Gas Turbine Diagnostics Based on Gas Path Analysis

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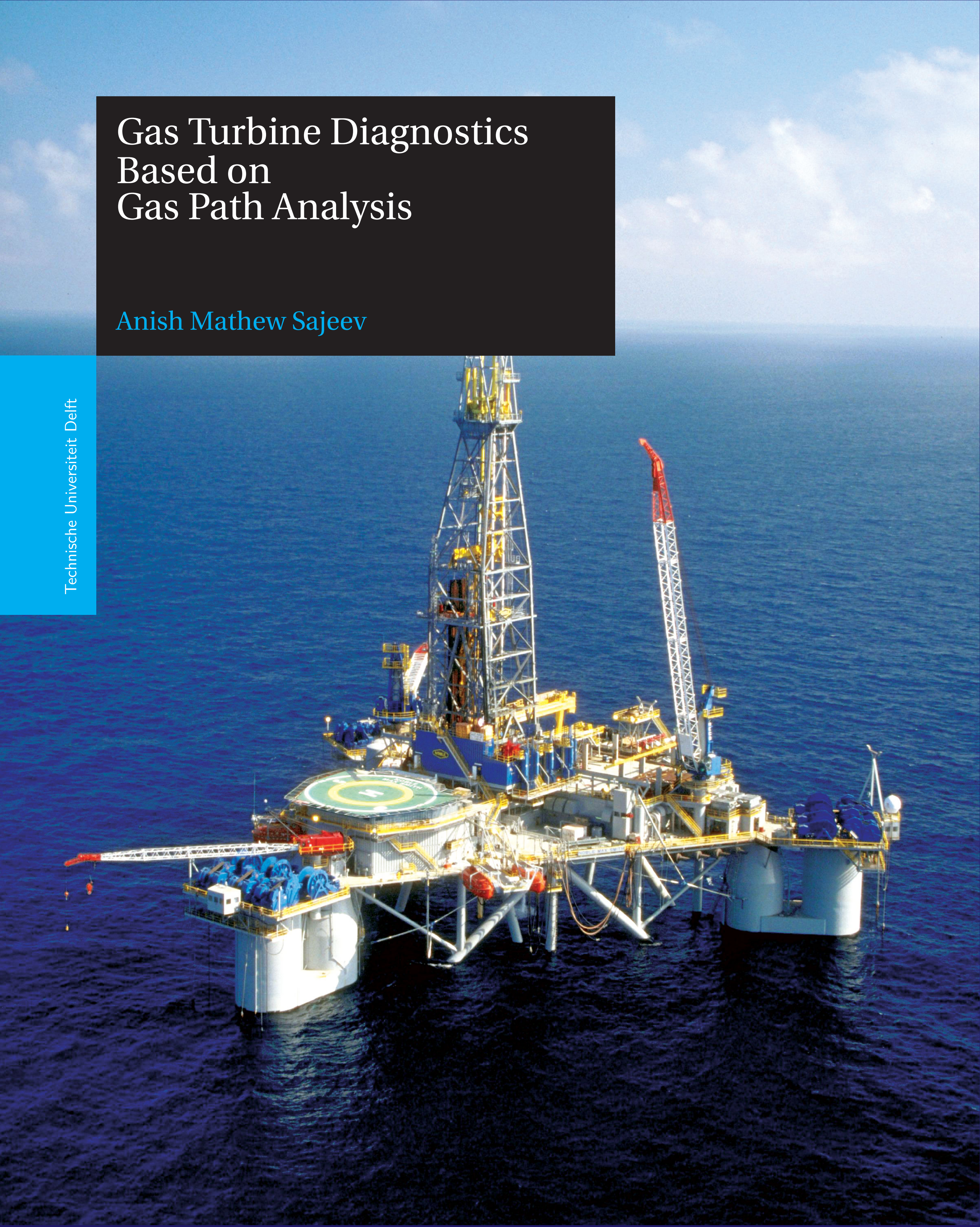

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Challenge the future

Gas Turbine Diagnostics Based on Gas Path Analysis

by

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in partial fulfillment of the requirements for the degree of

Master of Science
in Aerospace Engineering

at the Delft University of Technology,
to be defended publicly on Thursday, August 13th, 2015 at 01:30 PM.

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Summary

Efforts are being made to improve the availability of the machine. Better availability ensures economic operation of the gas turbine saving in the order of millions. One step towards such an approach is to develop real-time monitoring methods. Real-time monitoring allows users to monitor the performance of the gas turbine and ensure proper functioning of the engine. Moreover changes in gas path components can be used to identify the deteriorated components thereby decreasing the downtime of the engine. This project was carried out in collaboration with Shell Global Solutions. The aim of the project is to develop a performance monitoring method and propose a fault isolation mechanism. The study is carried out on a three shaft gas turbine, GE LMS100. This is the latest developed gas turbine with intercooler and is used extensively by the oil & gas industry. The challenge in developing a performance monitoring method for such an engine lies with the configuration of the gas turbine itself. Gas turbine Simulation Program (GSP) is used to model the gas turbine.

Different diagnostic techniques used for performance monitoring of gas turbine are studied and a suitable method is proposed by the end of the project. Component parameters of a healthy engine are simulated using GSP and deviation of operating points from their respective baseline indicates deterioration in performance of the gas turbine. An attempt is made to quantify the deviation in component measured parameters owing to respective deterioration cases. The fault isolation tool created will help in reducing the dependency on expert analysis and reduce downtime of the machine. The proposed method proves to be able to detect, quantify and isolate fault in the gas turbine based on a few indicating parameters. The conclusions and recommendations made from this project can be used to develop a complete engine health monitoring tool.

Acknowledgements

I would like to express my sincere gratitude to my academic supervisor Wilfried Visser and my industrial supervisors Prof. Ian and Lukasz. I received so much support and guidance which helped me in completing my thesis assignment. I gained a lot of technical expertise and developed personal skills while working under them. A special thanks to Lukasz who was my mentor and friend. He made sure that I would face no difficulties during the project and supported me a lot. I also thank Feijia Yin for making my life easy and helped me when I was facing issues with modelling. She always had time to help me and it is an invaluable contribution for my thesis.

I have to mention my friends Deepan Gethu, Paavan and Ashish who supported me during my study. I would also like to thank all my colleagues at Shell Global Solutions for making me comfortable in the team.

I dedicate this work to my dear mom Bobo, who sacrificed a lot of things for me. I would not be here without you loving and supporting me. I can’t express enough how much support I got from Angel, Francis, Nandhu and Preethi. I feel so blessed to have such a loving family. Above all, I praise The Almighty who made it all possible. I thank Him for being with me throughout my life.

Anish Mathew

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Nomenclature

Symbols

A	Cross sectional area	[m^2]
H	Influence coefficient matrix	[-]
F_c	Calibration factor	[-]
J	Jacobian matrix	[-]
N	Shaft speed	[RPM]
P	Total Pressure	[bar]
Pw	Shaft power output	[kW]
R	Universal gas constant	[N m/kg K]
SF	Scaling Factor	[-]
T	Total temperature	[K]
TIT	Turbine inlet temperature	[K]
W	Flow rate	[kg/s]

Greek Symbols

Δ	Change in parameter	[-]
η	Efficiency	[-]
δ	Ratio of pressure to standard sea level static pressure	[-]
ε	Tolerance	[-]
θ	Ratio of temperature to standard sea level static temperature	[-]
ρ	Density	[kg/m^3]
ω	Ratio of actual to reference power turbine inlet temperature	[-]

Subscripts

1	Gas turbine inlet
2	Low pressure compressor inlet
23	Low pressure compressor exit

33	High pressure compressor inlet	
3	High pressure compressor exit	
4	High pressure turbine inlet	
45.5	High pressure turbine exit	
46	Intermediate pressure turbine exit	
45	Power turbine exit	
9	Turbine exit	
amb	Ambient operating conditions	
cor	Corrected parameter	
c	Corrected health parameter	
ref	Reference value	
N1	High pressure spool speed	[RPM]
N2	Low pressure spool speed	[RPM]
_C	Corrected parameter	

Abbreviations

AI	Artificial Intelligence
AM	Adaptive Modelling
ANN	Artificial Neural Network
CBM	Condition Based Maintenance
DGPA	Differential Gas Path Analysis
EHM	Engine Health Monitoring
ER	Erosion
ES	Expert Systems
F	Fouling
GA	Genetic Algorithm
GPA	Gas Path Analysis
GSP	Gas Turbine Simulation Program
GT	Gas Turbine
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IGV	Inlet Guide Vane
IPT	Intermediate Pressure Turbine

LGPA	Linear Gas Path Analysis
LHV	Low Heating Value
LPC	Low Pressure Compressor
OEM	Original Equipment Manufacturer
PT	Power Turbine
RF	Rotor Fault
VGF	Variable Geometry Fault

Chapter 1. Introduction

Gas turbines are complex systems with high operational cost. The project aims to bring about fault isolation mechanism using gas path analysis. Various faults occur in a gas turbine and there are quite a lot of methods to monitor them [1]. An attempt is made to bring about the most suitable method and implementing in an online remote monitoring tool. Each and every configuration of gas turbine has to be approached with a unique method [2]. A three-shaft gas turbine with intercooler configuration is modelled to understand the behaviour of the gas turbine under various operating conditions. The objective is to develop a generic method of diagnostics of this configuration and identify the key parameters to monitor. The project will give a brief idea on how to proceed with modelling and monitoring such a gas turbine configuration with very limited data. Implementing the developed methods in a remote monitoring tool can save millions of dollars in terms of availability and reliability of the machine.

1.1 Problem Definition

Usage of gas turbines has increased tremendously over time. Gas turbines are found to be useful in many sectors including aviation, power generation and as mechanical drive in oil & gas industry [3]. The operational cost of the machine is very high and development in technology made sure the efficiency of the operation is high enough. To make the operation economical, the availability and the reliability of the machine has to be higher. Though the machine is highly reliable, availability of the device is subjective. Availability is measured as the number of hours the device is operational over a period of time [4]. High downtime affects the availability of the machine. Owing to the complexity of gas turbines, downtime is usually very high. To fix the challenge in reducing downtime, performance monitoring of the gas turbine and condition based maintenance were introduced. Condition based maintenance is a technique where maintenance is done according to the fault diagnosed in a specific component of the machine rather than performing a scheduled maintenance of the overall machine. It requires fault isolation mechanisms to monitor and predict the component at fault.

Company like Shell has a large fleet of gas turbines in their operations [5]. An attempt towards a complete engine health monitoring tool is required. The unique behaviour of every gas turbine configuration requires special attention in order to monitor and identify deterioration in gas turbines. A novel aero-derivative gas turbine 3-shaft configuration with integrated intercooler has been introduced to the industry [6] and a study on such a configuration is necessary to assess the capability of the present health monitoring tool at the sponsor company.

1.1. Objective

The objective of the project can be divided into a set of questions which can eventually lead to a better way of approaching the problem. The objectives are as follows,

- What are the various gas path faults?
- What are the causes and implications of such gas path faults?
- How does the remote online monitoring tool work?
- How to simulate performance of the gas turbine configuration under study?
- What are vital indicating parameters to monitor?
- How to implement the monitoring method in an online environment?
- What is the behaviour of the gas turbine under deterioration?
- What is the possible fault isolation method?
- Which is the best method for implementation in given the premise?

Based on these questions, the report follows the described structure. Chapter 2 describes the GT theory, various cycles of operation and explains in detail various gas path faults and their effects on components. The chapter ends with the common gas turbine deterioration cases to study. Gas turbine diagnostic methods are discussed in detail in Chapter 3 and also a small comparison is done.

Chapter 4 explains in detail the steps taken to simulate the gas turbine configuration and validate the model. Chapter 5 describes the online monitoring tool and the contribution of the case study to its performance. Performance monitoring trends are developed in this chapter. Chapter 6 discusses the behaviour of the gas turbine in various deterioration modes and suggests a fault isolation method that can be implemented in the sponsor tool. Finally Chapter 7 sums up the whole report with some future recommendations for using the method and conclusions.

Chapter 2. Gas Turbine Theory

Gas turbines (GTs) are one of the most important mechanical devices invented. Air is usually the working fluid of a GT. The thermodynamic cycle of such a device varies with the configuration and will be discussed further in the report. The basic principle is that the air is compressed, burnt with fuel and expanded using turbine. GTs can be used as mechanical drives in oil and gas sector, electricity generation in the power sector and propulsion in case of civil/military aviation engines. Since GT has applications in many fields, many configurations exist. Unlike the processes mentioned above, the device is a complex system with many components. The engine components can be distinguished as follows [1],

Gas-path components: compressor, combustion chamber, turbines

Rotating components: engine bearings, shafts, rotors, gear trains

Accessory components: fuel control, fuel pump, control system, lubrication system, ignition system, sensors and bleed system.

Realising the importance of gas turbines, there has been lot of enhancements in design, aerothermodynamics, cooling technology, materials etc., aiming to increase the application envelope of the devise as well as economic usage. Economic working means improvement in efficiencies, reliability and availability of machines.

In this chapter, gas path components and their operation is discussed. The thermodynamic performance of every individual component is independent and the operating point of the whole gas turbine is a single equilibrium point of operation satisfying mass, momentum and energy balance between all the components [7].

Conservation of mass equation is given by,

$$\frac{\partial}{\partial t}(\rho A) + \frac{\partial}{\partial x}(\rho A v) = 0 \tag{1}$$

Conservation of momentum equation is given by,

$$\frac{\partial}{\partial t}(\rho A v) + \frac{\partial}{\partial x}(\rho A v^2) = -A\frac{\partial p}{\partial x} \tag{2}$$

Conservation of energy equation is shown below,

$$\frac{\partial}{\partial t}(\rho A u) + \frac{\partial}{\partial x}(\rho A v h) = 0 \tag{3}$$

Where $\boldsymbol{\rho}$ is gas density, A is the cross sectional area, v is the velocity, p is pressure, u is specific internal energy and h is specific enthalpy. The following section will discuss the various ideal thermodynamic cycles involving gas turbines of different configuration.

2.1 Simple Ideal Brayton Cycle

Gas turbine works on the ideal Brayton cycle shown in Figure 2.1. The working fluid of the gas turbine is air. The first process 2 to 3 is the compression of the air. At constant pressure 3 to 4, fuel is injected and combusted in the combustion chamber. The gas is then expanded through a series of turbines as shown in step 4 to 5 and then released the fluid is released to the atmosphere through the exhaust or re-circulated back for compression. Between the stages 4 and 5, there is a point ("g") where the power extracted is used to compress the air. The process 2-3-4-g takes place in the gas generator. The excess power available at the turbine (stage g- stage 5) is used for other applications like propulsion, mechanical drive or power generation. This is called the specific gas power.

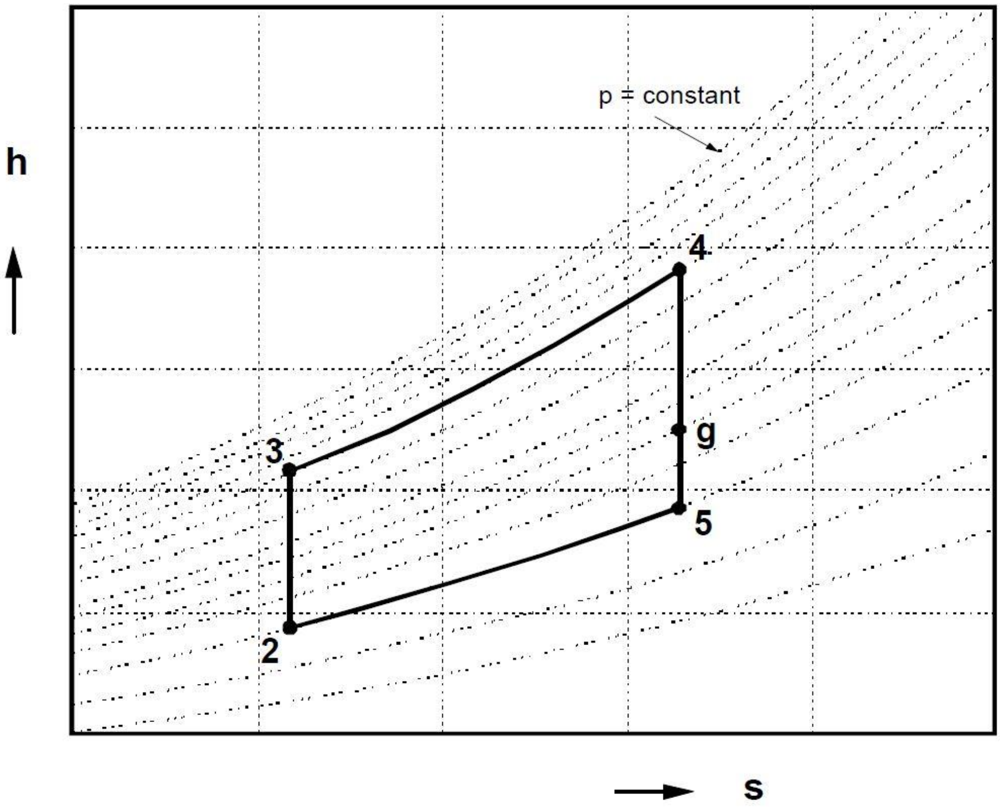

Figure 2.1: Ideal Brayton Cycle H-S Diagram [8]

Some basic relations are given below for calculating various parameters in a gas turbine cycle. In combination with conservation laws listed before, the operating point can be found. The relations shown are related with the ideal cycle shown in the Figure 2.1. These relations can be expanded or modified for different configurations.

Compressor power:

$$\dot{W}_{2-3} = \dot{m}c_p(T_3 - T_2) \quad [W] \tag{4}$$

Heat input rate:

$$\dot{Q}_{3-4} = \dot{m}c_p(T_4 - T_3) \quad [W] \tag{5}$$

Turbine power:

$$\dot{W}_{4-g} = \dot{m}c_p(T_4 - T_g) \quad [W] \tag{6}$$

Gas power:

$$\dot{W}_{gg} = \dot{W}_{g-5} = \dot{m}c_p(T_g - T_5) \quad [W] \tag{7}$$

Specific gas power:

$$W_{s,gg} = c_p(T_g - T_5) \quad [\frac{W}{kg}/s] \tag{8}$$

Waste heat:

$$\dot{Q}_{5-2} = \dot{m}c_p(T_5 - T_2) \quad [W] \tag{9}$$

Ideal isentropic gas equation:

$$\frac{P_3}{P_2} = \left(\frac{T_3}{T_2}\right)^{\frac{k}{k-1}} \tag{10}$$

The thermodynamic efficiency of the cycle is given by the relation,

$$\eta_{therm.dyn.} = \frac{W_{s,gg}}{Q_{s,3-4}} = \frac{T_g - T_5}{T_4 - T_3} \tag{11}$$

In order to increase the thermodynamic efficiency and/or power, few enhancement techniques are followed such as a recuperated cycle, intercooled cycle and reheat cycle [3].

2.2 Recuperated Cycle

The above Figure 2.2 shows the h-s diagram of the recuperated cycle. The recuperated cycle uses the waste heat from the exhaust and added to the compressed working fluid, decreasing the fuel flow needed. The amount of fuel needed to increase the temperature from stage 307 to stage 308 is conserved and hence the lower specific fuel consumption. This process can be done as high as the optimum temperature ratio. The same constrained is applied to the amount of heat that can be extracted from the waste flue gas.

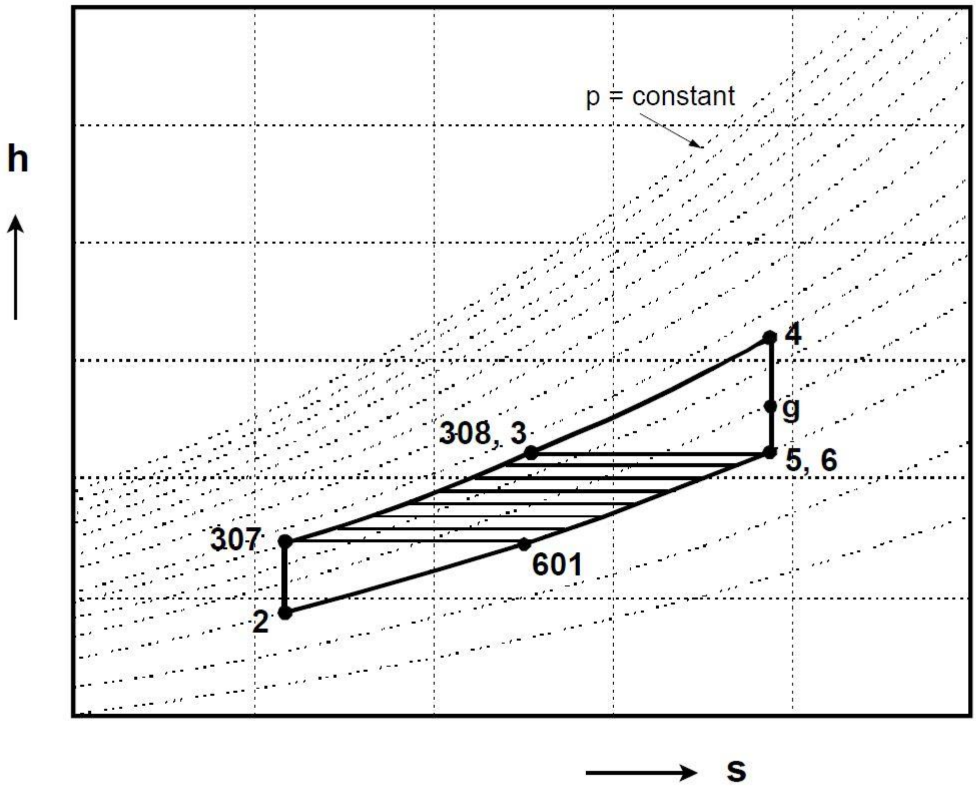

Figure 2.2: H-S Diagram of an Ideal Recuperated Cycle [8]

2.3 Intercooled Cycle

The desired process in compression would be an isothermal process. It is highly impractical to achieve. The work needed for compression can be reduced by splitting up the compression stages and inter-cooling the fluid. In the above Figure 2.3, the process of inter-cooling is shown by 2.3-2.5. The work required to pressurize the air from 2 to 3 can be reduced by this method. However there is a need for increased heat addition in order to reach the required peak temperature of the cycle. This means that this cycle produces higher power at lower thermal efficiency. By inter-cooling higher temperatures can be achieved at the turbine inlet.

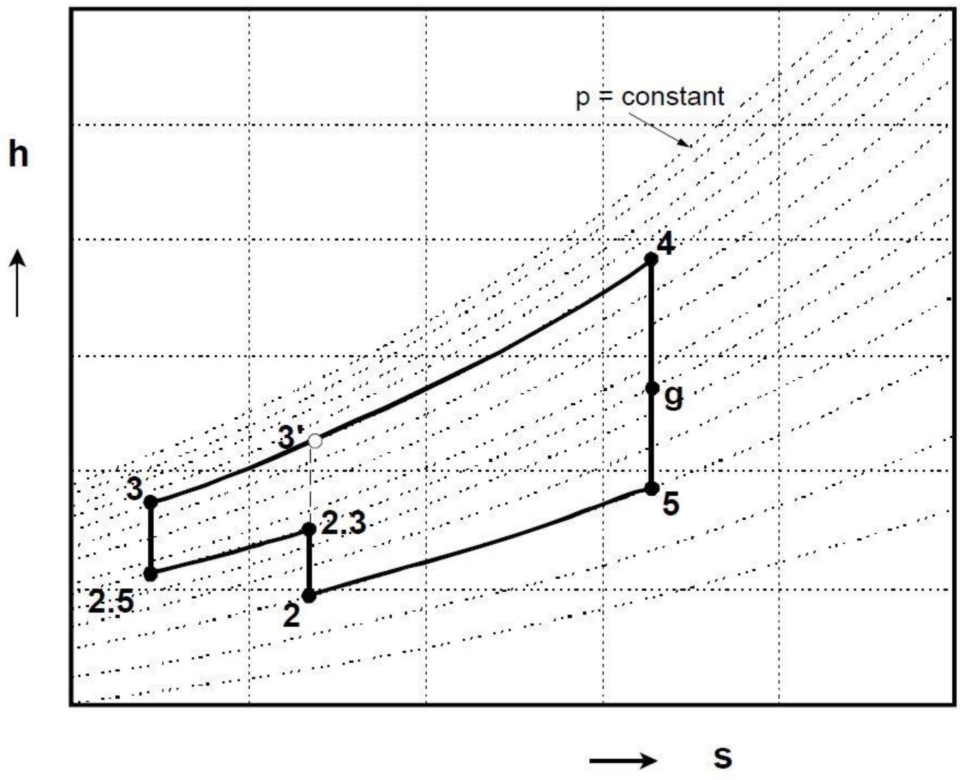

Figure 2.3: H-S Diagram of an Ideal Intercooled Cycle [8]

Specific compressor work:

$$W_{2-3} = \int V\, dp \qquad (12)$$

From the above equation it can be seen that reducing the specific volume of the fluid reduces the work required by the compressor. Inter-cooling between stages aims at reducing the specific volume thereby reducing the work required.

Intercooler effectiveness can be given by the equation,

$$\varepsilon = \frac{Q_{max}}{Q_{actual}} \qquad (13)$$

Where Q_{max} is the maximum heat that can be extracted considering the heat capacity and temperature of the flows.

$$Q_{max} = C_{p,min}(T_{hot,inlet} - T_{cold,inlet}) \quad \text{[W]} \qquad (14)$$

$$C_{p,min} = \min(\dot{m}_{air}c_{p,air}, \dot{m}_{coolant}c_{p,coolant}) \qquad (15)$$

Q_{actual} is calculated from either one of the flows by using the energy equation. It is considered that the heat lost from the hot fluid is equal to the heat gained by the coolant flow.

$$Q_{actual} = \dot{m}_{hot} c_{p,hot} (T_{hot,inlet} - T_{hot,outlet}) \quad [W] \tag{16}$$

2.4 Reheat cycle

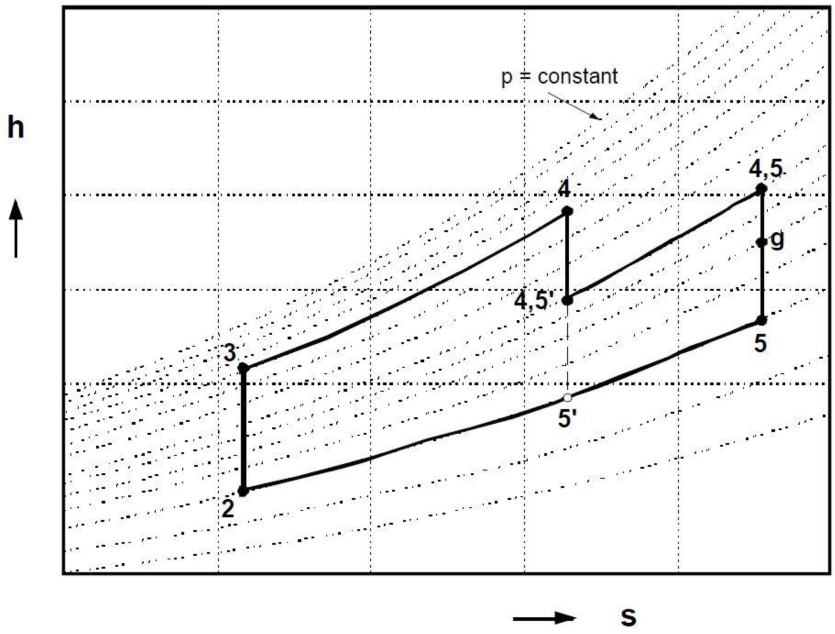

Figure 2.4: H-S Diagram of an Ideal Reheat Cycle [8]

The above Figure 2.4 shows the H-S diagram of a reheat cycle. After the first expansion stage from 4 to 4.5, heat is added again to raise the temperature at constant pressure. This increases the power available to be extracted. The reheated cycle has a higher specific power and lower thermal efficiency. The system is complex to implement.

All the above cycles are ideal and have made quite some assumptions. When it comes to real cycles,

- The working fluid is not an ideal gas and also constant specific heat values cannot be assumed.
- The expansion and compression processes cannot be isentropic due to the increasing fluid entropy.

- Mechanical losses, pressure losses in the combustion chamber and other components like inter-cooler and exchanger cannot be neglected.

2.5 Gas Path Faults

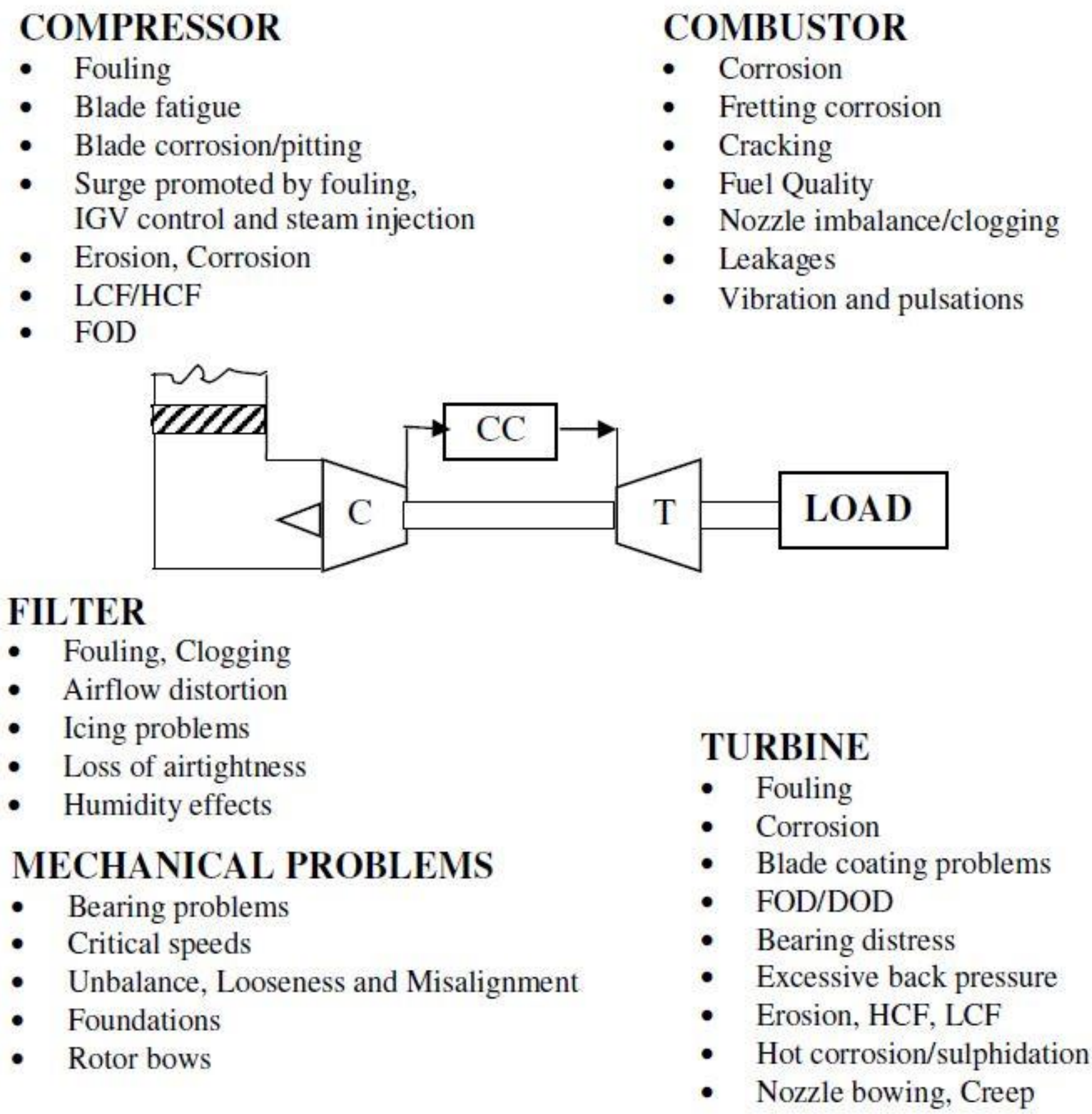

Figure 2.5: Faults in a GT [1]

The most common known faults are listed in the above Figure 2.5. The figure shows a simple single pool gas turbine configuration with compressor (denoted as 'c'), turbine (denoted as 't') and a combustion chamber (denoted as 'CC').

From these, combustor can be omitted since it is always considered to be highly efficient and deterioration is very rare [1]. Some of the faults are really complex and happen in combinations.

In this chapter a short description of the common faults is given. First we consider the process and discuss the possible failure mechanisms and causes and later generalise the failure mechanisms and their effects to be simulated considering gas path analysis.

2.6 Faults and their causes

The gas turbine components face threats of failure and the degree of damage by virtue of their operation. This chapter will discuss the fault that can happen with the engine components.

2.6.1 Compressor

Axial flow compressors are the most common type of compressors in large gas turbines. The compressor is multi staged and also the pressure ratio can be from 7:1 to as high as 40:1. With change in design and operation of gas turbine, failures are also differ. With more stage and pressure ratio, the operational margin reduces.

Dirt in the compressor section can cause several problems like reduced efficiency of the compressor, distortion of the mass flow leading to a surge, erosion and corrosion of the blades, block in the cooling air passages, unbalance and foreign object damage. To reduce this risk, filters are used which removes the particles from the inlet air. The working environment is not intense as a turbine. So, the intensity of problems is minimised. In sandy areas if the filter system is poorly designed or at fault, heavy deposits of dirt and sand can be seen. Evaporative cooling or water fogging is used to cool the inlet air [9]. These systems operate at high pressure and thus can cause erosion. The benefit of using evaporative cooling outweighs the erosion damage caused to the blades. Deposits on the compressor blades often contain sodium and potassium chlorides [10]. This when combined with water droplets can form acids causing pitting corrosion in the blade. This type of corrosion can be seen in Figure 2.6

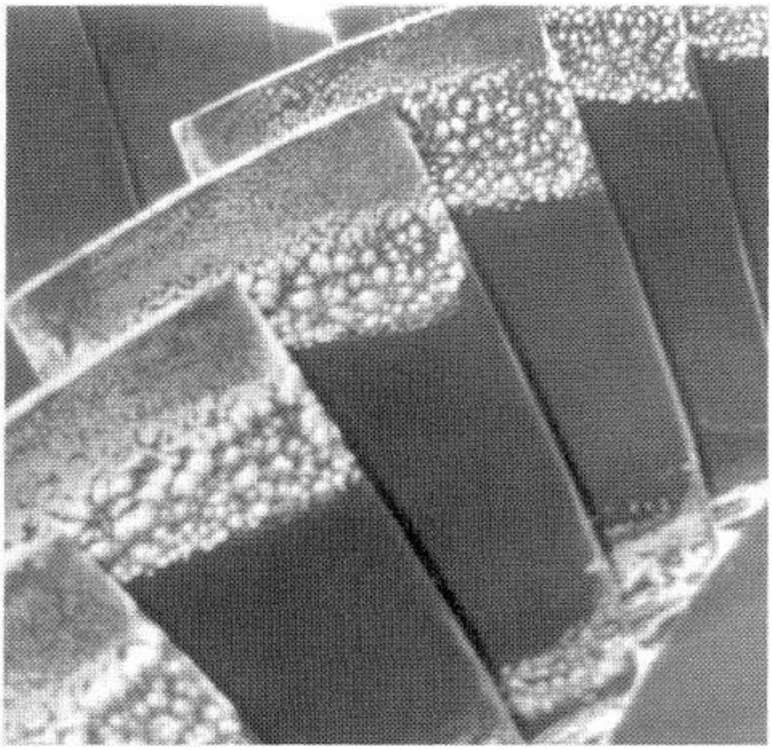

Figure 2.6: Salt Deposits on Compressor Blades [10]

Developments have made the compressor blades thinner, larger and three-dimensional. The blades are having less clearance and higher loading. Combination of having higher pressure ratios and smaller clearance gives more chance of tip rubbing with the casing. Boyce [4] denotes that the tip rubs occur near the bleed flow regions where the casing of the compressor can be a little out of round. Blade rubs can also occur due to rotor thermal expansion, blade bending caused by surge and excessive creep in the hot sections [10]. Tip rubs can cause an increase in tip clearance with a reduction in efficiency of the compressor. Figure 2.7 shows a tip rub where it is seen that the profile of the blade has been disrupted. In severe cases the blade may fail completely and trigger domestic object damage. FOD can cause many symptoms so it is difficult to use gas path analysis as a single tool to isolate the fault [10]. Vibration analysis can be used together with gas path analysis to yield better results. Damage can be as severe as shown in the Figure 2.8.

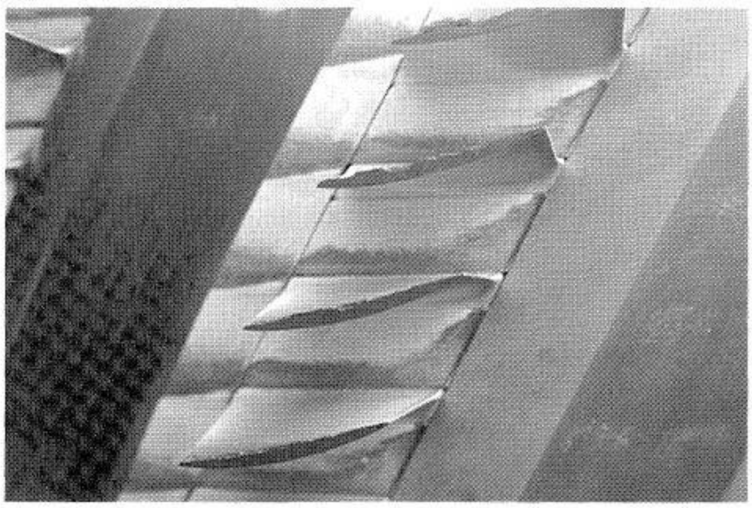

Figure 2.7: Blade Tip Rub [4]

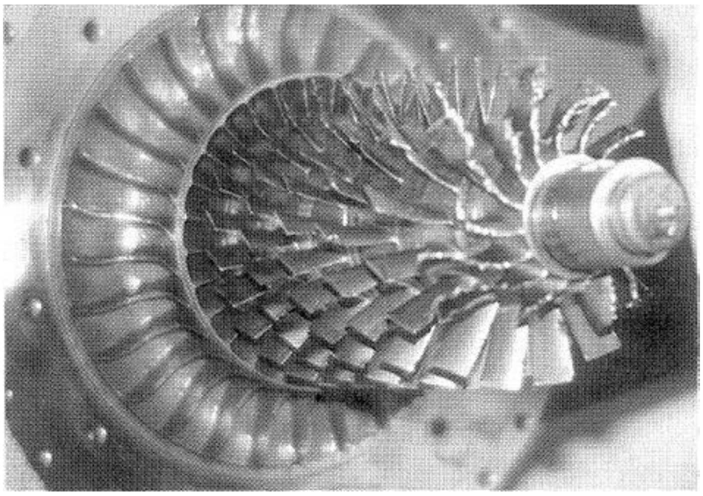

Figure 2.8: Foreign Object Damage [10]

Apart from the physical damage, deposits of foreign material can cause blade flutter, stall and surge. The deposits change the air angles leaving the blade and causes flow separation. Blade flutter problems can also be due to excessive bleeding of the compressed air at high stages of compression. For a safe operation, monitoring performance and vibration is a good choice [4]. The indicators can include,

- Gas turbine exhaust temperature
- Compressor discharge temperature and pressure
- Compressor efficiency
- Degradation of power
- Increase in heat rate
- High vibration readings

2.6.2 Turbines

The turbine section operates at very high temperatures. It reaches as high as 1500 ^{o}C. The initial stages of the turbine are protected with thermal barrier coatings. The turbine nozzle and blades depends heavily on the fuel properties and can be affected with erosion and corrosion due to the operating conditions. The liquid hydrocarbons which are present in the gaseous fuel can cause hot spots which leads to crack in the vanes and in blades.

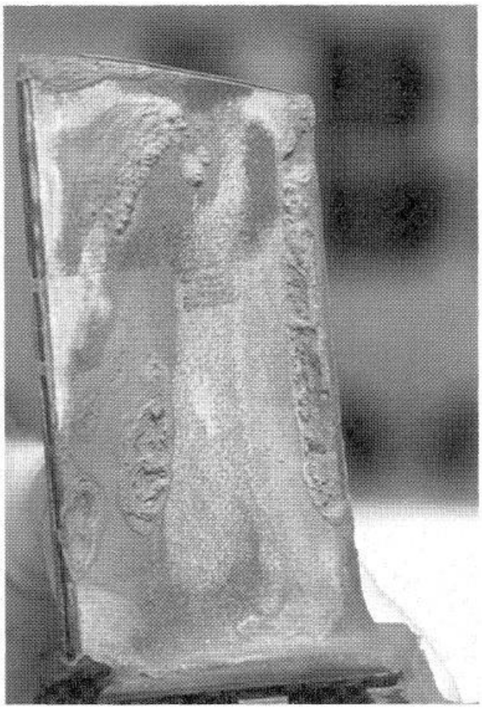

Figure 2.9: Corrosion in Turbine Blade [10]

The figure above shows the corrosion that can happen in a turbine blade. This has many side effects. This can cause the disrupted cooling causing the blade to fail completely. Due to the thermal and centrifugal stresses acting on a blade, elongation of the blade can happen which in turn can cause “blade rub”. Turbines face with higher chance of domestic object damage than foreign object damage given the position of the component along the gas path, shown in Figure 2.10. In cases of fuel injection failure, allowing more fuel to flow, excess fuel can reach the stages of the turbine and can cause a large flame. This causes *bowing* of the nozzle vanes. This distorts the mass flow of the turbine.

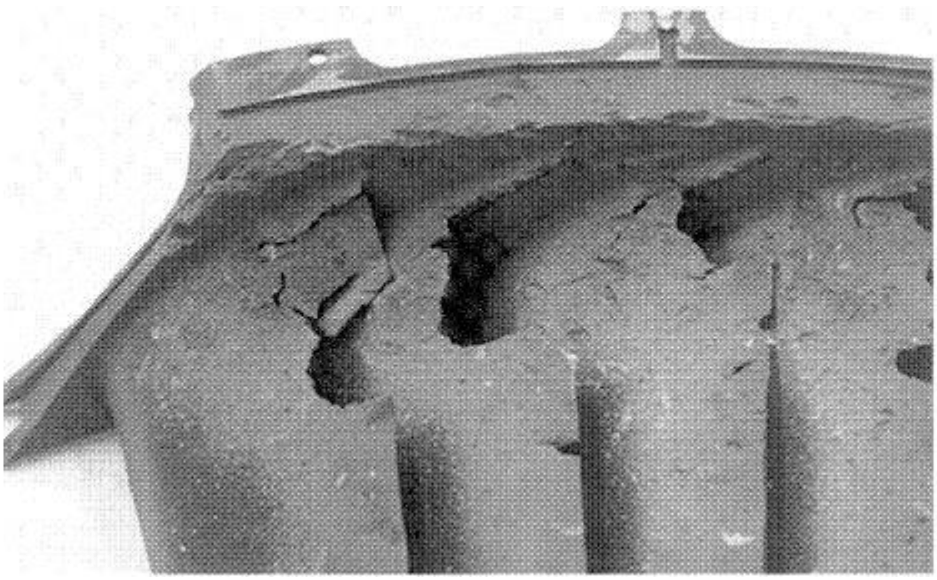

Figure 2.10: Domestic Object Damage of a Turbine Blade [9]

Sometimes the fuel can seep to the later stages also causing flames and uneven thermal expansion of the turbine rotor. This occurs when the combustion during starting up is not proper. This mechanism can be seen from the fact that the initial stages will have less damage than the downstream stages. The turbine blades are manufactured with shrouds to reduce the tip losses and to provide strength. However due to operations at high temperature, shrouds can lift from its position. This can affect the casing and also may cause complete failure of the blade. The flow capacity and the efficiency of the turbine are reduced drastically. This can compromise the casing and hence create uneven temperatures. Monitoring the spread of exhaust gas temperature can give a good overview of the functioning of the combustion chamber as well as the nozzle stages of the turbine [9].

The above mentioned mechanisms are very specific and to isolate such faults there is need for intensive maintenance schedule. Before boiling down to the cause of the problem, it is necessary to isolate the component at fault. Gas path analysis can be used effectively in that sense. The passages below will discuss the most common and generic modes of failure which can be detected using gas path analysis. The mechanisms are characterised by their effects on the independent parameters.

2.7 Generic Considered Fault Mechanisms

The following section discusses the definition and their characteristic impact on the engine health parameters suitable for a case study of a gas turbine.

2.7.1 Fouling

It is nothing but the accumulation of foreign and/or domestic particles and deposit on the blade surfaces. This causes change in the surface roughness and has an effect on the aerodynamic shape of the blade. Fouling can also cause reduction in throat area thereby affecting the flow. One of the major effects would be a decrease in mass flow and pressure ratio of the compressor. The efficiency of the compressor can also be affected. In turbine, fouling can affect the vanes, blades and seals. This reduces the efficiency of the turbine. A reduction in power generation, increase in heat rate and exhaust gas temperature can be expected. Fouling is limited by the force exerted by the working fluid

2.7.2 Tip Clearance

Tip clearance has a major effect on the flow capacity of the rotating equipment. If the tip clearance is increased, it reduces the efficiency and the flow capacity. Tip clearance shows a greater impact on the efficiency of the machine than caused by fouling [1]. Tip clearance can happen because of many reasons like wearing of blades, foreign object damage, erosion, corrosion and thermal stresses.

2.7.3 Erosion

Surface material erodes due to impact of materials at high temperature and pressure. Erosion causes deterioration of surface quality, airfoil profile, throat openings. It also increases tip clearance and seal clearances. The strength of the material is also compromised and can cause sudden failure. The effects of erosion can be of different levels of deterioration. In compressors, erosion can lead to decreased pressure ratio and mass flow rate. In a complex gas turbine configuration with multiple compressors, erosion can make the upstream compressor stages prone to stall [1]. The rear stages of high pressure compressors can be affected more due to the nature of its operation under high pressures. Erosion increases the mass flow thereby reducing the efficiency of the operation and so it affects the power generated.

2.7.4 Corrosion

There is a possibility of the foreign objects reacting with the components of the gas turbine under high pressure and temperature. This proves to be an adverse effect causing corrosion of materials. It affects the material properties of the components. The contaminants can enter the flow through the inlet or the fuel, steam injection. Rate of corrosion gets higher with higher temperatures and pressures. Elements such as vanadium, sodium and lead can be present as impurities in the fuel and can cause performance deterioration of turbines.

2.7.5 Object Damage

There are two ways damage can happen to the engine components. Domestic object damage is when a part of a component becomes loose and hits the components along the flow. Foreign object damage is when a foreign object enters through the inlet duct and damages the components along the fluid path. Object damage can be very drastic or in some cases can cause lesser extent of damage showing little symptoms.

2.8 Summary

This chapter discussed the working theory of a gas turbine and the thermodynamic relation between the components of a gas turbine. Various cycles of operation were discussed and the equations of conservation were also discussed. Using the relations, parameters at different stations of the gas turbine components can be calculated. Gas path deterioration cases were discussed in-depth and gave a good idea of the mechanism and other complexities. In order to simulate and study fault mechanism, a generalised list of faults for each component was listed. It is now feasible to study the behaviour of the gas turbine using simple and combinations of the faults in various components of the gas turbine. Fault in an intercooler component ends up in decreasing the effectiveness and hence increasing the temperature of the flow. The symptoms related to each faults has been listed so that it would be helpful to come up with a fault isolation mechanism.

Chapter 3. Fault Diagnosis Techniques

The previous chapter gave a good overview of the faults related to the process conditions and generalized faults that can happen. It is desirable to monitor the engine performance and diagnose the faults even before the damage is done since the faults can cause permanent damage to the components. Preventive maintenance proves to be a better way considering the longer run. In this chapter, study on different techniques followed by the industry will be discussed along with the advantages and their disadvantages. Engine health monitoring techniques may include a variety of methods and tools to diagnose and isolate faults [1] [11]. Engine health monitoring has given rise to condition based maintenance where they monitor the performance of a machine and performs maintenance procedures only to the specific machine under deterioration. This has reduced the downtime of the machine considerably [3]. Out of the many approaches a few important methods are discussed below.

3.1 Visual Inspection

This is one of the simplest methods of monitoring the engine. Visual inspection can be done to find leaks, cracks, improper installation and flaw in inaccessible sections like tears, burns, deposits, corrosion and deformation. To assist in the inspection light probes, dye penetrants, infrared imaging, X-ray inspection and other non-destructive testing methods are used. A complete engine monitoring systems rely on visual inspection to confirm the diagnosis done. The disadvantage with this method is that the experience of the tester is very important and the symptoms for a fault can be subjective. Moreover there are many catastrophic faults that leave no trace of symptom for the visual inspection to find out.

3.2 Fault Tree

Fault tree contains map of faults and the chain of symptoms. Using fault tree is one of the oldest methods for engine monitoring. The method is to find the varied engine parameter which is the root and find its chain of events to the top eventually narrowing down the physical fault. It does not consider multiple faults or a fault in sensor. Again it requires experienced personnel to relate the parameters to isolate the physical fault.

3.3 Fault Matrix

The fault matrix method compares change in measured parameters of an engine with a pre-calculated deviation matrix of a fault. The match between them helps to boil down to the cause of deterioration. With limited measurement the rate of accuracy achieved can be very low [11]. This is because multiple faults have a common range of symptoms which can be easily misinterpreted. It is possible to eliminate error to an extent by creating different fault matrix based on different health parameters [1].

3.4 Vibration Monitoring

Vibration monitoring is a common technique used widely to monitor rotating equipment. Gas turbines have many rotating parts which vibrate about an equilibrium position. Changes in vibration of the components can identify the defect components and along with gas path analysis can provide a very good engine monitoring system.

The Figure 3.1 shown below illustrates the principle behind using vibration monitoring system. The waveform obtained is made up of simpler waveforms of various components. This obtained waveform in time domain should be transformed into the frequency domain. Monitoring the frequency of every component gives an idea of the level of deterioration from the equilibrium. Spectral analysis is a powerful tool where the frequency is plotted against the frequency of a healthy engine. This helps the user visually to identify abnormality in the operation of the engine [12]. The engine can deviate from the OEM suggested vibration levels. The system is fed with a margin above which the engine is considered to deteriorate and considered for further investigation.

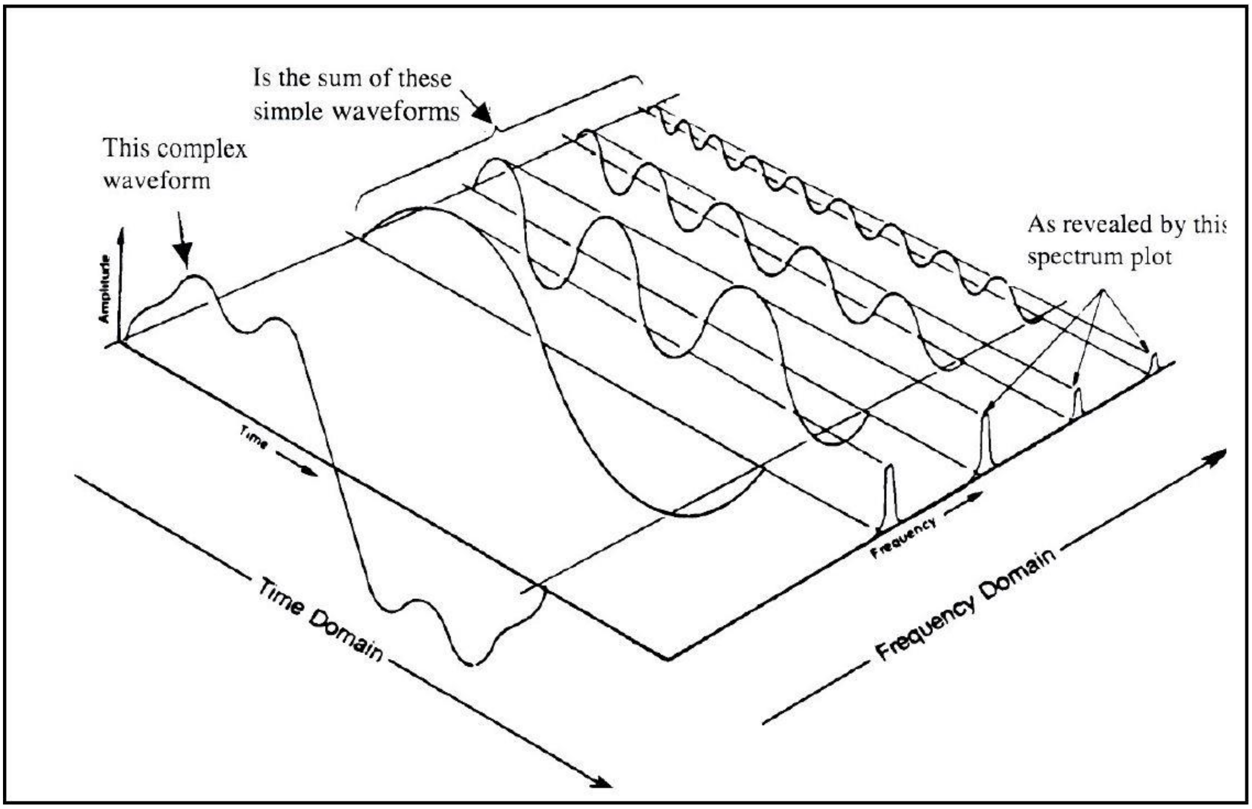

Figure 3.1: Time and Frequency Domain [12]

3.5 Gas Path Analysis

Gas path analysis (GPA) is the focus of this chapter. This method is very useful in terms of obtaining quantitative values of deterioration for multiple faults. Using this as a tool prognostics can be done hence increasing the reliability and availability of the machine. Gas path analysis depends on the logic of relation between the measurable values and the component characteristic parameters i.e., variation in measured parameters can be related to corresponding variation in the component characteristics. The accuracy lies with the data available and its credibility [13]. The robustness of the model is very important as the noise in sensor can cause serious accuracy issues.

GPA detects the change in measured variables and connects them with possible faults. The dependant variables are related to the independent variables thermodynamically. The working principle of GPA can be found in the Figure 3.2. Error with the sensors can cause wrong diagnosis. GPA has methods to give a relative variation rather than an absolute value which overcomes this problem. This gives GPA the ability to cope with a wide operational regime from the design region.

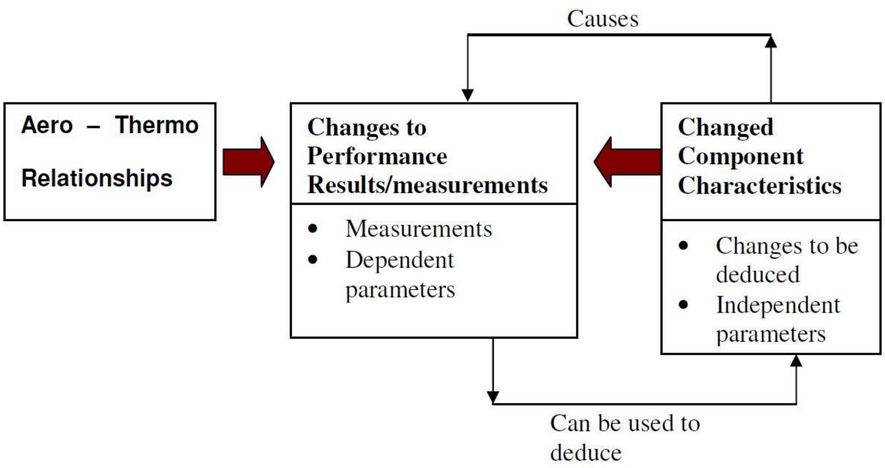

Figure 3.2: Working Principle of GPA [1]

3.5.1 GPA Approach

Based on the relation between the dependant and independent variables of the engine, GPA has few types of approaches.

Linear GPA

As the name suggests linear approach considers a linear relationship between the dependant and independent variables. It depends on the first derivative of the Taylor series expansion of the governing equations of the gas turbine. A fault coefficient matrix is obtained and can be used to find the health parameters of the engine. The relationship can be expressed as:

$$\boldsymbol{\delta y} = [\boldsymbol{J}]\boldsymbol{\delta x} \tag{17}$$

$$\boldsymbol{\delta x} = [\boldsymbol{J^{-1}}]\boldsymbol{\delta y} \tag{18}$$

Where δx are the changes in the independent parameters,

δy are the changes in the dependant parameters and

J^{-1} is the fault coefficient matrix.

Since the relationships are not linear, this method is applicable for ranges nearer to the design point of operation. Further away from the design point, this method generates values with more error. It does not consider sensor faults as well.

Non-linear GPA

This method is nothing but the iterated linear method discussed above. This process reduces the residual error between the output and the actual values. One of the techniques used is the iterated Newton-Raphson method to generate the fault coefficient matrix. The applicable range of this method is wider than the linear method as it handles abrupt changes in measurements. A representation is shown in the Figure 3.3.

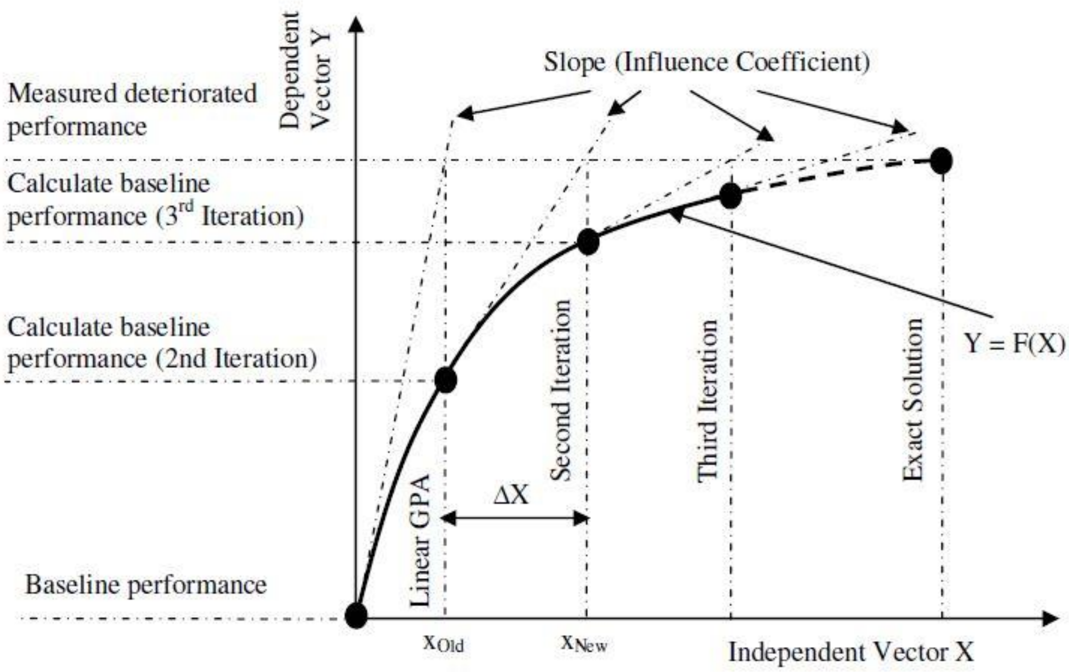

Figure 3.3: Linear and Non Linear Method [1]

The steps followed in a non-linear method are explained below.

A small change in the independent parameters (δx) will cause the dependant parameters (δy) to change.

$$F(x + \delta x) = y + \delta y = F(x) + \delta y \tag{19}$$

Applying Taylor series expansion for the left hand side of the equation gives,

$$F(x + \delta x) = F(x) + J\delta x + Higher\ Order\ Terms \quad (20)$$

Where J is the matrix with first order derivatives of the parameters. Neglecting the higher order terms and equating the above two equations:

$$\delta y = J\delta x \quad (21)$$

Inversion of the matrix J will help to find the independent health parameters δx from δy values.

The new parameters are found using the above relations. A minimisation function is used to reduce the actual value and the predicted value. The values of engine parameters are varied iteratively until the solution is converged and the function is minimized. The schematic representation is shown in the above figure where the first step alone is the linear method and doing the process iteratively forms the non-linear method of approximation. Measurement faults are not considered in the system as well. The fault matrix can be used to find the faults but has to be interpreted by an expert. The following topics will describe a few of the GPA based techniques used in the industry.

3.5.2 Differential GPA

Differential GPA is very similar to the non-linear gas path analysis. Both compare the actual and estimated values of the engine. Differential GPA can be done by using adaptive modelling. A healthy engine module is created within the system and it compares with the measured data. The model changes the health parameters of the module to match with the measured data. This can be quantified as the level of deterioration of the component. A schematic has been shown below.

The healthy engine parameters are calculated using a set of differential equations considering the conservation of mass and energy at various stations of the components. Error equations and unknown state equations are added to the model and are equal to the number of parameters to be estimated. This provides a matrix as shown in the Figure 3.5. According to W.P.J. Visser et al., the upper left part of the matrix forms the equation for the reference engine. In the matrix, f_1 to f_n are the error equations of the unknown states. The *m* additional equations shown at the lower left corner of the matrix are equal to the number of measurements. The equations are solved for the convergence criteria given by ε [14].

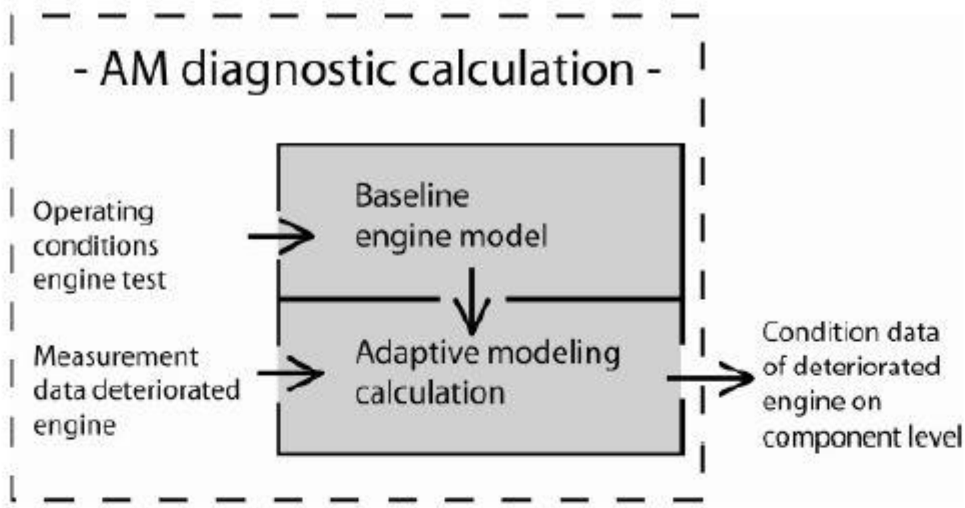

Figure 3.4: Adaptive Modelling GPA [11]

3.5.3 Expert Systems

Engine health monitoring techniques mostly have a similar approach. Expert systems can be used with any of the techniques and infer data using logic or rules. Expert systems have applications in bio-medical field, computer architecture design, chemical analysis and situation analysis. The literature has shown that expert systems can be used for engine health monitoring as well [1]. An expert system has a database of possible faults, relationship between parameters and necessary algorithms.

To implement expert systems there are some considerations like,

- Scope of problem
- Expected symptoms
- Model to be codified
- Coding language
- Verification and validation

These systems can be used along with Gas path analysis (GPA) and can be used to generate required symptoms for diagnosing a fault.

$$
\begin{array}{ccc|ccccc}
f_1(s_1)+ & \cdots & f_1(s_n)+ & f_1(s_{c1})+ & \cdots & f_1(s_{cm}) & = & \varepsilon \\
\vdots & & \vdots & \vdots & & \vdots & & \\
f_n(s_1)+ & \cdots & f_n(s_n)+ & f_n(s_{c1})+ & \cdots & f_n(s_{cm}) & = & \varepsilon \\
\hline
f_{m1}(s_1)+ & \cdots & f_{m1}(s_n)+ & f_{m1}(s_{c1})+ & \cdots & f_{m1}(s_{cm}) & = & \varepsilon_{m1} \\
\vdots & & \vdots & \vdots & & \vdots & & \\
f_{mm}(s_1)+ & \cdots & f_{mm}(s_n)+ & f_{mm}(s_{c1})+ & \cdots & f_{mm}(s_{cm}) & = & \varepsilon_{mm}
\end{array}
$$

Figure 3.5: Adaptive Modelling GPA - Equations [14]

3.5.4 Genetic Algorithms

Genetic algorithm works like natural selection and natural genetics [15]. It has three operators namely selection/reproduction, crossover and mutation. The selection finds the strings which are possible solution for a function. Closer the solution, better its chances to enter the next generation as in “survival of the fittest”. The crossover operation swaps information of the parameter string. The surviving fitter strings move to mutation phase where the values are changed randomly within the prescribed limits. Algorithms can be used when the fault diagnosis is considered as an optimization problem. This is possible since there is often more than one cause for a problem. One of the main disadvantages of using genetic algorithm is the computational time required. The flowchart of such an algorithm is shown in Figure 3.6.

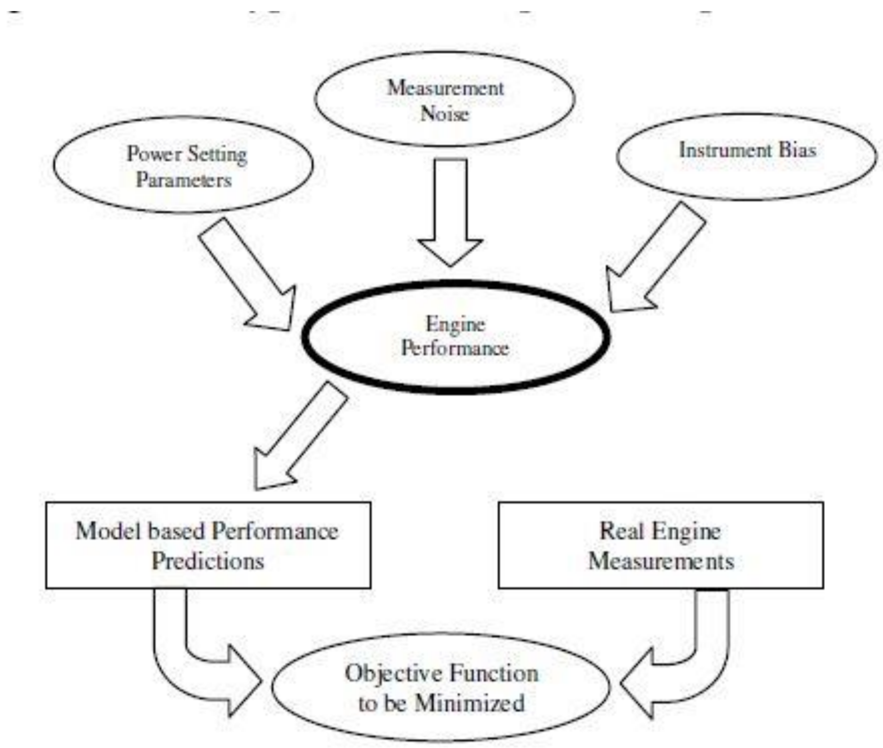

Figure 3.6: Schematic Diagram of a Genetic Algorithm [1]

3.5.5 Artificial Neural Networks

Artificial neural network works like the neural network of human brain. They are not thermodynamic based solvers. The neural network is trained such that an input will generate respective output. One type of neural network is the feed forward back propagation method [1]. ANN can be trained well to map the non-linearity of the relationships of the parameters. A model will consist of an input layer where the input parameters are fed into. The middle layer consists of weights according to which outputs are generated. In a feed forward back propagation method, error in desired output and the actual output is propagated back to adjust the weights accordingly.

The accuracy of this model depends on the extensive data used to train the model. Another disadvantage of this method is that, the networks should be trained every time maintenance is done. The time and data required to train the model is enormous but once the model is trained, the model can be used more effectively and accurately.

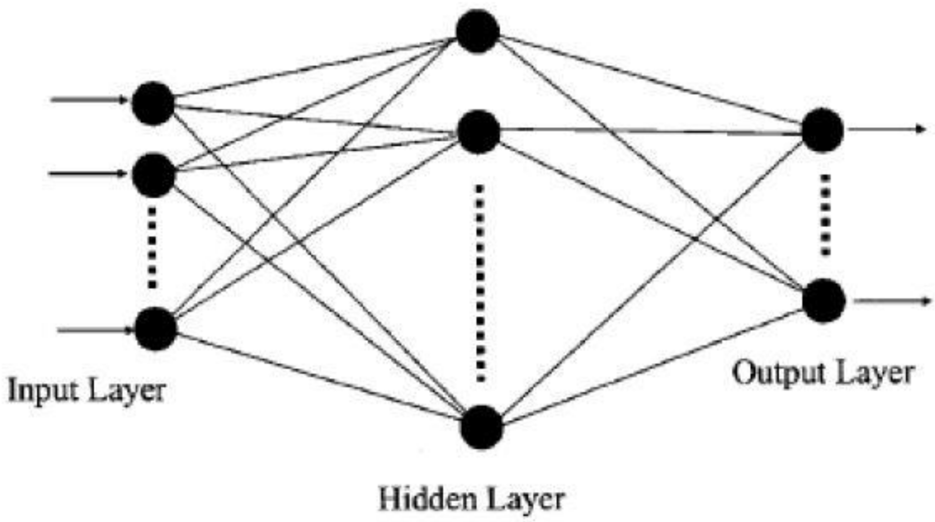

Figure 3.7: Feed Forward Back Propagation Network [1]

3.6 Comparison of GPA methods

Different methods of GPA have been discussed so far. Comparison between these methods is shown below in the Figure 3.8 below.

Diagnostic methods	Earliest year of use	Model based	Model complexity	Computation speed	Coping with noise	Coping with bias
Linear model-based methods						
Linear GPA	1967	Yes	Low	High	No	No
Optimal estimates	1980	Yes	Fairly low	High	Yes	Yes
Non-linear model-based methods						
Non-linear GPA	1992	Yes	Low	Fairly high	No	No
Conventional optimization	1990	Yes	Medium	Low	Yes	Yes
Neural networks	1989	No	Fairly high	High	Yes	Yes
Genetic algorithms	1999	Yes	Fairly high	Low	Yes	Yes
Rule-based expert systems	Early 1980s	No	High	High	Yes	Yes
Rule-based fuzzy expert systems	1997	No	High	Fairly high	Yes	Yes

Figure 3.8: Comparison of GPA Methods [13]

Systems like neural network, expert systems are not model based and need to have more experimental database and expertise. Model based systems will reduce the dependency on experts in the respective field. Although some of the methods need to be interpreted by experts for further usage. The model complexity and computation speed is very important when it comes to implementing it in an industry. Based on these two parameters, non-linear GPA proves to be the best. Adaptive modelling GPA requires more data as the system requires at least equal number of error equations. Linear and non-linear methods do not take sensor faults into account. This makes it very important to get reliable data from the field.

3.7 Conclusion

The various diagnostic techniques were discussed and compared. Given the limitations on the available data, application, and architecture of the software to be loaded, the non-linear gas path analysis proves to be the best approach. This method requires relatively less data, less change in the existing tool and provides sufficient accurate results for a condition based maintenance system. In order to achieve a complete engine health monitoring system, the gas path analysis can be coupled with vibration monitoring. Since the faults can be too complex to isolate a single component, vibration monitoring can be used effectively thereby increasing the effectiveness of the tool further.

Chapter 4. Gas Turbine Modelling in GSP

The gas turbine under study is discussed briefly in this chapter. The gas turbine modelling tool used to generate healthy clean engine model is introduced. Based on the literature study the preferred approach towards modelling the gas turbine configuration is discussed in detail. Finally the model developed is validated against the OEM provided performance curves. Validation of the model ensures the performance of the model is closely accurate to the real gas turbine engine.

4.1 Gas Turbine Simulation Program

Gas turbine simulation program is a 0-D component based modelling tool developed by the Dutch National Aerospace Laboratory in collaboration with the Delft University of Technology. GSP has a wide collection of gas turbine components in its library. The interface is simple and allows the user to model any configuration of gas turbine using the available components. The components are blocks loaded with thermodynamic relations. The modelling approach starts with modelling the design point of the gas turbine configuration. It is preferable to have an operating point where the user has more performance data. The off-design simulations require usage of component maps. In most of the cases component maps are considered proprietary and GSP has the capability to tune generic component maps. Moreover GSP can be used to analyse effects of ambient conditions, installation losses and deterioration of components on the performance of the modelled gas turbine [2]. This makes GSP a good choice to use for modelling and developing diagnostic methods for gas turbine. Adaptive modelling can also be done using GSP [16]. A simple non-linear gas path analysis approach is followed due to the reasons discussed in the previous chapter.

4.2 Gas Turbine Configuration

The gas turbine under study is LMS100 manufactured by General Electric. It is a three-shaft intercooled gas turbine with a free power turbine. It is an aero-derivative gas turbine based on combination of CF6 aircraft engines. The simple cycle thermal efficiency is up to 46%. The gas turbine is designed for various applications from power generation to mechanical drive. The variants offered include different combustion chamber systems for emission control, power turbine speed variation for mechanical drive and fixed speed power turbine for power generation [17] [18].

Table 4.1: Configurations of LMS100

PRODUCT CONFIGURATION	FUEL	COMBUSTOR
LMS100 SAC, 50/60 Hz	Gas, Liquid or Dual Fuel	Single Annular(SAC)
LMS100 SAC Steam, 50/60 Hz	Gas	Single Annular(SAC)
LMS100 SAC STIG, 50/60 Hz	Gas	Single Annular(SAC)
LMS100 DLE, 50/60 Hz	Gas	DLE2

The manufacturer also optionally provides an intercooler with the system. The intercooler can be dry or wet depending on the needs of the user. Provided the flexibility of the engine, the application in LNG industry is tremendous [6].

The operating envelope of the gas turbine depends on its application. The configuration under study is used in natural gas liquefaction plants. Natural gas is liquefied to allow transporting and storing it easily. The process involves cooling the gas to lower temperatures around -160^{o}C. After transporting, the liquefied natural gas is converted back to its gaseous state. Gas turbines are used as driver for the refrigerant centrifugal compressors. Usually the gas turbine operates at full base load conditions. Inlet guide vanes are used only during variable load operations. It is safe to model the engine considering full load operation and constant inlet guide vane angle.

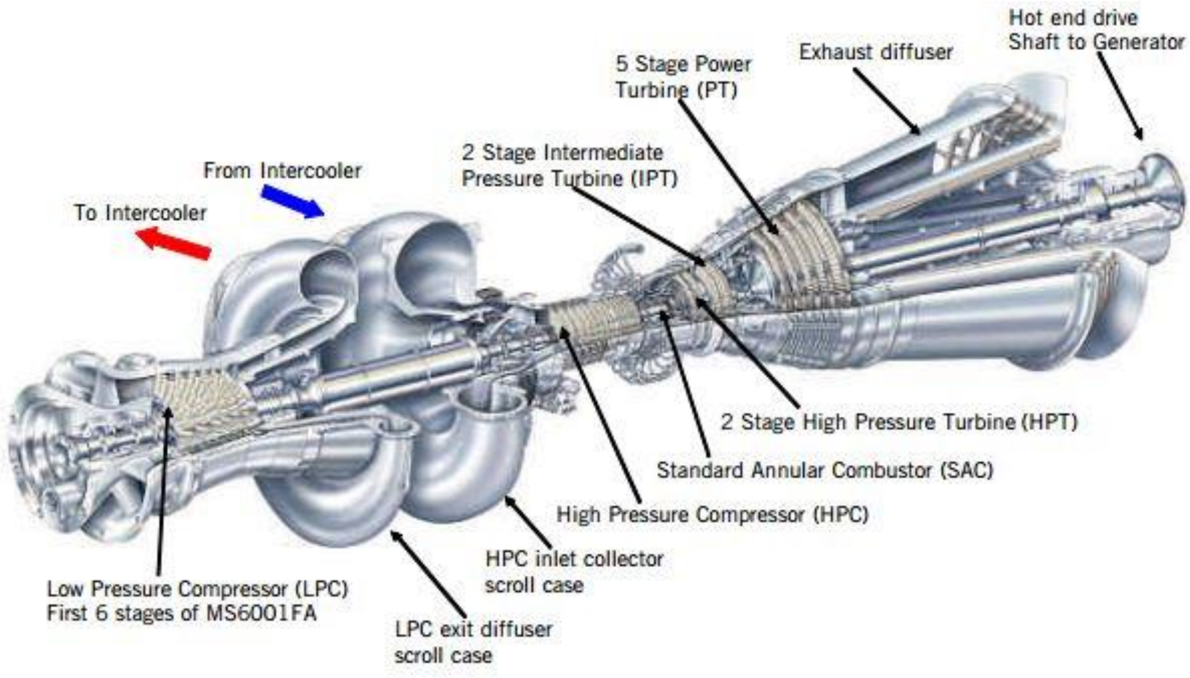

Figure 4.1: LMS 100 Schematic [17]

The specification of the selected gas turbine configuration is listed below in Table 4.2.

Table 4.2: LMS100 PB 50Hz - DLE Specification

Compressor Type	Axial
No. of Compressor Stages	20
Power Turbine Speed (rpm)	3000
No. of Turbine Stages	
- **Intermediate Pressure Turbine (IPT)**	2
- **High Pressure Turbine (HPT)**	2
- **Power Turbine (PT)**	5
Pressure Ratio	42
Combustor Type	DLE
ISO Power Output (MW)	102
Fuel	Natural Gas
Exhaust Temperature (^{o}C)	409

4.3 Modelling Procedure

To develop diagnostic methods for deterioration of a gas turbine, its behaviour at varied ambient conditions must be known. The modelling procedure would aim to simulate the gas turbine as similar as possible to the real engine. The healthy engine characteristics can be used in the online monitoring tool of Shell Global Solution for performance monitoring of their assets. This section gives information on the steps carried to model the present gas turbine configuration. The behaviour of the engine is studied under steady state conditions.

There are specific inputs required along these steps which will be explained in this section. The first is to model the design point of operation. Usually a condition with ample amount of data is used for design point modelling. The accuracy of the model simulation lies with the accuracy of the data. In order to simulate the off design conditions, the control schedule of the gas turbine and the component maps are required. Component maps are considered proprietary by the OEM and so generic maps have been used and tuned for better accuracy. Validation of the simulated data against the OEM provided performance curves is necessary to carry on with the diagnostic model as this seals the healthy parameter relationships of each of the gas turbine component.

The components used for modelling is show in Figure 4.2. It is seen that there are two compressor components, three turbine components, combustion chamber and intercooler. The information of the compressor being connected to the respective turbine is specified. The power turbine is specified as a free power turbine. There are two control components which are the manual fuel control and inter-cooler control. The manual fuel control can be used to specify the fuel flow or the turbine inlet temperature required. The intercooler control can be used to specify the coolant flow, temperature at the inter-cooler exit, effectiveness or the heat extracted from the flow as input. It is also possible to specify an effectiveness map to obtain varying effectiveness at different flow values.

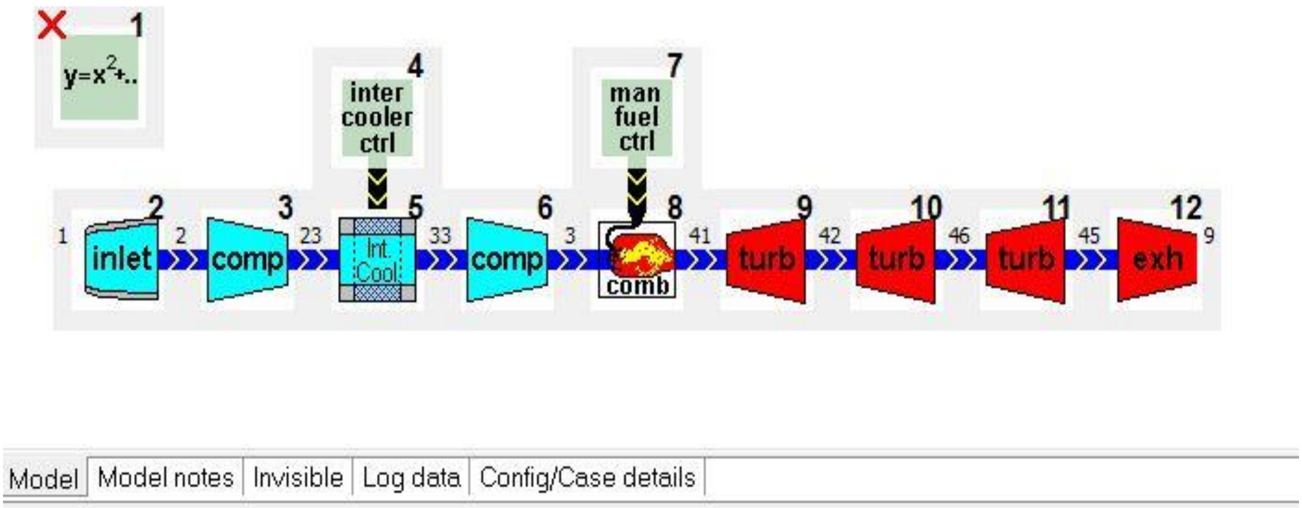

Figure 4.2: GSP Model of LMS100

4.3.1 Design Point Modelling

Design point modelling is iterative and requires numerous performance data of the gas turbine. The source of data can be obtained from site measurements and/or from the OEM provided performance data. Measurement data from one of the gas turbines is deemed enough to model and simulate. The simulated performance data can be used for the entire fleet of the same engine. It must be ensured that the measurement data is got from a healthy gas turbine which will account to the accuracy of the model. Data from the OEM is often considered proprietary and it is hard to obtain. LMS100 configuration selected for this particular project has not yet been commissioned and hence onsite data is not available. Certain performance data provided by the OEM at ISO rated conditions are available and the project is based on this information. The method to model design point is to tune the component parameters to achieve certain given performance. From Figure 4.2 it can be seen that the model has 10 stations and measurable parameters at these stations are required. It is necessary to calculated parameters at the intermediate stations where performance data were not available. Below in the Table 4.3, all the data needed to model the design point is tabulated.

Table 4.3: Design Point Data

Inlet Mass Flow [kg/s]	205.5	Calculated
LPC Pressure Ratio	4.12	Tuned
LPC Outlet Temperature [K]	454	Given
Coolant Mass Flow [kg/s]	76.8	Calculated
Intercooler Effectiveness	0.814	Tuned
Heat Extracted [MW]	26.649	Given
HPC Inlet Temperature [K]	329	Calculated
HPC Exit Pressure [bar]	42	Given
HPC Exit Temperature [K]	679	Calculated
Fuel Flow [kg/s]	4.917	Calculated
HPT Exit Temperature [K]	1214	Calculated
IPT Exit Temperature [K]	1081	Calculated
Exhaust Flow [kg/s]	213.09	Given
Exhaust Temperature [K]	682.15	Given
Power Output [MW]	101.097	Given
Heat Rate [KJ/kWh]	7921	Given
Compressor Efficiency LPC HPC	 0.8844 0.888	Tuned
Turbine Efficiency HPT IPT PT	 0.8775 0.915 0.917	Tuned

The temperature and pressure parameters are calculated using the mass – energy relations explained in Chapter 2. The component parameters are iteratively tuned to attain the calculated performance. No inlet and exhaust pressure losses were considered during the design point modelling as the performance data were rated at ISO conditions with no pressure losses. The operating conditions are shown in the Table 4.4

Table 4.4: Operating Conditions of the Model

Ambient Temperature [K]	288.15
Ambient Pressure [bar]	1.01325
Relative Humidity [%]	60
Elevation [m]	0

The cycle design point forms the basis for the calculation engine when off-design simulations are done.

4.3.2 Off-design Simulation

Cycle operating points deviating from the design point conditions given in the previous section are off-design points. In order to simulate the gas turbine in off-design conditions, component characteristics maps are required. Component maps relate the deviation in ambient conditions to the change in component performance. Apart from component maps, it is also necessary to find the controlling schedule of the gas turbine. The whole procedure again becomes iterative as the simulated performance must be validated against the OEM provided performance curves. The component maps and scheduling must be tuned to achieve relative accuracy of the model to the real engine performance.

Controlling Schedule

LMS 100 is featuring an inter-cooler and the controlling schedule also includes the inter-cooler. In GSP, the intercooler is controlled by using the intercooler control component. There are different control logics possible by specifying variable effectiveness, coolant mass flow or heat extracted. The coolant mass flow is varied to achieve a constant outlet temperature at the intercooler exit. This was specified in GSP using the '*equation control component*' and specifying the mass flow as '*free flow*'. This will ensure the user to maintain a specified temperature at the intercooler exit by varying the mass flow of the coolant. The temperature that has to be maintained is obtained from the design point data discussed in the previous section. As mentioned before the power turbine is free and hence the change in speed would not affect the gas generator as long as the power turbine is chocked. During base load operations, it is safe to assume that the power turbine is chocked. Thus the controlling schedule is gas generator exit temperature. The temperature at this station can be specified by using the *'equation control component'* and the fuel flow as *'free state'.* The validation of the simulated performance also validates using such a control schedule.

Component Maps

Component maps are proprietary and generic component maps are tuned to model the present gas turbine configuration. Generic component maps are available in public domain [19]. Component maps are selected based on the pressure ratio, mass flow capacity and geometry of the component. Pressure ratio is the most important factor as the number of stages required depends on it. Keeping these factors in view, a collection of compressor and turbine maps were selected. Using the control schedule discussed in the previous section, off-design simulations are made. These are validated against the OEM provided performance curves to get better accuracy. Different maps are used and simulated and compared with the results. The scaling of component maps is done in GSP. The scaling factors can give an idea of how much the map has to be tuned to match with the design point parameters.

$$SF_{PR} = \frac{PR_{design} - 1}{PR_{map} - 1} \qquad \text{Eqn.(22)}$$

$$SF_{W_c} = \frac{Wc_{design} - 1}{Wc_{map} - 1} \qquad \text{Eqn.(23)}$$

Based on the scaling factors obtained, component maps are selected which are close enough to the performance data. There is even better way to tune the compressor map by adaptive modelling. Adaptive modelling has better accuracy than non-linear methods [16]. However due to the amount of data that is required for using adaptive modelling, the present method is followed.

The position of the design point on the component map also is an important factor to be taken into account. The practical reason behind it is that the range of operation depends on the position of the design point on the component map. The position can be changed by specifying two values, '*map design rotor speed'* and *'map design beta value'*. Another reason is that the characteristics of the component depend on the contour of speed lines and slope of the efficiency lines around the operating point. Hence the design point location on the component map is iteratively tuned to offer better performance characteristics.

4.3.3 Model Validation

Model validation and off-design modelling go hand in hand. For every tuning made in the schedule or in the component map, the simulation result is validated. Model validation can be done using data from engine tests or from OEM provided data. For this present gas turbine, OEM provided curves include power output, exhaust mass flow and exhaust temperature plotted against ambient temperature. To validate the model, the ambient condition is incremented from 258.15 K to 320.15 K. The intercooler outlet temperature was fixed at 329 K and the power turbine inlet temperature was fixed at 1081 K. After numerous steps of tuning, the final validated curves are plotted below.

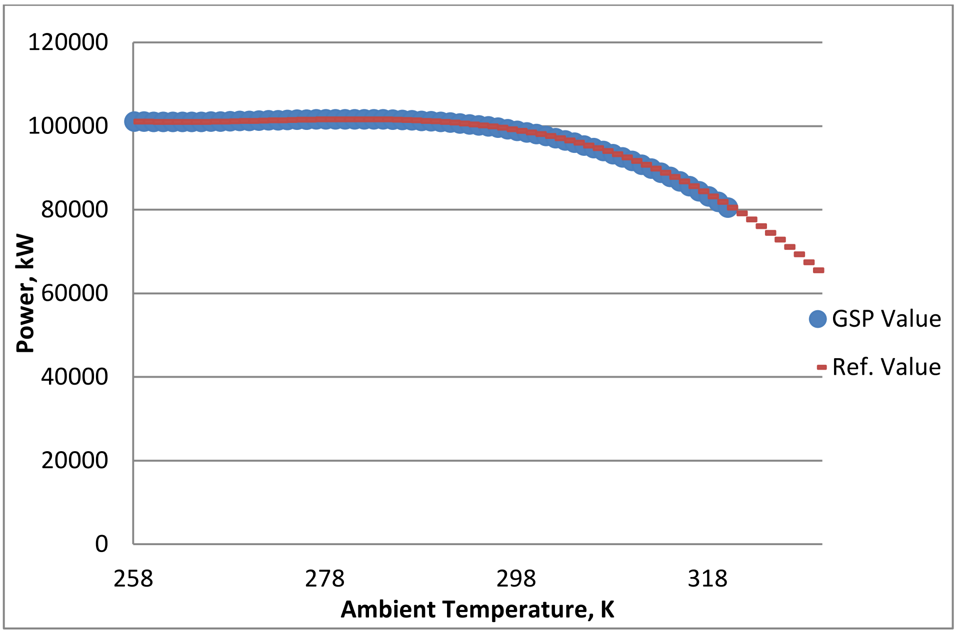

Figure 4.3: Model Validation - Power Output Curves

The simulated curves match with the performance curves with acceptable level of accuracy. The power output curve seems to be well in accordance to the OEM performance curve. The exhaust gas temperature and mass flow seems to deviate from the required performance curve at higher ambient temperature.

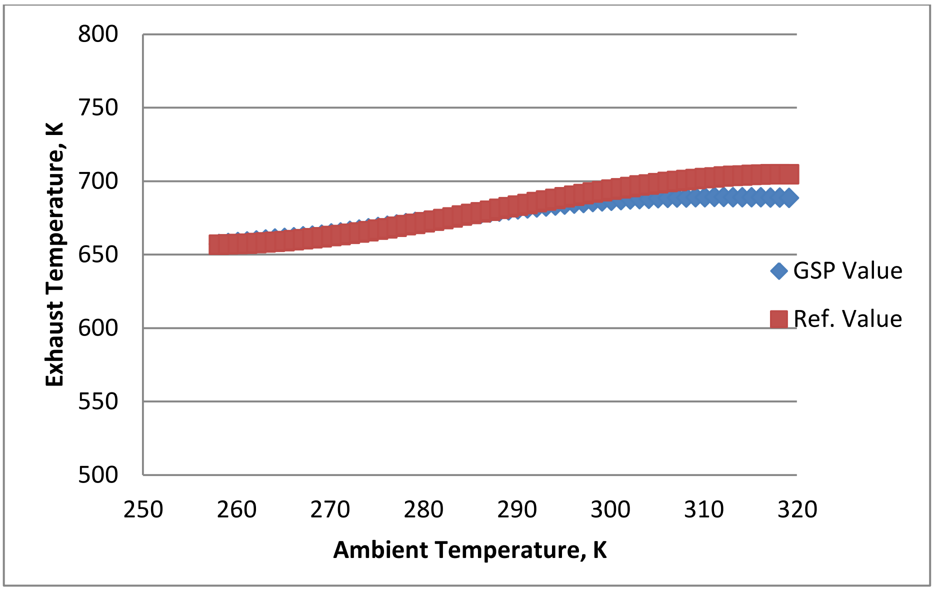

Figure 4.4: Model Validation - Exhaust Temperature Curves

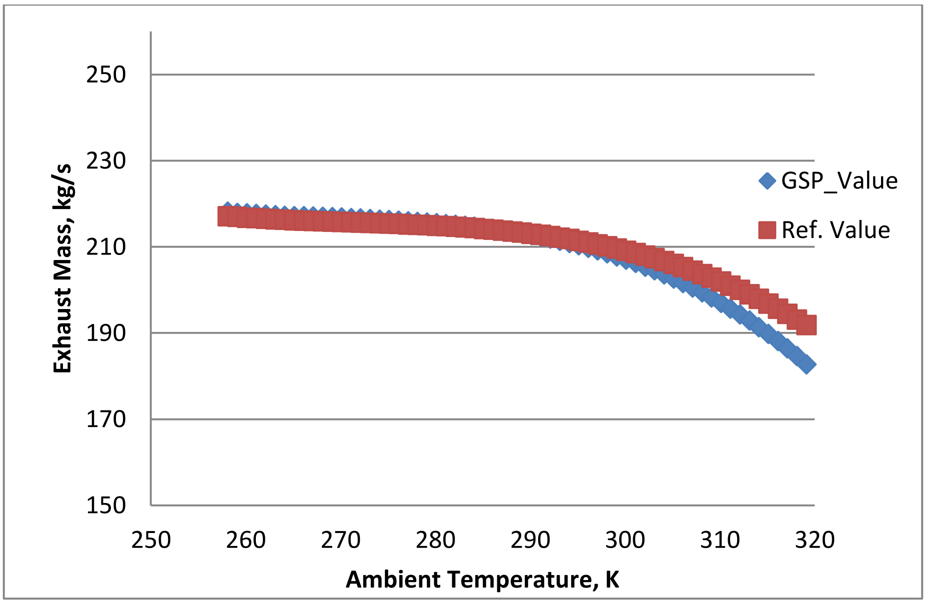

Figure 4.5: Model Validation - Exhaust Mass Curves

The maximum deviation is found to be 2.47% in the exhaust mass comparison and 1.85% in the exhaust temperature comparison. This accuracy level is deemed sufficient to consider and carry on with developing diagnostic methods.

The deviation in performance is due to the usage of generic component maps. To correct the deviation in the simulated performance, calibration factors can be applied. It relates the simulated and reference performance data by calibration factors. The simulated values are multiplied by these factors to obtain the required values [7]. This again requires a lot of measurement data which is not available and also the deviations are quite small to apply this method.

4.4 Summary

The approach to model LMS100 in GSP was described in detail. Various steps involved in modelling and simulating the off-design conditions are shown. Finally the model was validated against the OEM provided curves. The simulated performance is in good correlation with the reference performance curves. This allows the user to simulate for any condition and expect the performance to be in accordance with the real engine performance.

Chapter 5. Online Monitoring Tool

This chapter explains the online monitoring tool of the sponsor company. Application of a gas turbine diagnostic concept in such a tool is discussed. The working principle and the system architecture of the tool are explained. Understanding the concept of the tool will help in deducing the method of performance monitoring and apply diagnostics.

5.1 Concept of Online Performance Monitoring

Condition based maintenance requires constant performance monitoring of the machine. The monitoring tool at the sponsor company is designed just for that. Real time performance data of the machine such as the temperature, pressure, flow, power, speed, vibration and bearing conditions are saved on a pi server. Each parameter is assigned a specific tag such that any data can be accessed using the specific tag. The sponsor company has an exclusive calculation engine which uses the data to calculate theoretical performance and actual performance. The data is used to compare against the healthy performance trends developed for each and every component by the tool. Based on this comparison, the company provides technical expertise to diagnose the reason for deterioration in performance and to rectify the fault. This is done for all rotating equipment like compressors, gas turbines, pumps, motor and generators. The company offers varied levels of performance monitoring solutions. The levels are,

- Level 1 – Run Status
- Level 2 – Performance Monitoring
- Level 3 – Health Monitoring
- Level 4 – Advanced Health Monitoring

- Level 5 – Benchmarking Calculations

Level-1 being the lower order indicates only whether the machines are running. This gives the availability of the machine and other such basic values. Performance Monitoring (Level-2) gives the user, details on the operating point of the component, performance parameters, theoretical performance and other similar information required to assess the performance of the machine. Level-3 monitoring focusses on condition based maintenance. Diagnosis of health deterioration of the component is done and expert help in repairing the fault. Level 4 & 5 are beyond the scope of the project and hence not discussed below. Level 2 & 3 are considered important for this project and the following sections will focus on the same.

The tool has a dedicated module to calculate the performance of gas turbines. Healthy engine performance data and OEM provided performance data for each gas turbine are available. For Level-3 support, vibration analysis is used to diagnose deviation in performance. Based on the previous study to have a complete engine health monitoring system, gas path analysis can be effective when used together vibration data. One of the objectives of the project is to assist in developing a complete engine health monitoring tool. The remainder of this chapter will deal with performance monitoring (Level – 2) and health monitoring (Level – 3) is discussed in detail in the following chapter.

5.2 Gas Turbine Module Input

Gas turbine module of the tool can be used to any configuration of gas turbine. The sensor set of every gas turbine can be different and Sponsor Company uses a general set of data for this tool. To develop performance monitoring for the current configuration under study, it is important to know the inputs and output required of the tool. The Table 5.1 below shows the generic input and output accessed by the tool.

Table 5.1: I/O of GT Module

Inputs	Outputs
• Ambient conditions • Design data • Pressure loss at different components • Fuel properties and flow • Air flow • Pressure & Temperature at specific sections	• Overall thermal efficiency • Component efficiency • Turbine inlet temperature • Heat rate • Power Output

Based on this information, the proposed method of performance monitoring must take into account the various input data available at the site and also the outputs required.

5.3 Proposed concept

The proposed concept is based on gas path analysis. 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 path parameter can be accounted because of deviation in component's health. Off-design simulation of the gas turbine model earlier done can be used for the performance monitoring. The following sections will discuss the performance parameter trends, assumptions and method of implementing it within the present online remote monitoring.

5.3.1 Performance Trends

Trending performance parameters for a range of conditions is a usual method used in diagnostics and prognostics in the oil & gas industry. This chapter will discuss the considerations and the method used to develop performance trends for the LMS100 configuration. Performance trends can be used to validate the maintenance performed over a component. Using different parameter trends of the machine, deterioration modes of the engine can be deduced. Since the gas turbine operates in varied ambient conditions, the performance trends should be common and independent of its ambient conditions. Each parameter is corrected to neglect the effect of ambient conditions in which the engine is operating. The Table 5.2 below shows the corrected parameters.

Table 5.2: Corrected Parameters and relation

Parameter	Standard Correction	Correcting Relation
Gas mass flow rate, [kg/s]	$W_{cor} = \frac{W_{air}.\sqrt{\theta}}{\delta}$	$W_{cor} = \frac{W_{air}.\sqrt{\theta}}{\delta}$
Temperature, [K]	$T_{cor} = \frac{T}{\theta}$	$T_{cor} = \frac{T}{\theta.\omega^{0.1}}$
Pressure, [bar]	$P_{cor} = \frac{P}{\delta}$	$P_{cor} = \frac{P}{\delta.\omega^{1.6}}$
Fuel flow rate, [kg/s]	$W_{fuel_{cor}} = \frac{W_{fuel}}{\delta.\sqrt{\theta}}$	$W_{fuel_{cor}} = \frac{W_{fuel}}{\delta.\sqrt{\theta}}$

Shaft speed, [rpm]	$N_{cor} = \frac{N}{\sqrt{\theta}}$	$N_{cor} = \frac{N}{\sqrt{\theta}.\omega^{0.7}}$
Shaft Power, [kW]	$Pw_{cor} = \frac{Pw}{\delta.\sqrt{\theta}}$	$Pw_{cor} = \frac{Pw}{\delta.\sqrt{\theta}.\omega^{3}}$

Where the correction variables θ and δ are found by the relations shown below.

$$\theta = \frac{T_{ambient}}{T_{ref}} \qquad \text{Eqn.(24)}$$

$$\delta = \frac{P_{ambient}}{P_{ref}} \qquad \text{Eqn.(25)}$$

$$\omega = \frac{PT_{In\,Temp}}{PT_{In\,Temp,ref}} \qquad \text{Eqn.(26)}$$

T_{ref} is the reference temperature and P_{ref} is the reference pressure which are 288.15 K and 1.01325 bar respectively. $PT_{In\,Temp,ref}$ is the reference power turbine inlet temperature and the value used is 1081 K. Including ω value allows the baseline curve to include the effect of changing power turbine inlet. The values are found by trial and error method to reduce the discrepancy when plotting operating points at different control schedule. Figure 5.1 and Figure 5.2 below shows the effect of correcting the parameters using the modified correcting relation. The scatter plots show the standard corrected parameters and the modified corrected parameters. The graphs are plotted for varying power turbine inlet temperature from 1050 K to 1120 K. It can be seen that the corrected parameter values are converging into more or less a single line. Similarly all the corrected parameter trends converge closer when using the modified correction parameter.

The effect of relative humidity on the performance of the gas turbine is less and the claim is supported by the plots available in the appendix. The simulated results for a range of humidity values are plotted. Variation in engine operating line due to variation in ambient humidity can be referred in section Appendix A.

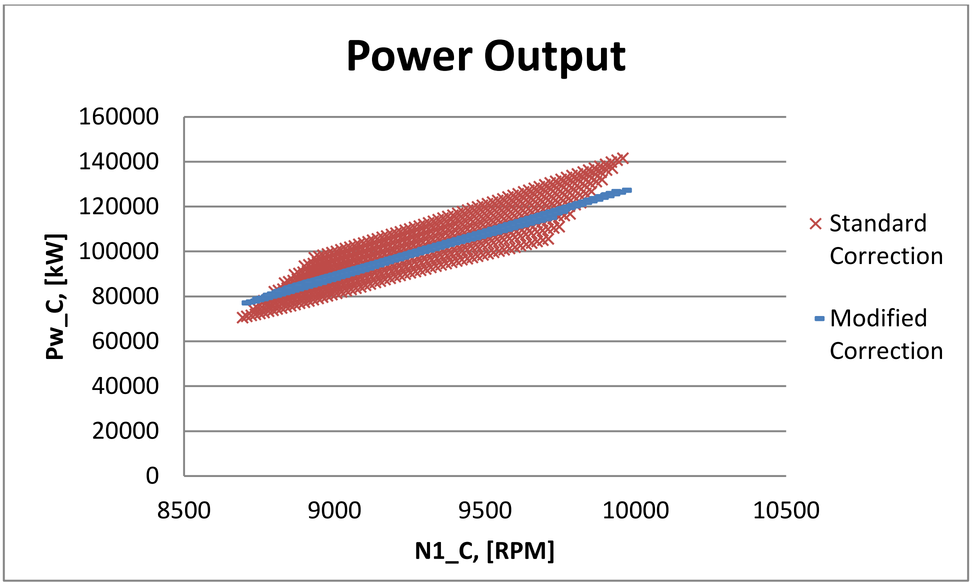

Figure 5.1: Comparison between standard and modified correction curves

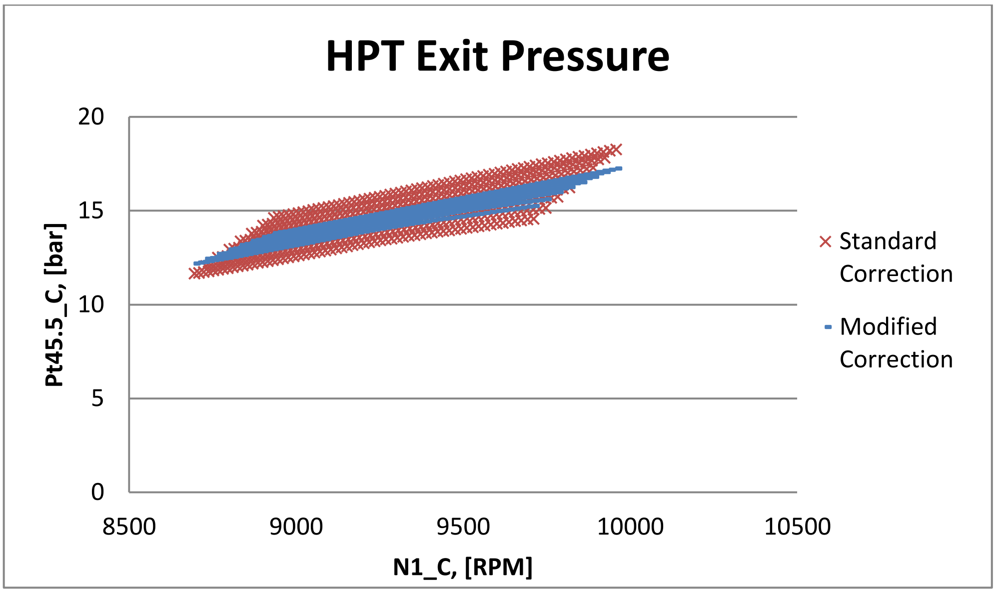

Figure 5.2: Comparison of standard and modified correction curves

Assumptions

The following assumptions are made during the simulations and should be duly noted before implementing in the remote monitoring tool.

- Inlet pressure losses are neglected as the performance rating provided by the OEM does not include them. Various inlet filtration systems are installed according to the operating conditions and this might have different impact on the pressure losses.

- No secondary flows are considered during this simulation. With mass and energy conservation perception, this is a valid assumption but the efficiency calculated by the model will differ.
- The simulations are carried out for base load conditions only.
- The intercooler design is not revealed and hence it is assumed that the intercooler is working at its rated condition.
- The power turbine is designed for variable speed applications. The model is designed with design power turbine speed as 3000 rpm.
- The outlet pressure losses are considered negligible.

Theoretical Background

The basic conservation equations for a 3-shaft gas turbine configuration are shown below.

- Mass flow compatibility between low pressure compressor and high pressure compressor.

$$\frac{m_a.\sqrt{T_{23}}}{P_{23}} = \frac{m_a.\sqrt{T_2}}{P_2} * \frac{P_2}{P_{23}} * \sqrt{\frac{T_{23}}{T_2}} \qquad \text{Eqn.(27)}$$

- Mass flow compatibility between high pressure compressor and high pressure turbine.

$$\frac{m_g.\sqrt{T_4}}{P_4} = \frac{m_a.\sqrt{T_{33}}}{P_{33}} * \frac{P_{33}}{P_3} * \frac{P_3}{P_4} * \sqrt{\frac{T_4}{T_{33}}} * \frac{m_g}{m_a} \qquad \text{Eqn.(28)}$$

- Mass flow compatibility between high pressure turbine and intermediate pressure turbine

$$\frac{m_g.\sqrt{T_{45.5}}}{P_{45.5}} = \frac{m_g.\sqrt{T_4}}{P_4} * \frac{P_4}{P_{45.5}} * \sqrt{\frac{T_{45.5}}{T_4}} \qquad \text{Eqn.(29)}$$

- Mass flow compatibility between gas generator and power turbine

$$\frac{m_g.\sqrt{T_{46}}}{P_{46}} = \frac{m_g.\sqrt{T_{45.5}}}{P_{45.5}} * \frac{P_{45.5}}{P_{46}} * \sqrt{\frac{T_{46}}{T_{45.5}}} \qquad \text{Eqn.(30)}$$

- Work requirement between the low pressure compressor and low pressure turbine

$$\eta_m . m_g . c_{pg}(T_{45.5} - T_{46}) = m_a . c_{pa}(T_{23} - T_2) \qquad \text{Eqn.(31)}$$

- Work requirement between the high pressure compressor and high pressure turbine

$$\eta_m . m_g . c_{pg}(T_4 - T_{45.5}) = m_a . c_{pa}(T_3 - T_{33}) \qquad \text{Eqn.(32)}$$

- Shaft speed compatibility between high speed spool components

$$\frac{N_1}{\sqrt{T_4}} = \frac{N_1}{\sqrt{T_{33}}} * \sqrt{\frac{T_{33}}{T_4}} \qquad \text{Eqn.(33)}$$

- Shaft speed compatibility between low speed spool components

$$\frac{N_2}{\sqrt{T_{45.5}}} = \frac{N_2}{\sqrt{T_2}} * \sqrt{\frac{T_2}{T_{45.5}}} \qquad \text{Eqn.(34)}$$

The operating point of the compressor has to satisfy the mass and energy compatibility equations mentioned above [3]. The various operating points comprise together to form the equilibrium line of operation. The operation of the gas turbine depends on the flow capacity of the power turbine. During base load, the power turbine is in chocked condition. So this fixes the mass flow capacity through the power turbine and indirectly other components. For a fixed mass flow capacity, the speed of the component will fix the other component parameter such as the pressure ratio and efficiency of the component. The present configuration has a gas generator with two spools and a free power turbine. It is necessary to find the relation between the spool speeds of both low pressure spool and high pressure spool. The Figure 5.3 below shows the high pressure compressor map with operating lines for varying power turbine inlet temperature from 1050 K to 1120 K.

For the same operating conditions, the compressor map of the LPC shows that the operating lines vary. The low pressure compressor map with operating lines is shown in Figure 5.4. This will cause the parameters to differ for different control settings. Figure 5.5 shows the variation in corrected LPC exit pressure against the high pressure spool speed.

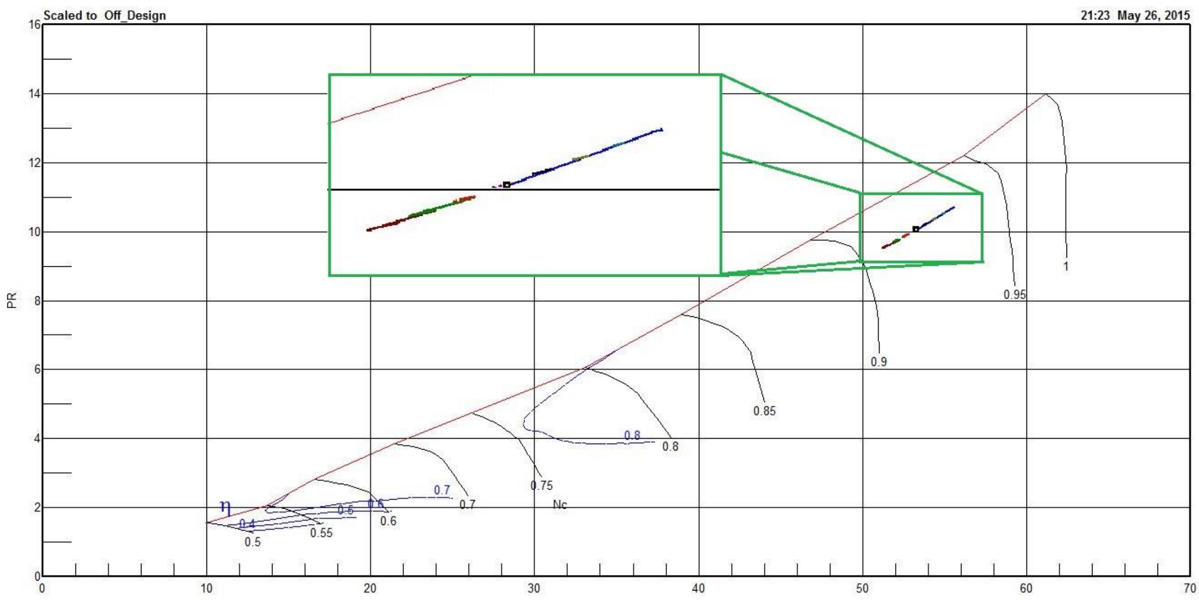

Figure 5.3: Zoomed section of HPC Map

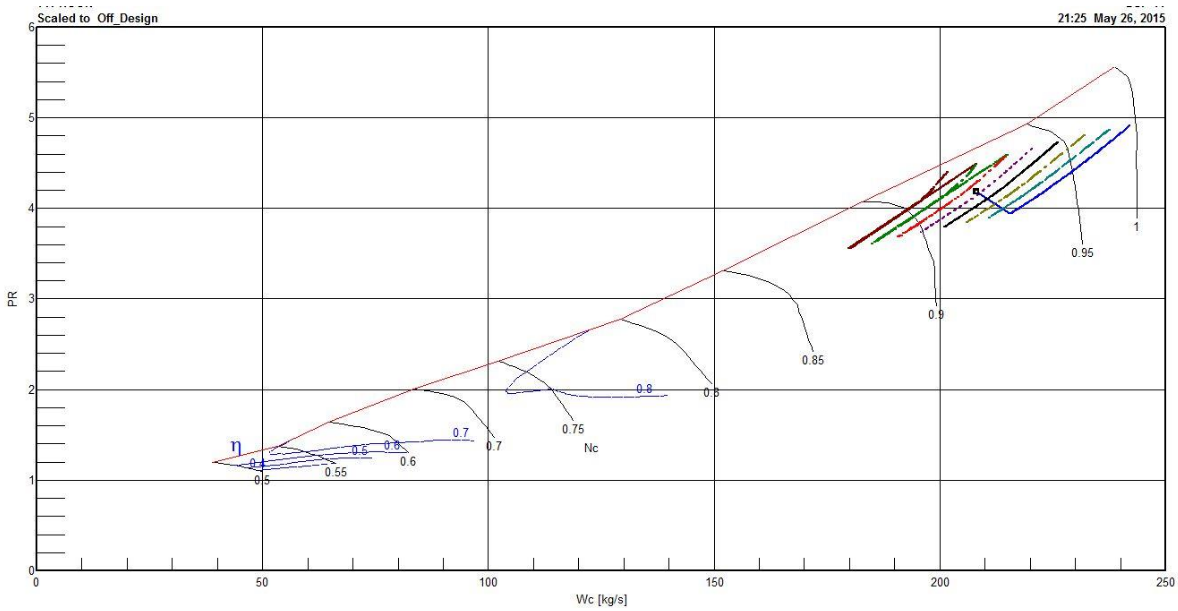

Figure 5.4: LPC Compressor Operating Lines

Correcting the measured parameters has decreased the variation between corrected parameters when engine is operated at different control settings. Thus the baseline trends simulated are plotted against the high pressure spool speed.

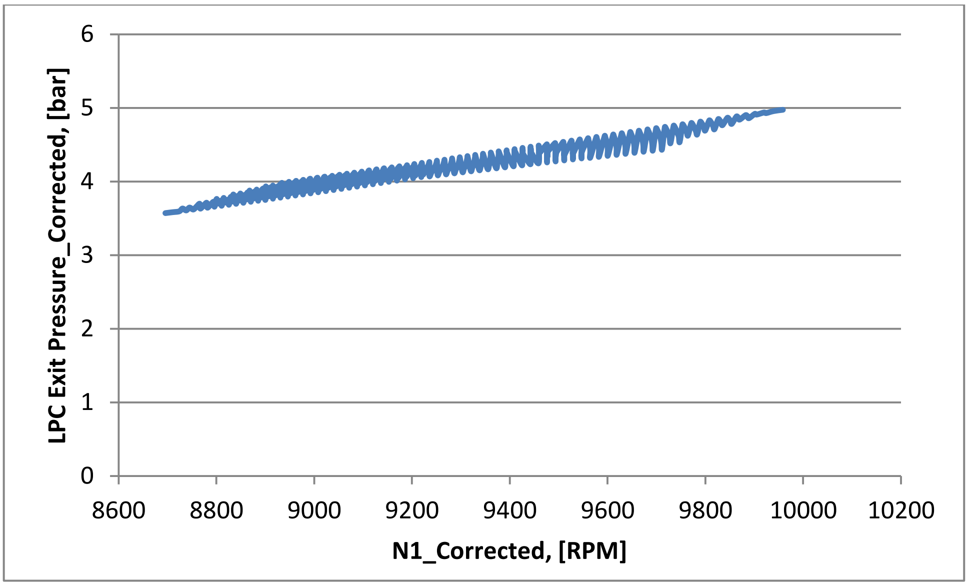

Figure 5.5: Variation of corrected LPC exit pressure against corrected high pressure spool speed

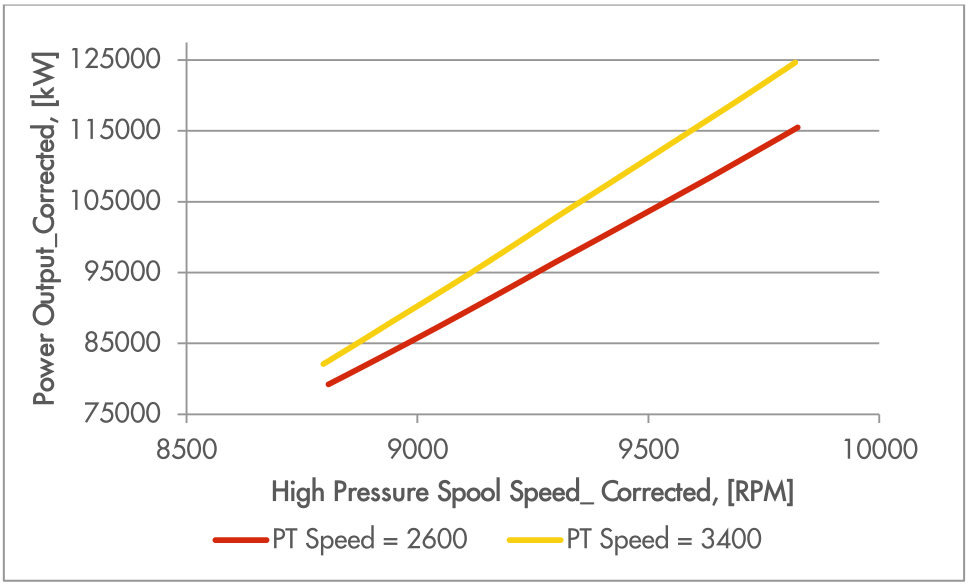

Figure 5.6: Corrected power output dependence on PT speed

Moreover the power turbine is operating in chocked conditions. This implies that the parameters upstream the power turbine is independent of the power turbine speed and the parameters of the power turbine itself are dependent on the high pressure spool speed as well as the power turbine speed. Figure 5.6 shows the dependence of power turbine parameters on the power turbine speed. The gas generator parameters are independent of the power turbine speed.

Clean Engine Trends

The clean engine trends are the baseline performance trends derived from the simulation of the LMS100 model in GSP. Considering that the intercooler output temperature as fixed, the power turbine inlet temperature has been varied over a range to obtain these trends as explained previously in off-design modelling section - 4.3.2. The operating range is displayed in the Table 5.3 below. Using the relations from Table 5.2, the parameters are corrected and plotted against the high pressure spool speed.

Table 5.3: Operating Range

Parameter	Range
Ambient Temperature, [K]	258.15 - 320.15
Ambient Pressure, [bar]	0.93 - 1.2
Relative Humidity, [%]	50 - 80
PT Speed, [RPM]	2600 - 3400
Intercooler Outlet Temperature, [K]	329
PT Inlet Temperature, [K]	1050 - 1120

The baseline trends simulated are plotted below. The gas generator parameters are plotted against the high pressure spool speed and the power turbine parameters are plotted against high pressure spool speed for a range of power turbine speed. The consolidated trends are shown in the figures below.

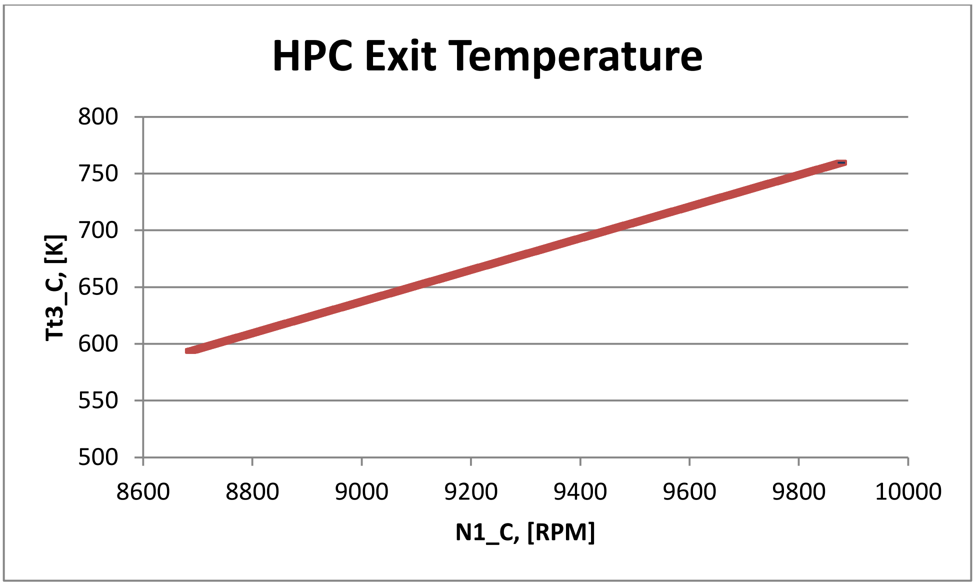

Figure 5.7: Corrected LPC exit temperature trend

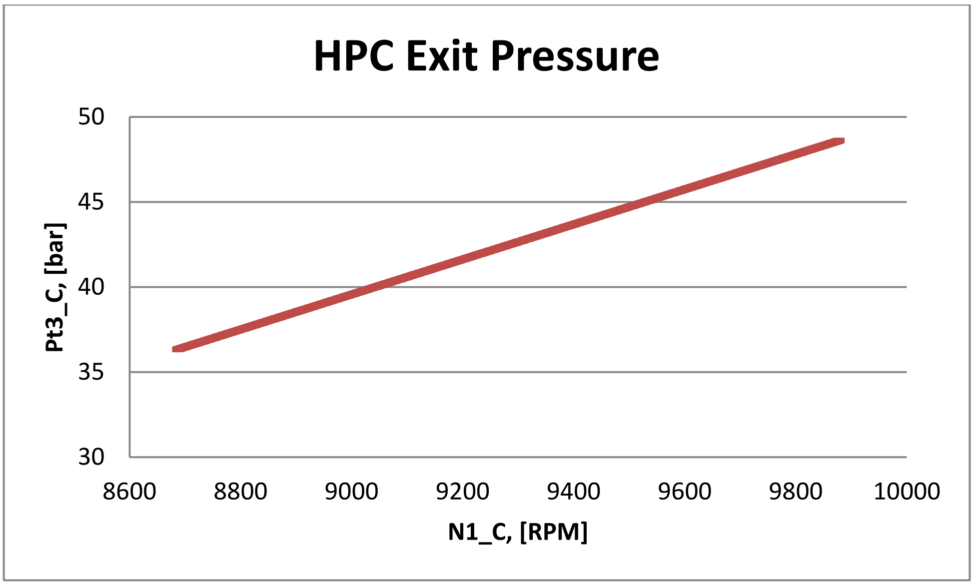

Figure 5.8: Corrected HPC exit pressure trend

Similarly LPC exit pressure, LPC exit temperature, HPT exit pressure, IPT exit pressure, IPT exit temperature and PT exit temperature are plotted against high pressure spool speed. The reader can refer to Appendix A to view the other plots. The clean engine trends developed are usually validated against real time engine measurement data. Since real time data is not available, GSP is used to simulate the operation of the gas turbine at various possible operating conditions. The following plots show the baseline trends and their corresponding operating points obtained from the simulation. The plots show that the correction factors used are appropriate and can be used in performance monitoring application.

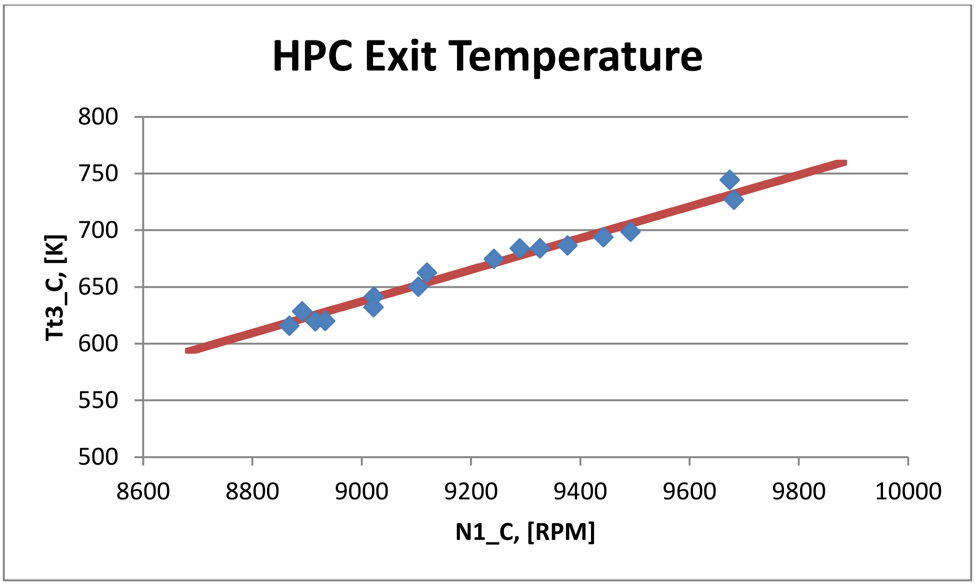

Figure 5.9 Operating points on baseline curve - HPC Exit Temperature

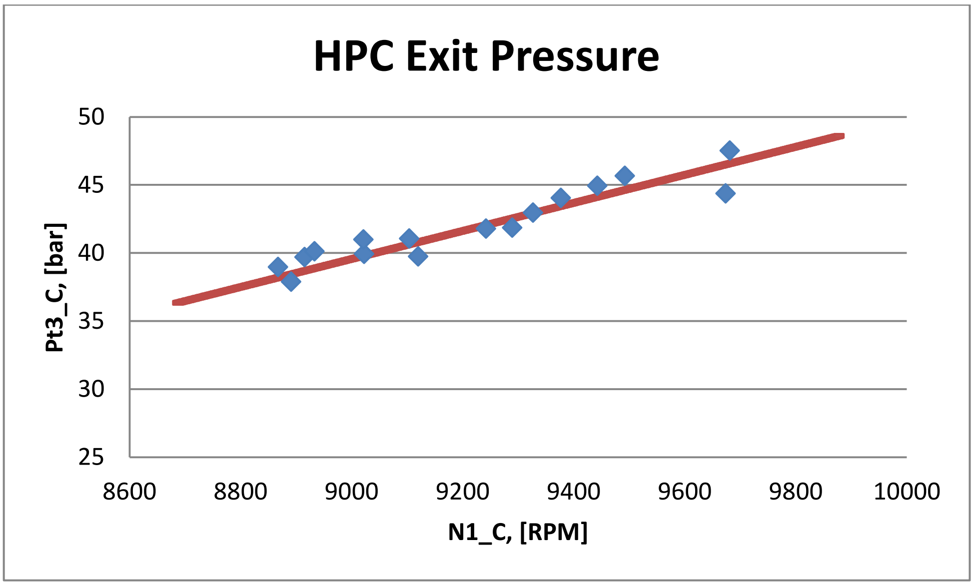

Figure 5.10: Operating points on baseline curve - HPC Exit Pressure

Apart from these two above shown plots, operating points of other corrected parameters can be found in the Appendix A section.

5.4 Summary

The remote online monitoring tool of the sponsor company was introduced and the various levels of performance monitoring were discussed. The project focusses on Level-two and Level-three performance monitoring and diagnostics. This chapter dealt in detail with the level-two health monitoring of the gas turbine. The parameters were corrected to its inlet conditions to neglect the effects of its ambient condition of operation. Correction parameter was determined by trial and error method. The mass and power compatibility equations helped in determining the operating point of the component. Further investigation led to plot trends of the gas generator performance parameters against high pressure spool speed and the power turbine performance parameters against speeds of both high pressure spool and power turbine. The generated performance trends can be used in an online monitoring environment. A lookup tool was created to facilitate plotting the clean engine trends. This can be used in the level two health monitoring stage of the sponsor tool. Plotting the actual operating conditions with the clean engine trends will indicate possible deviation from healthy trends because of component deterioration. Diagnostic method of component deterioration is discussed in detail in the following chapter.

Chapter 6. Diagnostic of Component Deterioration

In the present chapter, the method of diagnosing component deterioration is discussed. This method will be an addition to the present capability of the sponsor company tool to diagnose component deterioration using vibration analysis. Based on the extensive literature study, using gas path analysis with vibration analysis technique would provide a complete engine health monitoring system. The proposed method can also be extensively used for condition based maintenance. Various gas turbine components deterioration was discussed in section 2.6 and also their implication on gas path parameters is known. It was discussed earlier that the measured parameters of a component has non-linear relation with their respective health parameters. In this chapter, deterioration of health parameters are introduced to the LMS100 model in GSP and their respective deviation in measured parameters are noted. Various intensity of deterioration is simulated in GSP and sensitivity analysis is done. A diagnostic method is developed based on the deterioration data. Limitations and conclusion are given about the proposed diagnostic method.

6.1 Sensitivity Analysis

The common gas turbine component deterioration simulated includes variable geometry fault, fouling, corrosion, erosion and rotor fault. The simulation is done for a specific power turbine inlet temperature setting and it is compared to the parameters of healthy parameter trends. The operating condition of the model is from 258.15 K to 320.15 K. The deviation in corrected parameters is used for the sensitivity analysis.

The implication of deterioration over the health parameters of the component is shown in the Table 6.1 below.

Table 6.1: Deterioration Case and implication on health parameters

Deterioration Cases	Health Parameters	
	ΔW_c	$\Delta\eta$
Variable Geometry Fault	↓	-
Fouling	↓	↓
Erosion	↑	↓
Rotor Fault	-	↓
Corrosion	↑	-

Deterioration study can be done using GSP tool where the user can specify the percentage of deviation in the health parameters.

Table 6.2: Index table of Deterioration Cases

Deterioration Cases	Index - 1		Index - 2		Index - 3		Index - 4		Index - 5	
	ΔW_c	$\Delta\eta$	ΔW_c	$\Delta\eta$	ΔW_c	$\Delta\eta$	ΔW_c	$\Delta\eta$	ΔW_c	$\Delta\eta$
Variable Geometry Fault	- 2%	-	- 4%	-	- 6%	-	- 8%	-	- 10%	-
Fouling	- 2%	- 2%	- 4%	- 4%	- 6%	- 6%	- 8%	- 8%	- 10%	- 10%
Erosion	+ 2%	- 2%	+ 4%	- 4%	+ 6%	- 6%	+ 8%	- 8%	+ 10%	- 10%
Rotor Fault	-	- 2%	-	- 4%	-	- 6%	-	- 8%	-	- 10%
Corrosion	+ 2%	-	+ 4%	-	+ 6%	-	+ 8%	-	+ 10%	-

To facilitate simulating deterioration cases of varying intensity, the deterioration cases were indexed ranging from 1 to 5, increasing the intensity of deterioration. The magnitude of deterioration of various health parameters for their respective component deterioration cases are shown in Table 6.2.

Deterioration can happen in single components and also in multiple components at the same time. It is also possible that multiple deterioration cases can occur in a single component.

6.1.1 Single Component Deterioration

In this section single deterioration study is done considering either one of the component at deterioration. Various cases studied with different components are shown in the Table 6.3 below. Totally 48 cases of single component deterioration was studied.

Table 6.3: Single Component Deterioration Cases

Component	Deterioration case	No. of cases studied
Low Pressure Compressor (LPC)	Variable Geometry Fault	3
	Fouling	5
High Pressure Compressor (HPC)	Fouling	5
High Pressure Turbine (HPT)	Corrosion	5
	Rotor Fault	5
	Erosion	3
Intermediate Pressure Turbine (IPT)	Corrosion	5
	Rotor Fault	5
	Erosion	5
Power Turbine (PT)	Corrosion	1
	Rotor Fault	5
	Erosion	1

The following sections will discuss the sensitivity of the measurable parameters to their specific deterioration. Significant shift in the parameter trends are plotted from their respective clean engine parameter trend. Parameter trends of all other parameters not plotted in this section is available in the section Appendix B. The following figures show the deviation of measured parameters due to varying ambient temperatures from 258.15 K to 320.15 K. The difference in deviations is due to the error in modelling because of using inaccurate generic component maps. Even though deviation results shows variation with ambient temperature, the accuracy is deemed sufficient for using in the diagnostic tool.

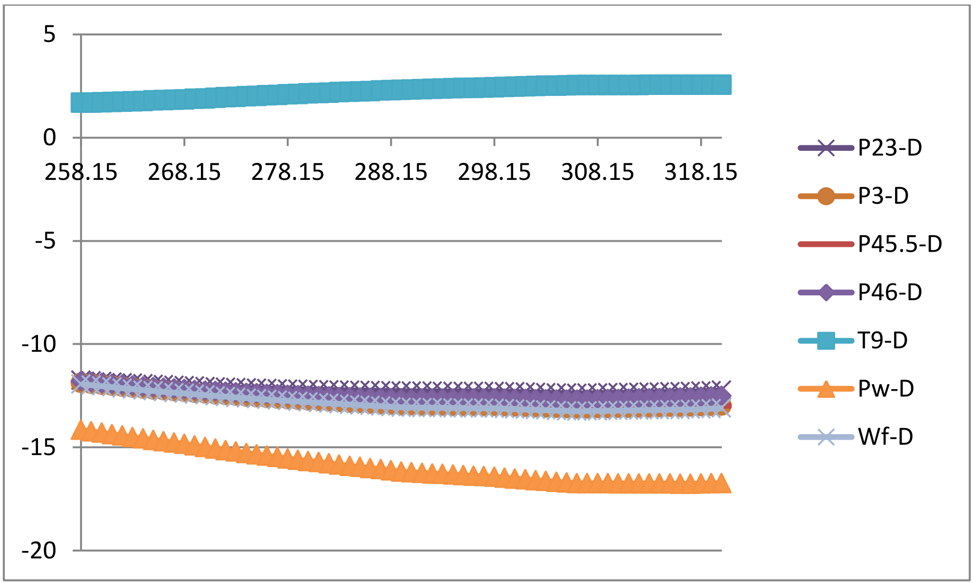

Figure 6.1: Deviation in parameters due to fouling in LPC

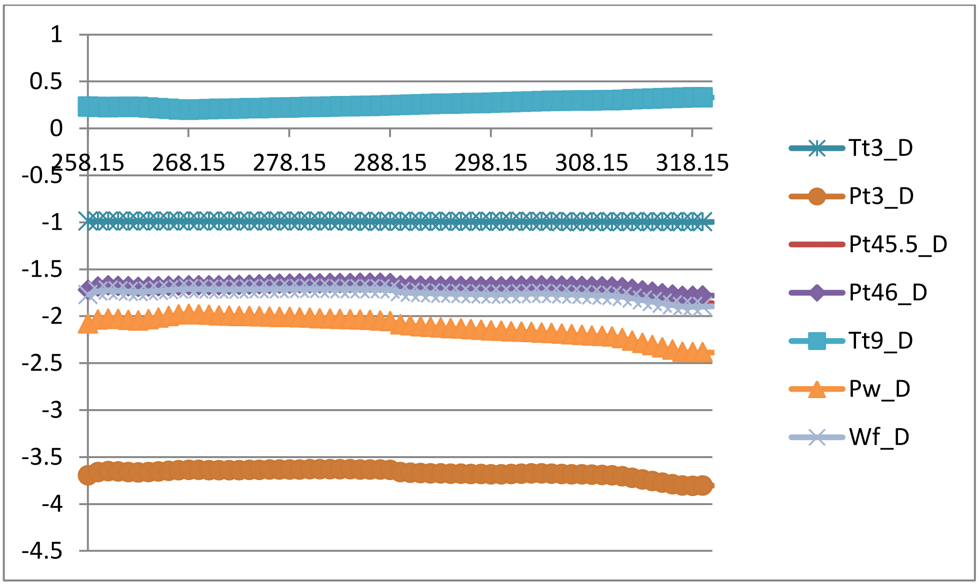

Figure 6.2: Deviation in parameters due to corrosion in HPT

The remaining plots showing deviation in parameters due to various deterioration cases can be found in Appendix B. Analysing the deviation plots of corrected parameters, it is safe to assume that the averaged deviation values can be used for quantifying deterioration effects. Thus the following sections will describe the deterioration case and the averaged deviation parameters for their respective deterioration intensity.

Variable geometry fault (VGF)

The variable geometry fault is simulated by introducing deterioration in the low pressure compressor. The corrected flow rate parameter is decreased in the GSP model to simulate this kind of deterioration. Variable geometry fault is denoted by VGF and its corresponding intensity according to the Table 6.2. Figure 6.3 shows the sensitivity of all measurable parameters to variable geometry fault. On investigating the data it can be seen that the deviation is significant at higher intensity of deterioration and increase in low pressure spool speed is the most sensitive parameter.

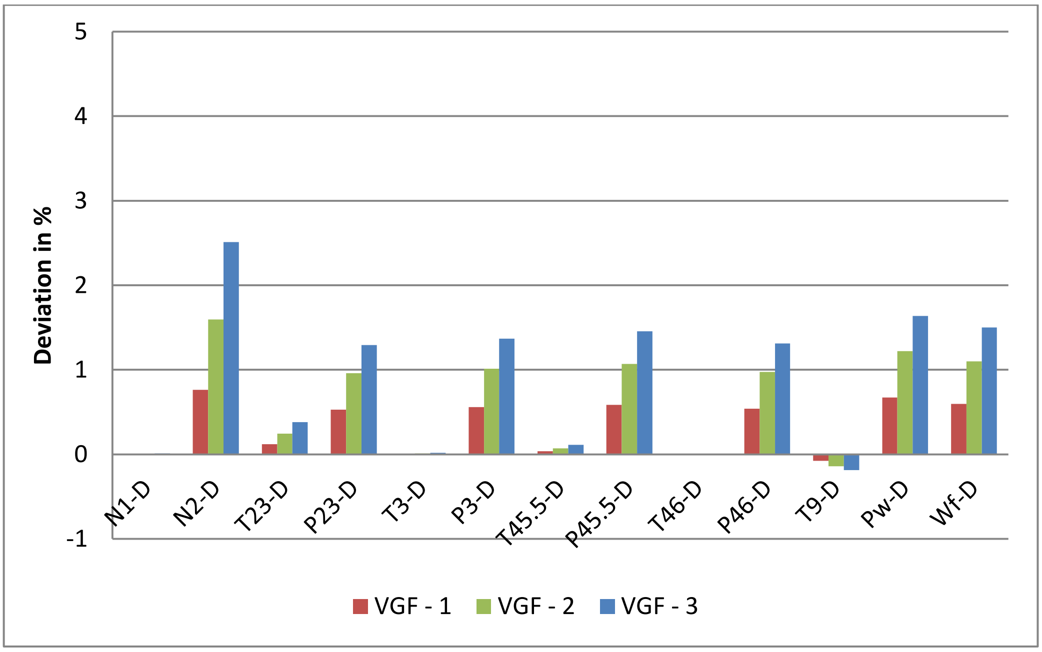

Figure 6.3: Sensitivity analysis of variable geometry fault

The analysis shows that the speed of the low pressure spool speed, N_2 increases. The pressure at the exit of the LPC increases and this affects the pressure at every station downstream the LPC. The high pressure spool speed does not change and the mass flow compatibility equations requires the low pressure spool to increase in speed thereby increasing the pressure ratio of the component. The intercooler negates the increase in temperature at the LPC exit. Since the temperature at the intercooler exit and power turbine inlet is fixed, there is excess flow of fuel. The pressure ratio available for the power turbine is high and the power output is increased.

Figure 6.4 shows the variation of N_2 speed for different deterioration level of VGF.

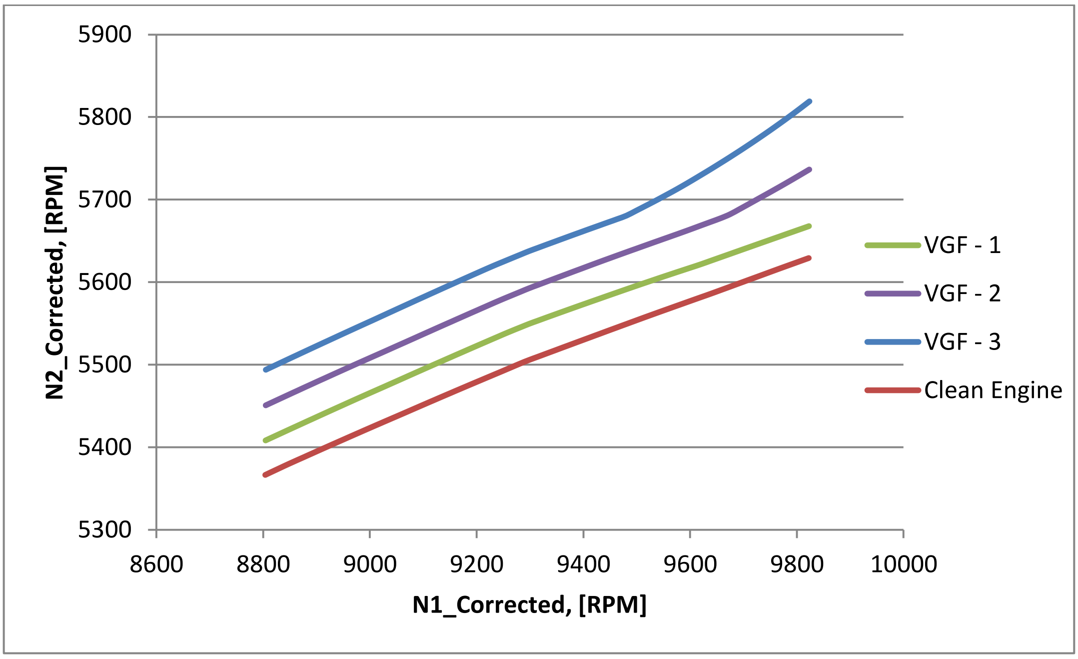

Figure 6.4: Variation of N2 due to VGF

Further figures below show that the deviation in corrected power and corrected fuel flow.

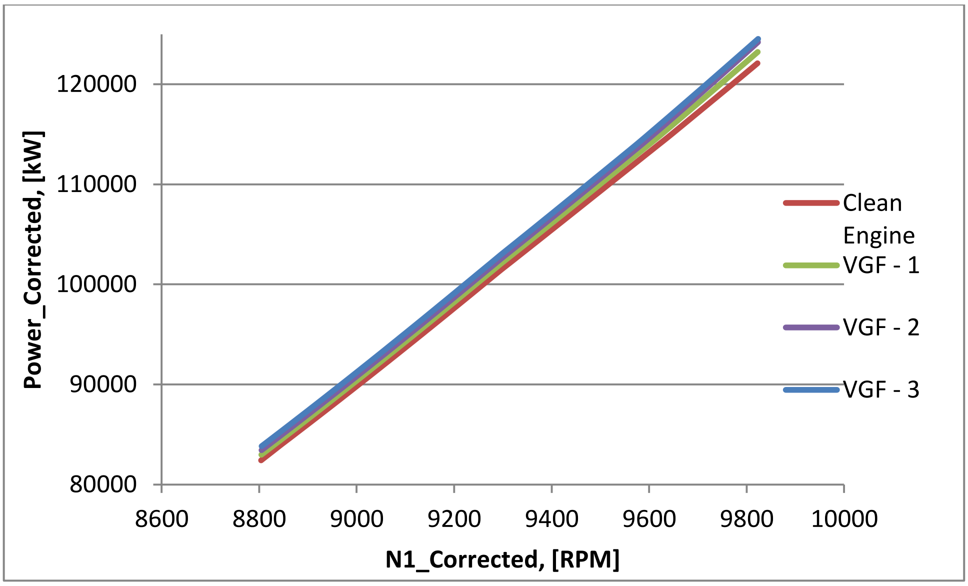

Figure 6.5: Variation of corrected power by VGF

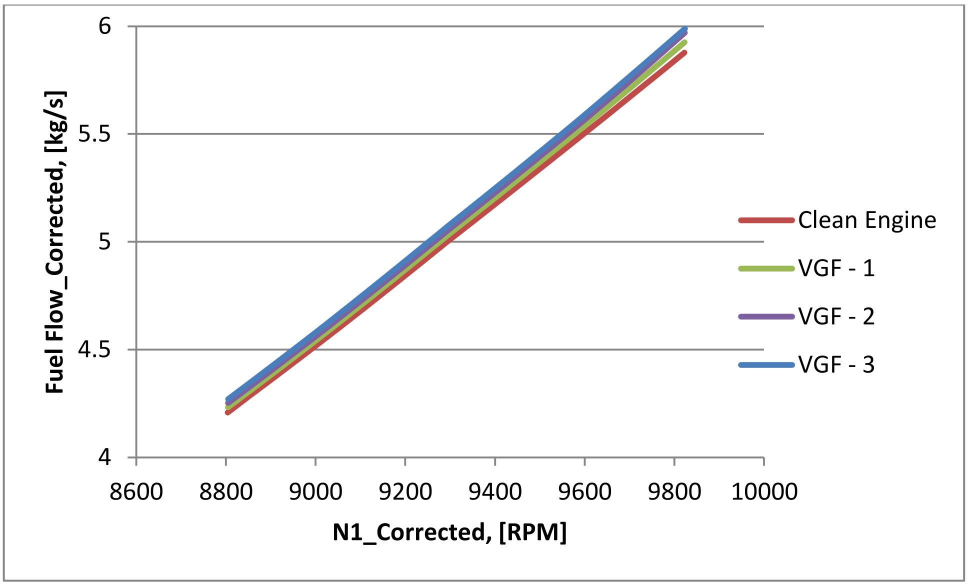

Figure 6.6: Variation of corrected fuel flow due to VGF

Fouling

Fouling is characterised by decrease in efficiency and corrected mass flow of the component. Fouling is denoted by “F” and its corresponding intensity according to the Table 6.2. Fouling in the low pressure compressor is simulated by introducing decrease in corrected flow and efficiency of the component. The Figure 6.7 shows the deviation of all the parameters due to fouling in LPC.

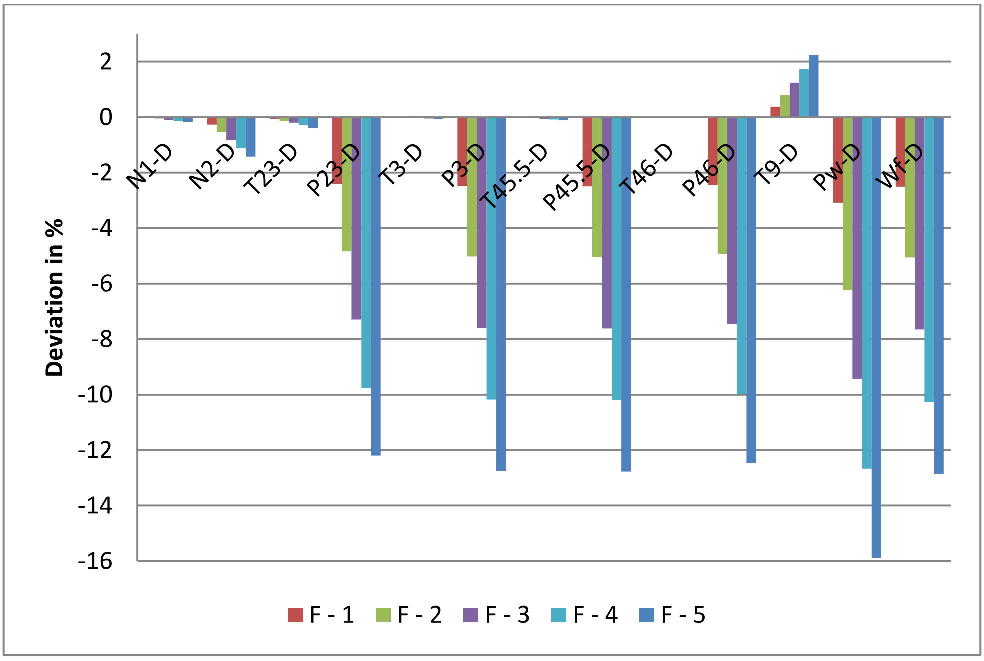

Figure 6.7: Deviation of parameters due to fouling in LPC

The most sensitive parameter measured due to fouling at LPC is the power output. The power drops from -2% to -16% upon increasing intensity of deterioration. Fouling in LPC does not affect the speed of the high pressure spool speed significantly.

The compressor equilibrium line shifts down, thus reducing the pressure ratio and speed of the LPC. Lesser pressure ratio in the compressor requires lesser work.

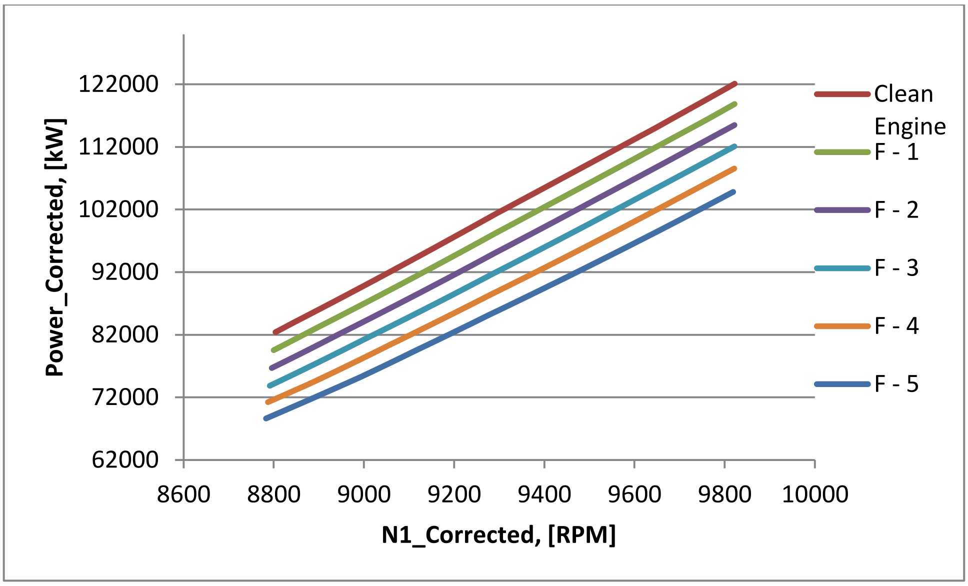

Figure 6.8: Variation in corrected power due to fouling in LPC

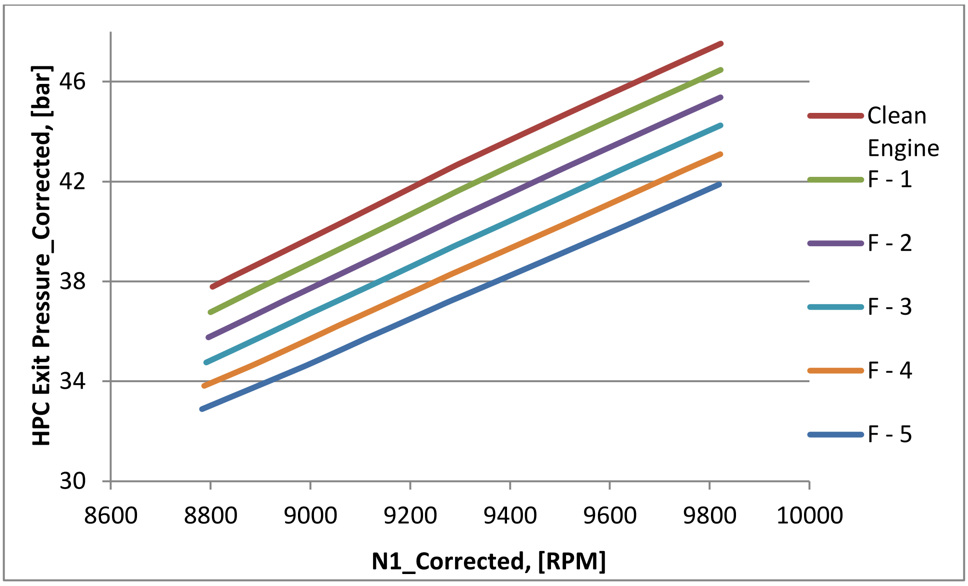

Figure 6.9: Variation in corrected HPC exit pressure due to fouling in LPC

Reduction in the mass flow allows the fuel flow to reduce to maintain the power turbine inlet temperature. The power output is reduced significantly. Figure 6.8 shows the deviation in corrected power output trends due to various intensity of fouling in LPC. There is equivalent amount of decrease in percentage of pressures at the compressor outlet and at the intermediate pressure turbine inlet. The exhaust temperature of the gas turbine is increasing but comparatively very less percentage of deviation.

The parameter deviation from the clean engine trends due to fouling in HPC is shown in the Figure 6.10. The analysis shows similar effects on the components as fouling in LPC but the magnitude of deviation in higher.

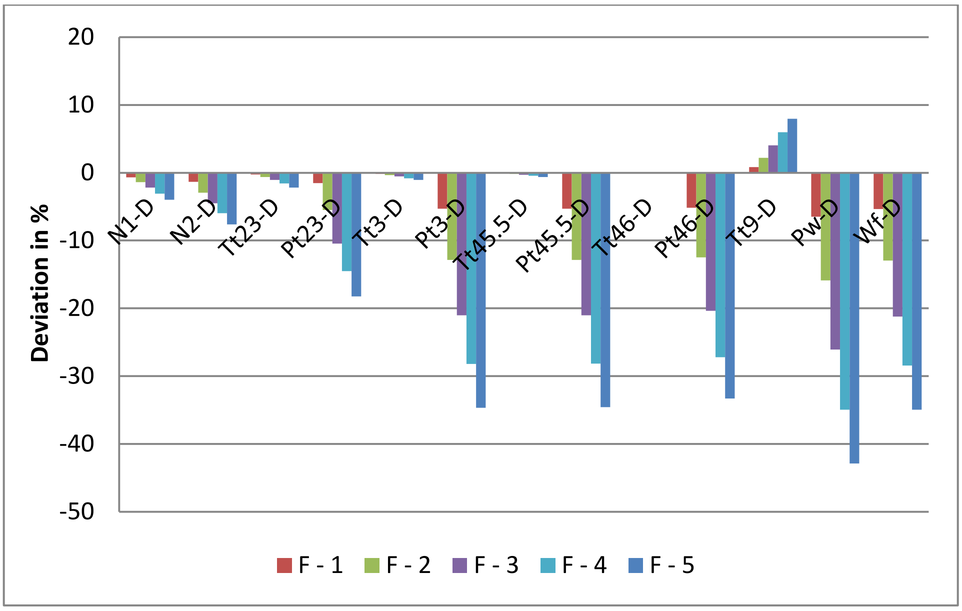

Figure 6.10: Deviation of parameters due to fouling in HPC

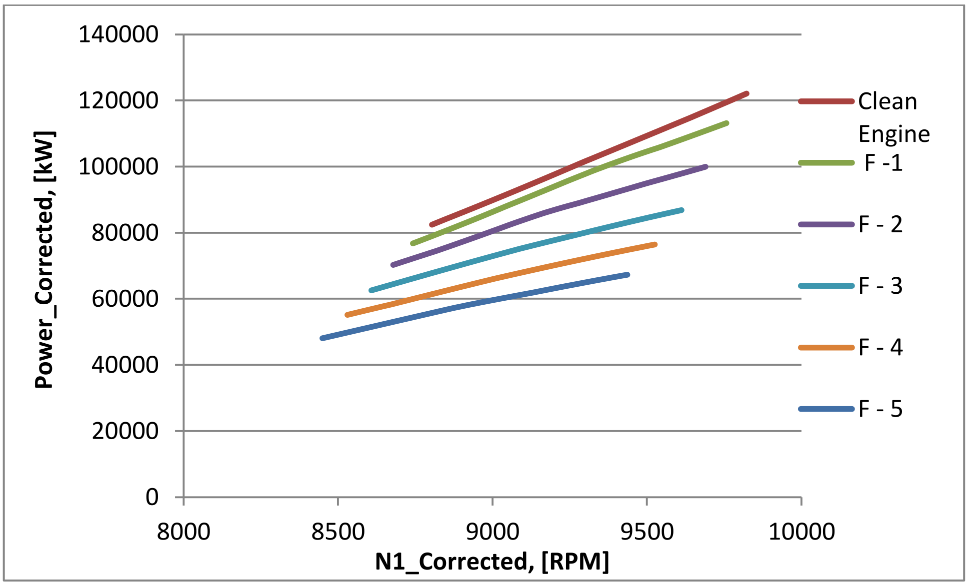

Figure 6.11: Variation of corrected power due to fouling in HPC

Fouling in HPC affects the speed of both spools. Reduce in efficiency and flow capacity shifts down the compressor equilibrium line of both the compressor components. Thus the power produced by the power turbine is decreased. There is an increase in the temperature of the exhaust flow.

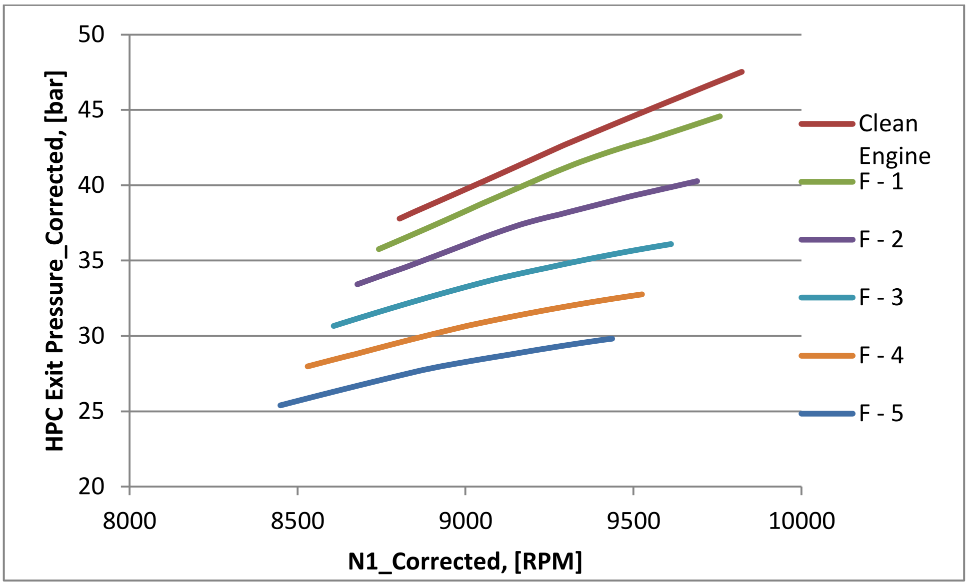

Figure 6.12: Variation of corrected HPC exit pressure due to fouling in HPC

Corrosion

Corrosion is indicated by an increase in corrected mass flow of the component. The same case can be used for deterioration like tip clearance, corroded vanes and nozzles. Corrosion is denoted by "Co" and its corresponding intensity according to the Table 6.2.

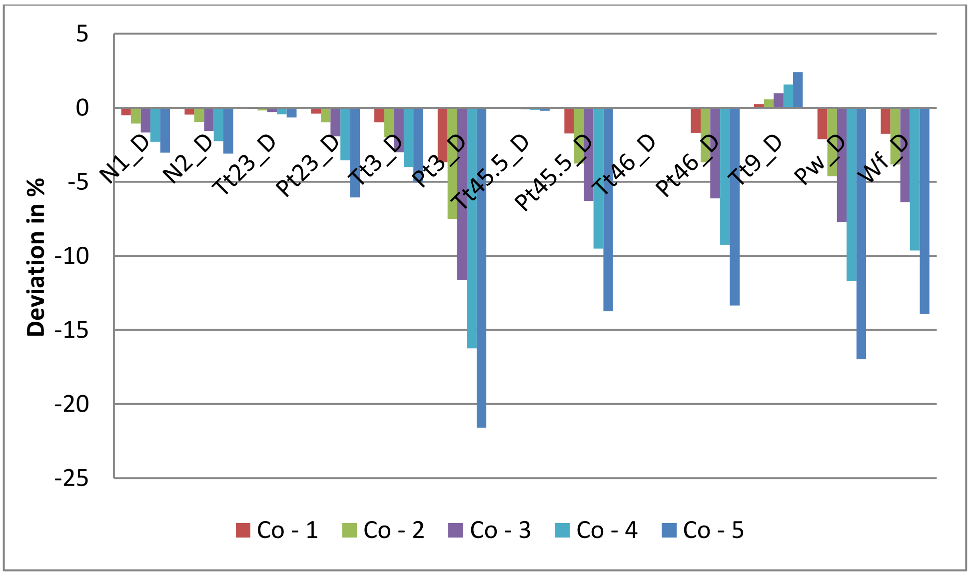

Figure 6.13: Deviation in parameters due to corrosion in HPT

The deviation of parameters due to corrosion in high pressure turbine is shown in Figure 6.13. The most sensitive parameter is the high pressure compressor exit pressure. Increased mass flow reduces the power extracted from the flow. This slows down the high pressure spool speed due to which the pressure at the exit of the high pressure compressor reduces. The equilibrium line of operation of the compressor components shift towards down left. Figure 6.14 and Figure 6.15 shows the variation in compressor exit pressure and the corrected power parameter.

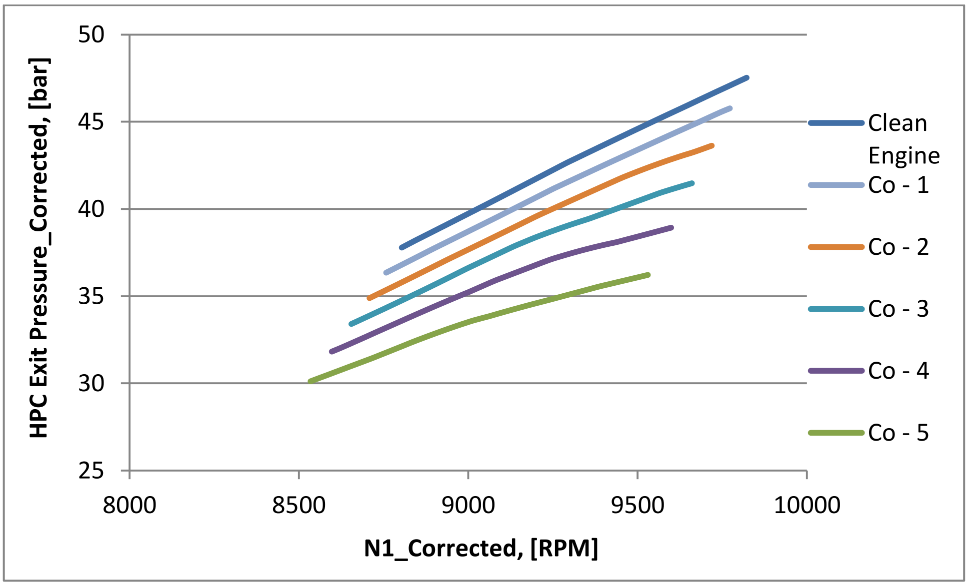

Figure 6.14: Variation of corrected HPC exit pressure due to Corrosion in HPT

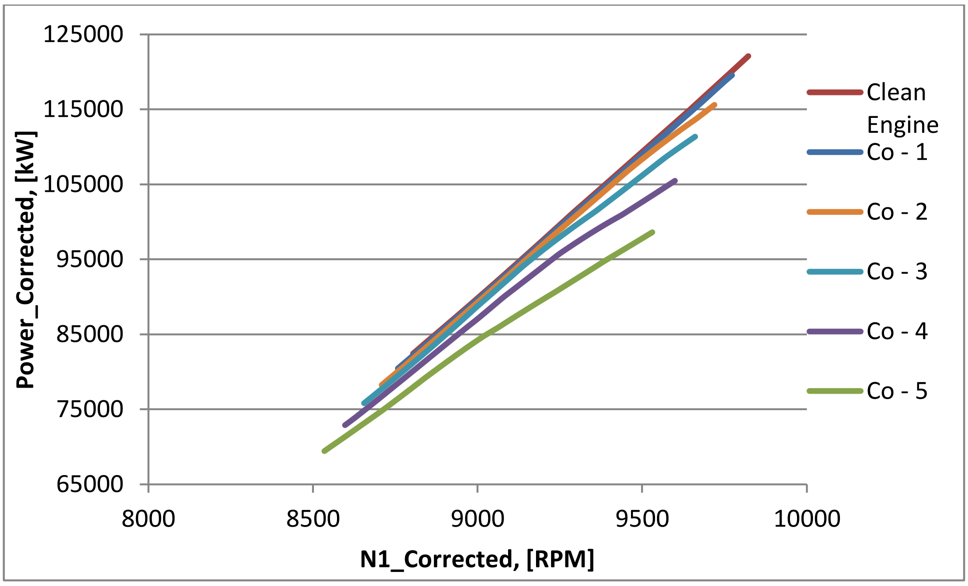

Figure 6.15: Variation of corrected power due to corrosion in HPT

Corrosion in intermediate pressure turbine has a unique pattern of deviation. The deviation pattern of parameters is shown in the Figure 6.16. The intermediate turbine extracts less power and allows excess mass flow. This slows down the low pressure compressor causing pressure drop at its exit. Whereas the high pressure compressor speeds up to match with the mass flow and increases the pressure ratio. This negates the reduction in pressure to some extent and there is a rise in exit temperature of the HPC.

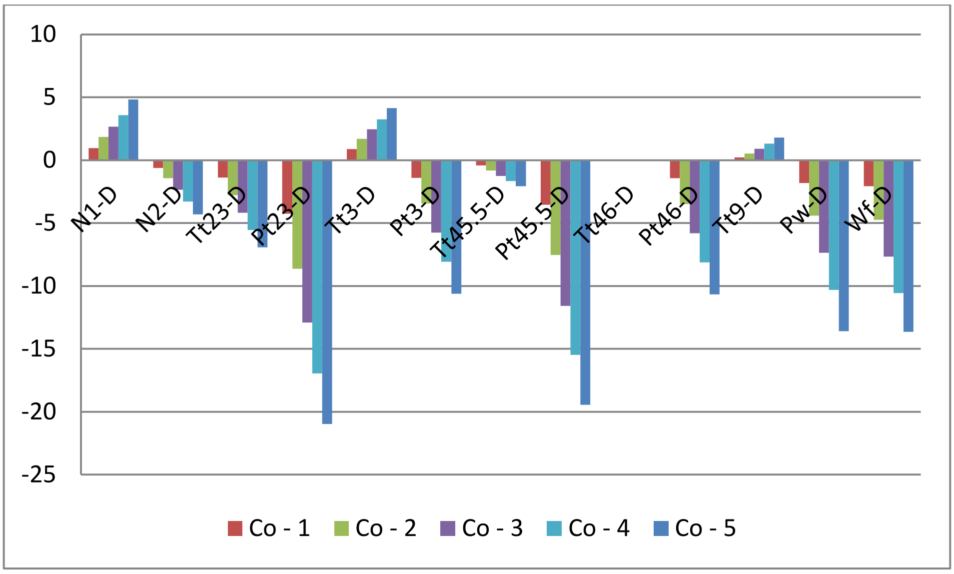

Figure 6.16: Parameter deviation due to corrosion in IPT

Still the overall pressure ratio is less than the clean engine value. Higher HPC exit temperature allows reduced fuel flow to match the temperature control schedule and followed by less power generation at the power turbine.

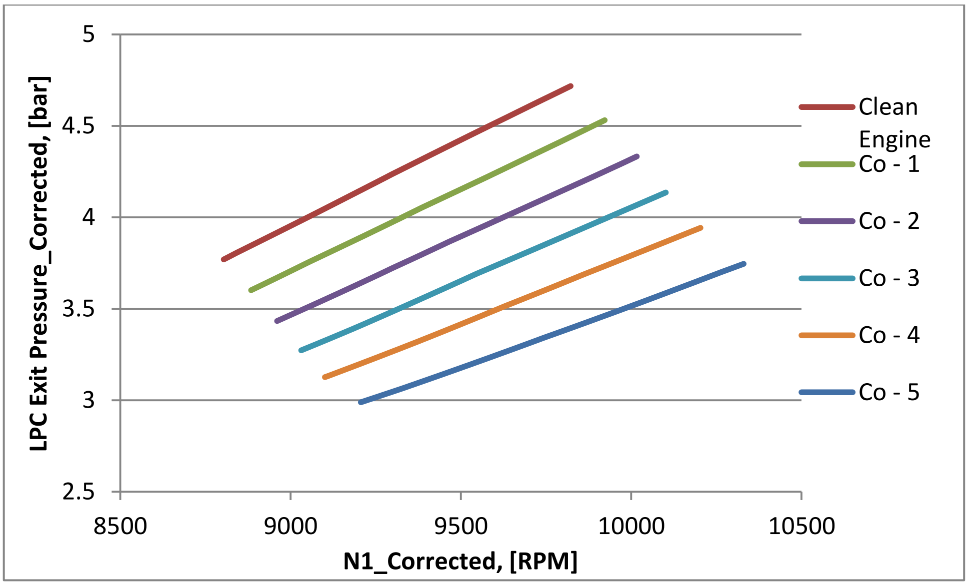

Figure 6.17: Variation of corrected LPC exit pressure due to corrosion in IPT

The exit pressure of the low pressure compressor is the most sensitive parameter and is shown in Figure 6.17. The pressure at the high pressure turbine exit also shows significant deviation and is shown in Figure 6.18.

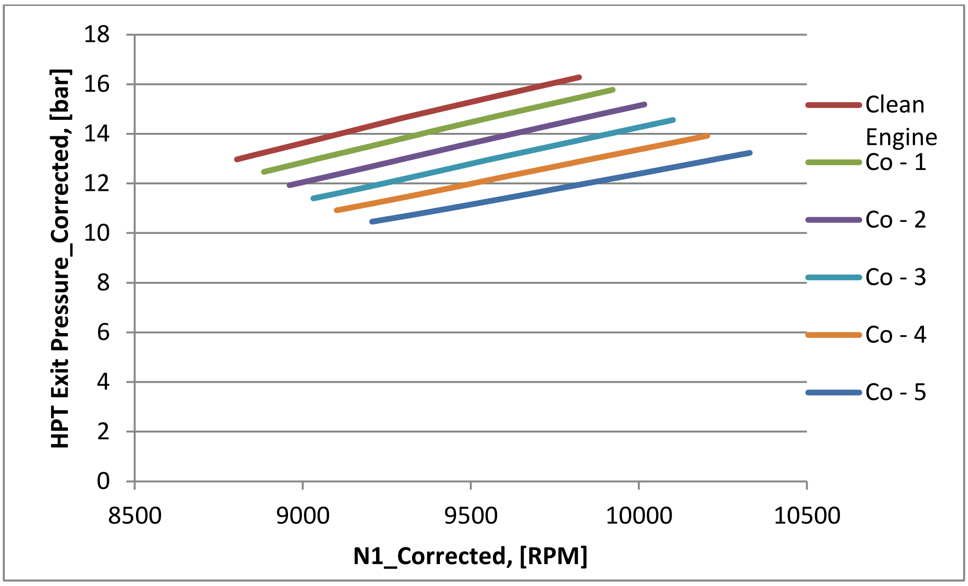

Figure 6.18: Variation of corrected HPT exit pressure due to corrosion in IPT

Corrosion in the power turbine leads to the power turbine operating in non-chocked conditions. The deviation of parameters can be seen in the Figure 6.19.

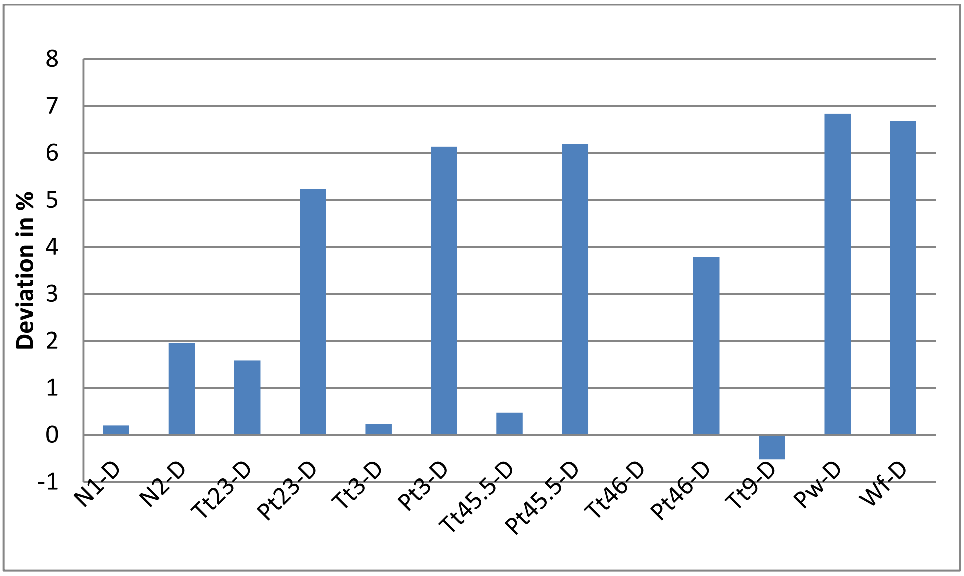

Figure 6.19: Parameter deviation due to corrosion in PT

Both the spool speeds increase to match the increased mass flow. Increase in low pressure spool speed is higher compared to the increase of the respective parameter in high pressure spool. Presence of an intercooler limits the deviation of compressor exit pressure. Therefore the fuel flow increases to maintain the power turbine inlet temperature. Power and fuel flow parameters are found to be the most sensitive in this deterioration case. The figures plotted below, Figure 6.20 and Figure 6.21 show the variation in fuel flow and compressor exit pressure due to corrosion in power turbine.

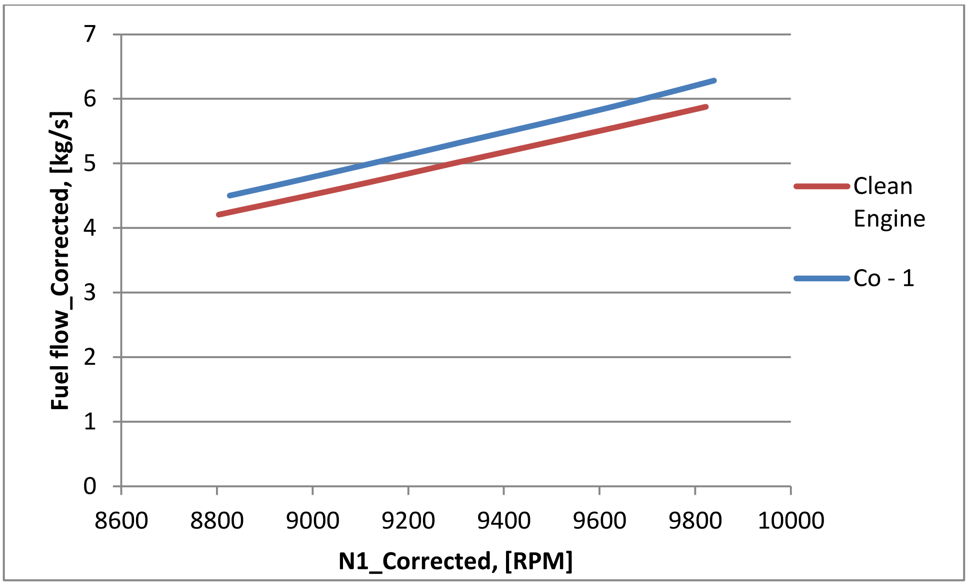

Figure 6.20: Variation in corrected fuel flow due to corrosion in PT

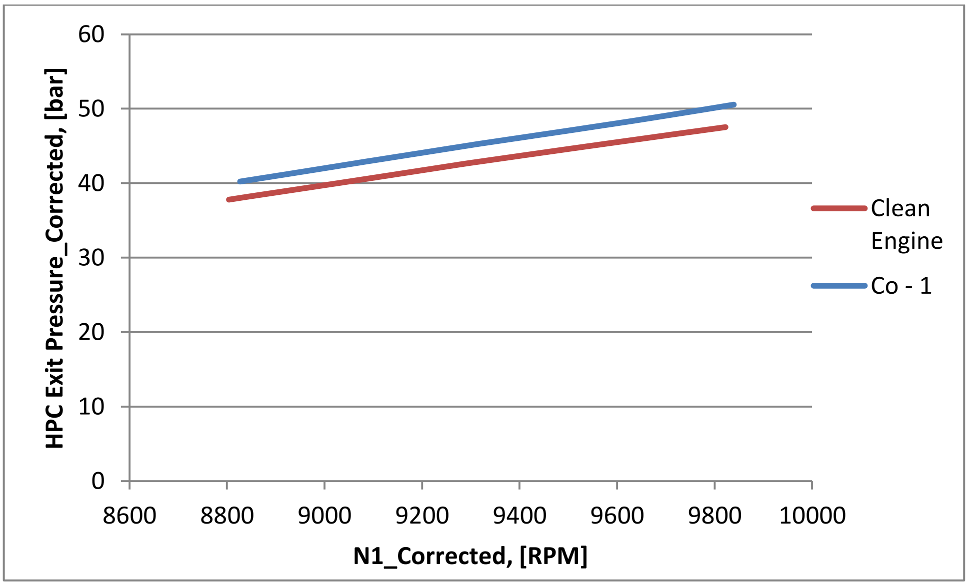

Figure 6.21: Variation in corrected HPC exit pressure due to corrosion in PT

Erosion

Erosion in a turbine is characterised by the increase in corrected mass flow and a decrease in the efficiency of the component. Erosion is denoted by “Er” and its corresponding intensity according to the Table 6.2. Figure 6.22 shows the deviation of parameters for various intensity of erosion in high pressure turbine. The power extracted from the flow by the HPT reduces and this reduces the speed of the respective spool compressor. The overall pressure of the compressor reduces and also indicated by the reduction in temperature at the compressor exit.

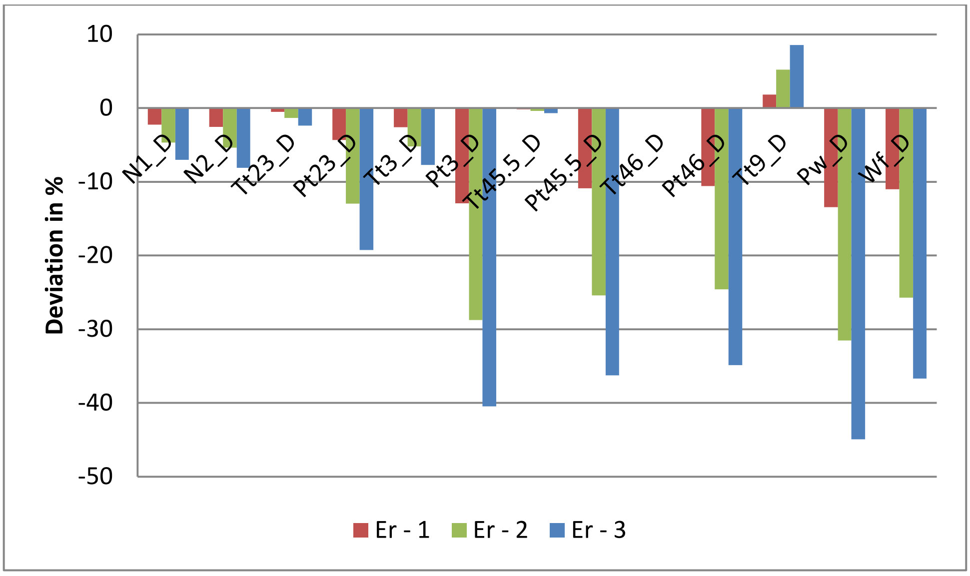

Figure 6.22: Deviation in parameters due to erosion in HPT

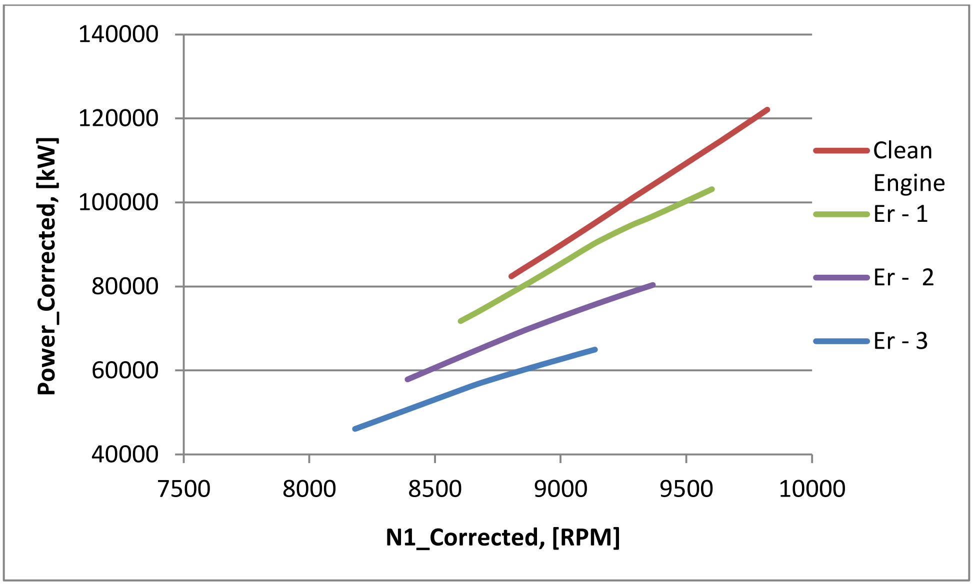

Figure 6.23: Variation of corrected power due to erosion in HPT

The deterioration has its greater impact on the power generated at the power turbine. The compressor exit pressure also decreases significantly. There is also an increase in the power turbine exit temperature. Decrease in both the spool speeds show the shift of the equilibrium operating line to down left.

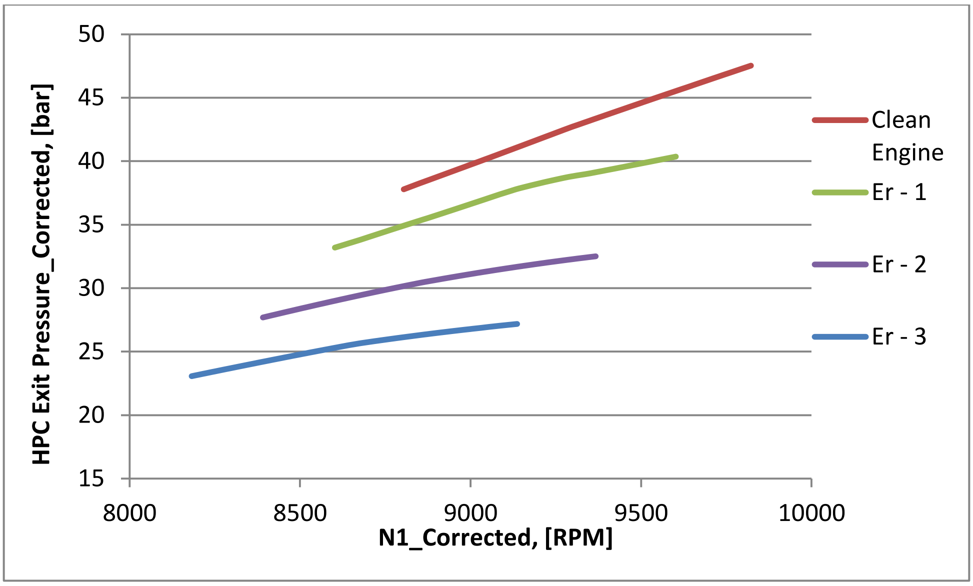

Figure 6.24: Variation of corrected HPC exit pressure due to erosion in HPT

Figure 6.25 shows the deviaiton of various parameters when the intermediate pressure turbine undergoes erosion.

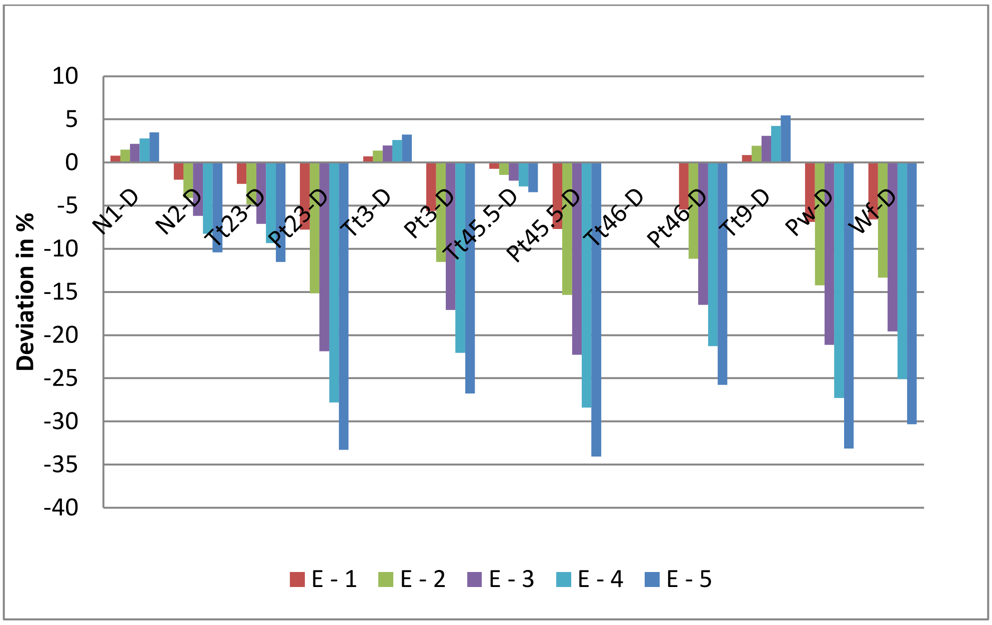

Figure 6.25: Parameter deviation due to erosion in IPT

Exit pressure reduction of LPC and HPT are the most significant deviation recorded. The reduction in power generated by the IPT causes the low pressure spool speed to reduce. This has an reducing effect on the pressure ratio and temperature at the LPC exit. The slight increase in mass flow at the IPT is matched by the high pressure spool by increasing the speed. This increases the pressure ratio of the HPC. Therefore the increase in compressor exit temperature. Figure 6.26 and Figure 6.27

show the shift in corrected HPT exit pressure and the corrected LPC exit pressure. The shift is towards down right direction because of the increase in speed of the high pressure spool.

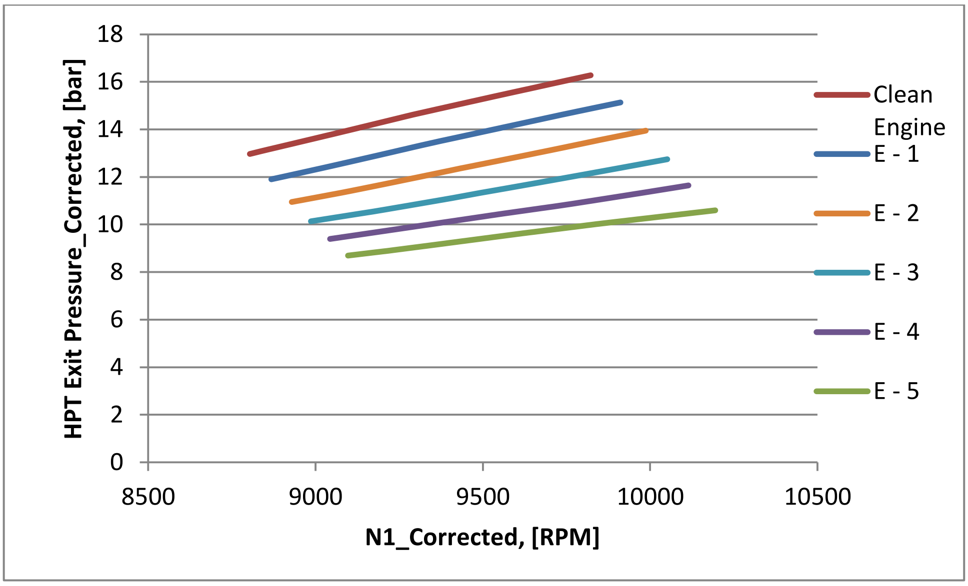

Figure 6.26: Variation in corrected HPT exit pressure due to erosion in IPT

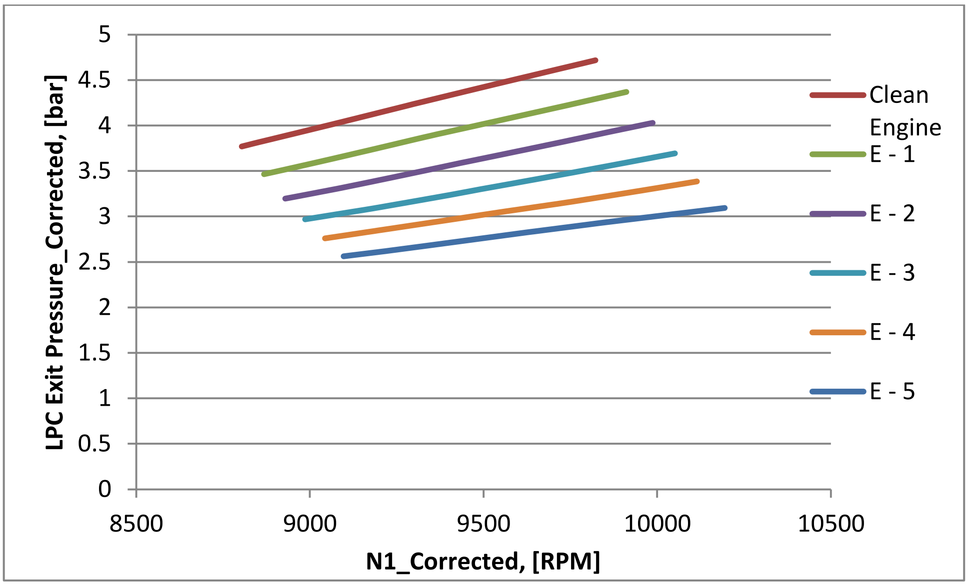

Figure 6.27: Variation in corrected LPC exit pressure due to erosion in IPT

Figure 6.28 shows the parameter deviation for erosion in the power turbine. Fuel flow, exit pressure of HPC and HPT are the most sensitive parameters. As erosion pertains to an increase in mass flow, the power turbine operates in non-chocked condition. Both the spools increase their speed to match the mass flow requirement at the power turbine. Thus it increases the pressure ratio of the compressors. There is less deviation in temperature due to the presence of intercooler and the control schedule. Fuel flow increases to maintain the temperature at the power turbine inlet. Now that the pressure ratio is higher the power generated at the power turbine is higher.

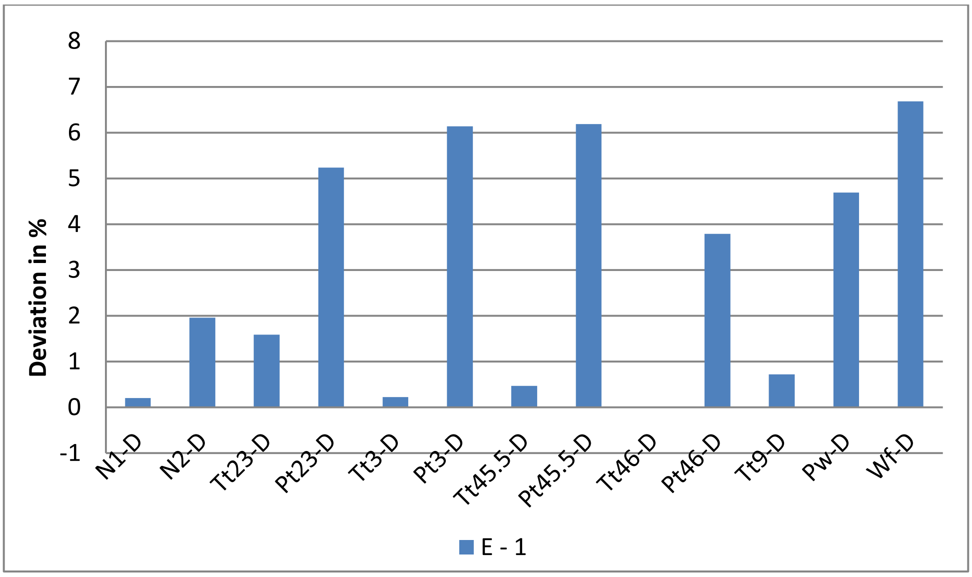

Figure 6.28: Parameter deviation due to erosion in PT

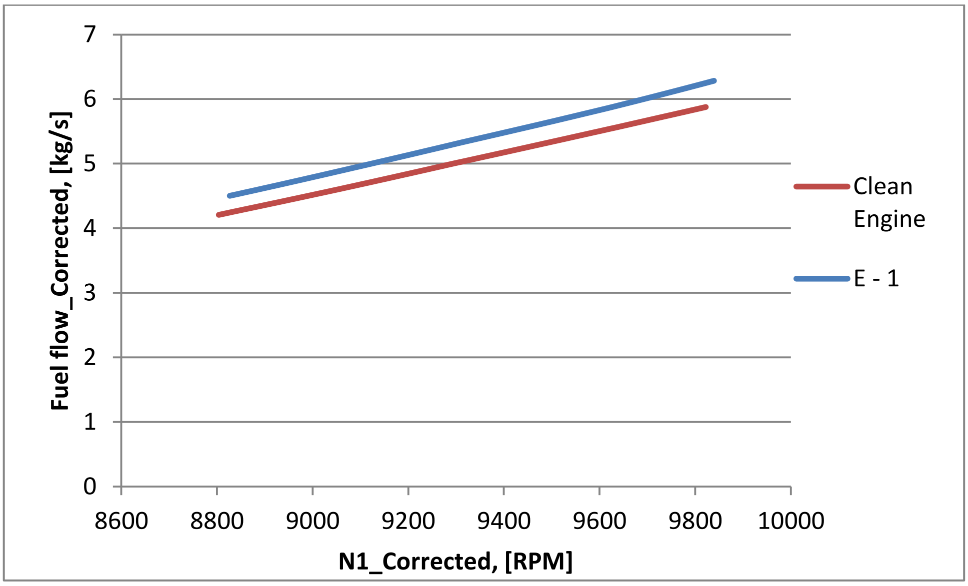

Figure 6.29: Variation in corrected fuel flow due to erosion in PT

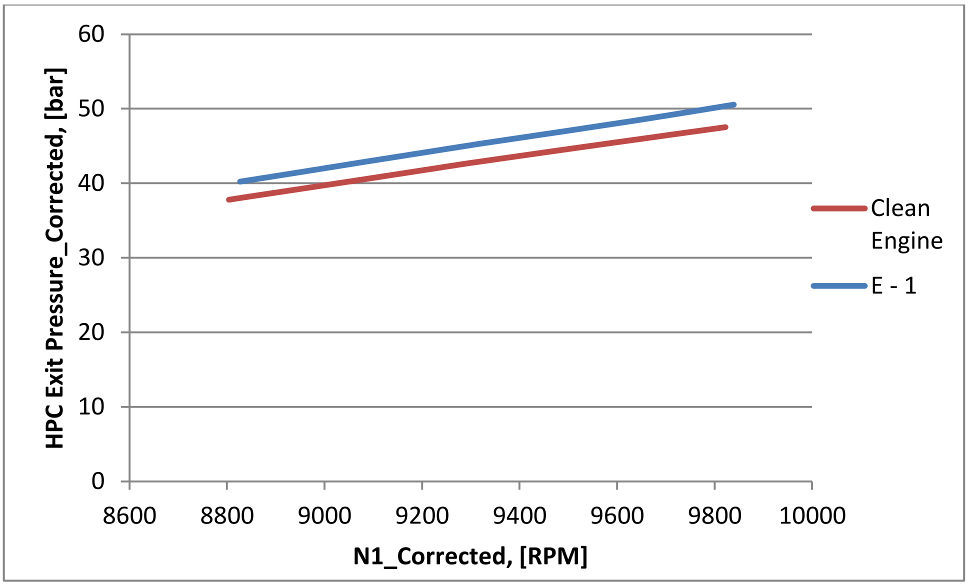

Figure 6.30: Variation in corrected HPC exit pressure due to erosion in PT

Figure 6.29 and Figure 6.30 shows the shift in parameter trends with respect to their respective clean engine parameter trend.

Rotor Fault

Rotor fault is simulated in GSP by introducing a deterioration of the component efficiency. Rotor fault is denoted by "Rf" and its corresponding intensity according to the Table 6.2. Figure 6.31 shows the deviation in the measurable parameters for various intensities of rotor fault in high pressure turbine.

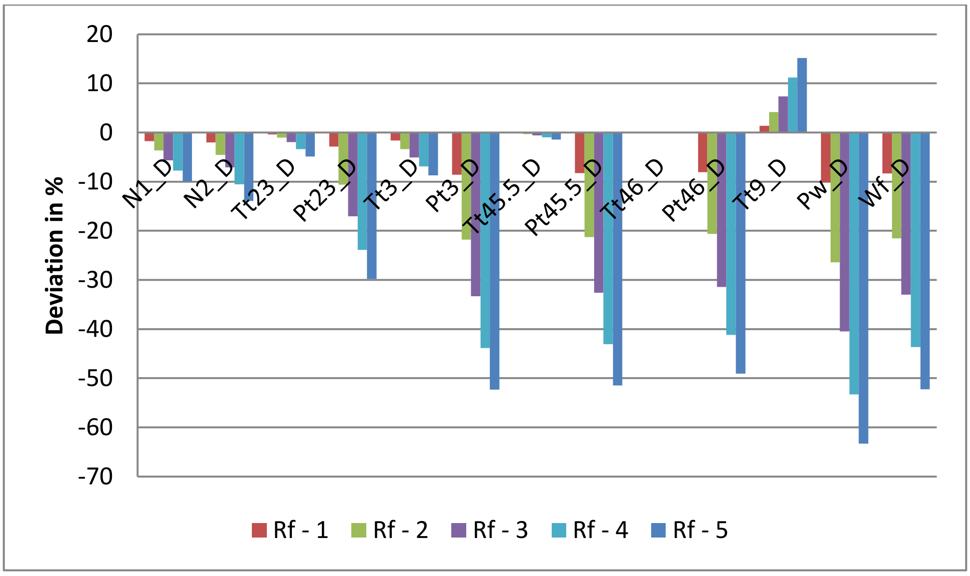

Figure 6.31: Deviation of parameters due to rotor fault in HPT

The power at the power turbine and the compressor exit pressure are the most sensitive parameters for this type of deterioration. The exit pressure of the high pressure turbine exhibits a significant drop in measurement. The turbine exhaust flow temperature displays a significant rise. Among the spool speeds, the low pressure spool speed decreases more than the high pressure spool speed. The deviation in the spool speed shows the operating line shifting in the downward direction. Figure 6.32 and Figure 6.33 shows the variation in corrected HPC exit pressure and corrected power due to rotor fault in HPT.

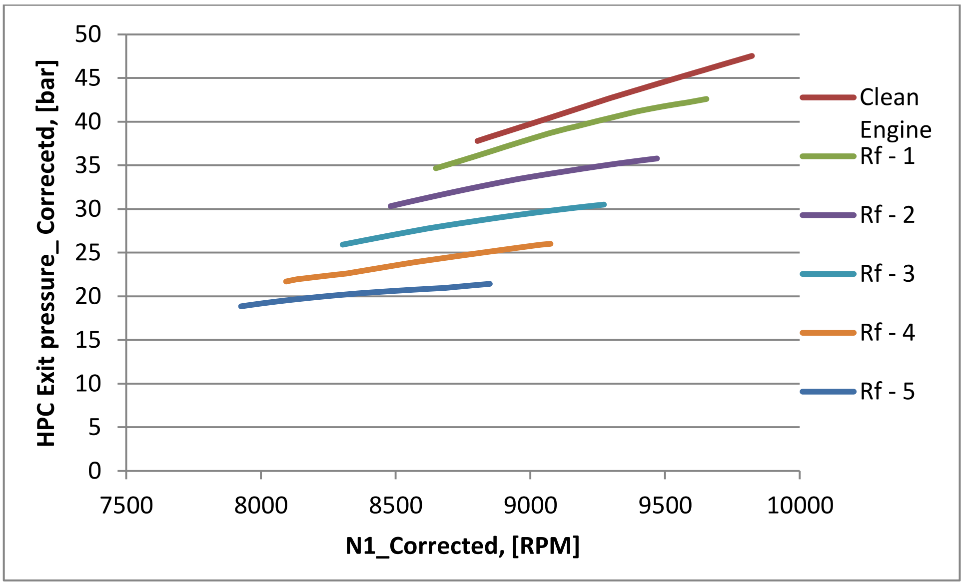

Figure 6.32: Variation of corrected HPC exit pressure due to rotor fault in HPT

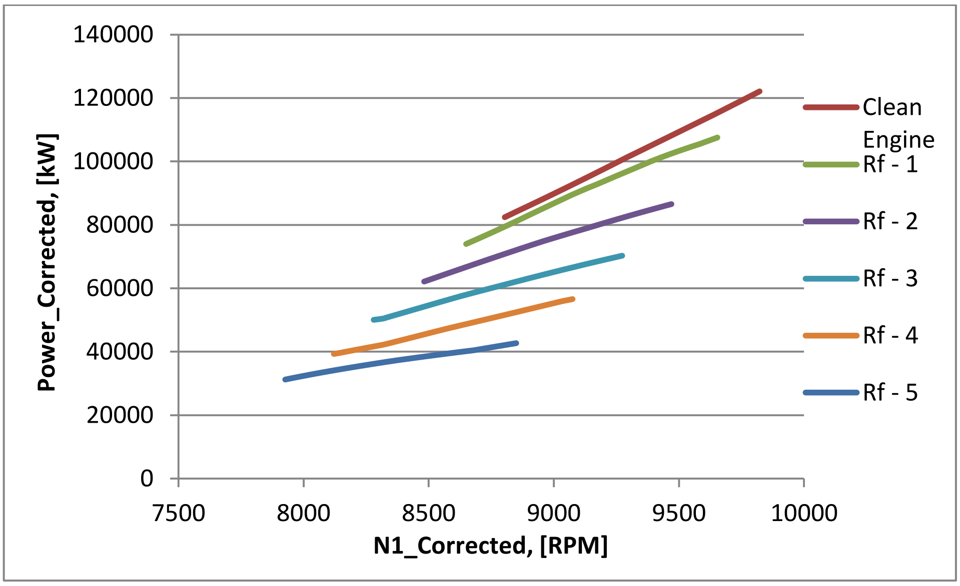

Figure 6.33: Variation in corrected power due to rotor fault in HPT

Figure shows the deviation of parameters from the clean engine trends due to rotor fault in the intermediate turbine. Deviation data shows that the trend of deviation is the same as the earlier case where rotor fault was simulated in HPT. The magnitude of deviation is much lesser than the previous stated case.

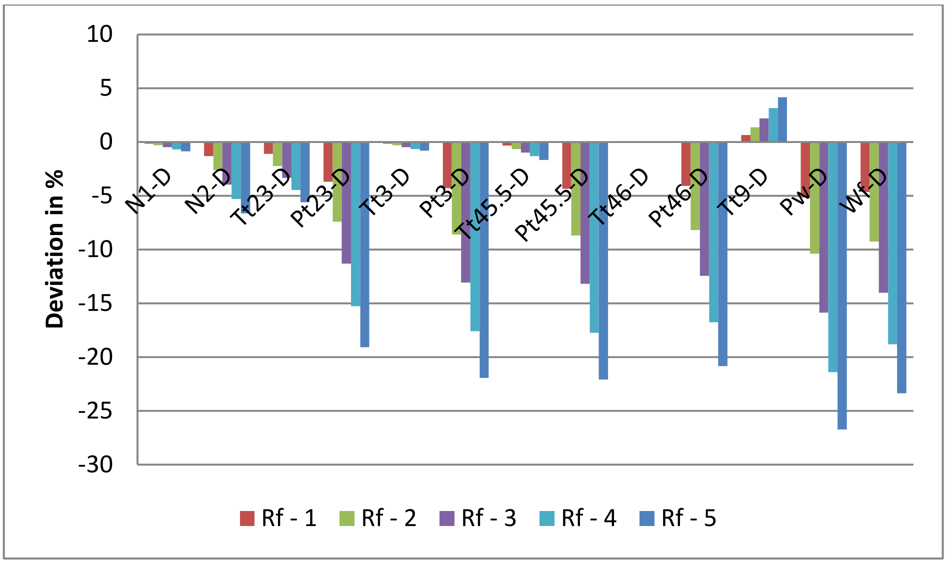

Figure 6.34: Parameter deviation due to rotor fault in IPT

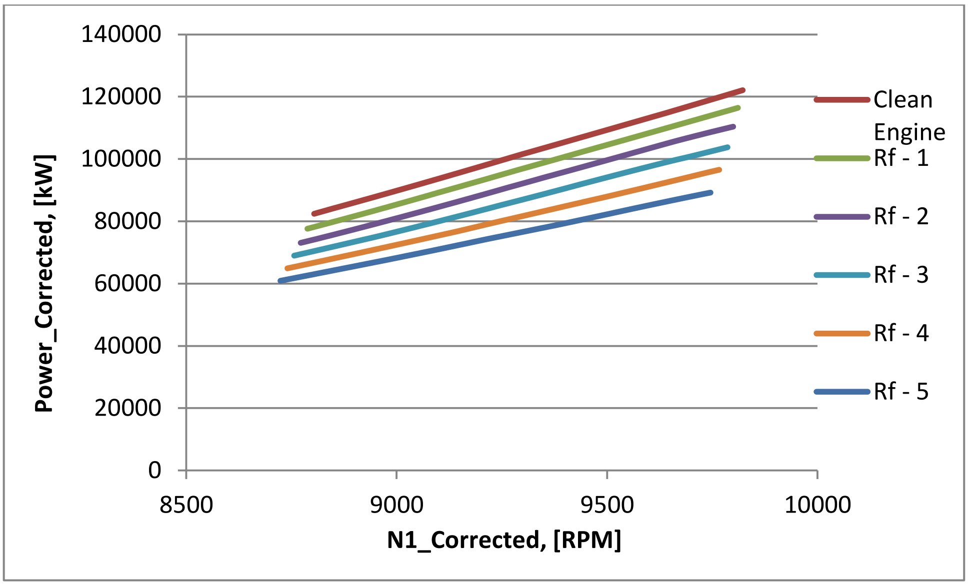

Figure 6.35: Variation of corrected power due to rotor fault in IPT

Rotor fault at IPT has negligible effect on the high pressure spool speed. Reduction in efficiency causes decrease in shaft speed. This effect causes drop in pressure ratio at the respective compressor and a reduction in corrected mass flow. That is the reason behind reduced corrected temperature at the LPC exit. Intercooler matches the temperature at the inlet of the HPC and hence no significant shift in HPC exit temperature. The fuel flow reduces to maintain the temperature of the power turbine inlet and finally a significant power reduction at the power turbine is seen. The downward shift in corrected power and corrected fuel flow is shown in the Figure 6.35 and Figure 6.36 respectively.

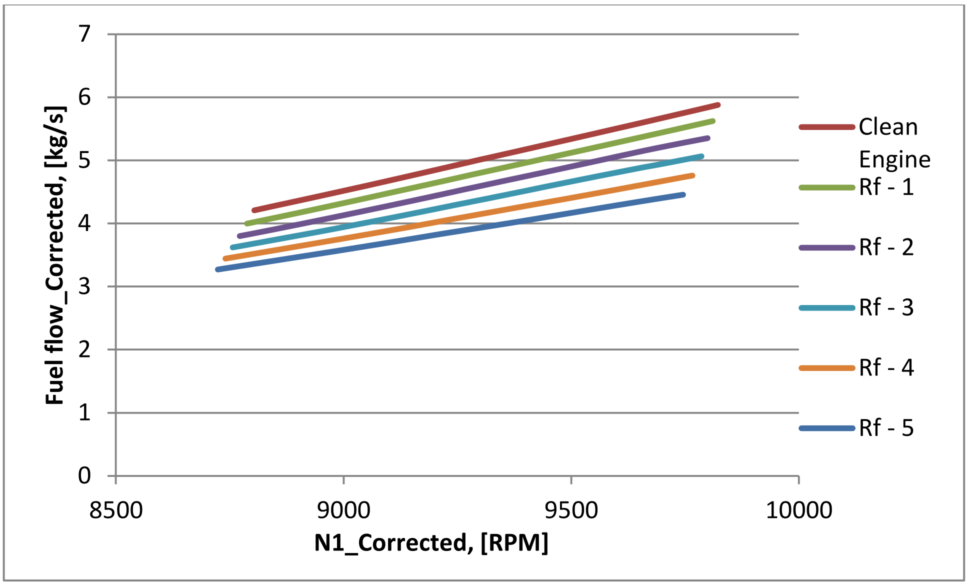

Figure 6.36: Variation in corrected fuel flow due to rotor fault in IPT

Since the rotor fault affect the efficiency of the turbine, simulating rotor fault in power turbine results in a unique deviation pattern. Figure 6.37 shows the various parameter deviations.

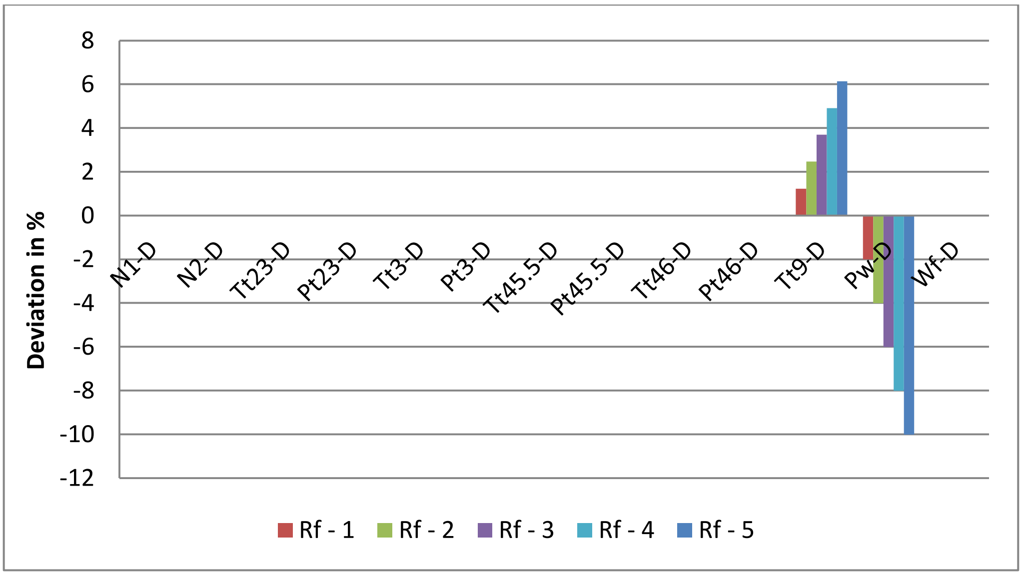

Figure 6.37: Parameter deviation due to rotor fault in PT

The power turbine operates in chocked conditions and the upstream stations have no effect of the rotor fault in power turbine as expected. The following figures show the respective parameter shift. The power drop and increase in power turbine exit temperature are the only two parameters indicating the referred deterioration case. In this case of a rotor fault in power turbine, the exhaust temperature of the gas turbine and the power generated are the only two indicating parameters. Figure 6.38: Variation in corrected power due to rotor fault in PT and Figure 6.39: Variation of corrected exhaust temperature due to rotor fault in PT shows the shift in corrected power and exhaust temperature.

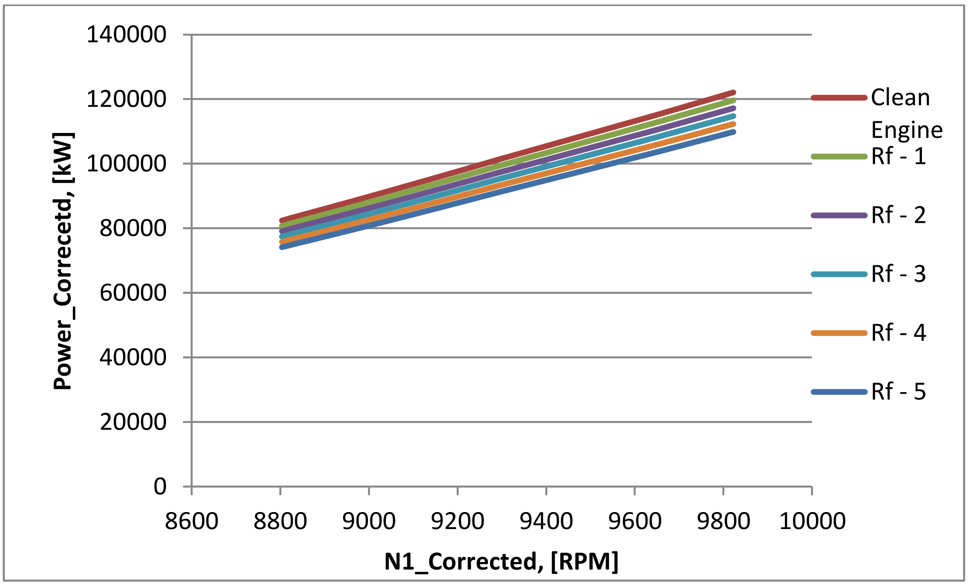

Figure 6.38: Variation in corrected power due to rotor fault in PT

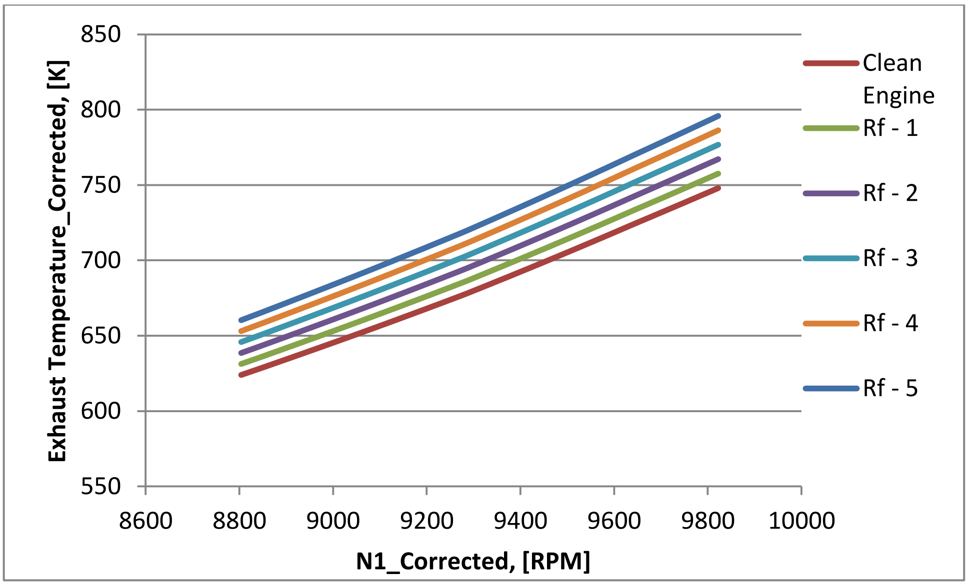

Figure 6.39: Variation of corrected exhaust temperature due to rotor fault in PT

Intercooler Deterioration

In order to study the gas turbine behaviour with respect to deterioration in the intercooler, extensive amount of data is needed. There is not enough data available to carry out the study and the intercooler is considered to work without any deterioration. Considering the fact that any deterioration case with the intercooler will either result in increase in temperature or decrease in pressure at the outlet, a generalised study can be performed. Off design steady state simulations were performed with specifying a range of temperature and pressure at the outlet of the intercooler. The reader is urged to refer to section Appendix C to learn more on the behaviour of the gas turbine when intercooler is under deterioration.

6.1.2 Multiple deterioration study

As discussed before deterioration can happen in multiple components. A single component can also be affected by multiple deterioration modes. It is important to study the behaviour of the gas turbine in such multiple deterioration modes. This section will discuss a few of the simulated multiple deterioration cases. The cases were simulated in GSP using the same method specifying the percentage variation in component health parameters. The deterioration mode and the intensity are represented in the same index as used for the single deterioration study. Figure 6.40 shows the parameter deviation due to fouling in LPC and corrosion in HPT.

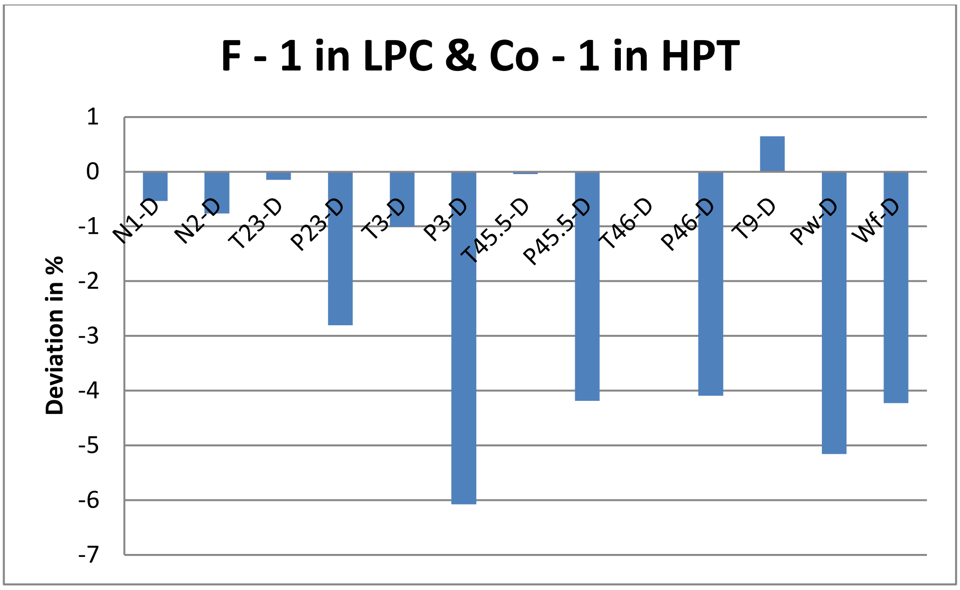

Figure 6.40: Parameter deviation due to fouling in LPC and corrosion in HPT

Figure 6.41, Figure 6.42 and Figure 6.43 shows their parameter deviations according to the deterioration cases simulated. It is noted that the deviation can be accounted to a simple addition of deviation of their respective single deterioration cases. This can be observed in all of the simulated multiple deterioration cases.

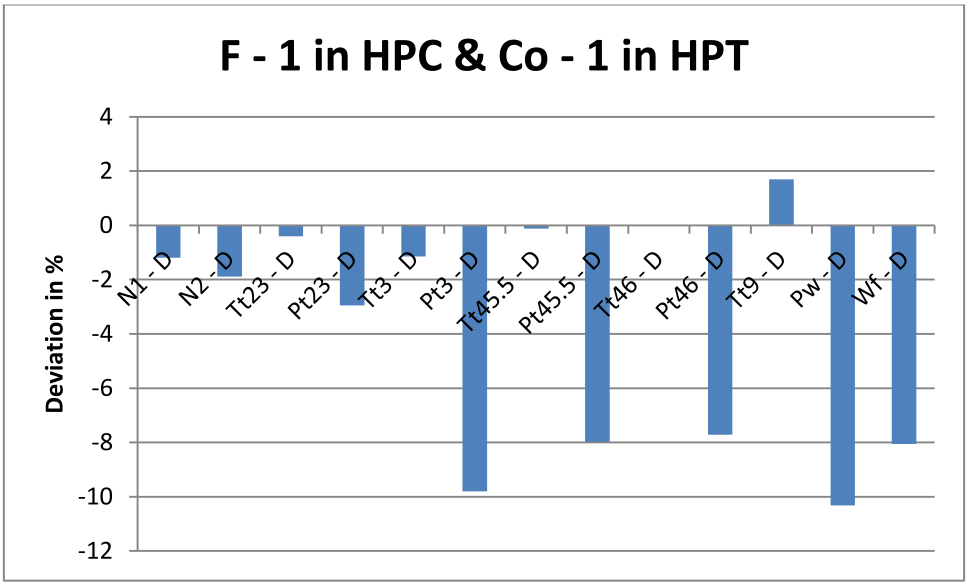

Figure 6.41: Parameter deviation due to fouling in HPC and corrosion in HPT

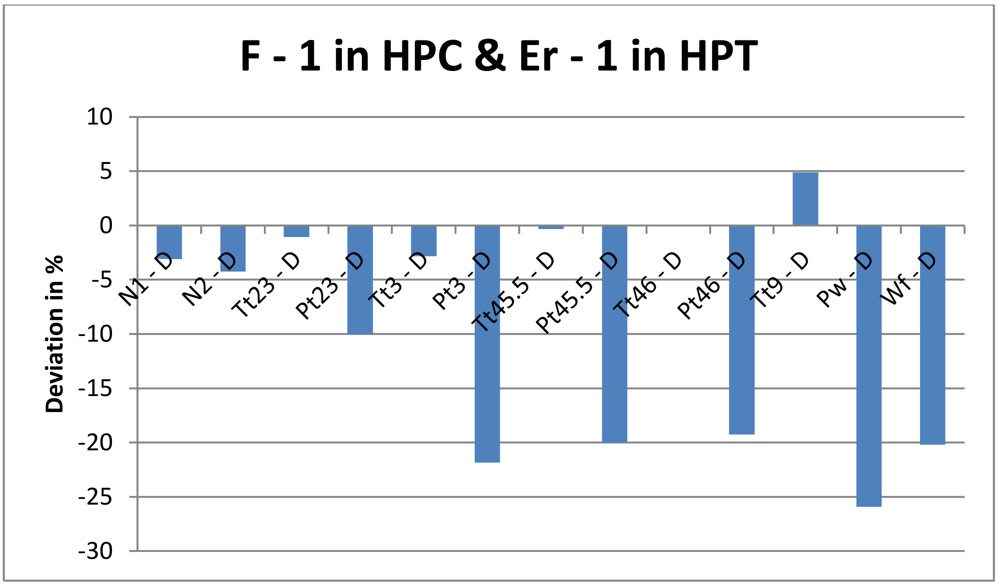

Figure 6.42: Parameter deviation due to fouling in HPC and erosion in HPT

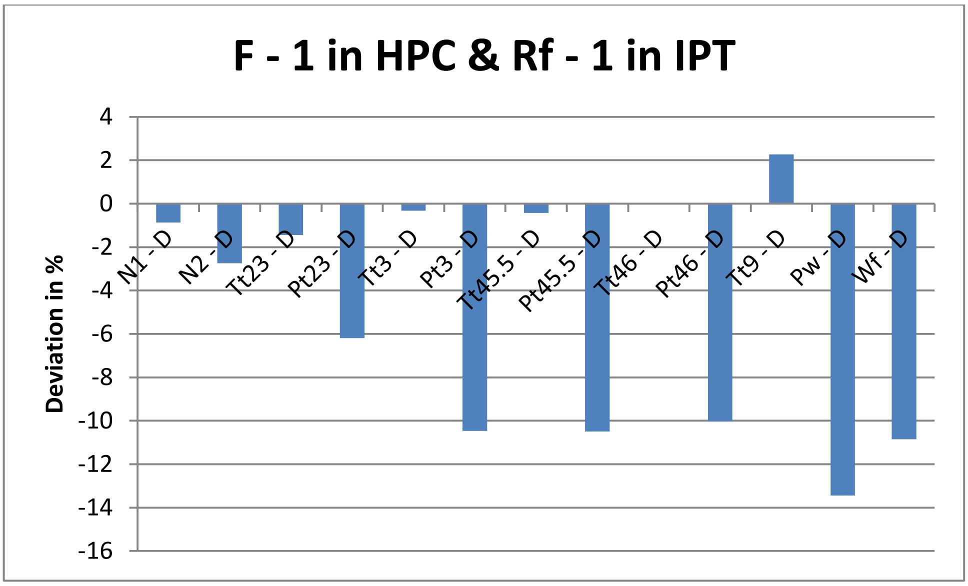

Figure 6.43: Parameter deviation due to fouling in HPC and rotor fault in IPT

So the developed deviation trends are enough to determine the deviation pattern of any multiple deterioration case.

6.2 Proposed methodology

From the simulated deviation data, consolidated trends of significant indicating parameters are plotted.

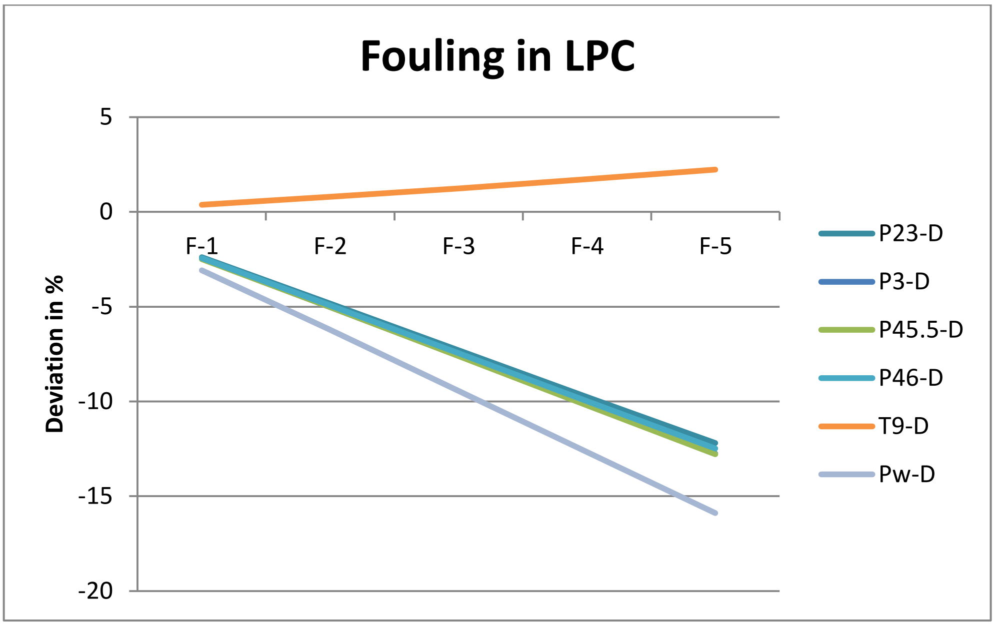

Figure 6.44: Deviation trend due to fouling in LPC

The deviation trends can be used as a means to identify the shift in health parameters of a component. The significance of having deviation trends is that it can be used to quantify the intensity of deterioration in components. The deviation trends are plotted for other deterioration cases and can be found in the appendix section Appendix B.

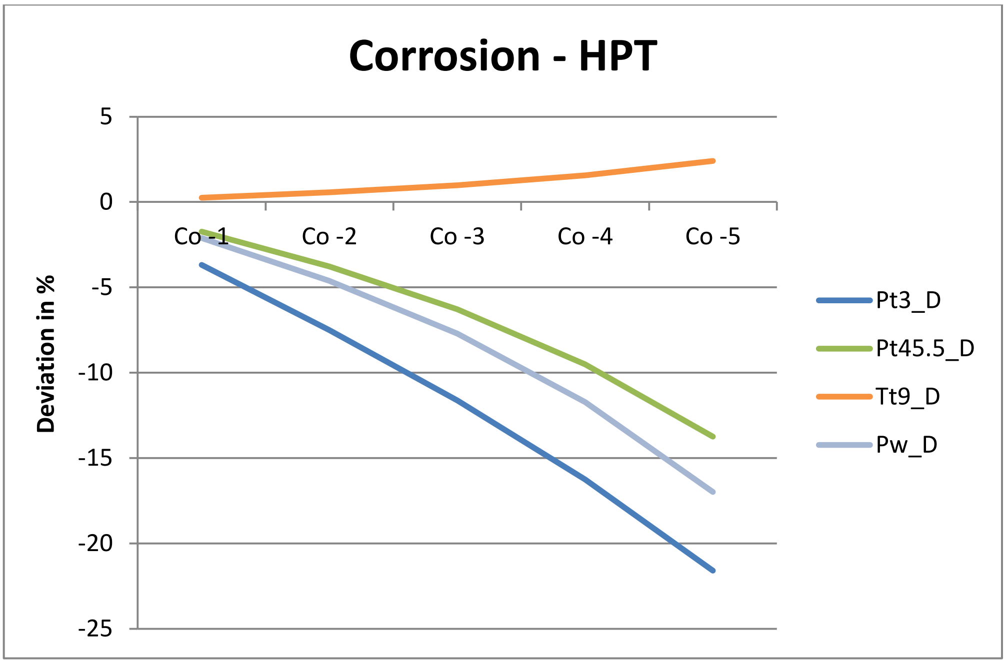

Figure 6.45: Deviation trend due to corrosion in HPT

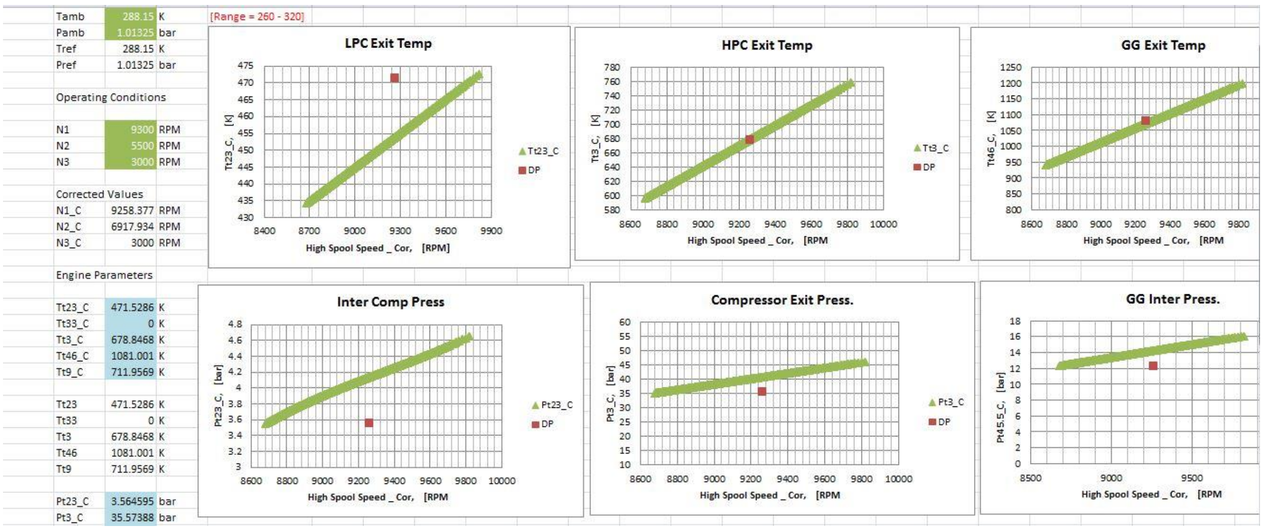

Figure 6.46: Indicating parameters of performance

The figure above shows the actual operating position of the various parameters with respect to their clean engine trends. Deviation is noted and matched with the deviation trends discussed before. To assist in relating the deviation to the cause of deterioration, a colour coded matrix was developed. Figure 6.47 shows the colour matrix which can be used for fault isolation. The colours are coded with respect to the positions on the line (OL), left to the line (L), right to the line (R), below the line (D), above the line (U), down-right (DR), down-left (DL), up-left (UL) and up-right (UR).

	LPC		HPC	HPT			IPT			PT		
Parameters	VGF	F - C1	F - C2	Er	Co	Rf	Er2	Co2	Rf2	Er3	Co3	Rf3
LPC Temp	U	OL	DL	DL	L	DL	DR	DR	D	U	U	OL
HPC Temp	OL	OL	L	DL	DL	DL	UR	UR	OL	OL	OL	OL
GG Temp	OL	OL	L	L	L	L	R	R	OL	OL	OL	OL
LPC Press	U	D	DL	DL	L	DL	DR	DR	D	D	U	OL
HPC Press	OL	D	DL	DL	L	DL	DR	R	D	D	U	OL
HPT Press	OL	D	DL	DL	L	DL	DR	R	D	D	U	OL
GG Press	OL	D	DL	DL	L	DL	DR	R	D	DL	OL	OL
Pow	U	D	D	D	D	D	D	D	D	D	U	D
T9	OL	U	U	U	U	U	U	U	U	U	D	U

Figure 6.47: Fault isolation matrix

The position of the actual parameters is noted and then it can be matched with the matrix to find the component undergoing deterioration. In the figure shown above, gas generator exit temperature is the vital indicator. The relative position of this parameter can be used to isolate the deterioration to the respective spool. The position of the other actual parameters like the HPC exit pressure and temperature is used to find to determine whether the fault can be due to change in the corrected mass flow of the component or efficiency or both of them. It can be seen that each column is unique and indicates the probable cause and component at deterioration. Using this method, dependency on expert analysis can be reduced. Along with the present vibration analysis, the exact deterioration mode can be found.

6.3 Summary

The trend of deviation of parameters due to various modes of deterioration was discussed. The behaviour of the gas turbine under each deterioration mode was discussed in detail. The significant indicator for such deterioration case was highlighted and deviations were plotted with the clean engine trends for comparison. Finally based on the position of the actual parameter, a colour coded matrix was designed. The matrix can be used to isolate the deteriorating component. Having deviation trends and the fault isolation matrix, the deterioration can be quantified and condition based maintenance can be applied.

Chapter 7. Conclusion & Recommendation

7.1 Conclusion

The significant conclusions made from the project are listed below.

- Gas turbine theory and their performance are well understood. Gas turbine components and their limitations in operation were discussed. A detailed study on deterioration and failure of components due to their nature of process was done.
- Various gas turbine diagnostics approach was studied and gas path analysis was found to be a suitable method for implementing in an online remote monitoring environment. However to achieve a complete health monitoring system, techniques like vibration analysis should be used together with GPA.
- A good understanding on the working of GSP was achieved. This helped in modelling and simulating the gas turbine configuration under study. GSP proved to be user-friendly and highly capable of simulating any configuration of gas turbine. GSP allows user to model and simulate using limited data as well as extensive method of approach can be done.
- A clear picture of the approach to model a three-shaft gas turbine with intercooler was laid out. The control schedule of the gas turbine was determined and the resulting off-design performance was validated with the OEM provided performance curves.
- The off-design simulation was carried out for base load conditions and the power turbine operates in chocked condition at base load. Vital indicators of performance monitoring were found and trends of the parameters were plotted. Deviation from these clean engine trends

can be used to compare the actual parameter measurement and state the performance status of the component.

- The control schedule of the gas turbine fixed the intercooler outlet temperature and the power turbine inlet temperature. So, the deviation trends show very little deviation of temperatures at different stations of the gas turbine. Thus the magnitude of deviation in pressure is the vital indicator of engine health.
- Deterioration study suggested that the operation of high pressure spool is more stable than the low pressure spool. Deterioration in low pressure spool has minimal effect on the high pressure spool components. Whereas the operation of high pressure spool has significant effects on all the components of the gas turbine.
- The behaviour study of the gas turbine under various deterioration modes helped in developing deviation trends to quantify deterioration in every component. Fault isolation matrix was developed to help identify and isolate the component under deterioration. The indications caused by different deterioration modes can be identical however the developed trends can be used to identify the component undergoing deterioration. To further pinpoint the deterioration reason, assistance from other technique like vibrational analysis must be needed.

7.2 Recommendations

The project was carried out to assess gas path analysis as a means to develop fault diagnostics tool. Assumptions and certain considerations were made during the simulations which are significant for the reader to understand before implementing the concept in the online monitoring environment.

- Accuracy of the developed clean engine trends developed depends on the data acquired from the public domain. The author was restricted from OEM provided information. Correcting the developed engine trends according to the provided data would yield better results. However trending the actual parameter measured can help in determining the deviation in performance.
- Simulation was carried out for base load conditions and neglecting duct losses. Correcting the trends for the pressure loss in the ducts can be done to improve the monitoring accuracy of the tool.
- The simulations have considered proper functioning of the intercooler system. A further study on the operation of the intercooler is needed to increase the scope of diagnosis for this configuration of gas turbine.

- The deviation trends available are regarding single component faults. In case of multiple component deterioration, the developed trends can be used as a thumb of rule to determine the deterioration mode.
- The fault isolation matrix can be extended to multiple component deterioration combined with vibration analysis. This will reduce the dependency of expert analysis and increase the value of the online monitoring tool.

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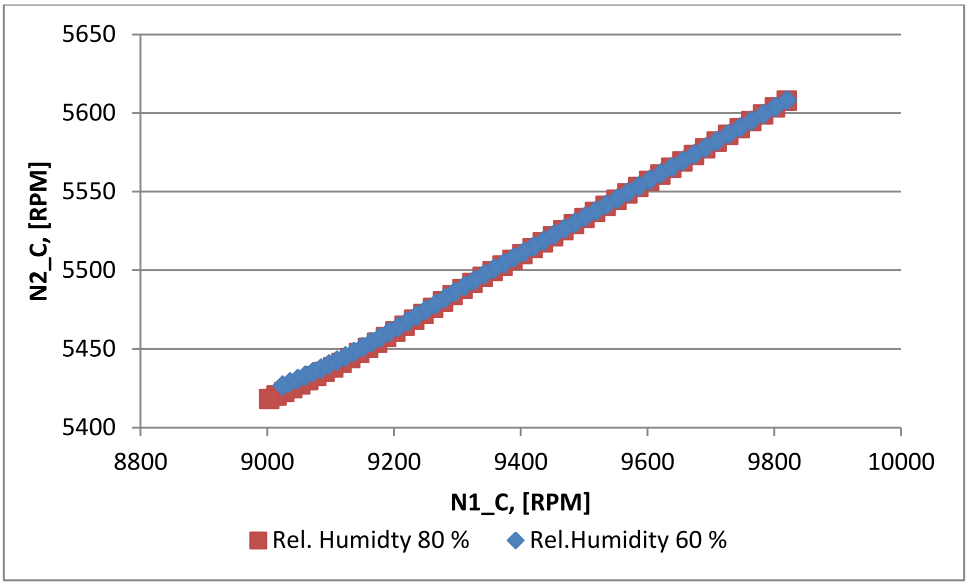
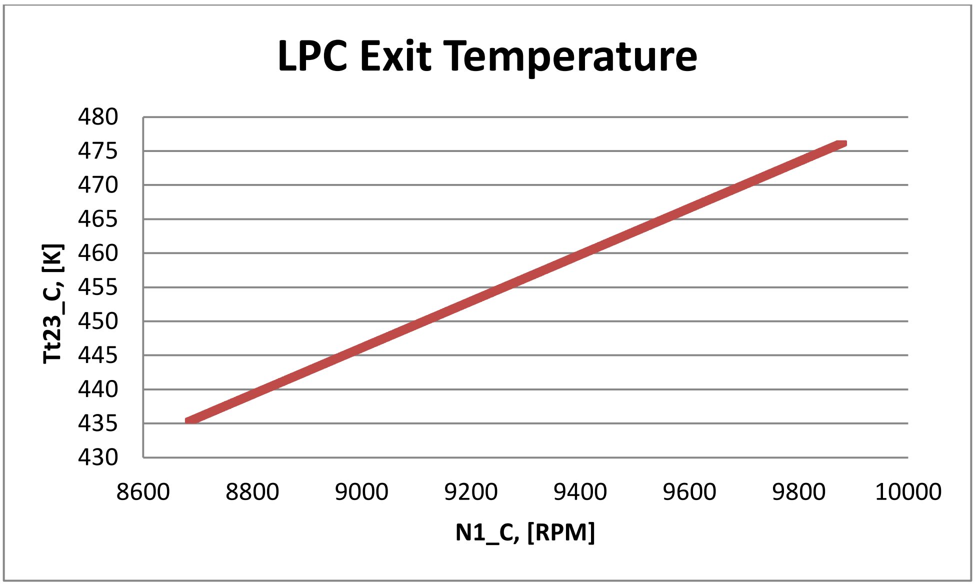
Appendix A. Clean Engine Trends



FigureA.1: Effect of varying relative humidity on LPC speed

This section the clean engine trends are plotted.



FigureA.2: Corrected LPC exit temperature trend

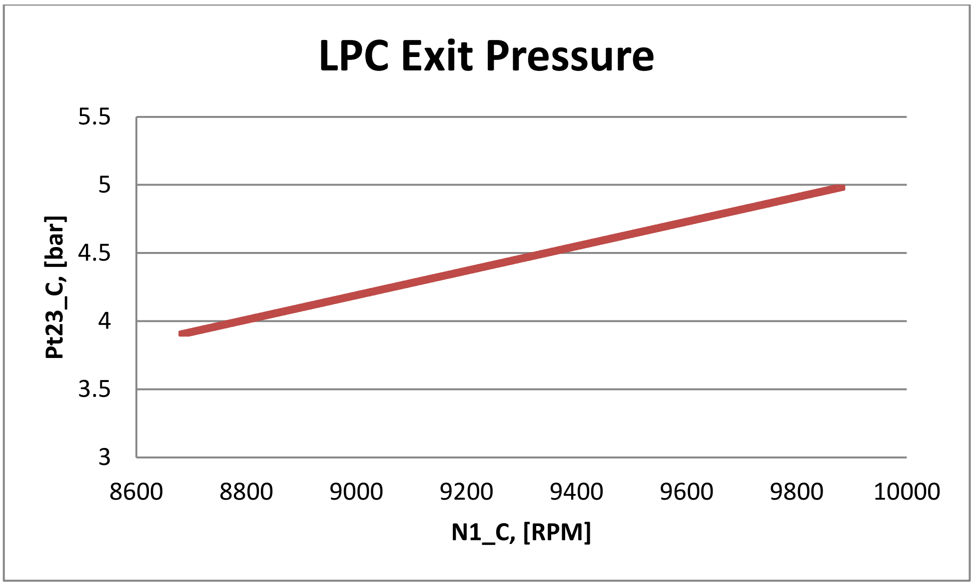


Figure A.3: Corrected LPC exit pressure trend

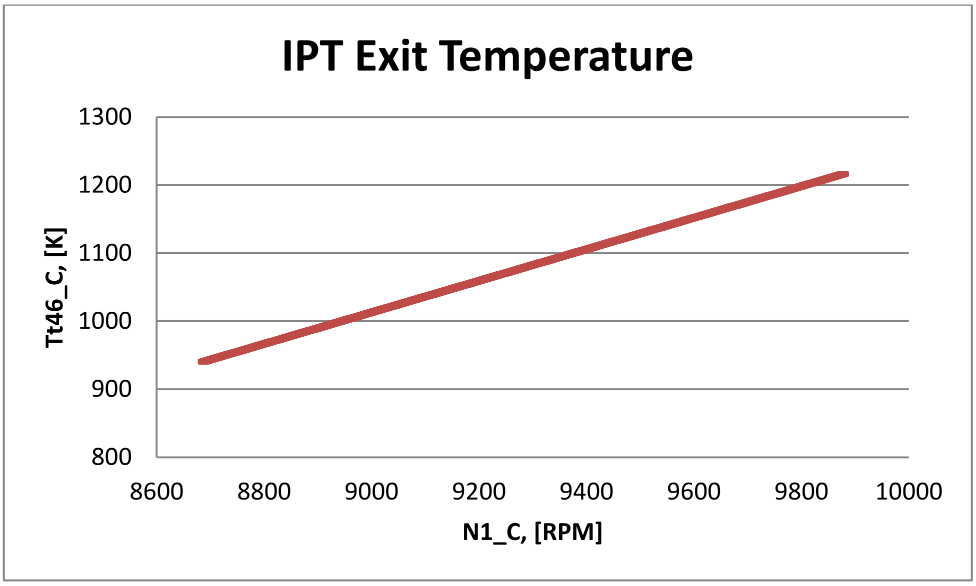


Figure A.4: Corrected PT inlet temperature trend

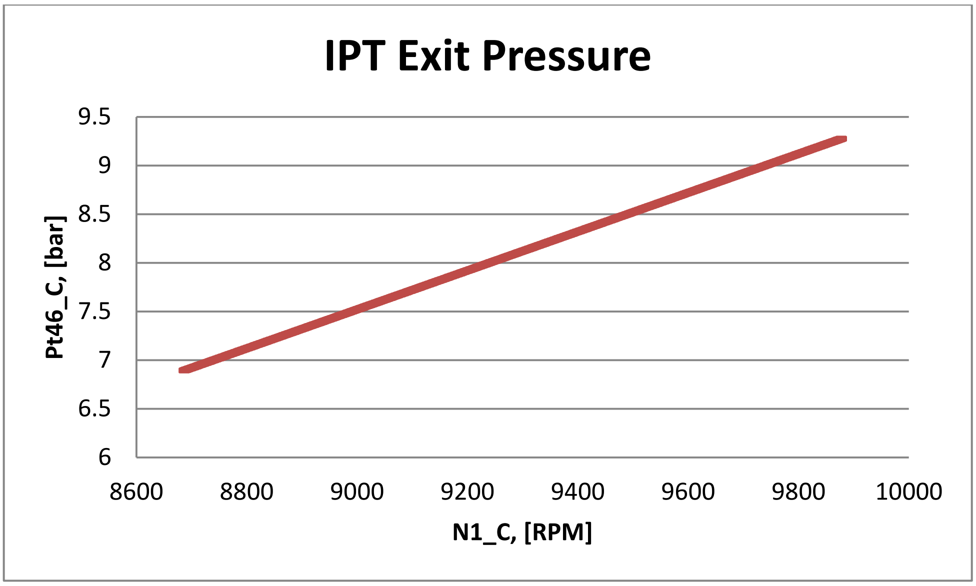


Figure A.5: Corrected gas generator exit pressure trend

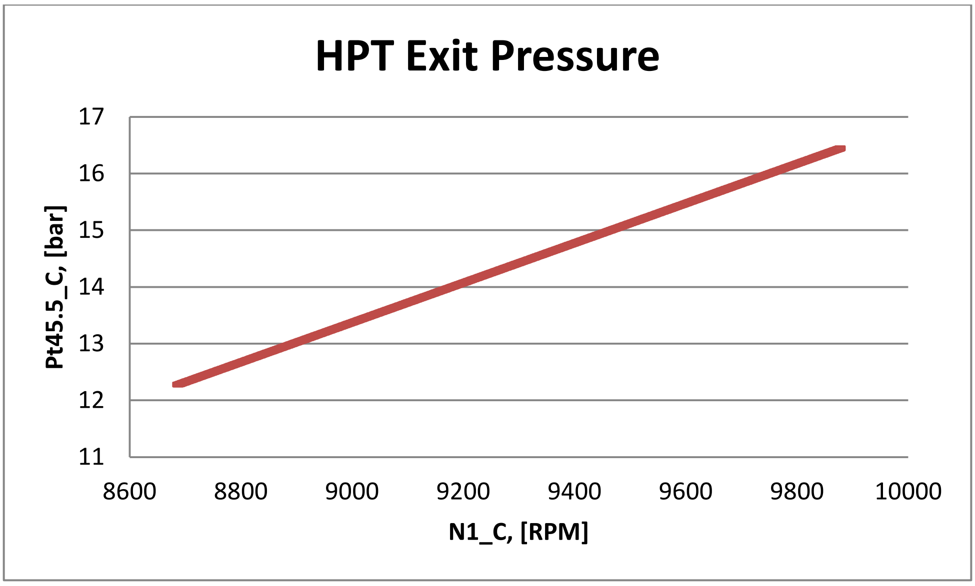
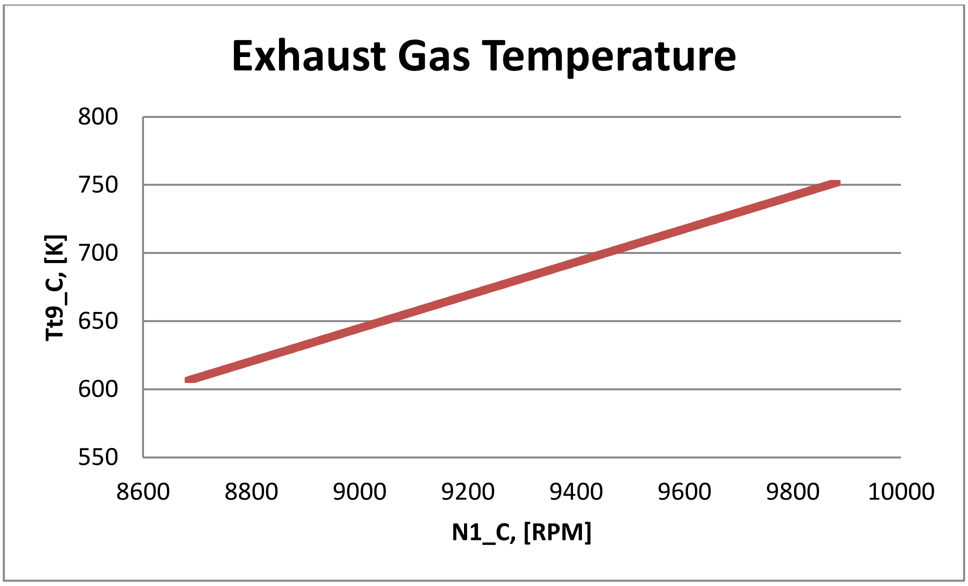


Figure A.6: Corrected HPT exit pressure trend



FigureA.7: Corrected PT exit temperature trend

The following plots show the operating points simulated at different operating conditions and control settings.

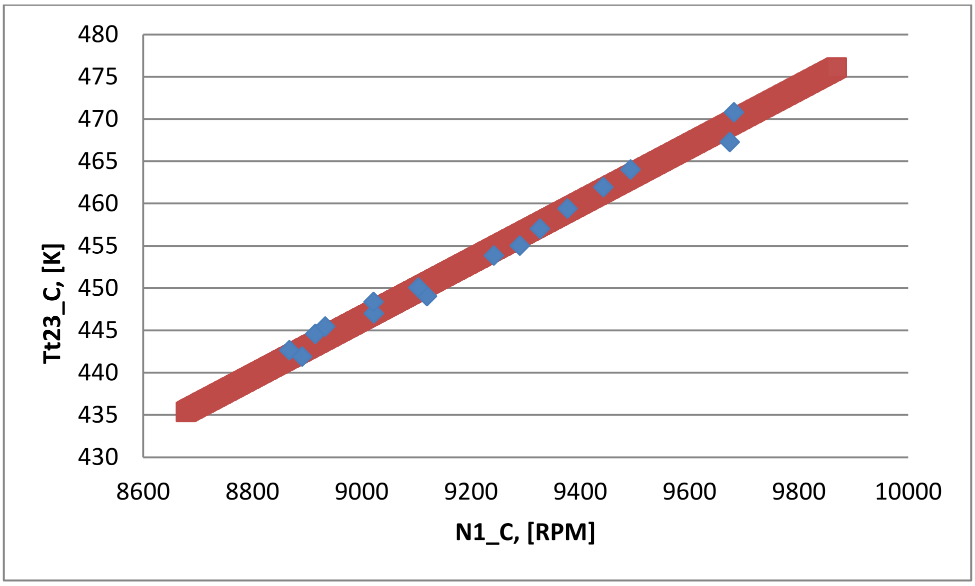


Figure A.8: Operating points - LPC Exit Temperature

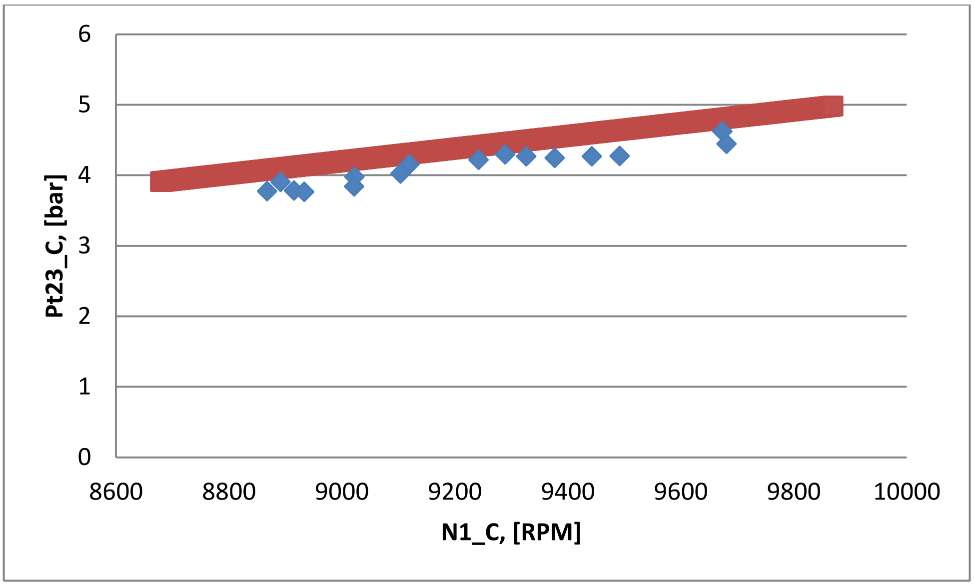


Figure A.9: Operating points - LPC Exit Pressure

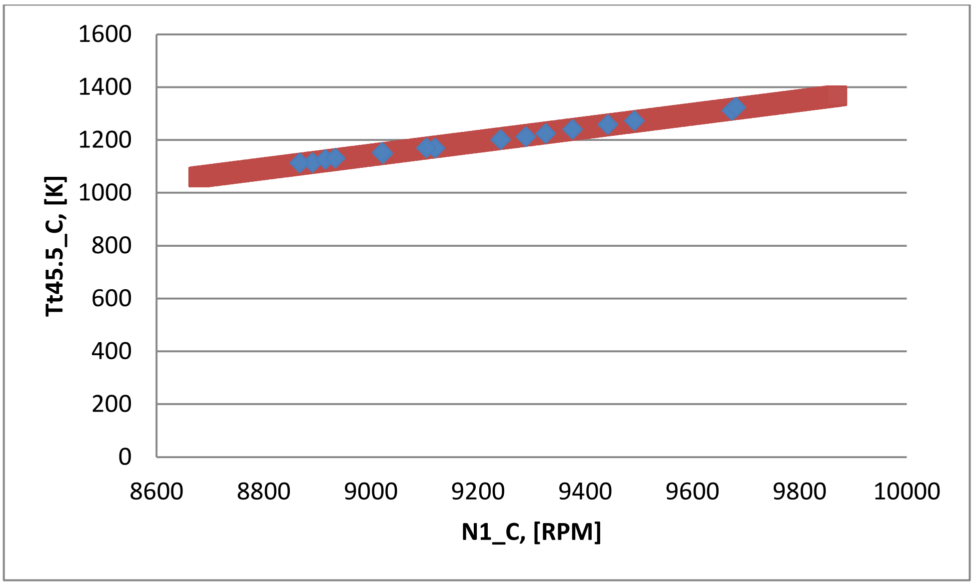


Figure A.10: Operating points - HPT Exit Temperature

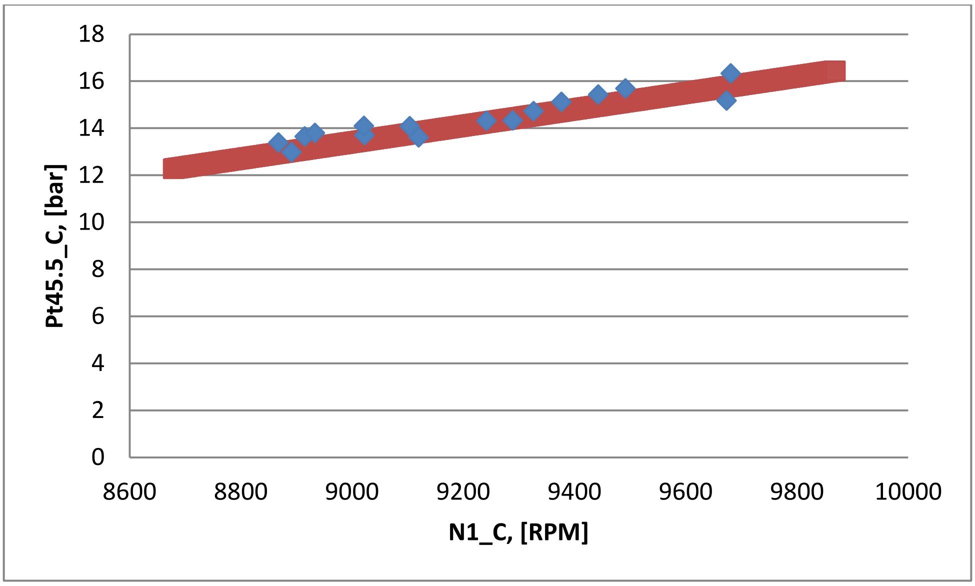


Figure A.11: Operating points - HPT Exit Pressure

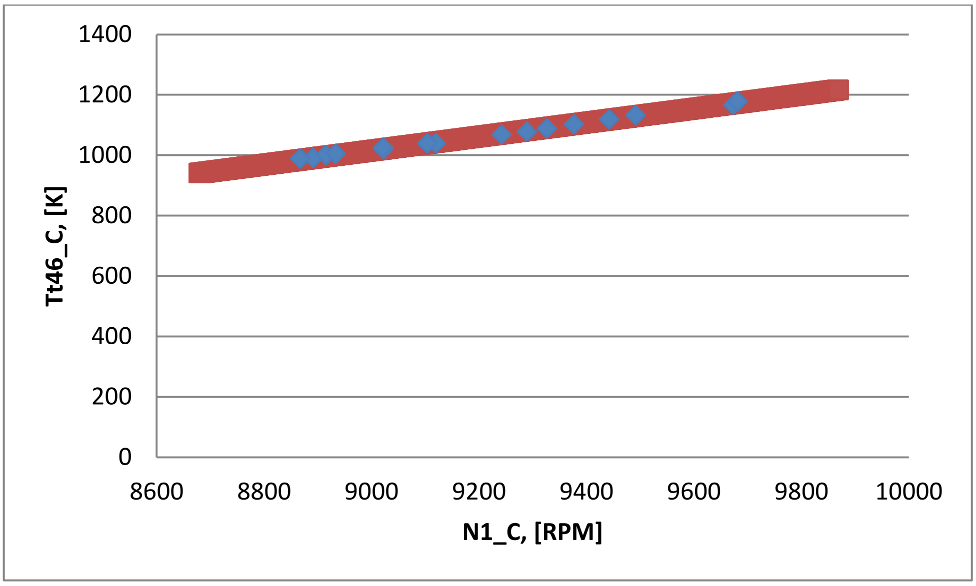


Figure A.12: Operating points - IPT Exit Temperature

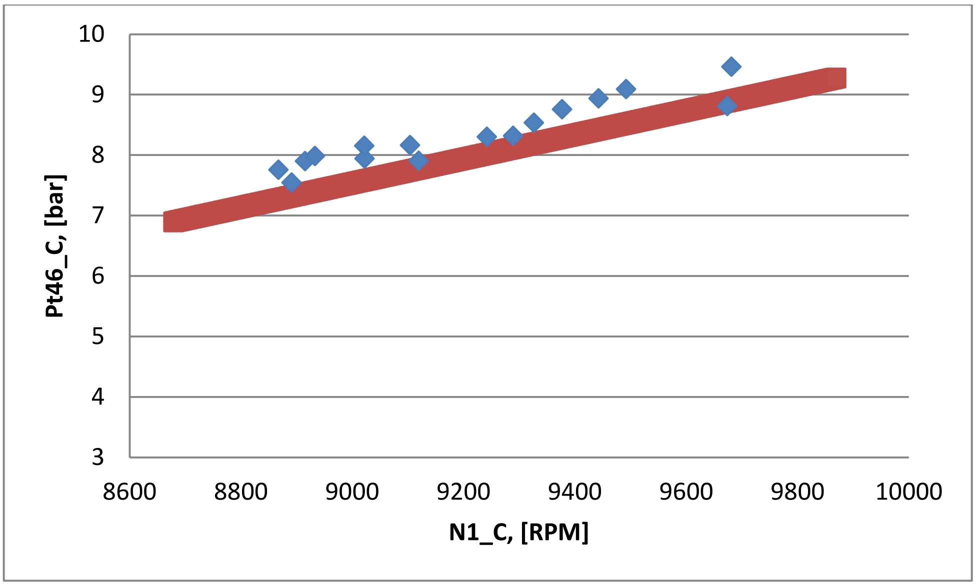


Figure A.13: Operating points - IPT Exit Pressure

Appendix B. Deterioration study

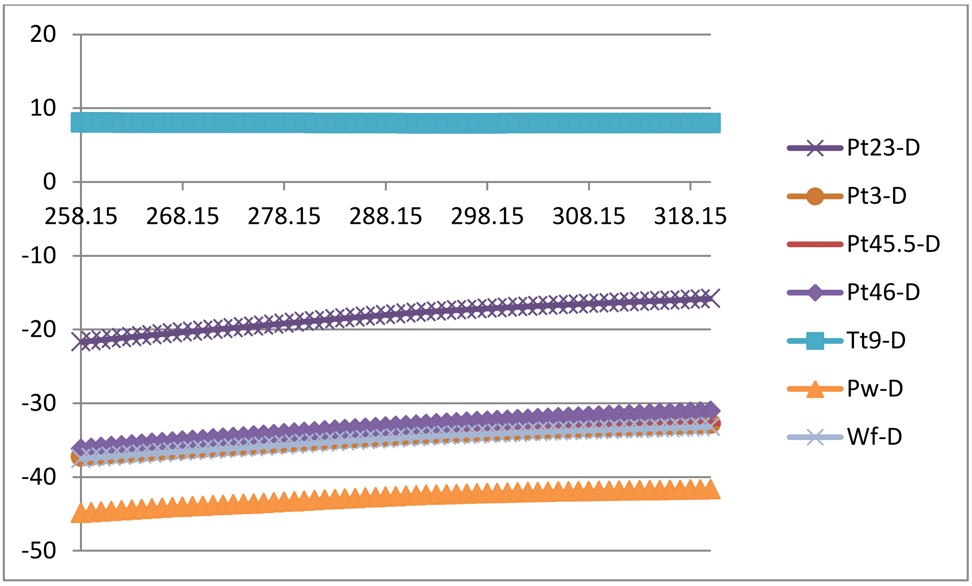


Figure B.1: Deviation due to fouling in HPC

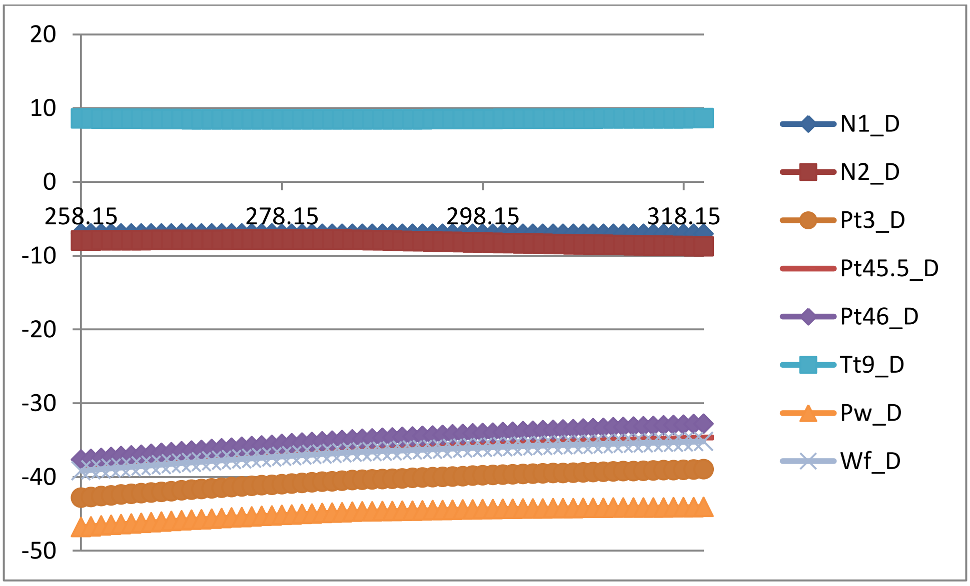


Figure B.2: Deviation due to erosion in HPT

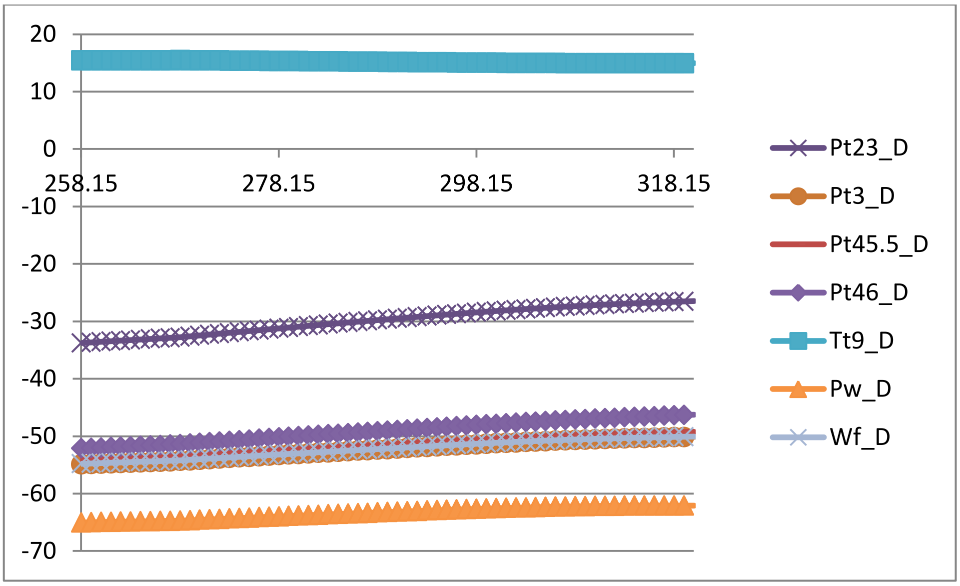


Figure B.3: Deviation due to rotor fault in HPT

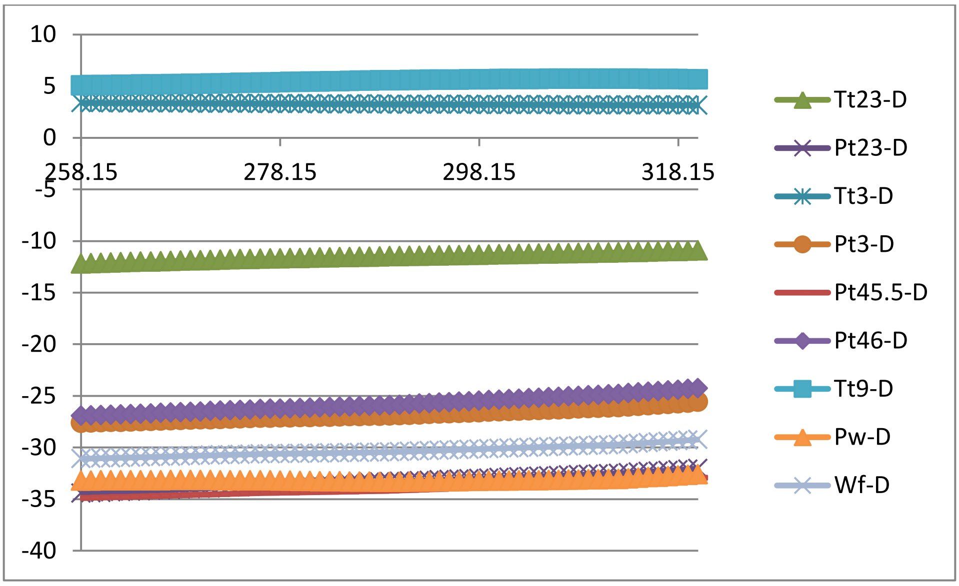


Figure B.4: Deviation due to erosion in IPT

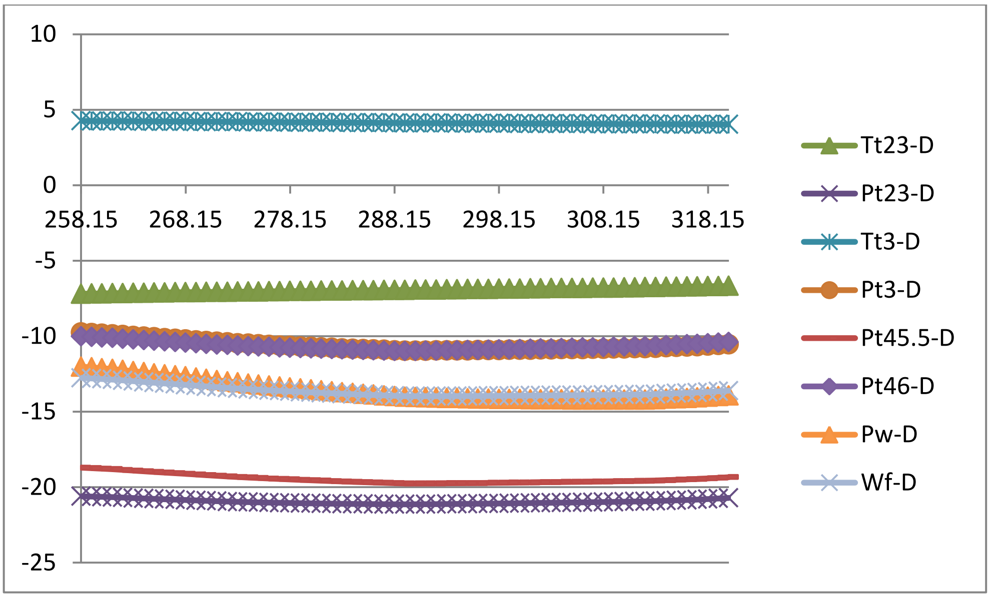


Figure B.5: Deviation due to corrosion in IPT

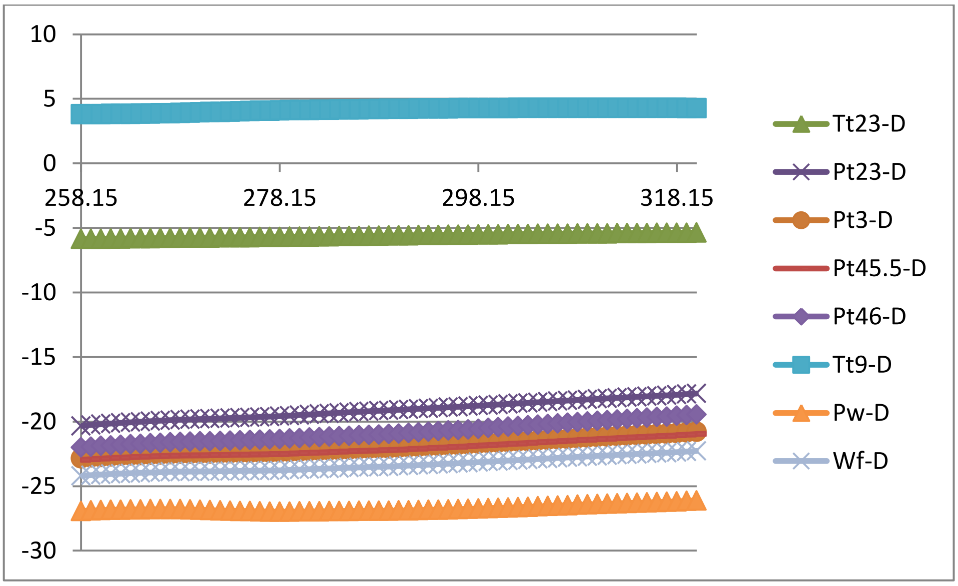


Figure B.6: Deviation due to rotor fault in IPT

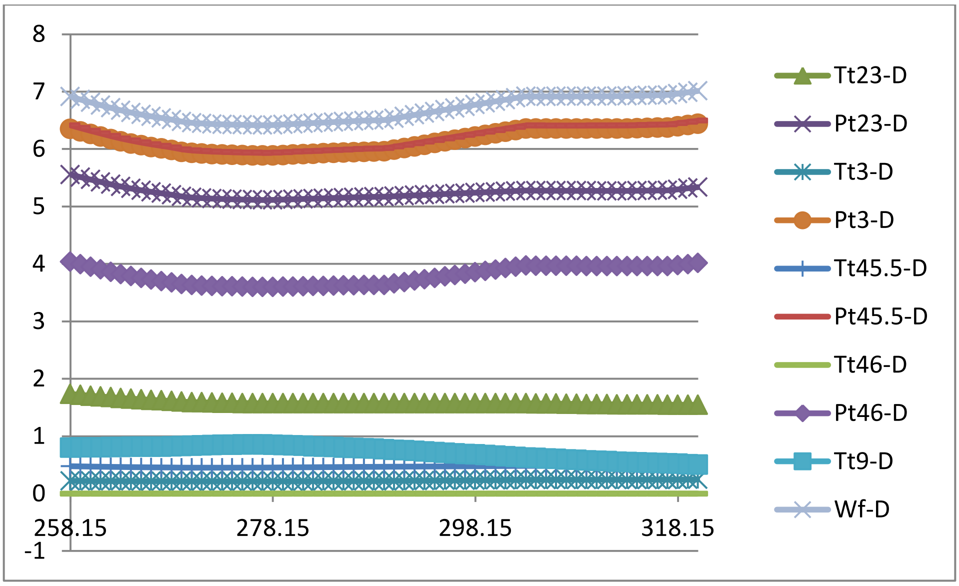


Figure B.7: Deviation due to erosion in PT

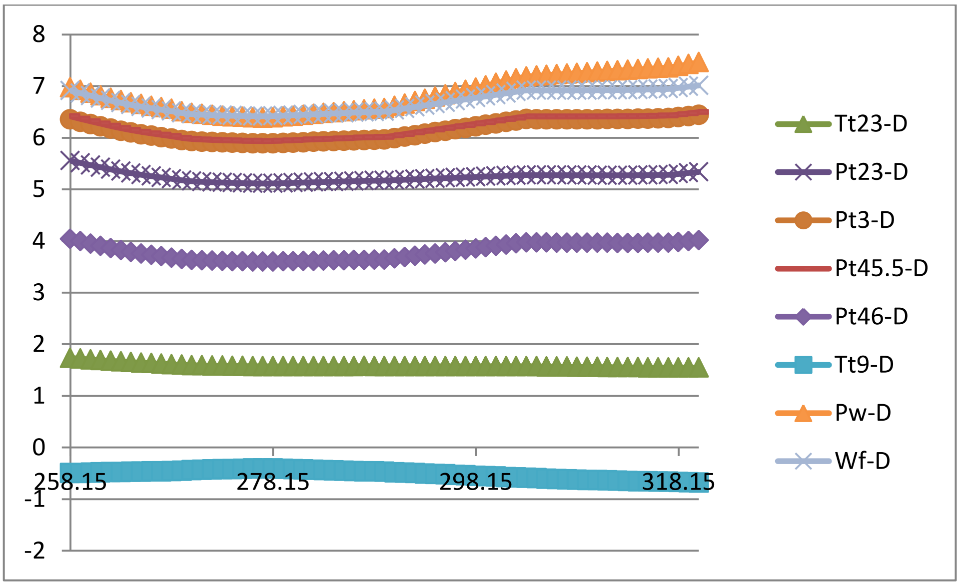


Figure B.8: Deviation due to corrosion in PT

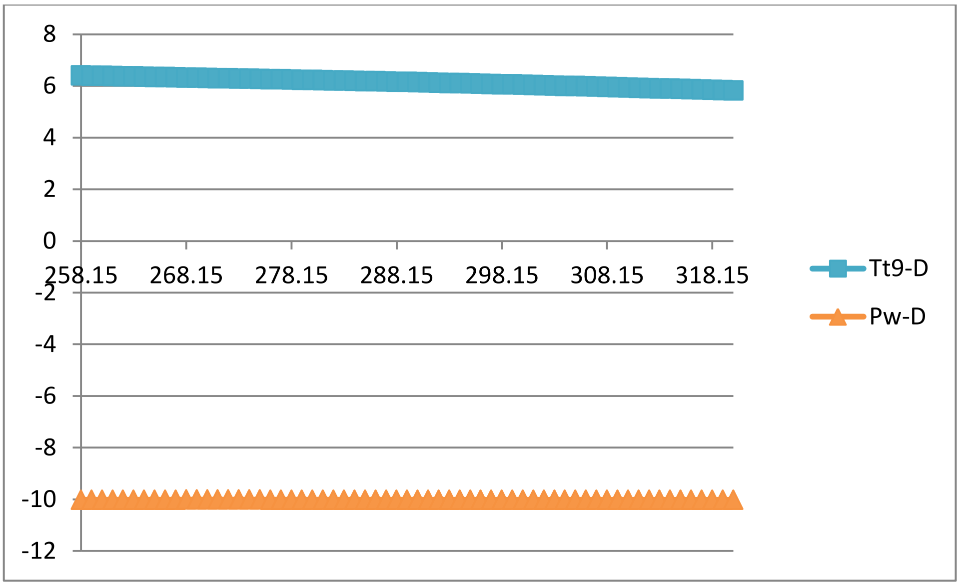


Figure B.9: Deviation due to rotor fault in PT

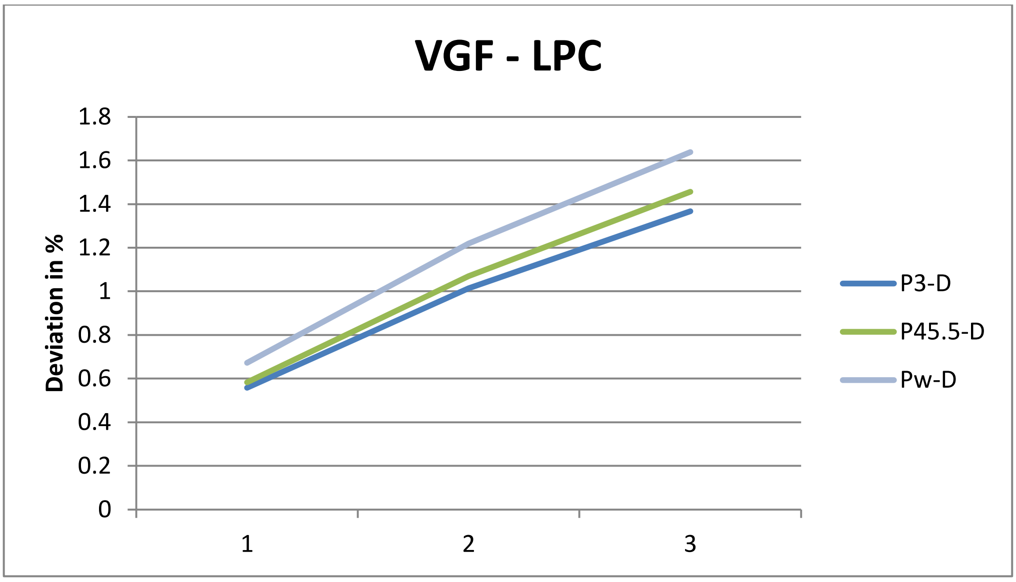


Figure B.10: Deviation trend of indicating parameters due to VGF

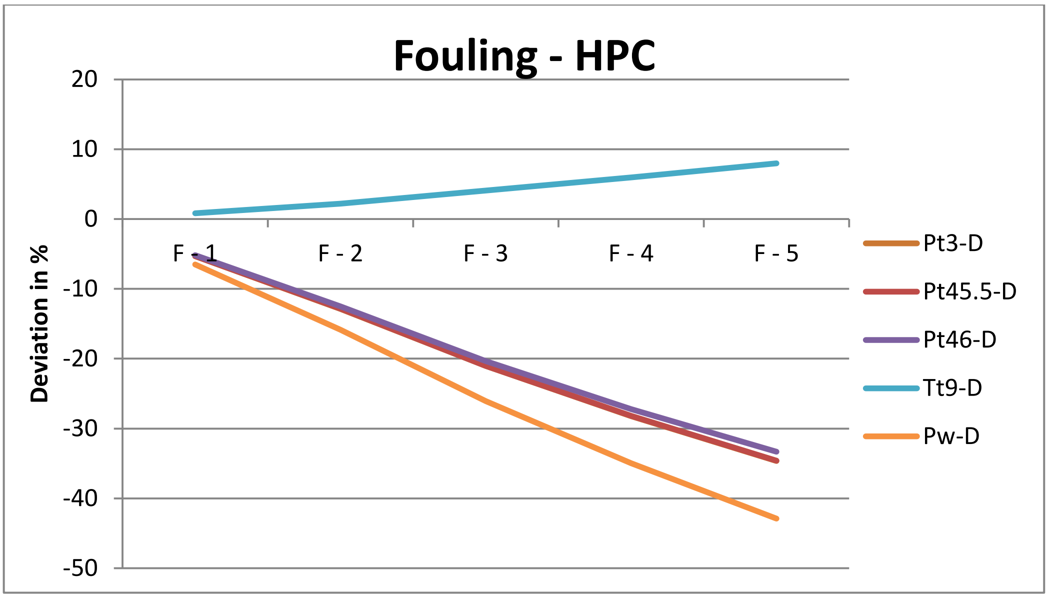


Figure B.11: Deviation trend of indicating parameters due to fouling in HPC

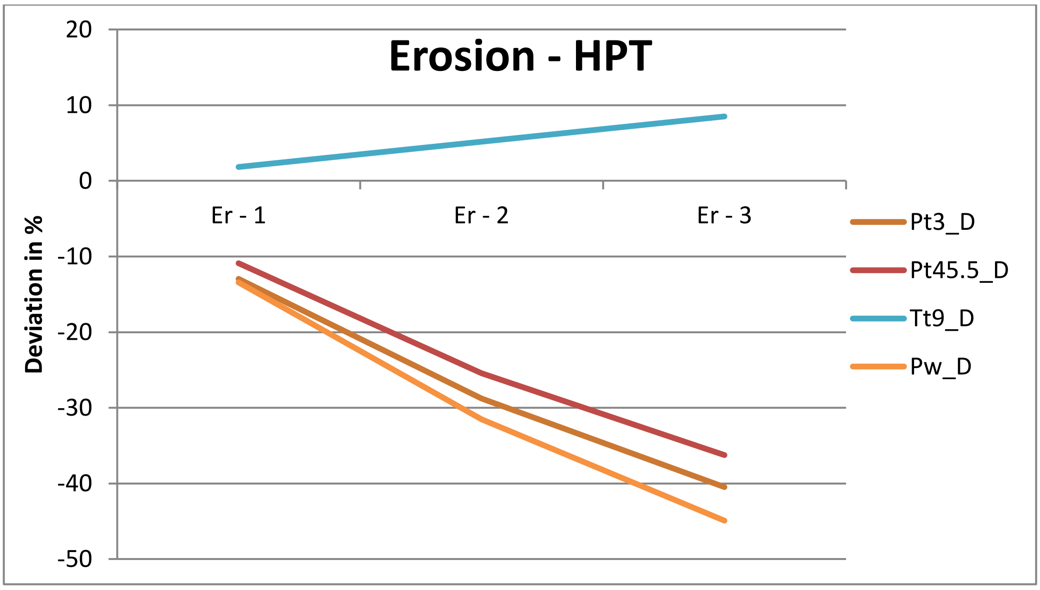


Figure B.12: Deviation trend of indicating parameters due to erosion in HPT

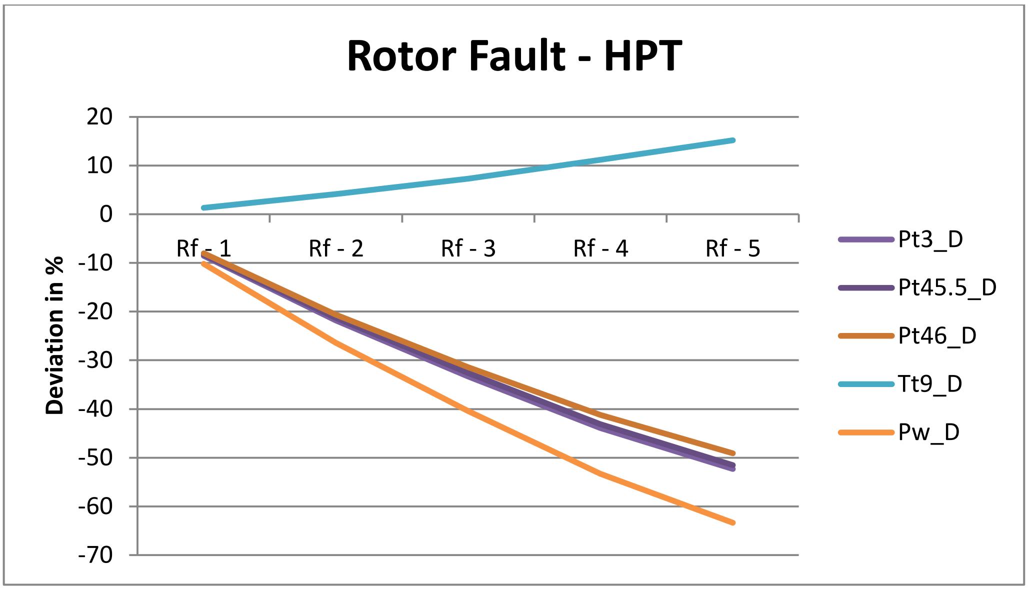


Figure B.13: Deviation trend of indicating parameters due to rotor fault in HPT

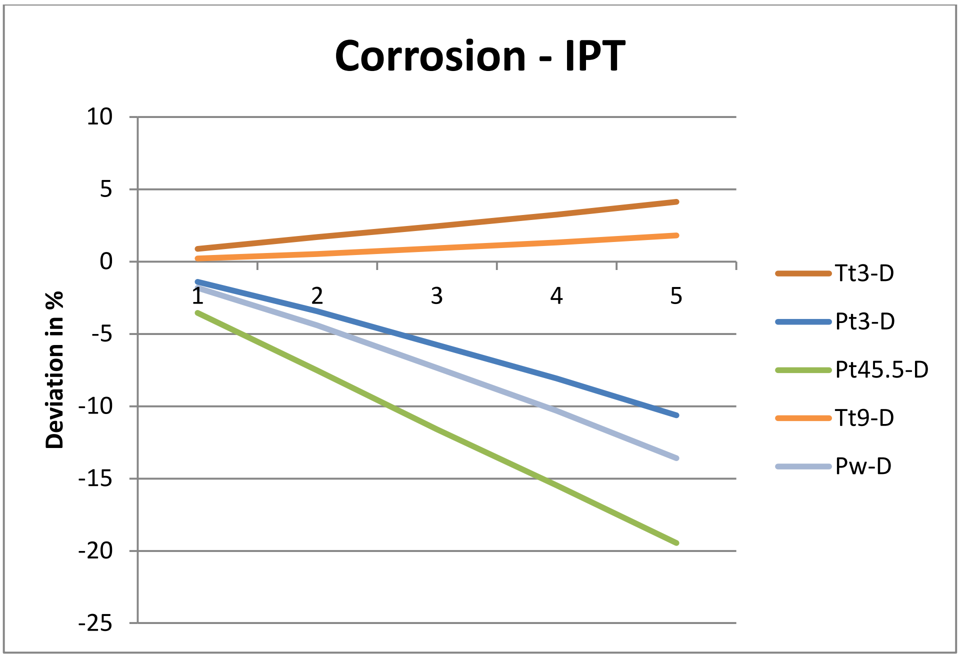


Figure B.14: Deviation trend of indicating parameters due to corrosion in IPT

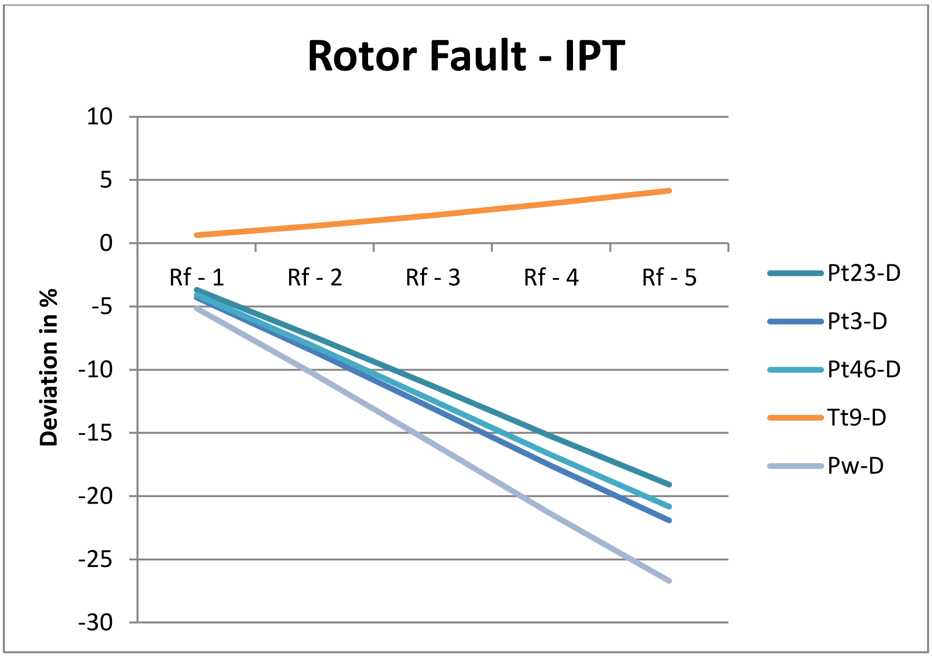


Figure B.15: Deviation trend of indicating parameters due to rotor fault in IPT

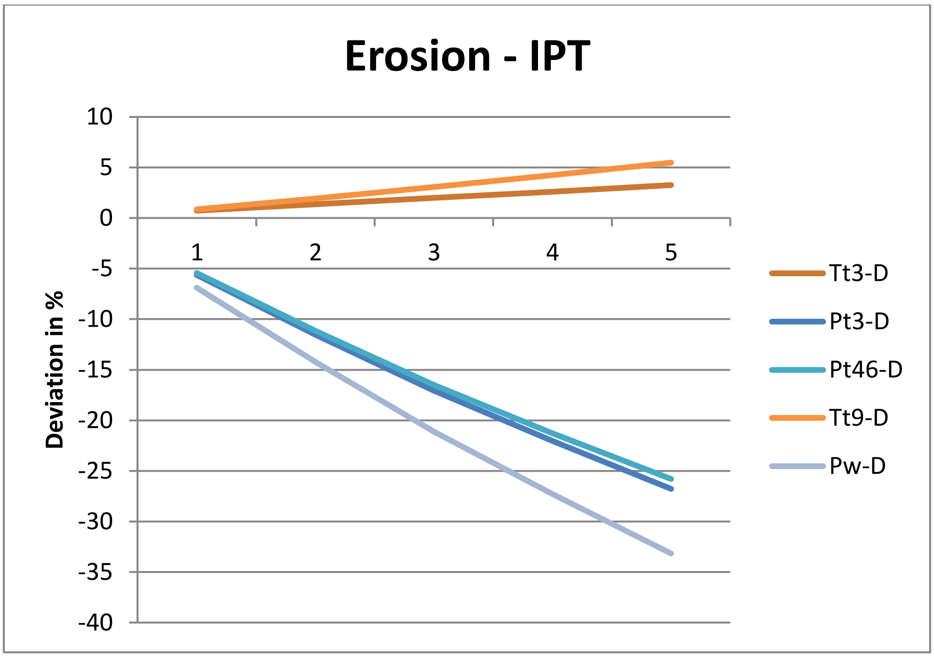
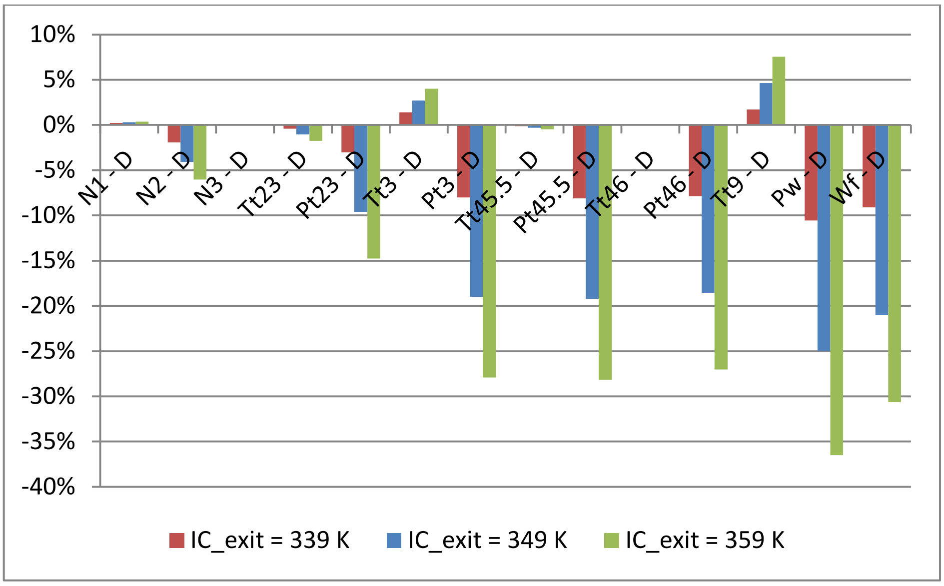


Figure B.16: Deviation trend of indicating parameters due to erosion in IPT

Appendix C. Intercooler Deterioration

The figure below shows the parameter deviation when the intercooler exit temperature rises from 329 K to 359 K.



FigureC.1: Parameter deviation due to increased intercooler exit temperature

The fuel flow reduces to maintain the power turbine inlet temperature. The reduction in mass flow in the turbine components reduces the power generated and hence reduces the speed of the low pressure spool. Eventually the pressure drops from their ideal value at both LPC and HPC exit stations. The reduction in power extracted but maintaining the PT inlet temperature causes the rise in gas turbine exhaust temperature. The vital indicating parameters for this deterioration case are the power output and increase in exhaust temperature.