Optimization of IBOM Power Plant (PG9171) using Fault Prediction on Gas Path Analysis

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Abstract— *Almost from the inception of the gas turbine engine (GT), users and engine manufacturers have sought an effective technique to determine the health of the gas-path components (fan, compressors, combustor, turbines) based on available gas-path measurements. The potential of such tools to save money by anticipating the need for overhaul and providing help in work scope definition is substantial, provided they produce reliable results. It furthermore therefore became desirable to monitor the engine performance and diagnose the fault even before the damage is done since the fault can cause permanent damage to the components. Preventive maintenance proves to be a better way considering the longer run. This project thus work describes how modern gas-path analysis can be used as a tool for gas turbine diagnosis. Gas path analysis is studied with the aid of fault predictions obtained from using fuzzy logic was found to be a more suitable method for gas turbine diagnosis because the set of fuzzy rules are described using common language. MATLAB Simulink environment is also used to predict the degree of fault in the gas turbine through its Gas path analysis. The linguistic variables used as inputs are temperature, pressure and speed while the linguistic variable used as output is failure. The universe of discourse for temperature is between [0, 55], pressure is [0, 1000], shaft speed is [0, 5000] and failure which is the fault is [0, 1]. A type 1 fuzzy logic model and the center of gravity method are used as the defuzzification module. From the results it is seen that the value for the highest possible fault is 0.909 and the lowest is 0.217 at 6.3 and 52.7 ^{O}C respectively. This research shows that the fault prediction probability increases at higher operating conditions of the gas turbine.*

***Keywords*— Gas Turbine, Fault Prediction, Gas Path Analysis, MATLAB Simulink, Fuzzy Logic.**

I. INTRODUCTION

The gas turbine is the most versatile item of turbo machinery today [1]. It can be used in several different modes in critical industries such as power generation, aviation, marine propulsion etc. However, the need to develop accurate and reliable models of GT for different objectives and applications has been a strong motivation for researchers to continue to work in this fascinating area.

This lends credence to the fact that models and control methodologies, based on white-box approaches rely on thermodynamic and energy balance equations, which are coupled and have a high degree of nonlinearity [2]. Consequently, models and control systems that are built with such simplified and/or non linearized equations are not accurate enough to capture system dynamics precisely. These models cannot account for the individual nuances of operating equipment and are not able to accommodate changes as the equipment ages [1]. Therefore, considering assumptions and using linearization methods for simplification and solving these complex dynamics are unavoidable.

The basic operation of a GT is Brayton cycle with air as the working fluid. The machine has three main components. The compressor which draws air into the turbine and pressurizes it, the combustion system typically made up of fuel injectors that injects a steady stream of fuel into the combustion chamber where it mixes with the air and burned at a temperature of more than 1093^{o}C producing a high temperature- high pressure gas stream and the turbine made up of an intricate array of alternate stationary and rotating aerofoil section blades where the high temperature-high pressure gas expands and spins the rotating blade of the turbine. The rotating blade of the turbine performs a dual function. They drive the compressor to draw more compressed air into the combustion chamber and they spin a generator to produce power. A fourth component is often used to increase efficiency (turboprop, turbofan) to convert power into mechanical or electrical form (turbo shaft, electric generator) or to achieve greater power to mass/volume ratio (after burner).

There is a rich source of research activities in the area of modeling, simulation optimization and control of GT, particularly using thermodynamic analysis and very few on other methods. However, in spite of all the efforts already done in this all important field, there is need to redirect our attention and focus extensively to other tools, models and software in order to resolve problems encountered during the processes of design, manufacturing, operation, maintenance and optimization of GT.

The following problem can be highlighted in the existing models and control systems of GT: The models and control methodologies, based on thermodynamic and energy balance equations, which are coupled and have a high degree of nonlinearity are not accurate enough to capture system dynamics precisely [3]. These models cannot account for the individual nuances of operating equipment and are not able to accommodate changes as the equipment ages, deteriorate gradually losing their operability and efficiency.

Therefore, considering assumptions and using gas path analysis to develop accurate and reliable models of GT for different objectives, application, simplification and solving these complex dynamics are unavoidable. Fault prediction offers such potentials and shall be utilize to develop a model for the performance optimization of GT in this work. This research shows how the application of fault prediction on the gas path parameters can be used for engine performance monitoring and targets the detection of core engine deterioration. Gas path analysis (GPA) technique is used to access the condition of individual engine component based on the aero-thermodynamic relationship that exists between components and direct measurement of gas path parameter.

II. RESEARCH GAP

This section shall present a comprehensive overview of some paramount research related to this work covering both the use of condition monitoring and gas path analysis. Odokwo et al applied graph networks approach to analyze and model a single-shaft open-cycle GT [4]. They used graph theory and algorithms to identify pressure and temperature drops, work transfer rates, rate of heat, and other system properties. Shalan et al investigated the comparative study on modeling of gas turbines in combined cycle power plants [5].

Simulink-VISUAL BASIC was used to investigate the stability of the turbine and its control system against overheat, as well as changes in frequency and load. The results showed that the existence of speed, frequency, and air control loops were necessary for the plant stability against disturbances. MarekDzida and Olszewski conducted a study on Comparing combined GT/steam turbine and marine low speed piston engine/steam turbine systems in naval applications [6].

The Monitoring and supervision of performance degradation is a widely studied topic in the gas turbine diagnosis research field where the performance parameters are estimated with different methods. If reliable performance estimations are available, it can be easier for the service engineers to efficiently plan service and maintenance of the gas turbine [7]. Saravanamuttoo *et al* investigated how compressor fouling affects the performance parameters using a linear fouling model [8].

Gas path analysis has a big influence on the gas turbine engine health and control. It has become one of the techniques in favour of condition maintenance strategy [9]. According to Jasmani *et al* the effectiveness of GPA using the measurement set selected with the introduced measurement selection method are then compared with the result of using standard measurement installed on existing GT [10]. Sajeev opined that GPA is very useful in terms of obtaining quantitative values of deterioration for multiple faults [11].

Urban stated that measurable engine parameters are treated as dependent variables, changes in which are mathematically interrelated to changes in component performance brought about by physical engine faults [12]. Provost stated that techniques are also presented for determining the gas path measurement in a GT that are needed to enable the required analysis of component changes and/or sensor biases to be performed [13].

III. METHODOLOGY

The gas turbine under study is PG9171 manufactured by general electric. It operates at a speed of 5000rpm. The gas turbine is used for electric power generation and has an output power of 132MW. It has an efficiency of 34.6%. The maximum and minimum ambient temperatures are 267K and 326K respectively. The technical descriptions of the above stated GT is shown in appendix A. The concept applied is based on GPA and AI. It relies on performance parameter trending at standardized conditions so that it can be compared to actual performance. As discussed earlier, a deviation in the measured gas parameter can be accounted because of the deviation in component health [4].

3.1 Thermodynamic Theory of Gas Turbine

In the GT cycle (topping cycle) as shown in fig 1, the air is compressed isentropically in the compressor from state 1 to 2 where its temperature rises from T_1 to T_2.The compressed air then enters the combustion chamber where the combustion of fuel takes place isobarically [14]. According to Ogbonnaya and Ugwu the thermodynamic theory is shown below:

The relationship between gas path measurable parameters is:

$$\frac{T_2}{T_1} = (\mathrm{rp})^{\gamma-1/\gamma} \quad (1)$$

$$T_2 = \mathrm{T}_1(\mathrm{rp})^{\gamma-1/\gamma} \quad (2)$$

And

$$T_3 = \mathrm{T}_4(\mathrm{rp})^{\gamma-1/\gamma} \quad (3)$$

Where,

T_1 = Compressor inlet temperature

T_2 = Compressor outlet temperature

T_3 = Turbine inlet temperature

T_4 = Turbine outlet temperature

r_p = Pressure ratio denoted by $\frac{P2}{P1}$

The work done by compressor is given as;

$$W_C = MC_p(T_2 - T_1) \quad (4)$$

Heat supplied to the combustor component

$$Q_{23} = MC_p(T_3 - T_2) \quad (5)$$

The Work done at turbine is given as;

$$W_T = MC_p(T_3 - T_4) \quad (6)$$

Heat rejected by the system is given as;

$$Q_{41} = MC_p(T_4 - T_1) \quad (7)$$

Where M = mass of air

C_P = specific heat capacity of air at constant pressure

According to Cengel and Boles thermal efficiency of the gas turbine can be calculated using [15].

$$\eta = \frac{MCp\,(T3-T4)-MCp\,(T2-T1)}{MCp\,(T3-T2)} \quad (8)$$

This can also be written as;

$$\eta = \frac{W_T - W_C}{Q_{23}} \quad (9)$$

Compressor Health Parameter

$$S_{fc}, f_c = \frac{Gc,cor,deg}{Gc,cor} \quad (10)$$

$$\Delta S_{fc}, f_c = \frac{(Gc,cor,deg - Gc,cor)}{Gc,cor} \quad (11)$$

$$S_{fc}, E_{ff} = \frac{\eta c,deg}{\eta c} \quad (12)$$

$$\Delta S_{fc}, E_{ff} = \frac{(\eta c,deg - \eta c)}{\eta c} \quad (13)$$

Where,

S_{FC}, F_C =Compressor flow capacity index

Gc, cor = Compressor corrected flow when the compressor is healthy

$G_{C,cordeg}$= Compressor corrected flow capacity when the compressor is degraded

$S_{FC,} E_{ff}$ = Compressor isentropic efficiency index

ηc= Compressor isentropic efficiency index when the compressor is healthy

$\eta c_{,deg}$= Compressor isentropic efficiency index when the compressor is degraded

Combustor Health Parameter

$$S_{fB}, E_{ff} = \frac{\eta B, deg}{\eta B} \quad (14)$$

$$\Delta S_{fB}, E_{ff} = \frac{\eta B, deg - \eta B}{\eta B} \quad (15)$$

Where,

$S_{FB,}E_{FF}$ = Combustor isentropic efficiency index

$\boldsymbol{\eta}_B$ = Combustor efficiency index when the combustor is healthy

$\boldsymbol{\eta}_{B,deg}$ = Combustor efficiency index when the combustor is degraded

The performance of actual combustor can be expressed as follows;

$$\boldsymbol{\eta}_{B,deg} = \vec{f}(\text{ load, } \Delta S_{FB,}E_{ff}) \quad (16)$$

Where, Load = engine load power

Turbine Health Parameters

$$S_{FT,}F_C = \frac{(GT, cor, \deg)}{GT, cor} \quad (17)$$

$$\Delta S_{FT,}F_C = \frac{(GT, cor, deg - GTcor)}{GT, cor} \quad (18)$$

$$S_{FT,}E_{ff} = \frac{(\eta T, \deg)}{\eta T} \quad (19)$$

$$\Delta\ S_{FT,}E_{ff=} \frac{\eta T, deg - \eta T)}{\eta T} \quad (20)$$

Where,

$S_{FT,}F_C$ = Turbine flow capacity index

$G_{T,cor}$ = Turbine corrected flow when the turbine is healthy

$G_{T,cor,deg}$ = Turbine corrected flow when the turbine is degraded

$S_{FT,}E_{FF}$ = Turbine isentropic efficiency index

$\boldsymbol{\eta}_T$ = Turbine isentropic efficiency when the turbine is healthy

$\boldsymbol{\eta}_{T,deg}$ = Turbine isentropic efficiency when the turbine is degraded

3.2 Gas Path Analysis

The GPA algorithm can be summarized into the main steps:

(i) measurement normalization

(ii) reference value generation,

(iii) estimation of performance deviation, and

(iv) diagnosis decision and this algorithm was introduced by Urban

The GPA method is based on thermodynamic relationships where one of the main objectives is to estimate deterioration in gas path components from a number of measured sensor signals which are denoted as measurement deltas (Δ). These equations could be used to estimate steady state and transient variations in the performance parameters for an arbitrary gas turbine engine during most conceivable sets of input conditions

$$\Delta Y = X\Delta X + C \tag{21}$$

Where, ΔY is the gas path measured parameter deltas, Δx is the deviation in performance, X is the influence coefficient matrix presented in Urban (1992), and C is the measurement noise. Elements in ΔY are typically: spool speeds ΔN, temperatures ΔT, and pressures ΔP. Elements in ΔX are typically: efficiencies Δη, and flow capacities ΔΓ of the gas path components such as compressors, turbines, and fans. The matrix X can be divided into two parts:

(i) An engine fault influence matrix Xe, and

(ii) A sensor fault influence matrix Xs, where the previous defined matrix X and health parameter Δx in equation (10) is extended with the sensor fault dependencies. To simplify the mathematics, the sensor measurement noise vector is assumed to be Gaussian with a zero mean.

IV. RESULT AND DISCUSSION

The number of rules used in this system is 27, calculated as $Terms^{Variables} = 3^3 = 27$. The fuzzy rule shows the combination of the MF terms used to determine the extent of the fault and generate five linguistic terms in the fault probability which are very low (VL), low (L), moderate (M), high (H) and very high (VH). The fuzzy rule used in this project is presented in table 2.

TABLE 2
FUZZY RULES

	A	B	C	D
1	Temperature	Pressure	Shaft Speed	Fault Probability
2	L	L	L	VL
3	L	L	M	VL
4	L	L	H	L
5	L	M	L	VL
6	L	M	M	L
7	L	M	H	M
8	L	H	L	L
9	L	H	M	M
10	L	H	H	H
11	M	L	L	VL
12	M	L	M	L
13	M	L	H	M
14	M	M	L	L
15	M	M	M	M
16	M	M	H	H
17	M	H	L	M
18	M	H	M	H
19	M	H	H	VH
20	H	L	L	L
21	H	L	M	M
22	H	L	H	H
23	H	M	L	M
24	H	M	M	H
25	H	M	H	VH
26	H	H	L	H
27	H	H	M	VH
28	H	H	H	VH

4.1 Membership Function Plot for Faults

The fault prediction values (y axis) is taken between 0.217 and 0.909 and the number of points (x axis) is as shown in table 2. The result is shown in figure 3 to 6, it can be seen that the value for the highest possible fault (y axis) is 0.909. It was observed that at higher temperature, pressure and shaft speed as shown in fig 4 to fig 6 that there is a rapid increase in fault prediction which increases the probability of failure of operating the gas turbine at these conditions.

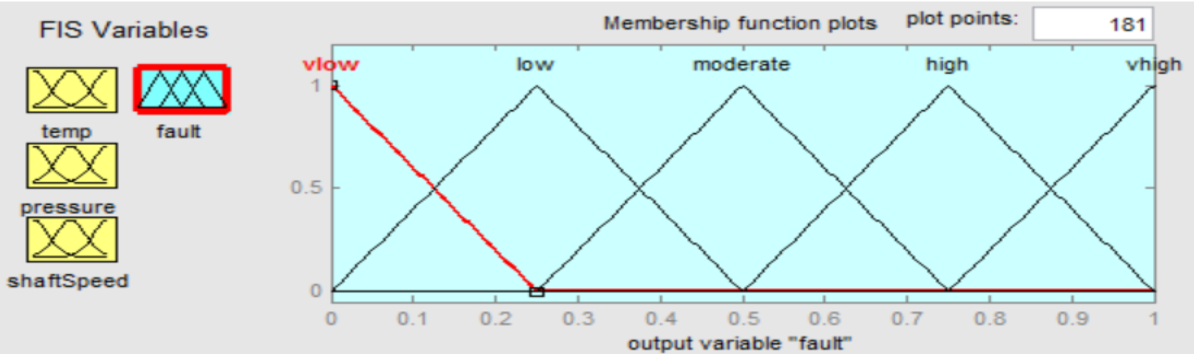

FIGURE 3: Membership function plot for Failure

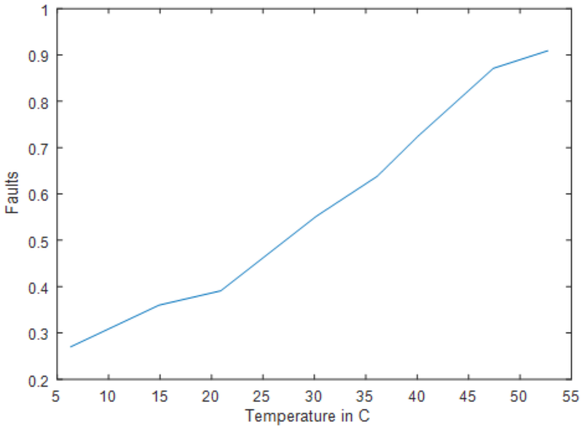

FIGURE 4: Temperature against Faults

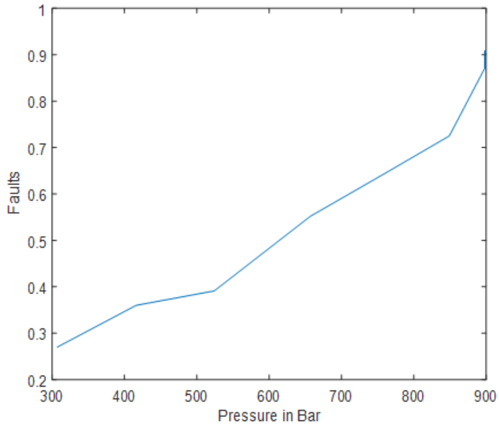

FIGURE 5: Pressure against Faults

There is rapid increase in temperature at 23 ^{0}C to 48 ^{0}C and a relative change from 0.4 to 0.909 in faults prediction. These changes can be seen to cause a bend in the figures above and faults is most likely to occur at this. The GT will experience less occurrence of faults from 5 ^{0}C to 20 ^{0}C.

There is rapid increase in pressure from 580 to 900 bar and a relative change from 0.44 to 0.909 in faults prediction. These changes can be seen to cause a rapid rise in the figures above and faults is most likely to occur. The GT will experience fewer occurrences of faults from 400 to 500 bar.

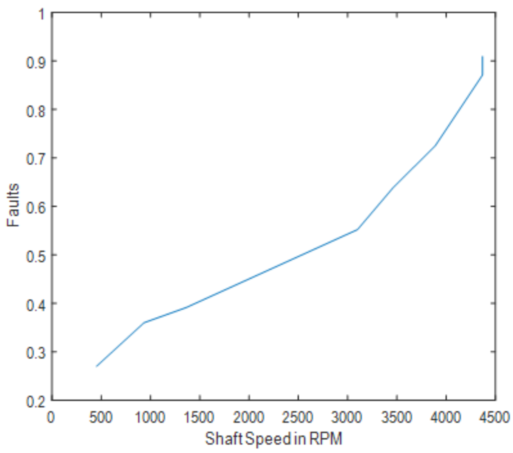

FIGURE 6: Shaft Speed against Faults

There is rapid increase in shaft speed from 3500 to 4500 rpm and a relative change from 0.6 to 0.909 in faults prediction. These changes can be seen to cause a rapid rise in the figures above and faults is most likely to occur. The GT will experience fewer occurrences of faults from 1000 to 3200 rpm. The input parameters as stated earlier are temperature, pressure and shaft speed and the output is the fault prediction. The Figures above shows the graphical representation of the input parameters on fault prediction.

V. CONCLUSION

Gas turbines are fielded as an attractive alternate power source. Although its dominance in industry and military application continues to be strong, the risk of running each unit within their safety margin has caused many eyebrows to be raised. The risk in this context is maintainability and reliability. That is why it is important to prevent to machine from break down through preventive maintenance as this will go a long way to reduce unintentional failure when the machine is needed the most. To this effect, GPA and fault prediction is the way forward for better operation of a gas turbine both in power generation and other applications.

The significant conclusions made from the project are listed below.

- A detailed study of types of gas turbine was carried out.
- Working principles of a GT cycle and their performance are well understood.
- A detailed study on fault prediction was undertaken.
- PG9171 GT of the Ibom Power Plant Company at Ikot Abasi was used as a case study.

5.1 Recommendation

Based on the research project, the following recommendations are made:

- Fuzzy logic should be applied as a useful tool because of its simplicity and its ability to tackle problem of uncertainty.
- Other principal parameters such as Temperature, Pressure and Shaft Speed should be used to analyse condition monitoring of the GT.
- To prevent gas path faults from occurring which leads to breakdown of the machine, the causes of the gas path faults should be dealt with.

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