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Multi-Level Risk Assessment of a Power Plant Gas Turbine Applying the Criticality Index Model

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Abstract

Turbines are a major component in Power Plants, utilized in the generation of electricity. To maintain the service lives of these Turbines, studies have shown that they need to be routinely maintained every two years and maintenance crews are encouraged to run a major overhaul at least once every five years. However, Turbine maintenance in Nigerian power generating Plants is unimaginably low; there are incessant plant shut downs, and up to 95% of both foreign and local manufacturers have either shut down production or have wound up altogether. This study was spurred on because of the problems posed by these limitations. Secondary data was taken, containing the failed component parts of a vital Turbine. These parameters were subjected to a Criticality Index Model analysis. Three classifications were thereafter obtained from the four suggested in this study. The failed component parts in severity Class I are grouped as catastrophic, and the failure of these parts could lead to complete system shut down because the failure of these parts could lead to the failure of other parts. The component parts in severity Class II, are grouped as being critical, and could make the plant unavailable for a long time but the failed component parts may not affect the other parts adversely. None of these component parts fitted the criteria that guided severity Class III. The failed component parts in severity Class IV may not affect adversely other parts in the Turbine but could make the Turbine unavailable for a short time. This study has carefully shown and expressed a step by step computation of the severity level of the Turbine component parts, using the Criticality Index model.

1 Introduction:

A gas turbine is a rotary engine that extracts energy from a flow of combustion gas. In all modern Gas Turbine engines, the engine produces its own pressurized gas, and it does this by burning either propane, natural gas, kerosene or jet fuel. The heat that is generated from burning any of these fuels expands trapped air, and the attendant high speed rush of this hot air spins the Turbine [3]. Invariably, higher combustion temperatures mean greater efficiency. [4] wrote that Gas Turbines transform the thermal energy generated by fuel combustion into mechanical energy, which in turn rotates the electrical generator's shaft. The exhaust gas is used to produce steam in a steam generator that is part of the steam cycle. They stated further that all Gas Turbines possess essentially the same subsystems, such as compressors, a combustion chamber and a turbine.

This study focuses on the assessment of the reliability of the component parts [8] and the creation of a result oriented maintenance policy suggesting either a corrective or preventive maintenance task that would be cost effective, increase productivity and reduce component part failure rates to the barest minimum [11].

The model that is used to determine the severity of failure of the Gas Turbine component parts is the Criticality Index Model. Patev et al [10] defined Criticality as a relative measure of the consequences of a failure mode and its frequency of occurrence. Criticality was also summarized as a procedure that uses each potential failure mode of a component in combination with the influence of both severity and failure mode probability used in calculating the Criticality Index that would be different for each failure mode and allow a distinction between critical and non critical modes. The Criticality Index expresses how often a particular task was on the critical path during the assessment. Tasks with a high criticality index are more likely to cause delay to the project completion as they are more likely to be in the critical path.

Patev et al [10] wrote that the main purpose of the criticality analysis is to rank every possible failure mode for a particular component identified in a Failure Modes and Effects Analysis (FMEA). The primary advantage of using criticality analysis is that it provides a common basis and consistent method for comparing various failure modes of a component.

Several models have been used to assess the severity or hazardous situation of component parts failures. One of such

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models is the Probability Failure Functions [1]. Andrawus et al [2] emphasized the use of a Hybrid of Reliability Centered Maintenance (RCM) and Asset Life Cycle Analysis (ALCA). These models were used to determine suitable maintenance strategies for Wind Turbines and also the Delay- time maintenance mathematical model. Hines and Usynin [7] mentioned some mathematical ,models to track the degradation (damage) of equipments. These are the Markov Chain-based Models, Shock Models and General Path Models.

In this study, the Criticality Index model has aided in assessing the levels or categories of the Gas Turbine component parts degradation and therefrom, suggesting maintenance strategies of how such failures can be averted.

2. Methodology

The methods and models used here, were those proposed by [6] and used for the calculation of failure parameters in section three. The selection criteria shown in Tables 1 - 3 are used to classify and evaluate the level of hazard severity of a particular group of failed components.

2.1. Selection Criteria

In determining the level of severity of failed machine components, failure occurrences over the operating time interval is considered by adopting the criteria [6], shown in Table 1, 2, and 3.

Table 1: Probability of Component Failure

Level A : frequent: High probability of failure: $\rho \geq 0.20$
Level B: Probable: Moderate probability of failure: $0.10 \leq \rho < 0.20$
Level C: Occasional: Marginal probability of failure: $0.01 \leq \rho < 0.10$
Level D: Remote: Unlikely probability of failure: $0.001 \leq \rho < 0.01$

The classification of severity is categorized according to Table 2

Table 2: Classification of Severity

Category I: Catastrophic: Significant system failure occurs that can result in injury, loss of life, or major damage
Category II: Critical: Complete loss of system occurs, performance is unacceptable
Category III: Marginal: system is degraded, with partial loss in performance
Category IV: Negligible: Minor failure occurs, with no effect on acceptable system performance

The conditional probability, β that failure mode K will result in the failure effect was selected from a range of values as shown in Table 3

Table 3:Conditional Probability values

Failure effect	β
Certain	$\beta = 1.00$
Probable	$0.10 < \beta < 1.00$
Possible	$0 < \beta \leq 0.10$
no effect	$\beta = 0$

3. Presentation of Results

3.1 Determination of Mean Time to Failure (MTTF)

The intensity function $\rho\left(t\right) = abt^{b-1}$ (1)

is considered in determining MTTF, where t is the cumulative failure time and T is the observed system failure time. The parameters a and b are obtained using the least squares curve technique expressed in (2) and (3).

$$b = \frac{n}{n1n\ \mathrm{T} - \sum_{i=1}^{n} 1n\ \mathrm{t}_i} \tag{2}$$

and

$$a = \frac{n}{T^b} \tag{3}$$

Therefore, MTTF is expressed as

$$MTTF = \frac{1}{\rho\left(T\right)} \tag{4}$$

Considering the values in columns 1 – 3 of Table 4 generated from records of experimental results and applying (1) – (4), we have,

$$b = \frac{30}{30\ 1\mathrm{n}\left(900\right) - 162.339712}$$

$$= 0.718871$$

$$a = \frac{30}{900^{0.718871}} = .225633$$

Substituting the values of a and b into (1), to determine the intensity at the end of the test, we obtain

$$\rho\left(t\right) = \left(0.225633\right)\left(0.718871\right)t^{0.718871-1}$$

$$= 0.162201t^{-0.281129}$$

$$\rho\left(t = T\right) = 0.162201\left(900\right)^{-0.281129}$$

$$= 0.023962$$

The MTTF at the end of the testing is then,

$$MTTF = \frac{1}{\rho\left(900\right)} = \frac{1}{0.023962} = 41.732 \text{ years}$$

At 95 percent confidence interval for the power law intensity model for type 1 testing in obtaining the new values MTTF, with N = 30, would give
0.604 x 41.732 = 25.206 hr for l
1.7383 x 41.732 = 74.408 hr for u
L and u are power law intensity parameters

Table 4: Gas Turbine Component Failure Record

	No. of part	Failure time in hours (1) x10^2	No. of Component removal	Cumm. Failure time in hours (2) x 10^2	In (Failure time (3)	No. of failure Occurrence (4)	Probability of occurrence (5)
Turbine - Unit Control system	10	17	0	17	2.833213	20	0.038
Turbine - Lube oil system	20	28	3	45	3.806662	60	0.113
Turbine - Starting system	10	12	1	57	4.043051	10	0.019
Turbine - Fuel feeding system	10	16	3	73	4.290459	20	0.038
Turbine - Hydraulic oil system	20	28	0	101	4.615121	23	0.043
Turbine - Air filtering system	30	10	2	111	4.709530	7	0.013
Turbine - Adj nozzles control system	60	14	4	125	4.828314	8	0.015
Turbine - IGV control system	20	3	0	128	4.852030	2	0.004
Turbine - Unit protection system	40	4	1	132	4.882802	1	0.002
Turbine - Antisurge system	10	15	0	147	4.990433	4	0.008
Turbine - Control oil system	20	7	2	154	5.036953	14	0.026
Turbine - Steam/water injection system	20	9	1	163	5.093750	2	0.004
Turbine - Oil vapour ejection system	20	6	1	169	5.129899	6	0.011
Turbine - Enclosure ventilation system	30	6	0	175	5.164786	2	0.004
Turbine - Compressor & HP turbine rotor	10	9	1	184	5.214936	6	0.011
Turbine - LP turbine rotor	20	4.2	1	188.2	5.237505	3	0.006
Turbine - Journal bearings	100	80.6	10	268.8	5.593968	62	0.017
Turbine - Thrust bearings	50	44.2	7	313	5.746203	34	0.064
Turbine - Burners	30	9	2	322	5.774552	14	0.026
Turbine - Combustion chamber liners	250	122	10	444	6.095825	63	0.119
Turbine - Transition piece	40	19	0	463	6.137727	17	0.032
Turbine - Compressor vanes	250	4	0	467	6.146329	4	0.008
Turbine - Hp turbine nozzles	60	41	4	508	6.230481	38	0.072
Turbine - LP turbine nozzles	60	52	6	560	6.327937	42	0.079
Turbine - Regenerator	10	18	0	578	6.359574	10	0.019
Turbine - Accessory gear	40	26	0	604	6.403574	18	0.034
Turbine - Auxiliary generator	10	21	0	625	6.437752	7	0.013
Turbine - Generator	10	240	0	865	6.762730	16	0.030
Turbine - Gen. lubrication system	20	25	1	890	6.791221	12	0.023
Turbine - Exhaust system	20	10	2	900	6.802395	5	0.009
Total	1400				162.339712	530	

Subjecting the failure parameters to verification process. [9] proposed Eq 5

$$\lambda = \frac{\chi^2}{2t} \tag{5}$$

Where t is the failure time. From the χ^2 distribution, the calculated χ^2 = 14.65x2(17) = 498.1

The table value gives $\chi^2{}_{2n=60,\,5\%} = 43.32$

Since the calculated value is greater than the table value, i.e, $\chi^2{}_{cal} \rangle\, \chi^2{}_{table}$, it indicates that there is a probability that 17 years could be the statistical threshold value with a chi-square distribution of 2n degree of freedom needed for the 30th failure to occur.

3.2. Determination of failure Rate, λ

The average failure rate over the interval (t_1, t) is

$$\lambda = \frac{t_1}{M\,,\left(t - t_1\right)}\left[\left(\frac{t}{t_1}\right)^{1-\alpha} - 1\right] \tag{6}$$

An approximate value for the growth parameter is given by

$$\alpha = -1n\left(\frac{T}{t_1}\right) - 1 + \left\{\left[1 + 1n\left(\frac{T}{t_1}\right)\right]^2 + 2\ 1n\left(\frac{M_F}{M_1}\right)\right\}^{0.5} \qquad (7)$$

Where t is the cumulative test time, M_1 is the average MTTF over the initial test cycle, t_1 is the length of initial test cycle in cumulative test time, α is the growth parameter, M_F is the final MTTF at the end of the growth program having a cumulative test time of T

$$\alpha = -1n\left(\frac{900}{17}\right) - 1 + \left\{\left[1 + 1n\left(\frac{900}{17}\right)\right]^2 + 2\ 1n\left(\frac{740408}{25.206}\right)\right\}^{0.5}$$

$$\alpha = 0.213$$

$$\lambda = \frac{17}{25.206}\left[\left(\frac{900}{17}\right)^{1-0.213} - 1\right]$$

= 14.65 hours

Standard deviation = $1/\lambda = 0.068$

The variance = $1/\lambda^2 = 0.0047$

From Table 4, Table 5 was generated. Subjecting Table 5 to the conditions in Table 1, the Turbine's component parts were classified. This classification lead to the determination of the fraction of the component parts failures in their different failure mode, α_{kp} used for obtaining the criticality index.

3.3. Determination of Conditional Probability P_i

The following parameters were used to determine the conditional probability factors used in this study

$$H_i = H_{i-1} - t_{i-1} - C_{i-1} \qquad (8)$$

$$H_i^1 = H_i - \frac{C_i}{2} \qquad (9)$$

$$P_i = 1 - \frac{t_i}{H_i^1} \qquad (10)$$

Pi = conditional probability of surviving the ith interval given survival to time, t_{i-1}

$\frac{t_i}{H_i^1}$ = Conditional probability of a failure in the ith interval given survival to time , t_{i-1}

Where

t_i = number of failures in the ith interval

C_i = number of removals in the ith interval

H_i = number of risk at time , t_{i-1}

H_i^1 = adjusted number at risk assuming that the removal times occur uniformly over the interval

Table 5: Classification of the Gas Turbine Component Parts

Level of Failure mode	Gas turbine components	Probability of Occurence	Cummulative probability of Occurrence		
D	Turbine - unit protection system	0.002	0.002	$\alpha_p = 0.045$	4
	Turbine - IGV control system	0.004	0.006		3
	Turbine - Steam/water injection system	0.004	0.010		9
	Turbine - Enclosure ventilation system	0.004	0.014		6
	Turbine - Lp turbine rotor	0.006	0.020		4.2
	Turbine - Compressor vanes	0.008	0.028		4
	Turbine - Antisurge system	0.008	0.036		15
	Turbine - Exhaust system	0.008	0.045		10
					55.2
C	Turbine - Starting system	0.019	0.019	$\alpha_p = 0.62$	12
	Turbine - Fuel feeding system	0.038	0.057		16
	Turbine - Hydraulic oil system	0.043	0.114		28
	Turbine - Air filtering system	0.013	0.127		10
	Turbine -Adj nozzles control system	0.015	0.142		14
	Turbine - Control oil system	0.026	0.168		7
	Turbine - Oil vapour ejection system	0.011	0.179		6
	Turbine - Compressor & HP turbine rotor	0.011	0.190		9
	Turbine - Thrust bearings	0.064	0.254		44.2
	Turbine - Burners	0.026	0.280		9
	Turbine - Transition piece	0.032	0.312		19
	Turbine - HP turbine nozzles	0.072	0.384		41
	Turbine - LP turbine nozzles	0.079	0.463		52
	Turbine - Regenerator	0.019	0.482		18
	Turbine - Accessory gear	0.034	0.516		26
	Turbine - Auxiliary generator	0.013	0.529		21
	Turbine - Generator	0.030	0.559		240
	Turbine - Gen. lubrication system	0.023	0.582		25
	Turbine - Unit control system	0.038	0.620		17
					614.2
B	Turbine - Lube oil system	0.113	0.113	$\alpha_p = 0.349$	28
	Turbine - Journal bearings	0.117	0.230		80.6
	Turbine - Combustion chamber liners	0.119	0.349		122
					230.6

Eqs (7) – (9) were used to generate Table 6, utilizing the values in Table 4 and 5.

Table 6: Conditional Probability Determination Table

	t_1	C_i	N	H_i	H_i^1	P_i
D	4	1	40	410	409.5	0.990
	3	0	20	405	405	0.992
	9	1	20	402	401.5	0.978
	6	0	30	392	392	0.985
	4.2	1	20	386	385.5	0.989
	4	0	250	380.8	380	0.990
	15	0	10	376.8	376.8	0.996
	10	2	20	361.8	360.8	0.972
			410			7.892
						0.987
C	12	1	10	520	519.5	0.977
	16	3	10	507	505.5	0.968
	28	0	20	488	488	0.943
	10	2	30	460	459	0.978
	14	4	60	448	446	0.969
	7	2	20	430	429	0.984
	6	1	20	421	420.5	0.986
	9	1	10	414	413.5	0.978
	44.2	7	50	404	40.5	0.890
	9	2	30	352.8	351.8	0.974
	19	0	40	341.8	341.8	0.944
	14	4	60	322.8	320.8	0.872
	52	0	60	277.8	274.8	0.811
	18	0	10	219.8	219.8	0.918
	26	0	40	201.8	201.8	0.871
	21	0	10	175.8	175.8	0.881
	240	0	10	154.8	154.8	$\boxed{-0.550}$
	25	1	20	−85.2	−85.7	$\boxed{1.292}$
	17	0	10	−111.2	−11.2	$\boxed{1.153}$
			520			14.944
						0.934
B	28	3	20	370	368.5	0.924
	80.6	10	100	339	334	0.759
	122	10	250	248.4	243.4	0.499
			370			2.182
						0.727

3.4.. Computation of Criticality Index

Here, the criticality index is used to determine the level of severity of plant component failure. The index is related by

$$C_k = \alpha_{kp} \; \beta_k \; \lambda_p \; t \tag{11}$$

Where, C_k is the criticality index for failures mode K, α_{kp} is the fraction of the component p's failures having failure mode k, β is the conditional probability that failure mode k will occur in the identified failure effect; λ is the failure rate.

Table 6 shows the computed criticality index for the various severity class.

Table 7: The computed criticality index for the various severity class

Level of Probability of Occurence	Severity Class	λ_p	t	β	α_p	C_k
D	*IV*	14.65	55.2	0.987	0.045	35.92
C	*I*		614.2	0.934	0.62	5210.58
B	*II*		230.6	0.727	0.35	785.93

4. Discussion of Result

A gas turbine that has been in operation for 20 years is investigated. There has been several downtimes recorded as a result of various component failures. The probability of failure occurrence necessitated the separation of components into groups, to aid in determining the level of failure severity. This was thereafter used to determine the criticality index of each severity class.

From the data shown in Table 4, the mean time to failure occurrence in the gas turbine system was 41.732 years which lead to a failure rate of 14.65 years. In a steady state condition, the standard deviation of the failure rate from its mean is 0.068 years with a corresponding variance of 0.0047 years. The probability of occurrence was used to measure the effect of component failure on the entire gas turbine system. The values in Table 5 and Equation (10) were used to compute the criticality index which was used to select the severity class of each range of turbine components in a group.

The criticality index for severity class I, II, and IV was 5210.58, 785.93 and 35.92. This means that components in class I are catastrophic, that is, there would be system shutdown due to large component failures as a result of lack of preventive and corrective plant maintenance operation; huge plant cost would accrue due to these losses. According to [4], Turbine component parts in Class I occurred when a component potential failure mode can cause severe damage to other components and / or to the equipment. This failure in their opinion can also cause the need for repair and / or replacement of a great number of components. These failed components can make the Turbine to be unavailable for a long period of time.

Class II components could be critical and also cause mass components' failure which would greatly and adversely affect the turbine's performance. This circumstance is deemed unacceptable. Carazas and Martha de Souza [4] were of the opinion that this severity Class contains component potential failure mode that can cause the unavailability of the equipment but does not cause damage to other equipment components. This failure mode also causes the need for repair and/ or replacement of the failed components. The Turbine could be unavailable for a long period of time. Class IV indicates that the component failure is minor and not expected to have any significant effect on the entire turbine until such a time that the turbine is expected to undergo normal maintenance checks. Carazas and Martha de Souza [4] in their study said that the severity in Class IV contains component potential failure mode that can cause the unavailability of the equipment but does not cause damage to other equipment components. This failure also causes the need for repair and / or replacement of the failed component. The Turbine is expected to be unavailable for a short period of time.

The Criticality Index values provided the information used to allocate maintenance task to components depending on their failed state before a major or catastrophic failure occurs. As the Criticality Index increases, the failure of the component parts can cause severe degradation in the Gas Turbine's performance significantly reducing the power output of the generator coupled to the Turbine shaft which affects the Gas Turbine main function [4].

Conclusion

The level of severity of failed gas turbine components was successfully investigated by determining the criticality index of each severity class. The criticality index model categorizes the amount of component parts damaged, so that the root cause of failure in the defective parts can be specifically identified. It also suggests an easy, and corrective action that is cost effective when applied within a reasonable time frame. The level of component failure in group C with severity class I, should be given a higher maintenance preference, followed by component failures in group B with severity class II, and finally, component failures in group D with corresponding severity class IV. This model is most appropriate and best suited for situations where there are fewer gas turbines, but with large product output and demand. The procedure adopted in this study has elucidated a step by step problem solving process. This model actually considers the interactive relationship between component parts and their performance in a complex environment, which is an improvement on other existing models such as the probabilistic risk assessment method [12], failure modes and effects analysis, and fault tree analysis [5].

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