The Simulation and Analysis of Fault Diagnosis and Isolation for Gas Turbine Control System

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Authors' Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

MUHAMMAD SHAHZAD QAMAR ASIF

Abstract

The gas turbine engines are vital elements of modern aviation and mechanical industry. However, due to complexity in nature and operation, they require a complete monitoring to avoid unforeseen damages and faults in routine operation. This study involves the development of some suitable strategies for diagnosis and isolation of certain faults in a simulated gas turbine engine and to recommend corresponding recovery measures. In order to proceed with study of fault diagnosis and isolation, mathematical model of the gas turbine engine is required because mathematical models are best source for analysis of different dynamic aspects of a system. The models not only depict a picture of system operation at different instants of time but also provide framework for design of their control systems. In the present research study, the gas turbine engine is modelled in Simulink /MATLAB using mathematical equations regarding flow in different parts of the engine. The model is then simulated, tested and validated against published results of a physical gas turbine system by using analogue matching procedure. The model validation confirms its suitability and reliability for further work of the research study.

After studying behavior of this mathematical model, a fuel flow controller is designed using Proportional-Integral (PI) controller. This fuel flow controller intends to control number of revolutions per second and hence thrust of the engine. The controller is tuned to get desired spool speed from the engine by controlling fuel flow rate in combustion chamber of the engine. After controlling the fuel flow, the modelled system is tested for fault detection and isolation (FDI). The deviation of parameters of faulty plants from those of healthy model are recorded as residuals. Residual analysis using model based methodology is adopted to carryout fault diagnostic studies. The analysis of these residuals provides us detailed knowledge of the faults based on their nature and location in the gas turbine system. This study deals with mainly three types of faults namely the sensor, actuator and component faults. The faults are implanted in the gas turbine model and simulations are run to collect data about the faults. The data obtained through comprehensive simulations and numerical results is used to differentiate among sensor, actuator and component faults in gas turbine engine. After having detailed knowledge about faults in the gas turbine system, suitable recommendations have been made to recover the system from these faults.

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Dedication

To

My Parents

Wife, Mrs Muqadsa Shahzad,

Sons, Uzair & Saad

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Nomenclature

N	*Number of revolutions (1/sec)*
T_{01}	*Temperature at compressor face (K)*
T_{02}	*Temperature at compressor exit (K)*
T_{03}	*Temperature at combustor exit (K)*
T_{04}	*Temperature at turbine exit (K)*
$\dot{m}_c$	*Air mass flow rate through compressor (kg/Sec)*
$\dot{m}_t$	*Gas mass flow rate through turbine (kg/Sec)*
$\dot{m}_f$	*Fuel mass flow rate (kg/Sec)*
m_{cc}	*Mass of gas in combustor (kg)*
P_{01}	*Pressure at compressor face (Pa)*
P_{02}	*Pressure at compressor exit (Pa)*
P_{03}	*Pressure at combustor exit (Pa)*
P_{04}	*Pressure at turbine exit (Pa)*
t	*Time (Sec)*
$C_{p,air}$	*Specific heat of air at constant pressure (J/kg.K)*
$C_{p,gas}$	*Specific heat of gas at constant Pressure (J/kg.K)*
$C_{v,med}$	*Medium specific heat at constant volume (J/kg.K)*
Q_f	*Lower thermal value of fuel (J/kg)*
η_{comb}	*Combustor efficiency*
η_m	*Mechanical efficiency*
η_c	*Isentropic efficiency of compressor*
η_T	*Isentropic efficiency of turbine*
I	*Moment of Inertia (kg.m^2)*
M_{load}	*Moment of load (Nm)*
S_{comb}	*Combustor pressure loss*
S_N	*Gas deflector pressure loss*
V_{comb}	*Combustor volume (m^3)*

Chapter 1: Introduction

Aerospace Propulsion in modern aviation industry is achieved by means of different types of gas turbine engines. The concept of air-breathing propulsion systems initiated in the beginning of the twentieth century. Many patents of air-breathing engines were tested by numerous scientists and researchers from all over the world working at different platforms (Mattingly and Ohain, 2006). Keeping in view the scientific and technical viewpoints, we can say that jet propulsion produced by air-breathing engines is a kind of internal combustion in which output power is achieved as rate of change of kinetic energy of the working fluid (gas) in the engine. The free stream air enters the engine through the intake as working fluid, and then it is compressed by the compressor. The compressed air contains enormous amount of energy and it is then burnt with fuel in combustion chamber. The working fluid, now the hot gas, is expanded in the turbine and nozzle areas to extract energy out of it as useful power or thrust (Mattingly and Ohain, 2006). Figure 1.1 shows actual picture and schematic diagram of basic operation in a gas turbine engine.

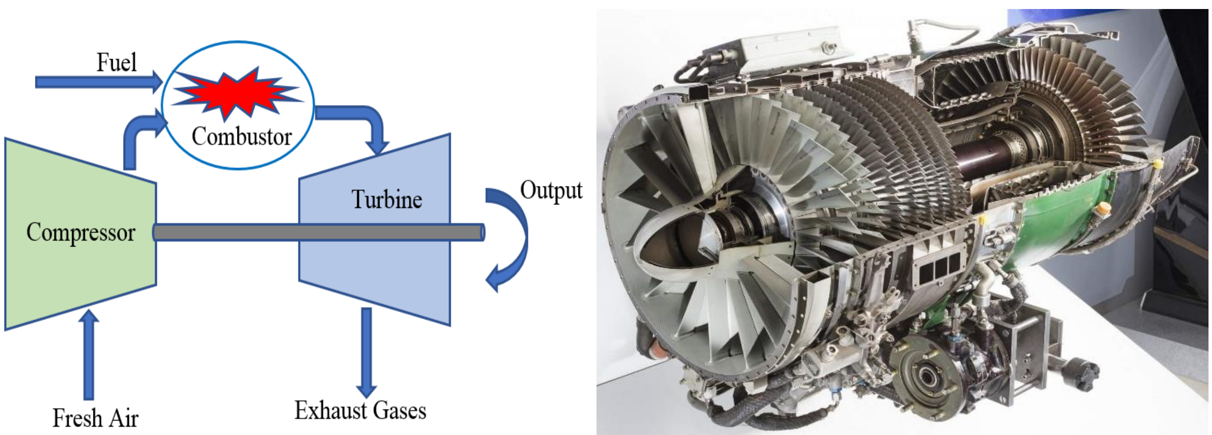

Figure 1.1: Basic operation of the gas turbine engine

The gas turbine engines have been given due importance in research and development of aerospace propulsion systems. Much of this development has been done in field of turbo-machinery and involved improvements in the aero-thermodynamic properties of the key stages of the engines. Gas Turbine Engines are important part of today's industry as well. They play a vital role in generation of power for many plants including power generation units in the industrial sector and aircrafts in the aviation industry (Mattingly and Ohain, 2006). The other important application of the gas turbines involve power generation for the marine industry (Kayadelen and Üst, 2013).

Deterioration in performance of gas turbine engines is caused by degradation of the gas path components like compressor, combustion chamber and turbine. Major reasons of degradation in performance include compressor fouling and increase of blade-tip clearance in the turbine due to wear and erosion, labyrinth seal leakage, and corrosion in the hot sections of the gas path components. These physical failures cause variations in the macroscopic computable parameters, such as temperature, pressure, spool speed, and fuel flow rate. In a complex multi-part and interconnected system, such as a gas turbine engine, a single fault in one component creates an anomalous output that might serve as the input excitation to other healthy components and degrade their performance as well. Consequently, gradual development of small anomalies in different components may cause cascaded faults ultimately leading to catastrophic failures and forced shutdown of the complete system. That's why, early warning of emerging faults is vital in an aircraft gas turbine engine for monitoring the degradation of various components and mitigation of failures (Sarkar et al., 2008).

In order to have a smooth operation and desired output power from the engine, controlling some of the critical parameters, like spool speed and exhaust gas temperatures is mandatory. The control systems enable to have command on the variations in gas turbine engine parameters caused by different factors. The control structure help engine to maintain the desired performance level by controlling and correcting the parameters deviating from the set point. However, there are certain conditions in which some faults may occur in the plant or the control system, that affect performance of the engine at overall level. The analysis and investigations of the faults occurring in the gas turbine control systems lead towards re-designing or modifying the control systems to recover from the faulty conditions. Therefore, a detailed analysis of the gas turbine models and control systems is vital to have efficient fault tolerant control systems. In this study, work is aimed to have an insight about working of the gas turbine control system and to formulate a mechanism for monitoring the gas turbine system for Fault Diagnosis and Isolation (FDI). The study involves designing a valid mathematical model of the gas turbine and its control system for FDI analysis.

The most common degradations in gas turbine engines may be classified as sudden or instantaneous degradations and gradual degradations. Ingestion of foreign objects, bird strikes, inadvertent handling issues etc. may become cause of sudden degradation. It usually gives no warning or practically no time to prepare for any action to avoid the failure. On the other hand, gradual failures like crack growth, corrosion, erosion and fouling, etc., are progressive in nature and will reflect as variations in some visible parameters (Babu, Samuel and Davis, 2016). The diagnostic approach towards such failures can be achieved by applying certain techniques and algorithms. Based on the accessible knowledge of the system, FDI can be conducted through three main approaches, namely model based, data-driven based and expert systems. In the model-based approach the complete prior knowledge of the system enables one to represent the system as a mathematical model, while in the other methods this mathematical model is not available (Abbasfard, 2013). In the model-based approach, by using the mathematical model of the system and numerical/simulated data, the FDI objective is achieved. In the current study, dynamic model of the single spool gas turbine engine is developed to study its control system and FDI associated with the engine operation. Our focus in the present study is aircraft gas turbine engine, however, the proposed FDI approaches with certain modifications, may be applied to multi-spool engines and industrial gas turbines as well.

1.1 Mathematical Modelling of Gas Turbine Engines and Control Systems

Performance analysis of the gas turbine propulsion devices may be done effectively through modelling and simulation techniques using different computer programs. Mathematical modelling has always been an important as well as economical tool of investigation and examination of the dynamic systems. The static and dynamic mathematical models of the systems have always been an important method to investigate the performance and behavior of these systems. The information extracted from simulating the mathematical models is used extensively to investigate opportunities of future developments and innovations. Over the years substantial efforts have been exerted in gaining a comprehensive understanding of engine dynamics and to design suitable control system for control of engine parameters. Keeping in view the day to day increasing costs of engine programs, mathematical modelling is used in a variety of ways. Good high-fidelity models, that accurately describe engine performance, are essential in developing analytical tools to enhance performance of the engines. In 1970s and 1980s, processing technology caused replacement of hydraulic systems of engine with digital systems. Hence, the level of processing power available has increased dramatically, which introduced much greater scope for advanced engine control strategies and methodologies (Kulikov and Thompson, 2004).

Gas turbine engine operation is complex in its nature. It needs detailed knowledge about thermodynamic equations and engineering principles. The designing of the models requires careful implementation of the equations in mathematical modelling software. The dynamic models are mathematical depiction of all the processes going on in the system. The dynamic models provide information about response of the system against a set of inputs given to system for operation. The control system engineers treat the dynamic models of gas turbine engines as virtual test bed to see how the system respond to fed inputs (Gaudet, 2007).

Controlling the complex systems enables the engineers to monitor the performance of these systems closely and provides them necessary feedback to devise the strategies in case of faults appearing in the plants during routine operation. Therefore, importance of control systems in case of gas turbine engines cannot be overlooked, as its operation involves costly equipment, heavy repairing costs, and above all human lives associated with the environment where these plants are used. The effective control system not only achieve the desired controlling objectives but also points out the new aspects of component operation.

1.2 Performance Monitoring of the Gas Turbine Engines

The technical systems are always prone to faults that adversely affect performance of the system. There may be situation where sensors predict a reading quite far from the actual one, which may lead to wrong decision making and can result loss of equipment and sometimes human lives come at risk too. The faults in actuator may cause performance breakdown of the control systems and hence the complete failure of the system. For example, the actuator blockage in gas turbine engine affect fuel flow rate to the combustion chamber for producing hot stream of gases. There are several other parameters of the engine that are directly or indirectly connected with mass flow rate of the fuel. Therefore, it becomes imperative for smooth working of the control system that the actuator faults must be addressed at early stages so that disastrous situations may be avoided. Similarly, component wear and tear results in loss of efficiencies and causes the plant to work below the expected line of performance (Blanke *et al.*, 2006). If the compressor or fan of the engine is hit by some foreign object, it may result in loss of power for the engine. This loss of power is caused by drop in the efficiencies and compressor pressure ratio due to inability of the compressor blades to compress air properly.

In order to ensure safe and desired operation from the complex plants, like gas turbine engines, the fault detection and isolation must be kept into consideration during operation of these machines. It is important to have a close look on these faults, whenever the system is subjected to them. The early diagnosis and isolation of these faults is important to have working of the systems as per required standards. Due to the increasing emphasis on economical operation and safety standards, the performance and health monitoring of gas turbine engines has become essential. For healthy operation of the plants, it becomes a dire necessity to devise a strategy for FDI of gas turbine systems. The analysis made through FDI techniques helps us to identify nature of the fault and its location in the system. The results of FDI are guiding principles for designing fault tolerant control systems.

1.3 Objectives of the Study

The objectives of present study about FDI of gas turbine engines, cover three fundamental aspects;

- Development of a dynamic mathematical model of gas turbine engine and its validation by comparison of the simulation results with actual data.
- Designing a fuel flow controller for controlling rotational speed of the engine. The controller should aim to generate appropriate mass flow rate of fuel for the mathematical model to get desired spool speed.
- Diagnosis and isolation of the faults, that are likely to occur in a gas turbine engine. Mathematical model of gas turbine control system is to be introduced to some distinct faults and then tested for fault diagnosis and isolation using appropriate strategies.

Study has been carried out using analysis of the previous work done in field of health monitoring of gas turbine engine and developing necessary mathematical models and simulations.

1.4 Outline of Thesis

This research report is focused to investigate the FDI of gas turbine systems. It includes formulation and detailed examination of mathematical model of the gas turbine engine based on thermodynamic and constitutive relations. The simulation of the dynamic system of gas turbine engine is based on operational data curves and fuel flow controller is designed in Simulink/MATLAB. The work on fault diagnostic studies is carried out using residual analysis of a faulty plant in comparison with an observer healthy system. The numerical and graphical results are recorded using MATLAB/Simulink. The succeeding paragraphs of this chapter discuss about outline of the thesis.

Chapter 2 deals with information extracted from review of literature for the subject research project. It contains highlights of work already done in the field of FDI for gas turbine power plants. It starts from reviewing the mathematical models of different gas turbine power plants and their control systems devised in past for different purposes. The later part of the chapter is based on comprehensive review of literature about fault studies of the gas turbine power plants. Different methods to devise FDI systems for gas turbine plants have been discussed in this chapter.

Chapter 3 contains information about mathematical modelling of the gas turbine engine. In this section, different thermodynamic equations and constitutive relations are discussed that are required for modelling of the engine. The chapter contains detailed information about the modelling strategy and values of different constants used in the equations. The tables of values and mathematical equations are given separately to impart whole information about mathematical model of the single shaft gas turbine engine. The simulation results of the open loop and closed loop models of gas turbine engine are discussed in detail. The simulation results are tested and validated in this chapter against available reference data through already published results and curves.

Chapter 4 aims to deliver information about designing control system for gas turbine engine. Simple Proportional Integral control system, known as 'PI controller', is designed for the model to control spool speed of the engine. The controller is designed to control fuel flow rate fed to the gas turbine engine. Different values of gain and integral terms are tested for efficient control of mass flow rate of fuel. The controller is designed in Simulink in MATLAB environment. The simulation results of the controlled model are discussed to verify its reliability for further use.

Chapter 5 delivers information about FDI analysis of the subject mathematical model of the gas turbine engine and its control system. In this section, residual analysis of different faults has been discussed in detail. The faulty plant is compared with an observer healthy model to have an idea about type and nature of the faults. The sensor, actuator and component faults are implanted in the mathematical model of the gas turbine plant. The deviation of the output from the actual outputs are recorded in evaluation phase. The fault signature table is used for analysis of the faults and enables us to recommend the necessary recovery tools. This section aims to convey necessary information about monitoring of the gas turbine performance for efficient operation within normal operating limits.

Chapter 6 consists of the concluding remarks about the research project. The conclusion is drawn on the basis of the results obtained after simulating the engine model and discussed in detail in previous chapters. This chapter also describes the distinct outcomes from this research project that may be used for the future researches in the field of designing fault tolerant control systems for gas turbine engines.

Chapter 2: Literature Review

Gas turbine engine is an important entity of modern aviation world and industry. It plays a vital role in propelling the aircrafts as well as running the power plants in industrial sector (Boyce, 2012). A gas turbine engine is a type of internal combustion engine, which generates power by burning the fuel with compressed air. The chemical energy of the fuel is converted into heat energy at the first instant and then this heat energy is converted into useful work or mechanical energy (Mattingly and Ohain, 2006). After taking air through the intake, compressor uses it for compression and feeds the compressed air to combustion chamber. Here the compressed air is burnt with fuel to generate heat energy. This heat energy then drives the turbine located after combustor. Turbine extracts the energy from hot flow, so it is basic building block of the gas turbine engine. The turbine blades are rotated by the hot flow and in this way the rotors extract useful energy from hot stream of gas.

Gas Turbine engines are mainly used as aviation gas turbines and industrial gas turbines to generate power for the respective propulsion or power generation units. Simple cycle gas turbine engines may be divided into six categories (Boyce, 2012).

(a) Heavy duty gas turbines: These are comparatively large units used for generating power ranging from 3 to 480MW in a simple-cycle configuration. The efficiency range for these gas turbines vary from 30% to 48%.
(b) Aircraft gas turbine engines: These units are used to generate power for aircraft propulsion systems. The power generated by these engines ranges from about 2.5 to 50MW with the efficiencies ranging from 35% to 45%.
(c) Industrial gas turbines: The power generated by these turbines ranges from about 2.5 to 15MW. These are used widely in petrochemical plants with efficiencies of about 30%.
(d) Small scale gas turbines. The power produced by these engines is in the range from about 0.5 to 2.5MW. They usually consist of radial inflow turbines coupled with centrifugal compressors. They normally operate with efficiencies ranging from 15% to 25%.
(e) Micro gas turbines. These turbines generate power in the range from 20 to 350kW. The dramatic growth of these engines started from the late 1990s associated with an expansion in the power generation industry.
(f) Vehicular gas turbines. The power generated by these turbines ranges from 300 to 1,500 HP. Chrysler Corporation, followed by the Ford Motor Company built the first vehicular turbine engine in 1954. The only vehicular turbine that has been very successful was the gas turbine engine used in US Army Abrams Tank (Boyce, 2012).

All the listed categories of the gas turbines are used to generate power for the respective power plants. The complexity of the structure of the gas turbines demands careful consideration to the supervision and monitoring the states during operation of the engine. Research and development in field of propulsion systems need detailed investigation of the behavior of the plants before using in the actual situation. It can only be done by designing prototypes of the engines or mathematical models depicting the similar performance of states as expected from the original plant.

2.1 Mathematical Models for Gas Turbines

The performance of the gas turbines is a complex phenomenon and there are some parameters that cannot be measured directly and can only be estimated due to excessive heat produced in the system. Mathematical models are prepared to depict the actual gas turbine systems and to estimate certain parameters which cannot be measured directly due to various constraints. Therefore, it is the most suitable way to predict about the performance of the gas turbine systems (Yarlagadda, 2010). Mathematical modelling is important to understand the behavior of the dynamic systems. It leads to comprehensive understanding of the different aspects of operation of a specific plant under enquiry. Different researchers have focused on performance evaluation of gas turbine engines through mathematical modelling techniques. There are some important factors which should be kept in mind while modelling the gas turbines. These factors include type of the gas turbine, its configuration, the modelling methods, the purpose of the modelling, the type and structure of the control system and the simulation objectives (Asgari, 2014; Asgari and XiaoQi, 2016).

2.1.1 Type of the Gas Turbine Engine

At the initial stage of the modelling and simulation, it is mandatory to obtain adequate data about the type of gas turbine unit under consideration. Although there are distinct types of gas turbines based on their applications in the industry, they have the same basic common parts, including the compressor, combustion chamber and turbine. Figure 2.1 shows a typical single shaft aero gas turbine engine.

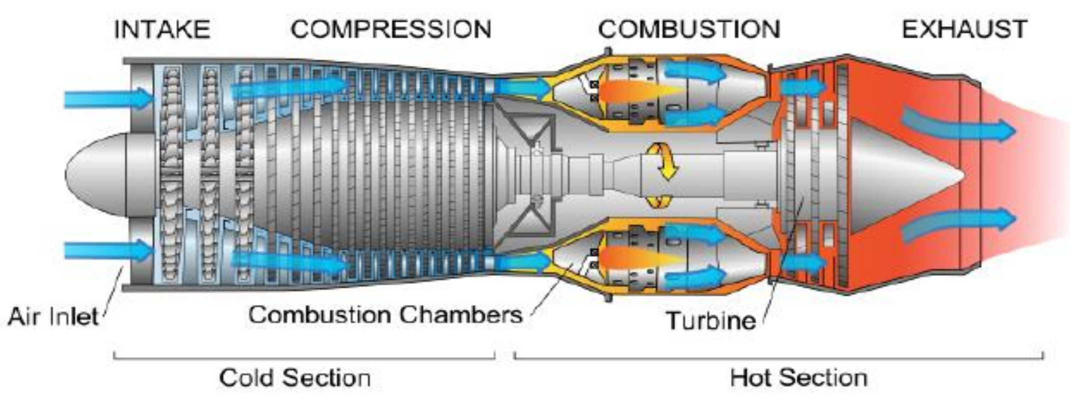

Figure 2.1: Single-shaft gas turbine engine (Asghari, 2014; 2016)

2.1.2 Gas Turbine Engine Configuration

The configuration of the engine is another important principle in the modelling phase. Although all gas turbines almost have the same basic structure and thermodynamic cycle but there are significant differences when they are studied in detail. For example, to increase the efficiency of engine, various methods like re-heating, inter-cooling or heat exchange are used. Therefore, there is always a specific configuration of the gas turbine engine (Asgari, 2014). Another dimension of gas turbine classification is the type of its shafts. They can be single or multi-shaft (two-shaft or three-shaft). In a single-shaft engine, the gas turbines consist of one compressor and turbine located on same shaft. Whereas in the multi-shaft gas turbines, there are more than one compressors and turbines attached to corresponding shafts rotating them. The high-pressure turbine (HPT) and low-pressure turbines (LPT) operate to generate power in a multi-shaft gas turbine engine (Boyce, 2012).

2.1.3 Methods of Mathematical Modelling

Modelling of gas turbines play a vital role in the production of the most effective, reliable and durable system for power generation in aviation industry. In addition, these models can also be used in industrial sectors for optimization, health monitoring, sensor testing, fault diagnosis, and troubleshooting etc. These factors were a strong inspiration for engineers and scientists to continue research in this field (Asgari and XiaoQi, 2016). There has been a lot of work done in the field of mathematical modelling of the gas turbines for various purposes. There are many sources concerning the modelling and control of the gas turbines. Different models of the gas turbines have been built so far from different points of view and for different purposes. Some researchers, such as (Visser, Kogenhop and Oostveen, 2006) attempted to propose a general model of gas turbine by using some commercial software, the proposed models are based on various scientific approaches and methodologies. The mathematical models aim to model the system dynamics with maximum accuracy. The designed models are supposed to generate the outputs that are desired from the actual systems. Although there may be some kind of modelling uncertainties but the overall output should not be affected on a greater scale. The mathematically designed models may be categorized into the following major types (Ljung and Glad, 1994);

(a) Linear and Non-linear Models
(b) Deterministic and Stochastic or Probabilistic Models
(c) Static and Dynamic Models
(d) Discrete and Continuous

2.1.3.1 Linear and Non-Linear Models

The model is said to be linear if it is built and governed by all the linear equations. Otherwise, it must be treated as non-linear model. Sometimes, due to inconsistent performance of the industrial machinery, the models are simplified for linear analysis. There are various methods for linearizing a nonlinear system. However, consideration of nonlinear dynamics is inevitable while we create the linear models of some sensitive and complex plants like gas turbines.

2.1.3.2 Deterministic and Stochastic Models

On the other hand, the models may also be deterministic or stochastic. In the deterministic model, all state variables are exclusively determined by the parameters used in mathematical model and the sets of preceding states of these variables. Therefore, the deterministic model is expressed without uncertainty due to the precise relationship between the measurable and derived variables. On the contrary, in a stochastic model, quantities are defined using stochastic variables or random processes. Consequently, in a stochastic model, state variables are described using a random probability distribution (Ljung and Glad, 1994).

2.1.3.3 Static and Dynamic Models

The variables used to depict the system behavior generally change with time. If there are direct and instantaneous relations between these variables, the system is said to be static. If the variables of the system are subject to change without direct external influence, in a way that their values are governed by the previously applied signals, then the system is known as dynamic system (Ljung and Glad, 1994).

2.1.3.4 Discrete and Continuous Models

Mathematical model is said to be continuous time, if it states the relation between continuous time signals. A function $f(t)$ is used to show continuous time models, which varies over a continuous time. On the other hand, the model is said to be the discrete time, if it directly states the relations between the signal values at certain discrete time instants. The differential equations are usually used to express relationship between signal values. In real time applications, signals are most often acquired in the form of a sample in discrete time measurements (Ljung and Glad, 1994).

2.2 Development of Mathematical Models for Gas Turbines

The non-linear mathematical model of gas turbine engine for loop shaping purposes was developed in (Ailer, Santa and Szederkényi, 2001). In their work, they used the non-linear dynamic equations based on the first engineering principles. The model was completed by using constitutive algebraic relations which describe the static behavior of the engine. Then that model was validated and tested against the experimental results. The same model was simplified in (Ailer *et al*., 2016) to investigate the dynamic properties of the engine under consideration. In (Pongracz *et al*., 2004), a simple nonlinear dynamic model was developed that was in a quasi-polynomial form. Nonlinear stability and zero dynamics analysis was applied to find a controller structure for input-output linearization. The authors estimated stability neighborhood of the system with turbine inlet pressure held constant (30-35%) of the operating domain of the turbine. The servo controller for the rotational speed was found to be asymptotically stable and robust against disturbances in the operating domain. The authors claimed that the proposed servo controller, had better qualitative and quantitative properties than a servo controller based on a locally linearized model.

In the work of (Klein and Abeykoon, 2015), it was aimed to model a turbojet gas turbine engine theoretically and computationally. On this basis, the pre-established equations were implemented in MATLAB Simulink to create a model of a turbojet engine. The influence of atmospheric conditions was also taken into account in creating the model. Furthermore, a software GasTurb was used to study the turbojet engines and provided useful results to explore the engine performance. The theoretical and Simulink models were in a good agreement within reasonable limits which verifies the correctness of the Simulink model established in the paper. The proposed model considered to be used in investigating the performance of various types of turbojet engines without performing time taking theoretical calculations.

In (Yarlagadda, 2010) the author followed the same modelling technique to build the dynamic model of gas turbine and analyzed the feasibility of thrust control mechanism by regulating air flow at intake of the aircraft to enhance engine RPM for the same value. All the components starting from air intake to nozzle were modelled as separate subsystems in Simulink and then joined together. To evaluate dimensionless parameters in thermodynamic relations, the author used 2-D look up tables for compressor and turbine maps. The performance characteristics of J-85 turbojet engine are examined through simulations with reduced inlet pressure to the compressor and matching thrust produced by the plant. The author concluded that specific thrust for engine increases with decreased inlet pressure of compressor. It is especially important for the circumstances of shorter runways and higher climb rates. With increase in the specific thrust value, the frontal area of the engine could be decreased and it is considered very important for applications in the military aviation industry (Yarlagadda, 2010).

In (Thirunavukarasu, 2013), the author anlysed a dynamic gas turbine system in a VTB (Virtual Test Bed) environment and focused his study to demonstrate the opportunities available to improve part load efficiency of gas turbine, when it is operated under variable speed. In his study, VTB developed gas turbine model and Gas Turb software were used for collection of results. The author compares the results of variable speed operation for single shaft and twin shaft gas turbine engine, he concluded that the efficiency increases as load decreases and the improvement is greater for single-shaft engines than for twin-shaft engines. In (Kaikko, 1998), the author presented a method for prediction of gas turbine performance from the component models. The non-linear set of equations corresponding to processes are solved and mass-energy balance is established. The emphasis has been placed upon axial gas turbines on industrial scale. The author intended to provide facilities to optimize gas turbine engine performance with respect to desired performance parameters.

In (Hosseinalipour, Abdolahi and Razaghi, 2016), static and linear dynamic models of Micro Gas Turbines (MGT) are discussed. The static model was designed using simple thermodynamic relations and component performance maps, whereas the linear dynamic model was constructed using linearized static and non-linear dynamic equations. A comparison is made between results achieved by static model and steady state values of the dynamic model. In (Asgari, 2014; Asgari and XiaoQi, 2016), author investigated the control strategies for gas turbine engine using ANN (Artificial Neural Networks). In Chapter 4 of (Asgari, 2014), he prepares the mathematical model of gas turbine engine using the same dynamic and constitutive relations described in (Ailer, Santa and Szederkényi, 2001). The model was run in Simulink for the same design point as described in (Ailer, Santa and Szederkényi, 2001). Then system based on ANNs is simulated and the results of both systems are compared. The author established a comprehensive view of the performance of over 18720 ANN models for system identification of the single-shaft gas turbine (Asgari, 2014).

In (Martin, 2009), joint academic and industrial study conducted for development of non-linear dynamic model of a turbofan gas turbine engine for research into advanced control strategies for gas trubine engines in civil aircrafts. The author tried to avoid the empirical approximations and provided physical justification for approximations used. Shaun R. Gaudet described the dynamic modelling method in (Gaudet, 2007) for all components of the gas turbine based on thermodynamic and mathematical calculations. The model was used to simulate engine start up to design point steady state and transient performance. The consequent dynamic model had also been used to predict performance of the engine at its operating limits. In (Turie, 2011) the author develops the gas turbine model that is based on component oriented approach. The author considers this approach to be flexible and user friendly for future works. In (Latypov, 2015), the author tried to establish a relation between exhaust jet velocity (and hence thrust) with burning of hydrogen as a fuel in combustion chamber of scramjet. Based on his calculations of exergy values, he proposed maximum limit of Mach number for scramjet as 12. Some other studies also focus on mathematical modelling of the gas turbine engine for performance prediction of the plants used in industry and aircrafts.

2.3 Control System for Gas Turbine Engines

Every aspect of the modern society is affected by the innovations in control systems. We can find them starting from our kitchen appliances to the heavy industrial systems. they have wide spread applications in science and industry, from moving the ships to propelling the airplanes. If we view from another angle, the control systems also exist naturally. An obvious example of the natural control systems is human body control systems. Our body is controlled by many such smaller control systems that govern functions of different parts of our body. The extent of importance of the control systems can be seen from the fact that economic and psychological systems have been suggested based on applications of control engineering (Nise, 2011). A simplest control system consists of an input, a plant or the process, and an output. They can be open-loop or the closed system. Open-loop systems are the simplest form of the control systems, that does not monitor or account for the changes in the systems, however they are simple and comparatively cheap in market. On the other hand, Closed-loop control systems supervise the output and make comparison with input of the process. In case of any error, it corrects output and hence compensates for the changes caused by any disturbance (Burns, 2001). The primary objectives of the analysis of the control systems are the following (Nise, 2011);

(a) Creating the transient response that is desired of the system.
(b) Minimize the steady-state errors.
(c) Attaining the stability in responses.

In (Nise, 2011) the author discussed the theory and practices for control engineering. He explained various concepts of modelling in frequency and time domains. He has also included case studies of linearization of different models. The writer has discussed in detail about stability of the systems, root locus techniques, state-space representation and steady-state errors. He has also introduced fundamentals of the digital control systems at the end of the book. The author has included tutorials about MATLAB, Simulink and Labview in the appendices of the book.

2.3.1 Types and Configurations of the Gas Turbine Control Systems

Type and configuration of the control system is one of the critical factors in the modelling and control of the gas turbine plants. The control system is a vital part of any industrial machine. Both, the type and configuration of control system are in close relation with the complexity of the system dynamics and allowed tasks throughout the entire period of operation. Without appropriate control, the system may cause severe problems, like compressor overheating, over speeding etc. (Giampaolo, 2006). The result of such problems may be shutdown of the system and grave damage to major parts of the gas turbine engine. Control systems have three basic functions for all gas turbines which include (Asgari, 2014; Asgari and XiaoQi, 2016);

(a) Start/Stop Sequence Monitoring
(b) Steady State or on-line control
(c) Protection Monitoring to protect against overheating, over-speeding, overload, vibration, Flameout and loss of lubrication.

In a power network with various gas turbines, all distinct control systems have close relation with principal distributed control system (Boyce, 2012). The control systems for gas turbine control system may be open loop or closed loop. In an open loop control system, the controlled variable is employed manually or using an already defined program. However, for closed loop controlling application, one or more variables from the output or calculated data are used to move the controlled variable. To keep an effective and proper closed loop control system, the controller must be appropriately coupled to plant or process parameters (Boyce, 2012).

The mathematical models of dynamic systems lead towards this important aspect of controlling different parameters for the system. In case of gas turbine engines, controlling the different parameters especially the fuel flow rate is quite beneficial. Different researchers have worked to attain comprehensive controlling systems for gas turbine engines. In (Azolibe and McGookin, 2015) the authors used a classical approach to develop automatic process controller integrated with automation system for fuel control of the civil transport aircraft engines. In this paper, the authors proved control accuracy and robustness by using PID controller. In (Rafferty and McGookin, 2012), a sliding mode controller and PID controller were developed for small scale remotely operated helicopter. In this paper, the surge and heading control systems were designed by assuming surge and heading dynamics as independent subsystems. In the later chapter of the thesis in (Asgari, 2014), General Electric PG 9351FA has also been modelled mathematically and PID controller is designed to analyze the performance of industrial gas turbines. In (Ang, Chong and Li, 2005), the authors emphasized upon inclusion of 'intelligent' techniques in software based PID systems that help to automate the entire design and tuning procedure to high degree. The authors also claim that it can help future development of control systems for improved quality and less maintenance problems.

In (Lyantsev, Kazantsev and Abdulnagimov, 2017), the form and identification method of nonlinear dynamic gas turbine models on acceleration mode on the base of experimental transition processes is proposed. The nonlinear dynamic model for turbojet engines on the transient (acceleration) mode is developed in the form of a system of nonlinear differential equations as in the normal form of Cauchy. A typical feature of the suggested model is a parameters representation of the system of differential equations in the form of functional dependencies on the acceleration parameter. The suggested identification method based on the use of a numerical optimization strategy and approximations of an experimental data by cubic splines, which significantly minimizes the identification error. The considered example of turbojet engine identification presented, that the identification error for the rotor rotational speed on the acceleration mode is less than 1%. In the subject study, the fast-calculating real-time nonlinear dynamic model is found to be appropriate for implementation in the software for hardware-in-the-loop test-beds and in the on-board software for automatic control systems of gas turbines.

The authors in (Ql, Maccallum and Gawthrop, 1992) describe the design of a closed-loop nonlinear controller to improve the dynamic response of a single-spool gas turbine engine. The nonlinear controller is developed by scheduling the gains of multivariable compensators as a function of engine non-dimensional rotational speed. The compensators, whose outputs are fuel flow and nozzle area, are designed using optimal control theory based on a set of linear models generated from a nonlinear engine simulation. Investigations are also made into developing simple algorithms to obtain an analytical expression for the characteristics of compressor. The detailed process of developing a nonlinear simulation model for the engine is also described. The open-loop fuel controller is studied using the digital simulation.

In (Tiwari and Sivaramakrishnan, 2012) the twin spool gas turbine engine is considered as a large order nonlinear multiple input and output dynamic system. The author has emphasized upon a robust control strategy for the gas turbine engine to attain an efficient control over the system parameters. He considered sliding mode control to be a powerful method having ability to deal efficiently with systems having uncertainties. He developed a sliding mode controller with reduced order model. The writer used this control model to study about three output parameters, the thrust produced by low pressure turbine, thrust achieved from high pressure turbine and temperature at exit of high pressure turbine. The author proposes in (Tiwari and Sivaramakrishnan, 2012) regulatory control along with integral servo tracking controller for twin spool engine model.

In (Yukitomo *et al.*, 1998), a newly designed PID tuning structure is proposed. This system is considered to have different functions to adjust the PID loop, which includes input signals generation for system identification, transmission of the model evaluation of the function, PID parameter controller using the frequency domain model matching method and a well-founded systematic system check. This system was applied to the temperature of the flue gases control systems at a gas turbine power plant. The author provides the results that show effective controllability of the tuned system. They have described different functions of the control loops and then apply this control system to gas temperature control of a gas turbine engine.

2.4 Performance Monitoring and FDI for Gas Turbine Engines

The purpose of the modelling may vary from case to case. Most of the modelling techniques are used to diagnose faults in the system and then to isolate them for recovery. It saves the man hours and heavy costs on repair and restoration of the plants. In (Isermann, 2006), the author discussed supervision, fault detection and diagnosis in five comprehensive sections. He tries to elaborate the concept of health monitoring by illustration examples of different dynamic systems in fifth section of the book. In Chapter 7 and 8, the writer provides a survey of different methods of fault detection based on measuring the single signals as shown in Figure 2.2 here. He has described method of limit checking that is related to measurement of absolute values and their trends. The advanced change-detection methods have also been discussed here in detail. Different statistical test like hypothesis testing, t-test, run-sum test, *F*-test, likelihood ratio tests are discussed here. Chapter 8 of the book especially focuses on periodic signals and include classical methods like Fourier and correlation analysis. In the following chapters of the book, process identification methods for fault detection are discussed. The author also explains about the state observers and state estimation methods.

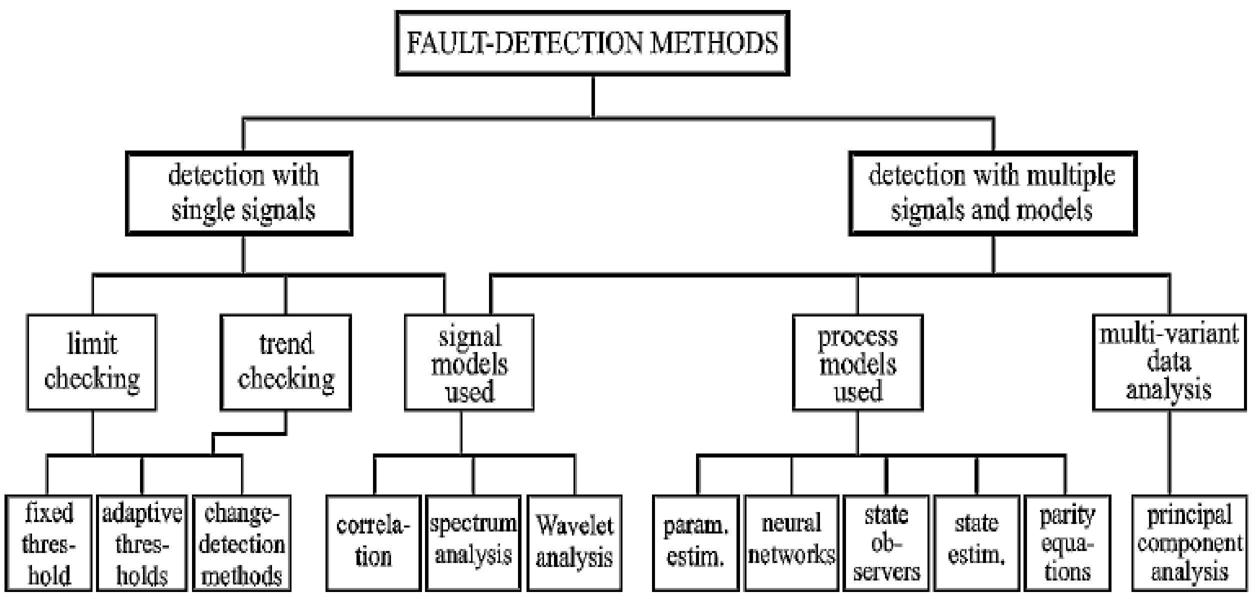

Figure 2.2: Survey of fault detection methods with signal models (Isermann, 2006)

According to writer in (Isermann, 2006), the changes in input or output behavior of process results in change of the output error and state variables (Isermann, 2006). He also throws light on state estimation with Kalman filters for noisy processes. The author tries to establish similarities between the parity equations and observer-based methods by showing comparison of the computational form of the residual equations and simulations. Part III of the book is focused on most important fault diagnosis techniques including classification and inference methods. Figure 2.3 shows survey of fault diagnosis methods discussed in this part of the book.

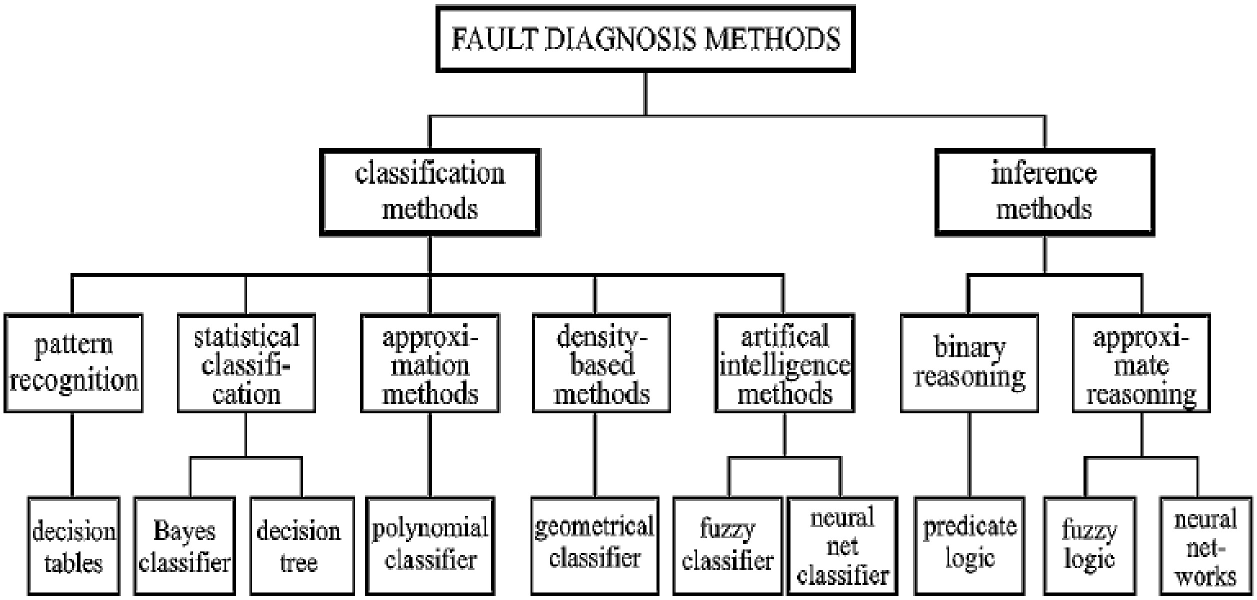

Figure 2.3: Survey on fault diagnosis methods (Isermann, 2006)

Gas turbine performance declines with degradation of the gas path components. The common causes of the performance deterioration include compressor fouling, wear tear of blade tips and erosion, foreign object damage, component damage resulting in drop in efficiencies, corrosion etc. (Li, 2002). In (Urban, 1975), the author describes use of degraded performance measurements to detect, isolate and accommodate the component faults and are shown in Figure 2.4.

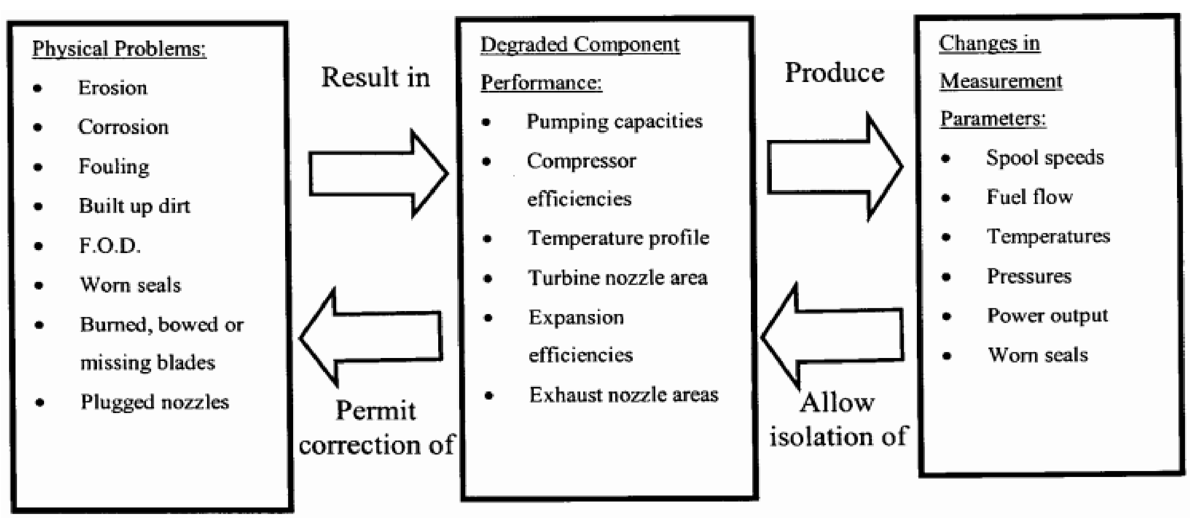

Figure 2.4: Gas Turbine Fault Diagnosis Approach (Urban, 1975)

In (Li, 2002), the author presents a review on performance-analysis based gas turbine diagnostics. By reviewing the previous researches on the subject, the writer tries to establish the differences between different diagnostic methods. According to him, the linear and non-linear model-based methods have clear physical meaning while non-model based methods, like neural networks and rule based expert systems are generated with experimental knowledge. In addition to this, the writer also states that artificial intelligence methods are more complicated than model-based approach. Model based fault diagnosis to perform fault diagnosis by means of models was discussed in dissertation by (Nyberg, 1999). The importance of the use of models for fault detection systems was elaborated. The author discussed design of linear residual generators and fault detectability analysis. A general framework, for describing and analyzing diagnosis problems, was proposed. Within this framework a diagnosis method structured hypothesis tests was developed. It was based on general hypothesis testing and the task of diagnosis was transferred to the task of validating a set of different models with respect to the measured data. The procedure of deriving the diagnosis statement, i.e. the output from the diagnosis system, was in this method formalized and described by logic. Arbitrary types of faults, including multiple faults, could be handled, both in the general framework and also in the method structured hypothesis tests. It was shown how well-known methods for fault diagnosis fit into the general framework. Common methods such as residual generation, parameter estimation, and statistically based methods could be seen as different methods to generate test quantities within the method structured hypothesis tests. Based on the general framework, a method for evaluating and comparing diagnosis systems was developed. Concepts from decision theory and statistics were used to define a performance measure, which reflects the probability of false alarm and missed detections etc. Based on the evaluation method, a procedure for automatic design of diagnosis systems was proposed.

The study carried out in (Pawsey, Rajendran and Pachidis, 2017) focuses on the characterization of turbine overspeed behaviour to be integrated into an engine overspeed model capable of predicting the terminal speed of the high-pressure turbine (HPT) in the event of a high-pressure shaft failure. It is observed from the characteristics that the torque of the HPT rotor decreases with increasing non-dimensional rotational speeds. The HPT mass flow function found to be decreasing initially and then increases with an increase in non-dimensional rotational speed. The intermediate-pressure turbine (IPT) mass flow function initially remains similar and then decreases with increase in rotational speed above values of 150%. In the study it was observed that the HPT rotor torque and IPT mass flow function decrease with rearward movement of the HPT rotor sub-assembly for all values of rotational speed. The high-fidelity characterization of turbines that follows the sequence of events after a shaft failure, as described in this work, can provide accurate predictions of terminal speed and thus act as a tool for testing design modifications that can result in better management and control of the fault regarding over-speed event in gas turbine engines.

In (Zedda and Singh, 2002), a diagnostic system was tested with a large number of cases produced with a Rolls-Royce accurate steady state performance simulation model of two spool, low bypass ratio turbofan engine. The author claims the diagnostic system to be flexible and discusses the tailoring of the optimizer according to faulty sensor measurements. In (Sarkar et al, 2008), a test bed and control system for generic two spool turbofan engine is built. The authors validated the algorithm of fault detection and isolation in this case. In (Palade et al, 1999), neuro-fuzzy techniques in FDI are focused in the paper. The author aims to detect and isolate faults in industrial gas turbine power plants. He also shows concern about how to get interpretable fault classifier for residual generation. The methodology for fault diagnosis, presented in (Isermann, 1993), was based on parameter estimation. The calculation of physical coefficients and symptom-fault tree processing had in several applications proven to give valuable early information on slow and fast developing faults. The author elaborates about the faults that they may appear in the components of a process, including actuators and sensors, in open loop or closed loop operations. The described methods can be applied as well for static as for dynamic linear and nonlinear process behaviour, depending on the specific operating modes of the process. The fault detection and symptom generation by parameter estimation in the study was claimed to have numerous advantages including its suitability for multiplicative faults and detection of small as well as drastic changes. Except in using different steady-state measurements, an input excitation is required in the case of dynamic models.

In (Cai, Ferdowsi and Sarangapani, 2016), the authors addressed a new model-based fault detection, estimation, and prediction scheme for linear distributed parameter systems (DPSs) described by a class of partial differential equations (PDEs). A novel observer based on PDE representation of a DPS was seen to have provided a more accurate estimation of the state which may be beneficial to both fault detection and estimation. The adaptive term incorporated in the observer appeared to estimate the fault function. The time to failure (TTF) can be predicted based on both estimated fault parameters and a failure threshold provided the fault type is known. The filter-based approach found to be quite important when dealing with implementation of the scheme on real practical systems, and it also allowed the estimation of actuator and sensor faults provided that the fault type is given. Theoretical claims were established through simulation results. The authors predicted that the future research may involve fault isolation and extension to other PDEs.

In (Camelia, Matei and Gabriela, 2014), the actuator's faults detection for steam super heaters using residual evaluation has been discussed in detail. The writer develops and simulate model in MATLAB/Simulink. He claims to experimentally verify his work using super heaters models. In (Simani, 2007), the author uses an identification scheme with dynamic observer and Kalman filter designs for diagnostic purposes. The tools proposed by author are analyzed and tested on single shaft industrial gas turbine simulator in presence of disturbances. Residual analysis (errors between estimated and measured variables) and statistical tests are used to detect faults and isolation in (Patton and Simani, 2001). The author also described about non-linear function approximator using a multi-layer perception neural network. In (Abbasfard, 2013) the author tried to develop a linear symbolic representation of the non-linear gas turbine model and used Kalman filters for fault diagnosis. But in contrary to (Abbasfard, 2013), in this research project nonlinear model of the gas turbine to keep the non-linearity of volume dynamics, compressor and turbine behavior throughout the fault diagnostic process. Although author in (Abbasfard, 2013) validates the symbolic linearization of her developed system, but keeping in view the sensitivity of the plant characteristics, we have used the non-linear model itself for purpose of fault diagnosis and isolation.

Summary

This chapter covers the important aspects of the literature dealing with the current study about fault diagnosis, isolation and recovery of the gas turbine engine. The literature review of the current study can be divided into three parts. The first part includes references from the research work carried out in field of mathematical modelling of different systems. The research work about the mathematical modelling reveals diverse ways and strategies of modelling the gas turbine systems. The knowledge about different computer programs especially MATLAB and Simulink play a vital role in modelling the complex systems like gas turbine engines. The second part of the review deals with designing control system for gas turbine engine. This part covers important references from the literature that are helpful in designing non-linear control for gas turbine engine for the subject study. It especially focuses on using PID controlling strategies for design of gas turbine control systems. The third and last part of the literature includes discussion about fault diagnosis, and isolation of gas turbine systems in case of different sensor, actuator and component faults. The methods of detection and isolation of the faults has been focus of discussion in this last part of literature review. All the literature reviewed in this chapter provide an insight and framework to carryout work in the current study about FDI of gas turbine engines.

Chapter 3: Mathematical Modelling of Gas Turbine Engine

Mathematical models present the depiction of the system behavior to a set of input values. They are a valuable tool to predict about the system performance without conducting extensive experiments. The physical experiments may require a lot of effort and time in comparison with the mathematical models that can be built using set of mathematical equations describing system dynamics. The simulations obtained after conducting experiments on the models, are a reliable source of investigating the system performance. The simulations may be analyzed and used to make predictions about the system behavior under a specific situation. The models are governed by certain equations and parameters on which the system performance is based (Kulikov and Thompson, 2004).

In case of gas turbine engine, the performance of the moving components i.e. turbomachinery is a matter of major concern. The changes of the parameters during transition from the cold flow (intake and compressor region) to hot flow (combustor, turbine and nozzle area). It is worth noting that it is not very difficult to build the models, but it requires great deal of accuracy to obtain reliable and authentic models of the systems under consideration. The first step in checking reliability of the models is to validate the models against experimental results. In this way, we can actually get the knowledge that models are behaving in exactly the same way as the actual systems do. All the mathematical models have distinct domain and limitations of validity (Ljung and Glad, 1994). The model responses are accurate within those limits and can change from if the model is operated outside those limits. So, knowledge of the performance constraints including operational limits is quite essential in analysis of the mathematical models.

3.1 Purposes of Mathematical Modelling of Gas Turbines

The mathematical models are designed and constructed for certain specific objectives by reducing amount of effort and resources on arrangement of the experimental setups. There are many different purposes for creating a gas turbine mathematical model, such as performance monitoring, fault finding and diagnostics, sensor testing, system/plant identification, and control system. Thus, in order to achieve a successful gas turbine model, a clear description of modelling goals is necessary.

3.1.1 Monitoring the states

One of the aims of creating gas turbine models is monitoring of the different states in the plant e.g. temperatures, pressures, mass flow rates etc. Monitoring of the state is considered to be the fundamental measure for preventive maintenance. It evaluates the gas turbine operation and indicates beforehand about the warning of unforeseen malfunctions that helps operators take the appropriate actions stated in the respective repair schedule (Clifton, 2006). The monitoring of the states during routine operation is quite helpful to avoid the unexpected damages to the engine system. Good health monitoring is also vital to achieve optimum performance from the system. Careful monitoring leads to some important benefits like improved production, time and cost-effective operation of the system etc. Good condition monitoring system should be able to control important parameters of the gas turbines, such as vibrations, temperatures, pressures, number of rotations, mechanical load, lubricating oil level and quality etc. In addition, it must be capable to forecast the future states of the system and prevent undesired trips, as well as fatal crashes.

3.1.2 Fault Diagnosis and Isolation

The gas turbine model can also be used for detection and isolation of the faults in the system. Fault diagnosis is an important tool to recover the systems to normal state before a major loss or damage to the machines or human beings. Therefore, mathematical models may lead towards predictive maintenance of the system along with the preventive maintenance. Troubleshooting is an important and effective tool when operators want to move from preventive maintenance to predictive maintenance to reduce the cost of maintenance (Lee *et al.*, 2017). The mathematical models are used to monitor the system performance to know when an error occurred exactly, what type of it is present, and where it has occurred in the system states.

3.1.3 Validation of the Sensors

The performance data of a system is quite helpful in upgrading future systems. This data can be acquired from the sensors. In gas turbines, the sensors play a vital role in communication of different system states like revolutions/seconds, temperatures, pressures etc. Therefore, in condition monitoring we get all of the performance data through sensors. So, it is quite obvious that the sensors should work correctly to tell about the correct values of the system outputs. If there is anything wrong with the sensor readings, then reliability of the system and human lives are at risk. The gas turbine mathematical models may also be used as sensor validation models. The validated sensors can strengthen automation of the system, providing reliable data for diagnostic and monitoring the system states (Asgari, 2014; Asgari and XiaoQi, 2016).

3.1.4 Identification of the system

Due to the nonlinear and complex nature of the system dynamics in gas turbine engines, the systems may always be difficult to identify. The mathematical models of the gas turbine engines can also be used for system identification purpose. Despite significant research conducted in this field over the past decades, there is still a need for gas turbine models with a greater degree of accuracy and reliability for system identification purposes (Asgari, 2014; Asgari and XiaoQi, 2016).

3.1.5 Control System Design

The models for the gas turbines can be constructed to develop and optimize the control systems. It is obvious that any control system must be efficient enough to calculate the system output by using delicate devices and take the essential remedial measure if value of the estimated data strays from the required value of that parameter (Burns, 2001). The equipment performance in a system is measured by the corresponding sensors and then it may be used to provide feedback to correct the required response. In order to explore and improve the control systems, the dynamic mathematical models have become inevitable in the modern scientific and technical world.

3.2 Approaches to Gas Turbine Modelling

The construction of the mathematical model of a system depends upon the available knowledge about the system dynamics and the tools that are going to be deployed to construct the model. The gas turbine engine models are constructed by keeping in view the thermodynamic relations and constitutive relations for different components operating in the engine. There are many ways to construct the mathematical models of the dynamic systems. Various types of the models have been designed time to time from different approaches and for different purposes. The modelling approaches may be classified into two major categories, namely white box, black box and grey box modelling of the systems. These approaches are discussed briefly in the succeeding paragraphs;

3.2.1 White Box Modelling

This type of modelling approach is used when there is sufficient knowledge about physical parameters of the plant is available. In this case, mathematical equations relating to the dynamics of the system are used to create the model. This model refers to the dynamic equations of the system, which are usually related and nonlinear in their nature (Asgari and XiaoQi, 2016). To simplify these equations to create a satisfactory model, make some assumptions based on ideal conditions, and use of different methods of linearizing the system, is inevitable. There are various programs, such as Simulink, MATLAB which are used for the said purpose. A non-linear mathematical model of a low power single shaft gas turbine engine was created and used by the researcher in (Ailer, Santa and Szederkényi, 2001) to study about loop shaping controls. The fundamental idea was to optimize the dynamic response of the gas turbine engine by use of nonlinear controllers. The model verification was done by open loop simulations and the comparing the results with the experimental data. Similar kind of model was also used by (Asgari, 2014; Asgari and XiaoQi, 2016) to compare it with ANN model of the gas turbine engine. The author in (Yarlagadda, 2010) has also prepared the Simulink model on the similar approach to relate thrust with reduced pressure at the inlet of the gas turbine engine of J85 engine.

3.2.2 Black Box Modelling

The black box modelling approach is used when sufficient information about physics of the plant or system is not available. In this scenario, the goal is to reveal the relationships between the system variables using the received working input and output data from the system characteristics. Artificial neural network (ANN), a subdivision of the artificial intelligence, is one of the major methods of modelling a system as black box (Asgari and XiaoQi, 2016). ANN is one of the rapidly increasing strategies in the field of modelling and simulation in the current era of science and engineering. The fundamental idea behind construction of ANN is to deliver a simplest model of the human brain to solve some of the complex scientific and technical problems in various areas. The example of this type of modelling strategy can be found in the work done by researchers in (Asgari, 2014) and (Asgari and XiaoQi, 2016). In their work, the authors try to deliver and construct models of different types of gas turbine engines for startup and steady state measures by using ANNs. Physics based and ANN based models have been prepared and compared using MATLAB and Neural Networks Tool Boxes.

3.2.3 Grey Box Modelling

The grey box modelling approach can also be used in addition to white box and black box modelling strategies. This type of approach comes into action when a practical model of a system is optimized by using some specific knowledge about the system parameters. In this situation, the practical knowledge may be coupled with the mathematical relations describing the system to enhance the modelling accuracy (Asgari and XiaoQi, 2016).

3.3 Development of Mathematical Model of Gas Turbine Engine

There are mainly two kinds of mathematical relations that describe a system or plant. One of them are static relations and others are dynamic relations. The later describes the changes in the system parameters with change of time. Theses dynamic mathematical relations in combination with certain constitutive relations are used for modelling the gas turbine system (Ailer, Santa and Szederkényi, 2001). The mathematical model of the gas turbine system has been prepared in accordance with thermodynamic equations for the system. The continuity and energy balance equations are used for relations representing gas dynamics in the engine. Mathematical manipulations required to formulate these equations in terms of the chosen variables are given in Appendix A. These relations in simplified manner are used for modelling of each component in gas turbine engine as per the structure and real-time operation. The steady state detailed model of the gas turbine plant at a given operating point helps to comprehend the dynamic behavior of the engine. It also specifies that a non-linear dynamic model is required if we need to capture the dynamic behavior of the gas turbine engine. This non-linear dynamic model can then be used effectively to design non-linear controller to improve dynamic response of the aircraft engine. The intended use of the developed model in current study is to carryout fault detection and isolation in the propulsion units.

Keeping in view the complex nature of working of gas turbine engine, a careful consideration has been given to operation of turbomachinery i.e. compressor and turbine in modelling the gas turbine engine in the present work. The model is expected to perform operation in the same way as a real-time gas turbine engine. Therefore, all aspects of operation of cold and hot flow in the engine are considered in modelling the engine. In the succeeding paragraphs, the modelling assumptions and mathematical equations of the model are discussed in detail.

3.3.1 Modelling Assumptions

Modelling of the complex machinery like gas turbine require deep insight into the working of different components of the system. To avoid the un-necessary errors, certain assumptions are to be made to make analysis of the dynamic systems simple and easy. In the current research study, the mathematical model is developed as per the modelling method and assumptions made by authors in (Ailer, Santa and Szederkényi, 2001). The intended use of the model in the study of (Ailer, Santa and Szederkényi, 2001) was to develop loop-shaping non-linear controller based on the Hamiltonian description of the system.

To design controller and carryout FDI of gas turbine engine in the present study, we need a simplified version of the mathematical model. In order to get a low order dynamic model suitable for control purposes simplifying modelling assumptions may be made. Following are the assumptions considered during modelling of the gas turbine engine;

(a) Physico-chemical parameters are considered to be constant in all major parts of the engine. These properties include specific heat at constant pressure and at constant volume, specific gas constant and adiabatic exponent.

(b) The heat loss (heat transmission, heat conduction, heat radiation) is neglected.

(c) In the intake of the engine a constant pressure loss coefficient (S_I) is assumed. It indicates that the total pressure loss in the intake duct is a fixed percentage of its inlet total pressure (P_0).

(d) The mass flow rate through the compressor is assumed to be constant. It means that $\dot{m}_{cin} = \dot{m}_{cout} = \dot{m}_c$. Moreover, no energy storage has been considered.

(e) The combustor is supposed to be a balanced volume region that indicates that the model may be taken as finite dimensional and the values of the variable parameters within this volume is same in comparison to that at its outlet. Here, the pressure loss (S_{comb}) and efficiency (η_{cc}) has also been assumed as constant.

(f) The mass flow rate through the turbine has also been assumed as constant. It means that $\dot{m}_{tin} = \dot{m}_{tout} = \dot{m}_t$. Moreover, there is no energy storage in turbine as well.

(g) The pressure loss coefficient (S_N) is assumed to be constant in the gas-deflector.

3.3.2 Modelling Equations

The detailed description of all the parameters used for modelling the dynamic system of gas turbine are appended in nomenclature mentioned on initial pages of the thesis. The behavior of the gas turbine engine can be described by thermodynamic equations and parameters. The dynamic and constitutive relations used for modelling the gas turbine system in the current research project are given vide Equation (3.1) to Equation (3.16). The modelling strategy is in accordance with first approximation out of two adopted by author in (Ailer, Santa and Szederkényi, 2001). The mass flow rates through compressor is shown as function of number of revolutions (N) and dimensionless mass flow rate of compressor ($q_{\lambda 1}$). Similarly, mass flow rates through turbine is shown as function of number of revolutions (N) and dimensionless mass flow rate of the turbine ($q_{\lambda 3}$). Dimensionless mass flow rates are calculated as function of number of revolutions and pressure ratio through respective turbo-machinery component. The modelling equations are discussed in detail in the succeeding paragraphs.

$$P_{02} = \frac{P_{03}}{S_{comb}} \tag{3.1}$$

$$P_{04} = \frac{P_{01}}{S_{comb}.S_N} \tag{3.2}$$

Where the values of combustor pressure loss (S_{comb}) and gas deflector pressure loss (S_N) are shown in Table 3.1. Temperatures at the exit of compressor, combustor and turbine are given by the relations described in Equations (3.3) to (3.5).

Table 3.1: Values of parameters used in modelling the gas turbine system (Ailer, 2002)

Quantity	Value	Quantity	Value
$C_{p,air}$	1004.5 J/kg K	γ_{air}	1.4
$C_{p,gas}$	1160.72 J/kg K	γ_{gas}	1.33
$C_{v,air}$	717.5 J/kg K	Q_f	42.8 MJ/kg
$C_{v,gas}$	872.72 J/kg K	I	0.0003 kgm^2
$C_{v,med}$	795, 11J/kg K	V_{comb}	0.006 m^3
R_{air}	287 J/kg K	η_m	0.98
R_{gas}	288 J/kg K	η_{cc}	0.96651
R_{med}	287.5 J/kg K	S_{comb}	0.93739
S_1	0.98879	S_N	0.96687

$$T_{02} = T_{01}[1 + \frac{1}{\eta_c}\{(\frac{P_{02}}{P_{01}})^{\frac{r-1}{r}} - 1)\}] \tag{3.3}$$

$$T_{03} = \frac{P_{03}\,V_{comb}}{\mathrm{m}_{comb}\ R_{med}} \tag{3.4}$$

$$T_{04} = T_{03}[1 - \eta_T\{1 - (\frac{P_{04}}{P_{03}})^{\frac{r-1}{r}}\}] \tag{3.5}$$

Mass flow rate through compressor and turbine is given by Equation (3.6) and (3.7) respectively;

$$\dot{\mathrm{m}}_c = K_1\,\mathrm{q}_{\lambda 1}\,\frac{P_{01}}{\sqrt{T_{01}}} \tag{3.6}$$

$$\dot{\mathrm{m}}_T = K_2\,\mathrm{q}_{\lambda 3}\,\frac{P_{03}}{\sqrt{T_{03}}} \tag{3.7}$$

The values of the constants K_1 and K_2 have been calculated from the air and gas properties (Ailer, 2002) and are shown in Table 3.1. The dimensionless mass flow rates of compressor ($\mathrm{q}_{\lambda 1}$) and turbine ($\mathrm{q}_{\lambda 3}$) are given by the following functions;

$$\mathrm{q}_{\lambda 1} = f(\frac{P_{02}}{P_{01}}, N_{corr}) \tag{3.8}$$

$$\mathrm{q}_{\lambda 3} = f(\frac{P_{03}}{P_{04}}, N_{corr}) \tag{3.9}$$

The equations governing the relations in the above-mentioned functions of dimensionless mass flow rates can be written as;

$$q_{\lambda 1} = a_1 \frac{N}{\sqrt{\frac{T_{01}}{288.15}}} \frac{P_{02}}{P_{01}} + a_2 \frac{N}{\sqrt{\frac{T_{01}}{288.15}}} + a_3 \frac{P_{02}}{P_{01}} + a_4 \tag{3.10}$$

$$q_{\lambda 3} = c_1 \left(K_3 \frac{N}{\sqrt{T_{03}}}\right) \frac{P_{03}}{P_{04}} + c_2 \left(K_3 \frac{N}{\sqrt{T_{03}}}\right) + c_3 \frac{P_{03}}{P_{04}} + c_4 \tag{3.11}$$

The isentropic efficiencies of the compressor (η_c) and turbine (η_T) are given by the following equations;

$$\eta_c = b_1 \frac{N}{\sqrt{\frac{T_{01}}{288.15}}} q_{\lambda 1} + b_2 \frac{N}{\sqrt{\frac{T_{01}}{288.15}}} + b_3 q_{\lambda 1} + b_4 \tag{3.12}$$

$$\eta_T = d_1 \left(K_3 \frac{N}{\sqrt{T_{03}}}\right) \frac{P_{03}}{P_{04}} + d_2 \left(K_3 \frac{N}{\sqrt{T_{03}}}\right) + d_3 \frac{P_{03}}{P_{04}} + d_4 \tag{3.13}$$

The value of the constant K_3 is measured by using gas properties in the engine (Ailer, 2002) and is shown in Table 3.2. From above equations, it is clear that in this model, efficiency of compressor and turbine is calculated as a function of corrected RPM and pressure ratio against the corresponding turbo-machinery component. The values of the constants a, b, c and d are given in Table 3.2.

Table 3.2 : Values of Constants used in modelling Equations (Ailer, Santa and Szederkényi, 2001)

I	a_i	b_i	c_i	d_i
1	0.00035319	-0.00059576	-0.03248	0.144
2	0.0011097	0.00028848	0.0018218	0.0021314
3	-0.4611	0.5265	0.047843	-0.19685
4	0.16635	0.42051	0.16026	1.07

The dynamic equations have been transformed into intensive variable form to contain the quantities that can be measured. The set of transformed differential balances is shown in Equations 3.14, 3.15 and 3.16, that include dynamic mass balance in combustion chamber, pressure form of the state equation derived from internal energy balance in combustion chamber and intensive form of overall mechanical energy balance for number of revolutions in gas turbine engine. Therefore, the gas turbine engine in this study can be represented by only three state variables present in independent balance equations. The final form of the dynamic non-linear equations for modelling is shown below;

$$\frac{dm_{cc}}{dt} = (\dot{m}_c + \dot{m}_f - \dot{m}_T) \tag{3.14}$$

$$\frac{dN}{dt} = \frac{dN}{4\pi^2 IN} \left[\dot{m}_T C_{p,gas} \eta_m (T_{03} - T_{04}) - \dot{m}_c C_{p,air} (T_{02} - T_{01}) - 2\pi \frac{3}{50} N M_{load}\right] \tag{3.15}$$

$$\frac{dP_{03}}{dt} = \frac{P_{03}}{m_{cc}} (\dot{m}_c + \dot{m}_f - \dot{m}_T) + \frac{P_{03}}{T_{03} C_{v,med} m_{cc}} \left[\dot{m}_c C_{p,air} T_{02} - \dot{m}_T C_{p,gas} T_{03} + Q_f \eta_{cc} \dot{m}_f - T_{03} C_{v,med} (\dot{m}_c + \dot{m}_f - \dot{m}_T)\right] \tag{3.16}$$

3.3.3 Use of Simulink for Modelling of Mathematical Equations

Simulink is a software package which is used for dynamic modelling, simulation and analysis of the dynamic systems. In environment of MATLAB Simulink provides graphical user interface for building models as block diagrams using click and drag operations of computer mouse. Library browser of Simulink includes many operations like sinks, sources, linear and non-linear components, mathematical operators, logical operators and connectors etc. Along with these operations there is also an option to have user defined and MATLAB functions to be used in the Simulink model. Each block in Simulink has a special feature and may be used as building block for the model.

The Simulink browser library is used to select the required block for the mathematical model designed in this project. The largely used blocks in constructing the gas turbine engine model include mathematical operators, subsystems, gain, constant, scope, MATLAB function, workspace and sub-systems. The mathematical model of dynamic system of gas turbine engine is shown in Figure 3.2. The detailed model inside the subsystem and MATLAB script used in model are shown in Appendix B-1 and B-2 respectively. The inputs for the system are P_{01}, T_{01}, mass flow rate of fuel ($\dot{m}_f$) and M_{load}. The main outputs for the system include number of revolutions (N) and temperature (T_{04}), while other parameters obtained as result of simulations may also be regarded as outputs of the system (Ailer, Santa and Szederkényi, 2001). The main parts of the gas turbine engine and station numbers associated with different components is shown in Figure 3.1. Model of the engine in Simulink window is shown at Figure 3.2. The mathematical model is simulated in Simulink under ode4 (Runge-Kutta) solver method with a fixed step size of 0.001. The model has also been simulated with other solving method ode1 (Euler) and the responses are found to be similar.

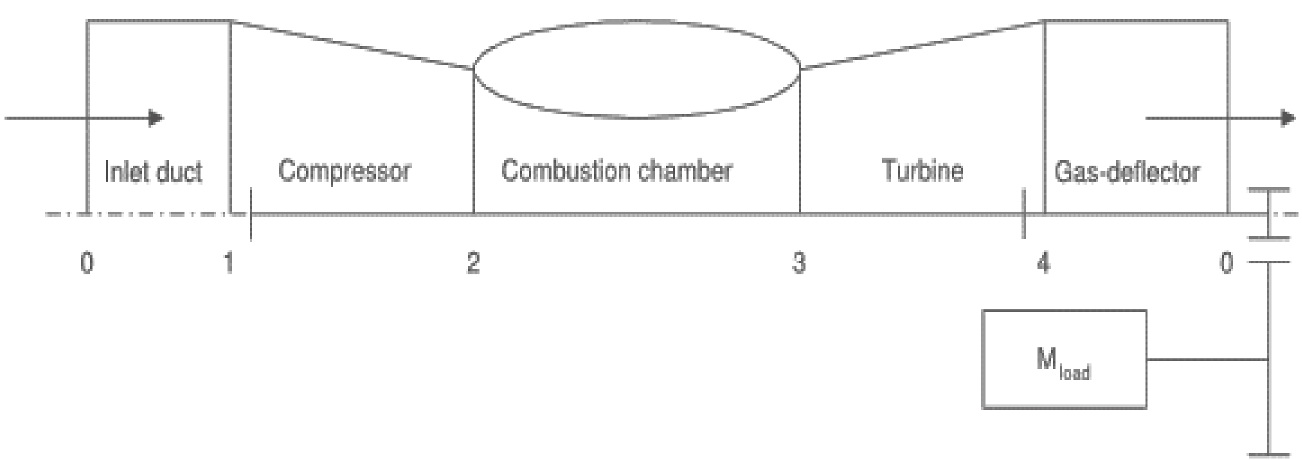

Figure 3.1: Main Parts of a gas turbine Engine (Ailer, Santa and Szederkényi, 2001)

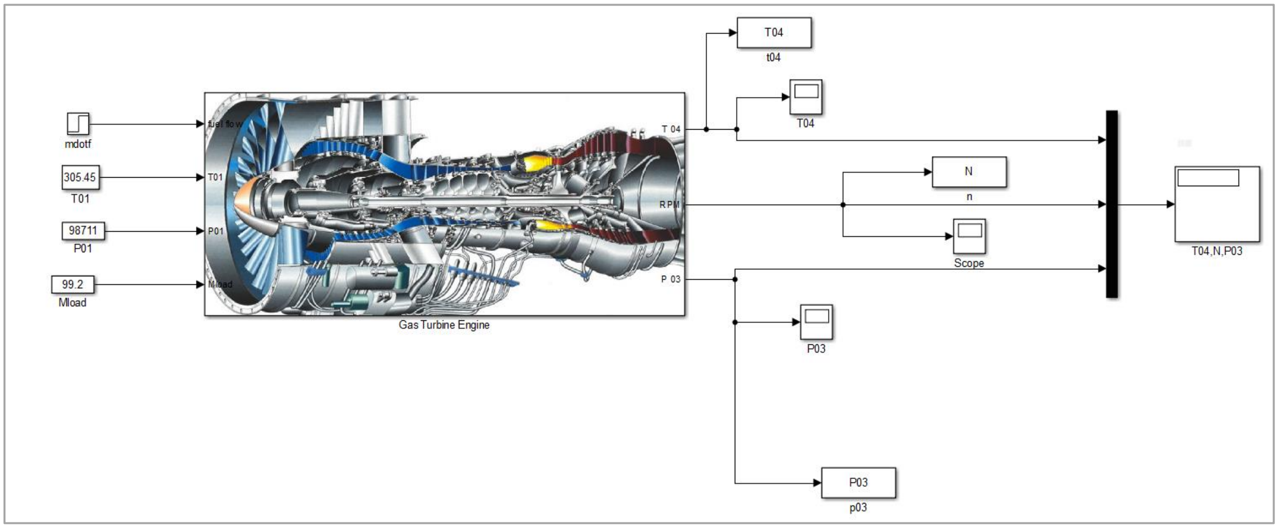

Figure 3.2: Simulink Model of Gas Turbine Engine

3.4 Simulation Results and Validation of the Model

The mathematical model based on thermodynamic and constitutive relations is simulated and the performance of the engine is tested at a typical operating point. The overall behavior of the gas turbine engine in the current study can be described by only three states as discussed in section 3.3. The set of possible disturbances for the engine include T_{01}, P_{01} and M_{load}. Typical values of these input states are taken as 305.45K, 98711Pa and 99.2 N-m respectively for simulating the engine model. Mass flow rate of the fuel is being introduced as a reference value of 0.0119 with addition of step size equal to 0.00119.

3.4.1 Simulation Results

The simulation results of the model for number of revolutions per second, pressure at compressor exit and temperature at turbine exit are shown in Figure 3.3, 3.4 and 3.5 respectively. The gas turbine engine remains stable and the response is up to the engineering expectations. Figure 3.3 shows that the number of revolutions are increasing with time till attaining the maximum value of 846 rev/sec corresponding to the operating point and mass flow rate of the fuel selected for operation. Figure 3.4 indicates the response of total temperatures T_{02}, T_{03} and T_{04} to the selected inputs. It is obvious that temperature at combustion chamber exit must be higher as compared with temperature in other parts and same has been shown by the simulations of T_{02}, T_{03} and T_{04}. Temperature at combustor exit (T_{03}) is higher and becomes comparatively less when the flow of gas is expanded by the turbine, which is clear from the simulation results. Figure 3.5 shows simulation results of the total pressures at compressor and combustor exit. The compressor of the gas turbine engine aims to compress the air in order to have good combustion and hence to get maximum heat energy from the flow. The simulation results clearly indicate that pressure at the compressor exit attains its optimum value and then undergoes a constant pressure loss after passing through the combustion chamber.

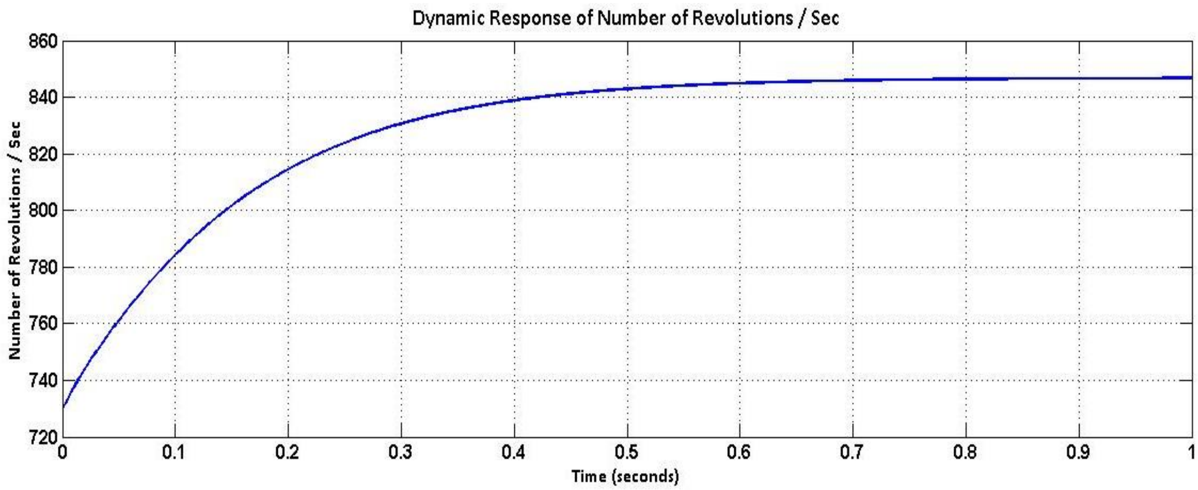

Figure 3.3: Plot showing number of revolutions (1/sec) against time (sec)

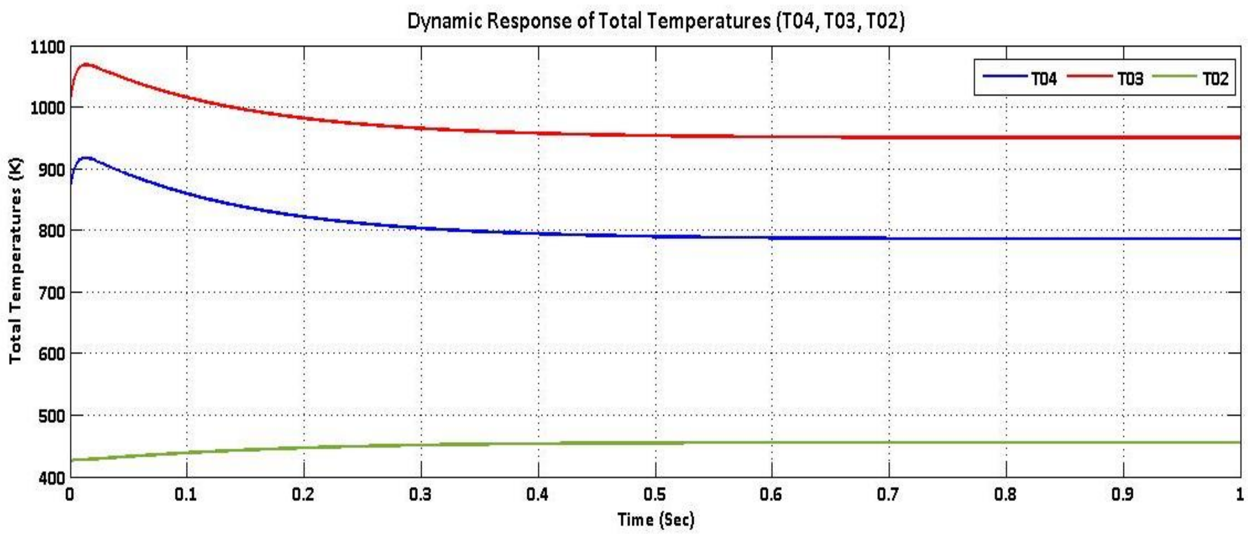

Figure 3.4: Plot showing total temperatures (K) against time (sec)

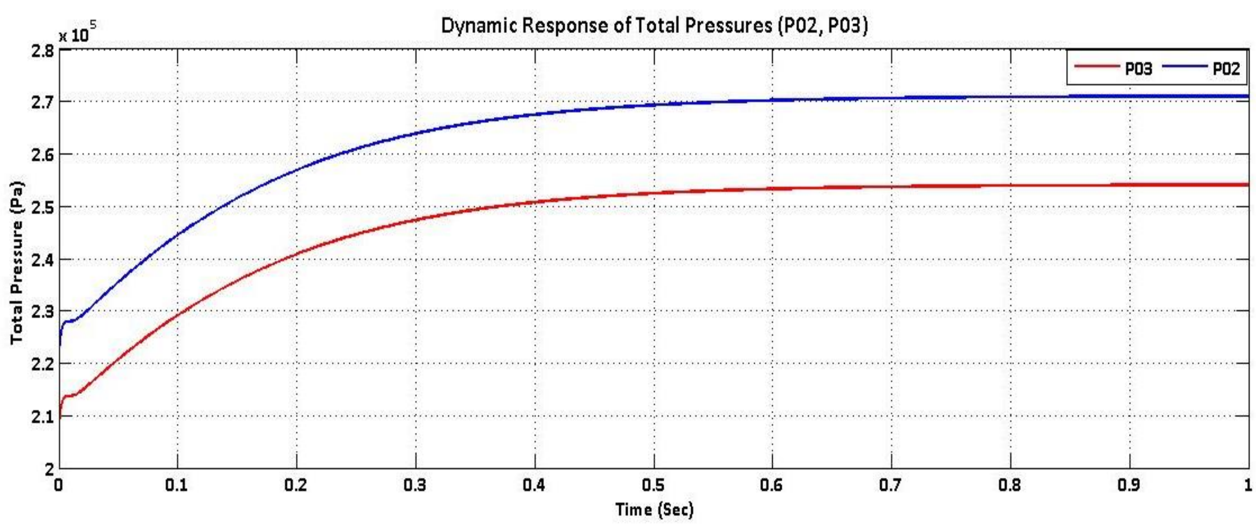

Figure 3.5: Plot showing total Pressures (Pa) against time (sec)

3.4.2 Procedure for Model Validation

The model validation is essential step in mathematical modelling of a system. The validation implies that behaviour of the mathematical model is similar to the physical operation of the plant. Accurate modelling leads towards efficient design of controller for the process. If the model is designed accurately, then controller is expected to perform as per the desired expectations from the system. The key features focused for validation of the model is number of revolutions per second of the engine and turbine exit temperature. In order to validate the model, the visual inspection of the data, also known as analogue matching (Worrall, 2008), is used. The simulation results and published graphs for the same simulations have been compared to validate the results. For numerical validation and to acquire data points accurately, a program tool known as GRABIT is used to acquire numerical data from graphs. It is a program code in MATLAB software that is used to extract data points from an image in either of BMP, JPG, TIF, GIF (up to 8-bit), and PNG file formats. It was created in MATLAB® R13 and has been tested up to R2006a. It starts a graphical user interface program for extracting the data from an image file. Multiple sets of data points may be extracted from a single image file, and the data is saved as an n-by-2 matrix variable in the workspace. It can also be renamed and saved as a MAT file. The screen shots of extraction of data and simulation window are shown Figure 3.6 and 3.7.

Following steps have been taken to extract the data points form the graphs published in (Ailer, Santa and Szederkényi, 2001):

a. The images of the graphs were loaded to the software.
b. Corresponding axes were calibrated by selecting four points on the image.
c. The points were grabbed by clicking on different points on the image.
d. The corresponding data points are compared with simulation data to validate the results of the mathematical model.

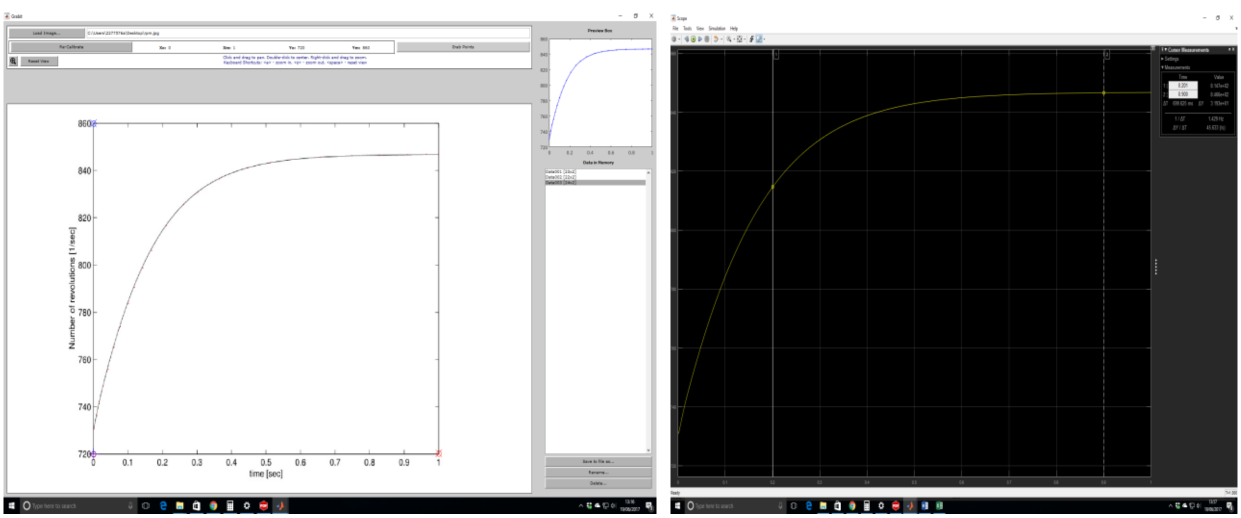

Figure 3.6: Screen shots showing extraction of data points for number of revolutions/sec

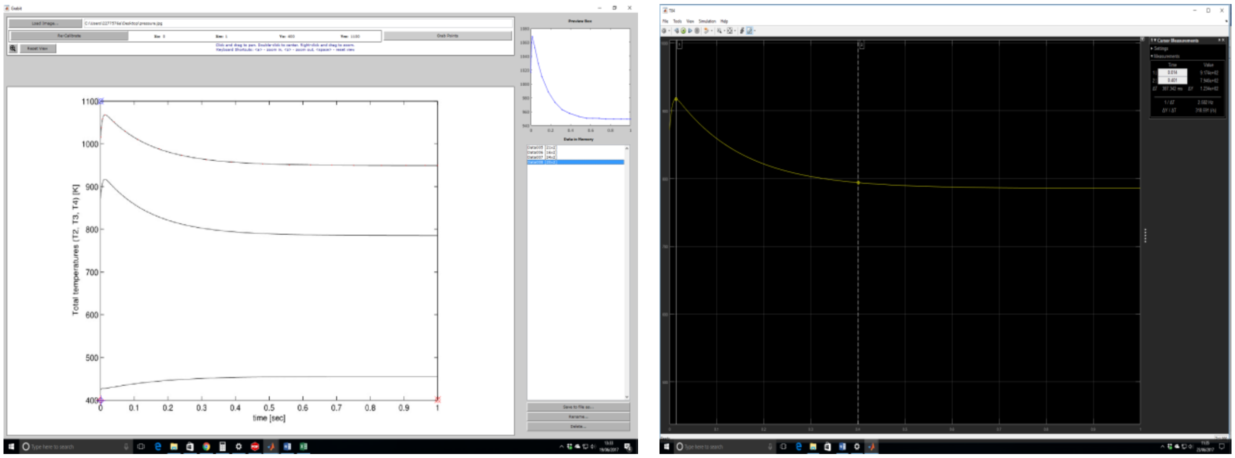

Figure 3.7: Screen shots showing extraction of data points for turbine exit temperature

3.4.3 Model Validation

The data extracted using GRABIT was compared with the data obtained from simulating the mathematical model of gas turbine engine and this data comparison is shown in Table 3.3. The extracted and simulation data is tabulated against time. The close agreement of the values is obvious from Table 3.3. The slight variation in the values may be caused due to sensitivity of selecting the points on image files in GRABIT.

Table 3.3: Comparison of simulation data with reference data

Time (sec)	Extracted Data (Rev/sec)	Simulation Data (Rev/sec)	Difference (Rev/sec)	Extracted Data (T_{04},K)	Simulation Data (T_{04},K)	Difference (K)
0.1	783.76	784.3	0.54	856.41	858	1.59
0.2	814.7201	814.4	-0.3201	819.99	821	1.00
0.3	830.7236	830.4	-0.3236	800.60	803	2.39
0.4	840.0623	839	-1.0623	794.39	793	-1.39
0.5	843.2249	842.9	-0.3249	788.14	789	0.85
0.6	844.4791	844.9	0.4209	787.19	787	-0.19
0.7	846.2378	845.9	-0.3378	785.33	786	0.66
0.8	846.3886	846.4	0.0114	785.28	786	0.71
0.9	846.5438	846.6	0.0562	786.04	786	-0.04
1	846.6931	846.7	0.0069	785.96	786	0.03

The simulation data and reference data for number of revolutions per second is plotted in Figure 3.8 (a). The blue dotted line in the graph represents the reference data and red line shows simulation data points. Both the lines tend to superpose each other that identifies the close agreement of the mathematical model simulations with the reference data published in (Ailer, Santa and Szederkényi, 2001). The similar kind of close agreement has also been found in the results for turbine exit temperature. Figure 3.8 (b) shows graph between simulation and reference data points for temperature T_{04}. The simulation results match with the reference data confirming validity of the mathematical model for future use. The numerical and graphical validation indicate the model reliability to be used in the current research project. The numerical and graphical results regarding system outputs were in good agreement with those discussed in a previously published paper (Ailer, Santa and Szederkényi, 2001).

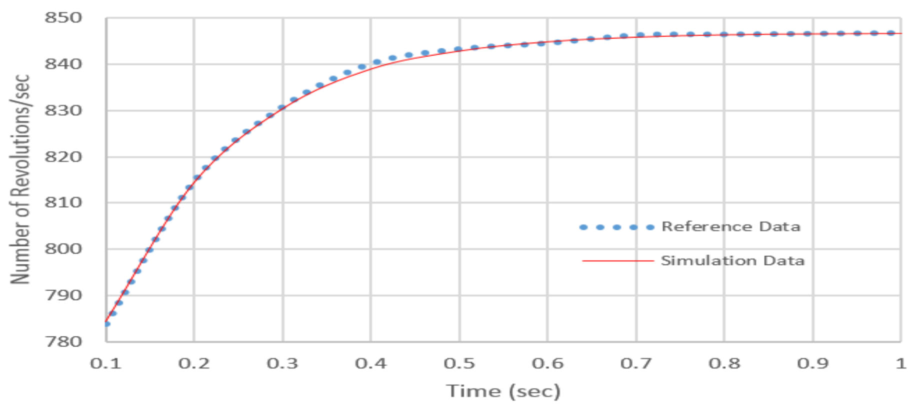

Figure 3.8: (a) Validation of model in case of number of revolutions/sec

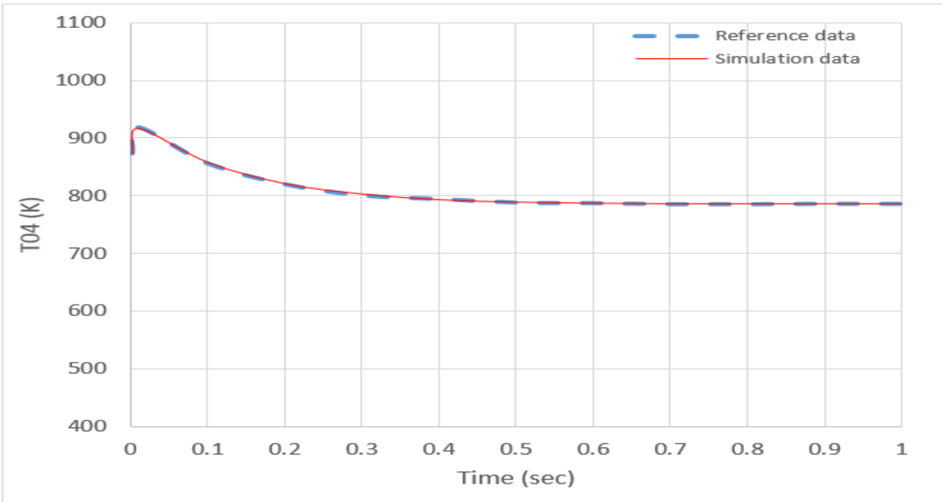

Figure 3.8 (b): Validation of model in case of turbine exit temperature

It can be seen that the response from the developed mathematical model is similar to the test stand data (Ailer, Santa and Szederkényi, 2001) and is found to be within the safe operating range for the gas turbine. The model behaves in the desired manner if limited to design point operation, however, off-design operation of the model still needs to be investigated. The validation of the developed model leads towards its utility for development of the fuel-flow controller and hence FDI studies of the gas turbine system in present study.

Summary

This chapter deals with mathematical modelling of the gas turbine engine. The contents of the chapter include purposes of mathematical modelling, different approaches to mathematical modelling and development of the model for current study. The purposes of mathematical modelling include monitoring the states of modelled system, fault detection and isolation, sensor validation, system identification and designing controller for the system operation. Discussion about different approaches to modelling include white-box, black-box and grey-box modelling strategies. Then design of the mathematical model for the current study has been discussed in detail. The discussion about designing the mathematical model includes modelling assumptions and the equations on which model is based. The behavior of the gas turbine engine, modelled in this study, can be represented by only three state variables present in independent balance equations. That includes dynamic mass balance in combustion chamber, pressure form of the state equation derived from internal energy balance in combustion chamber and intensive form of overall mechanical energy balance for number of revolutions in gas turbine engine. Simulink feature of MATLAB is used to develop the mathematical model. The last part of the chapter includes important aspect of validation of the model by *analogue matching*. The MATLAB program code GRABIT is used to extract data from published plots. The validation of model is supported by simulating model and then plotting simulation results in comparison to the reference data. The graphs and numerical data validates the mathematical model and thus it can be used for future work of the current study.

Chapter 4: Control System for Gas Turbine Power Plant

Gas turbine engines are highly responsive and high-speed pieces of machinery. An example to this effect is aircraft gas turbine, that can attain maximum take-off power from idle state in less than sixty seconds. Without a proper control system, the compressor can go into surge in less than 50 milliseconds (Giampaolo, 2006). Over the previous few decades, the jet engines have been used in a variety of types depending upon their operation and objectives. They may include single/multi spool, single/twin jets, fixed/variable geometry nozzles etc. Regardless of their structure or operational requirements, it is essential to have an automatic control system so that optimum performance may be achieved and possible hazards associated with malfunctioning of different components may be avoided. If a gas turbine engine is considered as a controlled object, there are two kinds of parameters related with its performance. They may be classified as control parameters and controlled parameters (Tudosie, 2011). The output parameters are regarded as controlled parameters like spool speed, combustor's temperature, thrust, fuel consumption etc. The set of gain values is used to control the output parameters and may be classified as control parameters. The input to the system is either input to controller or act as error signal for the controller. In this research work, spool speed (N) is considered as main controlled parameter which is directly related to amount of thrust generated by the engine. The spool speed is being controlled by means of the mass flow rate of fuel ($\dot{m}_f$) provided by the fuel management system within combustion stage of the engine. This control action is achieved by using PID control structure and associated design technique.

4.1 PID Controller

The basic control algorithm in control engineering is PID controller. Majority of the feedback systems are controlled by using this controller. It may be implemented in different forms like a stand-alone controller or as a part of DDC (Direct Digital Control) or a hierarchical distributed process control system (Astrom and Hdgglund, 1995). Idea of using feedback is quite simple but an influential tool to control a process. The principle of feedback is to control the process variable as compared to a set point/reference by manipulating its value. The feedback principle is illustrated by a block diagram in Figure 4.1.

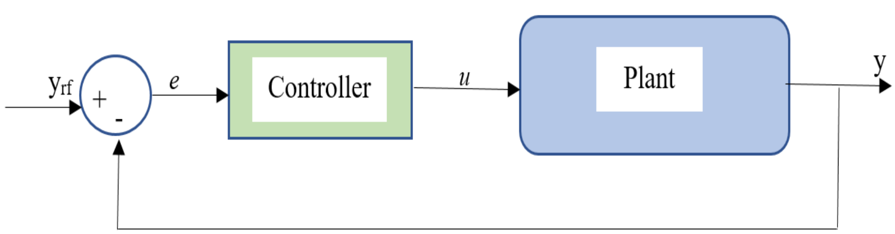

Figure 4.1: Block diagram of a process with a feedback controller

The feedback control system in above-mentioned figure is a simple on-off control. The term $e = y_{rf} - y$ is the control error. This is the simplest control in which no parameters are to be chosen.

But if we look at this feedback system, we can see there is control variable is not defined if error signal is zero. On-off control is successful as it keeps the process variable close to the reference value but it may result in oscillations of the variables. This sort of situation may be avoided by using proportional (P) control in which the characteristics of the controller are proportional to the control error for small errors. The problem with the proportional control system is that they produce static or steady state errors (Astrom and Hdgglund, 1995). The solution for that is to modify the control system by adding I(integral) and derivative(D) terms. This new scheme of control system is known as a PID controller. The integral term integrates the error, and derivative is the amplified component of derivative of error (Azolibe and McGookin, 2015). The diagram of a PID controller is shown in Figure 4.2 and Equation (4.1) show a typical PID control structure;

$$u(t) = K_p\, e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \qquad (4.1)$$

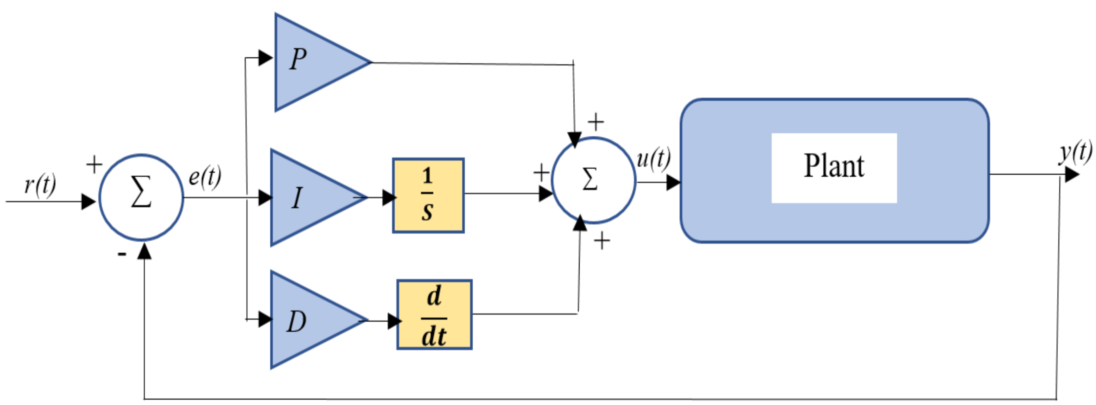

Figure 4.2: PID control structure

4.2 Control of Spool Speed of Engine by using PI Controller

PID control systems are widely used in technical and industrial sector due to their simplest operating algorithm, the simple tuning procedure of control parameter and robust performance (Marzoughi, Selamat and Marzoughi, 2010). Thermal power plants use substantial number of PID controllers in their local control loops. For example, in the combined cycle power plants, which are highly used nowadays due to their enhanced efficiency rating and low atmospheric effects, there are more than 100 PID control structures (Yukitomo *et al.*, 1998). Gas turbine engines are prone to excessively elevated temperatures, enhanced speeds and high-pressure distribution over different components. Another important attribute is that, gas turbines include raised level of automation for start-up, speed control, mechanical loads, synchronization and stop. However, start-up may be considered as the most dominant stage of any control system in gas turbines. The development of the control structures for control of the rotating speed of turbomachinery has been the focal point for many researchers for last many decades. The schematic diagram illustrating the particular feedback and control structure for engine RPM control in the present study is shown in Figure 4.3. The inputs to the system include fuel flow rate from fuel management system, P_{01}, T_{01} and M_{load}. The RPM and T04 are shown as outputs of the system, although other parameters like pressure ratio and efficiencies may also be considered as system outputs.

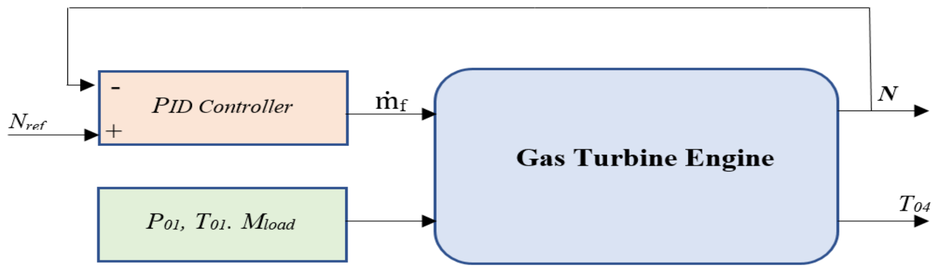

Figure 4.3: Schematic diagram of gas turbine control system

In the present research project, number of revolutions per second of the gas turbine engine are intended to be controlled and hence the thrust of the engine. This is done by controlling the fuel flow rate to the combustor of the gas turbine plant. A simple PI control is used to control mass flow rate of fuel used for combustion purpose. The reason for using the PI control system instead of PID is that the derivative term, along with its many advantages, may cause noise in the system resulting in much complexity for the control system. Thus, in this study PI control is found to be sufficient for controlling the gas turbine engine. The Simulink model of the gas turbine system with PI controller is shown in Figure 4.4 and the model inside subsystem of fuel flow controller is shown in Figure 4.5. The number of revolutions produced by the gas turbine power plant are fed back to the controller and are compared with a reference value of 1200 revolutions/sec. The controller then adjusts the value of the fuel flow rate required by the plant to produce corresponding number of revolutions as per the set point command.

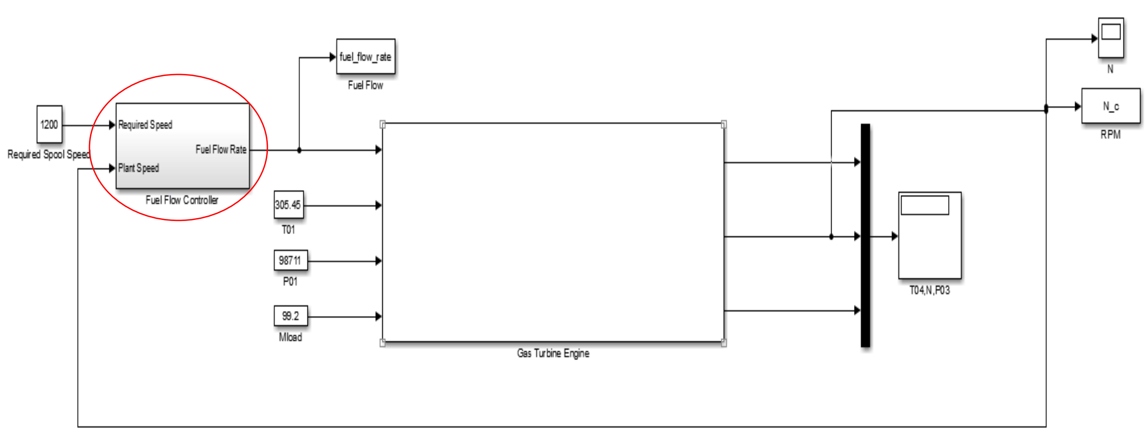

Figure 4.4: Simulink model of PI Control structure for gas turbine fuel management system

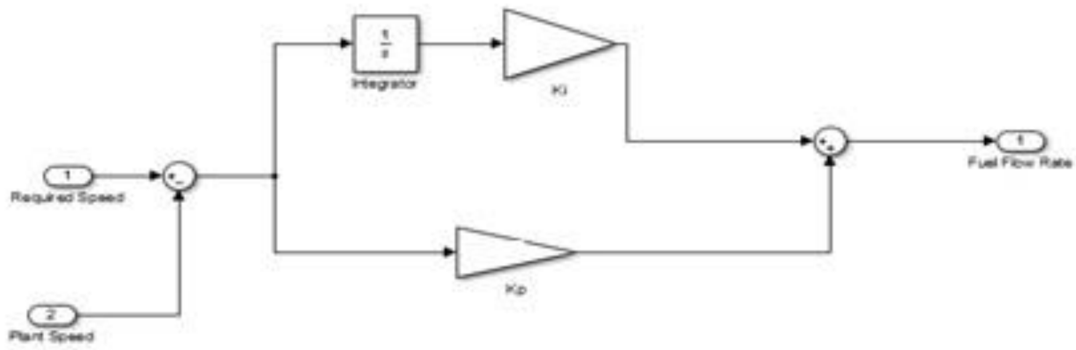

Figure 4.5: Model inside subsystem of Simulink model

4.3 Tuning Results of PI Controller

The fundamental purpose of the control system is to operate our plants in a safe and friendly manner. The design of tuned PI controller achieves the desired results with optimum accuracy. In order to attain the desired control, the gains K_p, K_i and K_d require to be tuned to a suitable value. Tuning is the process of selecting the gains of a PID controller to give the required performance specifications (Worrall, 2008). Various gain values are selected to attain desired response from the control system of the gas turbine engine.

In this study our aim is to obtain the control of number of revolutions per second without any steady state errors and overshoot in the response. For the same purpose, different values of gain (K_p) integral (K_i) terms are tested. Although, the manual tuning of the gains is an exhaustive task (Ogata, 2010), but the in the current study different values of K_p and K_i are tested to tune the controller, some of the tuning results closest to the desired response are shown in Appendix C. It is found that, at K_p=0.0002 and K_i=0.003, the controller response is in desired limits and it generates the required number of revolutions while keeping the system stable. At a time constant of 0.3 sec the system achieves the desired number of revolutions. A comparison of the system simulations with and without controller is shown in Figure 4.6. The MATLAB plot mass flow rate of the fuel going to combustion chamber (with controller) against time is shown in Figure 4.7. In order to enhance the number of revolutions to set point value, the controller provides amount of mass flow rate of fuel at an enhanced rate, that seems logical as far as operations of the gas turbine engine is concerned. The fuel flow rate touches a maximum value of 0.093 kg/sec at time 0.03 sec and then it comes back to lowest value of 0.028 kg/sec at time 0.05 sec. The fuel flow rate adjusts itself to a constant value of 0.032 kg/sec at time 0.3 sec corresponding to required value of number of revolutions. Therefore, we can say that the mass flow rate of fuel has been raised from 0.01309 kg/sec to a value of 0.032 kg/sec for generating required number of revolutions with PI control. Hence, the control system controls the spool speed at a higher rate by providing fuel at an enhanced rate.

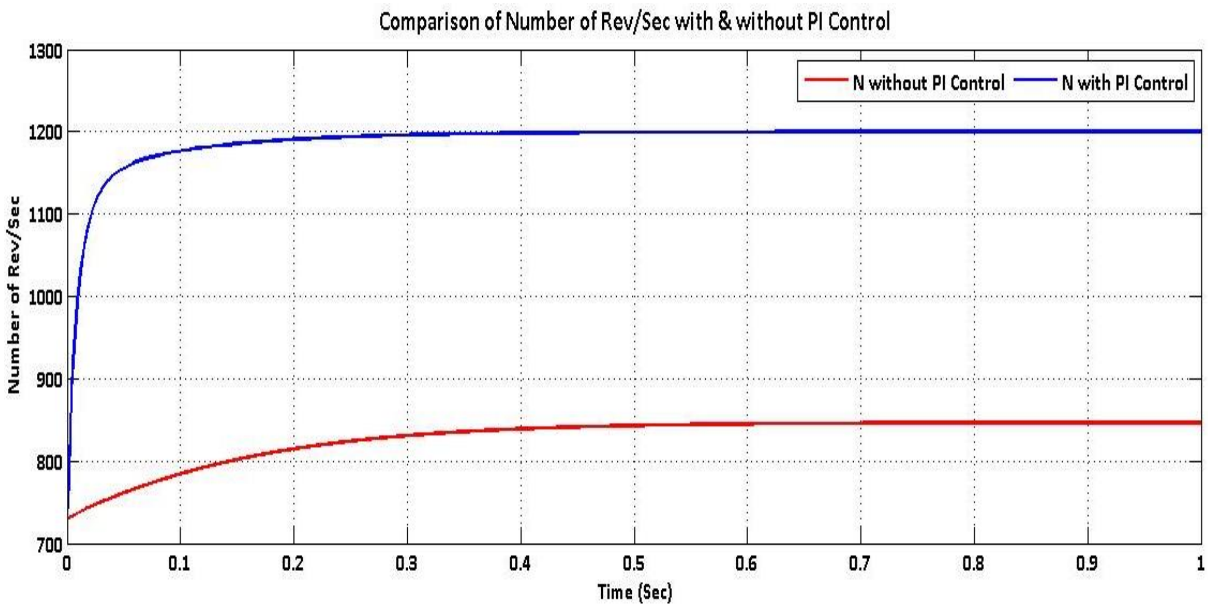

Figure 4.6: Plot showing RPM control by PI Controller

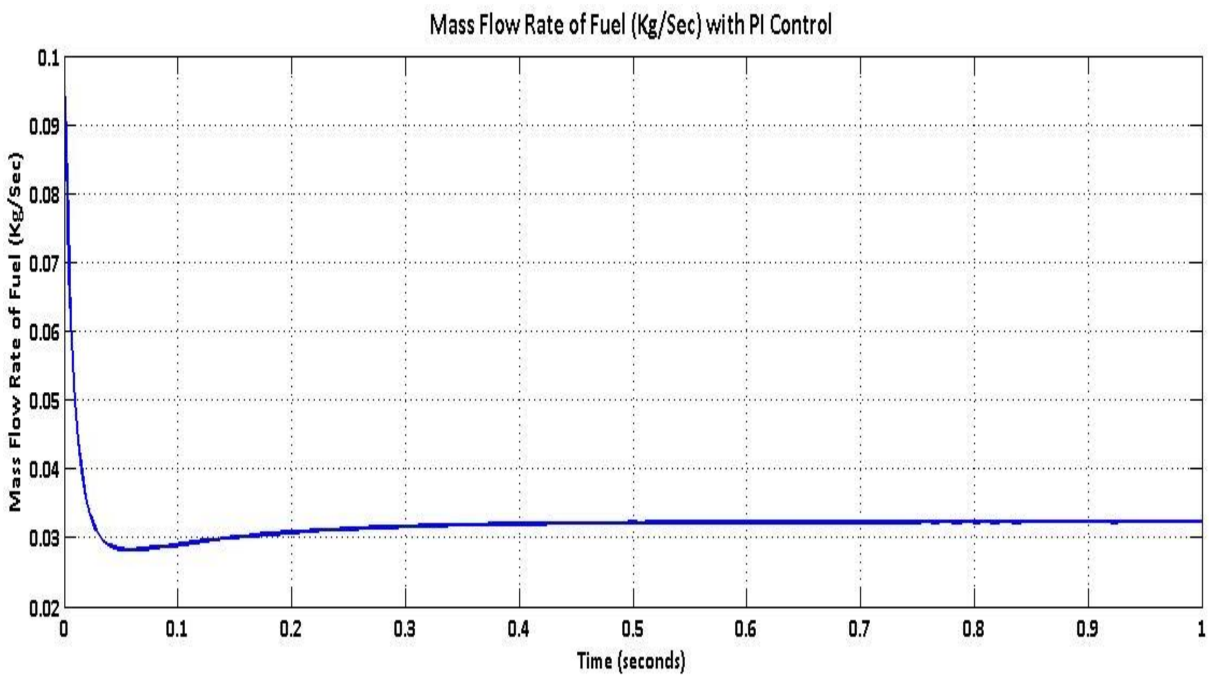

Figure 4.7: Plot showing Fuel Flow rate vs time with PI Controller

In the present study, our primary focus is to control the spool speed at relatively higher number of revolutions per second. However, other important parameters linked with higher rotational speed of the engine, especially the Exhaust Gas Temperature (EGT), also need to be controlled for efficient and safe operation of the gas turbine engine. The increased spool speed leads to surge and stall hazards for the compressor of the gas turbine engine. One of the possible indications of the surge and stall phenomenon may be the raised values of EGT.

Summary

This chapter of the thesis describes the design process of fuel flow control system for gas turbine engine. The chapter starts with description of importance of automatic control systems for complex plants especially the gas turbines. Then a PID control structure is explained by using block diagrams and theory. The main content of the chapter is designing the control structure for RPM control of gas turbine engine. The number of revolutions of engine are controlled by using PI control structure. The reason for avoiding derivative term in the control structure is to avoid noise and wear in the control element. Moreover, the PI control structure is found to be useful in controlling number of revolutions in the current study. This control structure is explained by using block diagrams and Simulink snapshots. The control structure aims to control the spool speed by means of controlling the mass flow rate of fuel provided by the fuel management system within combustion stage of the engine. The control action is achieved by using PID control structure and associated design technique. The tuning of the PID controller is done by varying gains manually to achieve the desired results. The simulation diagrams indicate that control of number of revolutions is attained by providing suitable amount of fuel flow rate. The working of control structure as per the desired response enables to carry out further study about fault diagnosis and isolation of the gas turbine engine.

Chapter 5: FDI System for Gas Turbine engine

The need for gas turbine engine monitoring and diagnostic systems is as old as the gas turbine engine itself, but the practical implementation of the such strategies has had to wait for the relatively modern developments in data sensing, hardware and software techniques(Ogata, 2010). The fault diagnosis in a gas turbine engine begins with identification of a specific condition of aero-thermodynamics, sensor and actuator components of the system. An early and precise diagnosis directly influences the availability of machine for operation and maintenance (Bird and Schwartz, 1994). Need of early detection of faults cannot be overlooked, as existence of faults in the plants may cause huge loss in terms of equipment and human resources (Abbasfard, 2013). The faults must be addressed as quickly as possible so that they may not exist for prolonged hours and deterioration of the systems may be avoided. As far as aircraft gas turbine engines are concerned, they are complex sort of systems involving various components. The operation of these components is interlinked so that if there is malfunctioning of a specific component, it may cause serious effect on performance and output of other components. Therefore, in case of aircraft gas turbine engines, fault detection at early stage becomes inevitable.

A fault in a dynamic system is said to occur if there is deviation of the system states from the pre-defined/safe operational parameters (Abbasfard, 2013). The performance of the entire system may be challenged if there is a single component fault in the dynamics of the plant. Fault detection and isolation (FDI) is a part of control engineering that deals with monitoring a system, diagnosing when a fault takes place and then isolation of that fault within system. FDI techniques may be classified into two main types, that include Model-based and process based FDI. In model based FDI, the mathematical or knowledge based models of the system are used to detect faults. In this research project, the same approach is followed for a gas turbine engine mathematical model. Different authors have worked in this field to devise certain fault detection models to save time and resources over repair or maintenance hours (Li, 2002).

5.1 Significance of Performance Monitoring in Gas Turbine Engines

Modern gas turbine engines are controlled digitally and condition/health monitoring is done online while they operate. New and smart instrumentation is required for this sort of online supervision and monitoring. An example in this context is the pyrometers' use in order to sense metal's temperatures of blade. This is because the metal temperatures of blades are critical concern than exit temperature of the gas. Another example is the diagnosis of surge and other flow instabilities in compressor by using dynamic pressure transducers. In the similar context, blades' high frequency excitation is detected through use of accelerometers, that is quite important thing in prevention of main failures in modern high load gas turbines. Currently, all gas turbines are controlled by controlling the exit temperatures of the turbine stages. The maximum output is expected from the gas turbine operation by controlling the temperatures at nozzle stages and the blades. The early warnings may be obtained about any malfunctioning of the compressor part by using pressure transducers. The pressure measurements at the exit of the compressor ratio is quite significant in controlling the operating margin between surge and choke. In this way, the early warnings from pressure transducers at exit of compressors are quite useful to avoid major failures and further problems related to compressor surge and tip stalls. Similarly, by using the pressure transducers in combustion chamber section, it can be ensured that burning in each combustor is even. This is specifically important for low Nitrogen Oxide combustors. This is done by controlling the flow in every flame tube until the spectrum from all the combustors are similar. This type of method is found to be very effective in efficient operation of the turbine section and plays a pivotal role in enhanced lifetime of the engine (Boyce, 2012).

Condition or health monitoring is not only crucial to have extended lifetimes of the engines, troubleshooting the engine faults and enhancing the intervals between engine repair times; but it can play a key role in savings of the heavy amounts incurred on the fuel consumptions of the engines. Figure 5.1 shows the distribution of the expenditures on life cycle of a gas turbine engine. From the Figure 5.1, it is obvious and interesting factor that the initial cost is about eight percent of the total cost on life cycle of the gas turbine engine, repair or operational cost is about seventeen percent and cost incurred on fuel is approximately seventy five percent (Boyce, 2012). Thus, fuel economy is critical factor in operation of the gas turbine plants, and in order to attain fuel economy and decrease the maintenance costs, early detection of the faults has an important place.

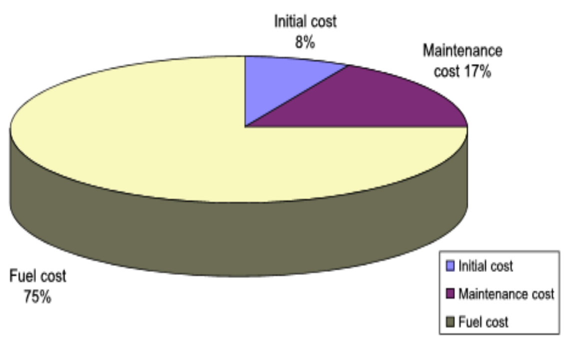

Figure 5.1: Distribution of the expenditures on gas turbine operation (Boyce, 2012)

5.2 Possible Faults Encountered by Gas Turbine Engines

Deterioration in any of the components of the gas turbine engine results in overall performance deterioration of the gas turbine engine (Aslund, Frisk and Eriksson, 2013). Several reasons may cause the overall degradation of the performance gas turbine system. Therefore, supervision and health monitoring of the gas turbine is essential to avoid unforeseen happenings during routine operation of the gas turbine engine. If it is done with precision and accuracy, then the work and maintenance of the plants by service engineers may be simplified at a greater extent. The present mathematical model of the gas turbine engine has been tested for fault diagnosis, isolation and accommodation of these faults. Following three types of faults were implanted in the gas turbine power;

a. *f1*: Sensor Fault (Typically Additive fault in RPM Sensor)

b. *f2*: Actuator Fault (Decrease / Increase in mass flow rate of fuel)
c. *f3*: Foreign Object Damage (FOD) indicating Compressor Efficiency Loss

The faults are implanted in the gas turbine engine mathematical model and it is being used as 'faulty plant' here. The mathematical model of gas turbine engine with fuel flow controller developed in chapter 3 & 4 of the current research project has been considered as 'healthy model' for the subject study of fault diagnosis. The faults are implanted using Simulink/MATLAB.

5.3 Fault Detection using Residual Analysis

There are numerous ways used to detect and isolate faults in the gas turbine systems. One of these strategies is comparison of the plant performance with a mathematical model of the same plant. In this method, the variation in outputs of the plant is recorded in contrast to model outputs. This method is known as method of *residuals*. The residuals are said to be differences between predicted output from model and the measured output from validation data set (Avram, 2012). Thus, the residuals are the differences between faulty and normal operation of a plant. They are variables having zero or nearly zero values under normal operating conditions. The residuals may deviate from zero in normal working condition just due to uncertainties in the modelling procedure (Abbasfard, 2013). It may be said that residuals actually show the consistency of the plant outputs with those of the model (Camelia, Matei and Gabriela, 2014). When we compare a faulty system/plant with an observer mathematical model of the same plant (healthy system), the portion of validation data that is not explained by the model is called residual. The block diagram of model based fault diagnosis architecture using residual analysis is shown in Figure 5.2.

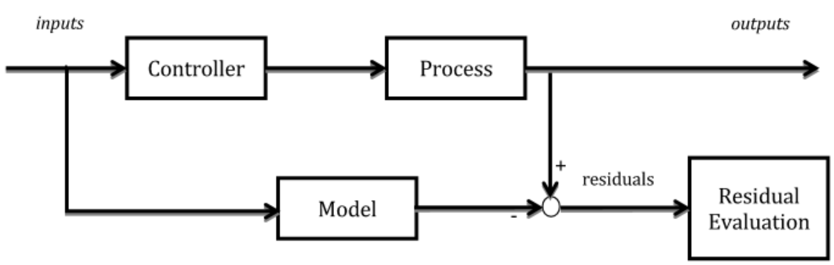

Figure 5.2: The output error residual in model based Fault Diagnosis (Avram, 2012)

The residual evaluation may be divided into two types, the whiteness test criteria and independence test criteria. The whiteness test criteria describe that a good model has the residual autocorrelation function inside the confidence interval of the related estimates, that leads to the fact that residuals are uncorrelated. It means that the whiteness test computes errors, that are left over after a model is fitted. The independence criteria explain that in a good model the residuals are uncorrelated with past inputs. Thus, the evidence of correlation depicts that model does not describe how part of the output relates to the corresponding input (Avram, 2012). In this study about FDI of gas turbines, the residuals are evaluated for the possible faults and then based on this analysis a comparison is made about detection of the corresponding faults. The nomenclature used for residuals analysis in current study is shown in Table 5.1 below.

Table 5.1: Residuals' Nomenclature

Residual Symbol	Output Parameter
r1	Number of Revolutions
r2	Temperature at compressor exit (T_{02})
r3	Temperature at Combustor exit (T_{03})
r4	Temperature at Turbine exit (T_{04})
r5	Pressure at compressor exit (P_{02})
r6	Pressure at combustor exit (P_{02})
r7	Mass flow rate of compressor ($\dot{m}_c$)
r8	Compressor efficiency (η_c)
r9	Turbine Efficiency (η_T)
r10	Compressor Pressure Ratio

5.3.1 Additive Fault in RPM Sensor (*f1*)

The fault in RPM sensor was implanted as additive fault. The value of number of revolutions per second was decreased in regular intervals and the output of different parameters of the faulty plant was compared with the outputs of the healthy model. The deviation of the plant parameter values from the healthy system have been recorded as residuals. The mathematical model for FDI evaluation in case of *f1* is shown at Appendix D-1 and its simulation results are shown in Figures 5.3 and 5.4 (a & b). It is evident from the Figure 5.3 that when the spool speed is wrongly read by the sensor as -80 rev/sec less than the actual one then the residual *r1* in spool speed is deviated from zero at t=0.3 sec that indicates existence of fault in the RPM sensor readings. We can also see that all other residuals are in '0' state that indicate that they are not affected at all by existence of fault in the sensor readings. The zero residuals, after occurrence of the fault, in all other parameters of the engine are evident from simulations shown in Figures 5.4 (a) and 5.4 (b). Therefore, we can say that in case of the wrong sensor readings the fault is not communicated in the internal structure of the engine, but these false readings can be hazard for the system parameters as far as protection mechanism is concerned.

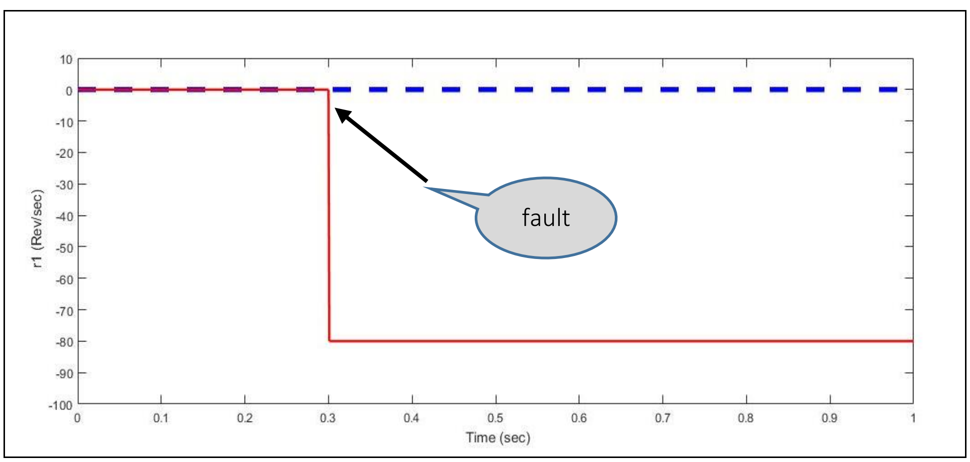

Figure 5.3: Residual plot of r1(spool speed) in case of f1

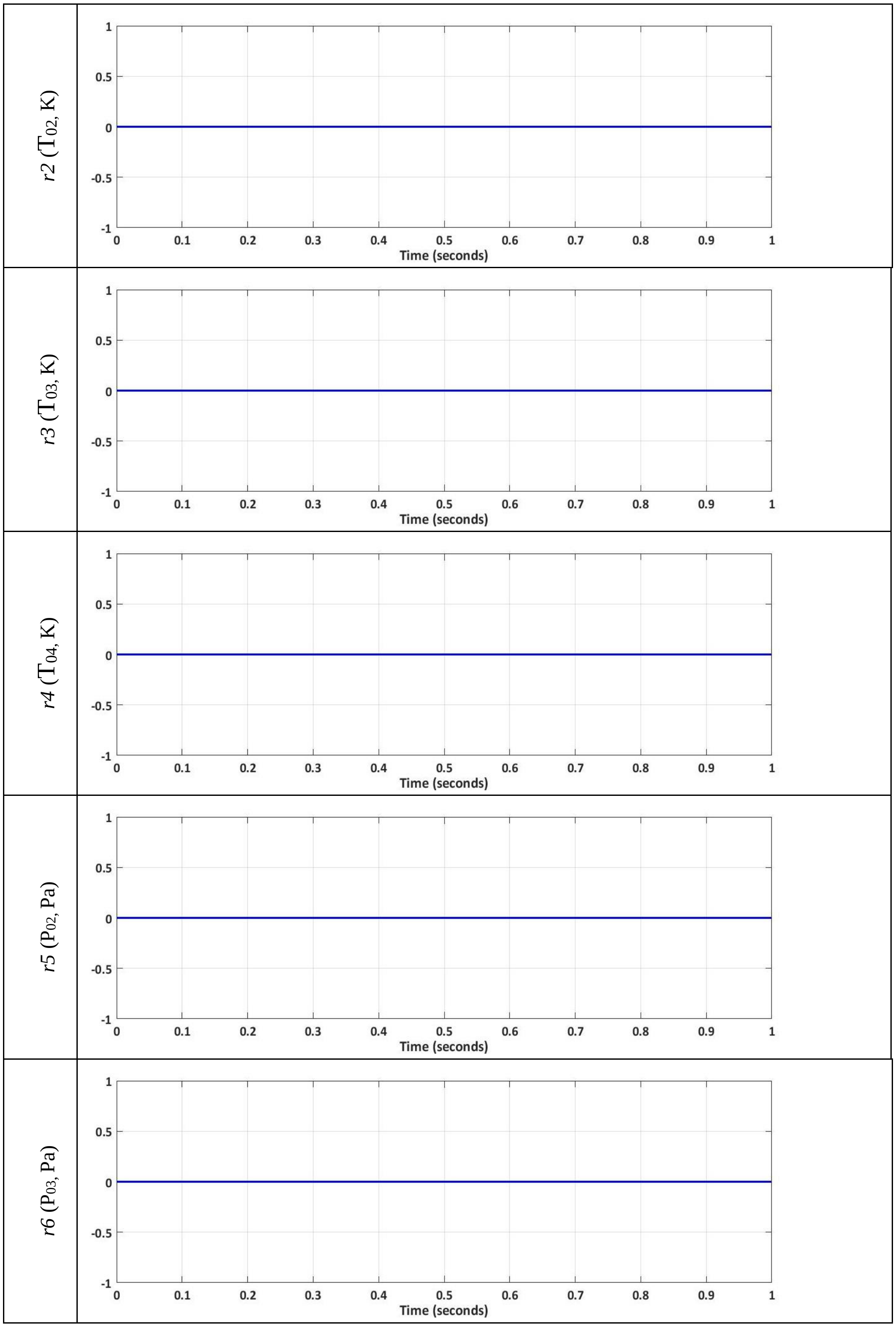

Figure 5.4(a): Residual plots (r2 to r6) in case of f1(-80 rev/sec)

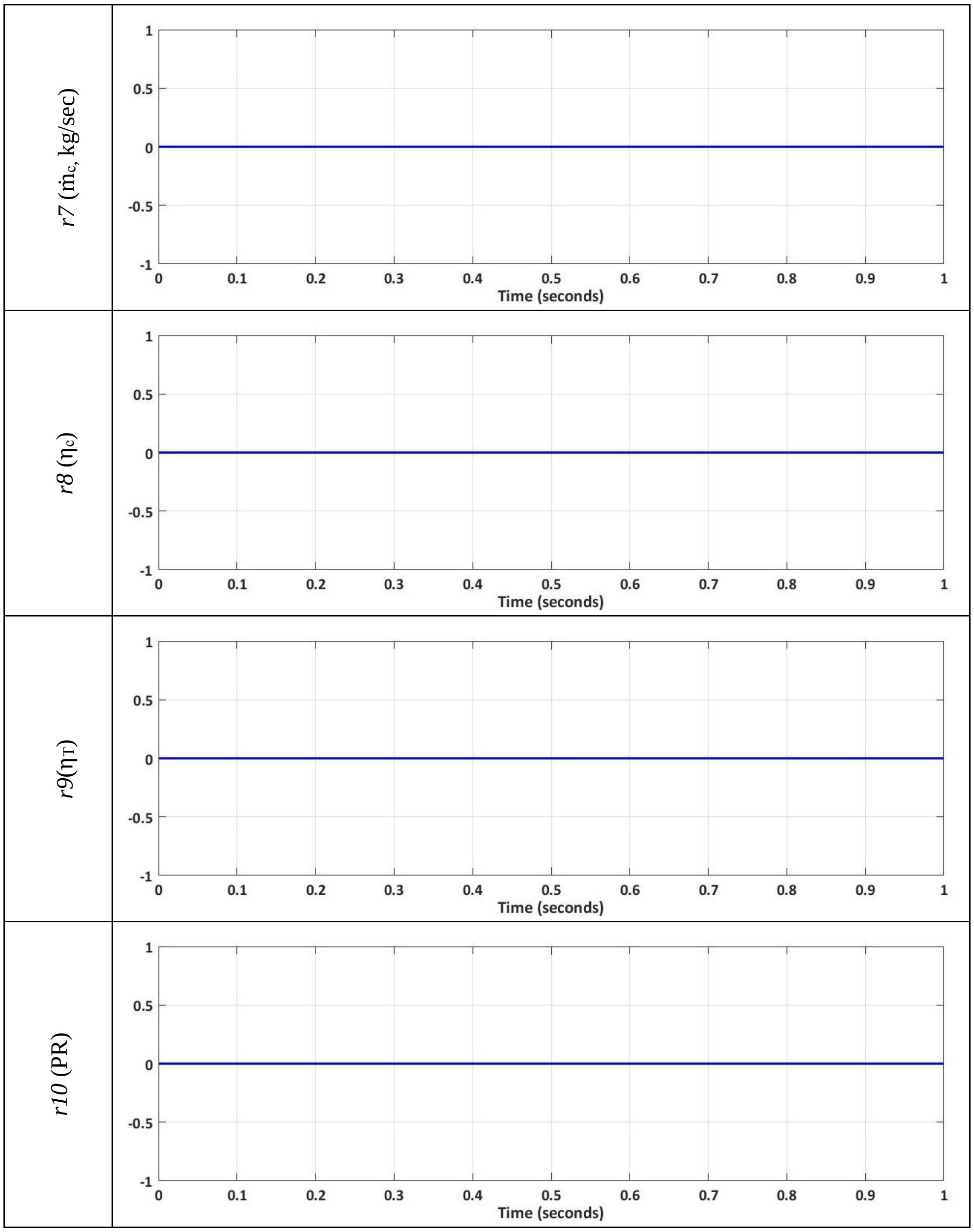

Figure 5.4(b): Residual plot (r7 to r10) in case of f1 (-80 rev/sec)

5.3.2 Variation in Mass Flow Rate of Fuel (*f*2)

The actuator fault in the present project is incorporated by varying mass flow rate of the fuel in mathematical model of the gas turbine engine. The addition or subtraction of the fuel flow rate values is done by using additive fault techniques. The actuator fault is implanted as additive fault in fuel flow rate at time 0.3 sec. The fault is further subdivided into *f2a* and *f2b* that represent decrease and increase in fuel flow rate respectively. The actuator blockage may cause *f2a*, in which the mass flow rate of the fuel has been decreased in percentage to the normal value of fuel flow rate in healthy state. In case of *f2b*, the mass flow rate of the fuel in enhanced in percentage to the normal value. The responses of the faulty plant are compared with that of healthy observer model in terms of residual analysis. The FDI model for fault *f2* is shown in Appendix D-2. The Simulation results for *f2a* and *f2b* are shown in Figures 5.5 and 5.6 (a & b).

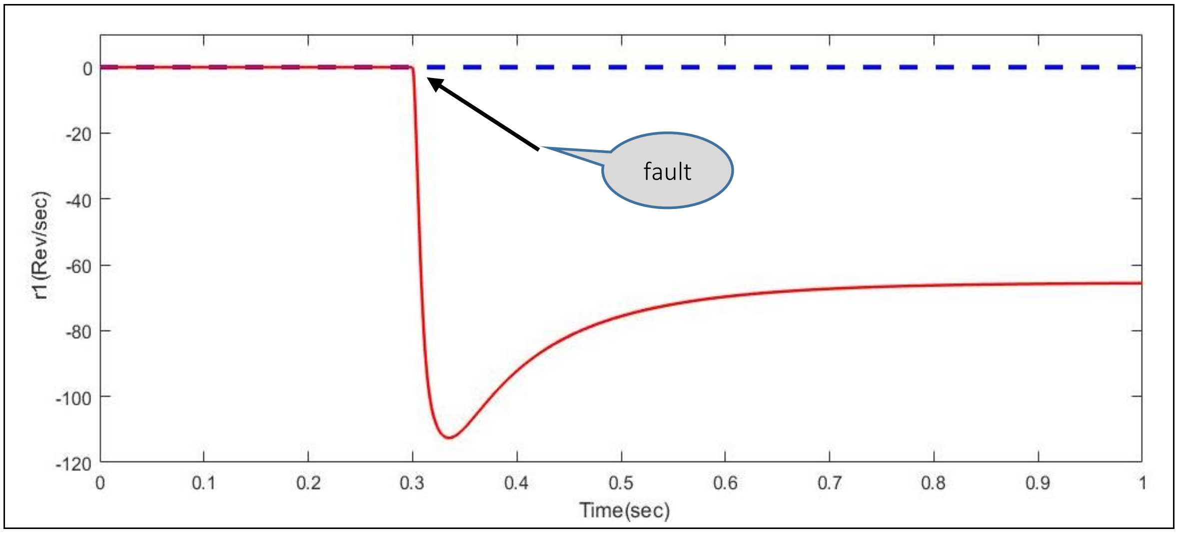

Figure 5.5: Fault detection through residual plot of r1(spool speed) in case of f2a (-78.13% in $\dot{m}f$)

The simulation results in Figures 5.5 and 5.6(a &b) show that in case of fault regarding decrease in mass flow rate of the fuel, the residuals *r2*, *r3, r4*, *r5*, *r6*, *r7*, *r8* and *r10* are decreasing while *r8* and *r9* are found to be increasing. The decrease in number of revolutions and pressure ratio is one of the consequences of such fault. On the other hand, the existence of fault regarding increase in mass flow rate of the fuel by 50% of the actual value, is evident from Figures 5.7 and 5.8 (a & b). The simulation results shown in Figure 5.8 (a & b) show that the residuals *r2, r3, r4, r5, r6, r7, r8* and *r10* are increasing while *r8* and *r9* are found to be decreasing with increase in fuel rate in combustion chamber. It can be seen that during *f2b*, the fault affects the spool speed, total temperatures, pressures, efficacies and pressure ratio of the gas turbine engine. The enhanced fuel flow rate also demands more mass flow rate through the compressor as well as indicated in Figure 5.8 (b). On the contrary, in case of *f2a* i.e. decrease in the fuel flow rate, the mass flow rate of air through the compressor is found to be decreased than in normal operation and it is evident from Figure 5.6 (b).

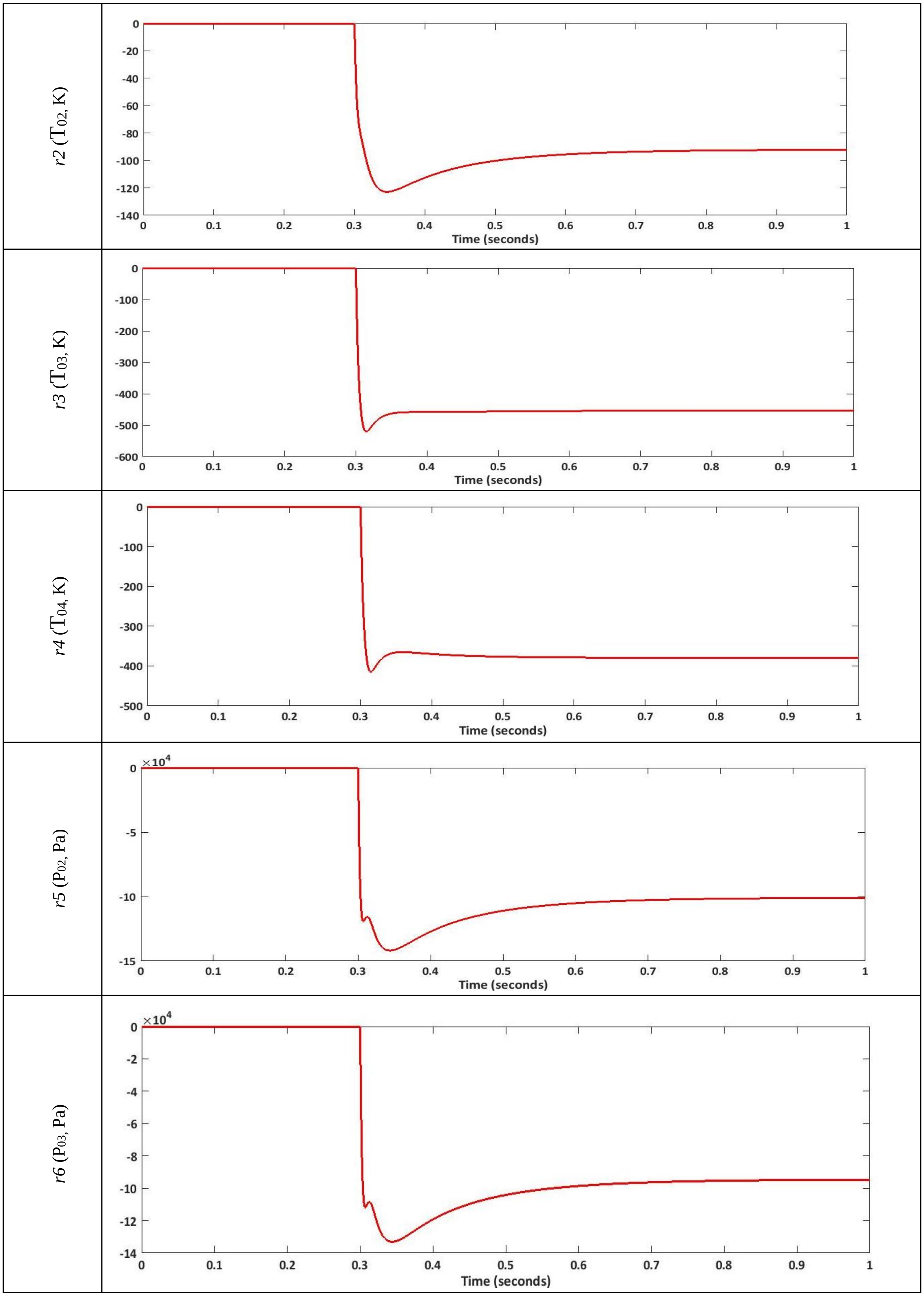

Figure 5.6(a): Residual plots (r2 to r6) in case of f2a (-78.13% in ṁf)

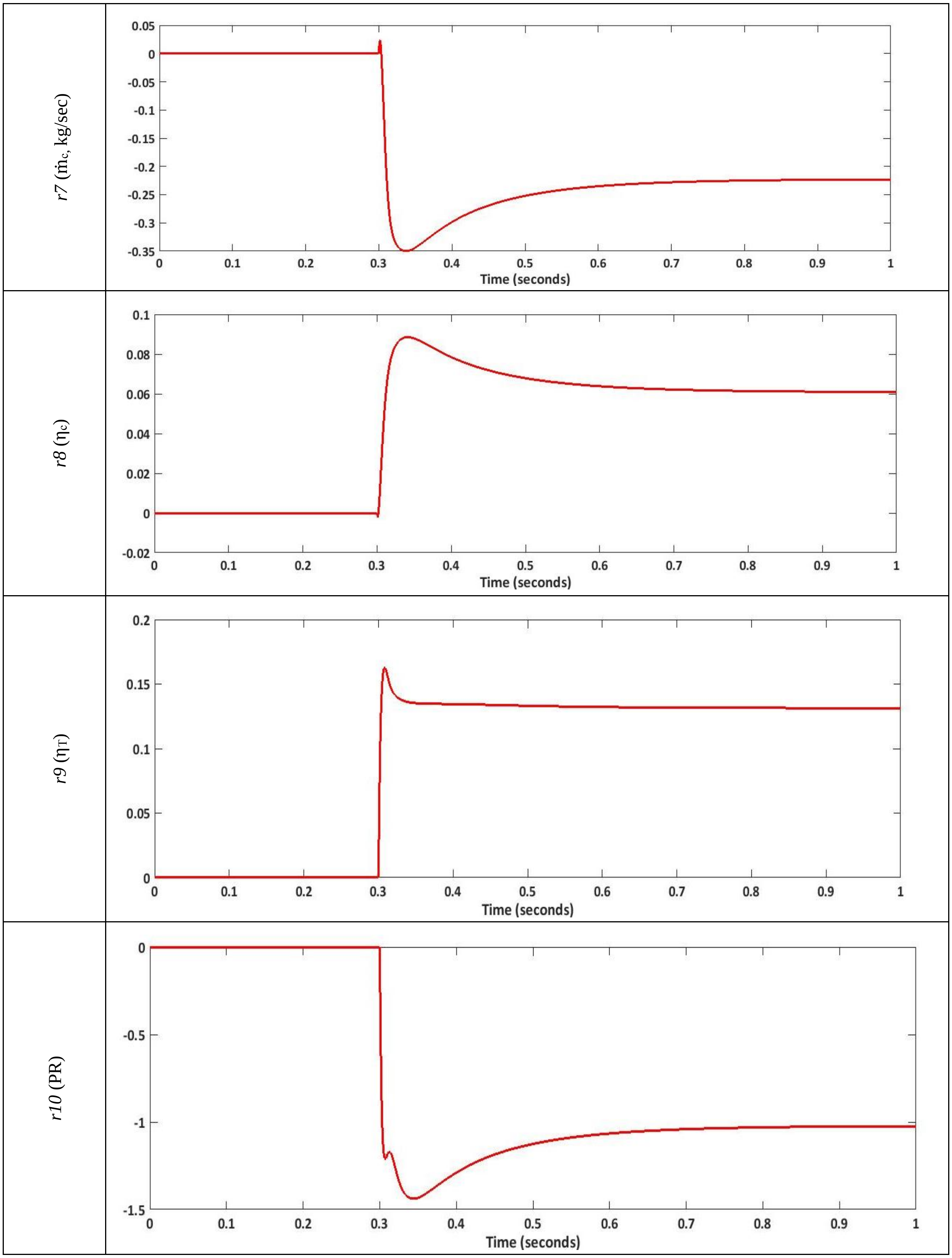

Figure 5.6(b): Residual plots (r7 to r10) in case of f2a (-78.13% in ṁf)

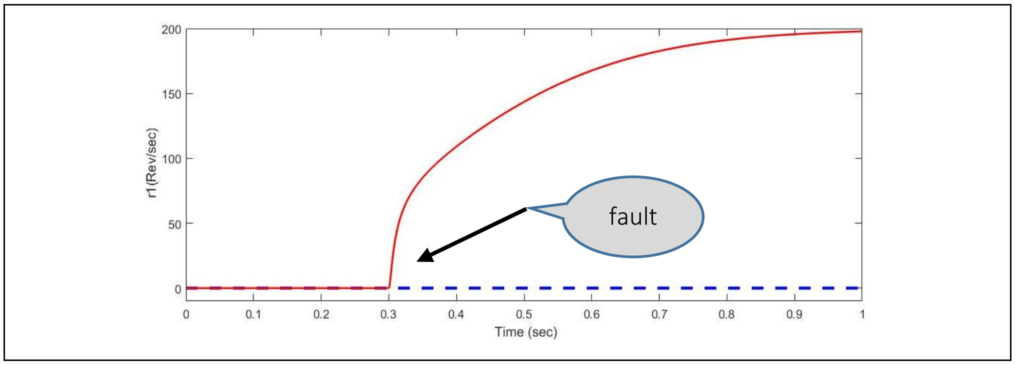

Figure 5.7: Residual plot of r1(spool speed) in case of f2b (+50% in ṁf)

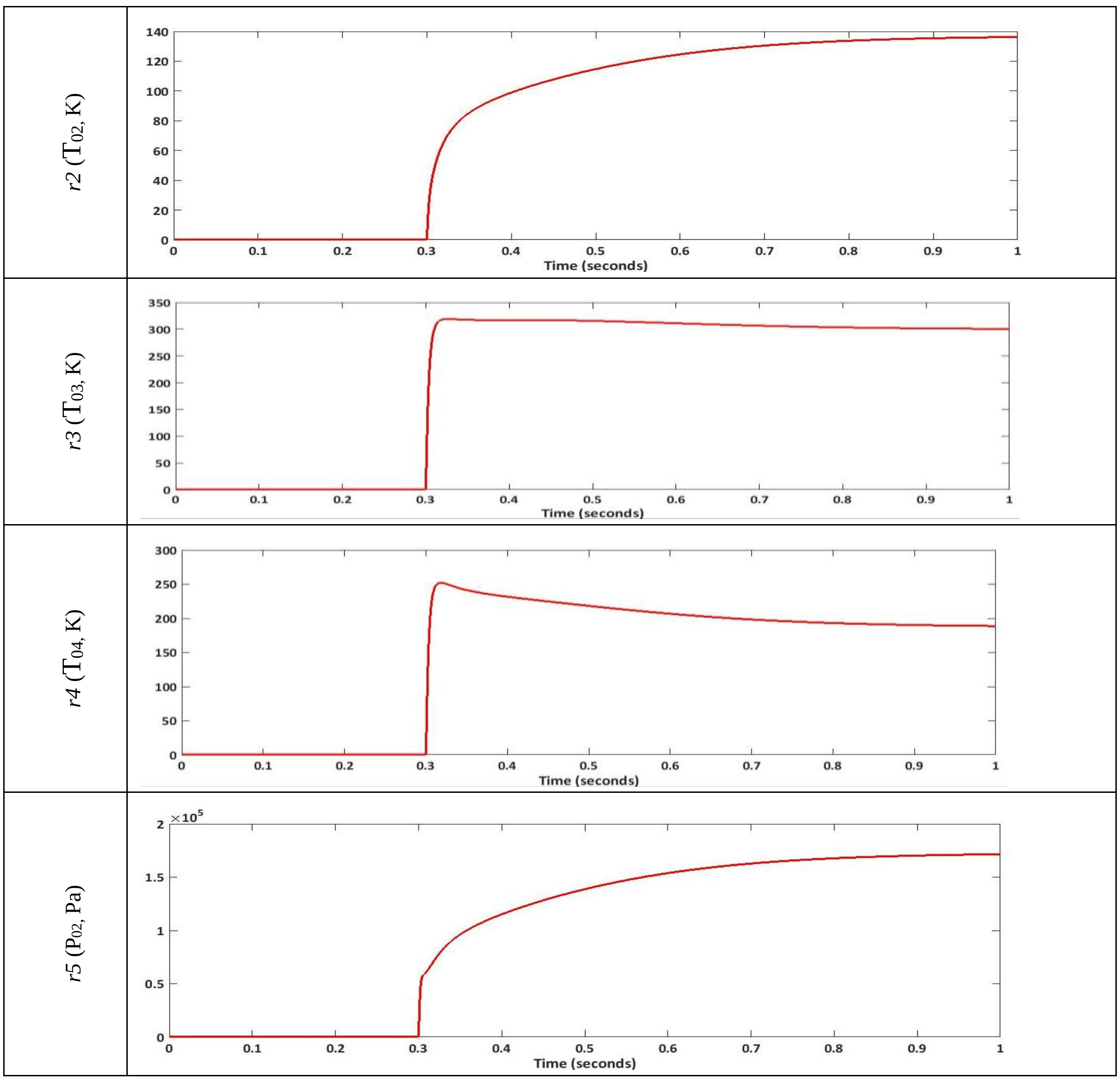

Figure 5.8(a): Residual plots (r2 to r5) in case of f2b (+50% in ṁf)

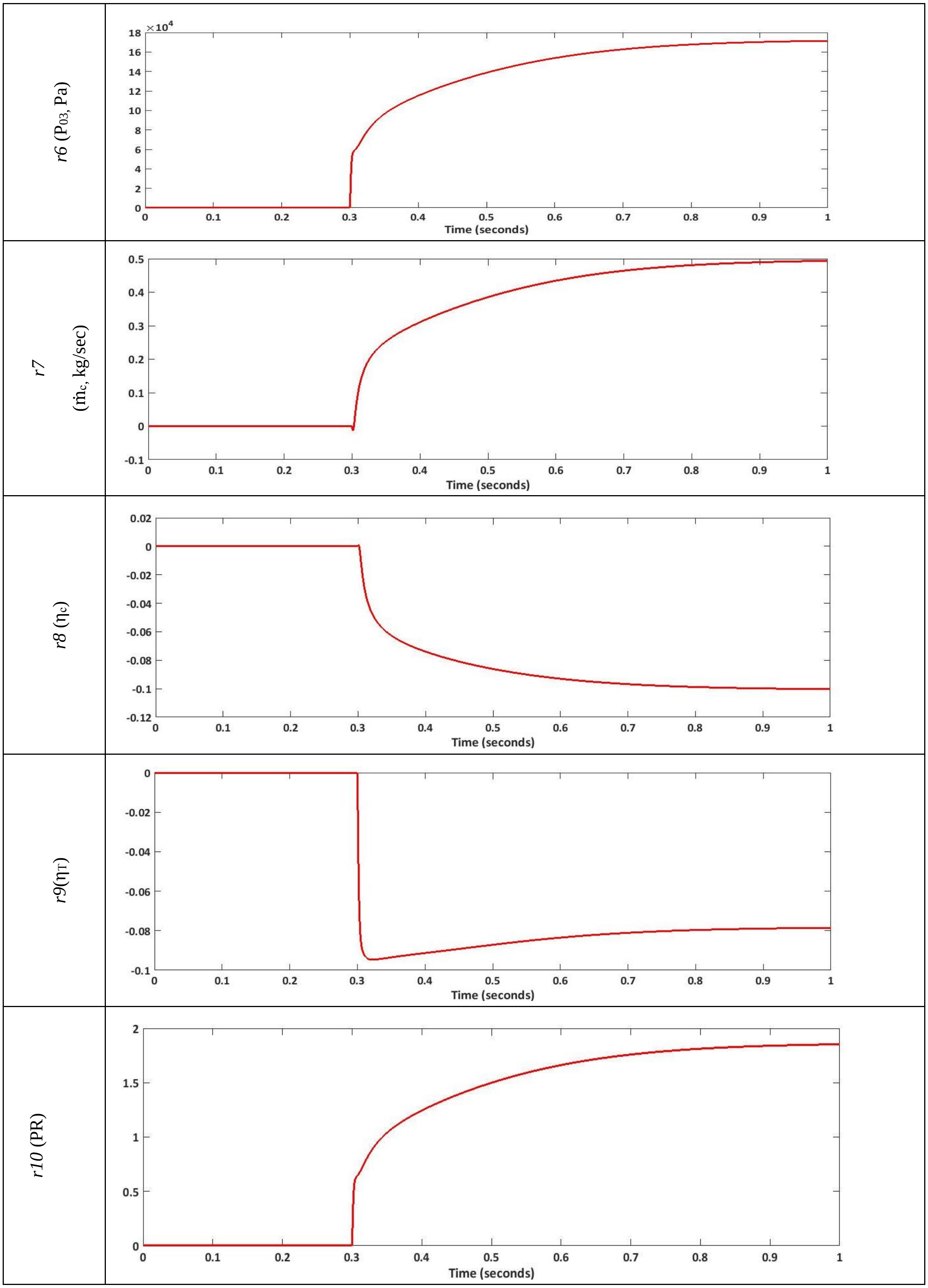

Figure 5.8(b): Residual plots (r6 to r10) in case of f2b (+50% in ṁf)

5.3.3 Foreign Object Damage (*f3*)

The one of the possible reasons for component faults in gas turbine engine may be bird strike or foreign object damage (FOD). Such FOD may damage the fan/compressor and hence performance of the engine is affected. One of the possible impacts of FOD on engine is loss of compressor efficiency. In the current project, the loss of efficiency at is modelled as fault *f3* that occurs at t=0.3 sec. The efficiency of the compressor is lowered in regular interval in percentage to the efficiency of compressor in normal operation. The responses of the faulty plant are compared with that of healthy observer model in terms of residual analysis. The FDI model for fault *f3* is shown in Appendix D-3 and simulation results for the said fault are shown in Figures 5.9 and 5.10 (a & b).

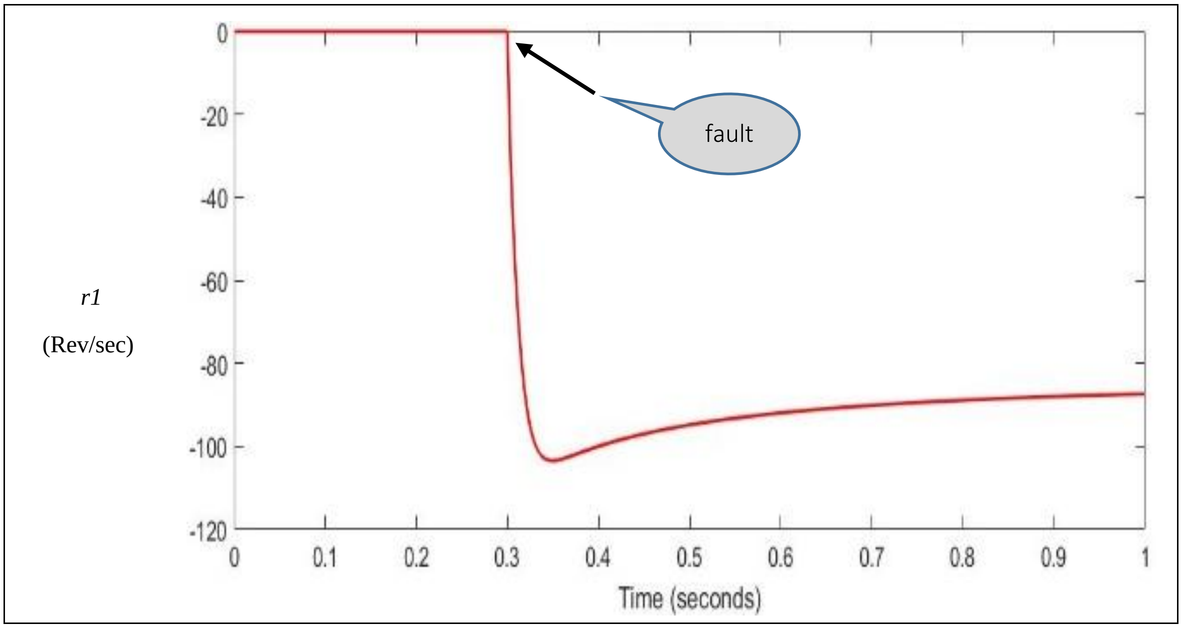

Figure 5.9: Results of residual plots (r1) in case of f3 (-26.9% in η_c)

The decrease in efficiency of compressor due to FOD is found to affect almost all the parameters of the engine. The simulation results shown in the Figures 5.9 and 5.10 indicate decrease in the residuals *r1, r5, r6, r7, r8, r9* and *r10*. However, it can also be seen that residuals of total temperatures i.e. *r2, r3* and *r4* are increasing accordingly. The residual in T_{02} is found to have a rapid rise but then managed to settle at about 25 K. It can also be seen in Figure 5.9 that the spool speed suffers a decrease after occurrence of the fault at t=0.3 sec. The rise in total temperatures and loss of pressure is evident from simulation results shown in Figure 5.10 (a & b). The mass flow rate of the air through the compressor also found to be decreased after existence of the fault. The same reason has also caused an overall drop in compressor pressure ratio, that is indicated by simulation result of residual *r10* as shown in Figure 5.10(b).

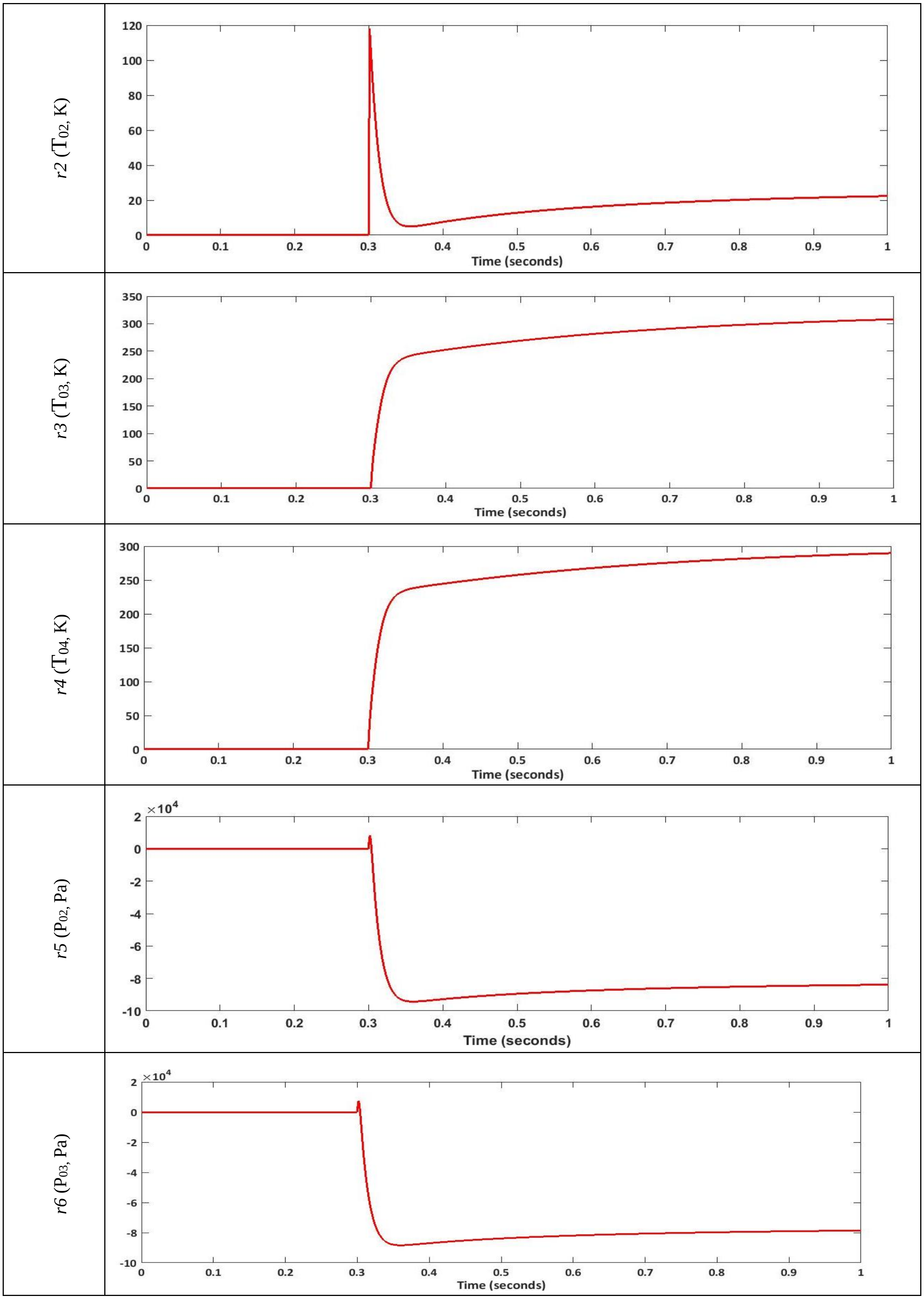

Figure 5.10(a): Results of residual plots (r2 to r6) in case of f3 (-26.9% in η_c)

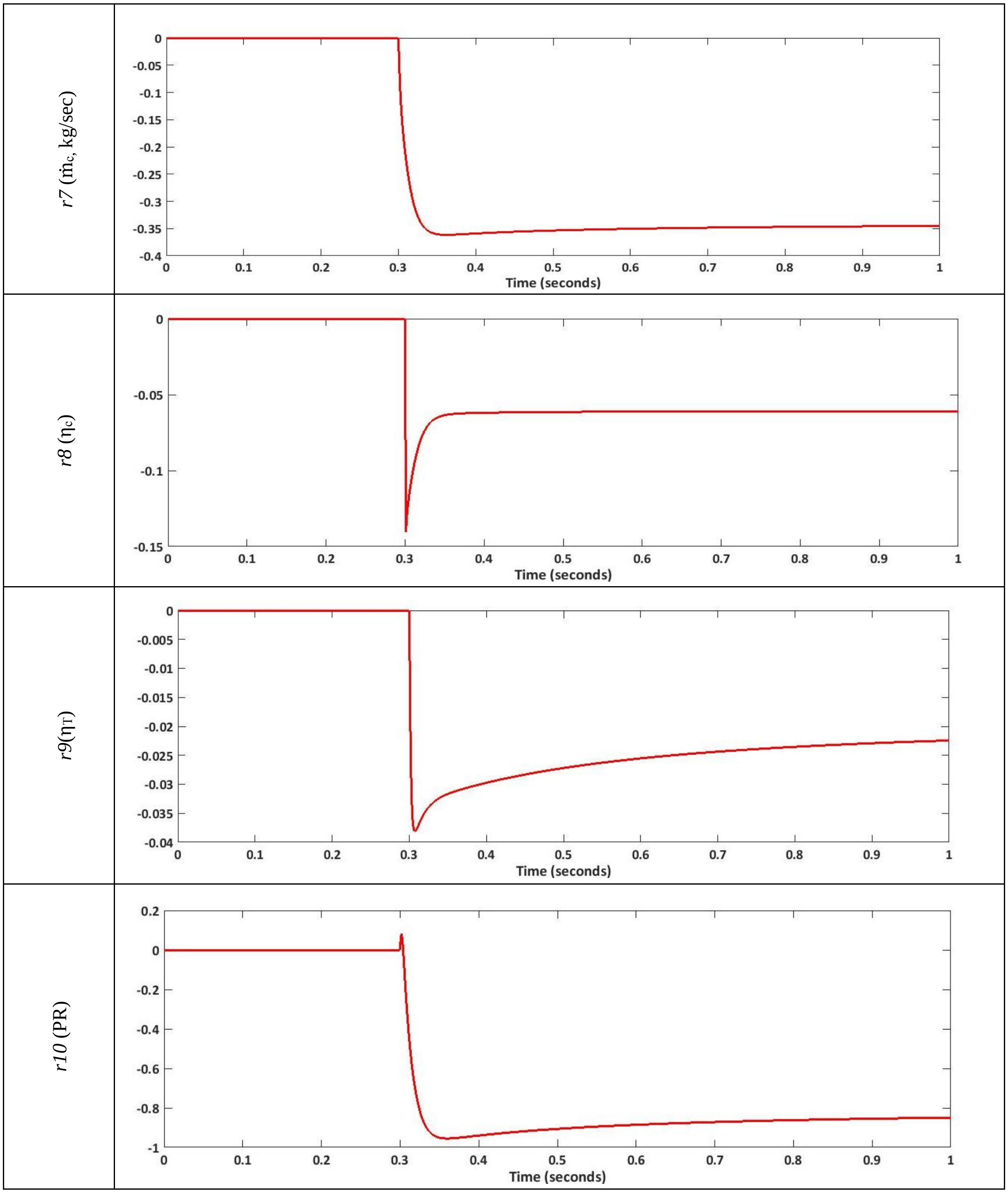

Figure 5.10(b): Results of residual plots (r7 to r10) in case of f3 (-26.9% in η_c)

5.4 Comparative Study of Residuals in *f1*, *f2* and *f3*

In order to have an insight into the faults occurring in gas turbine engine model, a fault signature table, just similar to a truth table, is used. The pattern or fault signature can be represented as vector of indications for each fault (Avram, 2012). In the current project, the values of "0" and "1" have been assigned to the fault signatures. The sign convention has also been kept into consideration for increase or decrease phenomenon in comparison to a healthy state. The state of "1" in a specific residual indicate existence of fault in the system and "0" state refers to the normal operation. All zeros in case of a fault signature represent normal operation of the system. All the fault signatures can be combined into a tabular or matrix form with columns representing fault and rows indicating symptom of the fault. After conducting simulation tests for *f1*, *f2* and *f3*, the fault signatures are collected and combined in Table 5.2.

It can be seen from the fault signature table that in case of no fault in the system of gas turbine, all the residuals are recorded as zero that indicates normal working behavior of the gas turbine engine. In case of RPM sensor fault, that seems to be easy to diagnose and locate, the symptom of change is observed in *r1* only and rest all the parameters are showing normal behavior.

Table 5.2: Fault signatures for f1, f2 and f3

Faults \ Residuals		r1	r2	r3	r4	r5	r6	r7	r8	r9	r10
No Fault		0	0	0	0	0	0	0	0	0	0
f1		-1	0	0	0	0	0	0	0	0	0
f2	***f2a***	-1	-1	-1	-1	-1	-1	-1	+1	+1	-1
	f2b	+1	+1	+1	+1	+1	+1	+1	-1	-1	+1
f3		-1	±1[1]	+1	+1	-1	-1	-1	-1	-1	-1

In case of actuator fault, there may be variation in mass flow rate of the fuel going into the combustion chamber. Therefore, the fault may affect the output parameters at a greater extent as compared to the sensor faults. In case of *f2a*, the amount of fuel flow rate is interrupted and reduced in comparison to its normal flow rate. The table of the fault signatures show the corresponding changes in other parameters of gas turbine system. It can be seen that with loss of mass flow rate of fuel the number of revolutions, T_{02}, T_{03}, T_{04}, P_{02}, P_{03} and compressor pressure ratios are

[1] The direction of the residual is found to be negative for change in $\eta_c < 0.0797$, and positive thereafter.

decreased than their respective normal values. This reduction is shown by "-1" in the table 5.2. On the other hand, in case of *f2b*, the amount of fuel flow rate has been increased in percentage to the normal value and the responses of the corresponding output parameters are recorded. It can be seen that with increase of the mass flow rate of fuel, the number of revolutions, T_{02}, T_{03}, T_{04}, P_{02}, P_{03} and compressor pressure ratios are increased than their respective normal values. However, compressor and turbine efficiencies are reduced in this case which is also opposite to the scenario in case of *f2a*. The mathematical model and control system used for subject study is tested for maximum decrease of 93.75% and maximum increase of 50% to its normal operating value of 0.032 kg/sec.

The study about fault caused by FOD in the present gas turbine model shows that plant is not supporting decrease in compressor efficiency less than 31.75% of its normal value. The simulations go unstable beyond loss of efficiency more than this value. At our normal operating point (healthy sate) the compressor efficiency 55% corresponds to a fuel flow rate of 0.03229 kg/sec, however in case of component fault, say foreign object damage, the compressor efficiency goes down gradually with gradual drop in efficiency. The fuel flow controller tends to compensate the fault and control rpm by providing fuel flow at an enhanced rate as shown in Figures 5.11 & 5.12 below.

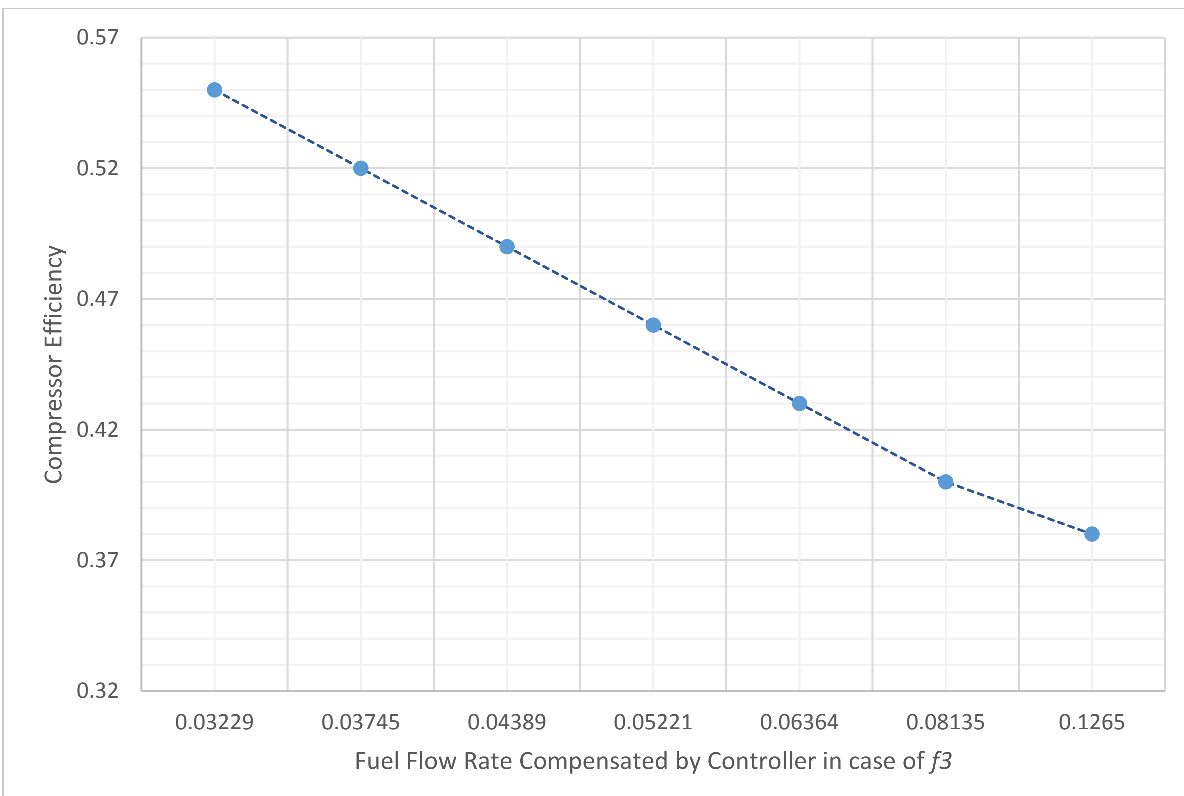

Figure 5.11: Comparison of efficiency loss and fuel flow rate

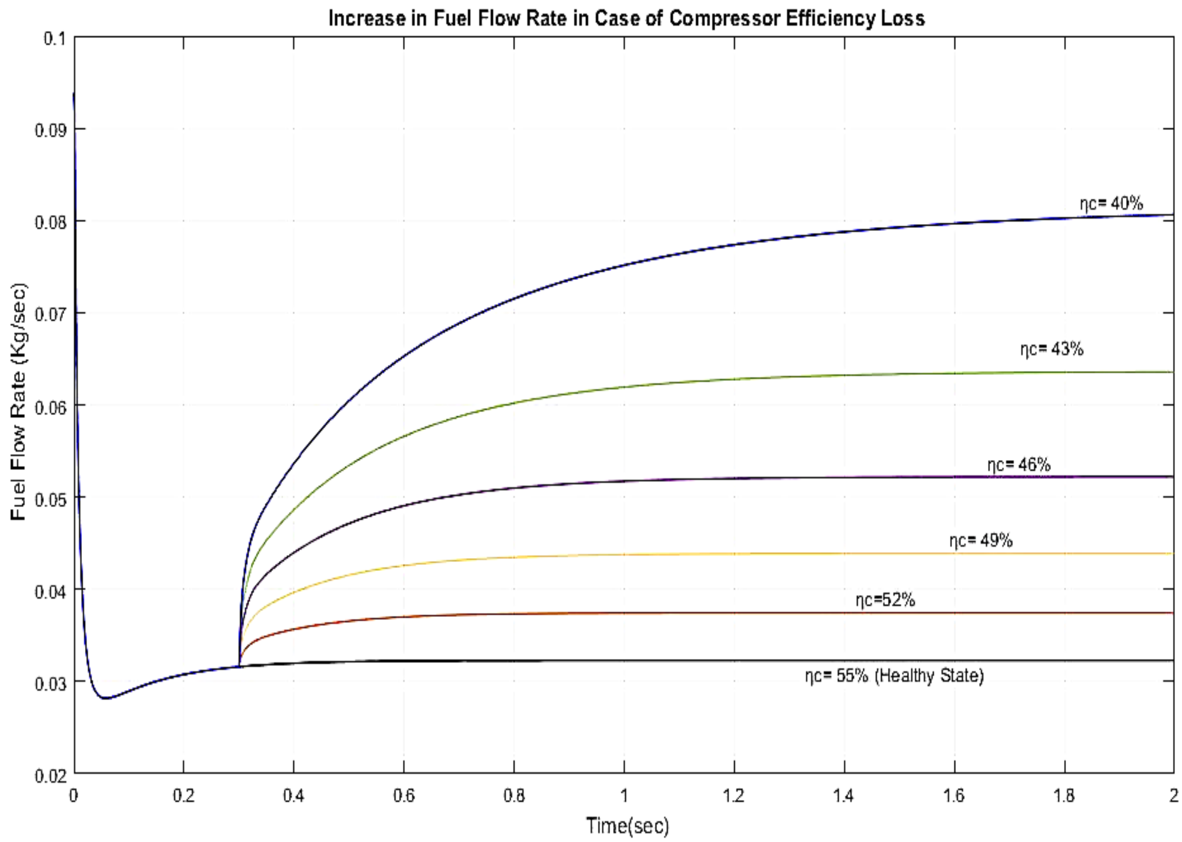

Figure 5.12: Rise in fuel flow rate in case of compressor efficiency loss

Figure 5.11 indicate rise in fuel flow rate with loss in compressor efficiency. We can see that in healthy sate with compressor efficiency of 55% the corresponding fuel flow rate is almost 0.032 kg/sec. However, with gradual loss of compressor efficiency due to FOD, the mass flow rate provided by the fuel management system is going to increase and reaches a value of about 0.081 kg/sec for plant operating with compressor efficiency of 40%. Therefore, it may be concluded from the analysis of Figure 5.11 that the fuel management system is trying to compensate the compressor efficiency loss by providing fuel flow rate at an enhanced rate.

Another important aspect in study of *f3* is variation of temperatures. It is pertinent to mention here that the temperatures at exit of turbine and combustor have been noted to rise substantially in case of efficiency loss. The excessive rise of temperature is obvious from analysis of the residual in T_{04} and T_{03} as shown in Table 5.3. we can note the residual increase in normal value of T_{03} from 33.72 K to 554.4 with a drop in efficiency from 55% to 40%. The similar residual increase has also been seen in T_{04} from 35.6K to 509.7K corresponding to same efficiency loss. In addition to this there has been a drop in compressor pressure ratio due to its failure to compress air at the desired level when fault *f3* takes place. The graph showing rise in T_{03} and T_{04} with drop of efficiency is shown in Figure 5.13 and the loss of pressure ratio after occurrence of the fault is shown in Figure 5.14.

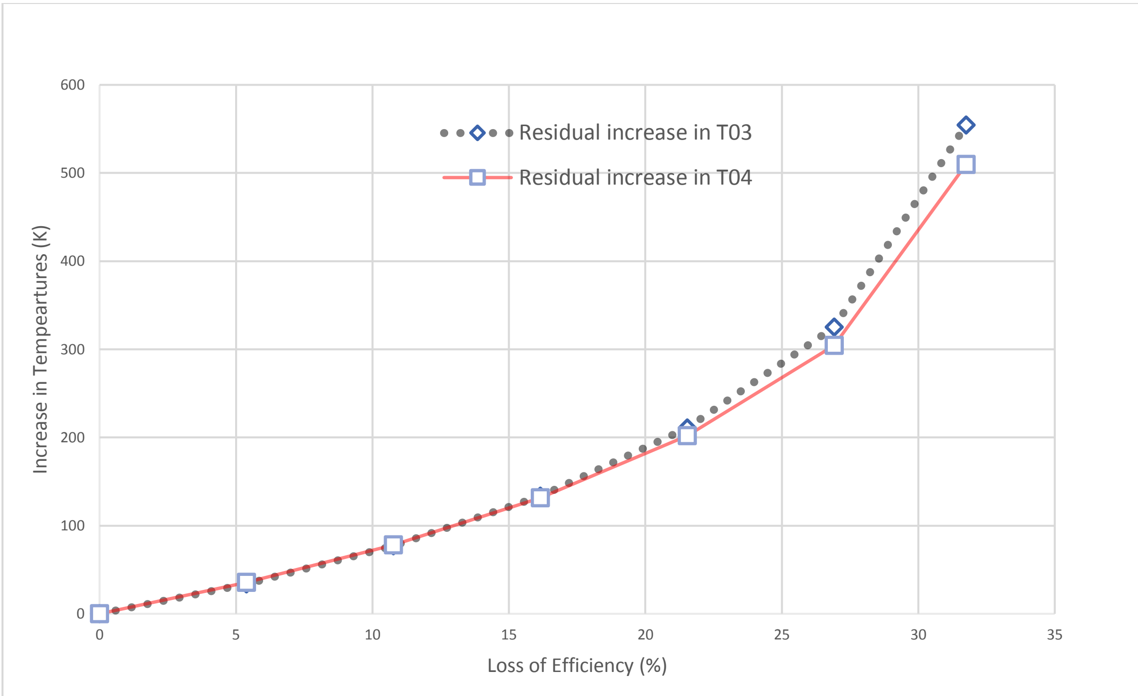

Figure 5.13: Increase in temperatures in case of FOD

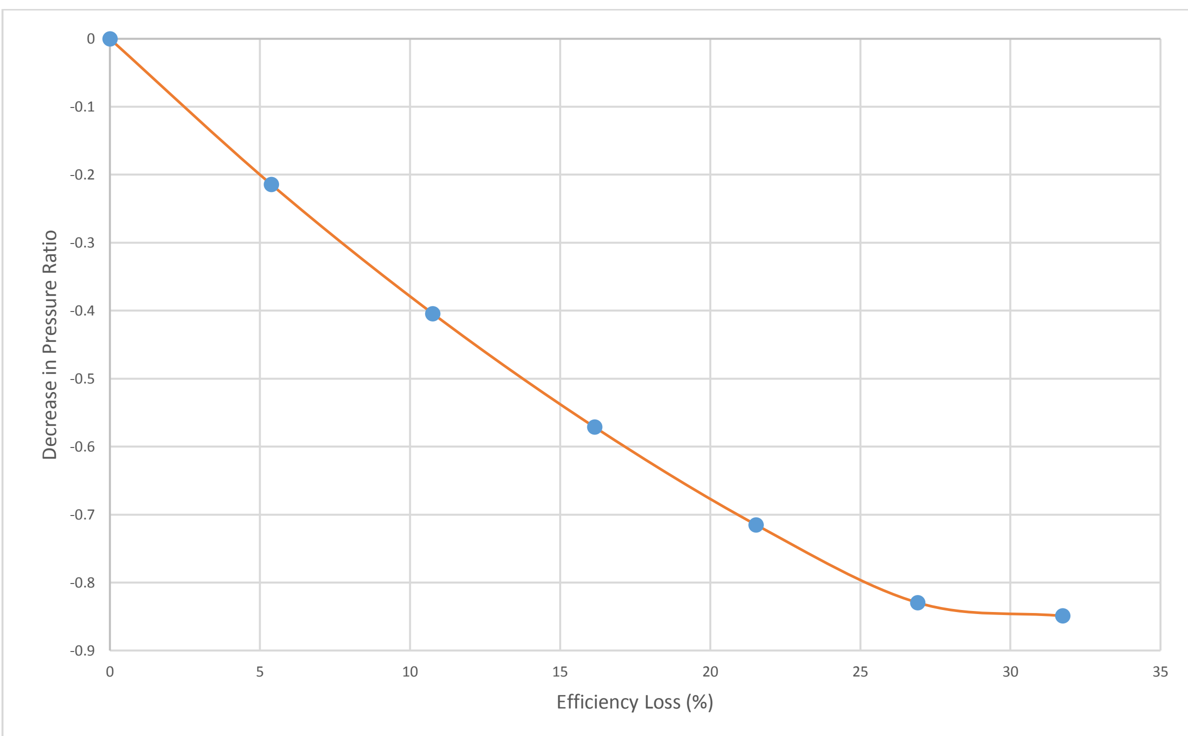

Figure 5.14: Decrease in compressor pressure ratio in case of efficiency loss

Table 5.3: Numerical analysis of residuals in case of faults in gas turbine

Residual Analysis of Faults in Gas Turbine Plant												
Additive Fault in RPM Sensor (*f1*)		Change (Rev/sec)	RPM	T_{02}	T_{03}	T_{04}	P_{02}	P_{03}	$\dot{m}_c$	η_c	η_T	PR
		0(No Fault)	0	0	0	0	0	0	0	0	0	0
		-80	-80	0	0	0	0	0	0	0	0	0
		-70	-70	0	0	0	0	0	0	0	0	0
		-60	-60	0	0	0	0	0	0	0	0	0
		-50	-50	0	0	0	0	0	0	0	0	0
		-40	-40	0	0	0	0	0	0	0	0	0
		-30	-30	0	0	0	0	0	0	0	0	0
		-20	-20	0	0	0	0	0	0	0	0	0
		-10	-10	0	0	0	0	0	0	0	0	0
Actuator Fault (variations in $\dot{m}_f$, *f2*)	**$\Delta\dot{m}_f$ (fall, *f2a*)**	Change (%)	RPM	T_{02}	T_{03}	T_{04}	P_{02}	P_{03}	$\dot{m}_c$	η_c	η_T	PR
		0(No Fault)	0	0	0	0	0	0	0	0	0	0
		31.25	-36.86	-45.89	-186.6	-149.6	-51.27	-48.064	-0.1206	0.03204	0.0558	-0.5194
		46.88	-48.75	-63.46	-277	-225.9	-70.37	-65.97	-0.1622	0.04358	0.08214	-0.7129
		62.5	-58.04	-78.77	-365.9	-302.7	-86.69	-81.26	-0.1955	0.05303	0.1073	-0.8782
		78.13	-65.42	-92.07	-453.6	-380.1	-100.9	-94.56	-0.2226	0.06081	0.1313	-1.022
		93.75	-71.34	-103.7	-540.2	-457.8	-113.4	-106.3	-0.2446	0.06724	0.1542	-1.149
	$\Delta\dot{m}_f$ (rise, *f2b*)	6.25	10.38	11.39	38.35	29.05	13.44	12.6	0.03326	-0.008421	-0.01146	0.1362
		12.5	23.5	23.81	77.03	57.56	28.46	26.68	0.07103	-0.01775	-0.02287	0.2883
		18.75	38.56	37.45	116	85.32	45.4	42.56	0.1144	-0.02813	-0.03413	0.46
		25	56.79	52.55	155.1	112	64.75	60.7	0.1647	-0.03972	-0.04506	0.656
		31.25	79.36	69.46	194	137	87.16	81.7	0.2242	-0.05272	-0.0554	0.8829
		37.5	108.2	88.66	232.2	159.5	113.5	106.4	0.2958	-0.06729	-0.06478	1.15
		43.75	146.4	110.8	268.5	177.5	145.2	136.1	0.3843	-0.08345	-0.07262	1.471
		50	199.7	137	299.6	187.3	184.2	172.6	0.4976	-0.1007	-0.0782	1.866
Foreign Object Damage (Decrease in η_c, *f3*)		Change (%)	RPM	T_{02}	T_{03}	T_{04}	P_{02}	P_{03}	$\dot{m}_c$	η_c	η_T	PR
		0	0	0	0	0	0	0	0	0	0	0
		5.38	-21.83	-2.554	33.72	35.6	-21.16	-19.84	-0.07538	-0.011	-0.008409	-0.2144
		10.76	-40.99	-2.135	76.78	78.14	-39.92	-37.42	-0.1469	-0.02252	-0.0149	-0.4044
		16.15	-57.91	1.821	133.3	131.4	-56.41	-52.87	-0.2152	-0.03458	-0.01941	-0.5714
		21.53	-72.74	10.37	210.6	201.8	-70.59	-66.17	-0.2807	-0.04731	-0.02163	-0.7151
		26.91	-85.07	25.91	325.1	304.2	-81.89	-76.76	-0.3421	-0.06161	-0.02067	-0.8296
		31.75	-88.89	58.92	554.4	509.7	-83.82	-78.57	-0.3798	-0.08168	-0.011	-0.8492

5.5 Suggestions for Recovery from faults in Gas Turbines

After discussing the fault detection and isolation in gas turbine engines, we may recommend some measures to recover from the faults discussed in section 5.3 and 5.4.

5.5.1 Recovery from Sensor faults (*f1*)

The misleading readings in the sensors of the gas turbine can result in wrong results in other parameters as well. In the current research project, RPM sensor readings are affected by an additive fault by decreasing/increasing the number of revolutions per second. When these wrong measurements are fed to the controller, it then measures fuel flow rate incorrectly. An example to this effect is, when the value of RPM is decreased by a factor of 50 rev/sec, the mass flow rate measured by the controller comes out to be 0.0479 kg/sec instead of normal value of 0.03229 kg/sec. When this wrongly measured fuel flow rate is fed to the control section, then there will be definitely wrong measurements all around. So this wrong measurement must be avoided to have a safe and desired operation of the gas turbine engine. In the model-based diagnostics, we can recommend that in case of RPM sensor fault the output from the healthy system may be fed to the plant instead of feeding the controller through plant output. A block diagram for such measure is shown in Figure 5.15 and detailed model for recovery from RPM sensor fault is shown in Appendix D-4.

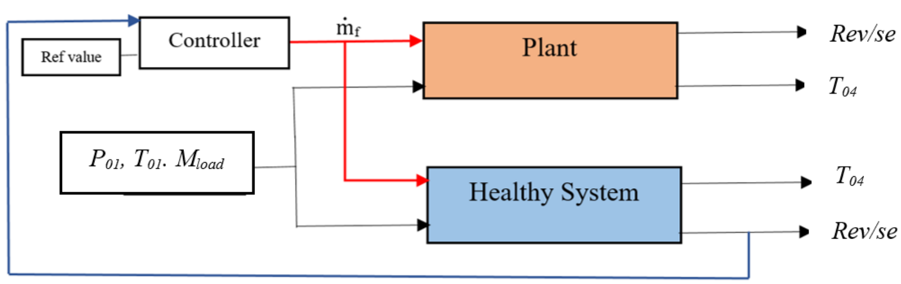

Figure 5.15: Model for recovery from RPM sensor fault in gas turbine

5.5.2 Recovery from Actuator faults (*f2*)

The actuator and component faults are complicated as compared to the sensor faults. In the current project, the mass flow rate of the fuel is affected as a result of fault in the actuator. The residual analysis of the comparison between plant and the observer model lead to the fault. The signature tables also help to pinpoint the fault in actuator systems. The fault lead to the incorrect measurement of the fuel flow rate which eventually affect the other output parameters. An example to this effect is, when fuel flow rate is decreased in comparison to its normal value, there is drastic change in the output parameters of the gas turbine engine. It is quite evident from Table 5.3, that with decrease in fuel flow rate corresponding pressure ratios and number of revolutions per second are dropped in comparison with their original values.

The recovery from the actuator fault needs a comprehensive fault tolerant control system with modifications in the current control system used to provide fuel flow rate to the plant. The modified control system may be used to achieve mass flow rate of the fuel desired for the operation of the gas turbine engine. The advantage of the integral term in PI control structure is that it eliminates the steady state error. The combination of the proportional and integral actions in the control structure helps effectively to attain the reference or the set point value RPM for operation of the gas turbine engine. But, integral term is prone to some other issues in the control algorithm in case of getting rid of actuator faults. The action of integral term may lead to instability and hence the output value may overshoot the reference value in this case. The integral term may also cause the phenomena known as reset windup. It happens when the actuator is not large enough to accommodate the request for desired mass flow rate from the controller. The actuator may not be able to provide fuel flow rate at the desired level in this situation. When saturation in the actuator stops the flow rate any further, the control structure assumes positive errors between reference and the observed value. The integrated error may continue to increase and demand for aggressive input (fuel flow rate) from the controller. On the other hand, the actuator may have stuck at its maximum value of output, and show its inability to take process variable any closer to the reference value of number of revolutions per second. The consideration of the mentioned facts would be of interest in design of the fault tolerant control system for actuator faults in gas turbine engines in the future studies.

5.5.3 Recovery from Component faults (*f3*)

The component faults adversely affect the machinery and hence all the outputs are affected as a result of undesired mechanical processes in the system. In the present research project, FOD is considered as potential fault for gas turbine engine. The fault may be diagnosed using model-based method, comparison of the residuals and fault signature matrix shown in Section 5.3. The damage caused by FOD adversely affects the performance of the engine and may cause fatal consequences for the aircraft. The fault is incorporated in the Simulink model of the engine as drop in compressor efficiency of the engine. It can be seen from Table 5.3 that loss of compressor efficiency may results in loss of pressure at compressor outlet and hence the pressure ratio across compressor. This is in good agreement with thermodynamic and mechanical principles of gas turbine engine. At the same time, excessive rise in the temperatures may also be observed associated with loss in compressor efficiency as a result of FOD. Physically speaking, after strike of any foreign object, the compressor blades are not able to compress the air at desired level. It is evident from Table 5.3 that the minor loss of efficiency does not lead to excessive deviation of parameters from the normal operating range of the values. In such situation, the FOD may be of trivial nature and engine compressor may not be affected to a much greater extent. It may be expected to undergo self-recovery and engine power is not lost in this case. Thus, the gas turbine system is recoverable if the fault is not of catastrophic nature. However, excessive deviation of the parameters is caused by much higher loss in the compressor efficiency. In this sort of situation, the turbine outlet temperature may rise high and emergency landing becomes inevitable for such disastrous damage to the engine compressor in order to have hardware maintenance or repair of the faulty components on ground.

Summary

The chapter deals with investigations carried out to study about the faults occurring in the gas turbine engine. The faults considered for the subject study include RPM sensor fault (*f1*), actuator fault (*f2*) and component fault (*f3*). The faults are implanted in the gas turbine control system in and simulations are run in Simulink to record observations. The faulty plant is compared with the healthy observer model and the deviation in responses of various parameters are recorded as *residuals*. The residual analysis about RPM sensor fault guides that the deviation is observed only in sensor reading and all other residuals are recorded as zero. However, in case of actuator and component fault, the residuals are observed in almost all the parameters of gas turbine engine. therefore, it seems to a little complicated to detect the faults for the actuator and component malfunctioning. But, the fault signatures, based on residual analysis, are helpful to tell about nature and location of the faults in the system. The entries of the fault signature table indicating rise or fall in the residuals in case of different fault situations are the guiding elements to differentiate among these faults. In the last part of the chapter, recommendations based on our FDI are included to help recovery of the system in a possible way.

Chapter 6: Conclusion and Future Work

6.1 Conclusions

The faults in gas turbine engines especially the aero engines, may be resulted into heavy expenditures for the maintenance and even cause serious damage to human lives as well. Therefore, the accurate working of the gas turbines is a dire necessity to avoid unforeseen occurrences in operation of these machines. This study was focused to carryout investigations regarding fault diagnosis and isolation of the gas turbines engines. The aim of the work presented in this thesis was to devise a strategy to detect sensor, actuator and component faults in gas turbines engine. In order to have an insight into the fault studies, mathematical model of the gas turbine control system was used. The simulations of the model were run in Simulink/MATLAB and results were used to make fault signature tables, and graphs showing existence of faults in machinery. Based on diagnostic study of the faults in gas turbine engines, certain recovery measures have also been recommended to restore the normal operation of the gas turbine engine.

The study may be divided into three major sections. The first section of the study was related to review of the related literature and to design a mathematical model of the gas turbine engine. In pursuance of the objectives of present study, a dynamic mathematical model of the gas turbine engine, based on thermodynamic and constitutive relations, was developed successfully. The model was validated at design point against the available experimental and already published results. The mathematical model was validated against a reference data by using *analogue matching* of plots and numerical data obtained through simulations. The model was found to be in good agreement with the reference data that ensured its reliability for its use in next part of the study. The second part of the study dealt with designing fuel flow control system for the gas turbine model. The controller was designed in Simulink by using PI controlling techniques. the aim of the controlling was to control spool speed of the engine through controlling fuel flow rate in the combustion chamber of the engine. The gains of the PI controller were set manually to achieve the desired rotational speed of the propulsion system. The fuel flow controller was found to be working as per expectations to control shaft speed and hence the thrust produced by the engine. However, the generation of the thrust at relatively higher spool speed may require additional control systems to control some other important parameters of the engine.

In the third and final phase of the study, fault diagnosis and isolation has been carried out using residual analysis. The developed mathematical model and controller were found to be useful, at a great extent, to detect and locate the sensor, actuator and component faults, once they occur in the propulsion system. The faults were implanted in the mathematical model of gas turbine control system and results were recorded using simulation data. The deviation in parameters due to faults in the faulty plant from those of healthy model were recorded as *residuals*. The analysis of the residuals helped to formulate the fault signatures on which the investigation about nature and location of faults is based. The fault signature table and simulation results helped to identify and differentiate among the faults taken into consideration for this study. Keeping in view the analysis of the faults, some recovery measures have also been suggested to restore the gas turbine system to their normal operation.

This work presented the development of a FDI system based on residual analysis for gas turbine health monitoring. The study on the comparison of the faulty signals with those from the healthy observer model is found to be helpful in formulating strategies to differentiate among faults of different nature and their location in the system. The presented work is expected to be useful in detecting and isolating the faults regrading RPM sensor, fuel flow actuator and damage caused by the foreign objects. The residual analysis based on the simulation results provides a framework to examine the discussed faults and their impact on other parameters of the engine to formulate strategies for recovering the system from faulty situations. The variations of mass flow rate of the fuel in case of fault occurrence is a one of the critical factors as far as fuel economy for operation of the gas turbine engines is concerned. In order to achieve desired mass flow rate of the fuel during operation of the gas turbine engine, the faulty components need immediate attention. Moreover, spool speed plays a key role in obtaining substantial amount of thrust from the gas turbine engine. Therefore, control of the spool speed is vital to have command on output of the engine. Keeping in view these important aspects of operation, this study is based on analysis of FDI of gas turbine engine. The discussion and results are expected to be beneficial to carryout supervision and monitoring of the system in a way to be prepared for handling and troubleshooting the system failures those are not of catastrophic nature.

6.2 Recommendations for Future Work

This study was focused to design a framework for fault diagnosis and isolation for gas turbine engines. The findings of the study may be used to design efficient fault tolerant control system for the gas turbine engines. This study aims to describe the ways in which gas turbine engine mathematical model may be used to study about faults happening in the system. Various parameters of the gas turbine engine are found to be affected by the implanted faults that was much expected as per the engineering principles and theoretical studies of the thermodynamic systems. This study includes controlling spool speed and hence the thrust of the engine by controlling fuel flow to combustion chamber.

As we know that the gas turbine engines installed on the air vehicles are sensitive equipment, and need health and conditioning monitoring as a regular feature. The faults emerging because of routine working may become cause of disaster, if not supervised accurately. The future study may include control of some other important parameters like exhaust gas temperature as the major element to be controlled. The future work may also include limitations imposed on working of the compressor and turbine like surge and stall phenomena etc. The same limitations, if modelled through mathematical equations, can be used to monitor the surge and stall phenomena more precisely. The outcomes of the proposed research may be helpful in overall improvement of the control systems of the gas turbine engine. A simple block diagram is shown in Figure 6.1 to have an insight into the layout of the future work in field of fault detection, isolation and recovery of gas turbine engine.

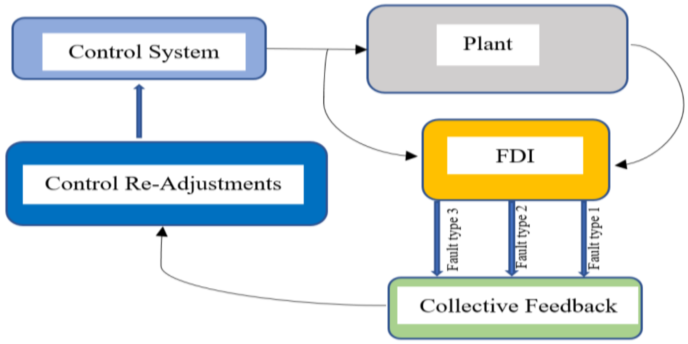

Figure 6.1: Layout of the future work in field of FDI of gas turbine engine

Based on the knowledge of FDI of the gas turbine engine, the future work is aims to have a comprehensive fault tolerant control system. The FDI is supposed to discover intelligent information about types of faults, and controller is expected to readjust according to types of faults accurately. The collective feedback is to be used to further investigate about the nature and types of faults. This proposed control system aims to handle faults in a sophisticated and robust manner. The control system would aim to operate using inputs from the fault signals and to operate accordingly to rectify those faults in possible ways.

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Appendices

Appendix A: Gas Dynamics Relations

The gas dynamics relations are derived from the continuity and energy balance equations. Mathematical manipulations required to formulate these equations in terms of the chosen variables are given in this Appendix. Continuity and energy balance for quasi-one-dimensional flow is given by the following equations;

$$\frac{d}{dt}(\rho A) + \frac{d}{dt}(\rho A v) = 0 \qquad (1)$$

$$\frac{d}{dt}(\rho A u) + \frac{d}{dt}(\rho A v h) = 0 \qquad (2)$$

With the expression $\dot{m} = \rho A v$.

Continuity equation:

Equation 1 transforms to;

$$\frac{d}{dt}(\rho A) = \frac{d}{dx}(\dot{m})$$

$$\frac{d}{dt}(\rho) = \frac{1}{A}\frac{d}{dx}(\dot{m})$$

Lumping the spatial variable, the Equation transforms to;

$$\frac{d}{dt}(\rho) = \frac{1}{V}(\dot{m}_1 - \dot{m}_2)$$

$$\frac{d}{dt}(\rho V) = (\dot{m}_1 - \dot{m}_2)$$

$$\frac{d}{dt}(W) = (\dot{m}_1 - \dot{m}_2)$$

This is the expression used for the Continuity equation for the system components.

Energy equation:

Equation 2 transforms to,

$$\frac{d}{dt}(\rho A u) + \frac{d}{dt}(\dot{m} h) = 0$$

$$\frac{d}{dt}(\rho A C_v T) = -\frac{1}{A}\frac{d}{dx}\left(\mathrm{m}\dot{C}_p T\right)$$

Again, lumping the spatial variable leads to;

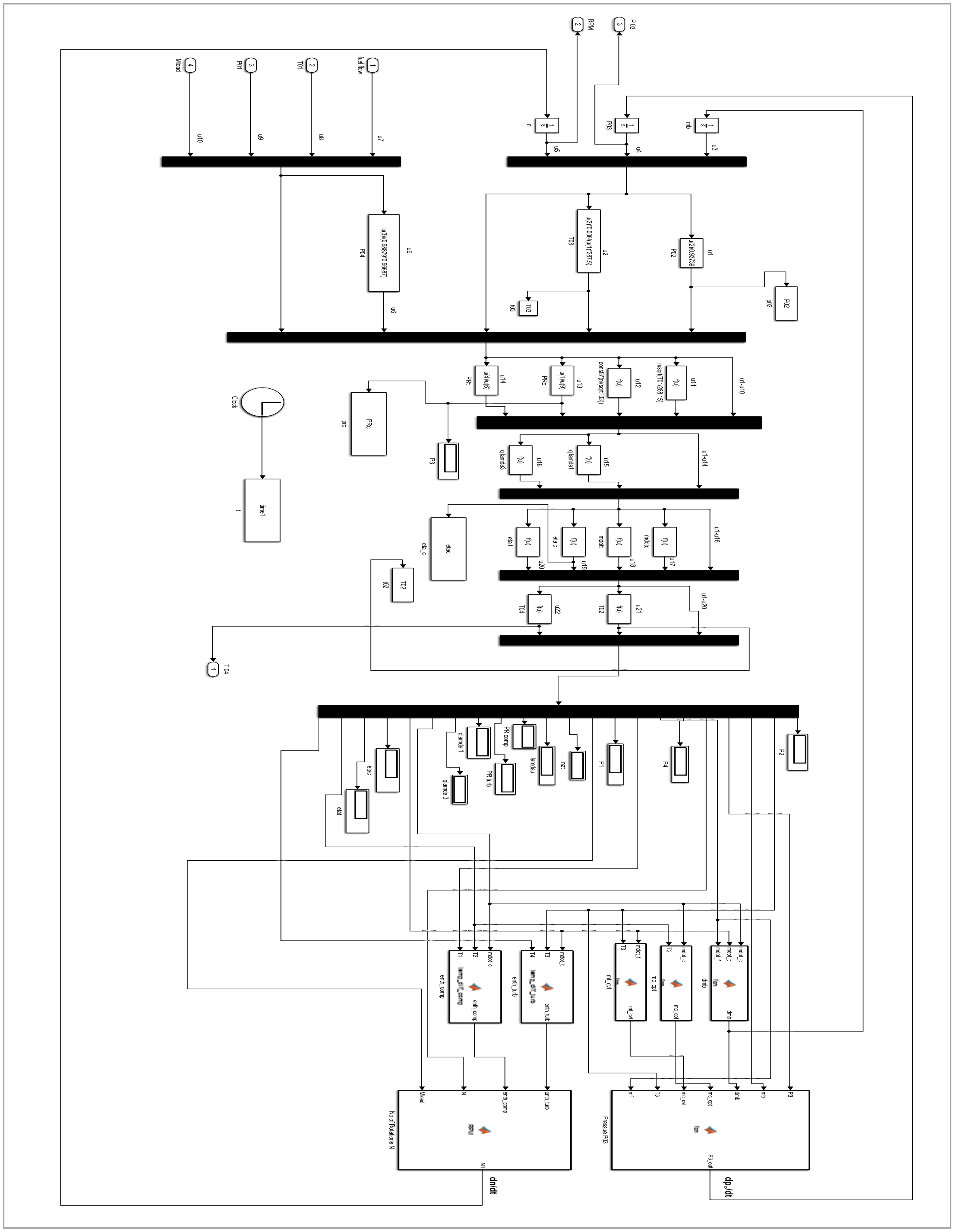
$$\frac{d}{dt}(\rho T) = \frac{1}{V}(\dot{m}_1 T_1 - \dot{m}_2 T_2)$$

$$\frac{d}{dt}(W T) = (\dot{m}_1 T_1 - \dot{m}_2 T_2)$$

This equation is further simplified and used for the energy balance relation for the system components in the modeling.

Appendix B: Mathematical Model of Gas Turbine Engine

Appendix B-1: Model Inside subsystem of Gas Turbine Engine

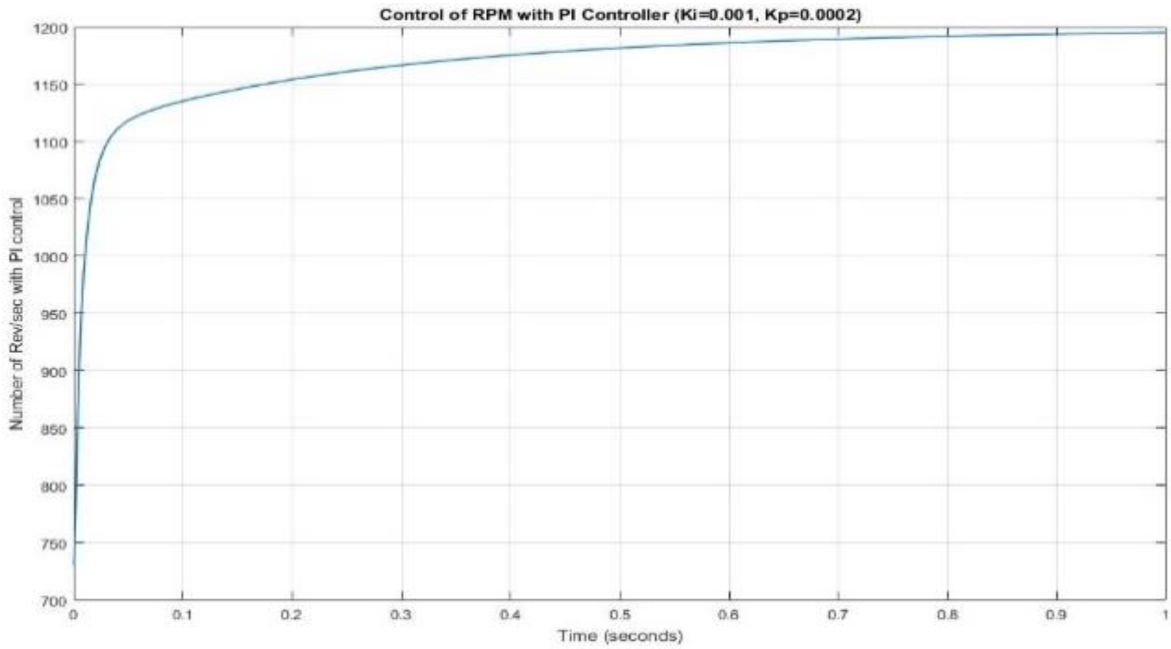


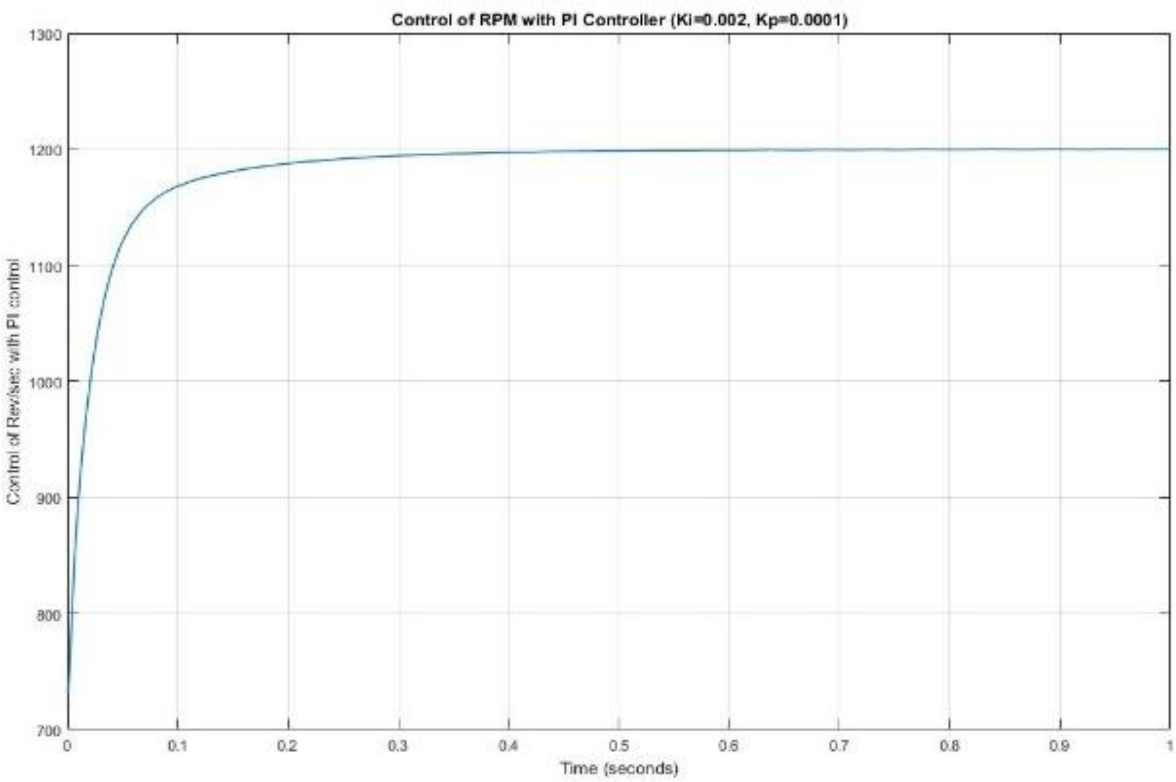
Appendix B-2: MATLAB Functions used in Mathematical Model

Some of the equations have been developed as MATLAB functions inside the mathematical model. These are given as under;

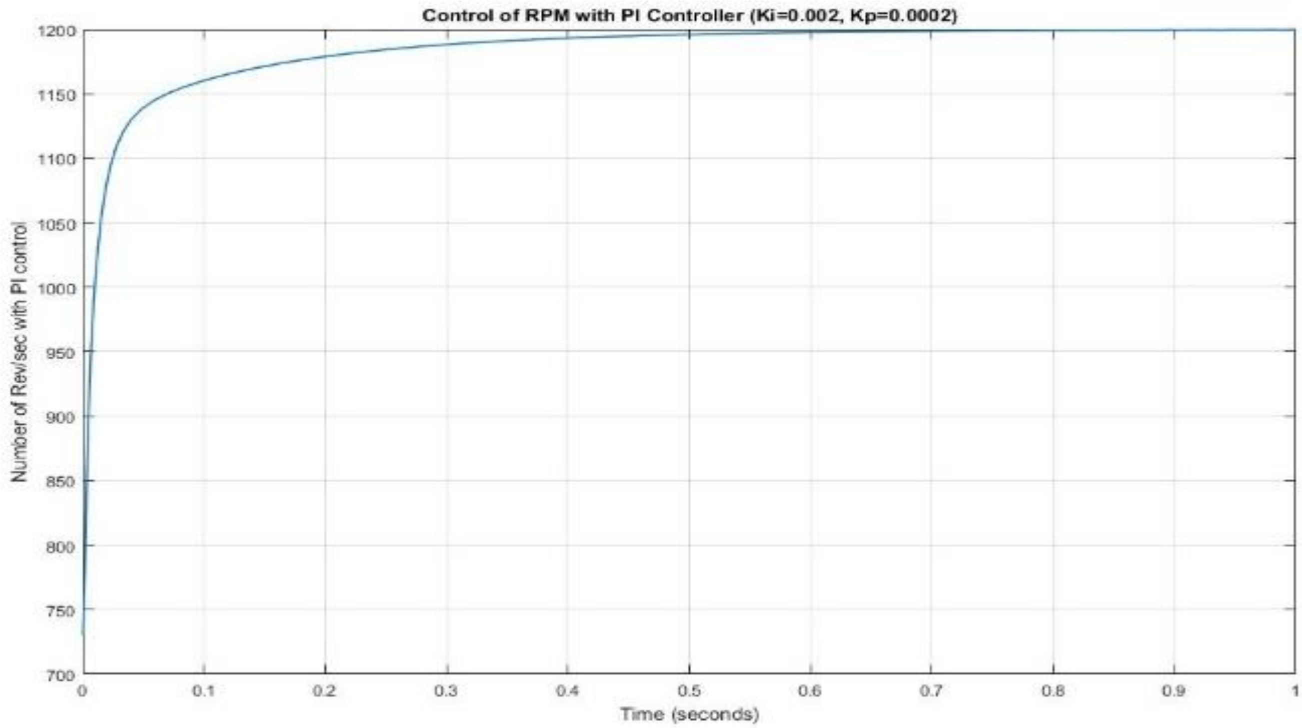
```
function dmb = fcn(mdot_c,mdot_t,mdot_f)
% combustor mass
dmb=mdot_c+mdot_f-mdot_t;
end

function mc_cpt=fcn(mdot_c,T2)
% product compressor mass and cpt
mc_cpt=mdot_c*1004.5*T2
end

function mt_cvt = fcn(mdot_t,T3)
% product turbine mass and cvt
mt_cvt=mdot_t*1160.72*T3;
end

function enth_turb=temp_diff_turb(mdot_t,T3,T4)
% enthalpy turbine
enth_turb=mdot_t*1160.72*(T3-T4)*0.98
end

function enth_comp=temp_diff_comp(mdot_c,T2,T1)
% enthalpy compressor
enth_comp=mdot_c*1004.5*(T2-T1)
end

function P3_out=fcn(P3,mb,dmb,mc_cpt,mc_cvt,T3,mf)
% p03 out
P3_out=(P3/mb)*(dmb)+(P3/(T3*795.11*mb))*(mc_cpt-c_cvt+(42800000*0.96651*mf)-
(795.11*T3*dmb));
end

function N1=RPM(enth_turb, enth_comp,N,Mload)
% RPM
N1=(1/(4*pi*pi*0.0003*N))*(enth_turb-enth_comp-(0.12*pi*N*Mload));
end
```

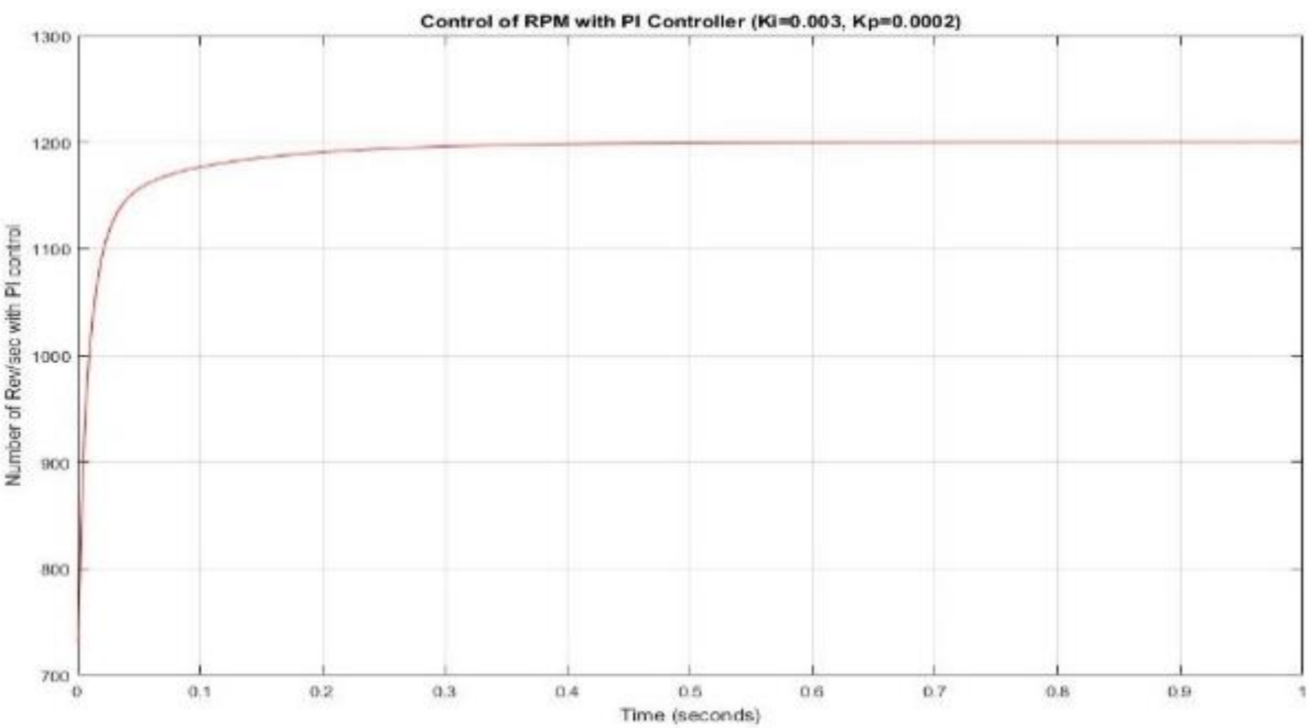
Appendix C: Simulation Results of PI controller with Different value of K_p and K_i



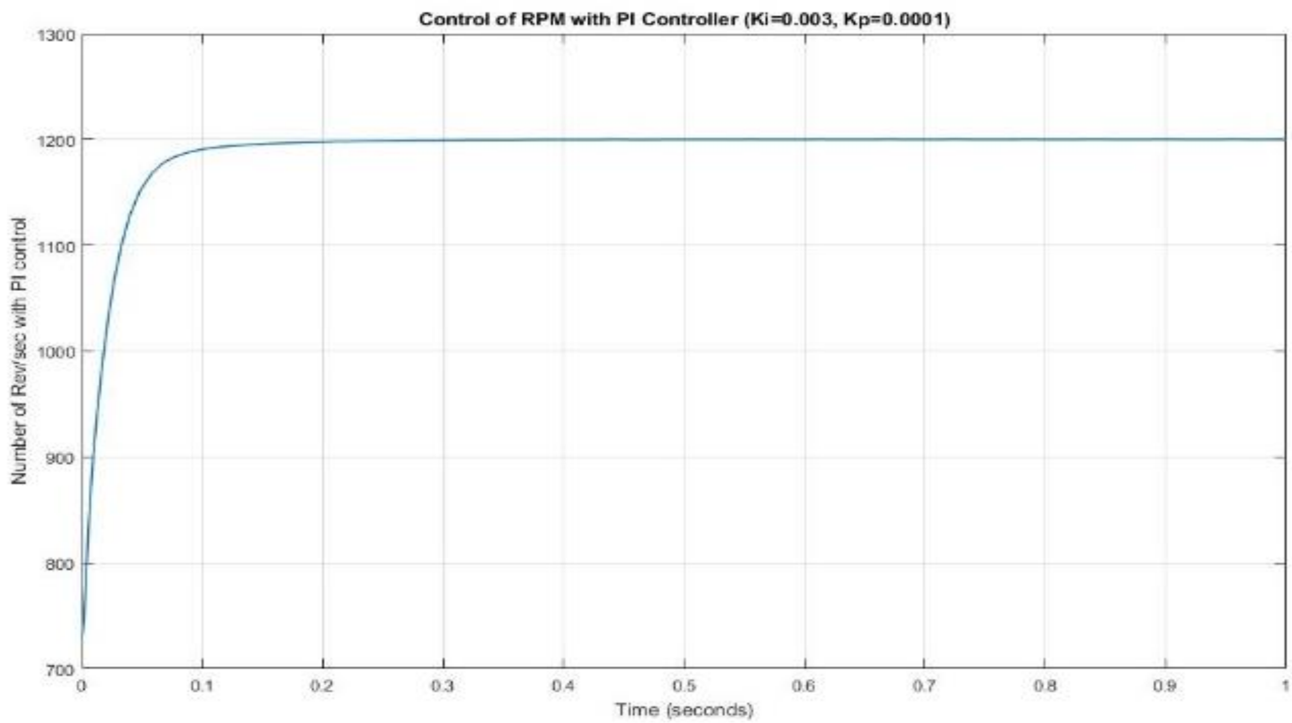


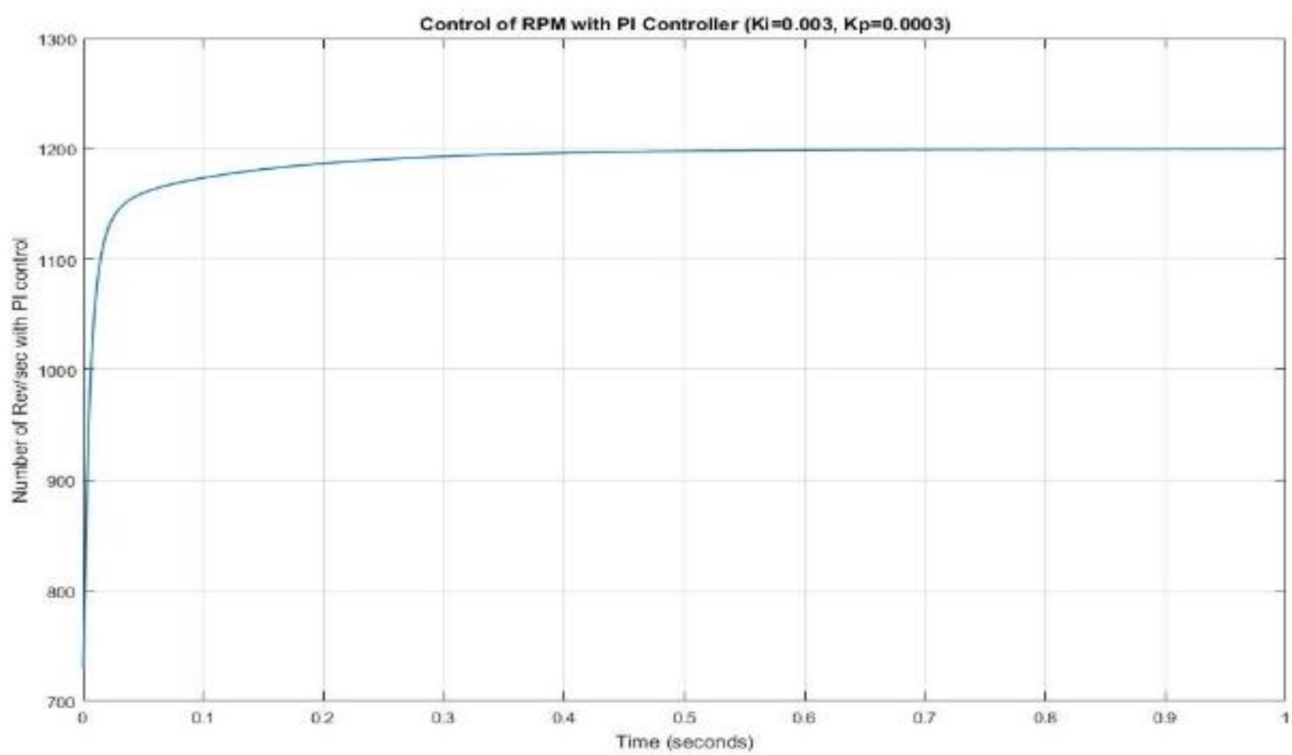
Appendix C (Cont’d): Simulation Results of PI controller with Different value of Kp and Ki





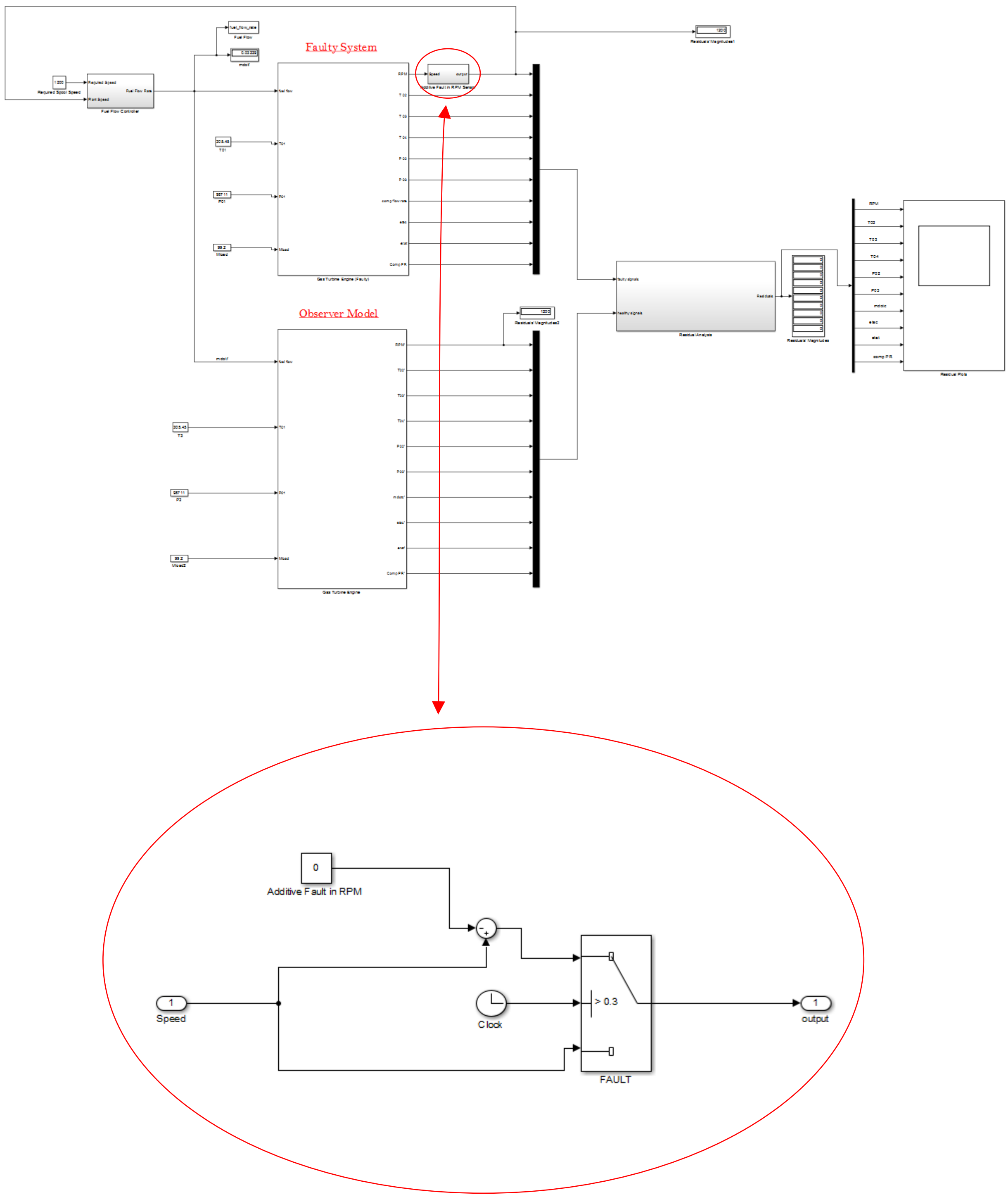
Appendix C (Cont'd): Simulation Results of PI controller with Different value of Kp and Ki



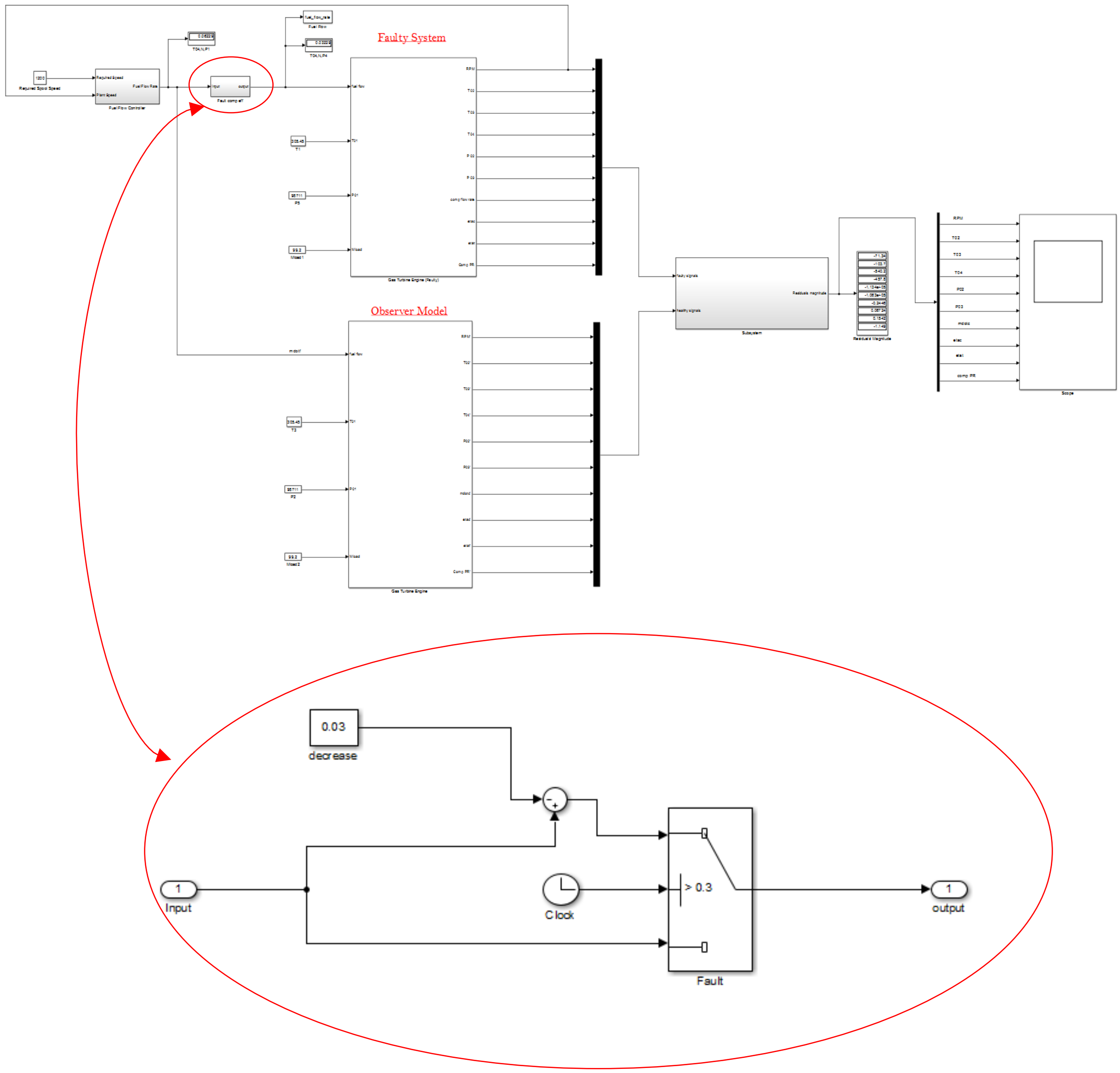


Appendix D: Mathematical Models of FDI of Gas Turbine Engine

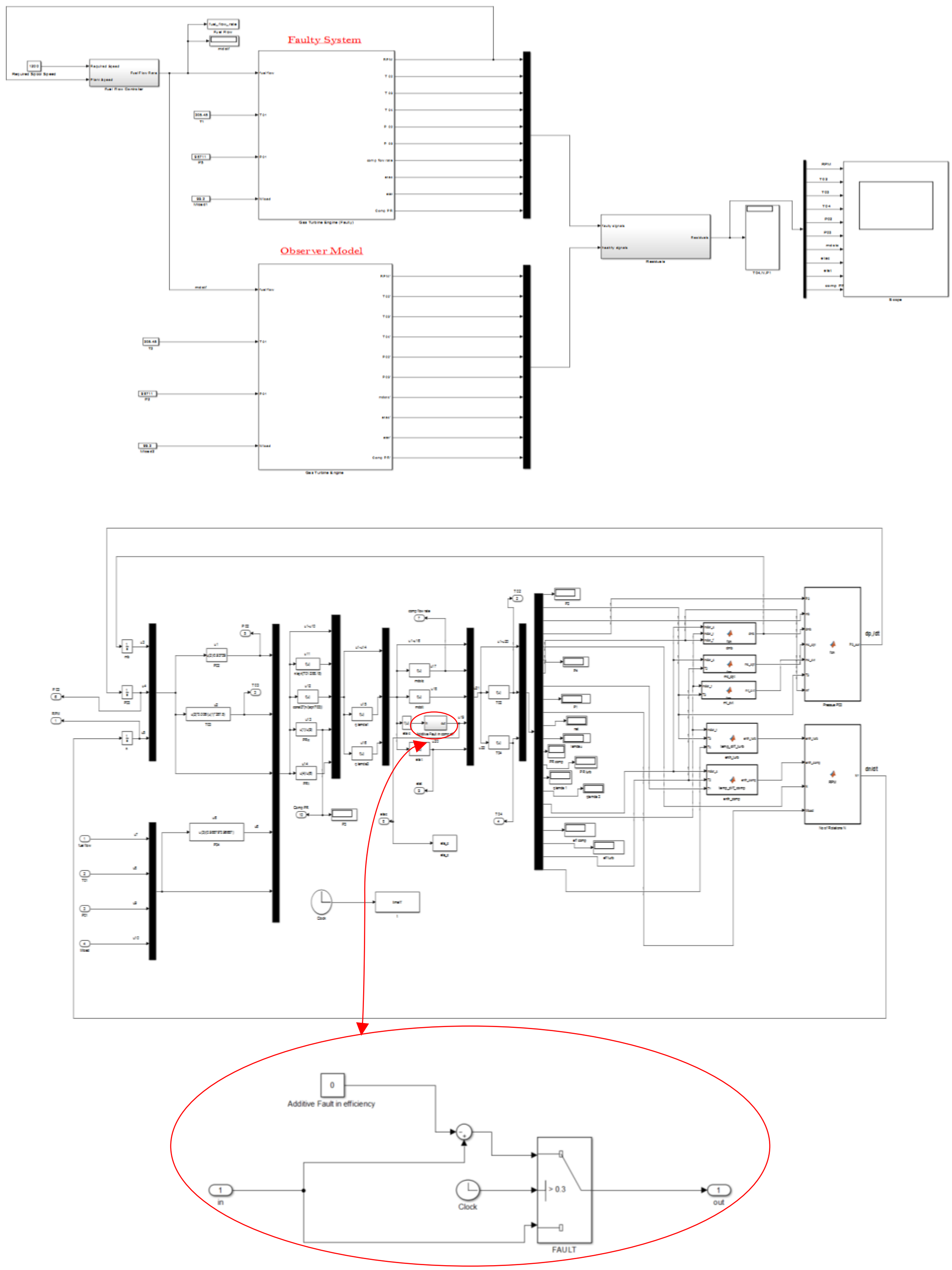
Appendix D-1: Simulink Model for Analysis of *f1* (Fault in RPM Sensor)



Appendix D-2: Simulink Model for Analysis of *f2* (Actuator Fault)



Appendix D-3: Simulink Model for Analysis of *ƒ3* (FOD: Decrease in η_c)



Appendix D-4: Suggested Model for Recovery in case of RPM Sensor fault