Exploration of Co-simulation Based Strategy for Thermal Power Plant

By

Jitesh Bajaj
13MICC08

DEPARTMENT OF INSTRUMENTATION AND CONTROL ENGINEERING
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY
AHMEDABAD-382481

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Exploration of Co-simulation Based Strategy for Thermal Power Plant

Major Project Report

Submitted in partial fulfillment of the requirements

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Master of Technology in Instrumentation and Control Engineering

(Control and Automation)

By

Jitesh Bajaj

13MICC08

Guided by

Dr. Jayesh Barve

DEPARTMENT OF INSTRUMENTATION AND CONTROL ENGINEERING

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

AHMEDABAD-382481

May 2015

Declaration

This is to certify that

I. The thesis comprises my original work towards the degree of Master of Technology in **Instrumentation and Control Engineering (Control and Automation)** at Nirma University and has not been submitted elsewhere for Degree.

II. Due Acknowledgment has been made in the text to all other material used.

-Jitesh Bajaj
13MICC08

Undertaking for originality of the work

I,**Jitesh Bajaj, Roll No. 13MICC08,** give undertaking that the Major Project entitled **"Exploration of Co-simulation Based Strategy for Thermal Power Plant"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Instrumentation and Control Engineering (Control and Automation)** of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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This is to certify that the Major Project Report entitled **"Exploration of Co-simulation Based Strategy for Thermal Power Plant"** submitted by **Jitesh Bajaj, Roll No. 13MICC08,** towards the partial fulfillment of the requirements for the award of Degree of Master of Technology in **Instrumentation and Control Engineering (Control and Automation)** of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

Dr. Jayesh Barve
Institute Guide, Professor,
Department of I&C Engineering,
Institute of Technology,
Nirma University, Ahmedabad

Prof. J.B Patel
Associate Professor
Department of I&C Engineering
Institute of Technology,
Nirma University, Ahmedabad

Dr.Dipak Adhyaru
Professor and Head,
Department of I&C Engineering,
Institute of Technology,
Nirma University, Ahmedabad

Dr K Kotecha
Director,
Institute of Technology,
Nirma University,
Ahmedabad

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Jitesh Bajaj
13MICC08

Abstract

The aim of the thesis is to explore a co-simulation strategy for combined power plant simulation case studies. The combined cycle power plants have the prime mover system coupled with electrical systems. A combined cycle power plant process consists of Gas Turbine, Heat Recovery Steam Generator (HRSG), Steam Turbine, Electrical Generator, Electrical Transformer, Substation and Transmission Grid etc. Due to the stiffness of the system, it is a daunting task to model and study full dynamics of both electrical and process plant on a single platform package. A co-simulation approach is proposed as a solution to this problem. The proposed statement of work is to develop a hi-fidelity electrical models using Matlab Simpower System and integrate with the in-house process models, and validate this simulation with some industrial test cases conducted earlier. Matlab Simpower system is a simulation tool-box of M/s Mathworks with a focus on electrical modeling and simulation.

A similar co-simulation strategy is also proposed to utilize the capability of individual tools/packages as an extension of this work. Towards this, a co-simulation of combined cycle power plant model and to develop a dynamic load flow analysis algorithm to understand the dynamics of the multi-generator power systems. The proposed problem statement is to be addressed and solved by implementing the dynamic load flow tool which could work for 5 bus system. Finally the results are to be compared with Matlab Simpowersystems and other electrical modeling tools.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 General

This report briefs the initial exploration for a co-simulation based solution for a combined cycle power plant simulations. Modeling and simulation using digital computer can augment and support design process. This systematic and analytic approach to engineering problems allow user to test, investigate and validate wider scope, alternative design, failure modes and safety of environment and human beings. Modeling is the process of representing real world problems by a set of equations. It can be classified based on fundamental first principle based, experimental based or using both. A good model is always a judicious tradeoff between reality and simplicity. Simulation practitioners have recommended increasing the complexity of a model an iterative manner. Model validation techniques include the simulation of the model under known input conditions, disturbances and comparing results with existing validated results.

The power plants based on Hydro, Nuclear, Gas, Thermal energy etc. have been the major source of the power generation in the world. The power plants works on the basic principle of converting the mechanical energy from the prime mover into the electrical energy which is fed to the electrical grid connected to it. For example in the thermal power plant the water is heated in large boilers using the fuel as coal, the steam produced in the boilers is fed to the Steam Turbine having a prime mover which is in turn connected to the Electrical Synchronous Generator which converts the mechanical energy to electrical energy. Similarly, depending upon the thermodynamic cycle a Gas Turbine is also a source of generating the electrical energy. The efficiency of the a simple cycle power plant is less than the combined cycle power plant which is the combination of the Gas Turbine and steam turbines, where multiple processes are integrated to increase the efficiency of the overall plant.

Combined cycle operation deploys a heat recovery steam generator (HRSG) that captures heat from high temperature exhaust gases produced by the gas turbine outlet to produce steam, which is then supplied to a steam turbine to generate additional electric power. The process for creating steam to produce work using a steam turbine is based on the Rankine cycle.

The prime mover connected to the steam and gas turbine is then connected to the electrical synchronous generator which converts the Mechanical torque to the electrical energy through the faradays law of electrical generation. The electrical energy produced is at a certain frequency which is decided by the area of operation and production. For example 50 Hz in India and 60Hz in United states.

Gas turbines are internal combustion engine in which burning of air and fuel mixture produces very hot gases that rotate the turbine to produce power. Gas turbine utilizes different variety of fuels like syngas, natural gas and synthetic fuels. Combustion occurs continuously in gas turbines, as opposed to reciprocating IC engines, in which combustion occurs intermittently. Gas turbine generally has three basic controls acceleration control for startup, speed control to maintain shaft speed and temperature control to avoid thermal stresses in the combustion chamber.

Electrical power systems include the combination of the electrical circuits and electromechanical devices such as motors, generators, transformers etc. Matlab Simpowersystem is designed to provide the Simulink drag and drop interface to model the simple as well as complex power systems. The libraries of the Matlab Simpowersystem contains typical power equipments such as Electrical machines like simplified synchronous generator, motor, induction motor etc., power system components like transformers, load , windings etc.

1.2 Organization Perspective

General Electric (GE) is an American multinational conglomerate corporation incorporated in New York and headquartered in Fairfield, Connecticut. The company operates through the following segments: GE Energy Management, GE Oil & Gas, and GE Power & Water. , Technology Infrastructure, Capital Finance as well as Consumer and Industrial.

GE Power & Water has the following businesses:

- Power Generation Products (previously known as Thermal Products)
- Power Generation Services
- Distributed Power
- GE Hitachi Nuclear Energy
- Renewable Energy
- Water & Process Technologies

1.3 Motivation

The motive of the modeling and simulation of the power plant is to study the behavior of the steam and gas turbines and hi fidelity electrical systems. This aim of the assignment is the modeling and simulation of the simplified models of gas turbine and steam turbine incorporated with a small electrical grid using MatlabSimpowersystem. The study is aimed to study the dynamics of electrical system and to compare the results with the high fidelity electrical modeling tools.

1.4 Problem Identification and Analysis

1.4.1 Study of Existing Plan for Electrical Transient Studies

The current study of the electrical system is done with Concorda PSLF [10] which is Positive Sequence Load Flow tool which is renowned over the world for its electrical transients analysis. Concorda PSLF Dynamic Tools perform transient stability analysis for multiple events on cases containing more number of electrical buses. This tool is a java based tool allowing the execution of multiple dynamic simulations.

Figure 1.1: Existing Approach of Easy5 -PSLF

1.4.2 Problem Identification

The business demanded to search for the any other electrical modeling tool with existing system and test their performance with the PSLF results and to recommend the results and study of the project being done.
The tool selected for the initial phase of the project was MatlabSimpowersystem, which is renowned for its electrical modeling. The Simpowersystem is widely used for study of electrical power system stability analysis. Simpowersystem is the tool for the development of complex, power systems, such as those in power plants thermal or nuclear , and power utility applications to study the electrical transients. Simpowersystem has lots of capabilities and some sensitivity test studies to be done so as to co-simulate with other tools like EASY5.
Another approach is also being explored to have the 5 machine -15 bus electrical network home grown solver with a good network solver to overcome the challenges

which would arise while performing co-simulation platform with Matlab.

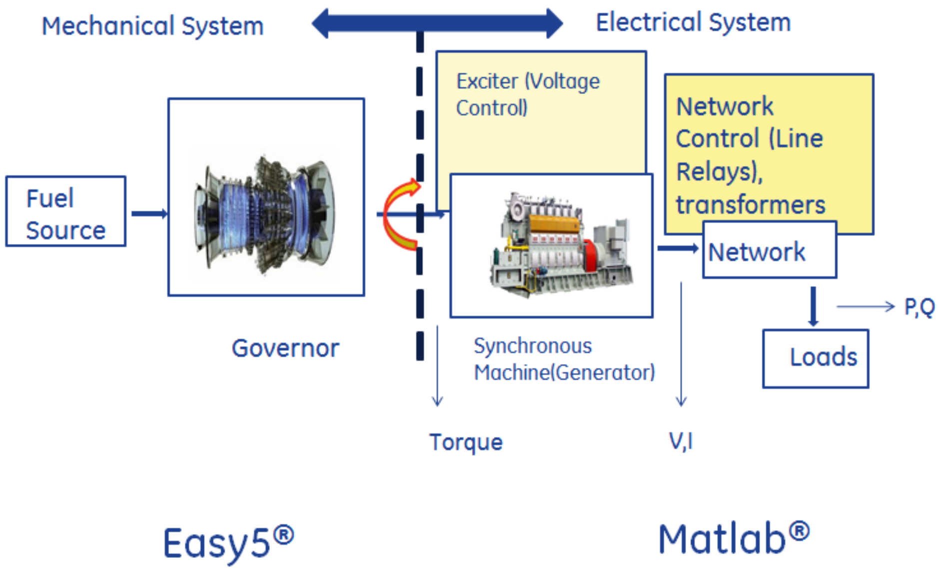

Figure 1.2: Purposed Solution Integration of Co-simulation platform

1.4.3 Problem Analysis and Proposed Solution

The problem was analyzed and purposed solution of implementing a co-simulation platform was decided to be adopted. The challenge was to form a bridge between Easy 5 and Matlabthrough some API or dll to pass variable to and fro between two simulation tools. The FMI protocol was used to incorporate the co-simulation platform as it is widely used by modelers and researchers these days. FMI take care of the step size communication step size and have some predefined structure for invoking a tool for the co-simulation environment.

Another solution was also proposed to have a fixed network electrical solver in Matlabor C++ as the business had a maximum case of two to three gas turbines for the study of electrical transients.

1.5 Organization of Project

The entire report is divided into following chapters, namely:

Chapter 1 Introduction to the project and motivation

Chapter 2 Literature survey and review of some papers

Chapter 3 Modeling and Simulation, focus on the Matlabmodels and EASY5 models

Chapter 4 Results and Discussions, focus on the Matlab, EASY5 model simulations results

Chapter 5 , Conclusion and Future Scope.

Chapter 2

Literature Survey

2.1 Steam Turbine

In order to characterize the behavior of the steam turbine a rigorous study on the steam turbine modeling is done via reading IEEE and Sciencedirect papers published in different years.

The IEEE paper Modeling of the Hydraulic Turbine and Governor for dynamic studies of High Pressure Turbine[1] focused on the modeling and simulation of the HPP turbine with water pressure as inlet and a synchronous generator. This aimed at the study of the nonlinear model of the turbine for studies concerning the large variation in Power output and frequency. This paper gave the very basic ideology to model the Hydraulic turbine. But the main focus was to model the Steam turbine which more or less works similar to hydraulic turbine.

The paper Steam Turbine Model published in Elsevier Journal [2] aimed at the modeling of the steam turbine which includes the three major sections i.e. high, medium and low pressure. The aim was to model High Pressure steam turbine. The behavior of the turbine is captured in the terms of mass and energy balance equations. The system dynamics were presented in the lumped manner for each section. The high pressure steam from the boiler system enters the turbine through the nozzle to increase the velocity of the steam. The pressure drop occurs as the steam passes through the buckets of the high pressure steam turbine. The mathematical relationship between the mass flow of the steam and pressure drop is given as follows:

$$\dot{m} = \frac{k\sqrt{Pin^2 - Pout^2}}{\sqrt{Tin}} \tag{2.1}$$

where K= Data collected from steam Turbine and Tables

Pin= Inlet Steam Pressure

Pout= Outlet Steam Pressure

Tin= Inlet Steam Temperature

m = Mass flow rate

For the development of the dynamic linear model the pressures, mass flow rate, temperature was gathered from the steam table. The energy equation of the steam turbine for the adiabatic expansion which relates to the output i.e. mechanical power Pm was given by:

$$Pm = \eta * \dot{m} * (hin - hout) \tag{2.2}$$

The subscript stands as follows-

Pm= Mechanical Power Output

= Efficiency of steam turbine

m = Mass flow rate

hin = Inlet heat enthalpy

hin = Outlet heat enthalpy

Following the work done in Power System Stability and control by Prabha Kundur implementation of the Speed governor of the steam turbine was done. The work was intended to model the steam turbine and governor especially High Pressure Steam turbine modeling. The block diagram of the Steam Turbine could be given as:

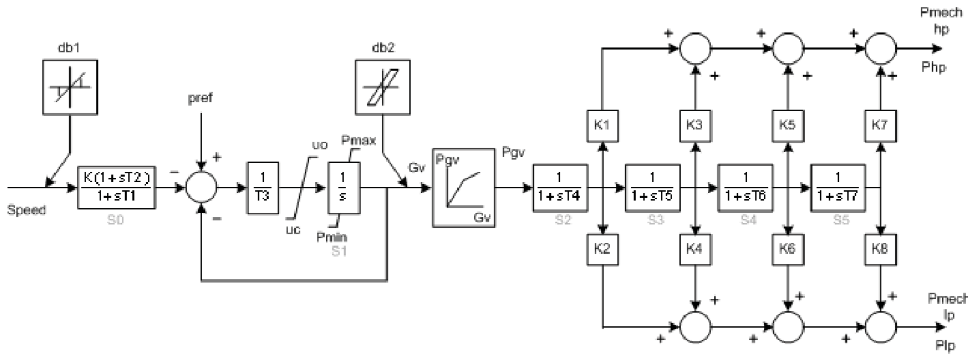

Figure 2.1: Steam Turbine with Speed Governing Model

2.2 Gas Turbine

The paper published in ASME of Engineering for power titled Simplified Mathematical Representation of Heavy duty Gas Turbine [3] by William I. Rowen was taken as reference for the modeling and understanding of the simplified gas turbine. The subject of the paper was to discuss about the working and control of the simplified gas turbine having three major controls Speed Control, Acceleration control and Temperature control. The paper discussed about both the gas fuel and liquid fuel based gas turbine. In the simulation part the speed control worked on the principle of the speed error and the corrective action applied for the 4 % droop setting. All the terminology used and quantities discussed were taken in PER UNIT system except the Temperatures. Full range of different heavy duty gas turbine from 18MW to 106 MW was covered with the simulation model.

The speed control in the gas turbine is the primary control as the shaft of the prime mover has to rotate at a synchronous speed depending upon the operational frequency i.e. 50 Hz or 60 Hz. The speed control worked on the synchronous speed error taken as the feedback and the set point provided with droop. The acceleration control was active during the startup of the gas turbine to limit the rate of rotor acceleration reaching to the governor speed thus to cancel out the case of mechanical stresses on the prime mover.

The temperature control was implemented because the output of the gas turbine is limited due to the firing temperature which is the temperature inside the combustion chamber which cannot be measured directly. It is taken as the reference of the exhaust temperature of the gas turbine which is measured through thermocouple and incorporation radiation shields.

These three controls in the simplified gas turbine model are fed to low selector switch based on the fundamental that which requires less fuel injection. The transfer of these controls is bumpless and without any time lags.

The basic flow diagram of the Rowens model is being discussed as follows in the diagram. The following assumptions were discussed in the paper were as follows:

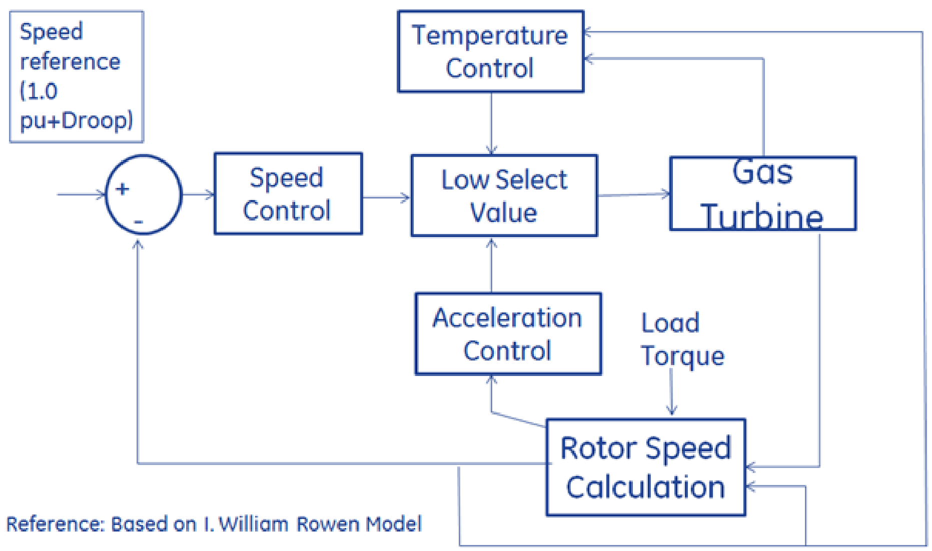

Figure 2.2: Low Fidelity Gas turbine Model based on William I Rowen

- The model is based on the simplified 1st order function with time lags.

- The exhaust temperature and load is not 100 percent accurate during the startup and the dynamics could be ignored.

- The model is to understand the basics of the gas turbine and the respective controls.

2.3 Electrical Power systems

2.3.1 Introduction to Power Systems

The major role of the power system is to generate the electricity using the power (mechanical) from prime mover to the electrical generator through simplified synchronous generators. From the electrical energy produced it is transmitted or distributed to different location and load connected to it. The transmission line interconnects all major generating station and main load centers in the systems. It forms the backbone of the integrated power system and operates at very high voltages i.e. 11 to 35 KV. Electrical power networks are in general three-phase system, the representation of the power system can be done using the positive sequence and taking the single phase only for the analysis.

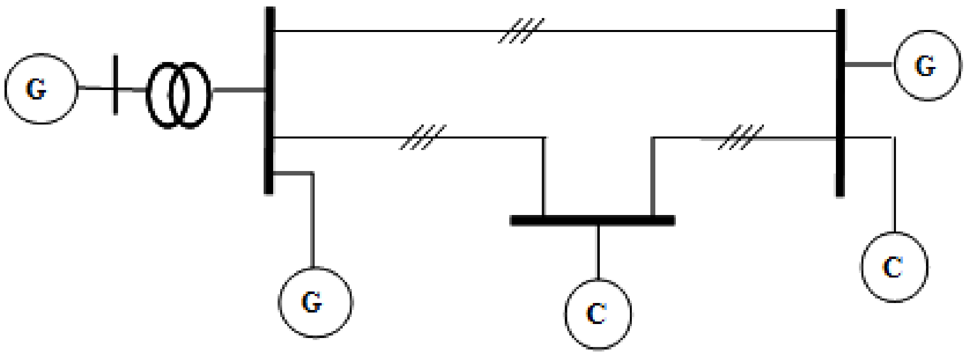

Figure 2.3: Single Line Diagram of Network

The operation and design of the electrical network is to maintain the stability and continuity of the power system. It is important to ensure that the system can withstand the failure of one or more parts of the power network without exceeding the specified safety limits. To implement preventive function to optimize the operation of the network, and ensure a certain recovery to a normal operating state. There are

two type of analysis done: static and dynamic simulation.
In static analysis, the electrical power system is at steady-state condition and the transient state is ignored. It is based on the fact that in order to ensure a good operation of a power grid, it is essential that the voltage in different areas of the network and the power (or current) flow is maintained within the acceptable limits.
In dynamic simulation, the response to any disturbance like the short-circuit, circuit tripping, loss of load, etc. is studied.
The swing equation was being discussed to study the small signal transients. The swing equation is given as follows:

$$J\frac{\partial w}{\partial t} = Pm - Pe - Kdw \tag{2.3}$$

Where,

J= Inertia of the Shaft
K= friction constant (damping factor)
Pm=Mechanical power generated from turbine
Pe=Electrical power delivered or consumed
w= angular frequency of the shaft

This equation is called as the equation of swing motion and is one of the important bases for angular and transient stability analysis. The solution of the equation gives evolution of the rotor angle , often called the internal angle of the synchronous machine, and can track the behavior of the machine against synchronism when a fault occurs in the network.
At steady-state there is always a balance between the mechanical power and electrical power. There is no acceleration and the machine runs at specified synchronous speed depending upon the region of operation. When there is a sudden load change or major fault in the network or a, the electric power suddenly changes. The mechanical power is expected to change this balance by acting on the turbine generation of the mechanical power. This is the role of speed (i.e., governor control). This action

is mechanical machinery has basically its own time constants which ranges between milliseconds that are naturally slower than electrical time constants which are generally in microseconds. This imbalance is to be reflected in the rotor speed which will accelerate or decelerate depending upon the imbalance in the system. In fact, if mechanical power is greater than the electric power, the excess energy will be transformed into kinetic energy in the rotor. This phenomenon or disturbance generally causes the rotor to accelerate and therefore deviate from its rated synchronous speed. This type of phenomenon occurs mainly during a sudden change in the network (e.g., short-circuit, rapid increase or decrease of the load, etc.).

These phenomena are accompanied by electromagnetic transients, which in turn impact the models used in synchronous machine. The synchronous machine is modeled from the simplest to the most complicated, depending on the phenomenon to be studied and the desired degree of accuracy.

2.3.2 Literature Survey on Power System Stability Analysis

The book Power System stability and control [4] by Prabha Kundur discussed about the various aspects of the power generation basics and components used the power generation systems. It showcased the different aspects of electrical system, structure, stability and control of the power stability in the power station and power plants. The study related to the per unit systems in the electrical systems was discussed in the book which is a major contributor to the studies related to power system s generations and stability.

For further literature survey the book Elements of Power system analysis [6] by William D Stevenson was done to study the power flow analysis and to accomplish the goal of load flow analysis in the electrical systems. The book helped in the study relation to solve the load flow analysis by different methods like GAUSS SEIDEL METHOD and NEWTON RAPHSON METHOD.

The paper Modeling of Power Systems Using of Matlab/Simpowersystem [7] discussed about the very basic study related to the electrical grid and idea about how the electrical grid works at different voltage levels.

The important literature survey on the study of load flow analysis and the grid modeling was done from the book Power System Analysis, Arthur R. Bergen and Ajay Vittal[8]. The book discussed about the creation of the simplified generator model, Bus impedance matrix, Bus admittance matrix. The book helped in the study related to the solving of the load flow analysis via Gauss Sidel Method and designing the whole concept of the Grid.

Another important literature survey was done from Power system dynamics and stability [13] by Peter W. Sauer and M.A Pai. The book helped to understand the electrical Phasor simulation and modeling of different component of electrical system. The book talked about running the Phasor simulations for the electrical systems. It helped in learning quickly all the synchronous generator model which could upto 7th order depending upon the type of study. The load flow algorithm was adapted from this book to get all the node voltages and angles on each bus of the system. The book was very useful to understand the multimachine dynamics which plays a vital role in the power system studies.

The IEEE guide for Synchronous Generator Modeling Practices in Stability Analyses[14] sponsored by Power system engineering and electrical machinery committees discussed about the dynamic nonlinear modeling of synchronous machine and different type of stability model. It basically encounters the saturation problem and use of exciter system.

The IEEE Guide for Synchronous Generator Modeling Practices and Applications in Power System Stability Analyses[15] discussed about the various categories of stability cases which are commonly performed during power system studies and the synchronous generator modeling practices and requirements.

The paper Power System Dynamic Response Calculations[16] by Brian Scott in 1979 discussed about the step by step the numerical solution of the electrical system modeling and the interface errors in occurred while the numerical integration. The paper concentrates on solution concepts and computational techniques rather than on the analysis of the numeric method. The paper also discussed about the different algorithms to solve electrical differential and algebraic equations by partitioned or simultaneous solution for these equations. Another similar paper Improved simulation techniques for power systems by R.B.I Johnson, M.J.Short includes the solution of the non-linear algebraic and differential equations which describe the dynamics of a power system. The numerical problem in time integration such as the treatment of discontinuities, control of round-off and truncation errors, and numerical stability are discussed.

2.4 Co-Simulation Platform

The core of the thesis depends upon the co-simulation platform. The study was made on the co-simulation of two modeling tools so as to have a seamless transfer of data between the tools.
The Matlabhas provided the Engine APIs to call the Matlabengine via dynamic link libraries (dlls). The study was done using the Matlab, the language of technical computing (Application program interface Guide) [9]. The manual discussed about the mex function to be called by integrated development environment (IDEs) using any programming language.

For our purpose the EASY5 works on FORTRAN compiler and the code was written in C++ and via the concept of programming language was called in the EASY5 model.

2.4.1 Functional Mockup Interface for Co-simulation

The intention of the FMI is to provide an interface standard for the coupling of simulation tools in a co-simulation environment. The data exchange between subsystems of different models in different tools is restricted to discrete communication points.

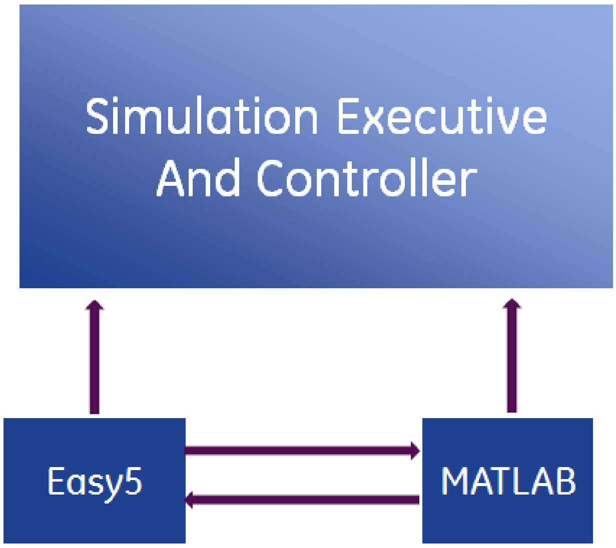

Figure 2.4: Co-simulation Platform

The models are solved independently from each other in different modeling tools by their individual solver and have different time stampings. Master algorithms control the data exchange and the synchronization of all simulation solvers between subsystems.

The function mockup interface has three major files which are always the part of the .fmu file which is a .zip file with an extension as .fmu

- An XML file contains the declaration and definition of all the variables in the function mockup unit and other static information about the model such as input, output, data types, index number etc.

- C code which contain all the solver details and equations of the model to be solved or the scripts of the different modeling tool to be ran

- An image file to represent the model

2.4.2 FMI-Matlab

The FMI for Matlabuses the Engine API functions, available in Matlabto call the Matlabfrom outside world. The methodology behind the approach was to incorporate those functions inside the FMI 2.0 standard and initiate the call.

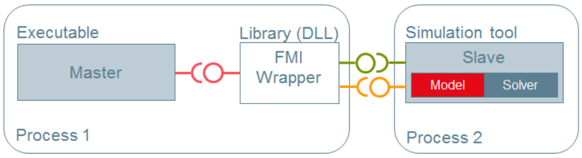

Figure 2.5: FMI-Matlab Communication

Chapter 3

Modeling and Simulation

3.1 Modeling and Simulation of Low fidelity Steam and Gas Turbine

3.1.1 Low fidelity High Pressure Steam Turbine Modeling with Governor

The process of a steam turbine generator of high pressure side is as follows:-

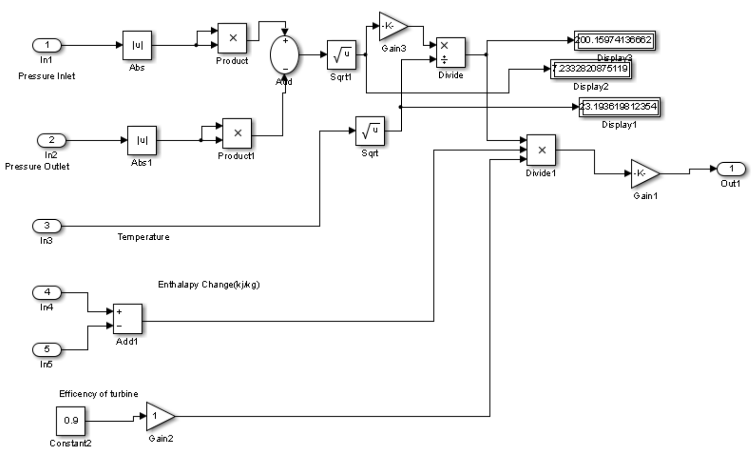

Figure 3.1: Steam Turbine with Speed Governing Model

From the reference of the paper discussed in the literature review in section 2.1, the following simplified low fidelity model of Steam turbine was built. The data taken for the simulation parameters was taken from the steam table available with the company. The simulation studies were done on this and still going for further analysis. The steam turbine developed was only the High Pressure section.

3.1.2 Simplified Steam Turbine Model with Simple Synchronous Machine and Loads

After the implementation of the simplified high pressure steam turbine the mechanical power developed was given to the input of the simple synchronous generator. The generator was connected with the same Megawatt load i.e. 100 MW and then through the transformer the circuit breaker a small load was connected to analyze the change in frequency. The speed governor was implemented to maintain the speed

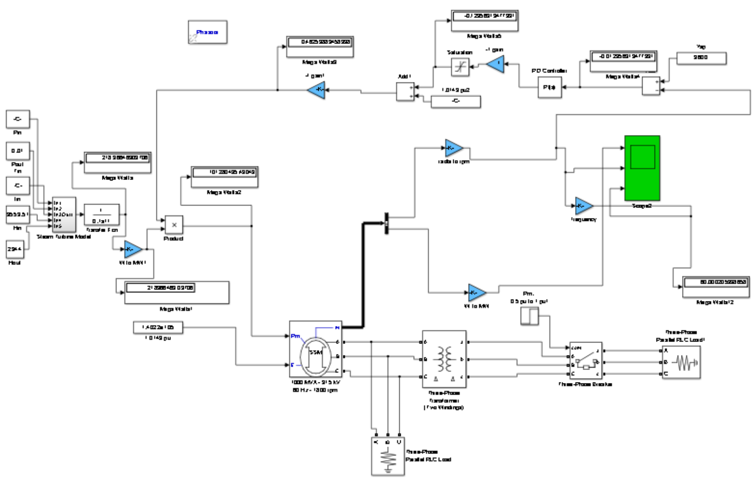

Figure 3.2: Simplified Steam Turbine Model with Simple Synchronous Machine and Loads

of the shaft at constant rpm even if there was small change in load.

3.1.3 Low fidelity Gas Turbine Modeling

Low fidelity Gas Turbine Modeling in Matlab

The simplified gas turbine model was discussed in the section 2. 2, with reference to the literature survey it was developed in Simulink Matlab. All the three controls were implemented. The solver used was ode4 (Runge- Kutta) for the simulation with a fixed step size of 1 ms. The simulation studies are further going on and the model was connected to infinite electrical grid model. The model was with the 4% droop setting and was setup for a turbine generation capacity of 106.7 MW. The model was simulated and results were collected and are showcased in chapter 4.

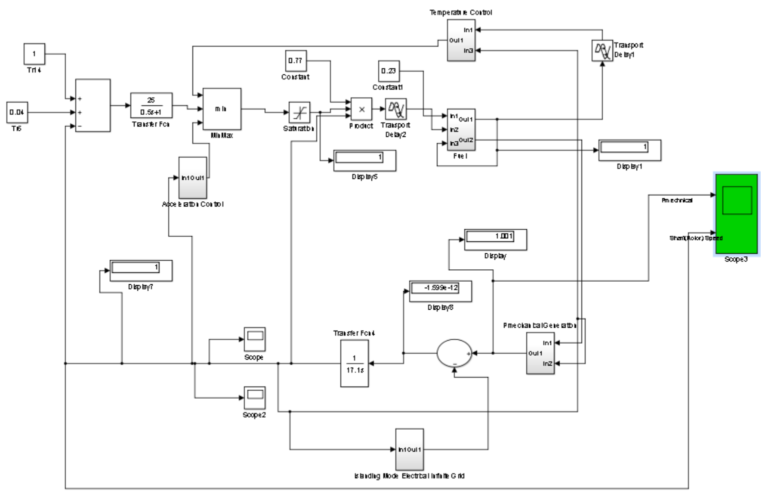

Figure 3.3: Low fidelity simplified Gas Turbine Model in Matlab

Low fidelity Gas Turbine Modeling in EASY 5

The simplified gas turbine model discussed in the chapter was built in the EASY 5. The model was run with the Euler solver with a step size 1ms. The model has a droop setting of the 4% and was capable of a generation of 106.1 MW. The whole model was in per unit system. The model was incorporated with the DLLs of the Matlab calling engines so as to have a co-simulation setup ready between the EASY5 and

Matlab Simpowersystems. The model was built using the General Purpose libraries of EASY5.

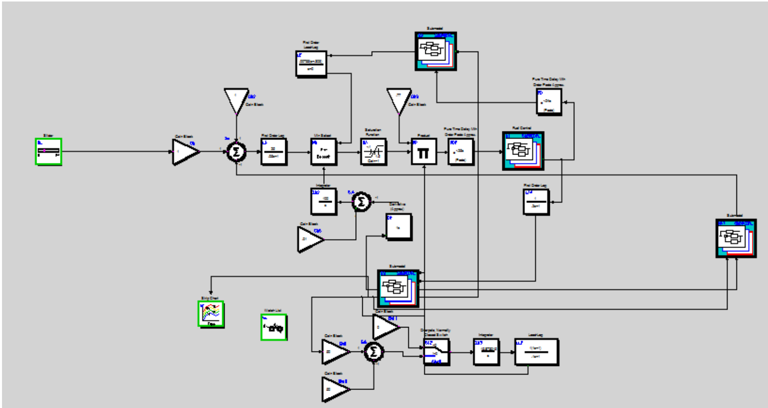

Figure 3.4: Low fidelity simplified Gas Turbine Model in EASY5

Simplified Gas Turbine Model with Electrical Model

The simplified gas turbine model discussed earlier was incorporated with the electrical system. Both the model was in Matlab Simulink environment. There were two gas turbine modeled and were taken to base load of 100 MW and then at some point 10% load was shed through circuit breaker opening. Both the turbine parameters were plotted and analysis was done.

3.2 Sensitivity test for Electrical systems in Simpowersystem for Co-simulation

The electrical modeling of one of the test site is under development in Matlab Simpowersystem. Some sensitivity tests were done on the model for the real time application while running with the co-simulation environment. For the application of our system the in the co-simulation environment and the test cases the model standalone had to pass through some sensitivity tests. The electrical model built in the Simpowersystem

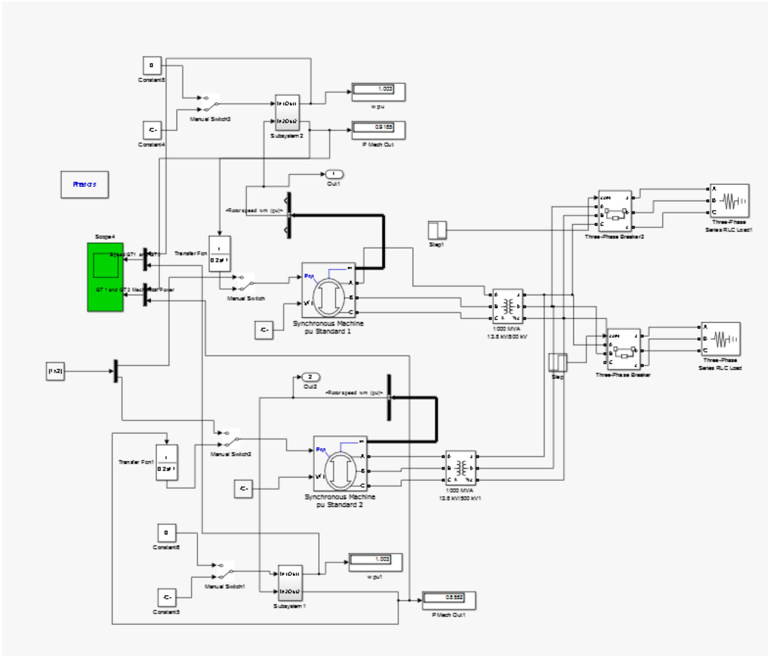

Figure 3.5: Simplified GT model with Electrical Network

contained 3 generators, transformers, loads and current measurement. Different case scenarios were simulated with different time stamping and study was completed.

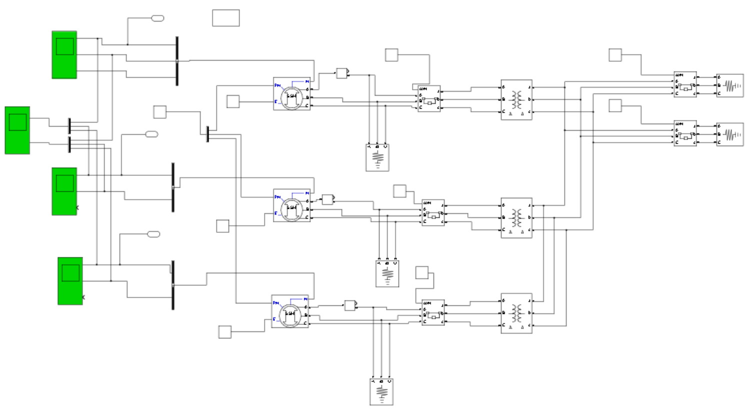

Figure 3.6: Grid Model of one of the Test Site

The grid model was developed as per the site of the plant. The following cases were done on the model:

3.2.1 Heavy load throw off contingency

In this case scenario all the three machines started at 85 MW each and were in islanded mode. The load throw off contingency was introduced in the network at t=0.5 seconds. The network was simulated with different time stampings and solvers to understand the transient stability of the system and to check whether we could use the model in the co-simulation platform.

3.2.2 Different numerical solver

Numerical solution of the ordinary differential equations is important in the converging of the states of the system. There are many solvers available in the Matlab Simpowersystem which have the effect on the simulation of the model. All these sensitivity test of the numerical solver methods were done on the system to know which system had the faster response than the other.

3.2.3 Heavy load throw off and machine trip scenario

In this case scenario all the three machines started at 85 MW each and were in islanded mode. The load throw off contingency was introduced in the network at t=0.5 seconds and at generation throw off the two GTs were done at t=0.6 second the results were plotted. The network was simulated with different time stampings and solvers to understand the transient stability of the system and to check whether we could use the model in the co-simulation platform.

3.3 Co-simulation of High Fidelity Gas Turbine Model with High Fidelity Electrical Model in Matlab

The high fidelity model of the gas turbine with all the actual controls was setup in the Easy 5 and a complex Simpowersystem model in Matlab. This setup was made to understand the effect of high fidelity model of the gas turbine with all the actual controls was setup in the Easy 5 and a complex Simpowersystem model in Matlab.

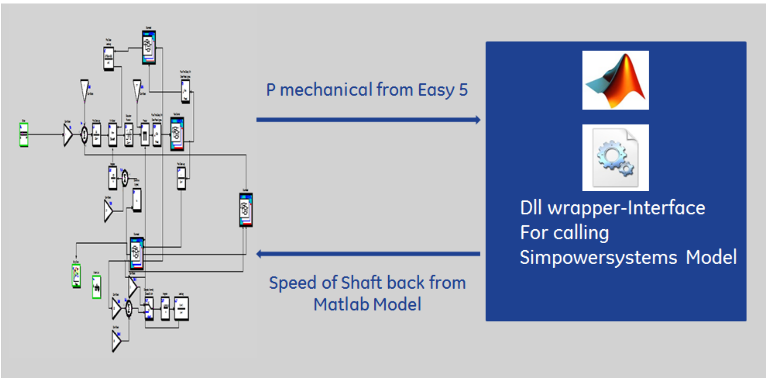

Figure 3.7: Pictorial View of Co-Simulation Platform Modeling

The plots were plotted between the different control and major parameters to understand the effect of electrical transients on the model and controls. The results were validated with the actual site results and model of electrical system in PSLF by concorda which as world renowned tool for electrical simulations.

Two case studies of a 2 GTs plant and a 3 GTs plants were done with the co-simulation environment and the results are discussed in the chapter of results and discussion.

3.4 Power System Stability : A Fixed Network Approach

The fixed network modeling of the electrical system arises from the drawbacks of Simpowersystem for co-simulation. The sensitivity test has proved that the Simpowersystem is a renowned tool for electrical simulations but for the co-simulation environment the step time of the model is less. The business has 90% of cases which has the maximum of 2-3 Gas turbines only. So, it is proposed to make the electrical modeling and network solver to be made in Easy5. For this a prototype is made in Matlab because of the Matlab computation benefits and solvers.

Power system stability is the ability of an electric power system, for a given initial

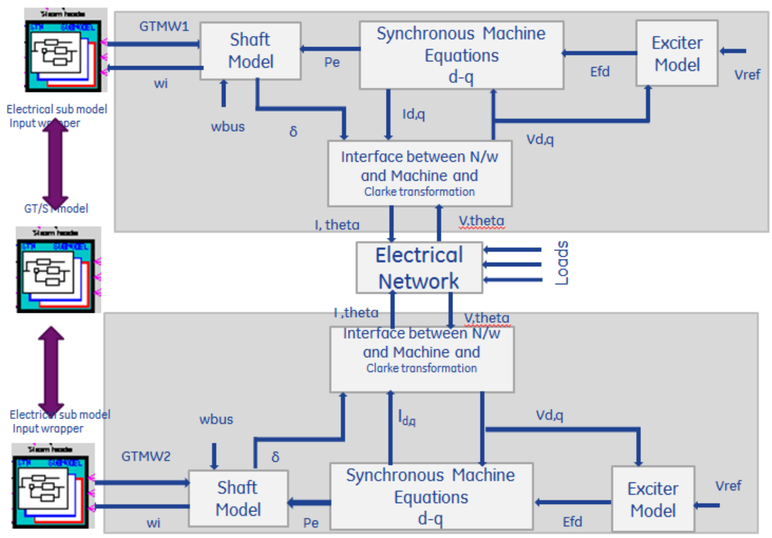

Figure 3.8: Block Diagram of Fixed Network Electrical Simulation

operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs and key operating parameters change continually. When subjected to a disturbance, the stability of the system always depends on the initial operating condition as well as the nature of the disturbance.

For this study with the high fidelity models of gas turbine, a fixed network solver approach is proposed. This section briefs about the modeling of synchronous machine, exciter and Load flow algorithm.

3.4.1 Swing Equation

Under normal operating conditions, the relative position of the resultant magnetic field and rotor axis is always kept fixed. The angle between these two quantities is known as the machine angle power angle or torque angle. During any imbalance in the system or fault the frequency of the system dips in other words the machine is not at its rated synchronous speed.

3.4.2 Load Flow Studies

A load flow study plays a vital role in aspects of power system planning and operation. The load flow study provides the steady state of the entire system voltages, real and reactive power generated and absorbed and line losses at all the specified.. Through the load flow studies the voltage magnitudes and angles at each bus in the steady state can be obtained. It is very important as the magnitudes of the bus voltages at different buses are required to be held within a specified operational limit. The bus voltage magnitudes and their angles are calculated from the load flow; the real and reactive power flow through each line can be computed very easily. Also based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed.

For the formulation of the real and reactive power entering a bus, Let the voltage at the ith bus be denoted by:

Chapter 4

Results and Discussions

4.1 Results and Discussion of Modeling and Simulation of Low fidelity Steam and Gas Turbine Simulations

4.1.1 Simplified Steam Turbine with Generator

The simplified steam turbine model discussed in the chapter 2 was implemented in Simulink Toolbox in Matlab.The results were as follows the:

- The power generator was fed to synchronous machine of 100 MW and the load flow analysis was done.

- The speed of the steam turbine shaft was at 3600 at the steady state condition. Due to 2 pole machine used the frequency generated by Synchronous machine was 60 Hz.

- At t=60, the load of 50 MW was connected to the electrical system through 3 phase circuit breaker, that was the reason for drop in frequency and speed at t=60.

Figure 4.1: Steam Turbine with Speed Governing Model

- For the frequency to be controlled at constant value the speed governor tries to bring back the frequency at 60Hz.
- This study was done to view the transients in the frequency due to load addition or rejection.

4.1.2 Simplified Low Fidelity Gas Turbine in Matlab

The simplified low fidelity I. Rowen model was implemented in Simulink Matlab as discussed in chapter 2. Following results were deduced from the simulation:

- The starting torque for the turbine shaft to rotate was at 0.4 pu. When the start command was hit the speed of the shaft started increseing to 1pu. The acceleration control was active during this to avoid the mechanical stress.
- At t=0, the gas turbine was at full speed no load condition and was ready to

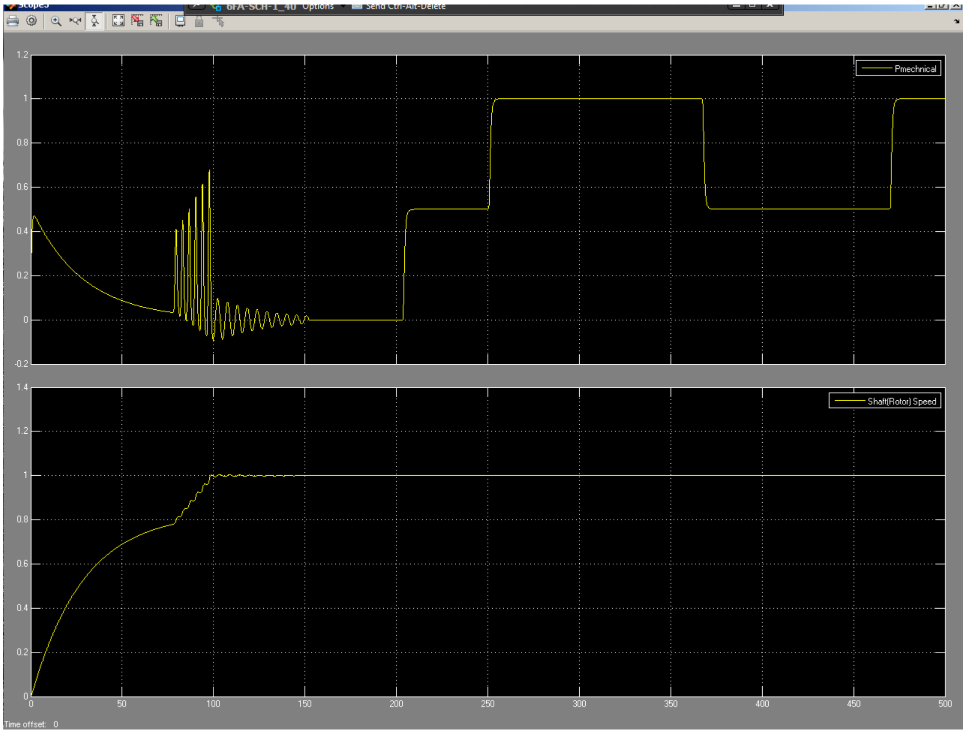

Figure 4.2: Steam Turbine with Speed Governing Model

be loaded.

- At this point the infinite grid was connected to the model. At t=210 the load command of 50% load was given to the turbine and turbine reached at 0.5 pu.
- At time t= 250 the command for baseload i.e. 1.0 pu was given and the turbine was loaded to baseload.
- This study was intended to understand the different control of the gas turbine and working.

4.1.3 Simplified Low Fidelity Gas Turbine in EASY5

The simplified gas turbine model low fidelity model discussed was also built in EASY5. The results were taken out and are discussed here as follows:

- The starting torque of the m/c was 0.2 p.u.

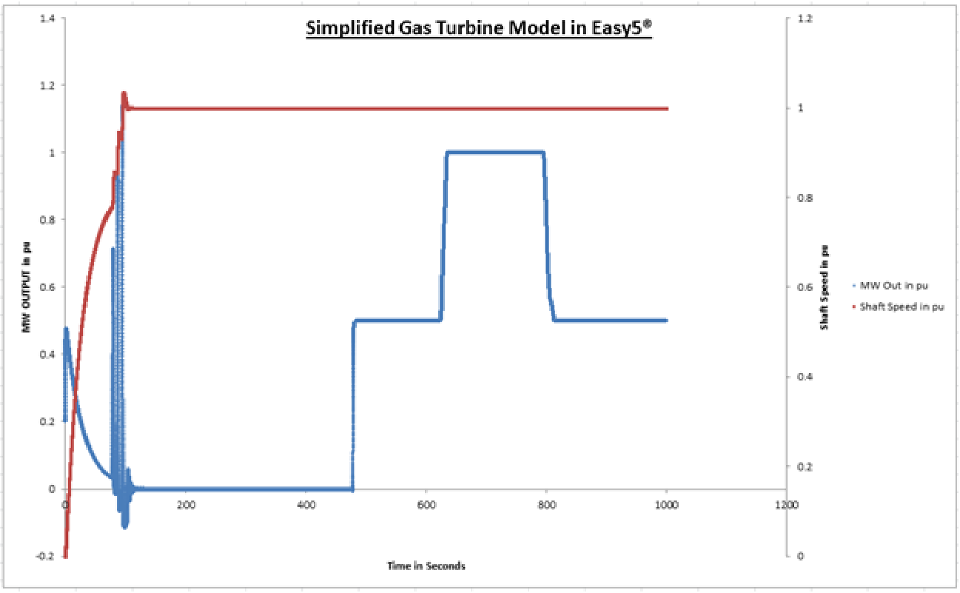

Figure 4.3: Simulation of Low fidelity simplified Gas Turbine Model in Easy5

- When the start command was give the Speed of the shaft increased to 1 p.u. Durring this period the accerlartion control was active
- Finally when the speed reached the 1.0 pu the Sync command was given so as to get the Power mechanical equal to power electrical and loading of m machine could be started.
- At t= 300 the machine was synchronised and the machine was ready to load.
- At t= 475 the machine was given the command of 0.5 pu which is a part load.
- At t= 650 the machine was given the command of 1 p.u and it reached baseload.

Dicussion: Comparing the results of the figure 4.2 and figure 4.3, it looks approximately same. But the important conclusion from this is that the oscillations are due to approximations made during the setup of model. The model was an important part to understand the basics of gas turbine simulations and controls acting on it.

4.1.4 Rowen's Gas Turbine with simplified controls-Electrical network connected to it

The simplified low fidelity I. Rowen model with Electrical netwrok was implemented in Simulink Matlab as discussed in chapter 2. Following results were deduced from the simulation.

The transients were introduced at t=175 and the 10% load was shed then with very simplified governor control the speed was brought back to 1 pu.

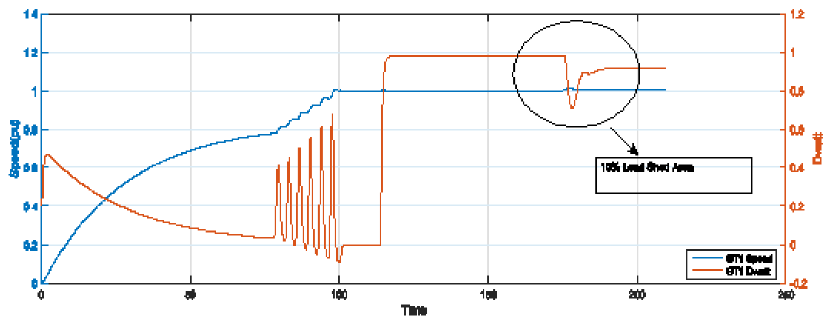

Figure 4.4: Response of Shaft Speed (GT 1) during a Load Throw off in GT 1

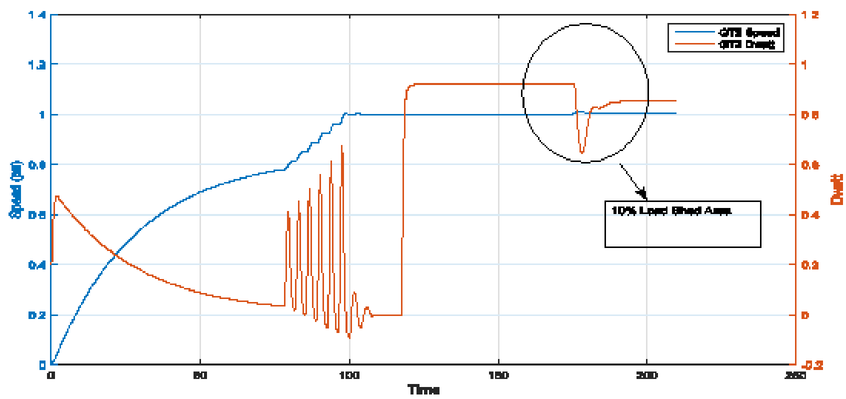

Figure 4.5: Response of Shaft Speed (GT 2) during a Load Throw off in GT 1

4.2 Results and Discussion of Sensitivity test done on Simpowersystem for co-simulation

Sensitivity test study was done to compare the dependency of the solver used and the step time on the Simpowersystem model for different cases. Following are the results plotted from the Matlab after the two cases:

Table 4.1: Sensitivity test done on Simpowersystem for co-simulation

Case /Simulation Time	Load throw off With ode 4 solver	Load throw off With ode 8 solver	Load and Machine throw off with 4 solver	Load and Machine throw off with 8 solver
0.1ms	Yes	Yes	Yes	Yes
1ms	No	No	No	No

a. Heavy load throw off at 0.6 sec

b. Load and machine throw off at 0.64 sec simultaneously

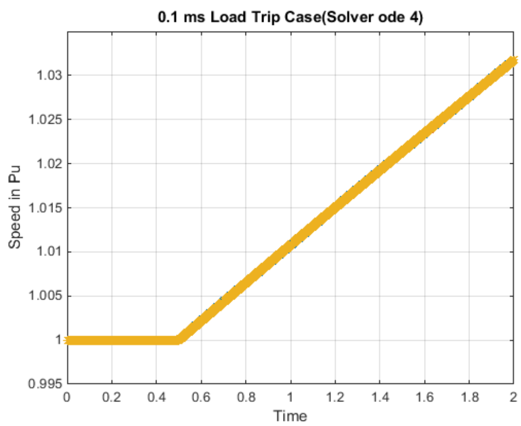

Figure 4.6: Sensitivity Studies Test Curves

This does not show that Matlab Simpowersystem is not an efficient tool but for the co-simulation with Easy5 these cases may not run.

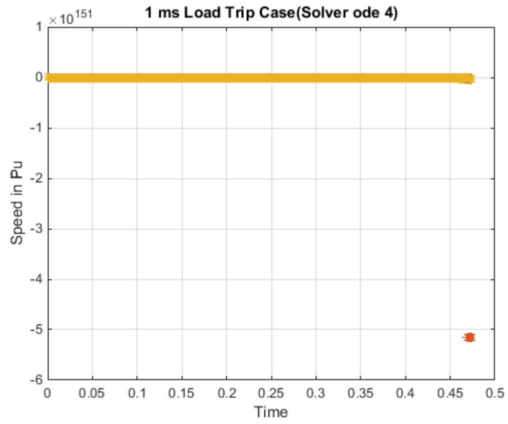

Figure 4.7: Sensitivity Studies Test Curves

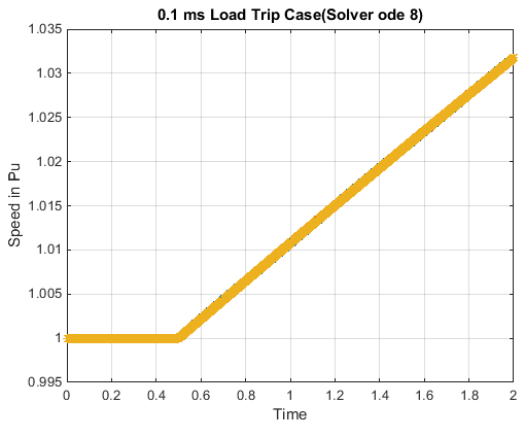

Figure 4.8: Sensitivity Studies Test Curves

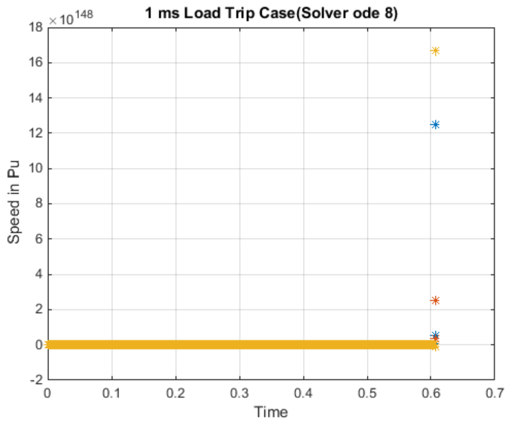

Figure 4.9: Sensitivity Studies Test Curves

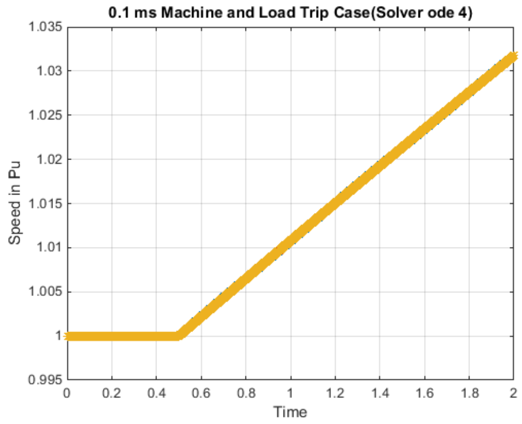

Figure 4.10: Sensitivity Studies Test Curves

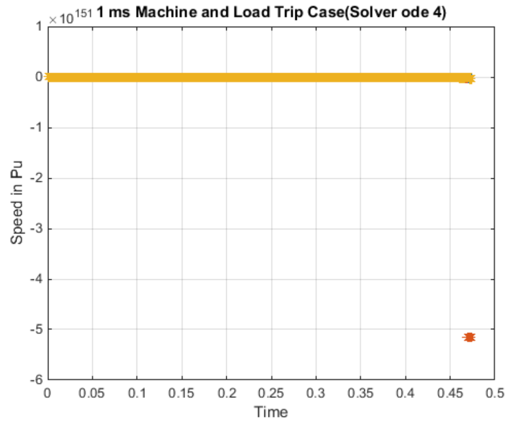

Figure 4.11: Sensitivity Studies Test Curves

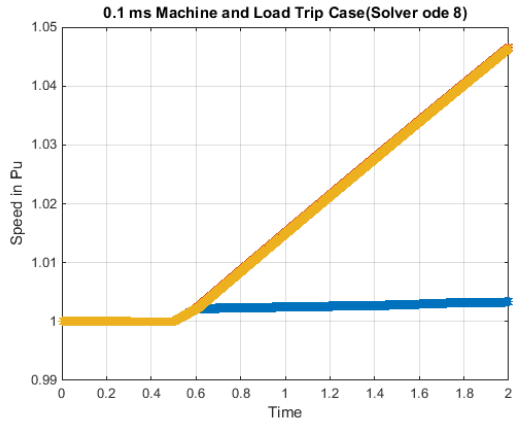

Figure 4.12: Sensitivity Studies Test Curves

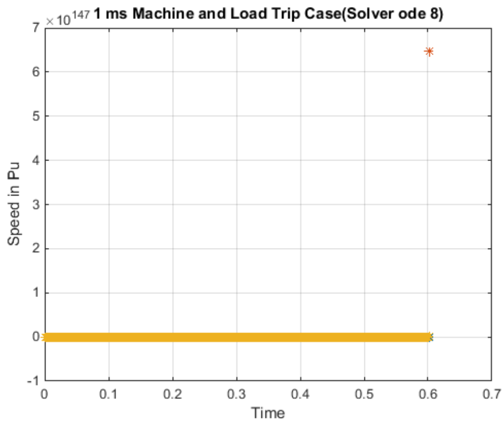

Figure 4.13: Sensitivity Studies Test Curves

4.3 Results and Discussion of Modeling and Simulation of High Fidelity Gas Turbine and high fidelity electrical modeling in Simpowersystem

4.3.1 Two Gas Turbine case

The high fidelity model of GEs in-house Gas turbine site was simulated in the Easy 5 and via co-simulation set up the model was interacted with the Matlab Grid model discussed and results were plotted. Following inferences were taken after the simulation.

- The high fidelity model in Easy5 had two Gas Turbines and was taken to base load.
- The control algorithms of the Gas Turbines were used and fall under proprietary information and could not be shared.
- The major and important parameters such as MW output, Inlet Guide Vanes angle, Fuel stroke Reference and Exhaust temperature were taken into consideration for the study.

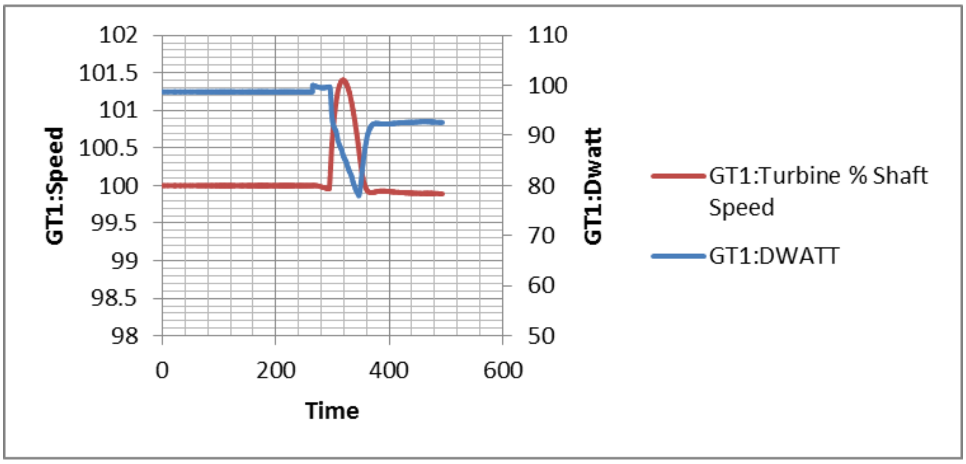

Figure 4.14: Response of Shaft Speed (GT 1) during a Load Throw off in GT 1

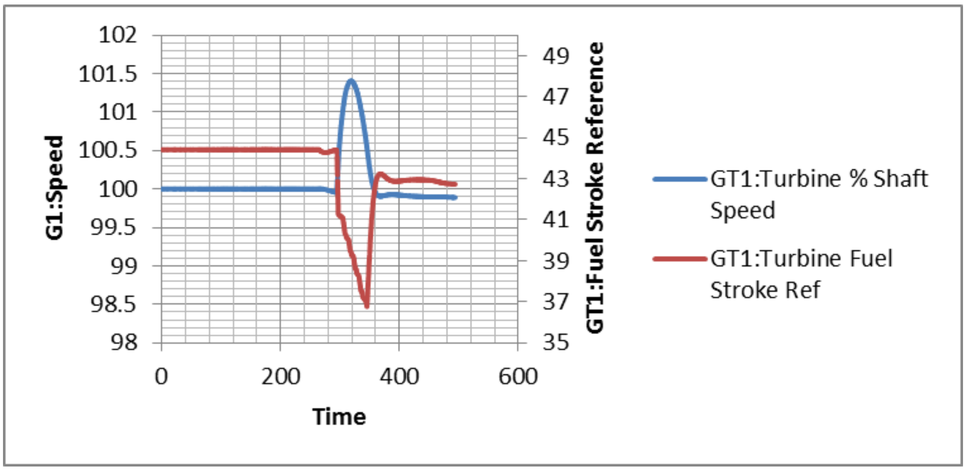

Figure 4.15: Effect on Fuel Stroke Reference (GT 1) during Transients

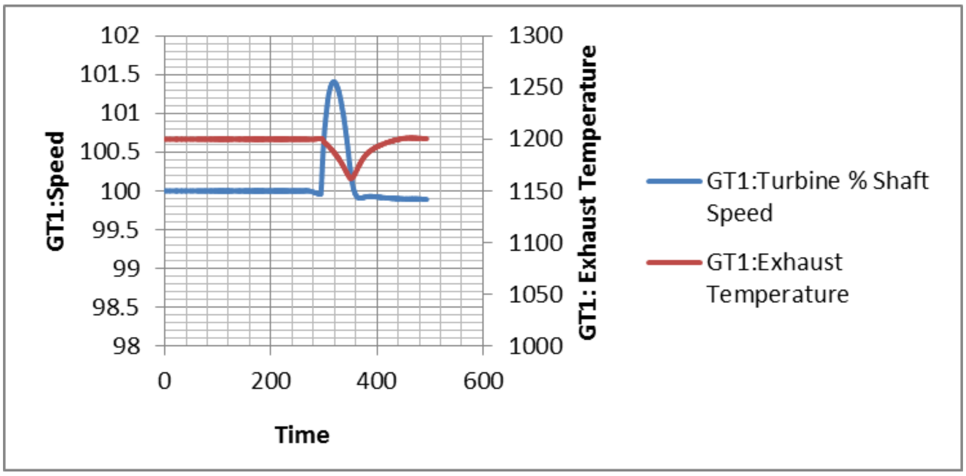

Figure 4.16: Effect on Exhaust Temperature (GT 1) during Transients

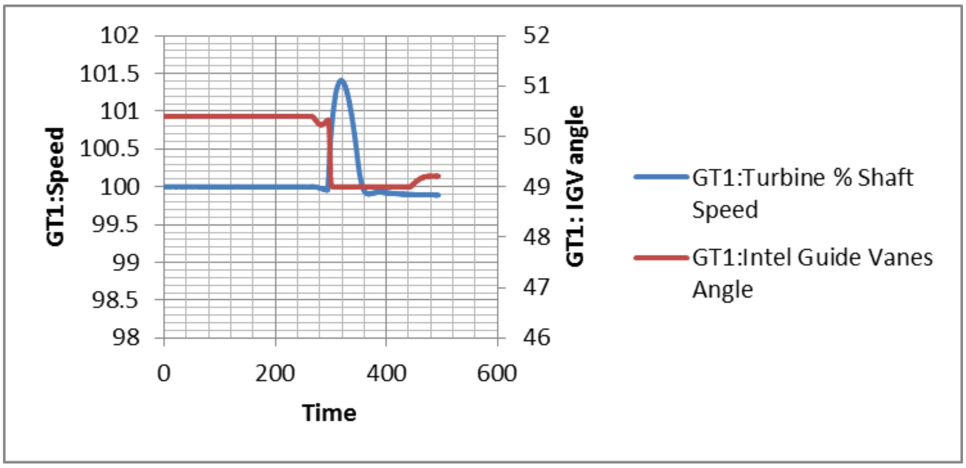

Figure 4.17: Effect on inlet guide vanes angle (GT 1) during Transients

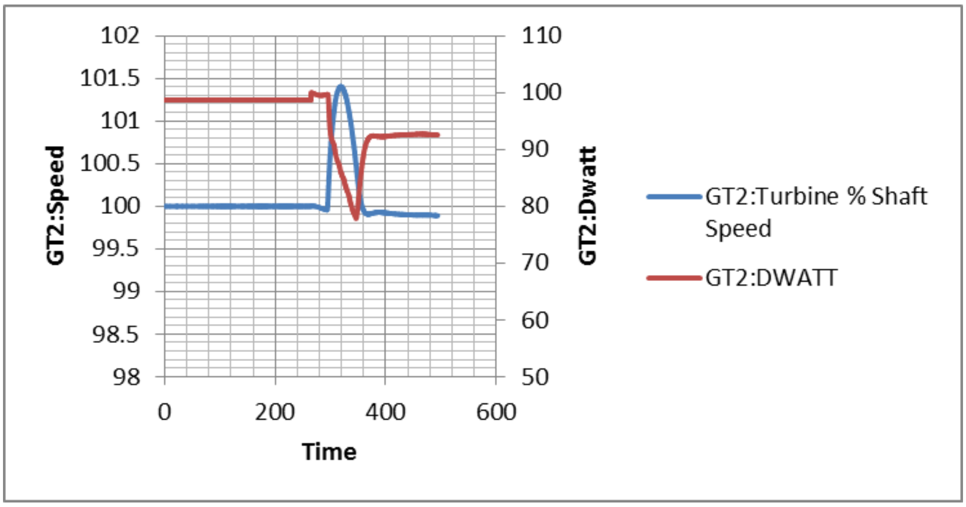

Figure 4.18: Response of Shaft Speed (GT 2) during a Load Throw off

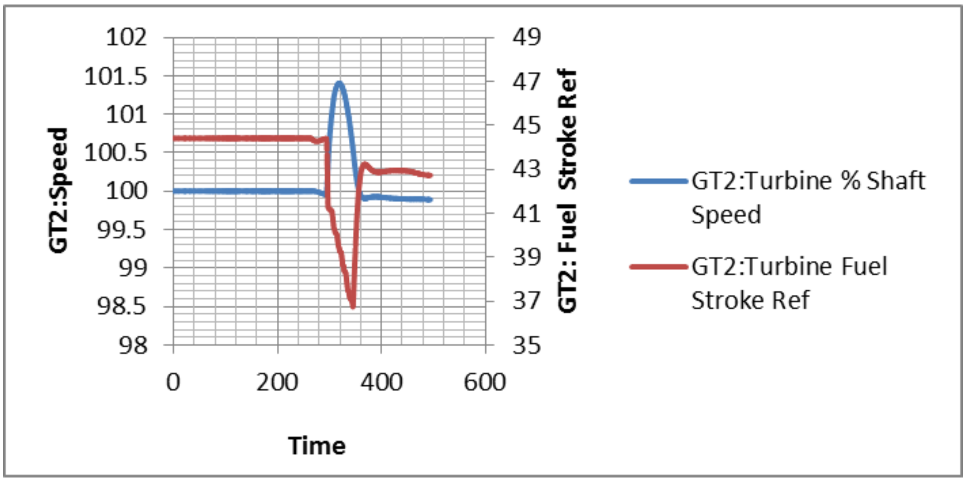

Figure 4.19: Effect on Fuel Stroke Reference (GT 2) during Transients

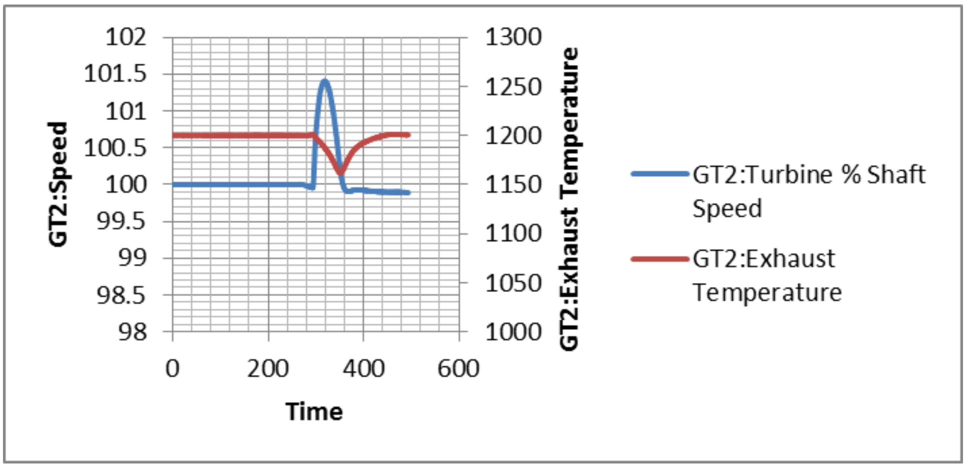

Figure 4.20: Effect on Exhaust Temperature (GT 2) during Transients

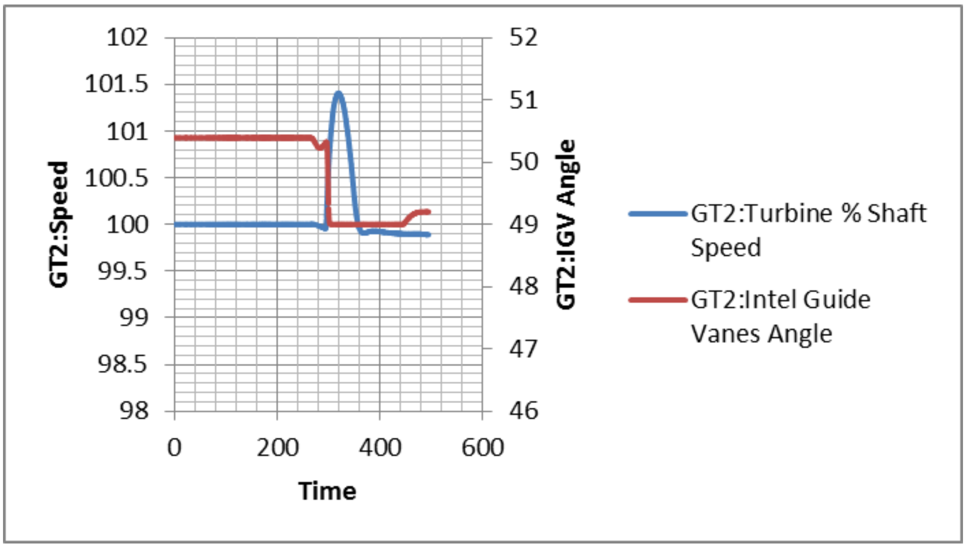

Figure 4.21: Effect on inlet guide vanes angle (GT 2) during Transients

Dicussion: The graphs 4.14 and 4.18 show the increase in speed of the shaft when there is a load shedding in the electrical side. The response is desired as the electrical power is decreased and mechanical power of the turbine is higher. The controls come into action by reducing the fuel command and airflow to the machine which can be seen in the graphs. The control is expected to work in this fashion and try to stabilize the speed of the shaft with in certain range to inhibit the malfunctioning the machine parts and other accessories. This study helped to us to understand the need of co-simulation platform for the electrical studies to be done not on a single platform or simplified governor.

4.3.2 Three Gas Turbine case and comparison with PSLF

Case 1: All the GTs are at 105 MW and after that a load shed of 105 MW

Inferences from Graphs

a. All the gas turbines start with 105 MW each with a load demand of 315 MW

b. At t=9 there is a shedding at load side of 105 MW and all the GTs are islanded

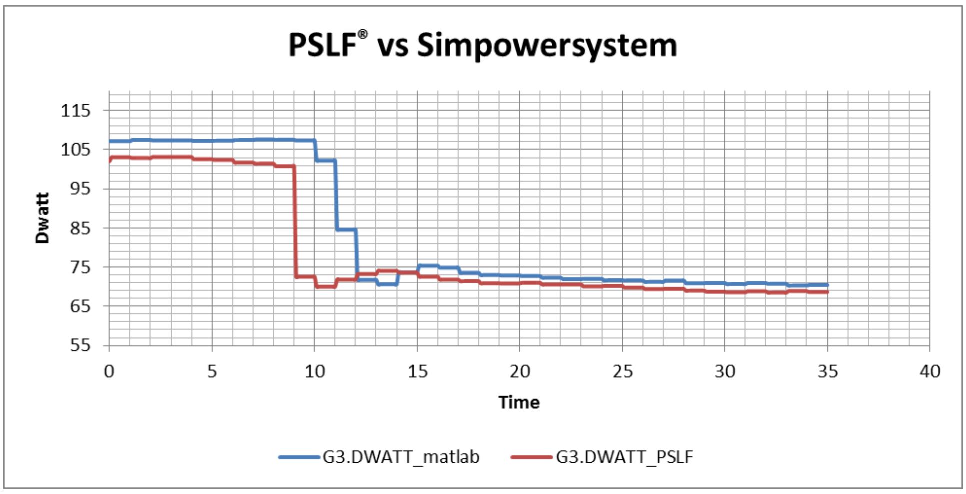

Figure 4.22: Effect on DWATT during Transients

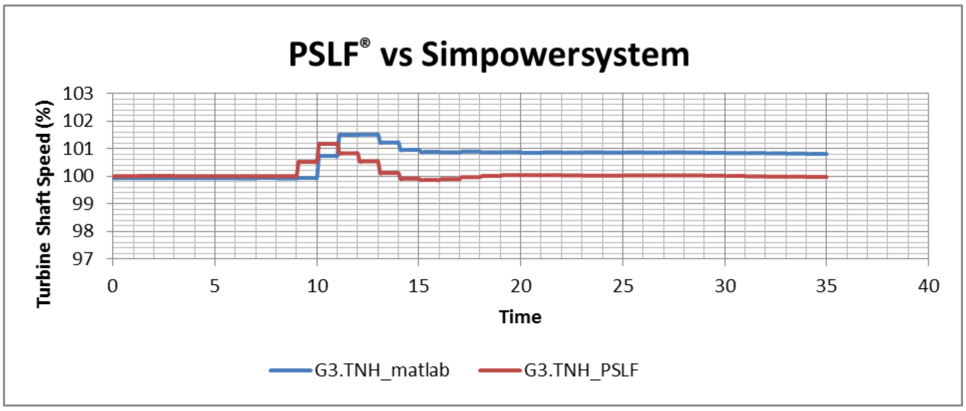

Figure 4.23: Effect on Turbine Shaft Speed during Transients

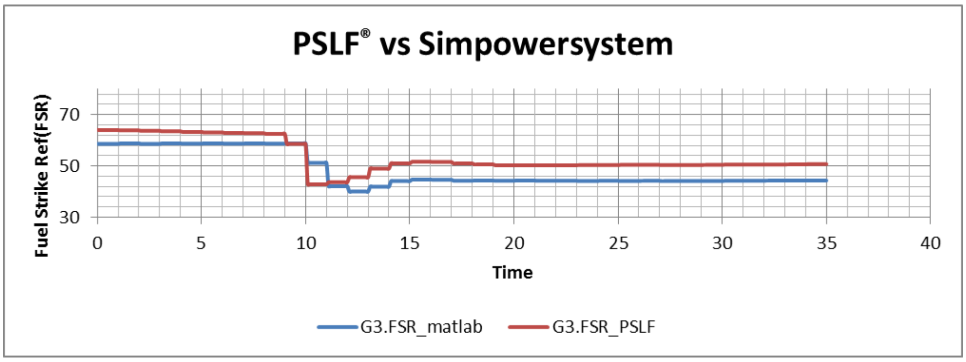

Figure 4.24: Effect on Fuel Stroke Reference during Transients

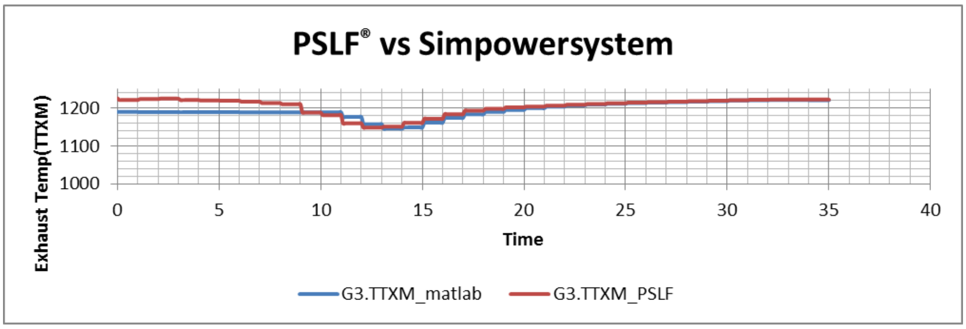

Figure 4.25: Effect on Exhaust Temperature during Transients

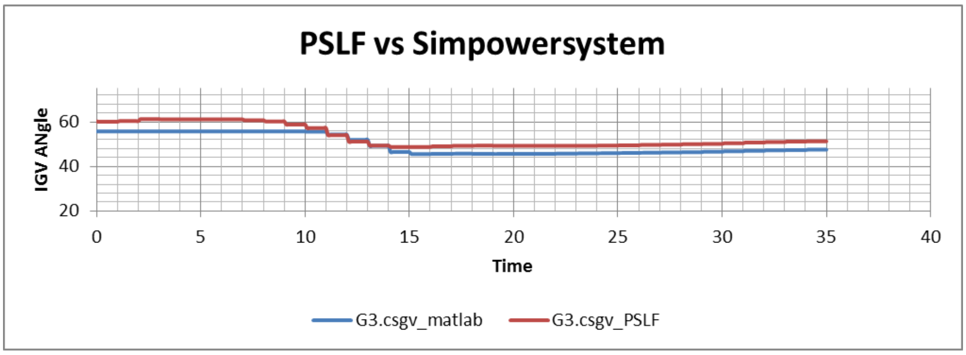

Figure 4.26: Effect on inlet guide vanes angle during Transients

c. Just after the shedding the Island command of 105 MW comes to all GTs and they try to bring back the speed to 100%.

d. A maximum overshoot of 101.5 % in speed is noted which was then compared with results of PSLF and comparison is done

e. Vital parameter of Gas turbine 3 is compared with the PSLF results and a satisfactory response is there.

f. The speed in case of Simpowersystem settles at 100.8% which is 0 6 higher than the PSLF but in stable range and this is due to the generator losses not being modeled in the Simpowersystem.

4.4 Results and Discussion of studies of Home Grown Electrical Solver

The load flow studies had been done and the following results were taken out and compared. The WSCC 9 bus system is used in many places for load flow references, the load flow for this case was simulated and following results were obtained.

Table 4.2: Load Flow Results

Bus No.	Voltage Magnitude	Phase Angle	Active Power Generation	Reactive Power Generation	Active Power Load	Reactive Power Load
1	1.04	0	0.7164	0.2704	0	
2	1.025	9.2800	1.6300	0.0665	0	0
3	1.025	4.6647	0.8500	-0.1085	0	0
4	1.025788	-2.216	0	0	0	0
5	0.995631	-3.988	0	0	1.250	0.5
6	1.012654	-3.687	0	0	0.9	0.3
7	1.025769	3.719	0	0	0	0
8	1.015883	0.7275	0	0	1	0.35
9	1.032353	1.9667	0	0	0	0

The results of the WSCC 7 bus system made in home grown electrical solver were compared with the Simpowersystems by replicating the same in it. One line diagram developed in Matlab.

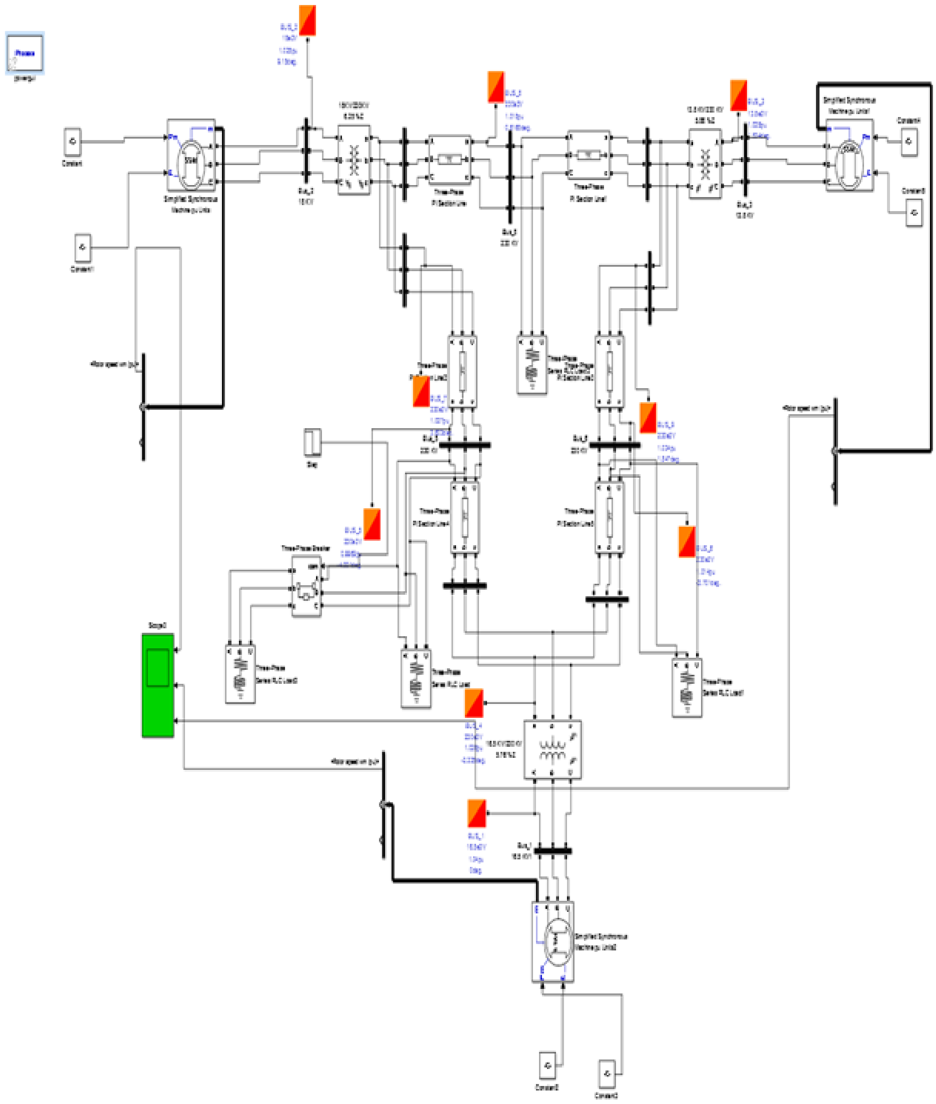

Figure 4.27: WSCC 9 Bus System

The load throw off of 10% load was simulated and the results of the home grown solver and Simpowersystem model was plotted

Inferences from Simulation:

a. There is a difference of the 0.0035pu in settling speed after the load throw of contingency, this is because of the approximate modeling of pi-model line,

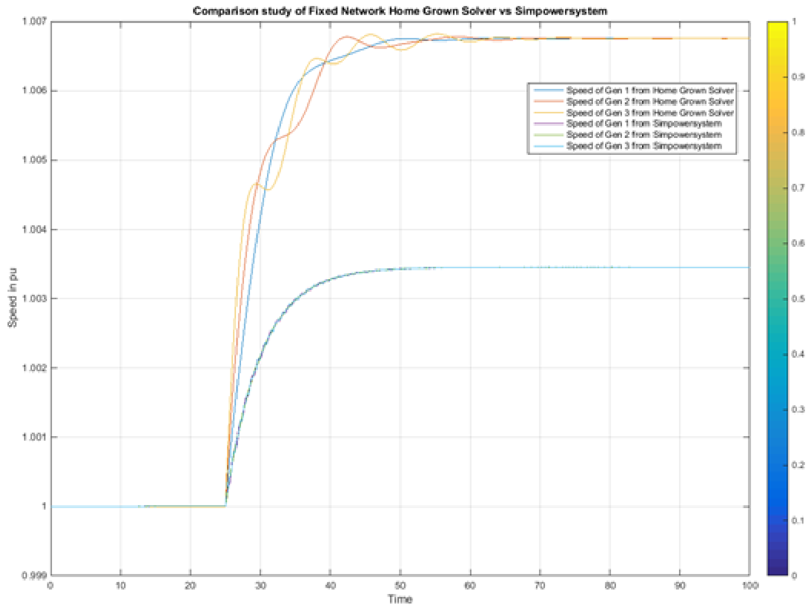

Figure 4.28: Comparison study of Fixed Network home grown solver vs Simpowersystem

circuit breaker and transformer in Home grown solver.

b. The Simpowersystems model is a high fidelity model and contains detailed modeling of these elements.

c. The fixed network algorithm is still under testing with other IEEE cases as well and next target is to model the detailed modeling of components in electrical network.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

The studies done during the phase of the internship focused on the modeling and simulation of steam and gas turbine, electrical system in the Matlab and network solver algorithm in Matlab. The studies are important in the learning of modeling and simulation of stiff electro-mechanical systems. After studying the co-simulation platform strategy and requirement, there is a great demand of co-simulation platforms where different models can talk to each other and handshaking of signals. The co-simulation platform, FMI based structured protocol has a great potential to make the tools comply with co-simulation standards.
Durring the studies of the thesis and work done following points, conclude the thesis:

- Electromechanical system of power plant are very critical in power generation. The system are very stiff and heavily coupled to each other.

- Standalone tools like EASY5, Matlab, PSLF etc are very pronouced tools used all over the world.

- Co-simulation of such different tools is required to study the coupling of mechanical and electrical systems.

- Functional mockup interface is a co-simulation platform protocol which has the potential and is getting renowed for its generic capabilities.
- Matlab Simpowersystem is a world wide tool used for electrical and mechanical system behaviorial studies, for the co-simulation with Easy 5 communication step size plays a vital role.
- Different test cases of co-simulation with Easy 5-Simpowersystem the response of the simulation is in comparision range with the Easy5 PSLF co-simulation.
- After studying the electrical power systems stability , the home grown network solver has produced a great learning for the modeling of electrical network, loads, synchronous genrerator. The electrical system is a combination of differential and algebric equation so tightly coupled with each other.
- Reseacrchers and academics thesis and results shows that there is a lot of potential to write your own algorithm of electrical solvers.

5.2 Future Work and Scope

- The future work will be to validate the results of the co-simulation of the Easy5 PSLF, Easy 5 Simpowersystem to be compared with the home grown electrical solver which needs to be validated and tested before release.
- To automate the process of making the co-simulation platform for Matlab under FMI standards.

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