	0.7385	0.050
		t	720	6668	1280	480	8250
	ST06	R(t)	0.8711	0.3679	0.3862	0.6385	0.7358
		t	43	778	179	205	32
	GT01	R(t)	0.0183	0.3679	-	-	-
		t	5265	417	-	-	-
	GT02	R(t)	0.1353	0.0009	-	-	-
		t	339	1580	-	-	-
Years			2008	2009	2010	2011	2012
Reliability R(t) &t	ST01	R(t)	0.3679	0.2706	0.5032	0.7738	0.7358
		t	2700	2722	1907	427	1280
	ST02	R(t)	-	-	-	0.3676	-
		t	-	-	-	4349	-
	ST06	R(t)	0.7358	1.4	0.2306	-	0.3679
		t	11	78	334	-	380
	GT01	R(t)	-	-	-	-	-
		t	-	-	-	-	-
	GT02	R(t)	0.3679	-	-	-	-
		t	222	-	-	-	-

Table 06 showed the Weibull distribution parameters for reliability of steam and gas turbines, from the table, gas turbine 01 and 02 was most affected, the reliability digit remains at nil for most periods of years assessed. Reliability assessment of the thermal station from the point of assessment of equipment faults preventive maintenance has guarantee very low reliability figure for most of those units assessed in this study and as such these cannot guarantee maximum and efficient plant performance.

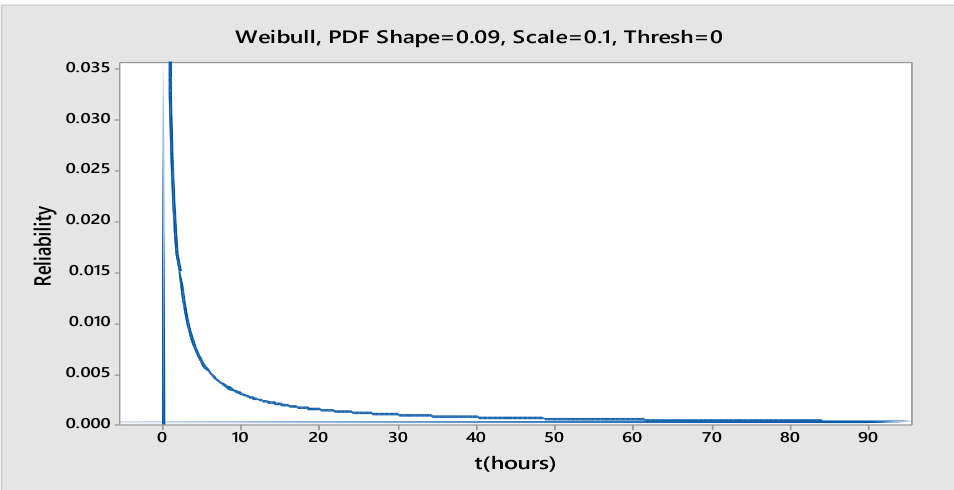

Figure 05. Weibull Reliability Probability Density Function (PDF) for ST01.

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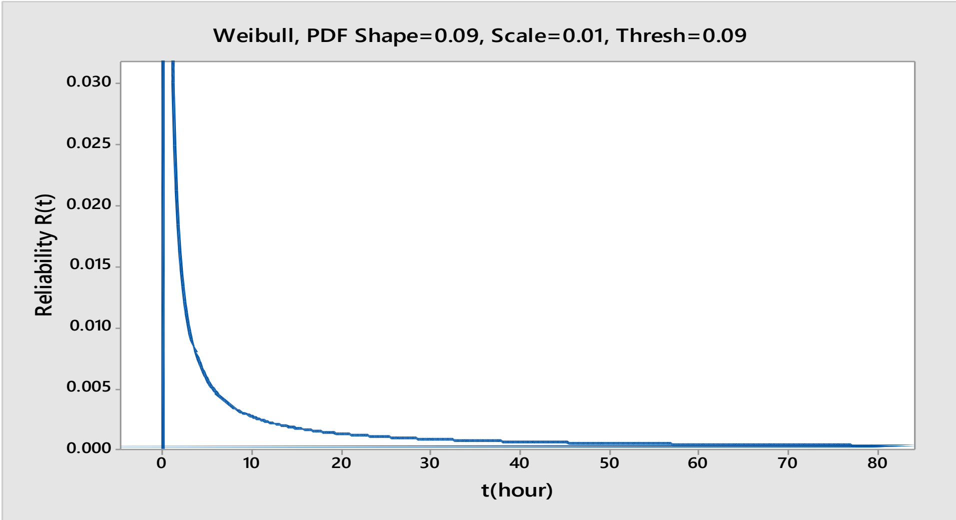

Figure 06. Weibull Reliability Probability Density Function (PDF) for ST02.

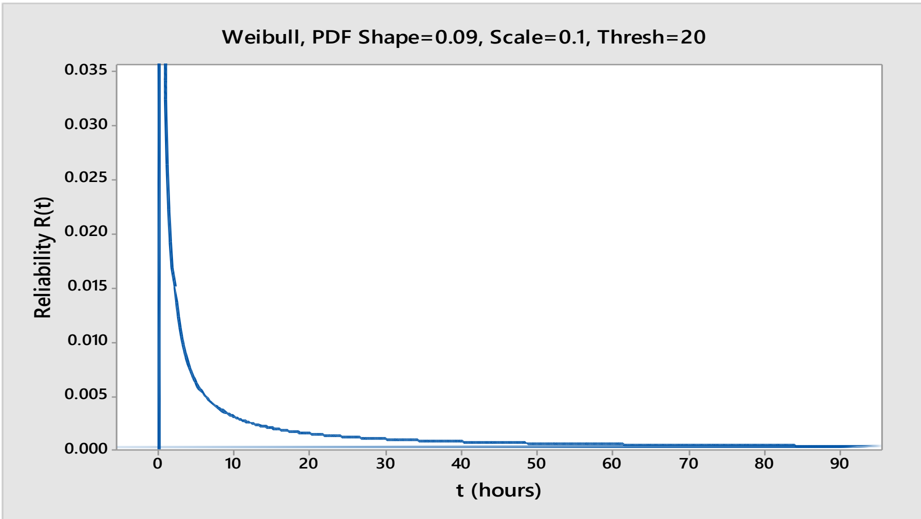

Figure 07. Weibull Reliability Probability Density Function (PDF) for ST06.

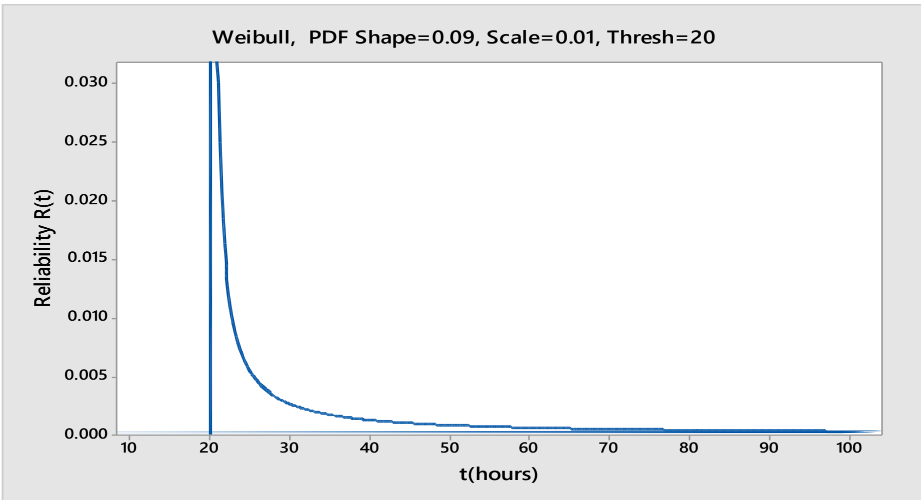

Figure 08. Weibull Reliability Probability Density Function (PDF) for GT01.

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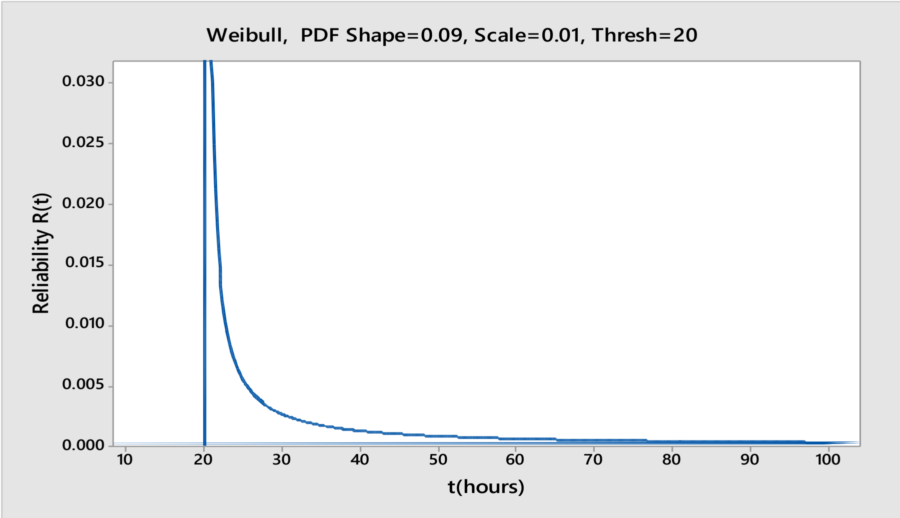

Figure 09. Weibull Reliability Probability Density Function (PDF) for GT02.

Weibull shape parameter of 0.09 as applied for both units as showed in figure 05-09, although the failure rate was high, each Weibull curve compressed on both axes. The vertical axis showed the density of stretchiness of the reliability of both turbines while the horizontal axis showed the minimum life of turbine or the aging condition in hours. The reliability of ST01 and aging condition of unit drop by 3.5% in every 77 hours from the year 2003 to 2012. ST02 reliability, 3% in 68 hours; ST06 reliability, 3.5% in76 hour; GT01 reliability 3% in 75 hours; and GT02 reliability 3% in 84 hour.

IV. Conclusion

Reliability of the thermal power station used as a case study can be achieved by reducing the failure rate of the turbines or subsystems in the power system or by increasing the mean time between failures. Power system reliability can be achieved by reducing the mean down-time. Station units contribute significantly to both system reliability and customer satisfaction. The station could experience more than 30% reliability if units were in full operating capacity. The improvement in system reliability found to be directly proportional to the total installed capacity of units in the generating system. Reliability assessment of the thermal station from the point of assessment of equipment faults preventive maintenance has guarantee very low reliability figure for most of those units assessed in this thesis and as such these cannot guarantee maximum and efficient plant performance. Gas turbine 01 and 02 was most affected. The reliability digit remains at nil for most periods of years assessed. The rate of percentage improvement in system reliability and the reliability of power supply to grid was found to be decreasing with increase in system failure of the installed capacity in the generating system. Finally it can be concluded that the modeling of various systems and the method of reliability evaluation presented in this study were an effective tool for the quantitative evaluation of system. Use of the modeling technique shown in this work especially that of the generating system can help to compare the reliabilities of generating systems and to evaluate and compare the contribution of units to the system. The reliability assessment techniques demonstrated in this thesis can be used as a reliable tool for evaluating various options during the planning or capacity addition stage. Since failure cannot be prevented entirely, it is important to minimize both its probability of occurrence and the impact of failures when they do occur. To maintain the designed reliability and to achieve expected performance, an effective maintenance program is a must and the effective maintenance is characterized by low maintenance cost.

V. References

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