DESIGN OF FUZZY LOGIC CONTROLLER FOR SMALL HYDRO PLANT

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in Power System Engineering)

By

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JUNE, 2006

CANDIDATE'S DECLARATION

This is to certify that the report which is being presented in this dissertation entitled "**DESIGN OF FUZZY LOGIC CONTROLLER FOR SMALL HYDRO PLANT**" in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Electrical Engineering**, with specialization in **Power System Engineering**, submitted in the Department of Electrical Engineering, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during a period from November, 2005 to June, 2006 under the supervision of **Dr. J. D. Sharma**, Professor, Electrical Engineering Department, Indian Institute of Technology, Roorkee.

The matter embodied in this report has not been submitted by me for the award of any other degree or diploma.

Date: - 26-06-06

Place:- IITR

(Sreenu Musham)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr. J. D. Sharma,
Professor,
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ACKNOWLEDGEMENT

"Aim for Success, not perfection. Never give up your right to be wrong, because then you will lose the ability to learn new things and move forward with your life."

- Dr. David M. Burns

My foremost and profound gratitude goes to my guide **Dr. J. D. Sharma,** Professor, Electrical Engineering Department, Indian Institute of Technology Roorkee, Roorkee, for his proficient and enthusiastic guidance, useful criticism, encouragement and immense help. I have deep sense of admiration for his innate goodness and inexhaustible enthusiasm. The valuable hours of discussions and suggestions that I had with him have undoubtedly helped in supplementing my thoughts in the right direction for attaining the desired objective. Working under his guidance will always remain a cherished experience in my memory and I will adore it throughout my life.

My heartfelt gratitude and indebtedness goes to all the teachers of **PSE** group who, with their encouraging and caring words, constructive criticism and suggestions, have contributed directly or indirectly in a significant way towards completion of this report.

I am highly grateful to Shri S.D Mishra and Shri G.K Singh, Lab. Technicians, CAD Lab. for providing the required facilities and cooperation during this work.

I also thank all the research scholars, my colleagues for their advice and sparing time to helping me out in the time of need.

Special, sincere and heartfelt gratitude goes to my parents, my brother, my sisters and my friends whose sincere prayers, best wishes, support and encouragement have been a constant source of assurance, guidance, strength, inspiration and upliftment to me.

(Sreenu Musham)

ABSTRACT

In this dissertation work, a Fuzzy Logic Controller is designed for run of river small hydroelectric plant to study its behavior under normal and emergency conditions using MATLAB SIMULINK.

The various components of small hydroelectric plant like, governor, penstock and turbine, synchronous generator, exciter, transmission Line are considered in simulation.

FLC's as Governor and Exciter are designed based on fuzzy set theory. The controller is suitable for real time operation, with the aim of improving the generating unit transients by acting through the exciter input, guide vane position.

In these FLC, generator speed deviation and acceleration are taken as controller inputs for both the Exciter and governor. These inputs are first characterized by linguistic variables using fuzzy set notations. A fuzzy relation matrix is built to give the relationship between controller input and controller output. To demonstrate the effectiveness of FLC, A Power system subjected to 3-phase fault under different operating conditions is performed. It is found that the FLC can improve the dynamic performance of a SHP over a wide range of operating condition. Since the FLC does not require model identification, it can be easily implemented in computer simulation.

Using this application, the dynamic behavior of a small hydroelectric plant under isolated and Gird connected conditions can be studied when subjected to disturbances such as- load-variation, three-phase symmetrical fault, speed reference setting variation. This will also help in tuning the parameters of governor, exciter and checking the preliminary design of small hydro plants.

CONTENTS

Nomenclature

General: -

X = state variable,
p = d/dt (derivative operator),
s = Laplace transform operator,

For Turbine and Penstock: -

L_p = penstock length in m,
L_t = common tunnel length in m,
A_t = common tunnel cross section area, m^2
A_p = penstock cross section area, m^2
Q_r = rated water flow rate of turbine, m^3/s
H_r = rated head of turbine, in m,
H_o = base head of turbine, in m,
G_r = rated gate position,
f_p = friction loss coefficient,
A_t = turbine gain constant,
T_w = water starting time constant, in seconds
T_{wt} = water starting time constant, for the common tunnel only,
T_{wi} = water starting time for the penstock of the ith unit,
P_t = turbine rating,
D_t = turbine damping constant,
Q_{nl} = no-load water flow rate,
Z_o = hydraulic impedance of penstock,
T_e = penstock wave travel time,
A = wave-velocity,
P_{mech} = mechanical power,
T_{mech} = mechanical torque,
j = number of units,
Qi = discharge in the penstock i.

For Governor: -

ω_{ref}	= reference speed,
ω_r	= rotor speed,
T_p and T_a	= pilot valve time constant of hydraulic governor,
K_s	= servo gain of hydraulic governor,
T_g	= main servo motor time constant of hydraulic governor,
R_t	= temporary droop of hydraulic governor,
T_r	= reset time of hydraulic governor,
R_p	= permanent droop,
K_p	= proportional gain of PID governor,
K_i	= integral gain of PID governor,
K_d	= derivative gain of PID governor,
T_c and T_d	= gate servo motor time constant of PID governor,
R_{max}	= maximum gate opening rate limit,
R_{min}	= minimum gate opening rate limit,
G_{max}	= maximum gate opening limit,
G_{min}	= minimum gate opening limit,
Gate	= gate position.

For Exciter: -

V_{ref}	= reference voltage,
V_{ter}	= generator terminal voltage,
T_t	= voltage time constant,
T_c and T_d	= transient gain reduction (TGR) time constant,
K_a	= amplifier gain constant,
T_a	= amplifier time constant,
K_e	= exciter gain constant,
T_e	= exciter time constant,
A and B	= saturation constant,
K_f	= stabilizing circuit gain constant,

T_f	= stabilizing circuit time constant,
K_c	= rectifier constant depending on commutating reactance,
K_d	= ac exciter synchronous and transient reactance constant,
I_n	= rectifier load current,
F_{ex}	= rectifier regulation depending upon I_n,
I_{fd}	= field current,
I_{lr}	= feedback rate limit,
K_{lr}	= feedback rate limit,
V_{max}	= maximum amplifier output,
V_{min}	= minimum amplifier output,
V_{rmax}	= maximum regulator output limit,
V_{rmin}	= minimum regulator output limit,
E_{fd}	= exciter output voltage,

For Synchronous machine:

d, q	= d and q axis quantity,
R,s	= Rotor and stator quantity,
l , m	= leakage and magnetizing inductance,
f,k	= field and damper winding quantity,
φ	= instantaneous flux linkages.

Chapter-1

Introduction

Chapter-1
Introduction

Presently the world is in the throes of an energy crisis that has recorded and will continue to reorder, our perceptions of how to power the infrastructures on which we have to depend. To reduce the dependency on fuels with price volatility, fast depleting natural reservoir of their other sources of energy and near saturation of larger hydro plants has prompted engineers to focus on other alternatives. Small hydro power is reemerging as one of the alternatives, which are easily developed, cost competitive and minimally disruptive to the environment.

1.1 Small Hydro Plant Model

The SHP Model represents the simulation of various components of high and medium head and small hydro plant. The main components of a hydroelectric system may be classified into two groups: the hydraulic system components that include the turbine, the associated conduits- like penstock, tunnel and its control system; and secondly the electric system components formed by the synchronous generator and its control system.

The performance of hydraulic turbines is strongly influenced by the characteristics of the water conduit that feeds the turbine. These characteristics include the effect of water inertia, water compressibility and pipe wall elasticity in the penstock. Hydroelectric turbines present a non-minimal phase characteristics due to water inertia; this means that a change in the gate opening produces an initial change in the mechanical power which is opposite to the requested. The water compressibility effect produces traveling waves of pressure and is rise caused by stopping the flow too rapidly. The wave propagation speed is around 1400 m/s.

This dissertation considers two cases; in general the synchronous generator is connected to infinite bus one with the fault disturbance and the other is load variation (reduction or increment in load), local load will be used at generator terminal. The functional block diagram for the simulated circuit is shown in figure 1.

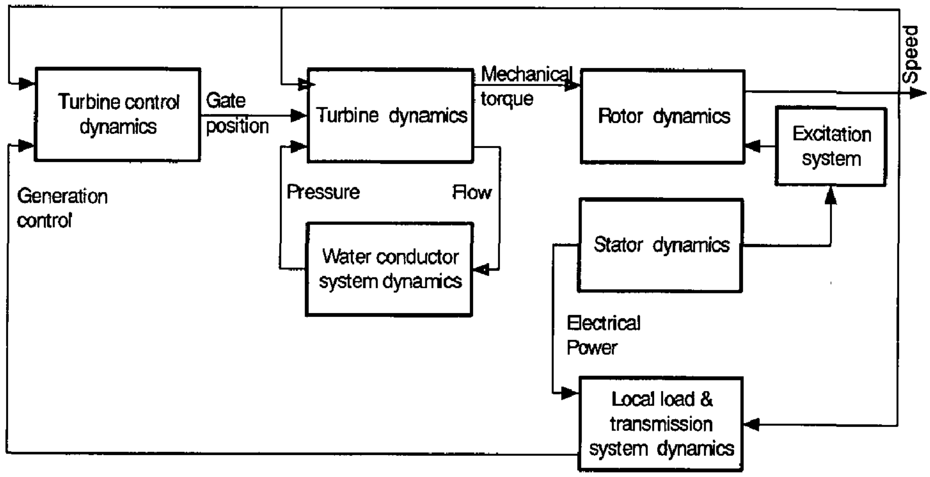

FIG. 1 FUNCTIONAL BLOCK DIAGRAM OF SIMULATED SYSTEM

1.2 Fuzzy logic control of SHP.

A typical Hydro power plant includes a dam or a mountain reservoir, penstocks a powerhouse and an electrical power substation. The reservoir stores water and create the head; penstock carry water from the reservoir to turbine inside the powerhouse [9]. The water rotates the turbine, which drive generators that produce electricity. A hydraulic turbine is a hydropower machine that directly converts the hydraulic power in moving water to mechanical power at the machine shaft. Turbine governors are systems for the control and adjustment of the turbine power output and evening out deviations between power and the grid load as quickly as possible. Excitation controllers have been widely employed to enhance system damping and to improve dynamic stability. The gain setting of these controllers are

1.3 Modeling and Simulation of Small Hydro Plants:-

Modeling and simulation of a small hydro plant is a valuable tool for planning operations and judging the value of physical improvement by selecting proper system parameters. This study helps in verifying cost and safety conditions, in selecting the best alternatives in the early phase of design and to determine the requirement of special protection devices. It also helps in finding parameters of control equipments like water level regulator, governor, exciter etc. and in determining the dynamic forces acting on the system which must be considered in structural analysis of the penstock and their support.

Dynamic response of the hydraulics, governor and electrical system associated with small hydro plants can also be obtained with this simulation, which provides information about the performance of the entire system following system disturbances such as turbine start up, turbine loading, load rejection and movement of wicket gates. It provides the effect of interaction between hydraulics system, the governor and the electric system. It helps in studying the stability problem associated with the system.

In brief, simulation studies provide answers to many critical questions to designing and planning engineers such as: -

- The analysis of the stability and operational problems and their remedies,
- Co-ordination of governor parameters with those of the hydraulics and electrical systems and selection of optimal governing parameters,
- Detailed assessment regarding the dimension of penstock and the necessity of a surge tank, when considering the effect of water hammer,
- Questions based on cost, operational; and environmental considerations.

1.4 Organization of Report:-

The project report is organized in to five chapters and the work included in each chapter is briefly outlined as follows:-

The present chapter-1 describes the concept of FLC, and also concerns with the purpose of modeling and simulation of small hydro plant.

Brief literature survey on the modeling concept of various components and Fuzzy logic control theory of small hydro plants is presented in chapter-2.

The chapter-3 deals with the block diagrams and/or mathematical equations of various components of small hydro plants.

Chapter-4 gives the details of fuzzy logic controller and design procedure of governor and excitation controller.

The chapter-5 concerns with data used for simulation purpose and results obtained after simulation.

The chapter-6 includes the discussion on simulated result obtained, limitations of the developed simulator and scope for future work.

Chapter-2

Literature Review.

Chapter-2

Literature-Review

There are many literatures available highlighting the design of Fuzzy logic controller modeling and simulation concept of various components of hydro-plants and focusing on:-

1). Defining stability boundaries of hydraulic turbine-generating system,

2). Computation of transients in hydraulic and electrical system and

3). Deciding the optimal governor parameters.

4). Design of Fuzzy logic controller for Exciter and Governor Control signal.

The literatures relevant to our field are summarized below:-

Working group on prime mover and energy supply models for system dynamic performance study [1] recommends the hydraulic model suitable for a relatively wide range of studies. The two main sections of the report provide models for:

a). Prime movers including water supply conduits and

b). Prime movers speed control.

The section on prime mover model includes both linear and nonlinear controls. Nonlinear models are required where speed and power changes are large such as in islanding, load rejection and system restoration studies.

Modeling of hydro plants in which multiple units share a common conduit was examined and a model is derived [2] by Hannet L.N, Feltes J.W, Fardanesh B, Crean W. and he also discussed the turbine/governor parameter settings and their relation to hydraulic coupling effects is discussed. A testing procedure to obtain governor models for hydro units is presented [5] by Hannet L.N, Feltes J.W , Fardanesh B.along with steps to identify values for model parameters.

Tzuu Bin Ng,G.j.Walker and J.E.sargison,presented [3]the model of the Francis turbine for single-machine hydroelectric power plant. It describes the problems with the exciting IEEE model and proposed additional nonlinear features have been adopted to improve the accuracy of the turbine model.

A non linear model for dynamic studies of hydro-turbine is proposed by E.DeJager, N.Janssens, B.Malfliet, F.Van De Meulebroke[6], he has given the model of single turbine including the water supply conduit and he considered the friction pressure loss into account and proportional to flow square, and also given the parameter estimation from field tests.
Design procedure for a fuzzy logic controller for generator exciter control has been developed by Hsu Y.Y [8] , that proves the Fuzzy Excitation control is superior to that self tuning controller in that it does not require model identification as the self tuning excitation controller does, making it easier to be implement on a micro computer.

A fuzzy logic controller for the hydropower plant which has several hydraulic turbines sharing a common conduit is designed and simulated by Mahamoud M[9], Power error signal, Frequency error signal, Gate position and Gate rate of change are taken as inputs.

The event dependent fuzzy controller [8], shows robust stability properties, since its KB takes actual operating conditions into consideration, it mentioned that the development and parametrizing of the fuzzy controller requires power system specific tuning. The solution presented is incentive against topological changes because it does not require retuning after switching operation. Fuzzy Control implementation of PSS has been reported in[11].

A survey of the FLC is presented in [12]; a general methodology for constructing an FLC and assessing its performance is described; and the problems that need further research are pointed out. The exposition includes a discussion of Fuzzification and Defuzzification strategies, the derivation of a database and fuzzy control rules, the definition of fuzzy implication, and an analysis of fuzzy reasoning mechanisms.

A design technique for a new hydro power plant controller using fuzzy set theory and artificial neural network was given in [7] Djukanovic M.B, Dobrijevic D.M, Calovic M.S, Novicevic M, Sobajic,D.J, Fuzzy logic control signals are adjusted using online measurements, they used adaptive fuzzy system which makes permanent changes its own structure as operating conditions change. Neural network classifier role is to identify the operating point and to activate an appropriate Fuzzy logic Controller [16], simulation with Kaplan turbine also shown.

A Fuzzy Power system stabilizer developed with inference mechanism of Fuzzy Logic Controller by 7 X7, 49 if then rules speed and active power deviations are as inputs [11]. They introduced two scaling parameters are the output of neural network which gets operating conditions of power system as inputs.

A fuzzy logic based method for the excitation control and governing signal control signals are presented [13]. Fuzzy logic is applied to generate two compensating signals to modify the controls during system disturbances; they have taken variations in speed, power, and terminal voltage as input variables.

Fuzzy approaches to intelligent control scheme[14], treat situations, where some of the designing relationship can be described by fuzzy sets and fuzzy relation equations. Most KB systems rely upon algorithms which are cumbersome to implement and require extensive computation are given.

Cai W.Y, Liu H.F, Chen G.D, Yie M.P, Cao Y.S, has given in [15] compound fuzzy neural control for the hydro turbine governing system, which is combined with the advantage of fuzzy control and neural control.

C. K. Sanathanan has demonstrated [20] that at least a second order transfer function is necessary to model a turbine penstock. Furthermore a properly synthesized second order transfer function is usually sufficient to guarantee accuracy required for control system designing and evaluation. A procedure for synthesizing reduced order transfer function is presented. The effect of hydraulic friction can be captured accurately in the reduced order transfer function.

The influence of water column elasticity on the stability limits of a hydro-turbine generating unit with long penstock operating on an isolated load is investigated by M. S. R. Murty and M. V. Hariharan in paper[21]. D-decomposition method is used for deriving the stability regions including the elastic water column. It also has been shown that a modified water column compensator enhances the stability regions and dynamic performance considerably.

P. Kundur [17] describes the development of detailed mathematical model of synchronous machine and briefly reviews its steady state and transient performance characteristics. It defines the derived parameters of synchronous machine that are directly related to observed behavior under suitable test conditions and develops their relationships to the fundamental parameters. The simplifications required for the representation of the synchronous machine in stability studies are also discussed. It describes the characteristics and modeling of different types of synchronous generator excitation system as recommended by IEEE. In addition, it discusses dynamic performance criteria and provides definition of related terms useful in the identification and specification of excitation system requirements. It examines the characteristics of prime movers and energy supply systems and develops appropriates model suitable for their representation in power system dynamic studies. It also illustrates the nature of transient stability problems, identifies the factors influencing them and describes modeling considerations and analytical techniques applicable to transient stability analysis.

The generator model is derived starting from the basic circuit equations and the use of Park's transformation by K. R. Padiyar[18]. The models of excitation system and turbine governor system, the analysis of single machine connected to Infinite Bus and the study of transient stability by simulation are also presented in this book.

In the book [19] by P. M. Anderson and A. A. Fouad, a mathematical model for a synchronous machine is developed for stability studies. Two models are developed, one using the current as state variables and another using the flux linkages. Simplifies model, which are often used for stability studies are also discussed. It also covers some practical consideration in the use of the mathematical model of synchronous machines in stability studies. Among these considerations are the determination of initial conditions, determination of the parameters of the machine from available data and construction of simulation models for the machine.

A model for depicting the dynamic behaviour of reservoirs is introduced in the paper [22] by P. A. Frick. As regulation of the head is very desirable under run of river mode operation of small hydro plants, so, a simple and inexpensive modification to presently used governors is also proposed to perform the head control.

A constant volume control method is proposed by the Corriga .G,FAnni,K.A,Sann S[23] that the method consists in controlling all the gates along the canal so as to maintain the volume of water, stored in each reach, constant to the greatest possible extent.

The book [24] by R.H. Richard approaches open channel hydraulics from the viewpoint of presenting basic principles and demonstrating the application of these principles.

Fritz[25] provides enough background about small hydro-plant. It deals with essential components of small hydro-plants, i.e. turbines and hydraulic structures, in enough depth to promote an understanding of their functions as well as to serve as a planning and designing tool.

Introduction to the fuzzy sets, fuzzy relations, fuzzy logic and designing fuzzy controller is given by the george j. klir, BoYuan in[29] and the book[30] dimiter draikov, provides the enough background about the fuzzy logic controller, that is structure of Fuzzy knowledge base controller, rule base, data base, inference engine, fuzzification and Defuzzification procedure.

Chapter-3

Modelling of variouscomponents of small hydro plant.

Modeling of Various Components of **Small Hydro Plants**

In this chapter, the modeling of various components of small hydro-plants and necessary equations representing their dynamic behavior is presented.

3.1 Penstock and Turbine Modeling: -

3.1.1 Non-Linear Model (Assuming Non-Elastic Water Column): -

The linear model of the hydraulic turbine is inadequate for studies involving large variations in power output and frequency. The block diagram in figure 3.1.1 represents the dynamic characteristics of the turbine with a penstock, which is suitable for large-signal time domain simulation [1]. The penstock is modeled assuming an incompressible fluid and a rigid conduit.

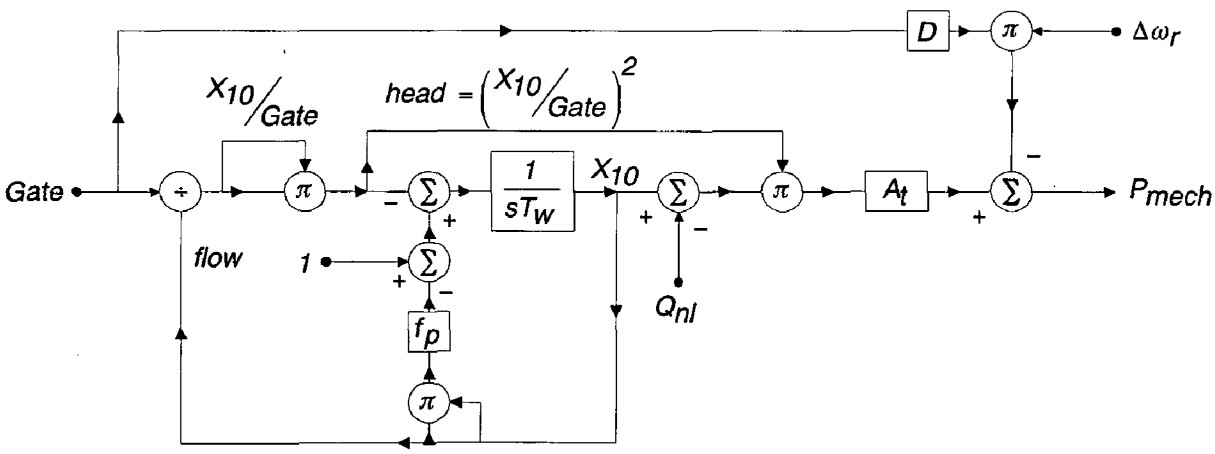

Figure 3.1.1 Non-Linear Model of Turbine (Non-Elastic Water Column

The mathematical equation representing dynamic behavior of the penstock-turbine is as below: -

$$\frac{dX_{10}}{dt} = \frac{1}{Tw}\left[1-\left(\frac{X_{10}}{Gate}\right)^2 - f_p\left(X_{10}\right)^2\right]$$

Mechanical power output is given by: -

$$P_{mech} = A_t \cdot \left(\frac{X_{10}}{Gate}\right)^2 (X_{10} - Q_{nl}) - D \cdot Gate \cdot \Delta w$$

3.1.2 Traveling-Wave Model: -

The modeling of the hydraulic effects using the assumption of inelastic water column is adequate for short and medium length penstocks. For long penstocks, the travel time of the pressure and flow waves, due to the elasticity of the steel in the penstocks and the compressibility of water, can be significant [1]. The non-linear model of turbine-penstock incorporating water column traveling wave effect is shown in figure 3.1.2.

The necessary equations characterizing dynamic behavior of the turbine are as below: -

$$\text{Assuming } \tanh(sT_e) \approx \frac{sT_e}{1 - sT_e}$$

$$\frac{dX_{10}}{dt} = \frac{X_{10} - V_1}{T_e}$$

$$V_2 = -Z_o T_e \frac{dX_{10}}{dt}$$

$$V_1 = Gate \cdot \sqrt{\frac{1 + V_2}{1 + f_p \cdot Gate^2}}$$

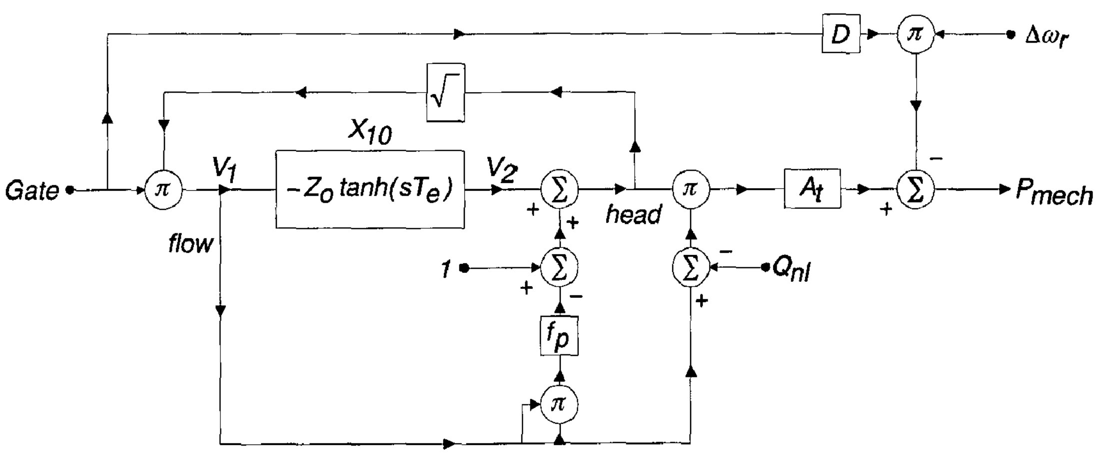

Figure 3.1.2 Non-Linear Model of Turbine (Including Water Column Traveling Wave Effects)

Mechanical power output is given by: -

$$P_{mech} = A_t \cdot \left(\frac{V_1}{Gate}\right)^2 (V_1 - Q_{nl}) - D \cdot Gate \cdot \Delta\omega$$

3.1.3 Non-linear Model of Penstocks and Turbines supplied from Common tunnel.(Assuming elastic water column in Penstock and tunnel).

The effects of water compressibility can be introduced into a multiple penstock model in a similar manner to the single penstock representation. The model now incorporates the nonlinear single penstock model shown in figure 3.1.2. The coupling of the tunnel is included by using the same form of transfer function between the head and the flow that, for tunnel, is the sum of the flows in the individual penstocks. The nonlinear model of hydraulic-turbine including the hydraulic interaction model is shown below. The head loss in the upper tunnel is proportional to the coefficient f_t times flow rate times absolute value of flow rate to maintain direction of head loss where the flow can reverse.

The flow at the turbine tunnel can be calculated using the continuity equation:

$$Q = \sum_{i=1}^{j} Q_i$$

the total flow in the common tunnel must be equal to the sum of the flows in the individual penstocks. The momentum equation for the water at the common tunnel is..

$$h_0 - h = L / gA\left(\frac{dq_1}{dt} + \frac{dq_2}{dt} + \frac{dq3}{dt}\right)$$

The momentum of water in the individual penstock is

$$h - h1 = L_1 / A_i g\left(q_{i0} \frac{dq_i}{dt}\right)$$

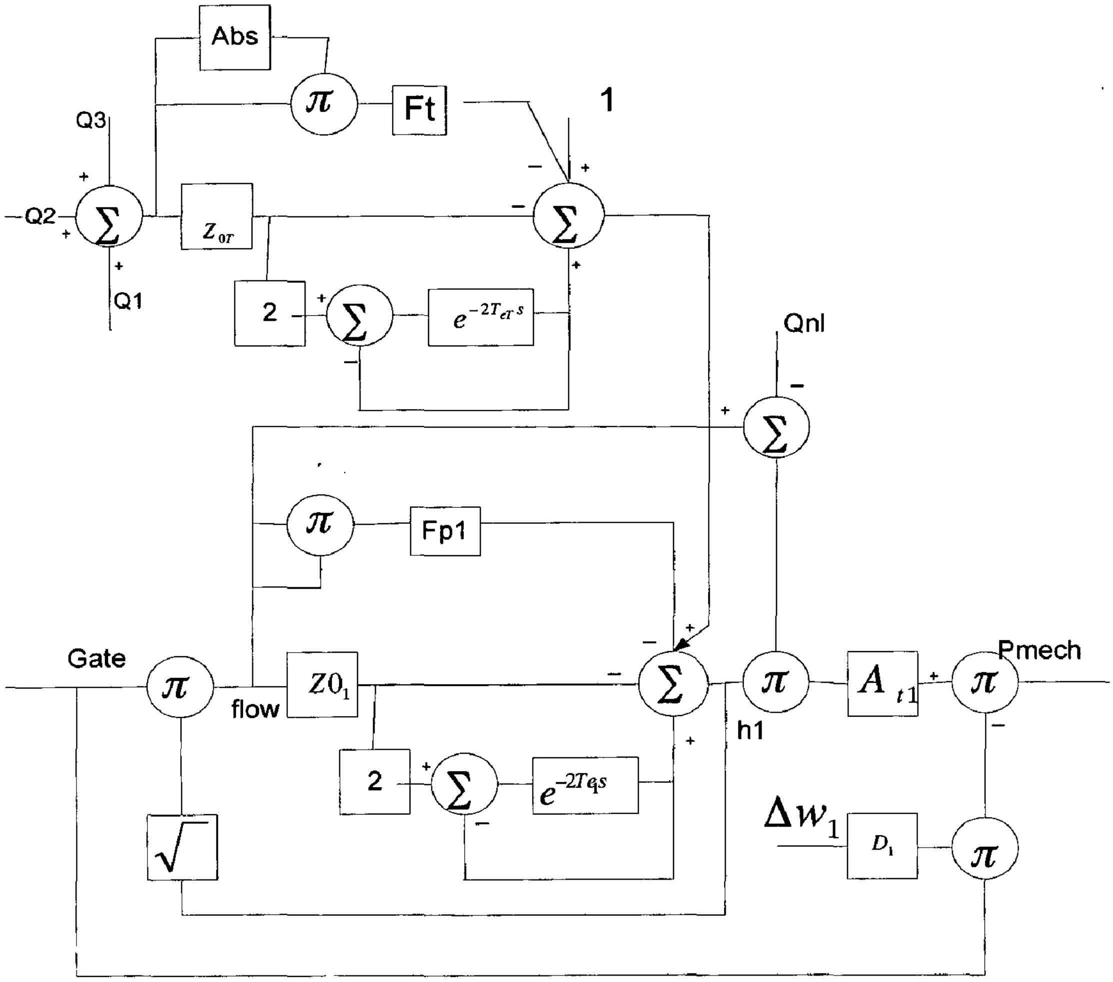

Figure 3.1.3 Non-linear model of multiple penstocks supplied from a common tunnel.

Using above 2 equations to eliminate h and expressing the head in per unit form by dividing by the rated static head h_0, can be written as

$$\begin{bmatrix} 1-h_1 \\ 1-h_2 \\ 1-h_3 \end{bmatrix} = \begin{bmatrix} T_{wt}+T_{w1} & T_{wt} & T_{wt} \\ T_{wt} & T_{wt}+T_{w2} & T_{wt} \\ T_{wt} & T_{wt} & T_{wt}+T_{w3} \end{bmatrix} \begin{bmatrix} \frac{dQ_1}{dt} \\ \frac{dQ_2}{dt} \\ \frac{dQ3}{dt} \end{bmatrix}$$

3.2 Governor Modeling: -

3.2.1 Electro-Hydraulic Governor Modeling: -

Modern speed governors for hydraulic turbines use electro-hydraulic systems. Functionally, their operation is very similar to that of mechanical-hydraulic governors. Speed sensing, permanent droop, temporary droop and their measuring and computing functions are performed electrically. As regulation of the head is very desirable under run of river mode operation of small hydro plants, so, figure 2.3.1 shows the block diagram of the hydraulic governor [1] with head controller [18] in which the turbine gate is controlled by a two-stage hydraulic position servo.

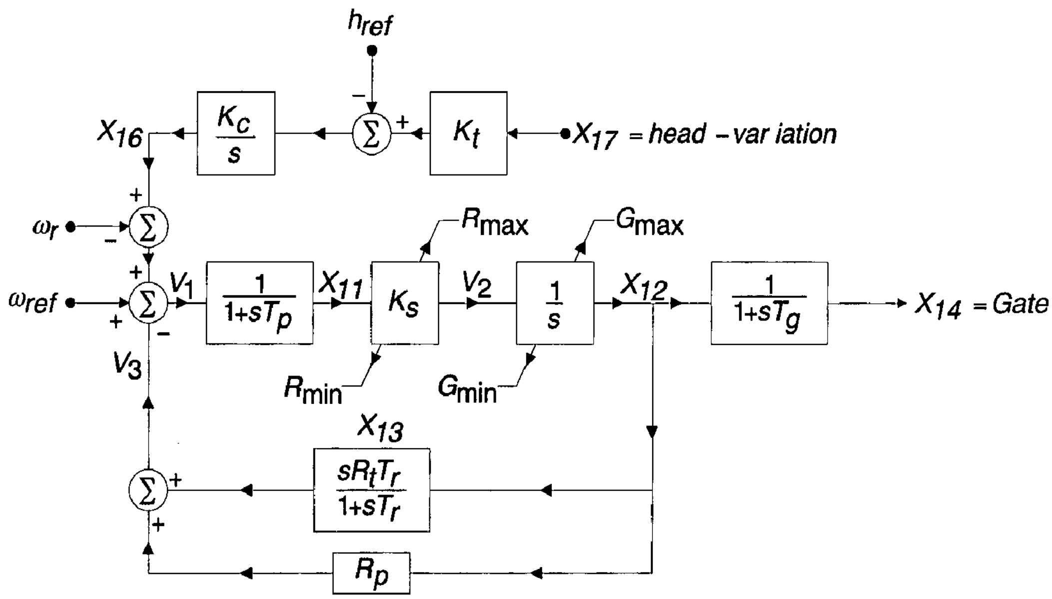

Figure 3.2.1 Electro-Hydraulic Governor Model

The necessary mathematical equations representing the dynamic benavior oı electro-hydraulic governing system are as below: -

$$\frac{dX_{13}}{dt} = \frac{X_{12} - X_{13}}{T_r}$$

$$V_3 = R_p X_{12} + R_t T_r \frac{dX_{13}}{dt}$$

$$V_1 = \omega_{ref} - \omega_r - V_3 + X_{16}$$

$$\frac{dX_{11}}{dt} = \frac{V_1 - X_{11}}{T_p}$$

$V_2 = K_s X_{11}$ if $K_s X_{11} < R_{max}$ and $K_s X_{11} > R_{min}$

$\frac{dX_{11}}{dt} = 0$ *and* $V_2 = R_{max}$ if $K_s \frac{dX_{11}}{dt} > 0$ and $K_s X_{11} \geq R_{max}$

$\frac{dX_{11}}{dt} = 0$ and $V_2 = R_{min}$ if $K_s \frac{dX_{11}}{dt} < 0$ and $K_s X_{11} \leq R_{min}$

$\frac{dX_{12}}{dt} = V_2$ if $X_{12} < G_{max}$ and $X_{12} > G_{min}$

$\frac{dX_{12}}{dt} = 0$ and $X_{12} = G_{max}$ if $\frac{dX_{12}}{dt} > 0$ and $X_{12} \geq G_{max}$

$\frac{dX_{12}}{dt} = 0$ and $X_{12} = G_{min}$ if $\frac{dX_{12}}{dt} < 0$ and $X_{12} \leq G_{min}$

$$\frac{dX_{14}}{dt} = \frac{X_{12} - X_{14}}{T_g}$$

$$\frac{dX_{16}}{dt} = K_c \left[K_t X_{17} - h_{ref} \right]$$

The gate position is given by: -

$$Gate = X_{14}$$

3.2.2 PID Governor Modeling: -

Some electro hydraulic governors are provided with three-term controllers with proportional-integral-derivative (PID) action. These allow the possibility of higher response speeds by providing both transient gain reduction and transient gain increase. Without derivative action, it is equivalent to hydraulic governor. The proportional and integral gains can be adjusted to obtain desired temporary droop and reset time. The derivative action is beneficial for isolated operation. Figure 2.3.2 shows the block diagram of the PID governor [1] with head controller [21].

The necessary equations representing dynamic behavior of the PID governing system are as below: -

$$V_1 = \omega_{ref} - \omega_r - R_p X_{13} + X_{16}$$

$$\frac{dX_{11}}{dt} = V_1 K_i$$

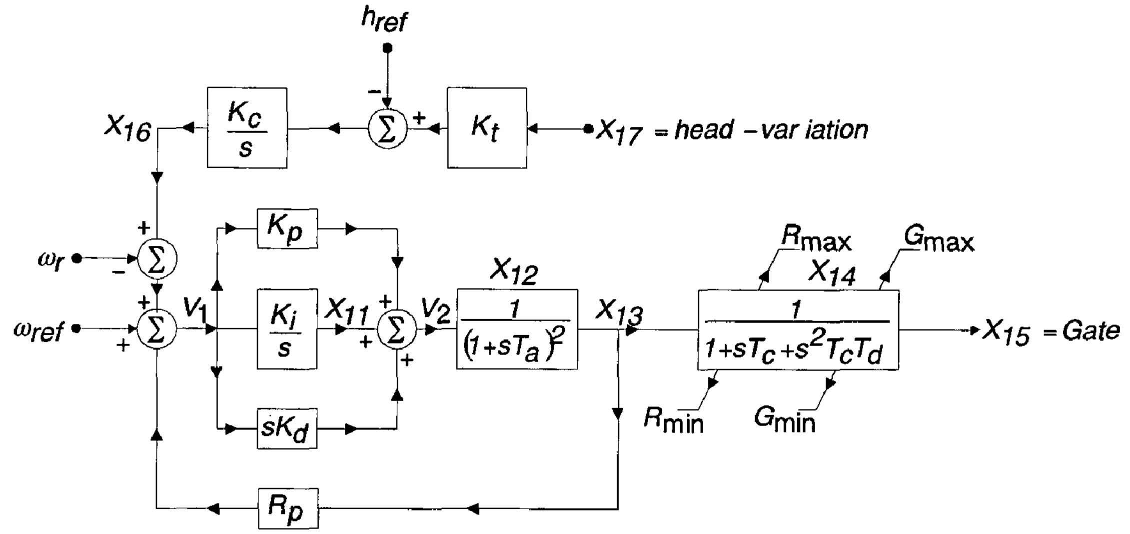

Figure 3.2.2 PID Governor Model

$$\frac{dX_{13}}{dt} = \frac{X_{12} - X_{13}}{T_a}$$

$$V_2 = V_1 K_p + K_d \left[-\frac{d\omega_r}{dt} - R_p \frac{dX_{13}}{dt} + \frac{dX_{16}}{dt} \right] + X_{11}$$

$$\frac{dX_{12}}{dt} = \frac{V_2 - X_{12}}{T_a}$$

$$\frac{dX_{16}}{dt} = K_c \left[K_t X_{17} - h_{ref} \right]$$

$$\frac{dX_{14}}{dt} = \frac{X_{13} - X_{15} - T_c X_{14}}{T_c T_d} \qquad \text{if } X_{14} < R_{max} \text{ and } X_{14} > R_{min}$$

$$\frac{dX_{14}}{dt} = 0 \text{ and } X_{14} = R_{max} \qquad \text{if } \frac{dX_{14}}{dt} > 0 \text{ and } X_{14} \geq R_{max}$$

$$\frac{dX_{14}}{dt} = 0 \text{ and } X_{14} = R_{min} \qquad \text{if } \frac{dX_{14}}{dt} < 0 \text{ and } X_{14} \leq R_{min}$$

$$\frac{dX_{15}}{dt} = X_{14} \qquad \text{if } X_{15} < G_{max} \text{ and } X_{15} > G_{min}$$

$\frac{dX_{15}}{dt} = 0$ and $X_{15} = G_{max}$ if $\frac{dX_{15}}{dt} > 0$ and $X_{15} \leq G_{max}$

$\frac{dX_{15}}{dt} = 0$ and $X_{15} = G_{min}$ if $\frac{dX_{15}}{dt} < 0$ and $X_{15} \leq G_{min}$

The gate position is given by: -

$$Gate = X_{15}$$

3.5 Synchronous Machine Modeling: -

Synchronous generators form the principal source of electrical energy in power systems. Power system stability problem is largely one of keeping interconnected synchronous machines in synchronism.

The magnetic circuits and all rotor windings are symmetrical with respect to both polar and inter-polar axis. Therefore, for the purpose of identifying synchronous machine characteristics, two axes are defined: -

1. The direct (**d**) axis, centered magnetically in the centre of the North Pole,

2. The quadrature (**q**) axis, 90° (electrical) ahead of the **d**-axis.

The position of the rotor relative to the stator is measured by the angle θ between the **d**-axis and the magnetic axis of the phase **a** winding.

The model takes into account the dynamics of the stator, field, and damper windings.

In developing the equations of a synchronous machine, the following assumptions are made: -

a. The stator windings are sinusoidally distributed along the air-gap as far as the mutual effects with the rotor are concerned,

b. The stator slots cause no appreciable variation in the rotor inductances with rotor position,

c. Magnetic hysteresis is negligible,

d. Magnetic saturation effects are negligible.

The equivalent circuit of the model is represented in the rotor reference frame that is dq- frame. All rotor parameters and electrical quantities are viewed from the stator. All rotor parameters and electrical quantities are viewed from the stator. The electrical model of the machine is shown below in figure 3.3.

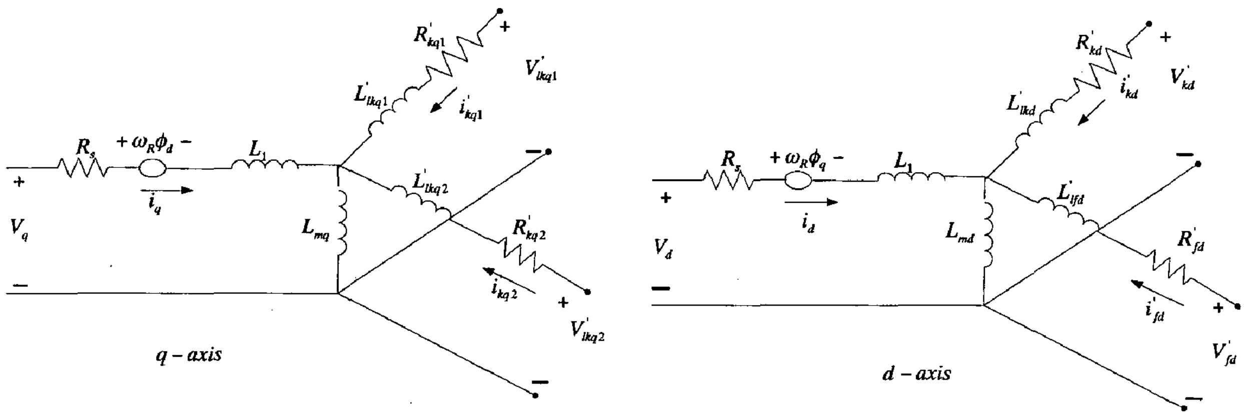

Figure 3.3 the dq axis, Electrical model of the synchronous machine

The necessary mathematical equations representing the dynamic behavior of electro-hydraulic governing system are as below: -

$$V_d = R_s i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \qquad \varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd})$$

$$V_q = R_s i_q + \frac{d}{dt}\varphi_q + \omega_R \varphi_d \qquad \varphi_q = L_q i_q + L_{mq} i'_{kq}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd} \qquad \varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd})$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\varphi'_{kd} \qquad \varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd})$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \qquad \varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \qquad \varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q$$

Chapter-4

Design of Fuzzy Logic controller.

Chapter-4

Design of Fuzzy Logic Controller

For the convenience, before going through the details of fuzzy controllers design, some basic definitions and mathematical operations of fuzzy sets are described below.

4.1 Fuzzy Sets and Terminology

1. **Fuzzy Set**: A Fuzzy set F in a universe of discourse U is characterized by a membership function μ_F which takes values in the interval [0, 1] namely,

μ_F : U→ [0, 1]. A fuzzy set may be used as a generation of the concept of an ordinary set whose membership function only takes two values {0,1}. Thus a fuzzy set F in U may be represented as a set of ordered pairs of a generic element u and its grade of membership function: $F = \{(u, \mu_F(u) \setminus u \in U\}$.

When U is continuous, a fuzzy set F can be written concisely as $F = \int_U \mu_F(u)/u$.

When U is discrete, a fuzzy set F is represented as $F = \sum_{i=1}^{n} \mu_F(u_i)/u_i$. ... 1

2. Support, Crossover point, and Fuzzy singleton:

The support of a fuzzy set F is the crisp of all points u in U such that $\mu_F(u) > 0$.

In particular, the element u in U at which $\mu_F = 0.5$, is called the crossover point and a fuzzy set whose support is a singleton point in U with $\mu_F = 1$, is referred to as fuzzy singleton.

4.1.2 Set Theoretic Operations

Let A and B be two fuzzy sets in U with membership functions μ_A and μ_B, respectively. The set theoretic operations of Union, intersection, and complement for fuzzy sets are defined via their membership functions.

3. Union (OR Operation): The membership function $\mu_{A\cup B}$ of the union $A \cup B$ is point wise defined for all $u \in U$ by

$$\mu_{A\cup B}(u) = \max\{\mu_A(u), \mu_B(u)\}. \qquad .... \qquad 2$$

4. Intersection (AND operation): The membership function $\mu_{A\cap B}$ of the intersection $A \cap B$ is point wise defined for all $u \in U$ by

$$\mu_{A\cap B}(u) = \min\{\mu_A(u), \mu_B(u)\}. \qquad .... \qquad 3$$

5. Complement (NOT operation) : The membership function $\mu_{\bar{A}}$ of the complement of a fuzzy set A is point wise defined for all $u \in U$ by

$$\mu_{\bar{A}}(u) = 1 - \mu_A(u). \qquad .... \qquad 4$$

6. Cartesian Product: If $A_1 ......A_n$ are fuzzy sets in $U_1 .....U_n$, respectively, the Cartesian product of $A_1 ......A_n$ is a fuzzy set in the product space $U_1 \times ..... \times U_n$ with the membership function

$$\mu_{A1} \times ....\times (u_{1,} u_2 ......u_n) = \min\{\mu_{A1}(u_1),....., \mu_{An}(u_n)\} \qquad \text{or}$$

$$\mu_{A1} \times ....\times (u_{1,} u_2 ......u_n) = \mu_{A1}(u_1).\mu_{A2}(u_2)...\mu_{An}(u_n) \qquad .... \qquad 5$$

7).Composition rule: Let A and b be two fuzzy sets with membership functions $\mu_A(x)$ and $\mu_B(x)$ respectively. A fuzzy relation R from A to B can be visualized as a fuzzy graph and can be characterized by the membership function $\mu_R(x, y)$, which satisfies the composition rule as follows;

$$\mu_B(y) = \max_x (\min(\mu_R(x, y), \mu_A(x))) \qquad .... \qquad 6$$

8. Fuzzy Relation: An n-array fuzzy relation s a fuzzy set in $U_1 \times ..... \times U_n$ and is expressed as $R_{U_1 \times ......\times U_n} = \{((u_1,..u_n), \mu_R(u_1,.u_n)) \setminus (u_1,..u_n) \in U_1 \times .... \times U_n$

Linguistic variables and Fuzzy sets

9. Fuzzy Number: A fuzzy number F in a continuous universe U, e.g., a real line, is a fuzzy set F in U which is normal and convex,

$$\max_{u \in U} \mu_F(u) = 1,$$

$$\mu_F(\lambda u_1 + (1-\lambda)u_2) \geq \min(\mu_F(u_1), \mu_F(u_2)), \text{ (Convex)}$$

$$u_1, u_2 \in U, \lambda \in [0,1]. \quad \ldots\ldots \quad 7$$

The use of fuzzy sets provides a basis for systematic way for the manipulation of vague and imprecise concepts.

10. Linguistic variable: A linguistic variable is characterized [12] by a quintuple (x,T(x),U,G,M) in which x is the name of the variable, T(x) is the term set of x, that is, the set of names of linguistic values of x with each value being a fuzzy number defined on U, G is a syntactic rule for generation the names of values of x, and M is a semantic rule for associating with each value its meaning

For example if speed change is interpreted as a linguistic variable, then its terms set T (speed change) could be

T (speed change) = { Negative large, Negative small, Very small,
Small positive, Large positive }

Where each term in T (speed change) is characterized by a fuzzy set in a universe of discourse U= [-1, 1].

4.2 Basic Configuration of Fuzzy Logic Controller

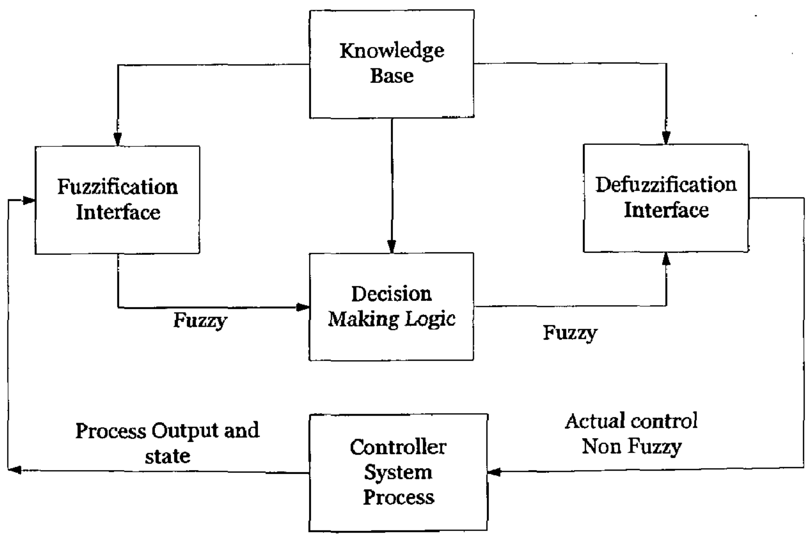

Figure 4.1 Basic configuration of Fuzzy logic controller.

The basic Configuration of an FLC is shown in figure, which comprises four principal components [12]: A fuzzification interface, a knowledge base, decision making logic, and a defuzzification interface.

1) The fuzzification is the process of transferring the crisp input variables into corresponding fuzzy variables, involves the following functions

a) Measures the values of input variables,
b) Performs a scale mapping that transfers the range of values of input variables into corresponding universe of discourse.
c) Performs the function of fuzzification that converts input data into suitable
Linguistic values which may be viewed as labels of fuzzy sets.

2) The knowledge base comprises knowledge of the application domain and the attendant control goals. It consists of a 'data base' and a linguistic (fuzzy) control rule base:

a) The data base provides necessary definitions, which control rules and Fuzzy data manipulation in an FLC,
b) The rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules.

3) The decision making logic is the kernel of an FLC; it has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control action employing fuzzy implication and rules of inference in fuzzy logic.

4) The procedure for calculating the crisp output of the FLC for some values of input variables is based on the following three steps [11],

[Step 1: Determination of Degree of firing (DOF) of the rules]

The DOF of the i^{th} rule consequent is a scalar value which equals the minimum of the two antecedent membership degrees. For examples, if $(\Delta\omega)$ is positive small with a membership degree of 0.7 and $(\Delta\varpi)$ is Positive medium with membership degree of 0.5 then the degree of this is 0.5.

Step 2: Inference Mechanism

The inference mechanism consists of two processes called fuzzy implication and rule aggregation. The degree of firing of a rule interacts with its consequent to provide the output of the rule, which is a fuzzy subset. The formulation used to determine how the DOF and the consequent fuzzy set interact to form the rule output is called fuzzy implication. In fuzzy logic control the most commonly used method for inferring the rule output are Mamdani method and Takago-sugani method.

Step 3: Defuzzification

To obtain a crisp output value from the fuzzy set obtained in the previous step a mechanism called defuzzification. It is employed because in many practical applications a crisp control action is required. The commonly used strategies are described below.

A. the Max criterion method

The max criterion produces the point at which the possibility distribution of the control action reaches a maximum value.

B. The Mean of Maximum method (MOM)

The MOM strategy generates a control action which represents the mean value of all local control actions whose membership functions reach the maximum. More specifically, in the case of a discrete universe, the control action may be expressed as $z_0 = \sum_{i=1}^{l} \frac{x_i}{l}$

Where x_i is the support value at which the membership function reaches the maximum value $\mu_z(x_i)$, and l is the number of such support.

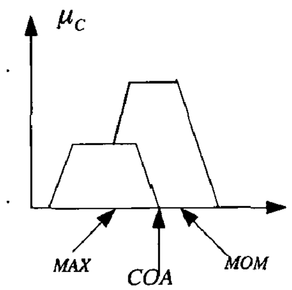

Figure 4.2: Diagrammatic representation of various Defuzzification strategies

Figure 4.2 shows a graphical interpretation of various Defuzzification strategies. COA yields superior results. However, the MOM strategy yields a better transient performance while the COA strategy yields a better steady state performance. An FLC based on the COA generally yields a lower mean square error than that based on the MOM.

4.3 Design Parameters of the FLC

The principal design parameters for an FLC are the following

1) Fuzzification strategies and the interpretation of a fuzzification operator.
2) Data base:
    a) Discretization/normalization of universe of discourse.
    b) fuzzy partition of the input and output spaces,
    c) completeness,
    d) choice of the membership function of a primary fuzzy set.
3) Rule Base:
    a) choice of process state(input) variables and control(output) variables of fuzzy control rules,
    b) source and deviation of fuzzy control rules,
    c) types of fuzzy control rules,
    d) Consistency, interactivity, completeness of control rules.
4) Decision making logic:
    a) definition of a fuzzy implication,
    b) interpretation of the sentence connective and,
    c) definitions of a compositional operator,
    d) Inference mechanism.
5) Defuzzification strategies and the interpretation of a Defuzzification operator.

4.4 Fuzzy Logic PID Governor and Excitation Controller.

A Fuzzy Logic Controller is a kind of state variable controller governed by a family of rules and a fuzzy inference mechanism. The FLC algorithm can be implemented using heuristic strategies, defined by linguistic described statements. It avoids data complexity and requires a small amount of measurable information of a discrete type (here the angular speed deviation and the acceleration are the inputs). The use of fuzzy set theory in control applications provides a means of dealing with uncertainties in the controller's inputs and outputs. The fuzzy logic algorithm reflects the mechanism of control implemented by people, without an analytical description of the control algorithm, and without using any formalized knowledge about the controlled object in the form of mathematical models.

In the hydro-turbine governing system, controlled object generally contains three parts: Penstock, water turbine and generator, and is a non-linear, non-minimum phase, and time variant system. Its parameters are variable with head H, gate opening **Y** and load disturbance [15]. Conventional PID control systems are based on a certain, linear model, which makes it impossible to solve the problems caused by uncertain factors.

The design of a conventional proportional –Integral and Derivative (PID) controller is based on a suitable mathematical model of the process, by using the set of differential equations. Contrary to this approach, in an FLC the expert knowledge or human operator's behavior is modeled, it allows certain impression and incomplete understanding of the mathematical model when dealing with the problem of control. Instead of solving a set of differential equations, the FLC provides an algorithm which converts the linguistic control strategy, based on the fuzzy rule-based expert knowledge, into a selection of system control free parameters. The basic configuration of FLC comprises four principal components: Fuzzification interface, knowledge base, decision making logic and Defuzzification interface.

4.5 Design Procedure of Fuzzy Logic Controller

To make the designed excitation/governor controller capable of providing desired system damping under disturbance conditions[7,16], some state variables representative of system dynamic performance must be taken produced. Consequently, an overlapping of approximately 25 % of contiguous fuzzy sets is the most suitable choice. It has been recommended in [7] that the number of fuzzy labels associated with a variable should generally be an odd number between five and nine. Overlapping of between 10 and 50% of the neighboring space is acceptable, and the sum of the vertical points of the overlap should be always less than one. The density of fuzzy set must be highest around the optimal control point of the system and should decrease as the distance from this point increases.

For determining how to modify the control variables for the observed values of the state variables, the two fuzzy associative matrices (FAM) must be established, for the excitation and governor control signals, respectively. These FAM banks are 7X7 and 7X8 dimensional matrices with linguistic fuzzy set entries respectively. The columns are indexed by seven fuzzy sets that quantize the speed deviation$_{(\Delta\omega)}$, X1 universe of discourse, while the seven values that quantize the acceleration$(\Delta\varpi)$, X2 universe of discourse are associated to row indices. Each matrix entry can be equal to one of seven control values. Then, 49, and 56 entries of the Exciter and Governor, in the FAM bank matrix represent a subset of 392(7X7 X8) possible two-antecedent FAM rules. In general practice most of the entries are blank.

A set of decision rules relating controller inputs to the output can be formulated on the basis of engineering judgment, expert knowledge, or previous experience. The synthesized FAMs for fuzzy logic based controller are shown in table 1 and table 2.

To find out the desired output signal, Fuzzy Excitation and PID Governor Controller are proceeds as follows

Step1: Use of membership function to represent controller inputs such as speed deviation$_{(\Delta\omega)}$ and acceleration $(\Delta\varpi)$ in fuzzy set notations.

Step 2: Use of composition rule to determine the membership function of the controller output Uc.

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4.5 Design Procedure of Fuzzy Logic Controller

To make the designed excitation/governor controller capable of providing desired system damping under disturbance conditions[7,16], some state variables representative of system dynamic performance must be taken as input signals to the fuzzy PID Governor and excitation controllers. In this dissertation work, generator speed deviation from Synchronous speed $(\Delta\omega)$ and acceleration [7,8] (first derivative of generator speed deviation $(\Delta\varpi)$ are chosen to be as input signals of the fuzzy PID Governor and excitation controllers.

$$\Delta\omega(m) = 1000[\omega_s - \omega(m)]$$

$$\Delta\varpi(m) = 50[\omega(m) - \omega(m-1)]\Delta T_{samp} \qquad \ldots\ldots. \quad 8$$

The output variables are control inputs to the excitation and speed governing systems:

$$u = [u_{ex}(m), u_{gov}(m)]^T$$

$$\text{for} \quad m\Delta T_{samp} \le t \le (m+1)\Delta T_{samp}; \qquad \ldots \quad 9$$

$$m = 1,2,..N$$

Where ΔT_{samp} is sampling time. The excitation and governor control signals are output variables of discrete type and are renewed at every sampling time, depending on input fuzzy variables. Under disturbance conditions dynamic performance of the system could be evaluated by examining the response curves of the two variables.

To determine the controller output from the measured system variables such as speed deviation $(\Delta\omega)$ and acceleration $(\Delta\varpi)$, fuzzy rule base matrix R, which gives the relationship between the fuzzy set characterizing controller inputs and the fuzzy set characterizing controller output, is first established and is stored in computer memory.

A general problem associated with the use of fuzzy logic controllers is the tuning of the FLC for a wide range of operating conditions [7]. There are two, solutions. One solution is to apply even dependent fuzzy controller, which shows robust stability properties, since its knowledge base takes into consideration the actual operating conditions. The other method is to use adaptive fuzzy systems which contrary to conventional fuzzy logic systems, can be adapted to gradual changes in their environment. An adaptive fuzzy system makes permanent changes to its own structure as operating conditions change, by modifying the rule characteristics, the topology of fuzzy sets and the methodology of Defuzzification. The second method is performed by introducing an algorithm that measures the change between sensor measurements and the expert system (adaptation machine). It decides what changes should be made in the weighting of rules and dynamic adjustment of fuzzy sets. The means which can be used to construct adaptive fuzzy systems are the dynamic hedging of fuzzy rules, the selection of alternative methods of Defuzzification, and the redefinition of truth in the fuzzy model and the structural modification of fuzzy sets.

The fuzzy set values of the input and output fuzzy variables are specified. Each universe of discourse can be quantized into overlapping fuzzy set values. State and control fuzzy variables, with their respective fuzzy set values, are shown in *Figure4.3*. The fuzzy set values of the fuzzy variables are chosen as follows:

$(\Delta\omega)$ **X1: Speed deviation**	$(\Delta\varpi)$**X2:Accelaration**	$u_{ex}(m), u_{gov}(m)$:
LN – Large Negative;	VLN- Very Large Negative;	VS- Very Small;
MN- Medium Negative;	LN- Large Negative;	S- Small;
SN- Small Negative;	MN- Medium Negative;	SM- Small Medium;
VS- Very Small;	SN- Small Negative;	M – Medium;
SP- Small Positive;	VS- Very Small;	ML- Medium Large;
MP- Medium Positive ;	SP- Small Positive;	L- Large;
LP- Large Positive.	MP- Medium Positive;	VL- Very Large.
	LP- Large Positive.	

Table 1

		$(\Delta\omega)$ **Speed deviation**						
		LN	MN	SN	VS	SP	MP	LP
$(\Delta\varpi)$	LP	M	ML	SM	VL	VL	VL	VL
Acce	MP	S	M	ML	L	L	VL	VL
lara	SP	SM	S	LN	ML	ML	L	VL
tion	VS	SM	SM	S	M	ML	L	L
	SN	VS	SM	S	S	M	ML	L
	MN	VS	VS	SM	SM	S	M	ML
	LN	VS	VS	VS	VS	SM	S	M

4.3(a) Fuzzy Associative matrix for the Exciter control signal

Table 2

		X1 $(\Delta\omega)$ **Speed deviation**						
		LN	MN	SN	VS	SP	MP	LP
X2	LP	L	L	L	VL	VL	VL	VL
$(\Delta\varpi)$	MP	M	ML	ML	ML	L	VL	VL
Acce	SP	S	ML	ML	ML	L	L	VL
lara	VS	S	SM	M	M	M	L	VL
tion	SN	S	SM	M	M	M	L	VL
	MN	VS	SM	ML	ML	ML	L	L
	LN	VS	SM	M	M	M	L	VL
	VLN	VS	SM	M	M	L	L	VL

4.3(b) Fuzzy Associative matrix for the Governor Control signal.

State fuzzy Variables speed deviation $(\Delta\omega)$ and acceleration $(\Delta\varpi)$ and the control fuzzy variables Exciter control signal and the governor control signal with their respective fuzzy set values are shown in figure 4.4 (a) to 4.4.(d).

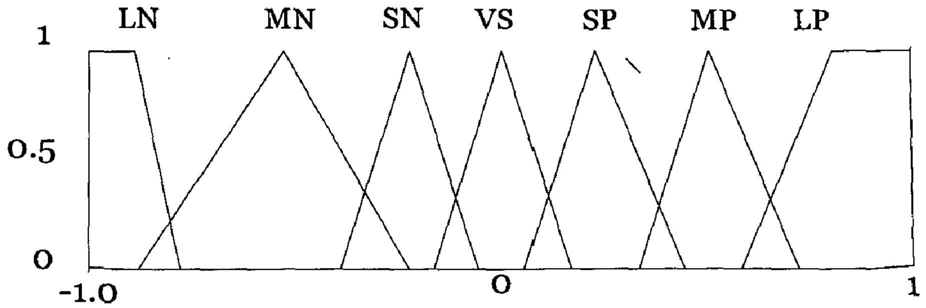


Figure 4.4 (a) Membership values of deviation of generator speed.

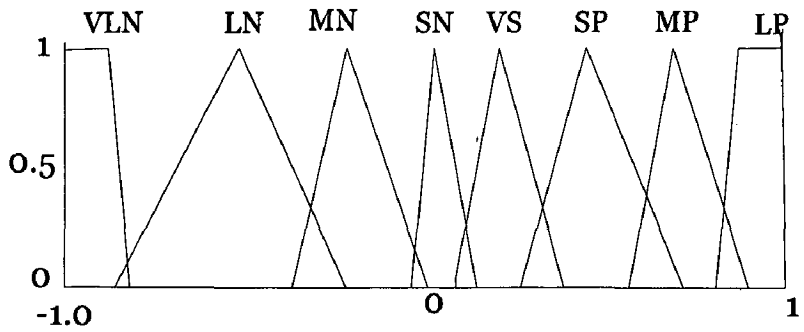


Figure 4.4(b) Membership values of acceleration .

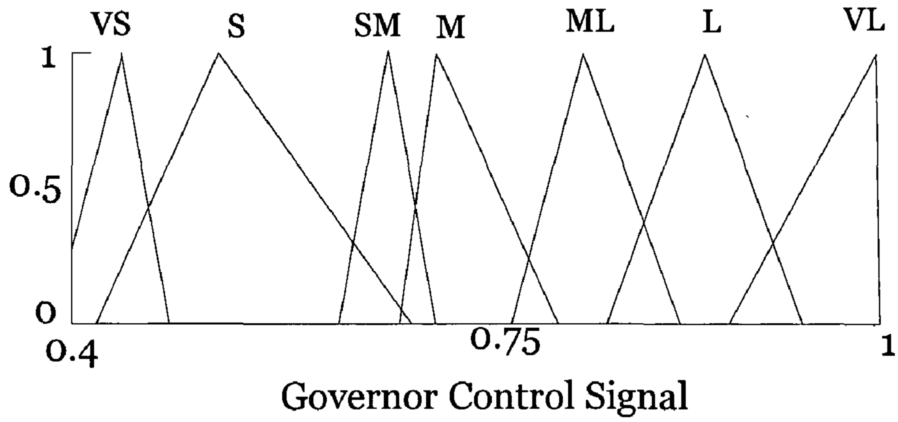


Figure 4.4 (c) Governor Control signals

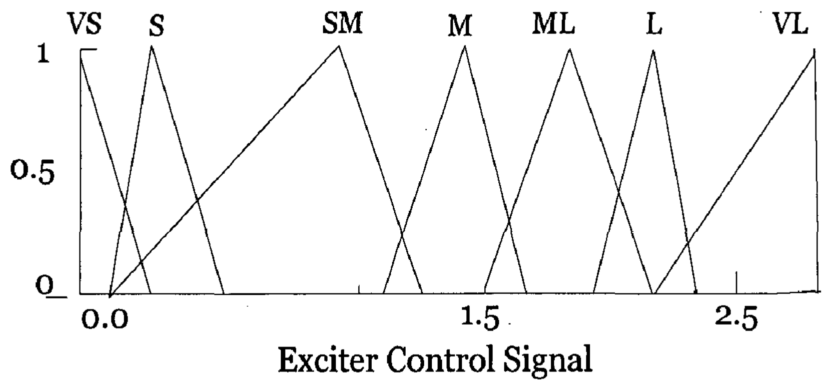


Figure 4.4(d) Exciter control signal.

Figure 4.4 (c) State fuzzy variables $((\Delta\omega),(\Delta\varpi))$ and the control fuzzy variables $u_{ex}(m), u_{gov}(m)$ with their respective fuzzy set values.

In practice, the quantizing fuzzy sets are usually symmetric triangular or trapezoids, centered about some representative values. If these fuzzy sets overlap too much, then they make the distinction between the fuzzy set values. In the other case, excessive overshoot and undershoot can be produced. Consequently, an overlapping of approximately 25 % of contiguous fuzzy sets is the most suitable choice. It has been recommended in [7] that the number of fuzzy labels associated with a variable should generally be an odd number between five and nine. Overlapping of between 10 and 50% of the neighboring space is acceptable, and the sum of the vertical points of the overlap should be always less than one. The density of fuzzy set must be highest around the optimal control point of the system and should decrease as the distance from this point increases.

For determining how to modify the control variables for the observed values of the state variables, the two fuzzy associative matrices (FAM) must be established, for the excitation and governor control signals, respectively. These FAM banks are 7x7 and 7x8 dimensional matrices with linguistic fuzzy set entries respectively. The columns are indexed by seven fuzzy sets that quantize the speed deviation $_{(\Delta\omega)}$, X1 universe of discourse, while the seven values that quantize the acceleration $(\Delta\varpi)$, X2 universe of discourse are associated to row indices. Each matrix entry can be equal to one of seven control values. Then, 49, and 56 entries of the Exciter and Governor, in the FAM bank matrix represent a subset of 392(7x7 x8) possible two-antecedent FAM rules. In general practice most of the entries are blank.

A set of decision rules relating controller inputs to the output can be formulated on the basis of engineering judgment, expert knowledge, or previous experience. The synthesized FAMs for fuzzy logic based controller are shown in table 1 and table 2.

To find out the desired output signal, Fuzzy Excitation and PID Governor Controller are proceeds as follows

Step1: Use of membership function to represent controller inputs such as speed deviation $_{(\Delta\omega)}$ and acceleration $(\Delta\varpi)$ in fuzzy set notations.

Step 2: Use of composition rule to determine the membership function of the controller output Uc.

Step 3: Determine a proper controller output from the membership function of the output signal.

Details of the above procedure are addressed in the following discussion.

4.5.1 Establishing the Fuzzy Relation matrix: Before the fuzzy excitation controller and Governor can be put in operation, a fuzzy relation matrix must be set up and stored in computer memory. To this end, a set of decision rules relating controller inputs to controller output are first compiled based on previous experience. These decision rules are expressed using linguistic variables such as LP, MP, SP, VS, SN, MN, and LN.

The FAM rules in these matrices can be taken as triples (MN, MP, L), (MN, MP, ML) which are in fact the set-level implications:

Rule 1:

If $(\Delta\omega)$ is Medium negative (MN), AND $(\Delta\varpi)$ is Medium Positive (MP)

Then the Excitation control u_{ex} should be Large negative (L), from the Exciter FAM, and the Governor control u_{gov} should be Medium large (ML) from Governor FAM. Through the combination of the two signals, there will be 49 decision rules in all for each Exciter and Governor controller. The most convenient way to present this decision rule is to use a decision table as shown in Table 1 and 2.

It is observed from Table 1 that each entry represents a particular rule. Using Fuzzy set notation, the decision table in Table 1, 2 can be converted into the fuzzy relation matrix in table 3 and 4, where controller output obtained by applying a particular rule is expressed in membership functions. For Example Rule 1 now becomes the following.

Rule 1': If $(\Delta\omega)$ is MN and $(\Delta\varpi)$ is PM, then Uc can be characterized by the fuzzy set

{(VS, 0.0), (S, 0.0), (SM, 0.0), (M, 0.0), (ML, 0.5), (L, 1.0), (VL, 0.5)}, for u_{ex}

and for u_{gov}

{(VS, 0.0), (S, 0.0), (SM, 0.0), (M, 0.5), (ML, 1.0), (L, 0.5), (VL, 0.0)}.

The Degree of belief in the "If Part" (condition part) of the rule can be specified through the use of membership functions as described below.

Table 3.

x_i	Exciter Input ($\Delta\omega$) and ($\Delta\varpi$)	Exciter output: VS	S	SM	M	ML	L	VL
		Membership Values						
		$\mu_R(x_i,VS)$	$\mu_R(x_i,S)$	$\mu_R(x_i,SM)$	$\mu_R(x_i,M)$	$\mu_R(x_i,ML)$	$\mu_R(x_i,L)$	$\mu_R(x_i,VL)$
X1	(LP,LN)	0	0	0.5	1	0.5	0	0
X2	(LP,MN)	0	0	0	0.5	1.0	0.5	0
X3	(LP,SN)	0	0	0	0	0.5	1.0	0.5
X4	(LP,VS)	0	0	0	0	0	0.5	1.0
X5	(LP,SP)	0	0	0	0	0	0.5	1.0
X6	(LP,MP)	0	0	0	0	0	0.5	1.0
X7	(LP,LP)	0	0	0	0	0	0.5	1.0
X8	(MP,LN)	0	0.5	1.0	0.5	0	0	0
X9	(MP,MN)	0	0	0.5	1.0	0.5	0	0
X10	(MP,SN)	0	0	0	0.5	1.0	0.5	0
X11	(MP,VS)	0	0	0	0	0.5	1.0	0.5
X12	(MP,SP)	0	0	0	0	0.5	1.0	0.5
X13	(MP,MP)	0	0	0	0	0	0.5	1.0
X14	(MP,LP)	0	0	0	0	0	0.5	1.0
X15	(SP,LN)	0.5	1.0	0.5	0	0	0	0
X16	(SP,MN)	0	0.5	1.0	0.5	0	0	0
X17	(SP,SN)	0	0	0.5	1.0	0.5	0	0
X18	(SP,VS)	0	0	0	0.5	1.0	0.5	0
X19	(SP,SP)	0	0	0	0.5	1.0	0.5	0
X20	(SP,MP)	0	0	0	0	0.5	1.0	0.5
X21	(SP,LP)	0	0	0	0	0	0.5	1.0
X22	(VS,LN)	0.5	1.0	0.5	0	0	0	0
X23	(VS,MN)	0.5	1.0	0.5	0	0	0	0
X24	(VS,SN)	0	0.5	1.0	0.5	0	0	0
X25	(VS,VS)	0	0	0.5	1	0.5	0	0
X26	(VS,SP)	0	0	0	0.5	1.0	0.5	0
X27	(VS,MP)	0	0	0	0	0.5	1.0	0.5
X28	(VS,LP)	0	0	0	0	0.5	1.0	0.5
X29	(SN,LN)	1.0	0.5	0	0	0	0	0
X30	(SN,MN)	0.5	1.0	0.5	0	0	0	0
X31	(SN,SN)	0	0.5	1.0	0.5	0	0	0
X32	(SN,VS)	0	0.5	1.0	0.5	0	0	0
X33	(SN,SP)	0	0	0.5	1	0.5	0	0
X34	(SN,MP)	0	0	0	0.5	1.0	0.5	0

x35	(SN,LP)	0	0	0	0	0.5	1.0	0.5
x36	(MN,LN)	1.0	0.5	0	0	0	0	0
x37	(MNMN)	1.0	0.5	0	0	0	0	0
x38	(MN,SN)	0.5	1.0	0.5	0	0	0	0
x39	(MN,VS)	0.5	1.0	0.5	0	0	0	0
x40	(MN,SP)	0	0.5	1.0	0.5	0	0	0
x41	(MN,MP)	0	0	0.5	1	0.5	0	0
x42	(MN,LP)	0	0	0	0.5	1.0	0.5	0
x43	(LN,LN)	1.0	0.5	0	0	0	0	0
x44	(LN,MN)	1.0	0.5	0	0	0	0	0
x45	(LN,SN	1.0	0.5	0	0	0	0	0
x46	(LN,VS)	1.0	0.5	0	0	0	0	0
x47	(LN,SP)	0.5	1.0	0.5	0	0	0	0
x48	(LN,MP)	0	0.5	1.0	0.5	0	0	0
x49	(LN,LP)	0	0	0.5	1	0.5	0	0

Table 3 the Fuzzy relation matrix for the Exciter output.

Table 4

		Governor output						
x_i	Exciter Input ($\Delta\omega$)and ($\Delta\varpi$)	VS	S	SM	M	ML	L	VL
		Membership Values						
		$\mu_R(x_i,VS)$	$\mu_R(x_i,S)$	$\mu_R(x_i,SM)$	$\mu_R(x_i,M)$	$\mu_R(x_i,ML)$	$\mu_R(x_i,L)$	$\mu_R(x_i,VL)$
x1	(LP,LN)	0	0	0	0	0.5	1.0	0.5
x2	(LP,MN)	0	0	0	0.5	0.5	1.0	00.5
x3	(LP,SN)	0	0	0	0	0.5	1.0	0.5
x4	(LP,VS)	0	0	0	0	0	0.5	1.0
x5	(LP,SP)	0	0	0	0	0	0.5	1.0
x6	(LP,MP)	0	0	0	0	0	0.5	1.0
x7	(LP,LP)	0	0	0	0	0	0.5	1.0
x8	(MP,LN)	0	1.0	0.5	1.0	0.5	0	0
x9	(MP,MN)	0	0	0.5	1.0	0.5	0	0
x10	(MP,SN)	0	0	0.5	1.0	0.5	0	0
x11	(MP,VS)	0	0	0	0.5	1.0	0.5	0
x12	(MP,SP)	0	0	0	0	0.5	1.0	0.5
x13	(MP,MP)	0	0	0	0	0	0.5	1.0
x14	(MP,LP)	0	0	0	0	0	0.5	1.0
x15	(SP,LN)	0	0.5	1.0	0.5	0	0	0
x16	(SP,MN)	0	0	0	0.5	1.0	0.5	0

X17	(SP,SN)	0	0	0.5	1.0	0.5	0	0
X18	(SP,VS)	0	0	0	0.5	1.0	0.5	0
X19	(SP,SP)	0	0	0	0	0.5	1.0	0.5
X20	(SP,MP)	0	0	0	0	0.5	1.0	0.5
X21	(SP,LP)	0	0	0	0	0	0.5	1.0
X22	(VS,LN)	0	0.5	1.0	0.5	0	0	0
X23	(VS,MN)	0	0.5	1.0	0.5	0	0	0
X24	(VS,SN)	0	0	0.5	1.0	0.5	0	0
X25	(VS,VS)	0	0	0.5	1	0.5	0	0
X26	(VS,SP)	0	0	0.5	1.0	0.5	0	0
X27	(VS,MP)	0	0	0	0	0.5	1.0	0.5
X28	(VS,LP)	0	0	0	0	0	0.5	1.0
X29	(SN,LN)	0.5	1.0	0.5	0	0	0	0
X30	(SN,MN)	0	0.5	1.0	0.5	0	0	0
X31	(SN,SN)	0	0	0.5	1.0	0.5	0	0
X32	(SN,VS)	0	0	0.5	1.0	0.5	0	0
X33	(SN,SP)	0	0	0.5	1	0.5	0	0
X34	(SN,MP)	0	0	0	0	0.5	1.0	0.5
X35	(SN,LP)	0	0	0	0	0	0.5	1.0
X36	(MN,LN)	1.0	0.5	0	0	0	0	0
X37	(MNMN)	0.5	1.0	0.5	0	0	0	0
X38	(MN,SN)	0	0	0	0.5	1.0	0.5	0
X39	(MN,VS)	0	0	0	0.5	1.0	0.5	0
X40	(MN,SP)	0	0	0	0.5	1.0	0.5	0
X41	(MN,MP)	0	0	0	0	0.5	1.0	0.5
X42	(MN,LP)	0	0	0	0	0.5	1.0	0.5
X43	(LN,LN)	1.0	0.5	0	0	0	0	0
X44	(LN,MN)	0	0.5	1.0	0.5	0	0	0
X45	(LN,SN	0	0	0.5	1.0	0.5	0	0
X46	(LN,VS)	0	0	0.5	1.0	0.5	0	0
X47	(LN,SP)	0	0	0.5	1.0	0.5	0	0
X48	(LN,MP)	0	0	0	0	0.5	1.0	0.5
X49	(LN,LP)	0	0	0	0	0	0.5	1.0
X50	(VLN,LN)	1.0	0.5	0	0	0	0	0
X51	(VLN,MN	0	0.5	1.0	0.5	0	0	0
X52	(VLN,SN)	0	0	0.5	1.0	0.5	0	0
X53	(VLN,VS)	0	0	0.5	1.0	0.5	0	0
X54	(VLN,SP)	0	0	0	0	0.5	1.0	0.5
X55	(VLN,MP	0	0	0	0	0.5	1.0	0.5
X56	(VLN,LP)	0	0	0	0	0	0.5	1.0

Table 4.The Fuzzy relation matrix for the Governor output

4.5.2). Specify the Membership Functions for Controller inputs.

To express the controller inputs in linguistic variables LP, MP, SP, VS, SN, MN and LN, the measured controller inputs $(\Delta\omega)$ and $(\Delta\varpi)$ are first normalized based on previous experience with conventional controller.

$$\Delta\omega_u = \frac{\Delta\omega}{0.55}$$

$$\Delta\varpi_u = \frac{\Delta\varpi}{0.8}$$

Using these normalized inputs, controller inputs can be described by membership functions for linguistic variables, as shown in table 4. Only the membership functions for different values of and are given in table. Linear interpolation will be used to determine the membership functions must be employed to determine the membership functions for a value which is not mentioned in table 4.

Table 4

Normalized Inputs $(\Delta\omega)$ or $(\Delta\varpi)$	Membership function of Exciter inputs						
	LN	MN	SN	VS	SP	MP	LP
-1.0	1	0.7	0.5	0.3	0	0	0
-0.7	1	0.9	0.7	0.5	0.2	0	0
-0.4	0.8	1	0.9	0.7	0.4	0.2	0
-0.1	0.6	0.8	1	0.8	0.6	0.4	0.2
0.0	0.4	0.6	0.8	1	0.8	0.6	0.4
0.1	0.2	0.4	0.6	0.8	1	0.8	0.6
0.4	0	0.2	0.4	0.7	0.9	1	0.8
0.7	0	0	0.2	0.5	0.7	0.9	1
1.0	0	0	0	0.3	0.5	0.7	1

Let us see the use of table 4 by an example. At a particular sampling instant, let the sampled controller inputs be say, $(\Delta\omega)$= 0.7 and $(\Delta\varpi)$=-0.4. From the table 4 the two controller inputs can be described by the following fuzzy sets.

$(\Delta\omega)$: {(LN, 0), (MN, 0), (SN, 0.2), (VS, 0.5), (SP, 0.7), (MP, 0.9), (LP, 1)}.

$(\Delta\varpi)$:{(LN, 0.8), (MN, 1), (SN, 0.9), (VS, 0.7), (SP, 0.4), (MP, 0.2), (LP, 0)}.

4.5.3).Determining the membership functions of controller Output:

Let us use the above example to demonstrate the use of composition rule to determine the membership function of controller output. It is obvious that there are 49 rules that can be used to generate the desired controller output. Consider that rule 1 and its equivalent rule1'. The "action part" (Then part) of the rule has been represented in fuzzy set notation using membership functions, but the "condition part" ("the If part") is still, to be represented using fuzzy set notation. An observation of Rule 1' of Excitation control reveals that the condition part consists of two predicates "$(\Delta\omega)$ is MN" and "$(\Delta\varpi)$ is MP" combined together by an "AND" operator. From AND definition we have the membership values for the condition part.

$\mu(x_1) = \mu($"$\Delta\omega$ is MN" and "$(\Delta\varpi)$ is MP")

=min (μ ("$(\Delta\omega)$ is MN", μ ("$(\Delta\varpi)$ is MP"))

From the above equations we have μ ("$(\Delta\omega)$ is MN"= 0 and

μ ("$(\Delta\varpi)$ is MP")=0.2. Thus the membership value of the condition part is

$$\mu(x_1) = \min(0,0.2) = 0.0$$

Given the membership value for the "condition part" and the fuzzy relation matrix, the membership values for the controller output characterized by the seven linguistic variables VS, S, SM, M, ML, L and VL can be obtain using composition rule. For example, the membership value for the linguistic variable SM can be computed as follows

$$\mu U_{c41}(VS) = \min(\mu_R(x_{41}, VS), \mu(x_{41})$$

$$= \min(0.5, 0.0) = 0.$$

This is the membership value of the controller output" SM" if only Rule 1 exits. To make the 49 rules in Table 3 into account, the membership values for the condition part of all the other 48 rules $\mu(x_1)$, i=1,2,...49 must be determined in the same way as we did in

(8) for $\mu(x_{41})$. Thus, the final value for controller output "SM" can be figured out by using () Thus the final value for controller output "SM" can be figured out bye using (composition)

$$\mu U_c(SM) = \max(\min(\mu_R(x_i, SM), \mu(x_i))$$

The membership values for all the other six variables $\mu U_c(VS)$, $\mu U_c(S)$, $\mu U_c(M)$, $\mu U_c(ML)$, $\mu U_c(L)$, $\mu U_c(VL)$ can be computed exactly in the same way. The final results for the Exciter are as follows

$\mu U_c(VS) = 0.5$

$\mu U_c(S) = 0.7$

$\mu U_c(SM) = 0.8$

$\mu U_c(M) = 0.9$

$\mu U_c(ML) = 1$

$\mu U_c(L) = 0.9$

$\mu U_c(VL) = 0.7$.

and for the governor are as follows.

$\mu U_c(VS) = 0.5$

$\mu U_c(S) = 0.5$

$\mu U_c(SM) = 0.7$

$\mu U_c(M) = 0.8$

$\mu U_c(ML) = 0.9$

$\mu U_c(L) = 1.0$

$\mu U_c(VL) = 0.7$.

The set of all possible FAM rules defines a FAM surface in the input-output produce space (R χ R χ R). The correlation minimum interfacing technique is used here, although the correlation product technique can be also applied.

Finally, defuzzification is performed as a mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of crisp (non-fuzzy) control actions. The mean of Maximum (MOM) defuzzification method is transient performance, while the Center of Area (C.O.A) strategy yields a better steady state performance.

Chapter-5

Data and Results.

Chapter-5
Data and Results

In this chapter, various data used for simulation purpose and results obtained after simulation are presented.

5.1 Data: -

The data for various components of run of river small hydro plant, which have been simulated in this project work, are given below: -

1. **Penstock and Turbine data** ([1])-

L_t	=	3850 m,	A_t	=	38.5 m^2 ,
L_p	=	250.0 m,	A_p	=	5.0 m^2,
f_p	=	0.0 m/ $(m^3/sec)^2$,	g	=	9.8 m/sec^2,
P_t	=	125 kW,	H_o	=	15.0 m,
H_r	=	10.0 m,	Q_r	=	4.43 m^3/sec,
Q_{nl}	=	0.00 m^3/sec,	G_r	=	0.70 p.u.,
D_t	=	0.01,	a	=	1400 m/sec,

2. **Governor data** ([6] and [1])-

a). Electro Hydraulic Governor ([1])-

T_p	=	0.05 sec,	K_s	=	4.00,
T_g	=	0.20 sec,	R_p	=	0.04,
R_t	=	2.60,	T_r	=	10.00 sec,
R	=	0.16,	R_{min}	=	-0.16,
G_{max}	=	1.00 p.u.,	G_{min}	=	0.00 p.u.,
K_t	=	0.15,	K_c	=	0.15,

b). PID Governor ([1])-

K_p	=	3.00,	K_i	=	0.70,
K_d	=	0.2,	T_a	=	0.05 sec,
T_c	=	0.02 sec,	T_d	=	0.02 sec,
R_{max}	=	0.2 p.u./sec,	R_{min}	=	-0.2 p.u./sec,
G_{max}	=	1.00,	G_{min}	=	0.00,
K_t	=	0.15,	K_c	=	0.15,

3. Exciter data –

a). DC1A Exciter ([6])-

T_t	=	0.001,	T_c	=	0.173,
T_b	=	0.06,	K_a	=	187,
T_a	=	0.01,	V_{max}	=	1.70,
V_{min}	=	-1.70,	T_e	=	0.01,
A_{ex}	=	0.014,	B_{ex}	=	1.55,
K_f	=	0.1,	T_f	=	0.001,

b). AC1A Exciter ([6])-

T_t	=	0.00001,	T_c	=	0.00001,
T_b	=	0.00001,	K_a	=	200.00,
T_a	=	0.02,	V_{max}	=	15.00,
V_{min}	=	-15.00,	V_{rmax}	=	7.30,
V_{rmin}	=	-6.60,	K_e	=	1.00,
T_e	=	0.8,	A_{ex}	=	0.10,
B_{ex}	=	0.03,	K_f	=	0.03,
T_f	=	1.0,	K_c	=	0.05,
K_d	=	0.38,			

c). ST1A Exciter ([6])-

T_t	=	0.015,	K_a	=	200,
T_a	=	0.01,	V_{rmax}	=	7.0,
V_{rmin}	=	-6.40,	K_c	=	0.04

K_{lr}	=	4.54,	I_{lr}	=	4.4,

4. Synchronous Generator ([6])-

H	=	3.7 sec,	K_D	=	0.05,
f_s	=	60.00 Hz,	R_a	=	0.003 p.u.,
L_l	=	0.150 p.u.,	L_d	=	1.305 p.u.,
L_q	=	1.76 p.u.,	L'_d	=	0.296 p.u.,
L'_q	=	0.65 p.u.,	L''_d	=	0.252 p.u.,
L''_q	=	0.23 p.u.,	T'_{do}	=	4.5 sec,
T'_{qo}	=	1.00 sec,	T''_{do}	=	0.0681 sec,
T''_{qo}	=	0.07 sec,			

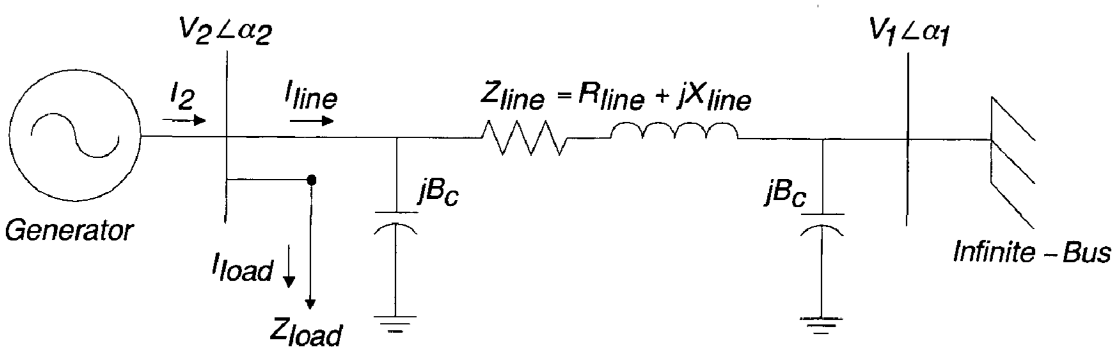
6. Transmission Line ([6])-

R_{line}	=	0.10,	X_{line}	=	0.30,
B_c	=	0.05,			

5.2 Results:-

The cases, which have been considered for simulation purpose, are summarized as below: -

Case-1



In this case, Generator is having local load at its terminal, is connected to infinite bus through a transmission line is shown in figure 5(a). The load power is 50 MW, 25 MVAR is connected to generator terminal. In this case 3-phase symmetrical fault is simulated at generator terminal at 5 seconds and it is cleared at 5.2 seconds. The results are shown with Fuzzy logic Controller (governor and Exciter) and also with Conventional Governor and exciter controller is used for this case. The values of parameters of governor, exciter and hydraulic components are same as given above. The actual simulation circuit is shown with Fuzzy Logic Controller in figure 5.1.1, and the simulation circuit with conventional controller is shown in figure 5.1.2.The corresponding results for the conventional and Fuzzy Logic controller are shown in the following figures from 5.1.3 to 5.1.12. on to the left side and right side of the page respectively.

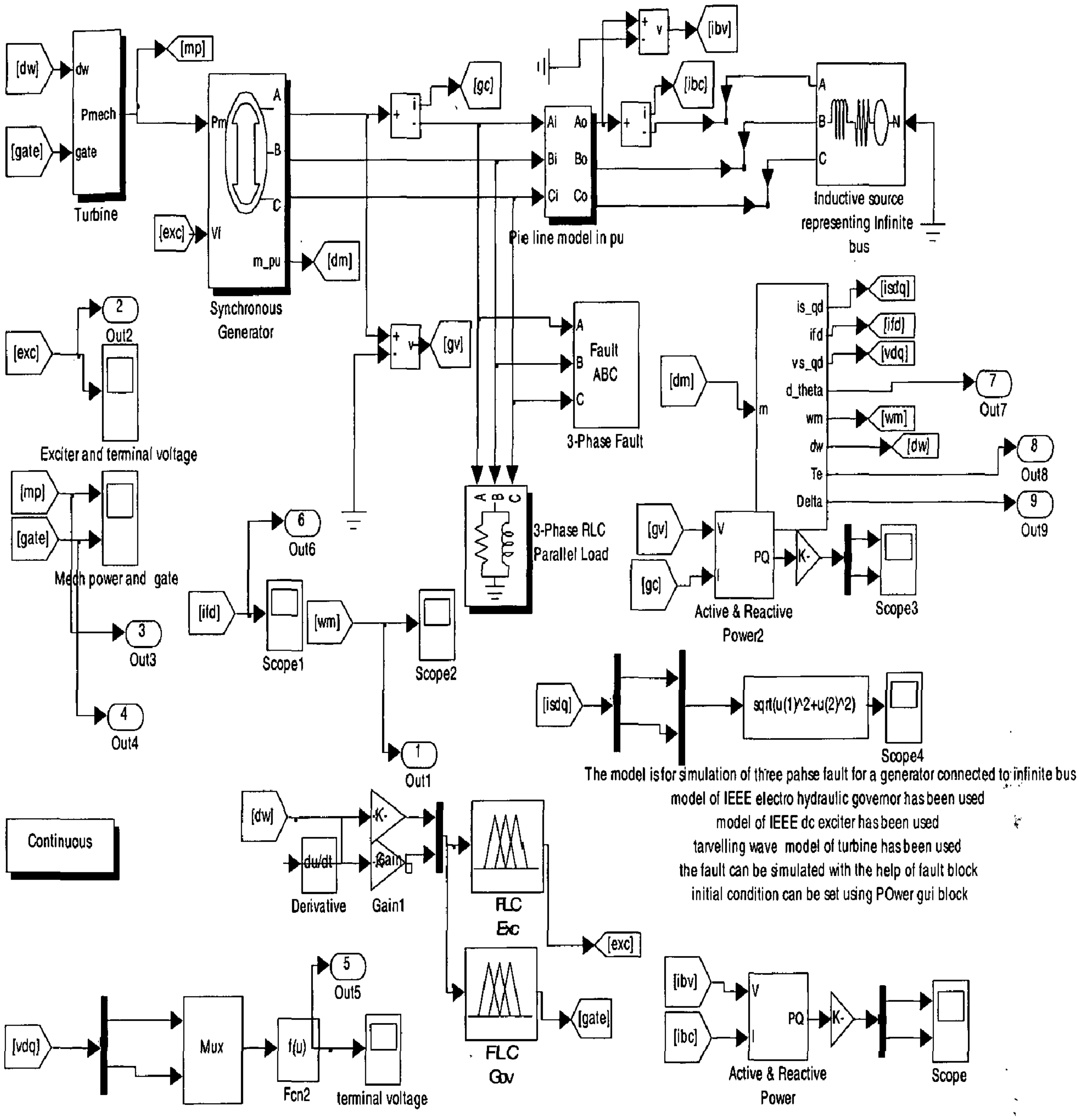


Figure 5.1.1 Actual simulation circuit synchronous generator connected to Infinite bus with Fuzzy Logic controller.

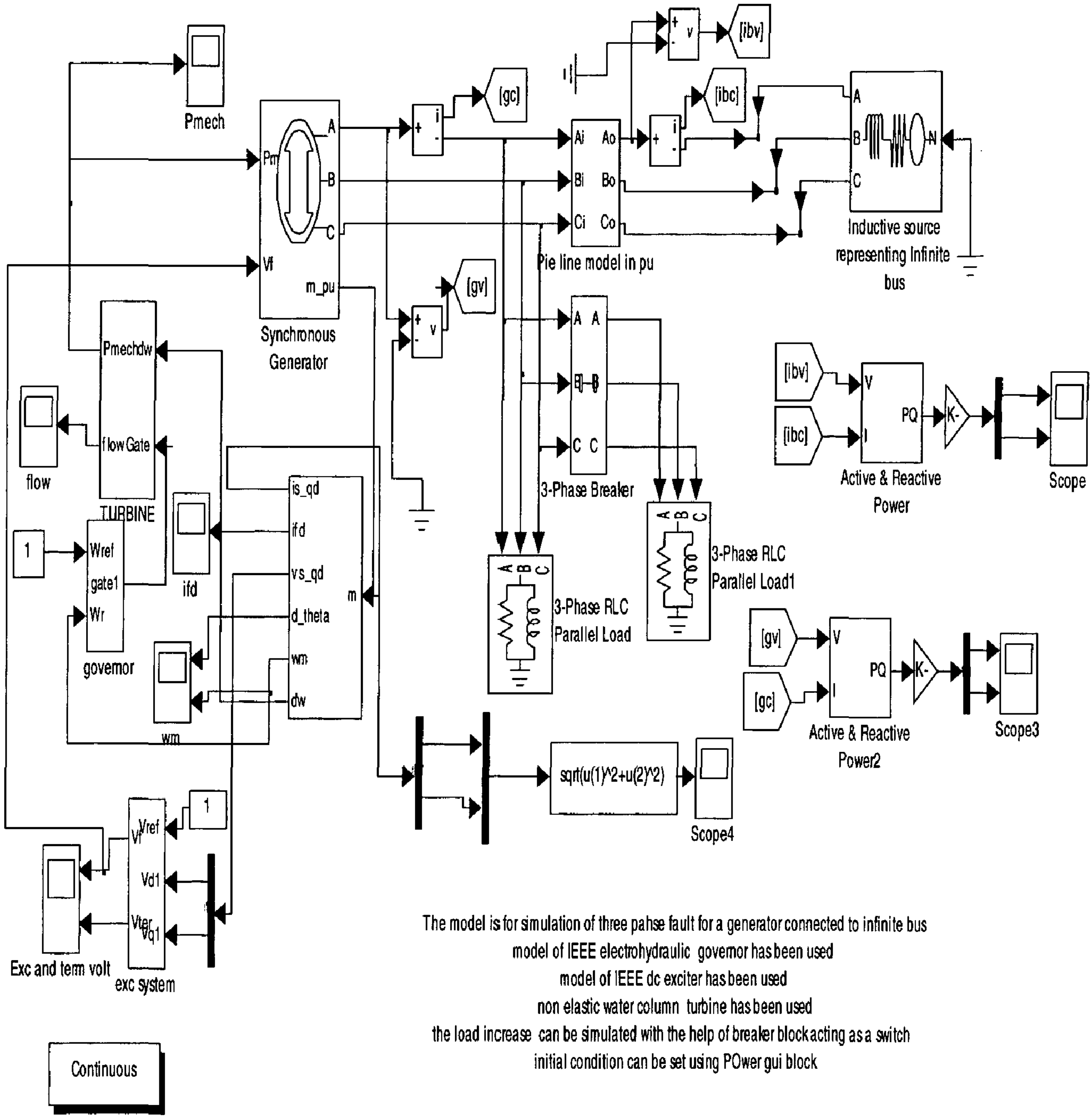


Figure 5.1.2 Actual simulation circuit synchronous generator connected to Infinite bus with Conventional Governor and Exciter.

Results for the synchronous generator connected to grid, and a 3-ϕ Fault is created after 5 seconds.

Conventional Controller **Fuzzy Logic Controller**

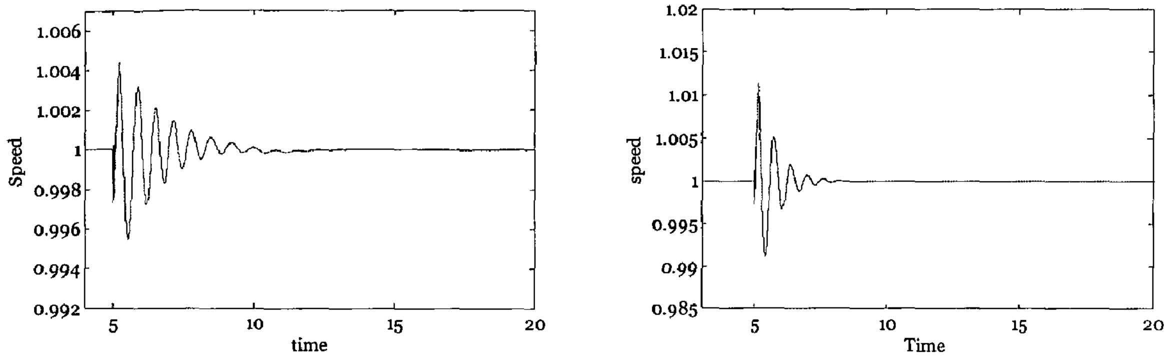


Figure 5.1.3 Speed Vs time characteristics.

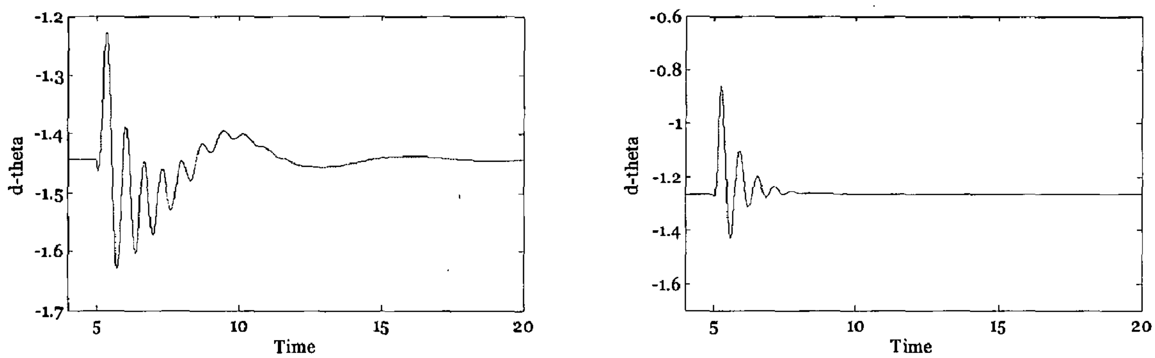


Figure 5.1.4 Rotor angle deviation Vs time characteristics.

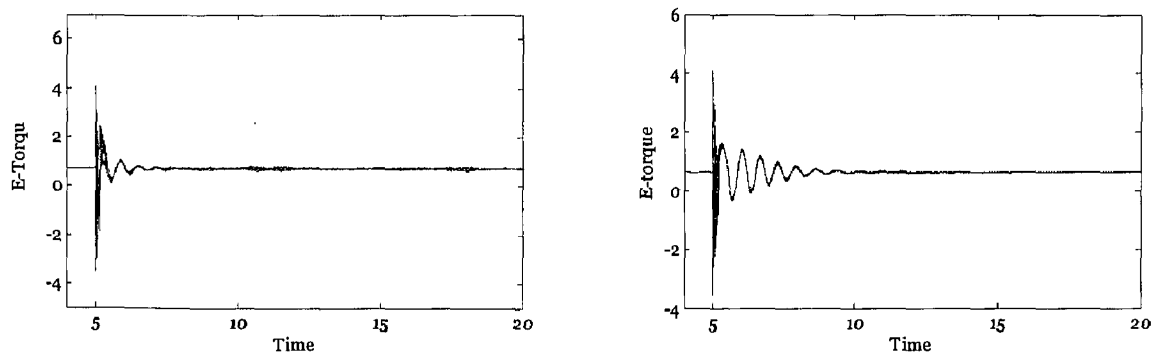


Figure 5.1.5 Electrical torque Vs time characteristics.

Results for the synchronous generator connected to grid, and a 3-ϕ Fault is created after 5 seconds.

Conventional Controller **Fuzzy Logic Controller**

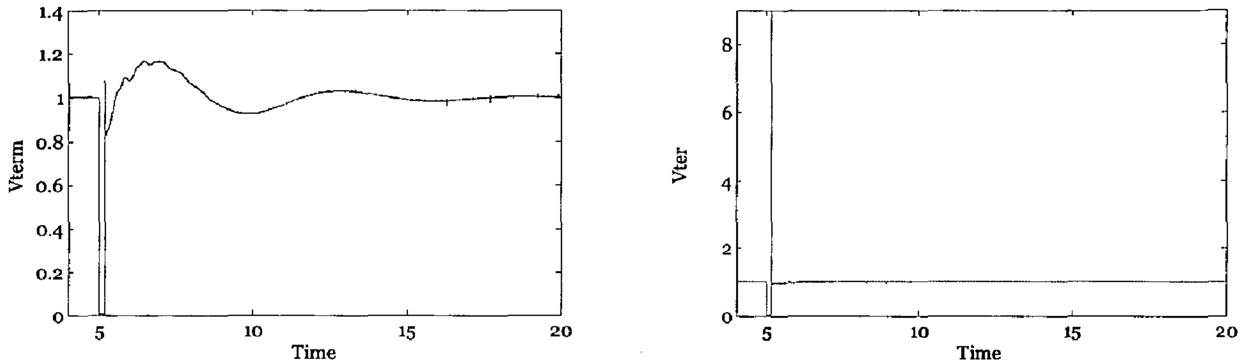


Figure 5.1.6 Terminal Voltage Vs time characteristics.

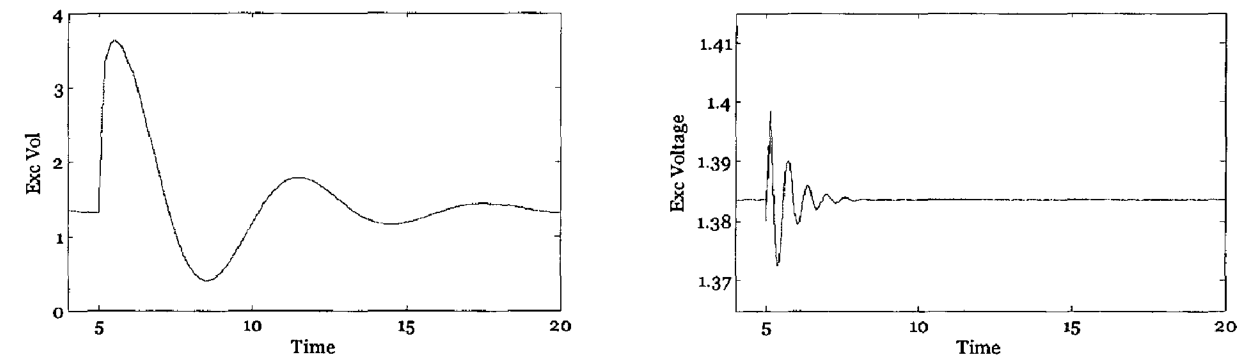


Figure 5.1.7 Excitation Voltage Vs time characteristics.

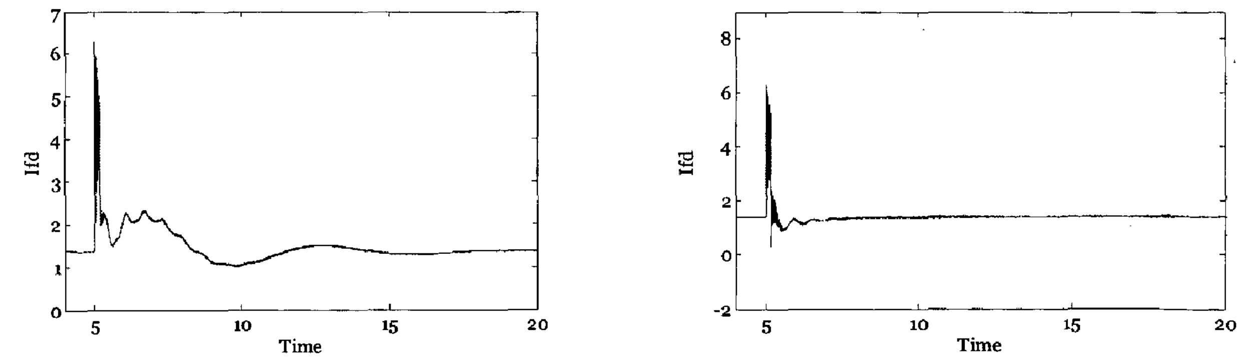


Figure 5.1.8 Field current Vs time characteristics.

Results for the synchronous generator connected to grid, and a 3-ϕ Fault is created after 5 seconds.

Conventional Controller **Fuzzy Logic Controller**

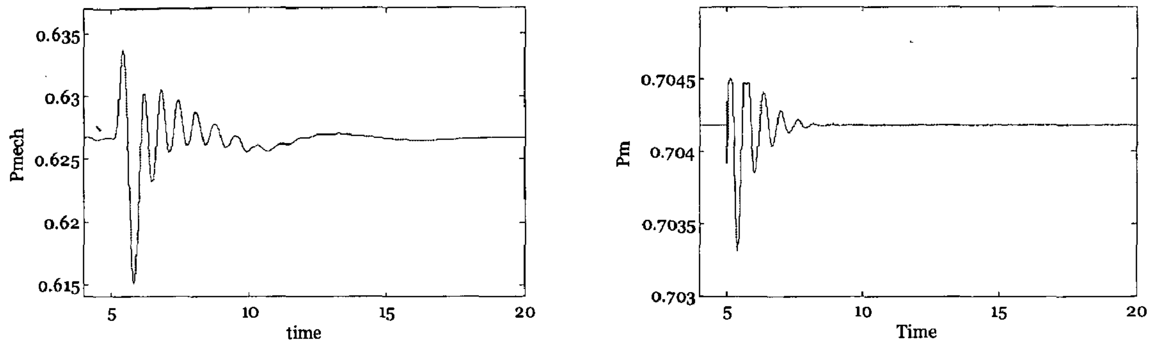


Figure 5.1.9 Mechanical Power Vs time characteristics.

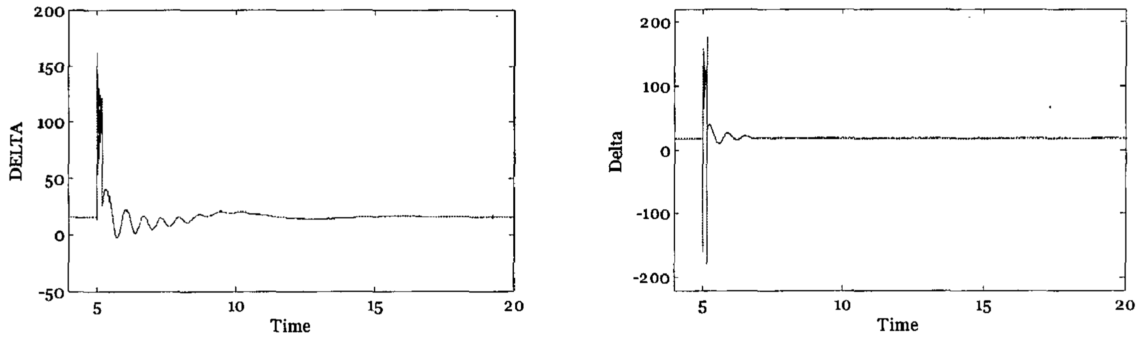


Figure 5.1.10 Load angle Vs time characteristics.

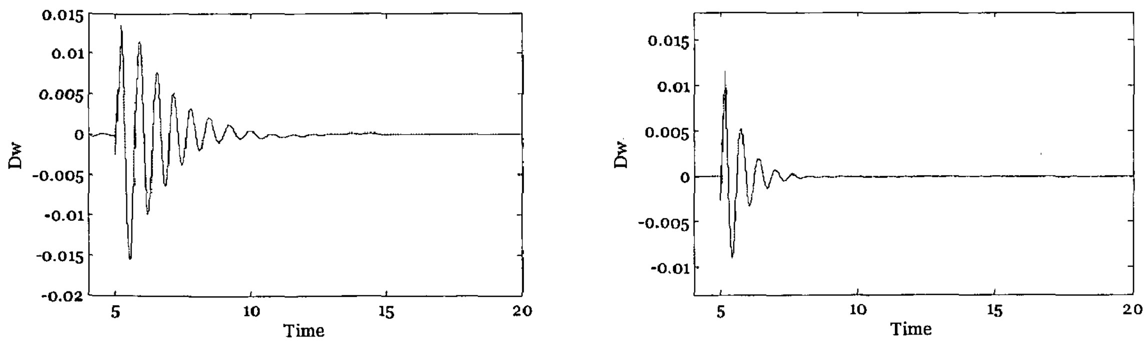
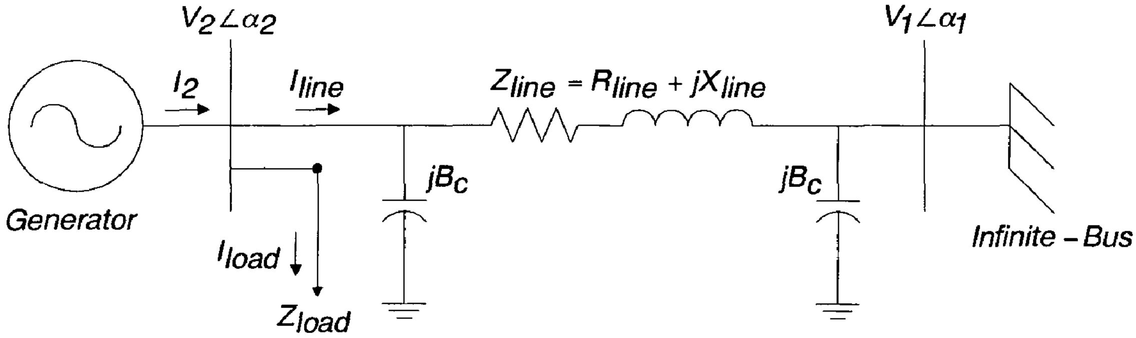


Figure 5.1.11 Speed Deviation Vs time characteristics.

Case-2



In this case, Generator is having local load at its terminal, is connected to infinite bus through a transmission line is shown in figure 5(b). The load power is 50 MW, 25 MVAR is connected to generator terminal. In this case the load is decreased and simulated at generator terminal at 10 seconds. The results are shown with Fuzzy logic Controller (governor and Exciter) and also with Conventional Governor and exciter controller is used for this case. The values of parameters of governor, exciter and hydraulic components are same as given above. The actual simulation circuit is shown in the next page in figure 5.2.1. The corresponding results for the conventional and Fuzzy Logic controller are shown in the following figures from 5.2.2 to 5.2.9, On to the left side and right side of the page respectively.

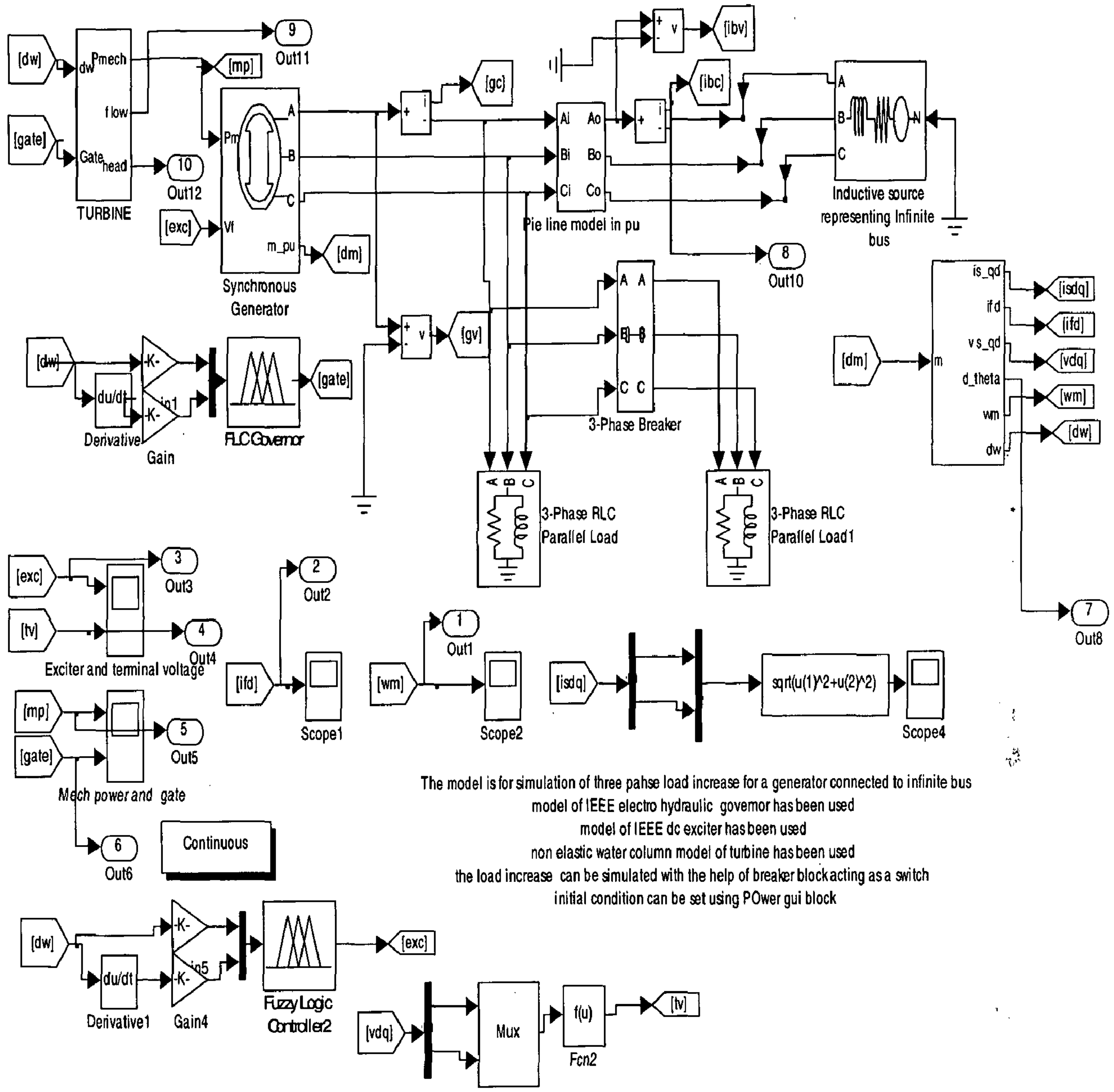


Figure 5.2.1 Actual simulation circuit for synchronous generator connected to Infinite bus and load is decreased.

Results for the synchronous generator connected to grid, and a load of 10 MW reduction.

Conventional Controller **Fuzzy Logic Controller**

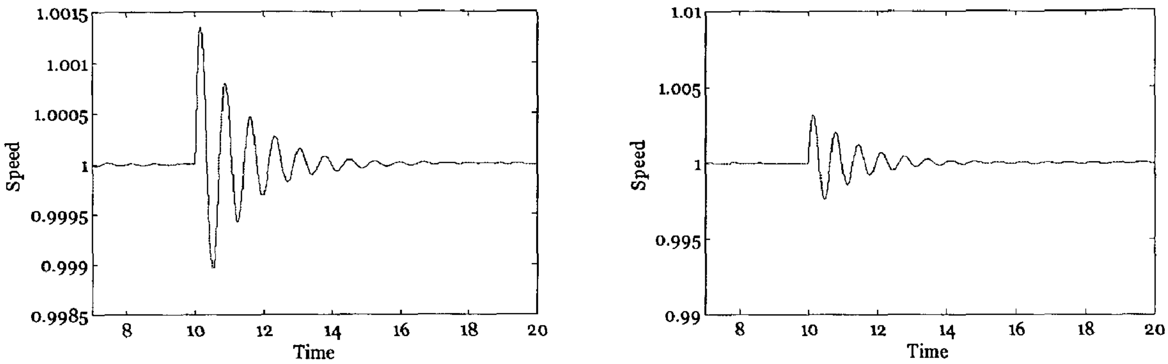


Figure 5.2.2 Speed Variation with time characteristics.

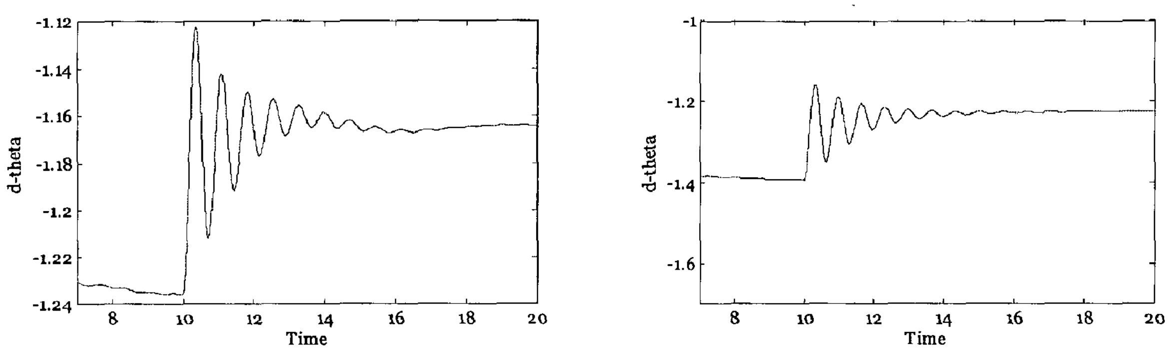


Figure 5.2.3 Rotor angle deviations with respect to time.

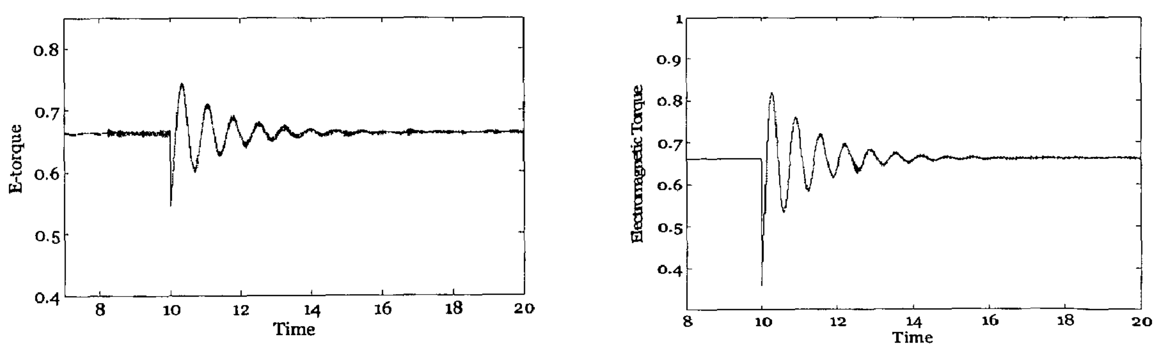


Figure 5.2.4 Electromagnetic torque Vs time characteristics.

Results for the synchronous generator connected to grid, and a load of 10 MW reduction.

Conventional Controller **Fuzzy Logic Controller**

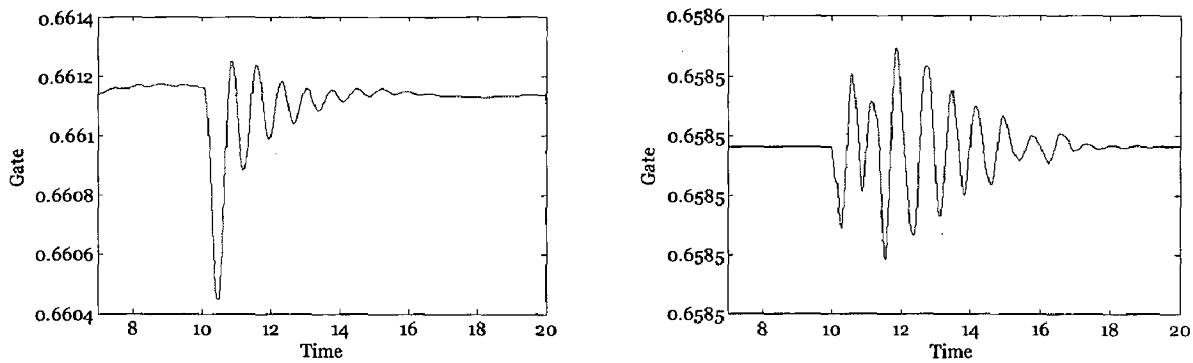


Figure 5.2.5 Gate Characteristics with respect to time.

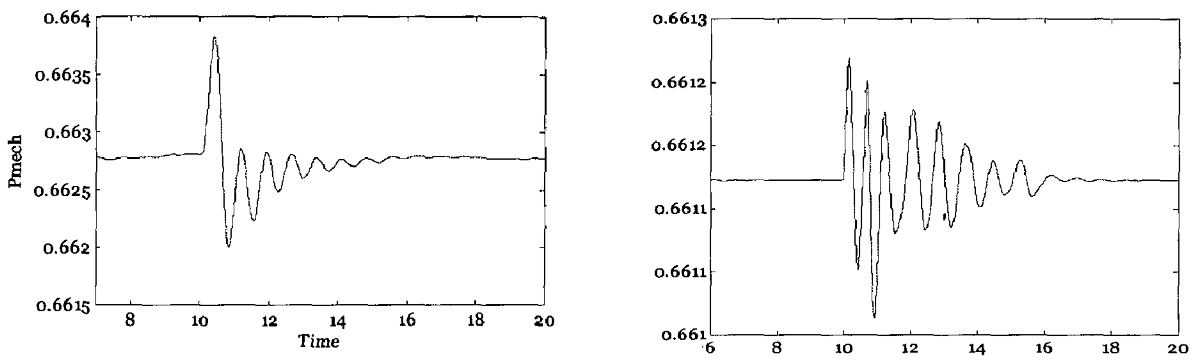


Figure 5.2.6 Mechanical Power variations with respect to time.

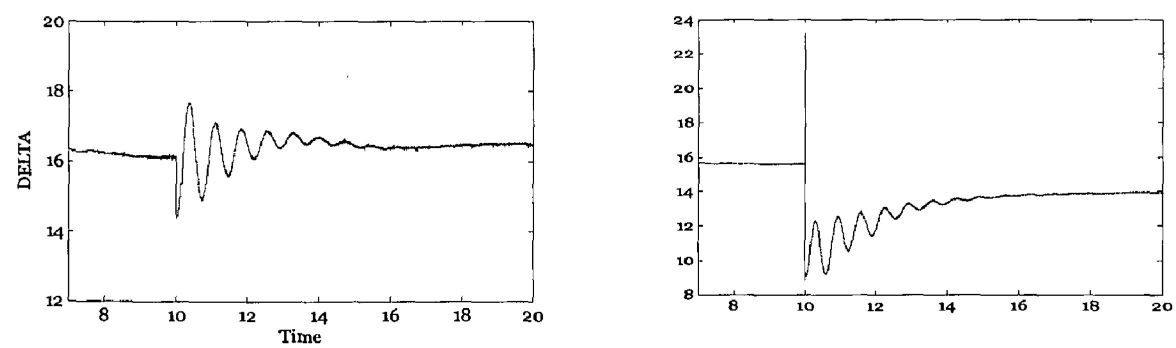


Figure 5.2.7 Load angle with respect to time.

Results for the synchronous generator connected to grid, and a load of 10 MW reduction.

Conventional Controller | **Fuzzy Logic Controller**

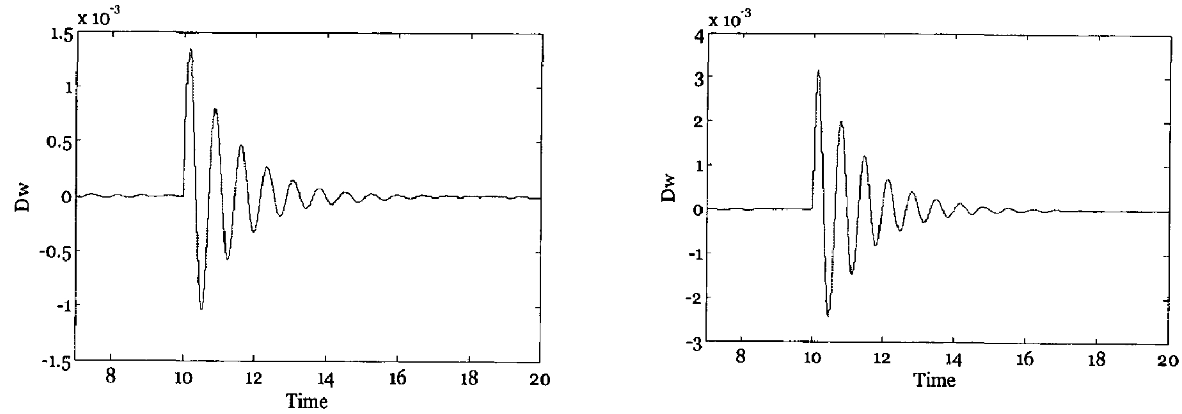


Figure 5.2.8 speed deviation with respect to time.

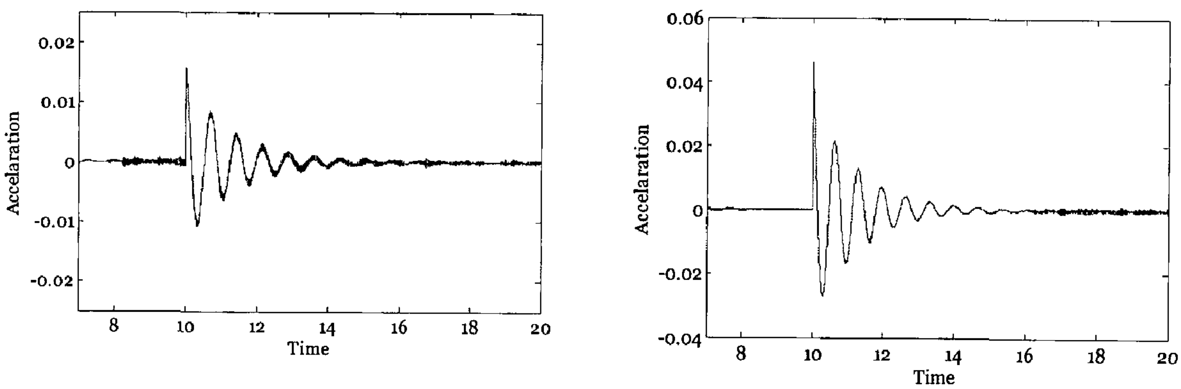
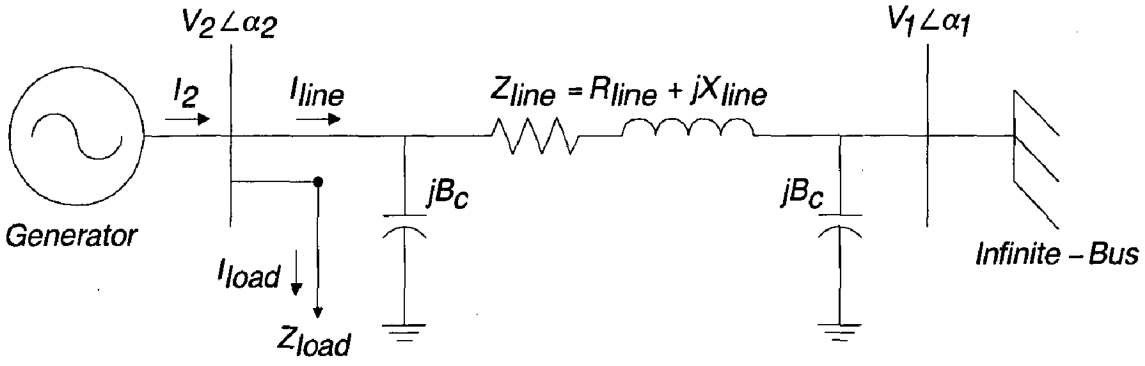


Figure 5.2.9 Acceleration with respect to time.

Case-3



In this case, Generator is having local load at its terminal, is connected to infinite bus through a transmission line is shown in figure 5(a). The load power is 50 MW, 25 MVAR is connected to generator terminal. In this case the load of 10MW is increased after 10 seconds and simulated at generator terminal. The results are shown with Fuzzy logic Controllers (governor and Exciter) and also with Conventional Governor and exciter controller is used for this case. The values of parameters of governor, exciter and hydraulic components are same as given above. The actual simulation circuit is shown in the next page in figure 5.3.1.. The corresponding results for the conventional and Fuzzy Logic controller are shown in the following figures from 5.3.2 to 5.3.8, On to the left side and right side of the page respectively.

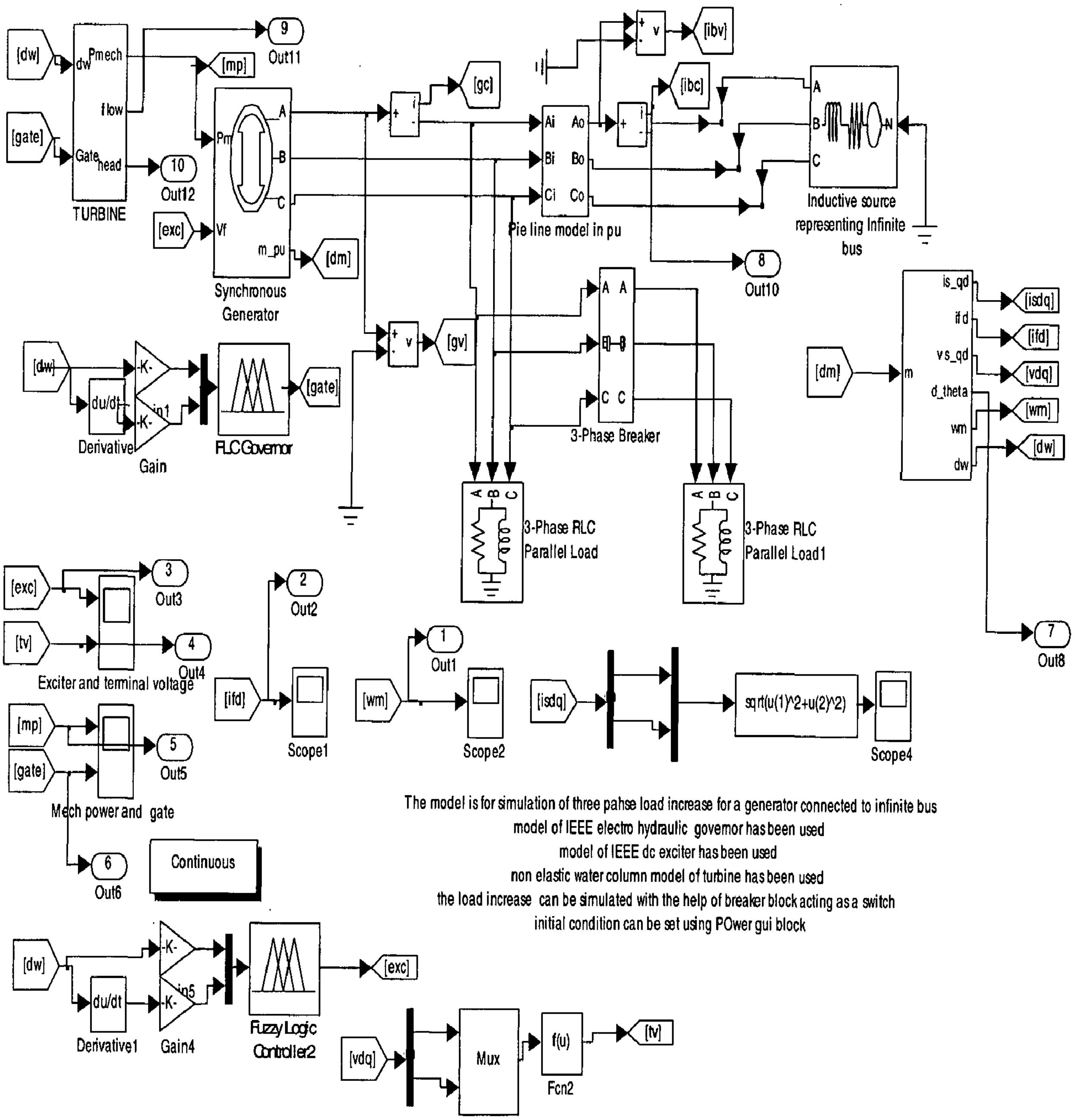


Figure 5.3.1 Actual simulation circuit for synchronous generator connected to Infinite bus and load is increased.

Results for the synchronous generator connected to grid, and a load of 10 MW increased.

Conventional Controller **Fuzzy Logic Controller**

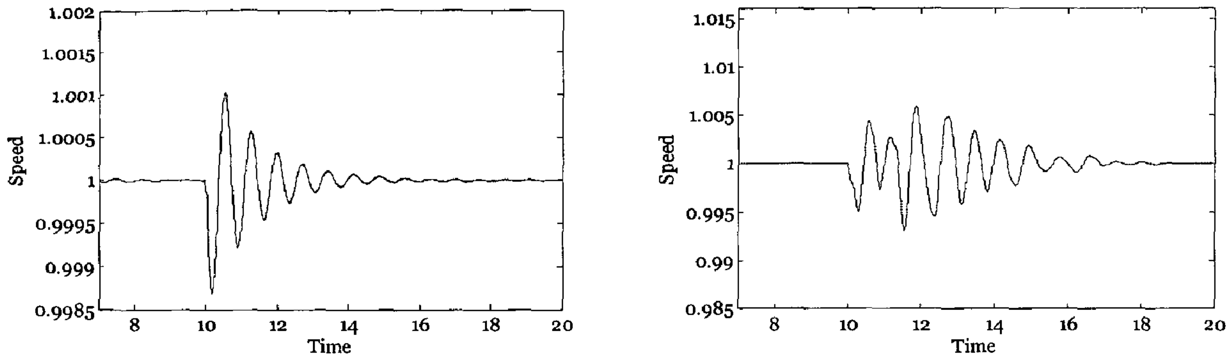


Figure 5.3.2 Speed Variation Vs time characteristics.

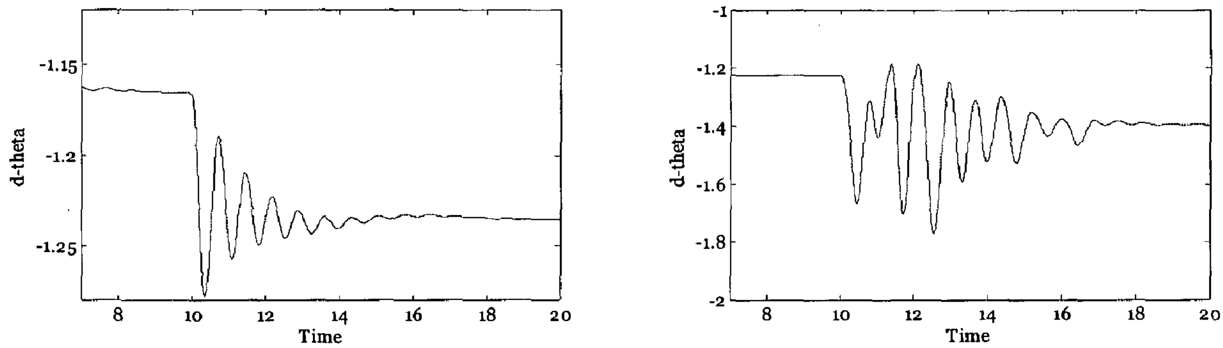


Figure 5.3.3 Rotor angle deviations Vs time characteristics.

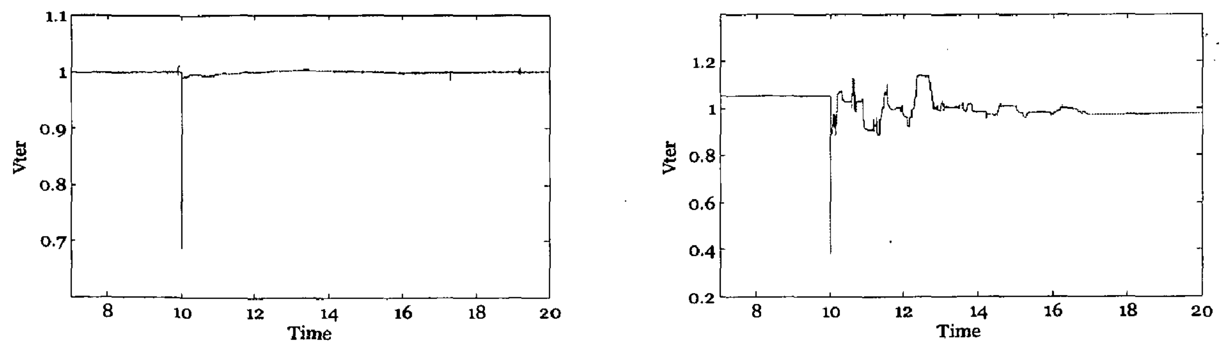


Figure 5.3.4 Terminal voltage Vs time characteristics.

Results for the synchronous generator connected to grid, and a load of 10 MW increased.

Conventional Controller **Fuzzy Logic Controller**

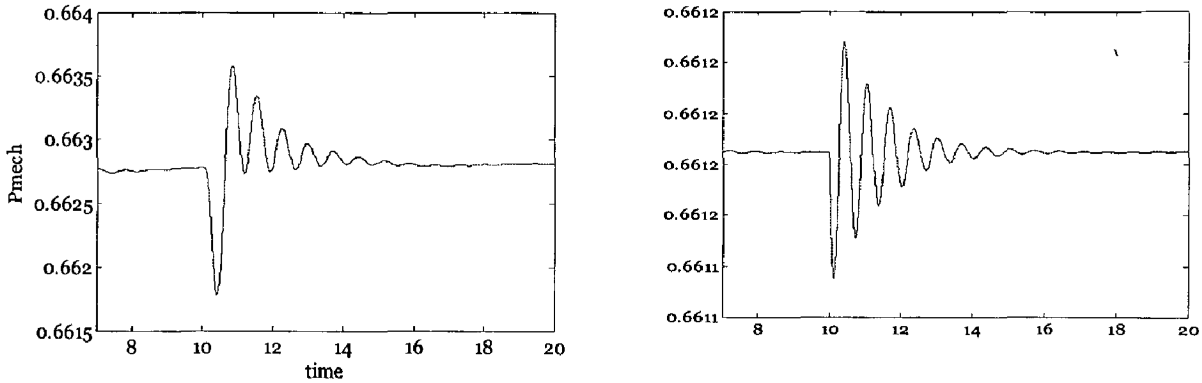


Figure 5.3.5 Mechanical Power Vs time characteristics.

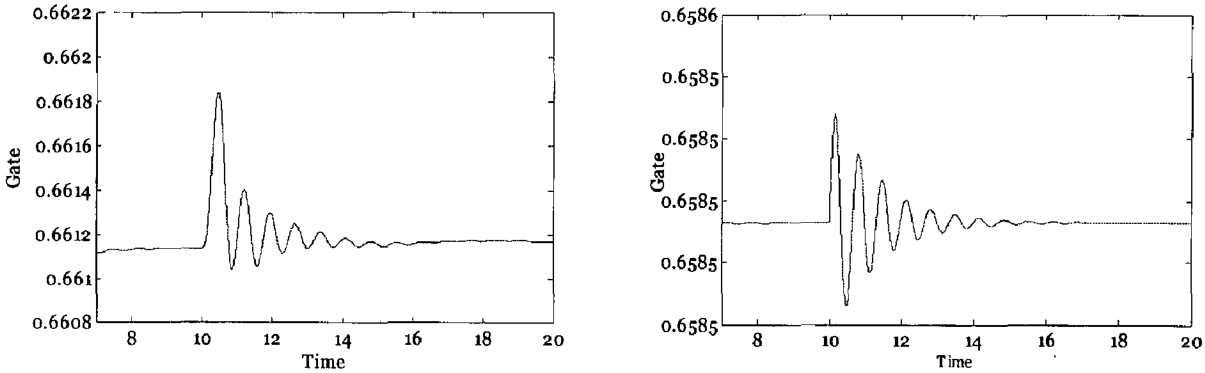


Figure 5.3.6 Gate Vs time characteristics.

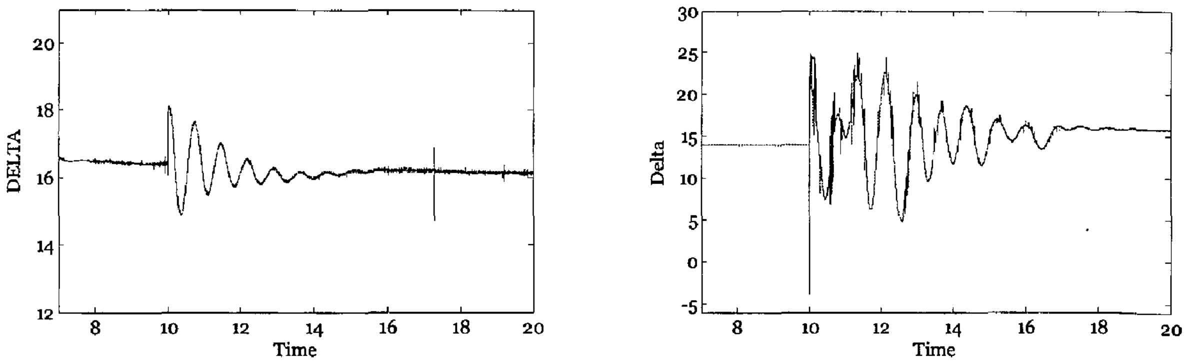


Figure 5.3.7 load angle Vs time characteristics.

Results for the synchronous generator connected to grid, and a load of 10 MW increased.

Conventional Controller **Fuzzy Logic Controller**

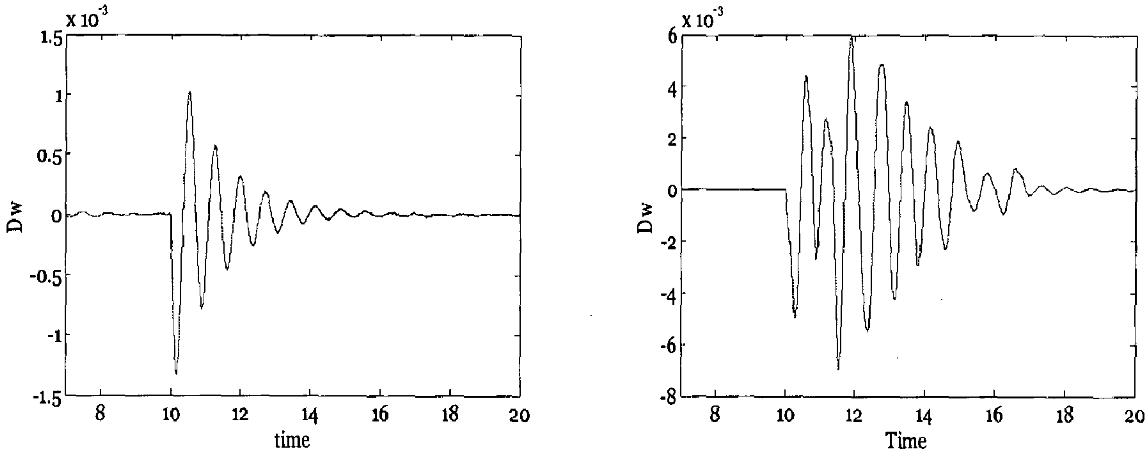


Figure 5.3.8 Speed deviation Vs time characteristics.

Case-4

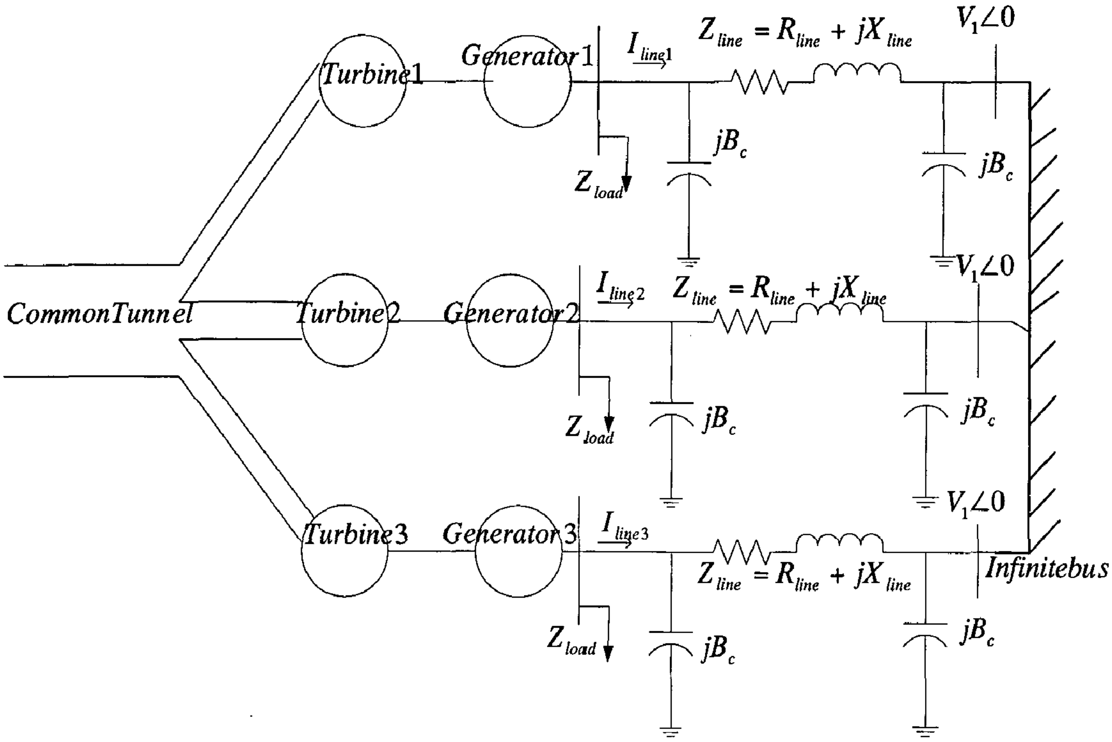


Figure 5(d) Common tunnel for three turbines and generators connected to Infinite bus.

In this case, a common penstock is used for three turbines, and each generator is having load at its terminal, and they are connected to infinite bus through a transmission line is as shown in figure 4(d). Infinite bus is treated as a swing bus and a load of 50MW, 25 MVAR is connected at each generator. In this case, 3-phase symmetrical fault is simulated at first generator terminal at 6 seconds and is cleared after 0.2 seconds. The system is simulated using Fuzzy Logic Controller (governor and exciter) and also with the electro hydraulic governor, DC1A exciter is used for this case. The values of parameters of governor, exciter and hydraulic components are same as given above. The actual simulation circuit for this case is shown in figure 5.4.1. The corresponding results for the conventional and Fuzzy Logic controller are shown in the following figures from 5.4.2 to 5.4.12, On to the left side and right side of the page respectively.

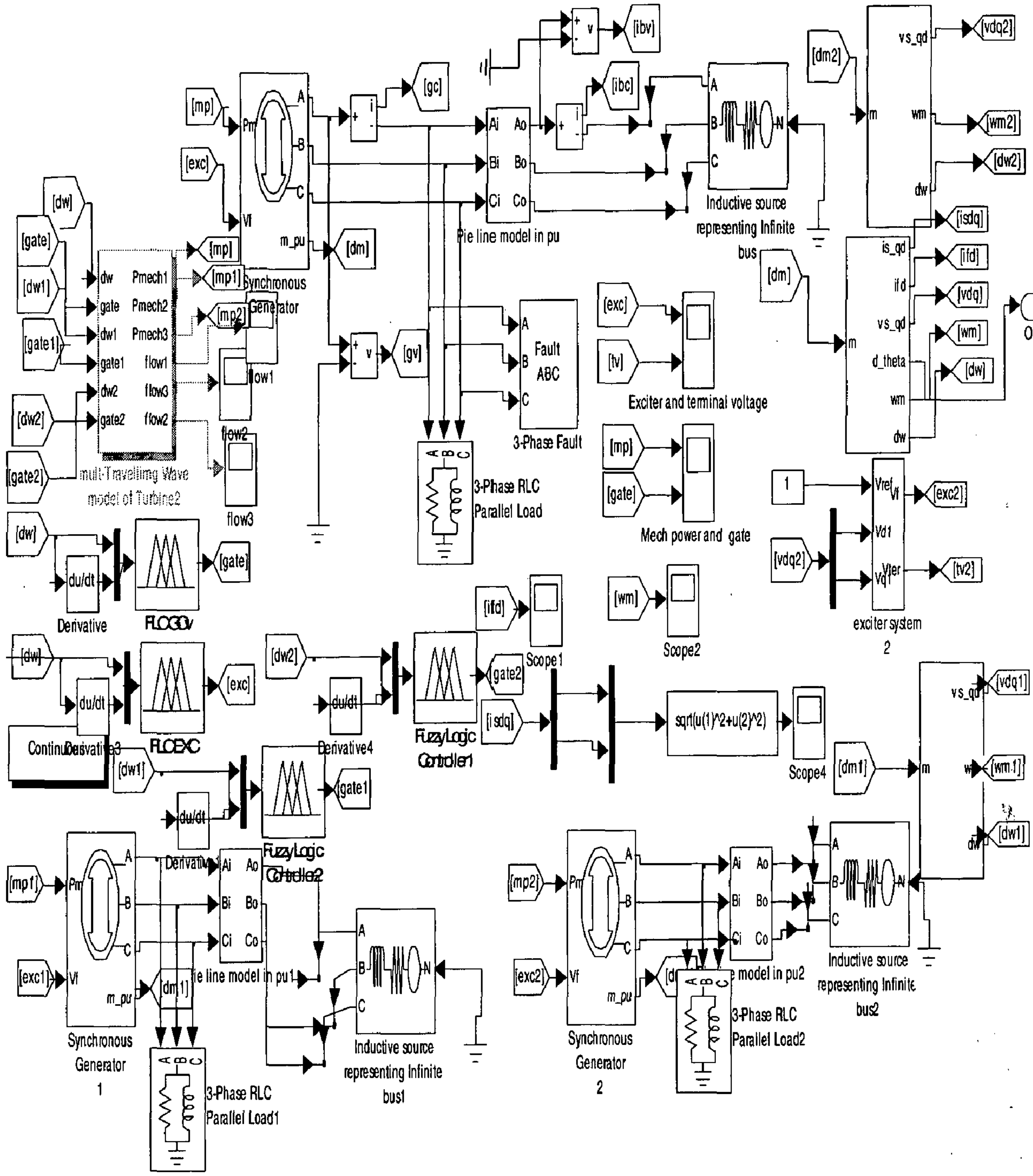


Figure 5.4.1 Actual simulation circuit for common tunnel supplying to 3 three turbines and they are connected to Infinite bus.3-phase fault is occurred at generator1.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, 3-phase fault at generator1.

Conventional Controller **Fuzzy Logic Controller**

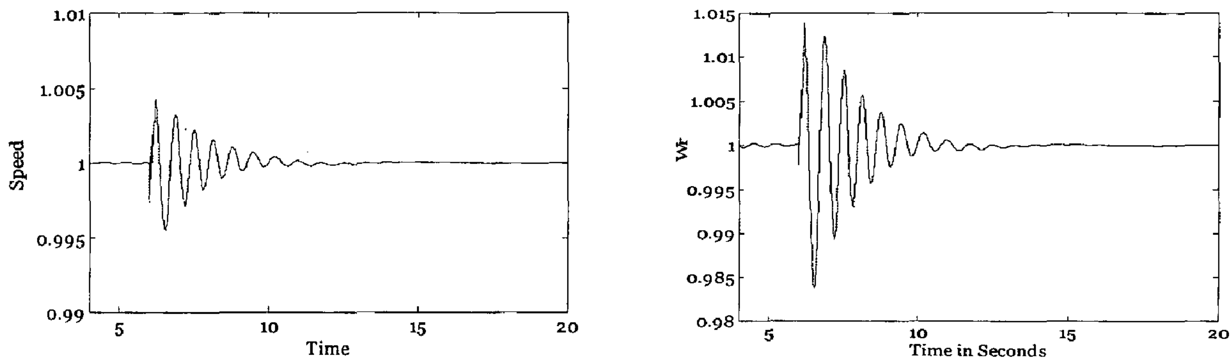


Figure 5.4.2 Speed Vs Time characteristics.

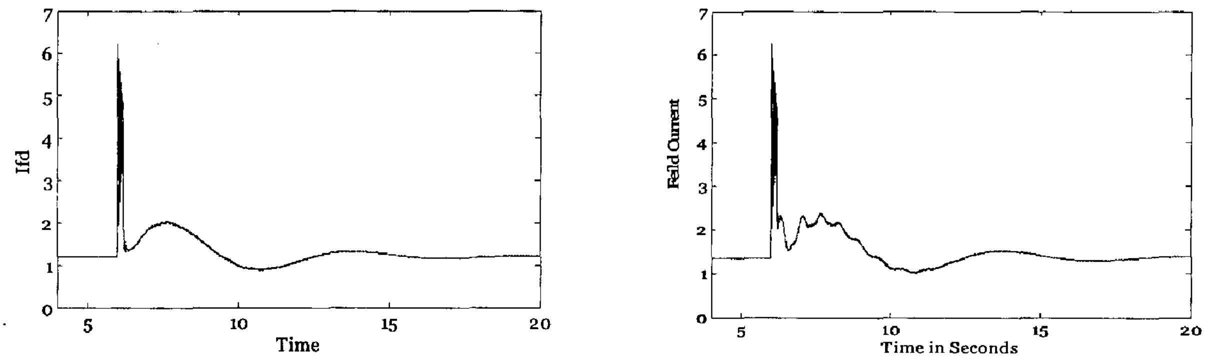


Figure 5.4.3 Field current Vs Time characteristics.

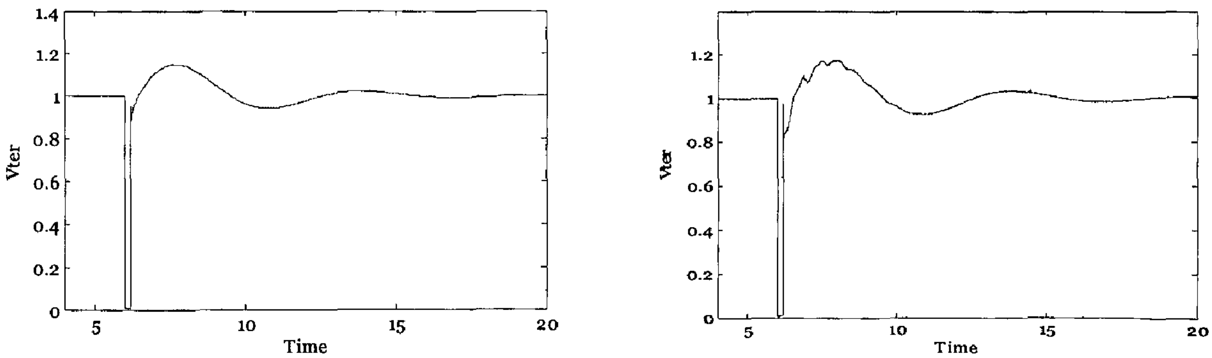


Figure 5.4.4 Terminal Voltage Vs time characteristics.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, 3-phase fault at generator1.

Conventional Controller **Fuzzy Logic Controller**

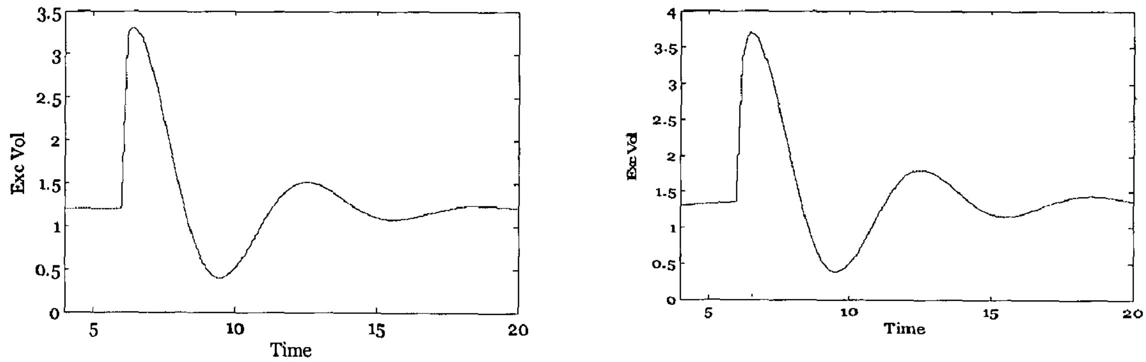


Figure 5.4.5 Excitation voltage Vs Time characteristics.

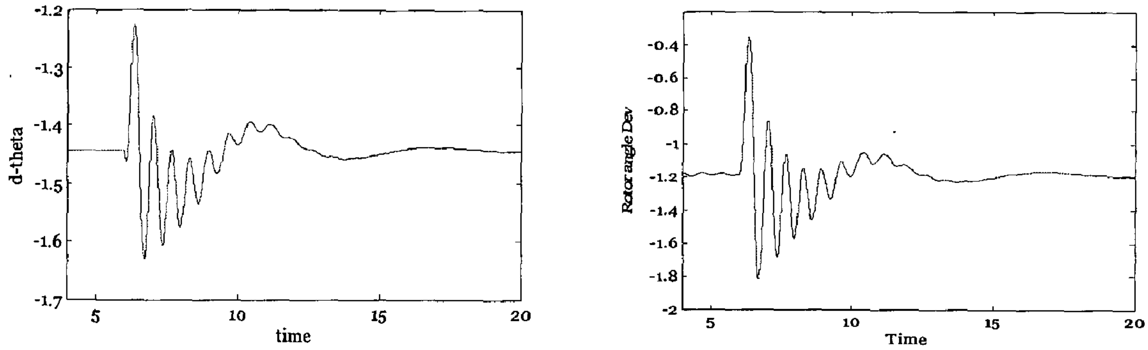


Figure 5.4.6 Rotor angle deviation Vs Time characteristics.

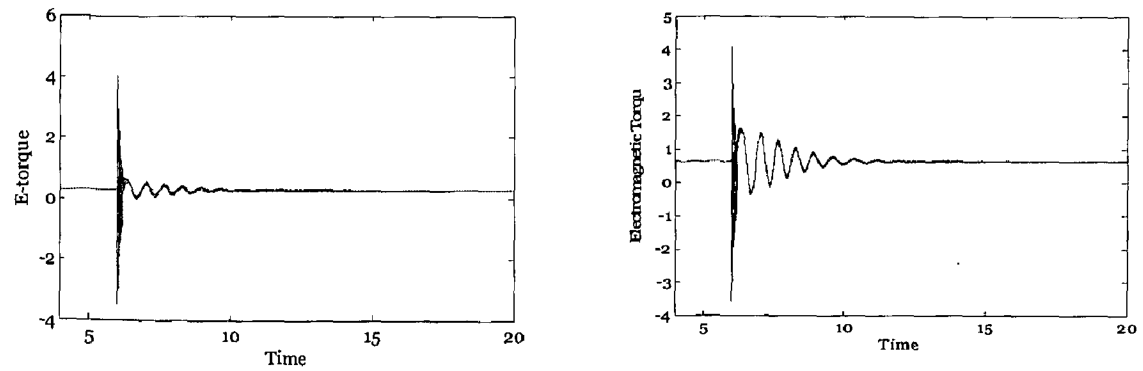


Figure 5.4.7 Electromagnetic torque Vs time characteristics.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, 3-phase fault at generator1.

Conventional Controller **Fuzzy Logic Controller**

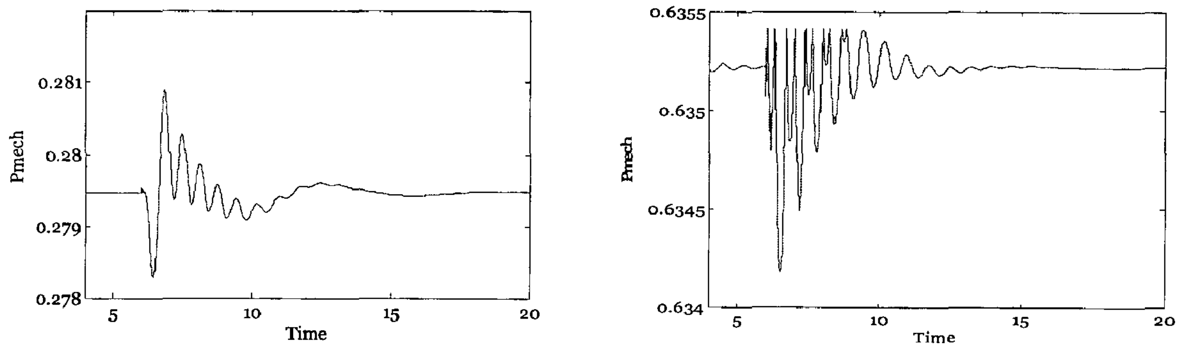


Figure 5.4.8 Mechanical power Vs Time characteristics.

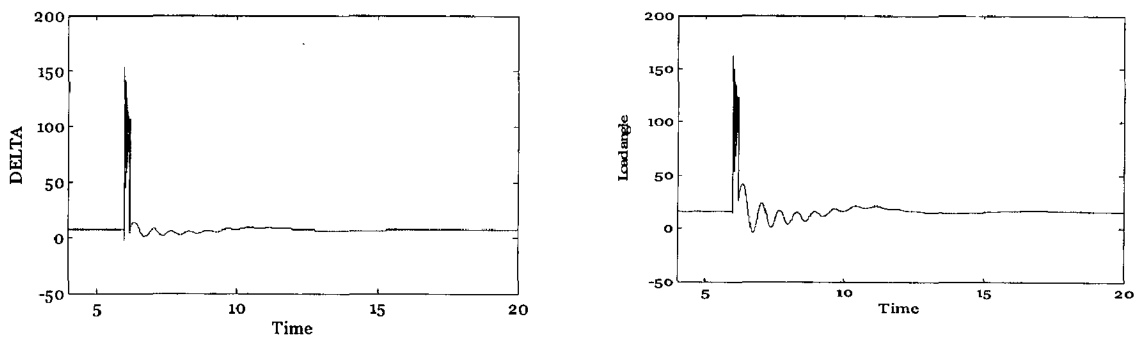


Figure 5.4.9 Load angle Vs Time characteristics.

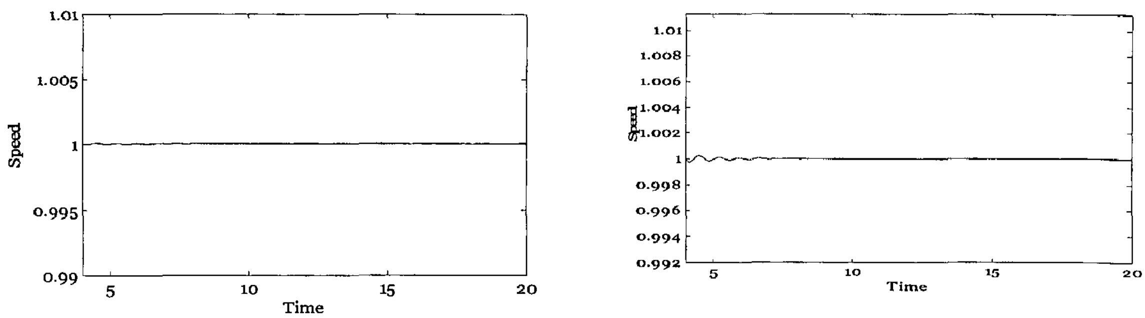


Figure 5.4.10 Speed of healthy generator Vs time characteristics.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, 3-phase fault at generator1.

Conventional Controller **Fuzzy Logic Controller**

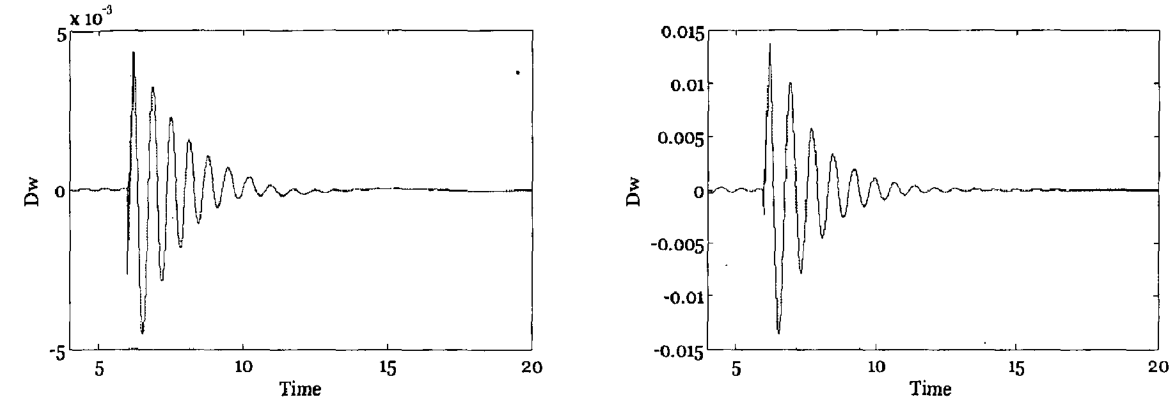


Figure 5.4.11 Speed deviation Vs Time characteristics.

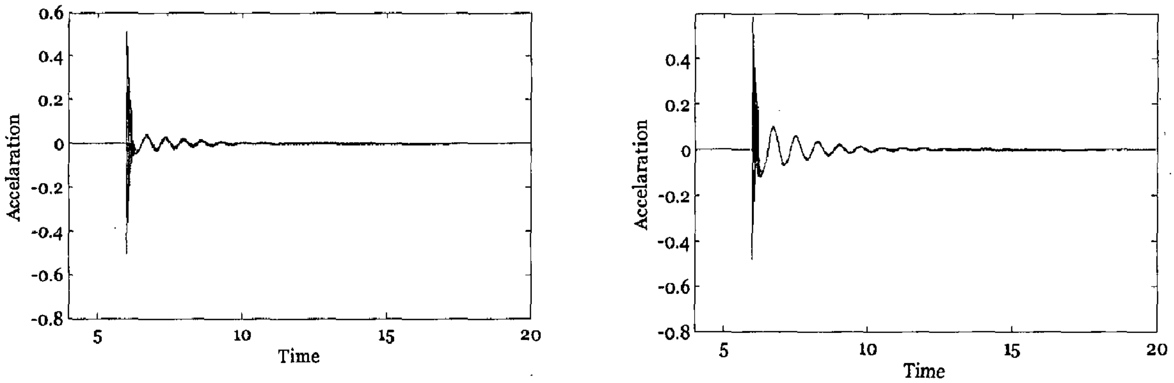


Figure 5.4.12AccelerationVs Time characteristics.

Case-5

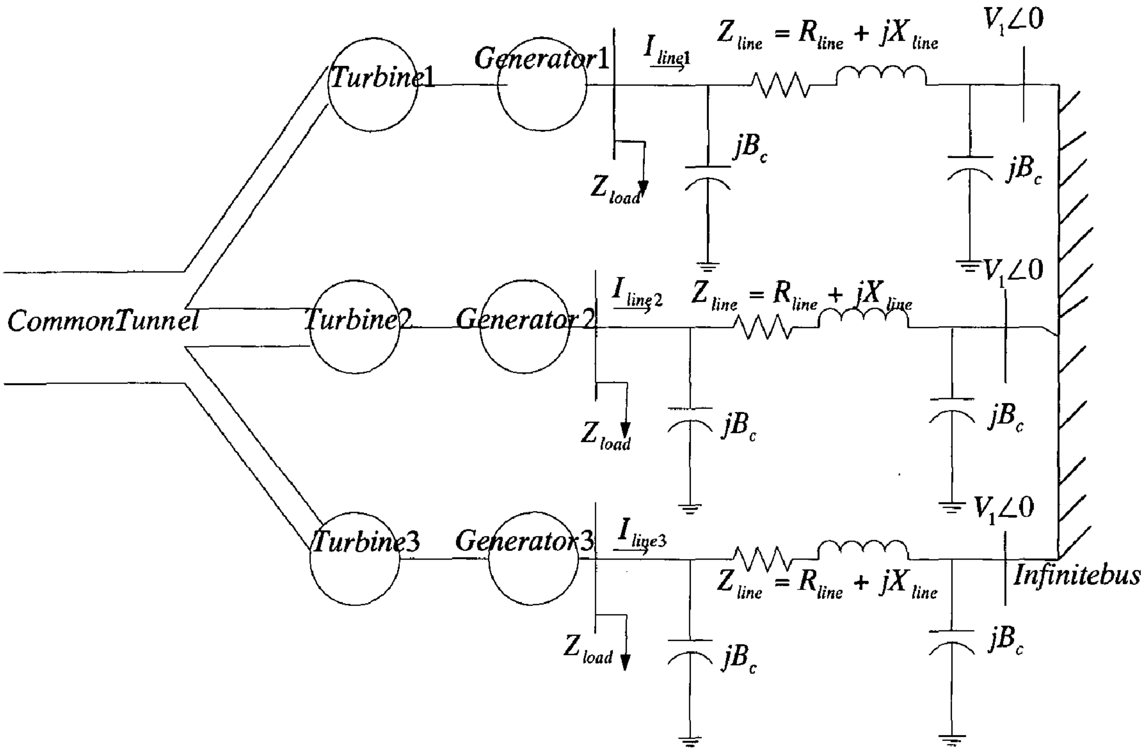


Figure 5(e) Common tunnel for three turbines and generators are connected to Infinite bus.

In this case, a common penstock is used for three turbines, and each generator is having load at its terminal, and they are connected to infinite bus through a transmission line as shown in figure 4(e). Infinite bus is treated as a swing bus and a load of 55MW, 28 MVAR is connected at generator1, and 50MW 25MVAR load is connected at other generators 2 and 3. In this case, 20 MW load is disconnected after 12 seconds for the first generator and that is simulated in this case with the conventional and FLC controller. The PID governor and DC1A exciter is used for this case. The values of parameters of governor, exciter and hydraulic components are same as given above. The corresponding results for the conventional and Fuzzy Logic controller are shown in the following figures from 5.5.2 to 5.1.8, On to the left side and right side of the page respectively.

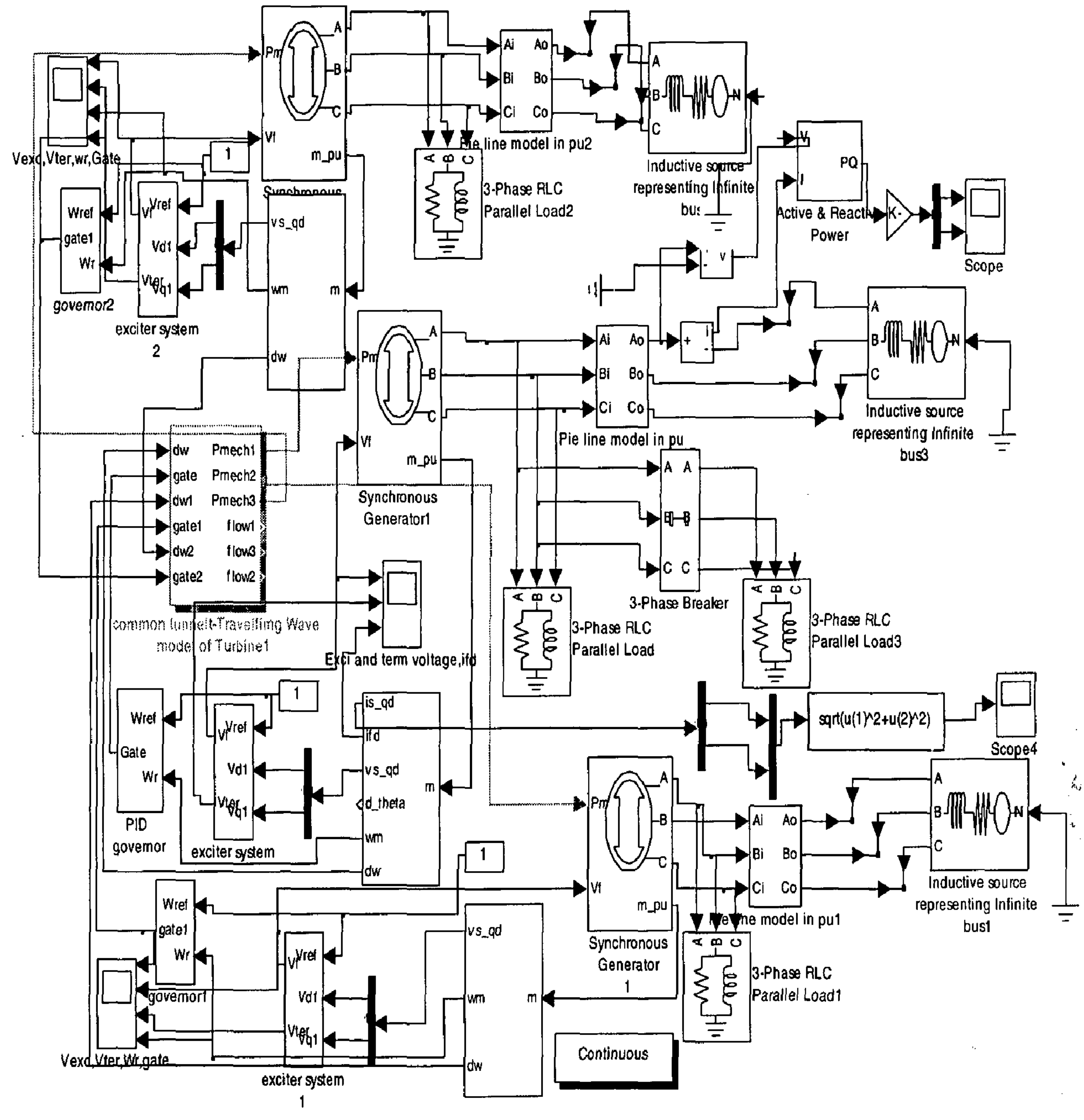


Figure 4.5.1 Actual simulation circuit for common tunnel supplying to 3 three turbines and they are connected to Infinite bus and load is decreased at one generator.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, load reduction at generator1.

Conventional Controller | **Fuzzy Logic Controller**

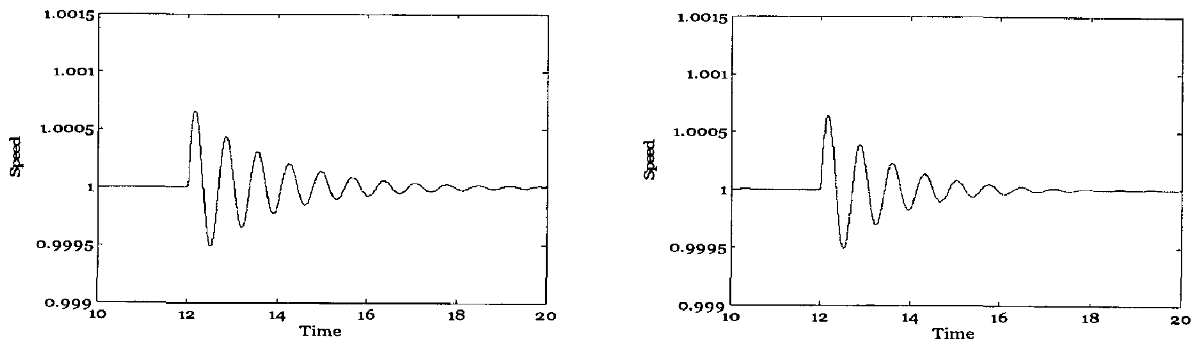


Figure 5.5.2 Speed Vs Time characteristics.

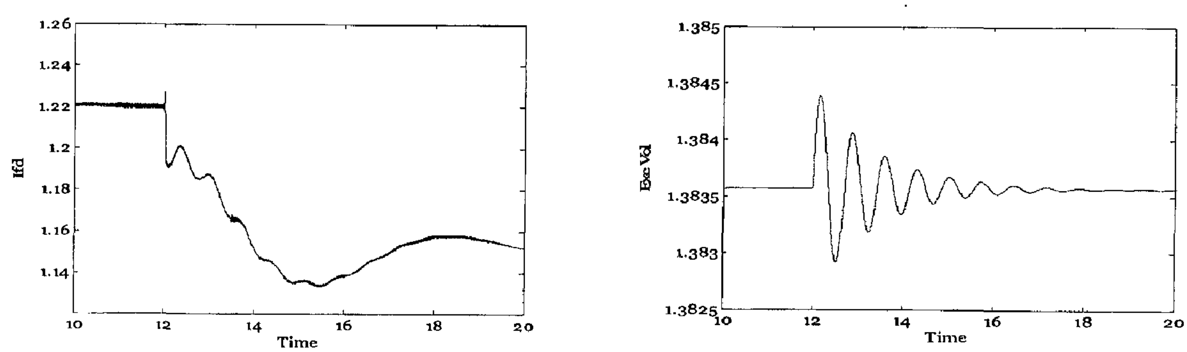


Figure 5.5.3 Field current Vs Time characteristics.

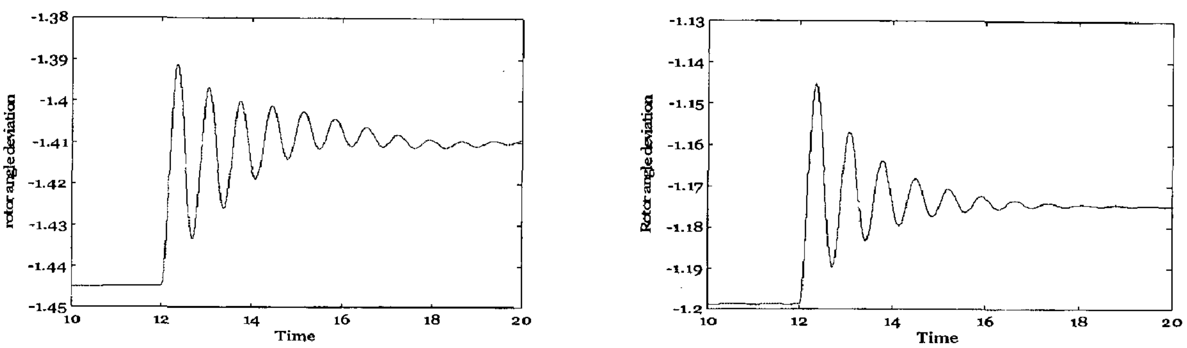


Figure 5.5.4 Rotor angle deviation Vs time characteristics.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, load reduction at generator1.

Conventional Controller **Fuzzy Logic Controller**

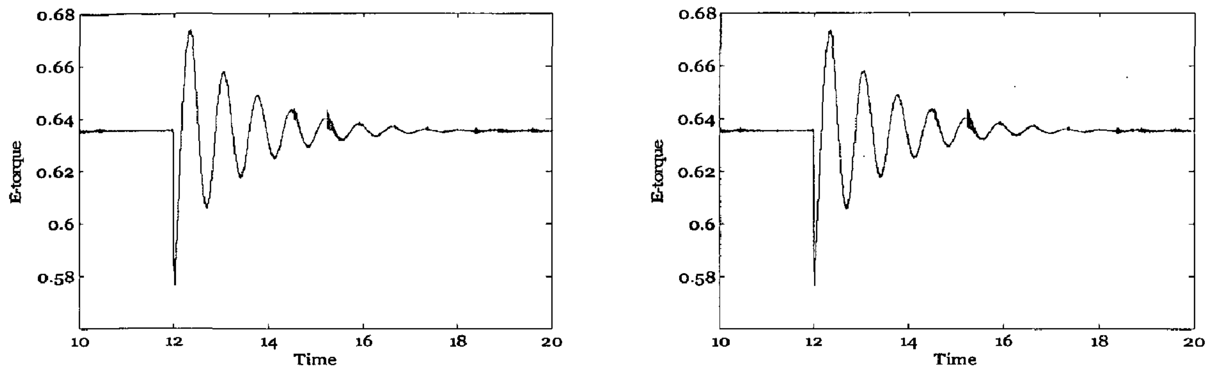


Figure 5.5.5 Electromagnetic torque Vs Time characteristics.

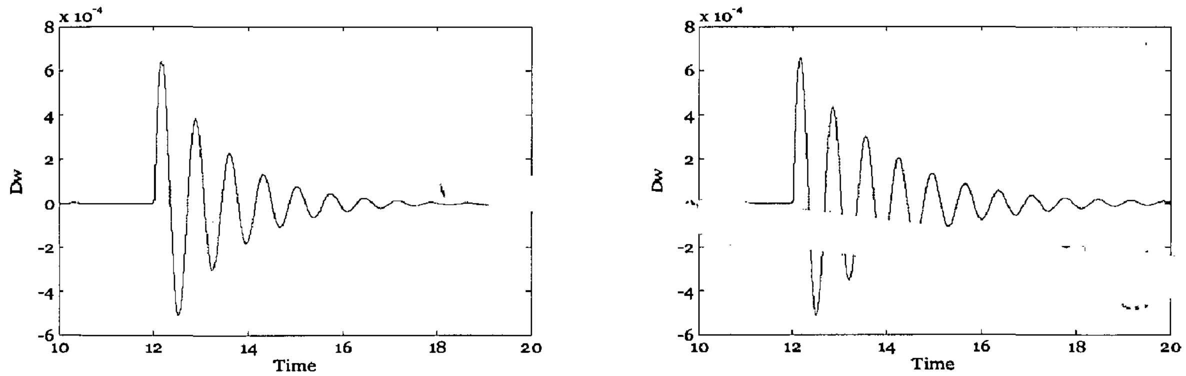


Figure 5.5.6 Speed deviation Vs Time characteristics.

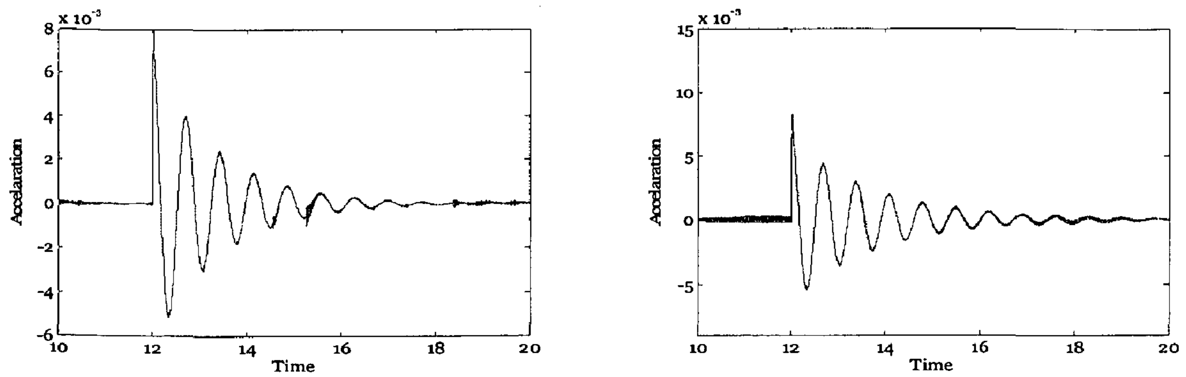


Figure 5.5.7 Acceleration Vs time characteristics.

Results for common tunnel supplying to 3 three turbines, and they are connected to infinite bus, load reduction at generator1.

Conventional Controller **Fuzzy Logic Controller**

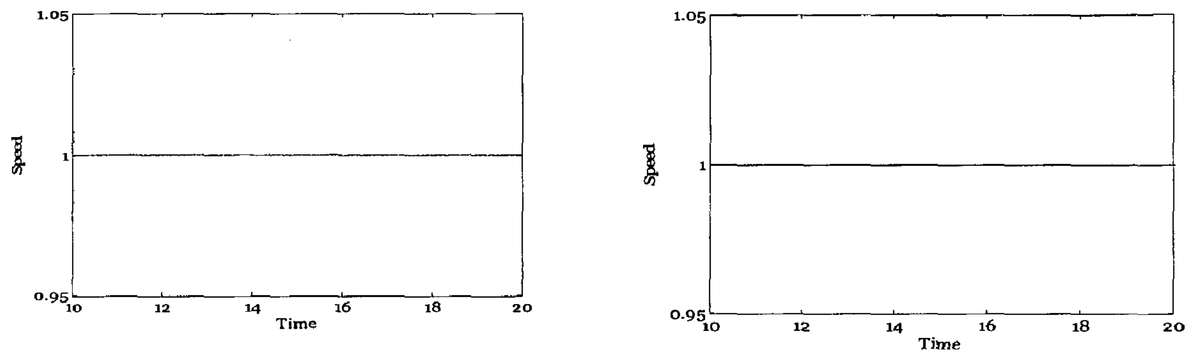


Figure 5.5.8 speed of generator 2, 3 Vs Time characteristics.

Chapter-6
Conclusions.

Chapter-6

Conclusion

In this chapter, discussion on results, limitation of developed simulator and scope for future work is presented.

6.1 Discussion on Results: -

Here have been presented results for five cases, which are very important to judge the machine behavior in power system. The power system is a spring-inertia oscillatory system with inertia on mechanical side and spring action is provided by the synchronous tie or isolated load. In this work, machine is considered with losses and dampers, which damp out the oscillations. In the simulation of the small hydro plant, conventional controller and Fuzzy Logic Governor and Exciter action, which help in stabilizing the system, have been presented.

Discussions for each case are summarized as below-

Case-1:

Due to 3-ϕ symmetrical fault, terminal voltage suddenly becomes zero and after clearing the fault, with conventional Controller it starts rising and after approximate 15 seconds of fault clearing, it becomes constant at a value higher than its initial value, with Fuzzy Logic Controller it has come to constant value after 8 seconds. Exciter current and voltage rises very sharply on occurrence of fault due to sudden decrement in the terminal voltage. Exciter current and voltage settle to a constant value after approximate 8 seconds of fault clearing with Fuzzy Logic Controller. Fig.5.1.3 shows the rotor speed increases and rotor oscillates very fast just after the fault. After 3 seconds of fault clearing, rotor speed settles to a constant value same as initial value with the FLC controller and it will take 8 seconds with conventional controller. Due to fault, electrical and mechanical power oscillates very fast and after approximate 4 seconds of fault clearing, both settles to initial value. Due to large oscillations in mechanical power, discharge curves show large deviations.

Case-2:

As the load is decreased, rotor speed increases very sharply and after approximate 6 seconds of disturbance, it settles to initial value with Fuzzy logic controller and it will take 10 seconds with the conventional controller. Terminal voltage also increases. it settles to initial value after 10 seconds of disturbance. Due to initial rise in terminal voltage, there is a sharp drop in exciter voltage and current. Exciter voltage attains steady state value after approximately 10 seconds of occurrence of disturbance with the Fuzzy logic controller. Due to decrease in load, load angle drops very fast. As electrical load is decreased, rotor accelerates and oscillates very fast. Electromagnetic torque is decreased as the load decreases. The mechanical power will increase suddenly and after 7 seconds, it attains a steady value same as the initial value, Rotor angle drops suddenly and settles finally after 8 seconds at a lower value and the Gate opening settles after approximate 10 seconds of disturbance with Fuzzy logic controller.

Case-3:

As the load is increased, terminal voltage deceases very sharply and after approximate 6 seconds of disturbance, it settles to initial value. Due to initial drop in terminal voltage, there is a sharp rise in exciter voltage and current. Exciter current and voltage attains steady state value after approximately 10 seconds of fault clearing. Due to increase in load, load current rises very fast. As load is increased, rotor decelerates and oscillates very fast. After 10 seconds fault clearing rotor speed attains a steady value same as the initial value. The characteristics of electrical torque and mechanical power are very much similar to that of rotor speed characteristic.

The electrical torque settles after approximately 10 seconds of fault clearing, mechanical power also settles after approximate 10 seconds of fault clearing. Due to increase in load, load angle increases , oscillations will take and after approximately 10 seconds of fault clearing it settles constant value more than the initial one.

Case-4:

Due to occurrence of fault, at generator1 terminal, armature current increases and terminal voltage decreases very sharply. After fault clearing, the natures of terminal voltage and armature current characteristics are very similar. Terminal voltage settles after approximate 15 seconds of fault clearing. On occurrence of fault, exciter current and exciter voltage rises very sharply due to sudden drop in terminal voltage. Exciter voltage becomes constant after approximate 15 seconds of fault clearing and exciter current settles after approximate20 seconds of fault clearing. Just after fault, internal angle drops and soon after it gains a constant value same as initial value. Due to initial drop of electrical power output, rotor gets over speeded for a minor and after a few oscillations; its speed becomes constant after approximate15 seconds after fault clearing. Initially, electrical torque decreases due to drop in terminal Voltage. Finally, due to increase in armature current and terminal voltage electrical torque increases and becomes constant after approximate 15 seconds after fault clearing. Mechanical power shows oscillating nature and becomes constant after approximate 15 seconds of fault clearing. The speed, terminal voltage and other characteristics of the generator2, and generator3 are almost constant.

Case-5

In this case, there is a sharp drop in excitation voltage and current, due to initial rise in terminal voltage on the occurrence of load reduction. Field current attains a steady value after approximately 5 seconds of disturbance. As the electrical load is decreased, rotor accelerates and oscillates very fast. After approximately 4 seconds of disturbance, rotor speed attains a constant value same as initial value with Fuzzy logic controller. Due to the decrease of load the rotor angle decreases sharply, oscillates and settles at less value after 5 seconds of disturbance. The rotor speed, excitation voltage, and terminal voltage of generators 2 and 3 are constant almost. The mechanical power and discharge in turbines 2 and 3 also not varied much and are almost constant.

On the basis of above analysis, it is concluded that as follows

In all the five cases, all the characteristics with Conventional controller and Fuzzy Logic controller are shown; Fuzzy logic controller is giving better results as compared to conventional controller. The time required for the fuzzy logic controller is almost half of that with the conventional controller in the first three cases with single turbine and is also comparable with common tunnel supplying three turbines. As FLC uses the expert knowledge or human operator's behavior, it allows a certain incomplete understanding of the mathematical model in the problem control, no need of solving the set of differential equations.

6.2 Limitations: -

The rule base is formed based the previous experience for The Fuzzy Logic controller. The components of small hydro-plants, which have been simulated in this dissertation work, are - Power Channel, Fore bay, Penstock, Turbine, Governor, Exciter, Synchronous Generator (connected to Infinite Bus) and Transmission Line. The developed software is fully applicable for simulation of small hydro-plants under sudden change in load, 3-phase symmetrical fault. Two models of penstock are used - one using non-elastic water column theory and another using water column traveling wave effect. Fuzzy Logic Controllers of Exciter and governor are used. Two types of governor models are used- Electro-hydraulic and PID governor. The exciters considered are type- DC1A, type-AC1A and type-ST1A. In connected to infinite Bus mode, only two buses are considered - Infinite Bus as Slack Bus and Generator Bus as PV Bus. As the transients associated with the transmission network decay very rapidly. Therefore, it is usually adequate to regard the transmission network, during the electromechanical transient conditions, as though it were passing directly from one steady state to another. In case of transmission line, modeling, short and medium lines are considered here, but by suitable data inputting, long transmission line can also be simulated.

6.3 Scope for Future Work: -

Although FLC gives optimal damping for different operating conditions, it could have some limitations when used with a multimachine network. Further studies are necessary on the effects FLC on the inter area oscillations and bus in a multi machine power system. Controller can be developed with fuzzy set theory and artificial neural networks. Fuzzy logic control signals are adjusted using the on-line measurements, can offer a better damping effects for generator oscillations over a wider range of operating conditions than conventional regarding. Kaplan turbine also can be used for simulations

Hydraulic structures are simulated here are-Reservoir, Power Canal, Fore bay and Penstock. Other hydraulic structures (such as Flume, Tunnel and Surge tank etc.) also can be added by appropriate changes in software. The number of damper windings in synchronous generator also can be increased by simple modification in generator equations. Here we have considered only 3-∅ symmetrical fault (with and without impedance), other faults (i.e. L-N, L-L-N, L-L faults) can be simulated by taking sequence components of currents, voltages and impedances into account. In addition, this software can be extended for multimachine systems.

References.

References

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