Modelling and Control of a Cascaded Reservoirs Hydropower System

by

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ABSTRACT

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The cascaded reservoirs hydropower plant is a complex nonlinear system that involves interacting input and output nonlinear parameters, nonlinear flow rates, and nonlinear dynamical hydraulic heads. This thesis aims to enhance the existing cascaded reservoirs hydropower systems and future ones by new designs of control and optimization systems based on fuzzy logic. In this thesis, a new nonlinear mathematical model of a cascaded reservoirs hydropower plant is developed. The developed model was accurate enough to represent and simulate the plant nonlinear dynamics and to design and test three new fuzzy control systems addressing three major cascaded reservoirs hydropower plant problems. The first one is a fuzzy turbine governor replacing the classical PID controller, the second is a fuzzy controller for three hydraulically coupled turbines under nonlinear and interacting process conditions, and the third is a fuzzy supervisory control and optimization system for geographically-separated systems using the same mass of water in a partially-pumped-storage scheme.

ACKNOWLEDGEMENT

In memory of my dearest parents whom I loved so much, I hoped that they would have been alive to see that I have achieved one of the good things they wished me to do.

To my wife, my brother, and my sisters, I am highly grateful for your kind support and patience.

To my supervisors, I am highly grateful for your kind support and guidance.

I declare that this thesis is of my own original work and the results obtained during this research work are to the best of my knowledge original, except where reference is made to the work of others.

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LIST OF SYMBOLS

q , Q	Volume flow rate	m^3/s
h , H , H_D , H_o	Water heads	m
A	Area of reservoir section	m^2
A_C , a_i	Area of discharge pipe/valve section	m^2
G	Gate effective area	m^2
P_m	Turbine output power	W
γ	Specific weight of water	N/m^3
eff , η	Efficiency	$p.u.$
v	Velocity	m/s
h_f	Head loss due to friction	m
h_L	Head loss	m
Ω	Turbine power correction factor	W
ρ	Water density	kg/m^3
δ	Environmental disturbance parameter	$p.u.$
f	Friction factor	$p.u.$
L	Conduit length	m
D	Conduit internal diameter	m
T_{acc}	Accelerating torque	$N.m$
J	Combined moment of inertia	$kg.m^2$
θ_m	Mechanical torque angle of the rotor	rad
t	Time	s
T_{mech}	Mechanical torque	$N.m$
T_{elec}	Electromagnetic torque	$N.m$
σ	Standard deviation	*same units as mean*
z	*Elevation*	m
g	Acceleration due to gravity	m/s^2
a_a	Acceleration	m/s^2
p_1, p_2	Pressure	N/m^2
F	Force	N
a_w	Speed of pressure wave	m/s
Δp	Pressure difference	N/m^2
m	Water mass	kg

Chapter 1. INTRODUCTION

1.1. Introduction

All physical systems are nonlinear and have time-varying parameters in some degree, whether the nonlinearity is undesirable or intended, the objective of nonlinear analysis is to predict the behaviour of the system. Linear analysis inherently cannot predict those features of behaviour which are characteristics of nonlinear systems [Dutton2000]. State of the art control techniques that stabilize the nonlinear systems and improve their performance may solve many existing industrial control problems and reduce operating costs, improve products' qualities, reduce energy losses, and improve safety of equipments and plants. One of the important industrial areas that involves complex nonlinear dynamics and control problems is that of hydropower plants. Traditionally, hydropower is an important and vital renewable energy resource as it continues to produce 20 percent of the world's electricity [AltEnergy2003]. Hydropower converts the energy in flowing water into electricity, the quantity of electricity generated is determined by the volume of water flow and the amount of head (the height from turbines in the power plant to the water surface) created by the water reservoir. A typical hydropower plant includes a dam or a mountain reservoir, penstocks, a powerhouse and an electrical power substation. The reservoir stores water and creates the head; penstocks carry water from the reservoir to turbines inside the powerhouse; the water rotates the turbines, which drive generators that produce electricity. Hydropower plants can be classified into two main categories as follows: i) Conventional, meaning that a hydropower plant is using one-way water flow to generate electricity, either run-of-river or storage reservoir. After electricity is produced the water is not reused. ii) Pumped Storage plants in contrast to conventional hydropower plants, reuse water as after water initially produces electricity, it flows from the turbines into a lower reservoir then during off-peak hours (periods of low energy demand), some of the water is pumped into an upper reservoir to be reused during periods of peak-demand [Gulliver1990]. The best sites for hydropower plants are traditionally swift-flowing rivers or streams, mountainous regions and areas with heavy rainfall. However an economical hydropower solution would use both the natural water resources such as accumulated rainfalls, sustained water, waste recycled water and the natural topography of ground that has various elevations; all in a cascaded water path of minimum water losses to form a cascaded reservoirs hydropower system. The importance of cascaded reservoirs hydropower systems compared to others is that a single bounded mass of water generates electric energy multiple times instead of once, this is because the water is continuously passed between multiple reservoirs at different elevations until it reaches the bottom or end reservoir. The important task here is to manage and control the multiple water reservoirs and flow rates in real time for a continuous stable and optimal power generation, not only on individual levels but also on the global level. The problem here is the complex nonlinear dynamics of such a system. The nonlinear dynamics of such a system can be classified as follows; firstly on the individual level each plant of the cascaded system has its own multiple and hydraulically coupled turbines where any uncontrollable hydraulic mass oscillations due to water hammer can destabilize the system and transfer the oscillations to the electric power grid, and export hydraulic transients to the rest of the cascaded hydraulic systems; secondly on the global level the system may receive time-varying and random inputs such as rain falls or a sudden increase or decrease of other water resources, in this case the system's local and global control strategies and the operational set points have to be revised so that the variable water resources conditions are always utilized for optimal power generation with minor water losses and do not exceed the reservoirs' and penstocks' operational capacities; thirdly the mathematical relationships between reservoirs' levels and flow rates are nonlinear, and the relationships between the valves' openings at turbines' admissions and the resultant generated powers are also nonlinear. In addition to those nonlinear dynamics, the system has to cope with random load demands or rejections from the grid where power and frequency regulations may always be needed. This research, therefore, aims to enhance the existing cascaded reservoirs hydropower systems and future ones by new designs of control and optimisation systems based on fuzzy logic.

1.2 Aims and Objectives

The aim of this research is to develop a new control and optimisation system for a cascaded reservoirs hydropower system based on fuzzy logic. In order to achieve these aims, the following main objectives were formulated:

- To develop a new mathematical model of the nonlinear plant in order to design the control system.
- To design a new fuzzy logic control and optimisation system.
- Implement numerical analyses, dynamical modelling and simulations for a cascaded reservoirs hydropower system to obtain final results.

1.3 Thesis Outline

The work in this thesis is organised as follows

- Chapter 1 is an introduction, aims and objectives and states the original contribution of this research work.

- Chapter 2 is an up to date review of the hydropower plants and machinery, the research and development work in modelling and control of hydropower plants, the cascaded reservoirs management and optimisation, and the foundation of fuzzy control systems.

- Chapter 3 presents the new mathematical modelling and simulation of cascaded reservoirs hydropower systems.

- Chapter 4 presents the development work and the implementation of a new fuzzy hydro turbine governor.
- Chapter 5 presents the development work and implementation of a new fuzzy controller for three hydraulically coupled turbines.
- Chapter 6 presents the development work and implementation of a new fuzzy real time control and optimization system for a cascaded reservoirs hydropower plant.
- Chapter 7 presents the observations on the stability for fuzzy control systems.
- Chapter 8 presents conclusions and discussions of the results of this research work
- Chapter 9 presents the recommended future work.

1.4 Original Contributions

- Developed a new mathematical model for a cascaded reservoirs hydropower system and carried out dynamical modelling to simulate its nonlinear dynamics in order to design the fuzzy control systems.
- Developed a new fuzzy governor to replace the classical PID hydro turbines' governors, capable of controlling nonlinear processes.
- Developed a new fuzzy control system for three hydraulically coupled hydro turbines in a nonlinear and interacting process.
- Developed a new supervisory fuzzy control system for a cascaded hydropower system comprises of three reservoirs and power houses with a real time optimization capability.
- Developed new multilayered fuzzy control architectures to control hydraulic turbines.

This research has led to the publication of five journal papers as per Appendix G

Chapter 2. LITERATURE REVIEW

2.1 Introduction

In this chapter an intensive literature review was carried out to gather an expert knowledge in hydropower systems, their nonlinear dynamics, their up to date control techniques, and the up to date research and development work in this area. The work of this chapter starts with a review of hydropower plants and machinery in section 2.2 including a brief history of hydropower and its contribution in electricity generation. Then the work proceeds to review the hydraulic transients in section 2.3, the hydraulic turbines governing control in section 2.4, the hydropower plants simulation and control systems design in section 2.5, the cascaded reservoirs management and optimization in section 2.6, and finally a review of fuzzy logic control in section 2.7.

2.2 Hydropower Plants and Machinery

The force of falling water has been one of humankind's important sources of power and energy. The origins of waterwheels can be traced back to ancient Egypt, Persia and China where these were used for irrigation as well as grinding grain for flour. At the end of the last century and the beginning of this century, the primary objective in developing hydropower was to utilize it through a mechanical drive to the driven machinery. These devices consisted of ropes, belts and some types of gear trains. The early hydraulic units were relatively small and their outputs rarely exceeded a few hundred kilowatts. Tremendous strides have been made in the field of hydro-dynamics in order to develop and improve equipment to meet increasingly complex requirements of larger and larger hydroelectric power plants. Today hydropower remains a significant source of electricity in all parts of the world. Large scale hydroelectric generation remains one of the cheapest and least controversial sources of electricity in many countries around the world. Hydropower provided much of the energy for the industrial revolution in England, and the industrial development in the northeastern United States till the 1930's. From the 1940's to 1970's, hydropower's contribution to the electricity generation mix steadily declined [AltEnergy2003 et al.]. The advent of abundant and inexpensive fossil fuels, first coal then oil and finally natural gas, coupled with advances in generation technology which led to the economies of scale, resulted in large scale development of thermal power plants in the many industrialized countries. The perceived economy and low cost of nuclear power plants convinced many such countries to embark on aggressive nuclear programs in the 60's and 70's. However, the recent increase in gas and oil prices in the world, and the increased concern about adverse environmental impacts of coal burning and nuclear energy, have improved the relative attractiveness of hydropower. According to the "The Carbon Trust" (an independent not-for-profit company set up by the UK Government in April 2001), a new report has been published showing that the UK might move to a low carbon economy by developing and exploiting new low carbon technologies. Similar concerns are now visible in many industrialized and industrializing countries. This has resulted in renewed interest in abandoned small hydro sites accompanied by the development of modern hydro turbines, which can work under low head and small flow conditions [CarbonTrust2003]. The industrialized nations, which contain about 30 percent of the world's hydroelectric potential, produce about 80 percent of all hydroelectricity. Over a third of this capacity is produced in Europe, about a third in North America, and about 6 percent in Japan. On the other hand, about 20 percent of all hydroelectric potential is present on the African continent, of which only about 2 percent is actually exploited (half of that amount comes from three large dams: Aswan in Egypt, Akosombo in Ghana, and Kabria on the Zambezi River). Asia (excluding former USSR) accounts for about 30 percent of the world potential, but produces only 7 percent of the world total. Major hydropower developments are now underway in China, India and Pakistan. The world's largest operational hydro plant is the Itaipu project shared jointly by Brazil and Paraguay - it has 12,600 MW of installed capacity [AltEnergy2003 et al. CarbonTrust2003].

The utilization of the power in water heads is evaluated by power plant efficiency η_i, which is the ratio between the mechanical power output from the hydraulic turbine shaft and the gross hydraulic power of the power plant. The plant efficiency η_i is a variable quantity that depends on the design of the water conduits to and from the hydraulic turbine and the operating conditions. The conduits are normally made with flow cross sections based on optimal design criteria. The hydraulic turbine may be operated with different flow rates Q from time to time according to the variable grid load and the variable heads and flow discharges in the plant. These circumstances mean that the hydraulic turbine necessarily is equipped with a control system for regulating its power input and output. This is normally done by regulating the in-flow of the hydraulic turbine through a gate at the turbine inlet. The input power to the hydraulic turbine is not efficiently similar at all operating conditions because of the fact that the hydraulic turbine performs at the optimal efficiency for only one single combination of flow rate, water head and rotational speed. This means a nonlinear characteristic, which is denoted as the efficiency of the hydraulic turbine machine and generally expressed by [Kjølle2001 et al. Streeter1998a]:

$$\eta_T = \frac{mechanical\ \ ouput\ \ power}{net\ \ input\ \ power} \qquad [2.1a]$$

where, *net input power* means the gross hydraulic power of the power plant minus power losses in the conduits to and from the hydraulic turbine. Another quantity is defined as the *admission* k and expressed as:

$$k = \frac{operating\ \ flow\ \ rate}{flow\ \ rate\ \ at\ \max\ \ efficiency} \qquad [2.1b]$$

An example of the efficiency characteristic of a Pelton hydraulic turbine as a function of the admission is shown on Figure 2.1 and for a Francis hydraulic turbine is shown in Figure 2.2. The efficiency characteristic is different from one turbine type to other.

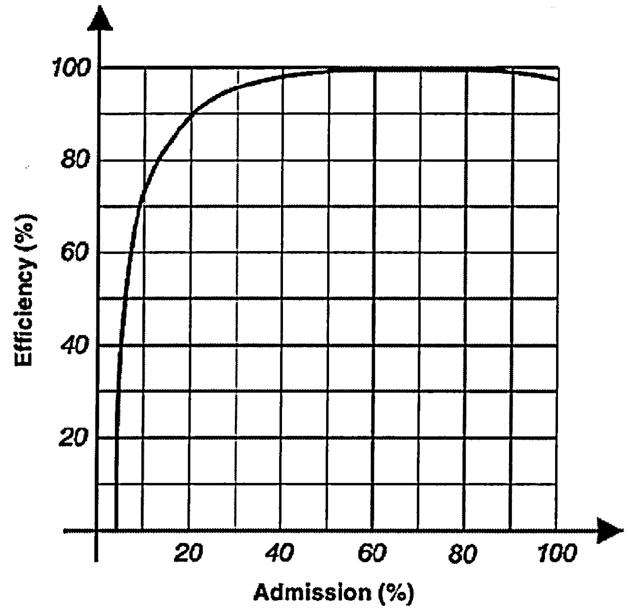


Figure 2.1 Example efficiency characteristic of a Pelton turbine

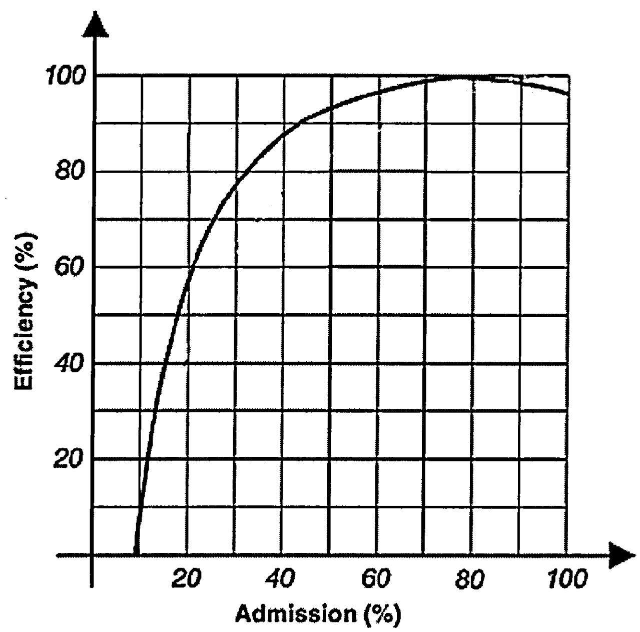


Figure 2.2 Example efficiency characteristic of a Francis turbine

2.2.1 Conventional Hydropower Plants

As illustrated in Figure 2.3, a conventional hydropower plant uses one-way water flow to generate electricity, either run-of-river or storage reservoir. After electricity is produced the water is not reused. The discharge water is conveyed through a conduit system (tunnels and penstocks) operating a hydro turbine, from the turbine the discharge is conducted through so-called tailrace channels to a downstream river or reservoir.

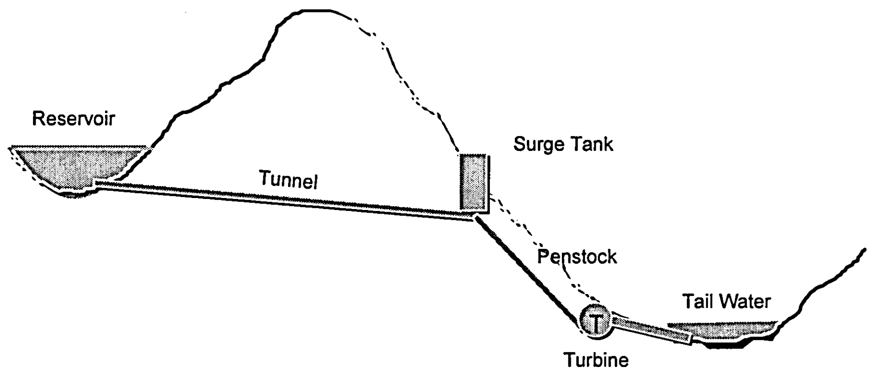


Figure 2.3 Conventional hydropower plant

2.2.2 Pumped Storage Hydropower Plants

In contrast to conventional hydropower plants and as illustrated in Figure 2.4, the pumped storage hydropower plant reuses water. After water initially produces electricity, it flows from the turbines into a lower reservoir then during off-peak hours (periods of low energy demand) the turbine is reversely driven by power from the grid to be a pump, then some of the water is pumped into an upper reservoir to be reused during periods of peak-demand. Note that the turbine can be driven in reverse by power from the grid, when it becomes a pump. The role of a pumped storage hydroelectric plant is either to maintain financial profitability (selling expensive-buying cheap) or to regulate the frequency of the electricity supply on the grid against disturbances due to changing load conditions. This is accomplished by the very rapid start-up dynamics and dynamic response of a hydropower plant compared with a thermal generation plant.

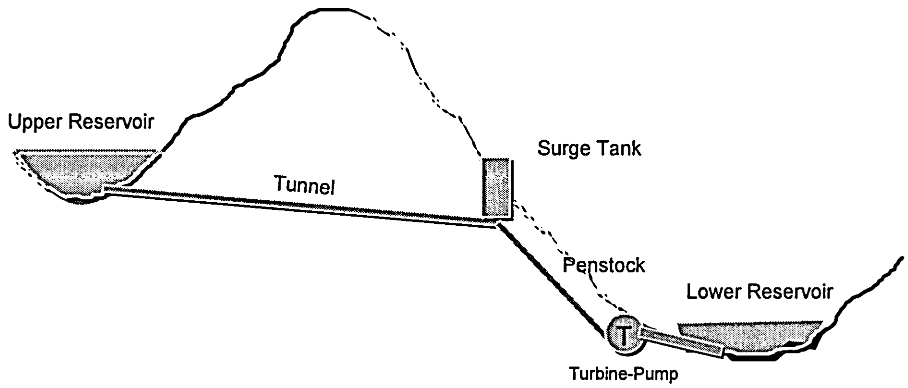


Figure 2.4 Pumped storage hydro power plant

2.2.3 Cascaded Reservoirs Hydropower Plants

In contrast to conventional hydropower plants and the natural topography of ground that has various elevations; the turbine discharge is conducted through the tailrace channel to a downstream reservoir feeding another hydropower plant. A cascaded reservoirs hydropower scheme can be simply two cascaded reservoirs with two power houses or a complex network of remote distributed reservoirs and channels such as accumulated rainfalls, mountain lakes or ponds, and streams, as illustrated in Figure 2.5. Also a futuristic cascaded reservoirs hydropower solution may use any accumulated rain falls, sustained water, and waste recycled water of community areas that have various elevations by constructing a collecting reservoir for each area. The United Kingdom is one of the potential locations for such futuristic cascaded hydropower solutions; a good example would be the city of Sheffield that has (for example) four different community areas at four various elevations: Crookes, Upper Walkley, Lower Walkley and Hillsborough with a river at the bottom. The importance of cascaded reservoirs hydropower schemes compared to others, is that a single bounded mass of water generates electric energy multiple times instead of once, this is because the water is continuously passed between multiple reservoirs at different elevations until it reaches the bottom reservoir with minor losses.

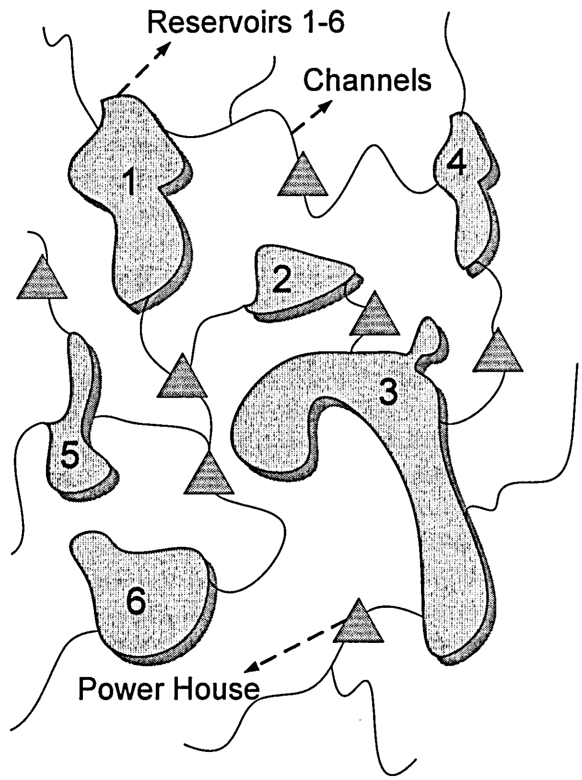


Figure 2.5 Complex networks of remote distributed reservoirs

2.2.4 Hydraulic Turbines

A hydraulic turbine is a hydropower machine that directly converts the hydraulic power in running water to mechanical power on the machine shaft. This power conversion involves losses that arise partly in the machine itself and partly in the water conduits to and from the machine. The turbine types in water power plants are distinguished as two main groups, the *Impulse Turbines* presented in section 2.2.4.1 and the *Reaction Turbines* presented in section 2.2.4.2. The most commonly used turbines today are [Streeter1998 et al.]:

- Impulse type: Pelton turbines
- Reaction type: Francis turbines
  Kaplan turbines
  Bulb turbines

The four types of turbines Pelton, Francis and Kaplan and Bulb turbines mainly have distinct operational ranges. The determination of the turbine type is normally dependent on the available water head and discharge capacity, and the construction cost of the plant.

2.2.4.1 Impulse turbine – Pelton

A Pelton turbine is shown in Figure 2.6 [Nedian2003]; the water jet from the nozzle hits the buckets that are spaced equidistantly around the runner disc. Basically the flow energy to the impulse turbines is completely converted to kinetic energy before transformation in the runner. This means that the flow passes the runner buckets with no pressure difference between inlet and outlet. Therefore only the impulse forces being transferred by the direction changes of the flow velocity vectors when passing the buckets create the energy converted to mechanical energy on the turbine shaft. The flow enters the runner at nearly atmospheric pressure in the form of one or more jets regularly spaced around the rim of the runners. This means that each jet hits momentarily only a fraction or part of the circumference of the runner. For that reason the impulse turbines are also denoted partial turbines.

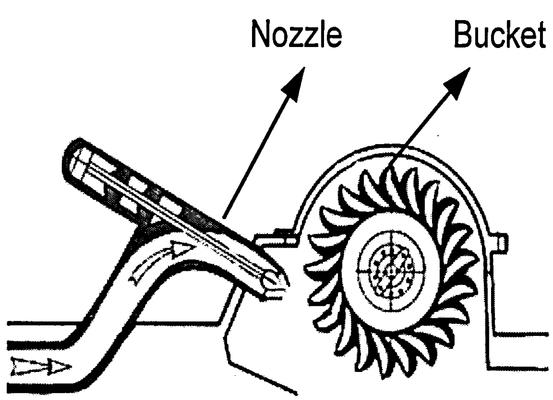


Figure 2.6 Impulse turbine – Pelton

2.2.4.2 Reaction turbines - Francis

In the reaction turbines two effects cause the energy transfer from the flow to mechanical energy on the turbine shaft. Firstly it follows from a drop in pressure from inlet to outlet of the runner. This is denoted the reaction part of the energy conversion. Secondly changes in the directions of the velocity vectors of the flow through the channels between the runner blades transfer impulse forces. This is denoted the impulse part of the energy conversion. The pressure drop from inlet to outlet of the runners is obtained because the runners are completely filled with water. Therefore, these groups of turbines also have been denoted as full turbines. Francis and Kaplan are the reaction turbines normally applied. The transfer of hydraulic energy into mechanical energy is principally similar in these turbines. However, the hydraulic design of Francis turbines differs significantly from that of Kaplan and Bulb turbines. The Francis turbine is illustrated in Figure 2.7 [Mansoor2000b].

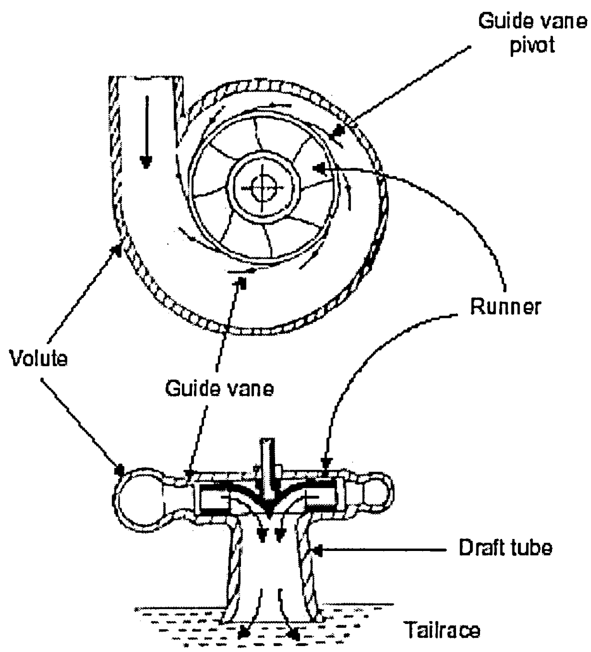


Figure 2.7 Reaction turbine – Francis

2.2.5 Conduit System

From the water intake to the turbine is a conduit system constructed as an open channel, tunnel, penstock or pressure shaft or a combination of these. Open channels are usually dug in the ground, blasted in rock or built up as a chute of wood or concrete. In high head power plants there is normally a so-called head race tunnel between the water intake and the pressure shaft. It may either be drilled and blasted or bored with a tunnel boring machine. The latter method leaves a much smoother wall surface than the first one, and consequently the head loss is significantly smaller for the same cross section. At the end of the head race tunnel there is a sand trap. Beside the sump in the tunnel floor the cross section of the tunnel is gradually increased to reduce the water velocity and allow for a better sedimentation of suspended particles. At the downstream end of the head race tunnel there is also a surge chamber system. At the end of long head race tunnels it is also normal to install a gate. This makes it possible to empty the pressure shaft and penstock upstream of the turbine, for inspection and maintenance, without emptying the head race tunnel. Before the water enters the pressure shaft it passes a fine trash rack. This is the last protection of the valve and the turbine against floating debris or smaller stones if the sand trap is full or omitted. A steel penstock connects the shaft with the valve in the machine hall. Inside the rock the penstock is embedded in a concrete plug. Penstocks are normally welded pipe constructions of steel plates. A flange connects the penstock with the valve. Penstocks above ground are mounted on foundation concrete blocks where the penstock may slide to accommodate thermal expansion. At the upstream end of a penstock an automatic isolating valve is normally installed. This valve closes automatically if a pipe rupture should occur. As fluid flows through the conduit, energy loss occurs because of internal friction within the fluid. This is expressed mathematically as follows [Kjølle2001 et al. Mott1990]:

$$h_f = f \times \frac{L}{D} \times \frac{v^2}{2g} \qquad [2.2]$$

where;

h_f = the head loss due to friction, m

f = the friction factor, $p.u$

L = the hydraulic conduit length, m

g = acceleration due to gravity, ms^{-2}

D = the hydraulic conduit internal diameter, m

v = the velocity, m/s

2.2.6 Turbine Gate

The water flow into the turbine is controlled by means of a gate whose position is driven by a hydraulic actuator and servo motor controlled by the turbine governor (controller) with a gate position feedback signal. The relationship between the inflow of the turbine and its gate opening position (effective area) is represented as follows [Streeter1998a et al.]:

$$Q = G\sqrt{2gH} \qquad [2.3]$$

The relationship between a turbine's gate position and its output mechanical power is not necessarily linear; normally a run test is carried out on the turbine to obtain a gate-power curve as per the example shown in Figure 2.8 [Mansoor2000b et al.].

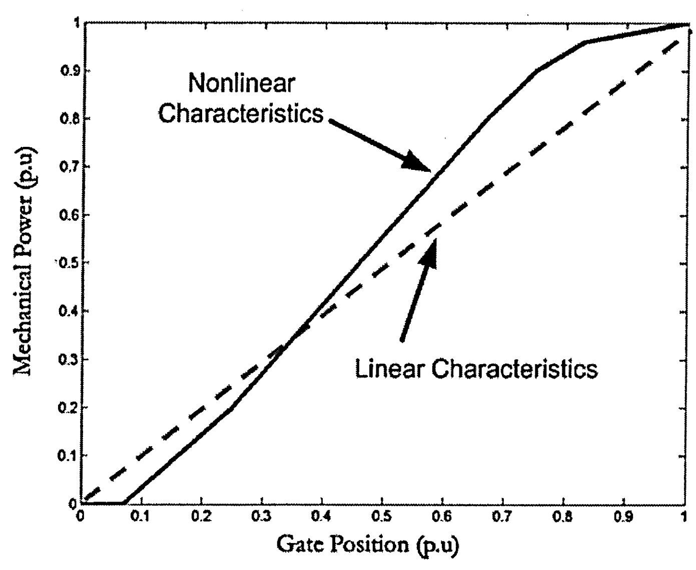


Figure 2.8 Example hydro turbine Gate-Power curve

2.3 Hydraulic Transients

For a closed conduit system where the conduit walls are assumed rigid and the fluid is assumed incompressible, the term steady flow means that the flow is gradually varied and it is a function of time only. For a closed conduit system where the fluid is assumed slightly compressible and conduit walls are assumed to be elastic, the term unsteady flow means that the flow is rapidly varied and it is a function of time and location. Hydraulic transients can be distinguished as two main types [Streeter1998], [Wylie1982]:

- Catastrophic transients due to unstable hydro turbine operation (mass oscillation) where a rapid valve closure causes sudden pressure rises and waves. Here, resonance may develop and cause a forcing function of a period close to the fundamental or harmonic period of the conduit. At this condition the conduit system may be ruptured or the penstocks and stress carrying parts of the turbine may be affected.

- Routine transients due to change in valve settings, starting or stopping of turbines, changes in power demand for turbines or changes in reservoir elevation (head).

The methods for controlling the hydraulic transients can be summarized as follows [Streeter1998], [Wylie1982]:

- A surge tank will reduce water hammer pressure variations and keep the mass oscillations within acceptable limits and decrease the oscillations to stable operation as soon as possible. It acts like a reservoir closer to the flow control point.

- Valve operation to be limited to slow changes. If rapid shutoff is necessary, the diversion of the flow should be considered and then shutting off the valve should be slow.

- A pressure relief valve automatically opens and diverts some of the flow when a set pressure is exceeded.

- A stable hydraulic turbine controller that is able to keep the rotational speed of the turbine-generator unit stable and constant at any grid load and prevailing conditions in the water conduit.

In the light of the above and in order to tune the parameters of the turbine controller, a hydraulic transient analysis would be considered to determine how long it takes for a pressure wave to travel the full length of the penstock plus tunnel after a rapid valve closure until it reaches the surface of the reservoir, and what is the pressure rise.

2.4 Hydraulic Turbine Governing Control

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 fast as possible. The turbine governors have to comply with two major requirements [Jaeger1977 et al. Streeter1998b]:

- To keep the rotational speed of the turbine-generator unit stable and constant at any grid load and prevailing conditions in the water conduit.
- At load rejections or emergency stops the turbine admission has to be closed down according to acceptable limits of the rotational speed rise of the unit and the pressure rise in the water conduit.

Alterations of the grid load cause deviations between the turbine power output and the load. For a load decrease the excess power accelerates the rotating masses of the unit to a higher rotational speed. The following governor reduction of the turbine admission means deceleration of the water masses in the conduit and a corresponding pressure rise. To keep the rise of the rotational speed below a prescribed limit at load rejections, the admission closing rate must be equal to or higher than a certain value. For the pressure rise in the water conduit the condition is opposite, i.e., the closing rate of the admission must be equal to or lower than a certain value to keep the pressure rise as low as prescribed. For power plants where these two demands are not fulfilled by one single control, the governors are provided with dual control functions, one for controlling the rotational speed rise and the other for controlling the pressure rise. This is normal for governors of high head Pelton and Francis turbines.

For Pelton turbines the principle is:

- To set the closing rate of the needle control of the nozzles to a value that satisfies the prescribed pressure rise.
- To bend the jet flow temporarily away from the runner by a deflector so the speed rise does not exceed the accepted level.

For Francis turbines the principle is:

- To set the closing rate of the guide vane opening to a value that satisfies the rotational speed rise limits.
- To divert as much of the discharge as necessary through a controlled by-pass valve so that the pressure rise in the conduit is kept below the prescribed level.

The turbine closed loop control system is shown in the block diagram of Figure 2.9 [Kjølle2001 et al.]. The input reference signal is compared with the speed feedback signal.

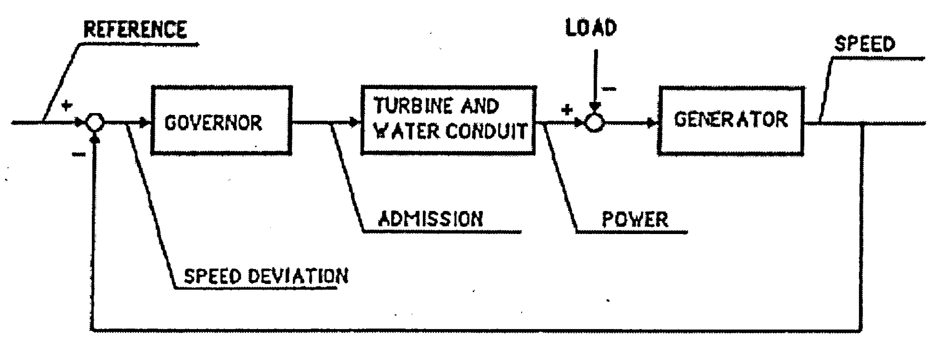


Figure 2.9 Block diagram of a turbine closed loop system

By a momentary change in the load a deviation between the generator power output and the load occurs. This deviation causes the unit inertia masses either to accelerate or to decelerate. The output of this process is the speed, which again is compared with the reference. One of the most widely used control laws in hydro power station governing systems is the PID type controller, where the PID stands for Proportional-Integral-Derivative. The rotational speed is dependent on the load for power/load equilibrium conditions, which means higher rotational speed at zero loads than at maximum; load and this dependency are linear. This type of governor function is designated as *proportional control* and denoted by the label P. For units delivering the power to a grid system the frequency has to be constant at any load. Governors for these units therefore have adjustment means also for automatically recovering of the speed according to the grid frequency during regulation processes. This type of governor function is designated as *integral control* and denoted by the label I. Some of the governors are provided also with a derivative function in addition to the above functions. It may be utilized for improvement of the phase angle of the frequency response for the governor system. This type of governor function is designated as *derivative control* and denoted by the label D. Mechanical hydraulic governors are provided with PI-functions only while electro-hydraulic governors are designed with PID functions. Governors with PID-functions have large ranges for adjustment of each of the PID function parameters. Figure 2.10 shows an example of a PID governor connected to the gate hydraulic servo system [IEEE1992 et al. Kjølle2001]. In the case in which only a load frequency control mode is required, the turbine governor may be provided with a special function called the *permanent droop (R%)* where the governor opens the guide vanes to a fixed position determined by the relationship between speed (frequency) of the power system and a speed reference. The permanent droop operates as a steady state offset with regard to a constant frequency reference. It is defined as the percentage change in the frequency for a 100 % change of the power output from the unit ($R\% = \Delta F/\Delta P$). For example a unit with a set value of the permanent droop at 5 % will respond with 40 % power increase for a change in frequency from 50 Hz to 49 Hz. The permanent droop is adjustable and in practice it is chosen in the range 0 - 6 %. In connection with the permanent droop another notion also plays a certain role that is the *strength of regulation* which is defined as the load distribution between turbine-generator units connected to the same grid. It is dependent on the permanent droop setting of these units.

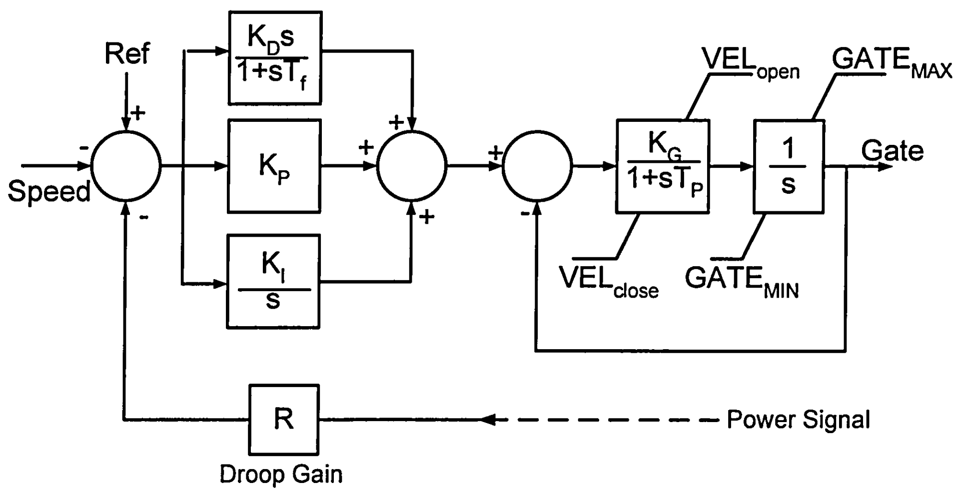


Figure 2.10 PID hydraulic turbine governor

The turbine governing demands may be distinguished and summarised as follows [Kjølle2001 et al.]:

- *Frequency and load regulation:* The governor should be able to maintain stability of the generating unit when running on an isolated grid. Generally the units are designed for stable operation up to full load. In this mode of operation the governor should keep the frequency within certain limits of deviation. Load regulation on a rigid system is the most common operation mode. Each unit has little influence on the grid system frequency. The governor controls the load to the desired value. The variation of the load as a function of the change in frequency is dependent on the permanent droop setting. A special mode of operation is the manual mode where the guide vane openings are controlled manually by means of a mechanical hydraulic load limiter. In this mode only the load can be controlled.

- *Start and stop sequence control:* During the startup period the unit should be run up to nominal speed as quickly and smoothly as possible. A start can be carried out both manually and automatically. The admission must be opened only when permitted by all-overriding start conditions. In shut down mode the admission should be closed as quickly as possible but limited by the magnitude of the pressure rise in the tunnel and pressure shaft system. Due to safety reasons, the shut down signal will be given simultaneously to different stages in the governor, e.g. closing of the load limiter or the emergency operated shut down valve. The shut down valve will also function if the ordinary voltage supply has failed. The stop command can be given both manually and automatically.

- *Disconnection, load rejection:* Disconnection means opening the generator main circuit breaker. The generator is thereby separated from grid and the turbine power output results in a speed rise of the unit. The function of the governor is then to shut down the turbine at a slow enough rate to keep the resulting pressure rise in the penstocks below the guaranteed level.

- *Load limiting:* Load limiting must be possible according to external conditions. The load limiter device may be operated both manually and automatically.

2.5 Hydropower Plants Simulation and Control System Design

Generally the hydropower plants that were engineered in the past suffer from instability and oscillatory behavior. Although the available state of the art control techniques were applied at that time, those control techniques in their best forms are based on PID classical controllers and governors which are insufficiently "intelligent" to control and stabilize these systems. Another reason for instability of such systems is the mismatch between the actual plants and their approximated mathematical modeling and the unavailability of accurate computer simulations. In recent years the control systems of some of those plants are being re-engineered by firstly developing more accurate mathematical models and computer simulations, and secondly by the design of advanced control systems [Fasol1997 et Al. Mansoor2000a,b] Also research and development work is continually ongoing to produce more accurate hydropower plant nonlinear models and to design new control systems or to improve the performance of existing ones with the main objectives being to reduce any of the plants' oscillatory behaviors and increase the plants' efficiencies. Here are some important case studies of old hydroelectric plants being re-engineered and an up to date survey of the research and development work of hydropower plant modelling and control.

Dinorwig pumped storage hydropower station-UK [Mansoor2000a,b]: Dinorwig is the largest pumped storage scheme in Europe operating on a 600 meter water head. The station is equipped with six reversible pump-turbines driving synchronous generators which can be brought from reserve at zero power up to full power in 15 seconds. The role of the Dinorwig power station is primarily to regulate the frequency of the electricity supply on the British national grid against disturbances due to changing load conditions. When a sudden demand for power occurs, Dinorwig provides short-term supply while a base load (coal or nuclear) station is brought on-line; this is usually done under manual control. Dinorwig commonly uses one unit for continuous frequency regulation which is achieved by measuring the grid frequency (nominally 50 Hz) and actuating the turbine's guide vanes by means of a digital electronic governor. The feedback control law is basically an individual PID compensator for each generating unit. Research work was undertaken at the University of Wales to investigate the oscillatory behaviour of the plant. The advanced computer simulation proved that the physical characteristics of the plant are causing nonlinear dynamics, multivariable coupling and time varying parameters which, in turn, cause the oscillatory behaviour. The simulation also highlighted the limitation of adjusting the parameters of the PID feedback loops and indicated that more advanced controllers are required in order to maximize the plant's operational envelope. A recommendation to investigate the use of advanced control techniques such as neuro-fuzzy systems was given. The plant is presently controlled by multiple PID digital governors (PLC based) with switchable gains.

Reisseck-Kreuzeck hydropower plant-Austria [Fasol1997]: The Reisseck plant is a three reservoirs system operating on a water head of 1772.5 meters which is the highest water head worldwide, and has three turbine-generator sets. The Reisseck plant was commissioned and put into operation almost 40 years ago. From the beginning, there have been serious stability problems, especially in speed-controlled no-load operational mode. The unstable control loops persistently went into limit cycles around the setpoint, thus making synchronization difficult. Above all, fluctuations of the pressure, with inadmissible high amplitudes endangering the penstock, were caused by the instability. To simulate the actual plant characteristics and re-design the control system, a detailed high-order nonlinear simulation model was obtained through a theoretical system analysis. The first result was a nonlinear model of 35^{th} order, simplified to a 25^{th} order simulation model. This model was used to simulate the plant accurately but still too difficult to be controlled by PID controllers. The simulation model was partially linearized and reduced to a 5^{th} order "design model". The plant's extreme sensitivity to oscillations aggravated the design of the new control algorithms, especially at no-load and isolated network operational modes. This problem was solved by carrying out a root-locus stability analysis to demonstrate the cause of the previous instability, and designing a complex cascaded structured governor, combined with a switching circuit to control the start-up procedure. The design procedure, in this case, was based on heuristic considerations intensively supported by simulation using a reduced low order design model.

Hydraulic turbine and turbine control models for system dynamic studies: The IEEE System Dynamic Performance Subcommittee [IEEE1992] developed hydraulic models suitable for a relatively wide range of studies and computer simulation. They aimed in their developed models to simulate some of the difficult hydropower plants' dynamics that were not simulated before such as low frequency oscillations, and system restoration following a break-up, load rejection and acceptance, water hammer dynamics and pumped storage generation with complex hydraulic structure. They decoupled the complex dynamics of a hydropower plant into subsystems' dynamics and developed two types of nonlinear models for each subsystem, the first type assumed inelastic water column analysis and the second type assumed elastic water column analysis. It was recognised in their conclusions that specific applications may require development of further and special models to include more dynamical effects such as deadbands, hysteresis, and response to disturbances.

Modelling of hydraulically coupled turbines: Hydraulically coupled turbines means that a group of hydraulic turbines are sharing a common conduit (tunnel or penstock), which causes the "interacting disturbances problem". This problem means that a valve stroke for controlling one of the turbines causes pressure waves in the common conduit that transfers the disturbance to the neighbouring turbine units and also to the common reservoir. In [Vournas1993], a complex transfer function representing two hydraulically coupled turbines was derived for the dynamic analysis of a hydropower plant in Greece. That analysis proved that the effect of hydraulic coupling is evident in the time response of the mechanical power output of unit 1 for a 10% step gate opening of unit 2, which is a considerable interaction between the two units. The derived transfer functions are based on some approximations neglecting the water compressibility. In [Hannett1999] a similar work was undertaken to develop a model for three hydraulically coupled turbines of a hydropower plant in New Zealand. It was concluded that the use of simplified models which neglect the coupling effect can lead to errors in tuning of the control system leading to unstable operation. The derived transfer function is in the form of matrix representation based on some approximations neglecting the water compressibility and pressure wave effect.

2.6 Cascaded Reservoirs Management and Optimization

The short term scheduling of cascaded reservoirs hydropower systems has been one of the principal and difficult optimization problems in economic operation and control of those plants. The optimization function here is to minimize the non hydraulic power production expenses over a scheduling period (week/day ahead planning) by releasing water from each reservoir and through each power house over all the planning time intervals, so as to minimize the total cost of non hydraulic energy, while satisfying diverse hydraulic and load balance constraints. This is a difficult optimization problem because it involves a wide variety of physical constraints, weather forecast, and random inputs. Despite the difficulty of this optimization problem, many successful optimization techniques were reported such as *Simulated Annealing Algorithm (SAA) [Mantawy2002], Neural Networks [Molina 2000], Lagrangian Relaxation [Ngundam2000], Genetic-Embedded Fuzzy System [Huang1998], Grey Linear Programming [Liang1997], Linear Quadratic Dynamic Programming [Ozelkan1997], Stochastic Optimization [Lamond1995] and Penalty-Based Optimization [Sylla1995].* There is a common problem in all of these optimization techniques, namely that they are only for off-line numerical analyses and not interfaced to the hydropower plant real time control system. It is the plant operators who alter the set points of the plant control system manually and change the operation policy based on the results of these off-line optimization techniques.

2.7 Fuzzy Logic Control Systems

Exclusively, the symbols used in this section are standard fuzzy logic terminologies that are defined within the text of this section; they are not included in the symbols list of this thesis neither referred to nor used in any other parts of the thesis.

"Artificial intelligence" is the name used to cover several smart technologies such as fuzzy logic, expert systems, neural networks, genetic algorithms, and cellular automata. Some of these have been applied to real-world problems such as fuzzy logic and neural networks. Fuzzy logic was introduced in 1965 by Lotfi A. Zadeh, Fuzzy Logic had not been applied to a real-world problem until 1974 when Mamdani used it to control a non-linear steam engine system [Zadeh1996]. Fuzzy Logic has emerged as a profitable tool for the controlling of complex processes; it is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large systems. It provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information [Daugherty1992 et al. Kang1992]. Fuzzy Logic incorporates a simple, rule-based IF X AND Y THEN Z approach to solving a control problem rather than attempting to model a system mathematically. Most engineering systems have been described by mathematical models governed by physical laws and hence controllers can be designed according to these models. But the need for fuzzy logic arises when there is no mathematical description or in the presence of uncertainty or complex nonlinear processes. In fuzzy logic, input and output data are encoded in fuzzy values and they interact in the "IF-THEN" rules which gives great flexibility in formulating a system description using the available knowledge about it. A fuzzy description is even modifiable and is more tolerant of changes. A fuzzy set A is a collection of elements defined in the universe of discourse U, a fuzzy set allows its elements to have partial membership values ($\in [0,1]$) rather than taking one of two values only $\{0,1\}$. The degree to which the element $u \in U$ belongs to the set A is characterised by the membership function. The membership function can reflect directly the degree of uncertainty about a particular element in the universe of discourse. Fuzzy quantities are described by the membership functions and there are special notations and operators to manipulate them. These operators determine how the fuzzy sets are interacting. A fuzzy set A is defined as a set of ordered pairs on the universe of discourse U with a membership function μ_A, as follows [Ross1995]:

$$\mu_A : U \to [0,1] \quad [2.4]$$

$$A = \{(u, \mu_A(u)) / u \in U\} \quad [2.5]$$

The pair $(u, \mu_A(u))$ is called a singleton, and consists of an element u followed by its membership function $\mu_A(u)$ in the set A. In classical crisp sets the singleton is the element u itself. An example of a fuzzy set A may be written as follows:

$A = \{(0.2, 0.5), (0.4, 0.75), (0.6, 0.1), (0.8, 1)\}$ [2.6]

2.7.1 Fuzzy Terms and Operators

The fuzzy terms and operators are defined and summarized in Appendix F.

2.7.2 Fuzzy Membership Types

The fuzzy membership types are defined and summarized in Appendix F.

2.7.3 Fuzzy Controllers

A standard structure of a fuzzy controller is illustrated in Figure 2.11 [Ross1995 et al. others]. The control task starts with the fuzzification of the crisp input signals into linguistic values or fuzzy sets then the signals are manipulated by a set of IF-THEN rules before defuzzifying them into crisp output values. Fuzzy controllers can be classified into two main types "Mamdani" and "Sugeno".

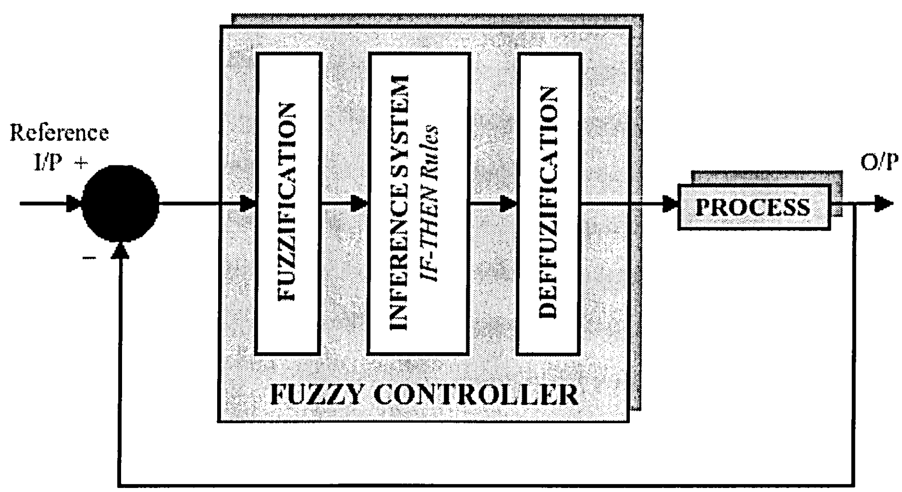


Figure 2.11 Fuzzy controller

2.7.3.1 *Mamdani Fuzzy Controller*

In 1974, E. H. Mamdani demonstrated that formulating a set of fuzzy IF-THEN rules in a special way could control a plant comprising a steam engine and boiler combination. The plant being controlled was non-linear and had a time delay. Mamdani built his fuzzy rules in the following form [Zadeh1996 et al. Ross1995]:

IF x_1 is A_1, x_2 is A_2, ...**AND** x_n is x_n **THEN** y is B

In a fuzzy linguistic description, a rule from the steam engine control scheme might be rewritten as follows:

IF *Pressure Error* is ***Negative Big*** AND *Change in Pressure Error* is ***Negative Big*** **THEN** *Heat Change* is ***Positive Big.***

2.7.3.2 *Sugeno Fuzzy Controller*

Instead of using fuzzy values in the consequent part of the rule, Sugeno suggested a fuzzy rule that has a crisp value in the consequent part. Hence, the above Mamdani rule is revised to the following form:

IF x_1 is A_1, x_2 is A_2, ...**AND** x_n is x_n **THEN** $y=f(x_1, x_2, \ldots, x_n)$

where *f* is a function of the input set $x_1, x_2, \ldots, x_n$.

2.8 Summary

A hydropower system is an important and economical renewable energy resource; however it involves complex nonlinear dynamics and control problems that lead to instability of the plant and energy losses. These problems can be summarized as follows:

- Hydropower plants suffer from oscillatory behaviour due to the hydraulic transients in conduits and the hydraulic coupling between turbines. This problem requires a state of the art control system design based on a nonlinear plant model that represents all dynamics of the plant.

- Using a classical PID turbine governor is not sufficiently reliable in controlling the nonlinear plant dynamics and preventing oscillations, it needs to be re-tuned by altering its control parameters and gains for each operational mode, and it does not deal with the hydraulic transients and the hydraulic coupling problems.

- Hydraulic mass oscillations are also transferable to the power grid which causes load disturbances to other power plants on the same grid. In a cascaded hydropower system the hydraulic transients are also transferable to other hydraulic units of the system.

- The importance of cascaded reservoirs hydropower systems compared to others is that a single bounded mass of water generates electric energy multiple times instead of once, this is because the water is continuously passed between multiple reservoirs at different elevations until it reaches the bottom or end reservoir. A cascaded reservoirs hydropower plant may involve a complex network of reservoirs and channels/conduits.

- Cascaded reservoirs hydropower plants are expected to suffer from the same hydropower plants' problems mentioned above. On top of that they require a supervisory control and optimization systems.

- Fuzzy logic is extensively used in processes where system dynamics are either complex or of highly nonlinear characteristics. Therefore it will be utilized in this research work to design the control system of a cascaded reservoirs hydropower plant that can deal with the above mentioned problems.

Chapter 3. MATHEMATICAL MODELLING AND SIMULATION

3.1 Introduction

In this chapter a nonlinear mathematical model for a cascaded hydropower plant is developed. The developed model is accurate enough to represent and simulate the plant nonlinear dynamics and to test the fuzzy logic control system. The cascaded reservoirs hydropower plant is a complex nonlinear system that involves all of the common hydropower plants' control problems mentioned in section 2.8. In addition it would need an exclusive supervisory control and optimization system. Therefore, it was decided to decompose the system into a collection of decoupled subsystems and derive a nonlinear mathematical model for each subsystem so as to design three fuzzy control systems addressing three major cascaded reservoirs hydropower plant problems; the first one is a fuzzy turbine governor replacing the classical PID controller, the second is a fuzzy controller for three hydraulically coupled turbines under nonlinear and interacting process conditions, the third is a fuzzy supervisory control and optimization system. The development and simulation work in this chapter starts with a new cascaded reservoirs hydropower plant nonlinear model presented in section 3.2 which involves the development of a mathematical model for each of the hydraulic reservoir dynamics presented in section 3.2.1, turbine dynamics presented in section 3.2.2, three hydraulically coupled turbines' dynamics in section 3.2.3, pressure wave dynamics in section 3.2.4, and generator dynamics in section 3.2.5. Finally the simulation of the cascaded reservoirs hydropower plant is in section 3.6.

3.2 Cascaded Reservoirs Hydropower Plant Model

A cascaded reservoirs hydropower plant comprises multiple reservoirs and power houses at different elevations where the water is continuously passed between them. Depending on the natural topography of the ground, a cascaded reservoirs hydropower plant can be as simple as two reservoirs or a complex network of reservoirs and channels. Also, a futuristic cascaded reservoirs hydropower plant may use any accumulated rain falls, sustained water, and waste recycled water of community areas that have various elevations by constructing a collecting reservoir for each area. To develop a model for a cascaded reservoirs hydropower plant with the objective of designing its control system, the plant has to be decomposed into dynamical subsystems models. Each dynamical subsystem model has to represent all the nonlinear dynamics that normally destabilize the subsystem and that lead to disturbance and instability of the main system. Doing this and by the design of a control system that successfully addresses the problems of each subsystem *(local plant levels, local control systems)* leads to a controllable and stable plant on the global level providing that a supervisory control system exists to monitor and to revise the control strategy for each subsystem *(global plant level, supervisory control system)* so as to keep the stability of the cascaded hydropower plant and achieve its optimal operational policies. In the light of the above, a general cascaded reservoirs hydropower plant nonlinear model can be represented as shown in Figure 3.1 where the system is decomposed into hydropower cascaded subsystems with one reservoir and one powerhouse per each subsystem. Each subsystem's reservoir is receiving three inputs; the first input is the water output of the preceding subsystem and the second input $Q_{1,2\ldots i}$ is another water resource exclusively available at that elevation or community area of this subsystem; the third input is an environmental disturbance input $\delta_{1,2\ldots i}$ which is caused by some environmental variables such as the change in climate temperature and the change in water density, both variables affect the energy accumulation and conversion. Each subsystem's power house is receiving the reservoir water through a conduit system where there are another two inputs, a conduit disturbance input $d_{1,2..i}$ due to hydraulic transients and $f_{L1,2...i}$ which represent the head friction losses. Each subsystem's powerhouse $G_{P_{1,2...i}}$ is receiving the water head and generating a mechanical power $P_{m1,2...i}$ at plant efficiency $\eta_{1,2....i}$. Each pair of subsystems is connected together via an open water channel or a closed conduit $g_{C1,2...i}$.

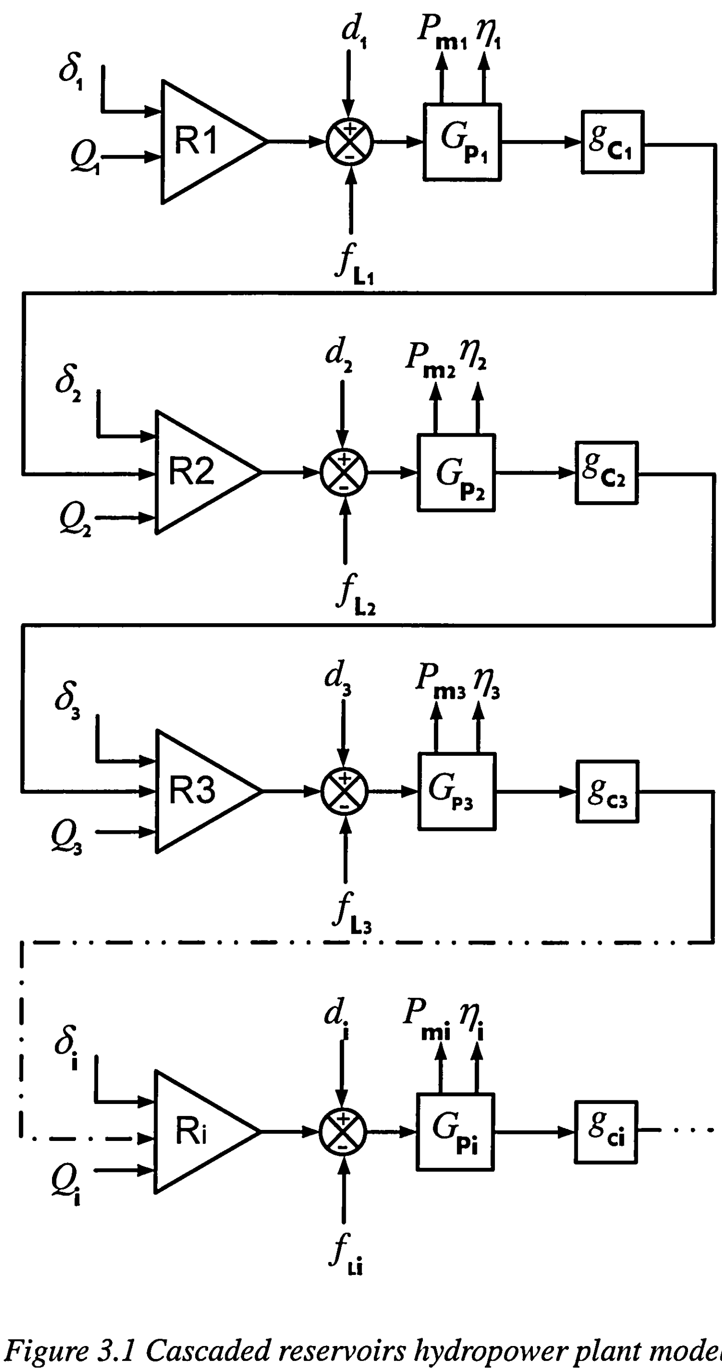


Figure 3.1 Cascaded reservoirs hydropower plant model

The model of Figure 3.1 was used to design the supervisory control system. For designing the local control systems, each subsystem of the cascaded hydropower plant of Figure 3.1 is decomposed into decoupled dynamical modules as illustrated in Figure 3.2, and a mathematical model for each module is developed.

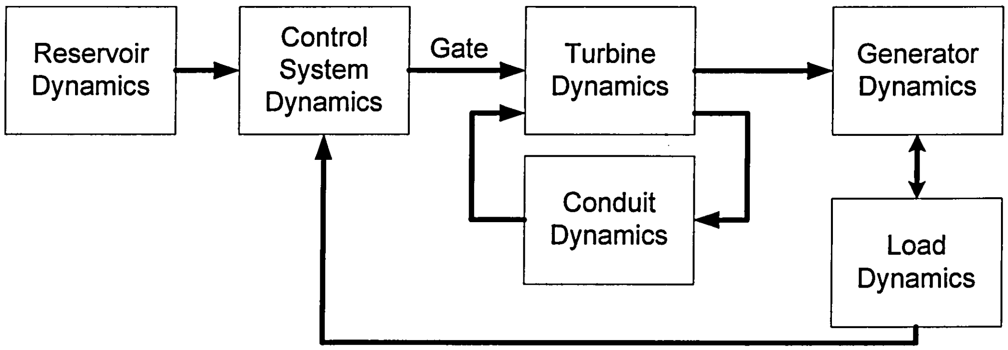


Figure 3.2 Hydropower plant dynamical subsystems

3.2.1 Modelling Of Hydraulic Reservoir Dynamics

The dynamics of the reservoir within a cascaded system are dependent on both the upstream and downstream dynamics. The upstream dynamics are variable input conditions such as rainfall, a discharge flow from another power plant, or a local water resource, plus the environmental disturbances. The downstream dynamics are dependent on the hydraulic conditions inside the main tunnel and penstocks, the flow rates admitted to the turbines and their gate valves' strokes. The rate of accumulation or consumption of the reservoir water is dependent on both the input flow rate and the discharge flow rate.

3.2.1.1 Reservoir Discharge Flow Rate

As illustrated in Figure 3.3, the discharge flow rate of the reservoir is determined by applying the energy equation between a reference point 1 on the water surface and a point 2 at the discharge. It may be written as follows [Streeter1998a]:

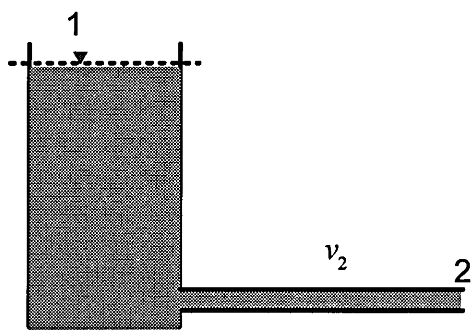


Figure 3.3 Reservoir discharge Flow Rate

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g} + h_f + \sum h_L \qquad [3.1]$$

where;

p_1, p_2 = the pressures, N/m^2

v_1, v_2 = the velocities, m/s

γ = the specific weight of water, N/m^3

g = acceleration due to gravity, ms^{-2}

h_L = the head loss, m

z_1, z_2 = the elevations, m

$p_1 = p_2 = 0$, and v_1 is approximately zero.

$$H = (z_1 - z_2) = \textit{the water head}, m \qquad [3.2]$$

Solving for v_2 gives:

$$v_2 = [2g(H - h_f - \sum h_L)]^{1/2} \qquad [3.3]$$

The volume flow rate is computed by multiplying the velocity v_2 by the cross sectional area of the discharge conduit a. The discharge volumetric flow rate Q_O may be written as follows:

$$Q_O = av_2 = a[2g(H - h_f - \Sigma h_L)]^{1/2} \quad [3.4]$$

Hence, the discharge flow rate of any of the reservoirs within the cascaded system may be written as follows:

$$Q_{Oi} = a_i[2g(H_i - h_{fi} - \Sigma h_{Li})]^{1/2} \quad [3.5]$$

3.2.1.2 Reservoir Rate of Accumulation and Consumption

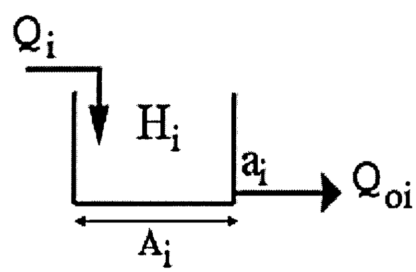


Figure 3.4 Single reservoir

For a single reservoir system as shown in Figure 3.4, the relationship between the water head and the input and output flow rates may be written as follows:

Rate of accumulation or consumption = Inflow – Outflow

$$A_i \dot{H}_i = Q_i - Q_{Oi} \quad [3.6]$$

From equations 3.5 and 3.6, the rate of accumulation/consumption of any of the reservoirs within the cascaded system may be written as follows:

$$A_i \dot{H}_i = Q_i - a_i[2\ g(H_i - h_{fi} - \Sigma h_{Li})]^{1/2} \quad [3.7]$$

where;

A_i = the area of reservoir, m^2

3.2.2 Modelling of Turbine Dynamics

The mechanical power Pm available from a hydraulic turbine is the product of the available hydraulic head H and the flow rate Q, an efficiency factor η_T, and a conversion factor. It may be written as follows

$$P_m = \rho\, g\, Q\, H\, \eta_T \qquad [3.8]$$

where;

P_m = the turbine output power, Watts

η_T = the turbine efficiency (p.u.), dimensionless.

ρ = the water density, kg/m^3

g = acceleration due to gravity, ms^{-2}

H = the head at the turbine admission, m

Q = the actual turbine flow, m^3/s

Adding the environmental disturbance parameter δ, equation 3.8 becomes:

$$P_m = \delta(\rho\, g) Q\, H\, \eta_T \qquad [3.9]$$

The environmental disturbance parameter δ represents the changes in climate temperature and water density which will affect the generated power and accordingly it affects the efficiency of the hydropower plant.

Based on equations 2.3 and 3.9, the turbine mechanical power is a function of the gate. Knowing that this relationship is not necessarily linear as shown in Figure 2.8 and the turbine is not 100% efficient, other parameters have to be added to the turbine power equation which are the no load flow q_{NL} (which is subtracted from the actual flow to yield the effective flow) and a speed deviation damping effect Ω (it is a function of the turbine gate opening). Accordingly equation 3.9 may be written as follows:

$$P_m = [\delta\, \eta_T\, (\rho\, g)(Q - q_{NL}) H] - \Omega \qquad [3.10]$$

For simplicity equation 3.10 may be written as follows:

$$P_m = A_t H(Q - q_{nl}) - \Omega \qquad [3.11]$$

where A_t is a turbine gain and may be written as follows;

$$A_t = \delta \eta_T (\rho g) \qquad [3.12]$$

Also the head at turbine admission and the flow rate in equation 3.11 are functions of the upstream dynamics which are the dynamics of the penstock, the common tunnel and the common reservoir; therefore, they are also affected by any hydraulic transients in the system caused by any of the hydraulically coupled machinery such as neighboring turbine units, valves, or hunting of control system. Therefore, a model combining the turbine dynamics and its penstock dynamics needed to be developed. To do so, Newton's law of motion is applied to the water mass of the penstock as follows:

$$F = m \times a_a \qquad [3.13]$$

$$F = \frac{m\partial v}{\partial t} \qquad [3.14]$$

$$\Delta P \times A_c = \frac{m\partial v}{\partial t} \qquad [3.15]$$

$$\Delta P = (H_D - H_T)\rho g \qquad [3.16]$$

$$\rho \times g \times (H_D - H_T) \times A_c = m\frac{\partial v}{\partial t} \qquad [3.17]$$

$$m = L \times A_c \times \rho \qquad [3.18]$$

$$v = \frac{Q}{A_c} \qquad [3.19]$$

From equations 3.16-3.19, equation 3.17 may be written as follows:

$$\left(H_D - H_T\right) = k\frac{\partial Q}{\partial t} \qquad [3.20]$$

where,

$$k = \frac{L}{g(A_c)} \qquad [3.21]$$

This relates the dynamics of the penstock to the head at turbine admission and the turbine flow rate. From equations 3.11-3.21 and adding the losses in water head due to friction as per equation 2.2, the dynamic model of a combined turbine-penstock system is shown in Figure 3.5.

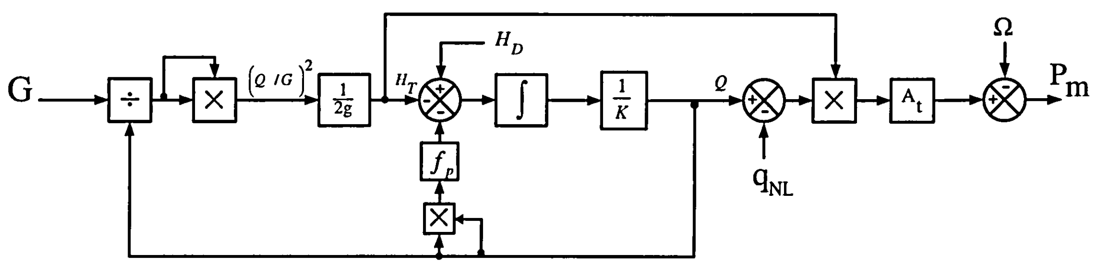


Figure 3.5 hydraulic turbine model

3.2.3 Modelling of Three Hydraulically Coupled Turbines Supplied from a Common Reservoir and Tunnel

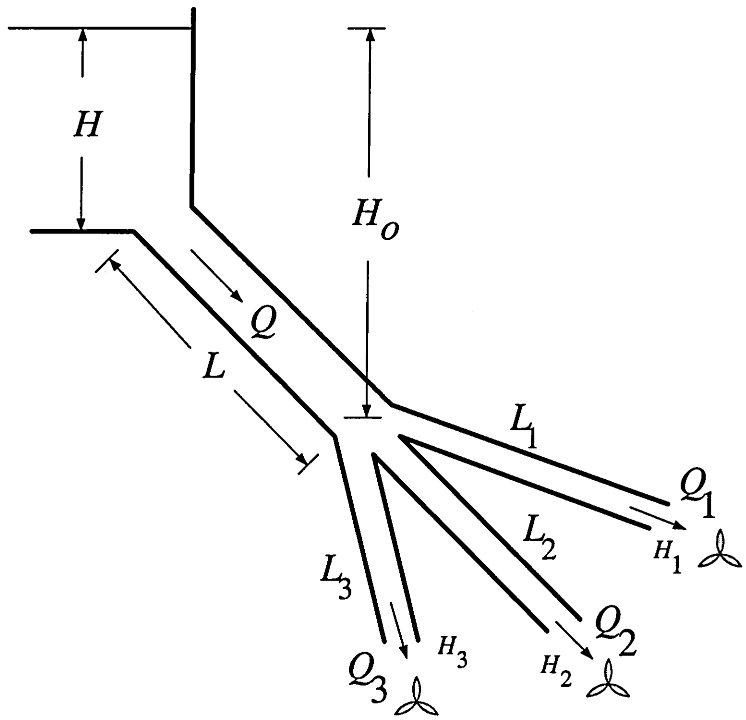


Figure 3.6 Three hydraulically coupled turbines

In addition to the dynamics of a hydraulic turbine in a hydropower plant discussed and modeled in section 3.2.2, the turbine is also affected by the dynamics of neighboring turbine units that share the same tunnel and reservoir (hydraulic coupling). To develop a mathematical model for three hydraulically coupled turbines supplied from a common tunnel and reservoir as per the arrangement illustrated in Figure 3.6, Newton's law of motion will be applied to the water mass for every hydraulic conduit in the plant. Applying Newton's law of motion to the main tunnel yields:

$$F = ma_a \qquad [3.22]$$

$$F = \frac{m\partial v}{\partial t} \qquad [3.23]$$

$$\Delta P \times A_c = \frac{m\partial v}{\partial t} \qquad [3.24]$$

$$\Delta P = (H_D - H_o)\rho g \qquad [3.25]$$

$$\rho \times g \times (H_D - H_o) \times A_c = m\frac{\partial v}{\partial t} \qquad [3.26]$$

$$m = L \times A_c \times \rho \qquad [3.27]$$

$$v = \frac{Q}{A_c} \qquad [3.28]$$

From equations 3.25-3.28, equation 3.26 may be written as follows:

$$(H_D - H_o) = \frac{L}{g(A_c)}\frac{\partial Q}{\partial t} \qquad [3.29]$$

This represents the dynamics of the tunnel at the junction point (bottom of the tunnel).

From the continuity equation of $\sum Q = 0$ the flow in the main tunnel may be written as follows:

$$Q = Q_1 + Q_2 + Q_3 \qquad [3.30]$$

Hence, equation 3.29 may be written as follows:

$$(H_D - H_o) = \frac{L}{g(A_c)}\left[\frac{\partial Q_1}{\partial t} + \frac{\partial Q_2}{\partial t} + \frac{\partial Q_3}{\partial t}\right] \qquad [3.31]$$

Similarly, applying Newton's law of motion to each of the three penstocks yields:

$$(H_o - H_1) = \frac{L_1}{g(A_{c1})}\left[\frac{\partial Q_1}{\partial t}\right] \qquad [3.32]$$

$$\left(H_o - H_2\right) = \frac{L_2}{g(A_{c2})}\left[\frac{\partial Q_2}{\partial t}\right] \tag{3.33}$$

$$\left(H_o - H_3\right) = \frac{L_3}{g(A_{c3})}\left[\frac{\partial Q_3}{\partial t}\right] \tag{3.34}$$

Using equation 3.31 to substitute for H_o in equations 3.32-3.34, yields:

$$\left(H_D - H_1\right) = \left[\frac{L_1}{g(A_{c1})} + \frac{L}{g(A_c)}\right]\frac{\partial Q_1}{\partial t} + \left[\frac{L}{g(A_c)}\right]\frac{\partial Q_2}{\partial t} + \left[\frac{L}{g(A_c)}\right]\frac{\partial Q_3}{\partial t} \tag{3.35}$$

$$\left(H_D - H_2\right) = \left[\frac{L_2}{g(A_{c2})} + \frac{L}{g(A_c)}\right]\frac{\partial Q_2}{\partial t} + \left[\frac{L}{g(A_c)}\right]\frac{\partial Q_1}{\partial t} + \left[\frac{L}{g(A_c)}\right]\frac{\partial Q_3}{\partial t} \tag{3.36}$$

$$\left(H_D - H_3\right) = \left[\frac{L_3}{g(A_{c3})} + \frac{L}{g(A_c)}\right]\frac{\partial Q_3}{\partial t} + \left[\frac{L}{g(A_c)}\right]\frac{\partial Q_1}{\partial t} + \left[\frac{L}{g(A_c)}\right]\frac{\partial Q_2}{\partial t} \tag{3.37}$$

Equations 3.35-3.37 may be written in a simpler form as follows:

$$\left(H_D - H_1\right) = K_1 \dot{Q}_1 + K\left[\dot{Q}_2 + \dot{Q}_3\right] \tag{3.38}$$

$$\left(H_D - H_2\right) = K_2 \dot{Q}_2 + K\left[\dot{Q}_1 + \dot{Q}_3\right] \tag{3.39}$$

$$\left(H_D - H_3\right) = K_3 \dot{Q}_3 + K\left[\dot{Q}_1 + \dot{Q}_2\right] \tag{3.40}$$

Which relate the dynamical head, the tunnel dynamics, penstocks dynamics and the interaction dynamics for each of the three hydraulically coupled turbines in the plant.

where,

$$K_1 = \left[\frac{L_1}{g(A_{c1})} + \frac{L}{g(A_c)}\right] \tag{3.41}$$

$$K_2 = \left[\frac{L_2}{g(A_{c2})} + \frac{L}{g(A_c)} \right] \quad [3.42]$$

$$K_3 = \left[\frac{L_3}{g(A_{c3})} + \frac{L}{g(A_c)} \right] \quad [3.43]$$

$$K = \left[\frac{L}{g(A_c)} \right] \quad [3.44]$$

And the flow rate for each turbine may be written as follows:

$$Q_1 = G_1\sqrt{2gH_1} \quad [3.45]$$

$$Q_2 = G_2\sqrt{2gH_2} \quad [3.46]$$

$$Q_3 = G_3\sqrt{2gH_3} \quad [3.47]$$

From equations 3.38-3.47, 3.6 and adding the losses in water head due to friction as per equation 2.2, the dynamical nonlinear model of three hydraulically coupled turbines supplied from a common tunnel and reservoir is shown in Figure 3.7.

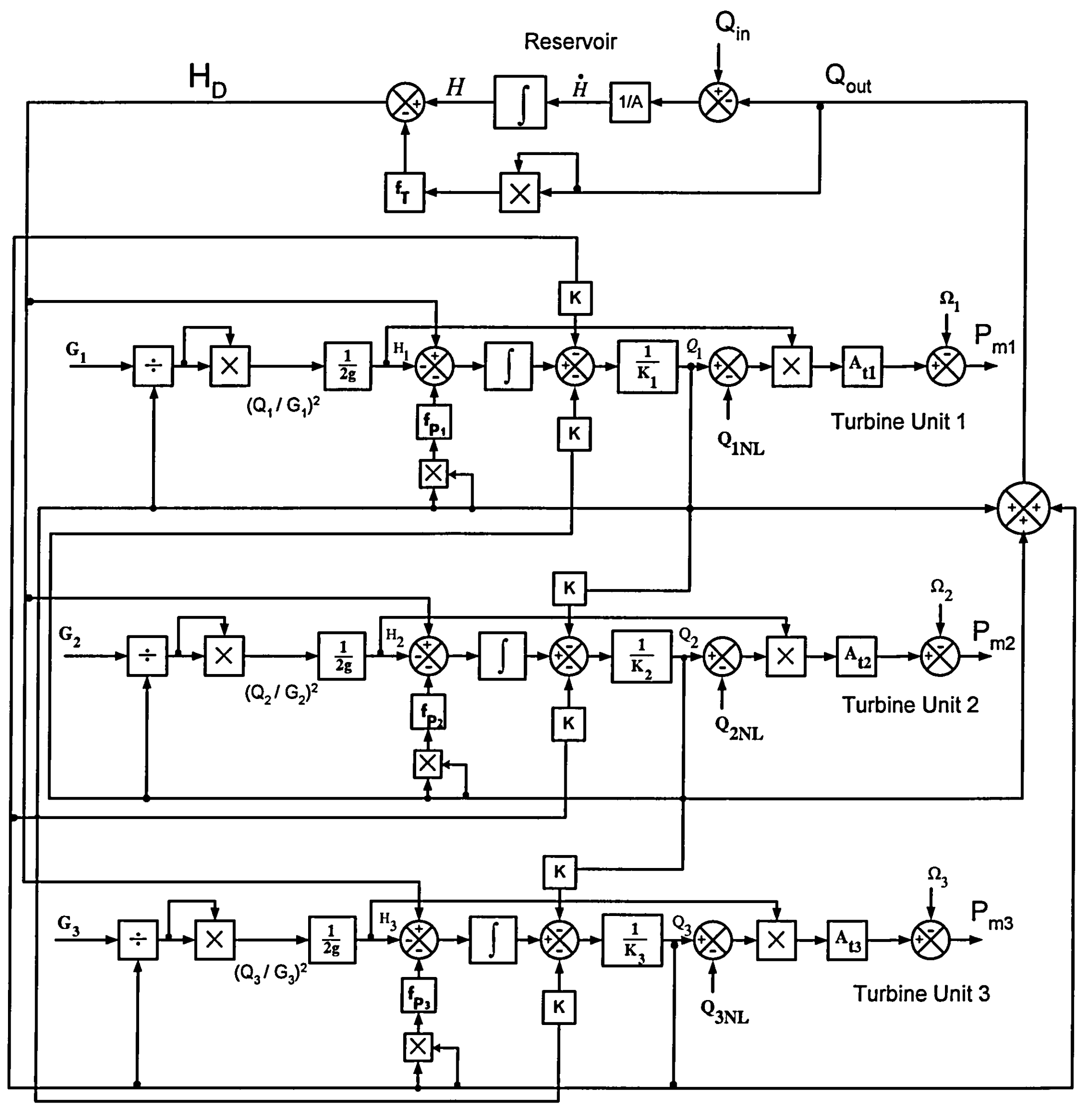


Figure 3.7 Dynamical nonlinear model of three hydraulically coupled turbines

3.2.4 Pressure Waves Dynamics

A sudden change of flow rate in hydraulic conduits due to valve closure may involve a great mass of water moving inside the conduit. The force resulting from changing the speed of the water mass may cause a pressure rise in the conduit with a magnitude several times greater than the normal static pressure in the conduit. This may fracture the conduit walls or cause damage to other hydraulic machinery in the plant, and is known as the water hammer phenomenon. However, the elasticity of both conduit walls and the water column play very important roles in water hammer phenomenon, as the water column is somewhat compressed and the conduit walls slightly expand due to the corresponding increase of stress in the wall. These effects provide a little extra volume allowing the water to move from one section to another continuously until it comes to a complete stop in both. Under these conditions the conduits will carry a series of positive and negative pressure waves, as shown in idealized form in Figure 3.8, which travel back and forth in the conduits up to the reservoir surface, causing changes in the reservoir level, until they are damped out by friction. The pressure wave is travelling at a repeated cycle period of $(4L/a_w)$ seconds, where (L) is the length of the conduit and (a_w) is the speed of the pressure wave. The pressure waves in the conduit can be modelled by treating it as a hydraulic transmission line terminated by an open circuit at the conduit end and a short circuit at the reservoir. Under this assumption the incremental head and flow at the end of the conduit, may be represented by equation 3.48 [IEEE1992 et al.].

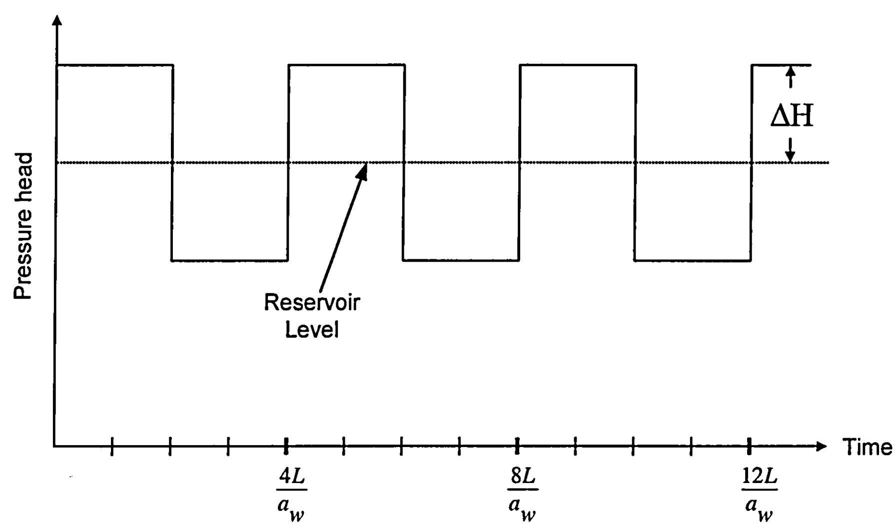


Figure 3.8 Pressure wave due to water hammer

$$\frac{H(s)}{Q(s)} = -Z_O \tanh(T_e s) \qquad [3.48]$$

where,

Z_o = the surge impedance of the conduit in per unit.

T_e = is the wave travel time, sec.

As discussed in section 2.3, the water hammer pressure may be alleviated by installing a pressure relief valve which automatically opens and diverts some of the flow when a set pressure is exceeded, or by a bypass valve which is considered in the design of the fuzzy control system in chapter 5. Also a surge tank will reduce water hammer pressure variations and keep the mass oscillations within acceptable limits and decrease the oscillations to stable operation as soon as possible. It acts like a reservoir closer to the flow control point.

3.2.5 Generator Dynamics

The synchronous generator converts the mechanical power of the hydraulic turbine to electrical power at a specific voltage and frequency. The electric dynamics have very short time constants compared to hydrodynamics and can be ignored [deMello1969 et al. Mansoor2000b]. The mechanical equations of a rotating machine are based on the swing equation of the rotating inertia. The swing equation relates the machine's rotor torque angle to the acceleration torque, which is the difference between the shaft torque and electromagnetic torque. Constant shaft speed for a given machine is maintained when there is equilibrium between the mechanical shaft and braking electrical torques. Any imbalance between the torques will cause the acceleration or deceleration of the machine according to the laws of motion of a rotating body. The swing equation may be written as follows [deMello1969 et al. Mansoor2000b]:

$$T_{acc} = J\frac{\partial^2 \theta_m}{\partial t^2} = T_{mech} - T_{elec} \qquad [3.49]$$

where;

T_{acc} = the accelerating torque, N.m.

J = the combined moment of inertia of the generator and turbine, Kg.m2

θ_m = the mechanical torque angle of the rotor, rad.

t = time, sec.

T_{mech} = the mechanical torque, N.m.

T_{elec} = the electromagnetic torque, N.m

The mechanical torque in terms of the hydraulic turbine mechanical power may be written as follows:

$$T_{mech} = \frac{Hydrualic\ Turbine\ Mechanical\ Power}{Angular\ Velocity} = \frac{P_m}{\omega_m} \qquad [3.50]$$

3.3 Simulation of a Cascaded Reservoirs Hydropower Plant

Simulation models were implemented in Matlab for a cascaded reservoirs hydropower plant using the developed mathematical equations of this Chapter, the model of section 3.2, the model of section 3.2.2 and the model of section 3.2.3. The cascaded reservoirs hydropower plant comprises three reservoirs and three power plants. Each power house has one tunnel, three penstocks and three hydraulically coupled turbines. The aim of this simulation work is to demonstrate the performance of the cascaded reservoirs hydropower system and its nonlinear dynamics, so as to be able to design and test the fuzzy logic control system. Each Matlab model and its physical parameters are attached in Appendix A.

3.3.1 Plant Simulation at Medium Turbines' Gate Positions

By starting up the plant from its initial conditions at constant turbines' gate positions of 50%, the following results were obtained:

- *Nonlinear Characteristics:* Figure 3.9 shows the nonlinear head characteristics for each plant's reservoir, the head losses for each plant, the power generated from each plant and the total generated power of the cascaded system. As can be seen, the energy is transferable within the cascaded system from the top subsystem to the bottom one at variable discharge rates dependent on the reservoirs' initial conditions and the turbines' gate positions. While keeping the turbines' gate positions constant at 50%, nonlinear and incrementally increasing hydraulic head and generated power envelopes from one subsystem to the next are noticed. This is because each reservoir has a different rate of discharge based on the upstream conditions (discharge of preceding system). The rate of discharge is maximum from the top reservoir and minimum from the bottom one; this gives the end subsystem the biggest hydraulic head and power envelopes among subsystems.

- *Head Losses:* As shown in Figure 3.9 and in contrast with previous remarks, the head losses due to friction are incrementally increasing from the top subsystem to the bottom one. This is logical because friction losses are proportional to the flow rates. This gives the end subsystem the biggest hydraulic head losses envelope among other subsystems.

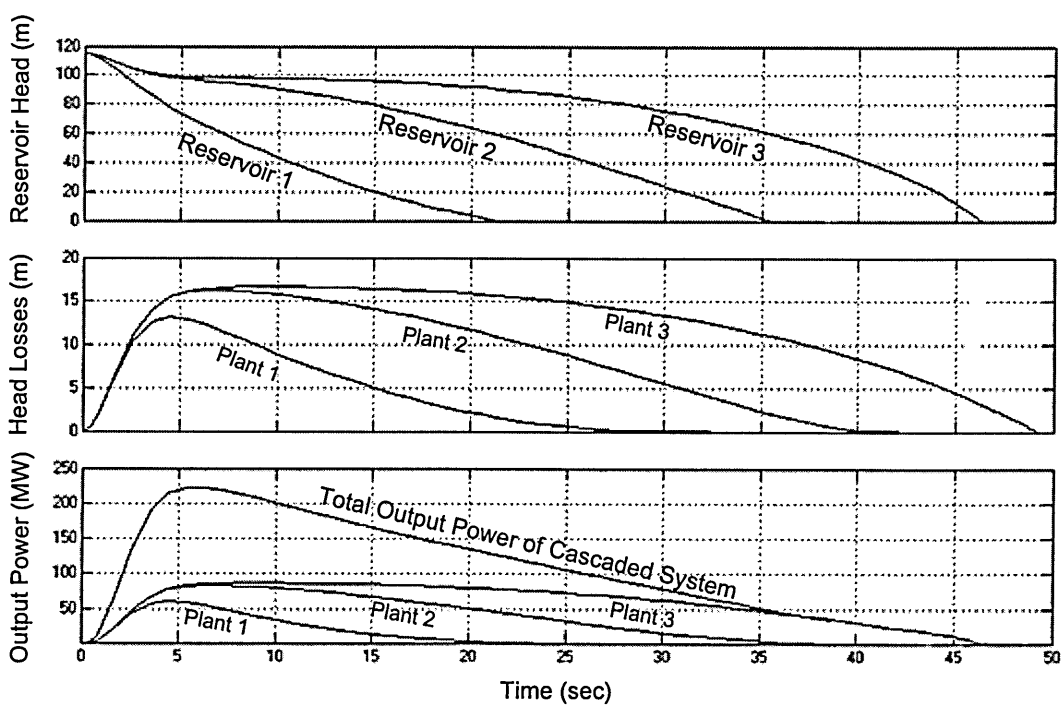


Figure 3.9 Simulation of the cascaded hydropower plant at 50% gate positions

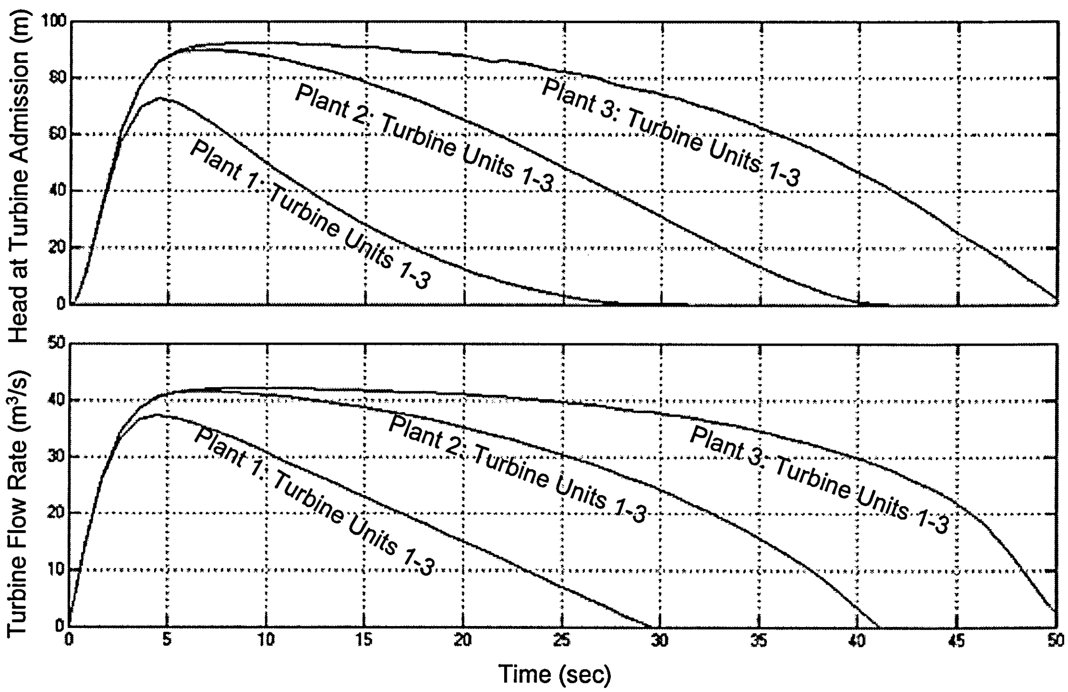


Figure 3.10 Simulation of turbines' heads and flow rates at 50% gate positions

- *Turbines' Heads and Flow Rates:* Figure 3.10 shows the nonlinear head and flow rate characteristics for each turbine unit in each cascaded subsystem. In contrast to the previous simulation, the end subsystem's turbine units have the biggest hydraulic head and flow rate envelopes among turbine units in the cascaded subsystems.

3.3.2 Plant Simulation at High Turbines' Gate Positions

By starting up the plant from its initial conditions at constant turbines' gate positions of 90%, the following results were obtained:

Figure 3.11 shows the nonlinear head characteristics for each plant's reservoir, the head losses for each plant, the power generated from each plant and the total generated power of the cascaded system. Figure 3.12 shows the nonlinear head and flow rate characteristics for each turbine unit in each cascaded subsystem. These simulation's results agree broadly with the previous simulation results of section 3.3.1. However it was generally expected that linearly increasing the gates' positions towards higher values would also linearly increase the total operational power envelope of the system. But this simulation indicated that it is not necessarily true that setting fixed gates' positions (in absence of the control and optimization system) of a cascaded hydropower plant to higher values would maximize its total operational power envelope. This can be seen by comparing Figures 3.11 and 3.9 where only a small increase in the generated power at the 90% gates' positions compared to the 50% gates' positions, can be seen. This is because of the fact that the friction losses are proportional to flow rates which are much higher at maximum gates' positions, the nonlinear relationship between a turbine's generated power and its gate position, and the nonlinear upstream and down stream dynamics on each cascaded subsystem and accordingly on each turbine in the cascaded system. Therefore, and by temporarily neglecting any load or control system dynamics, a cascaded hydropower system exclusively working on its initial conditions would have its own *optimal operational point* at a certain gates' positions not necessarily the *maximum positions* but we may say the *optimal positions*, knowing that the *optimal operational point* would be also a time variant as long as new changes in the reservoirs' inputs are taking place.

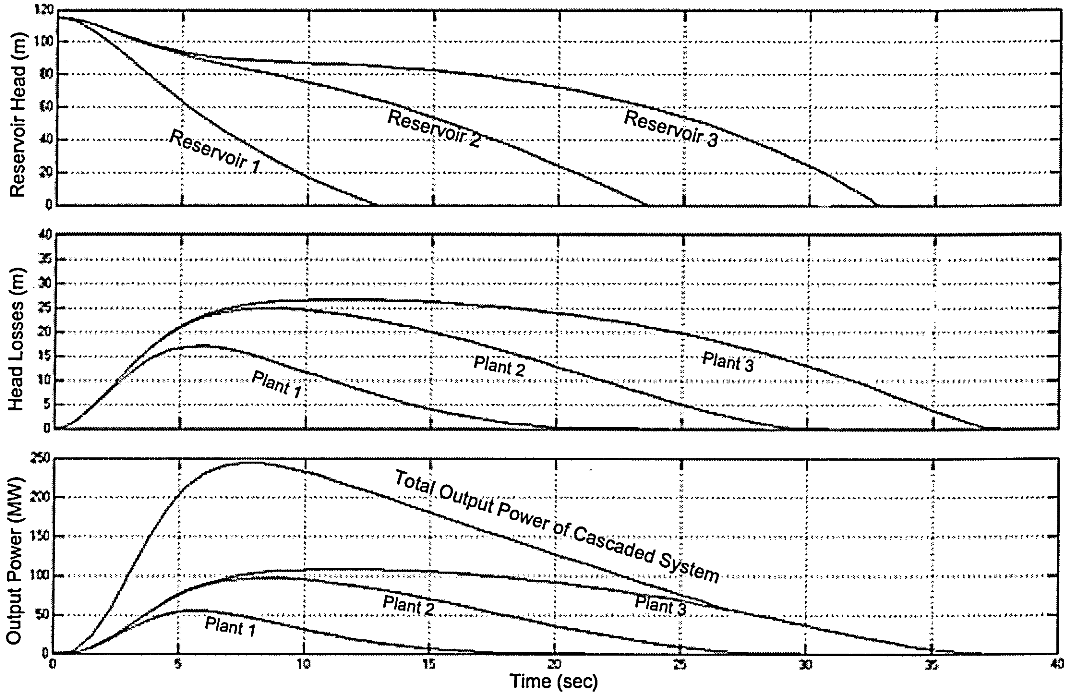


Figure 3.11 Simulation of the cascaded hydropower plant at 90% gate positions

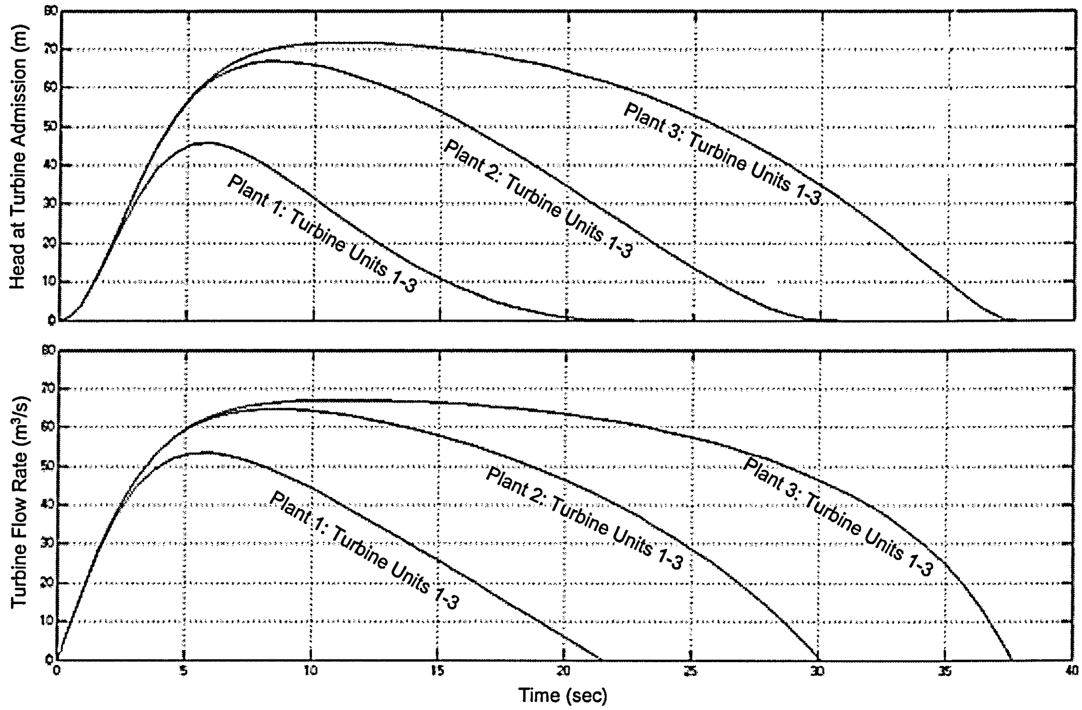


Figure 3.12 Simulation of turbines' heads and flow rates at 90% gate positions

3.3.3 Plant Simulation at Low Turbines' Gate Positions

By starting up the plant from its initial conditions at constant turbines' gate positions of 30%, the following results were obtained:

Figure 3.13 shows the nonlinear head characteristics for each plant's reservoir, the head losses for each plant, the power generated from each plant and the total generated power of the cascaded system. Figure 3.14 shows the nonlinear head and flow rate characteristics for each turbine unit in each cascaded subsystem. In contrast with the simulation results in section 3.3.1, in this simulation the cascaded hydropower plant behaved logically with a resultant general performance and generated powers being less than the previous 50% and 90% gates' positions which assures the conclusion of section 3.3.2.

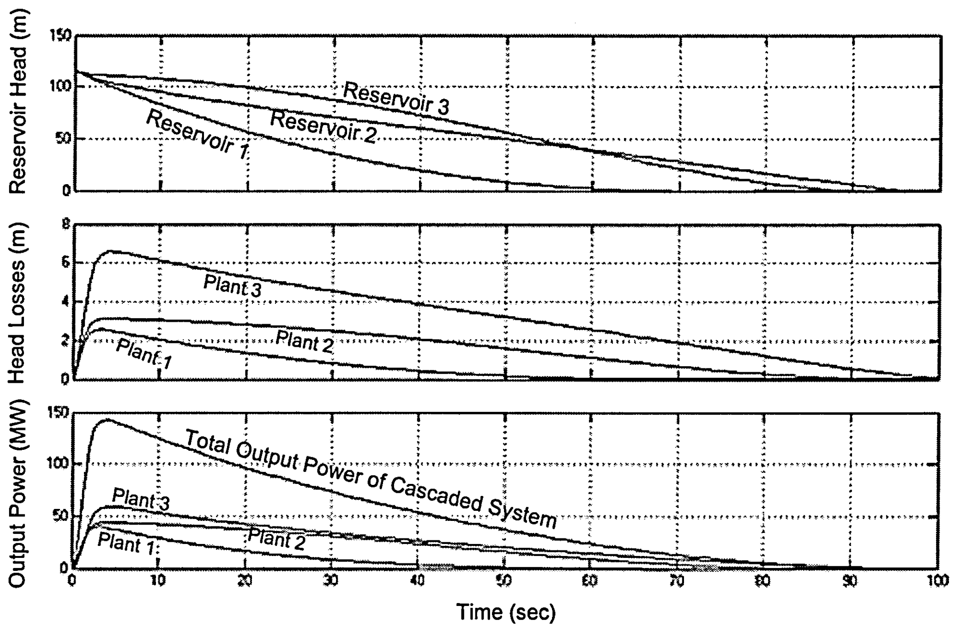


Figure 3.13 Simulation of the cascaded hydropower plant at 30% gate positions

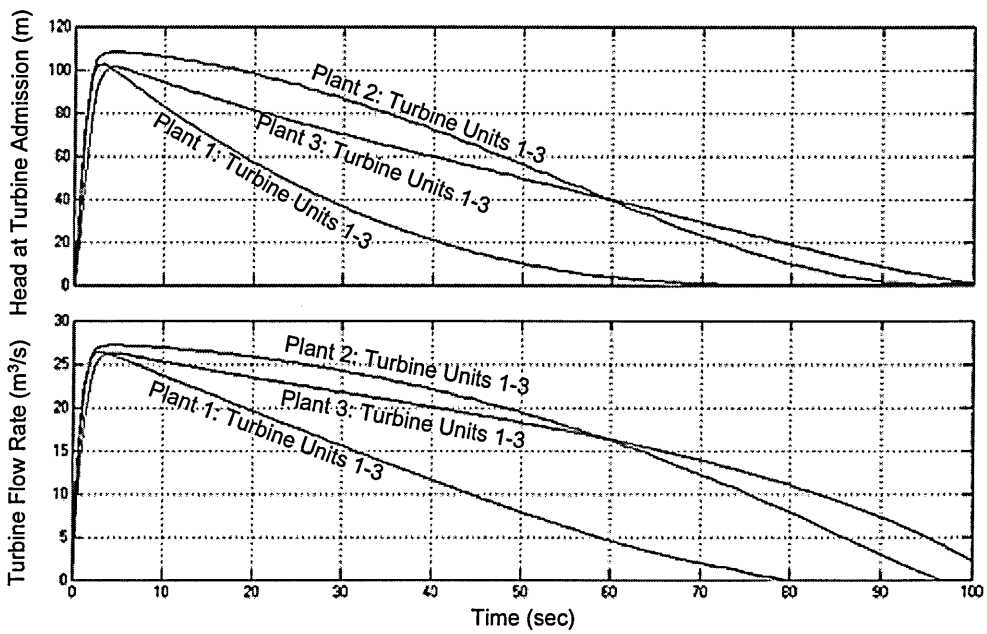


Figure 3.14 Simulation of turbines' heads and flow rates at 30% gate positions

3.3.4 Simulation of Environmental Disturbances

Hydropower plants in general are expected to be sensitive to environmental conditions such as changes in the climate temperature and the water density. For a cascaded hydropower plant, each subsystem may be exposed to different environmental conditions because it is located on a different topographical level or geographical location. This simulation shows that a cascaded hydropower plant's subsystem is sensitive to changes in water density as shown in Figure 3.15a and sensitive to changes in climate temperature as shown in Figure 3.15b.

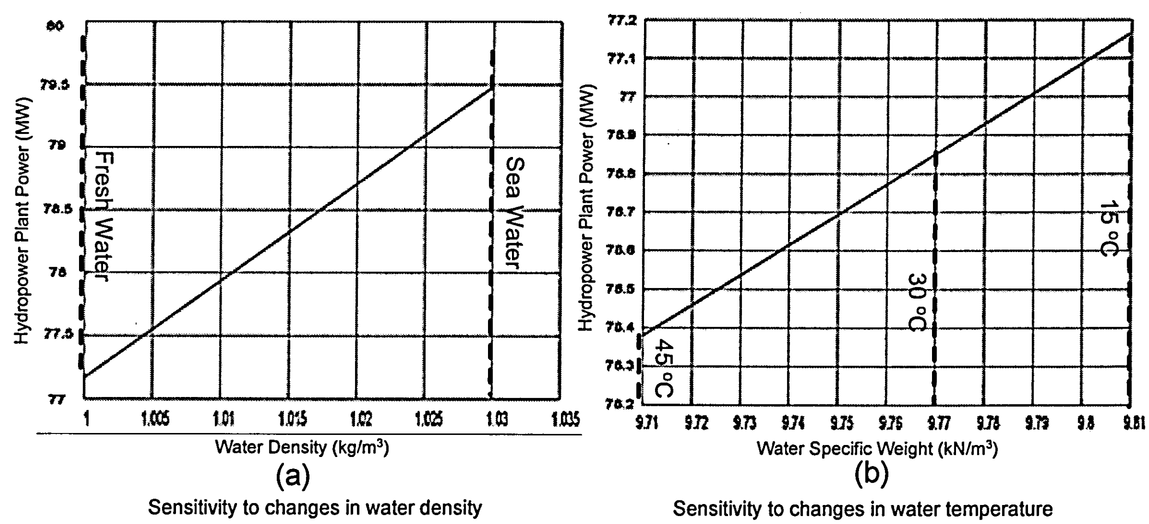


Figure 3.15 Cascaded hydropower plant, sensitivity to changes in density and temperature

3.3.5 Simulation of Water Hammer Effect

In contrast to the pressure wave dynamics presented in section 2.3.4, under water hammer conditions the conduits will carry a series of positive and negative pressure waves which travel back and forth in the conduits up to the reservoir surface causing changes in the reservoir level until they are damped out by friction. The pressure waves travel at a repeated cycle period of $(4L/a_w)$ seconds, where (L) is the length of the conduit and (a_w) is the speed of the pressure wave. Figure 3.16 shows the effect of a 10% magnitude pressure wave due to water hammer in the tunnel of the first hydropower subsystem. The head of the first reservoir was directly affected by the pressure wave which affected the hydraulically coupled turbine units of the same subsystem and their generated powers. It did not affect directly the other subsystems because of friction losses between the subsystems and their reservoirs which damp low magnitude pressure waves. The rest of the cascaded system is indirectly affected due to the power grid coupling which makes these hydraulic transients transferable to the power grid where other power houses on the gird will see those transients as a change in the load demand. Higher magnitude pressure waves would be expected to be damped by surge tanks of the cascaded system that normally reduce water hammer pressure variations and keep the mass oscillations within acceptable limits and decrease the oscillations to stable operation as soon as possible.

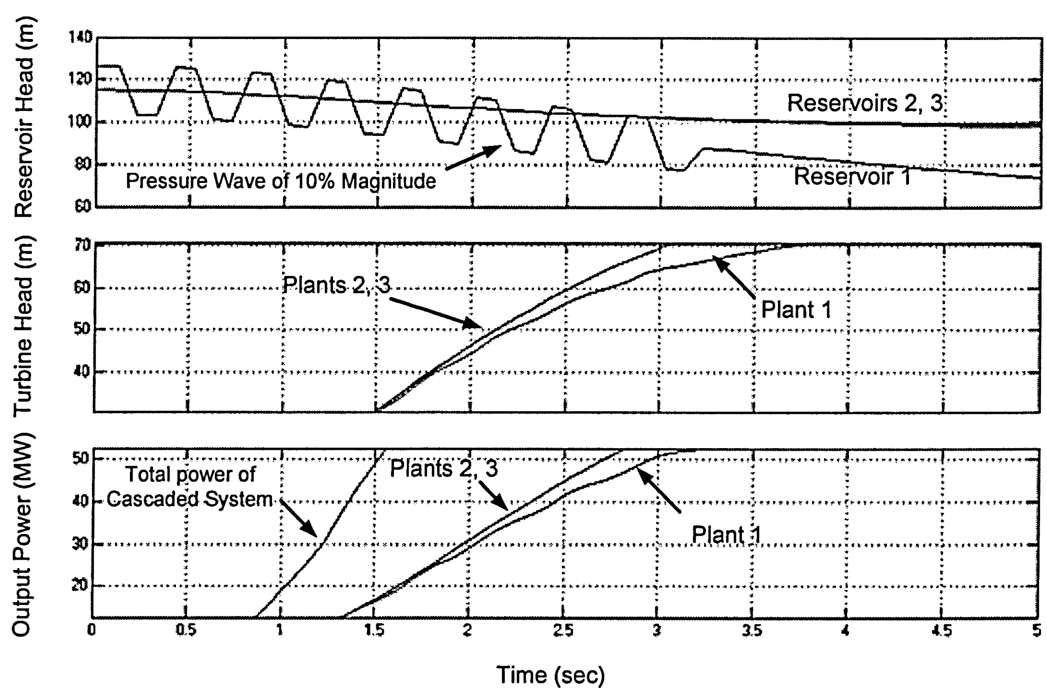


Figure 3.16 Simulation of water hammer effect on a cascaded hydropower plant

3.3.6 Simulation of Three Hydraulically Coupled Turbines

The developed model of Figure 3.7 was implemented in Simulink as per Appendix A, and used to carry out a computer simulation to investigate the effects of the hydraulic coupling; the results are shown in Figure 3.17. To simulate a load rejection on turbine unit 1, the dynamical head is kept constant at $115\,m$ and turbine units 2, 3 gate openings are kept constant at a value of $\approx 50\%$ $(1\,m^2)$ while turbine unit 1 gate opening has dropped from $\approx 50\%$ $(1\,m^2)$ to $\approx 10\%$ $(0.2\,m^2)$ for 2 sec. This drop in gate 1 position has caused a deviation of $\approx 21\%$ in the output power of neighbouring turbine units. Two seconds later the turbine unit 1 has picked up its load demand and its gate opening has increased from $\approx 10\%$ $(0.2\,m^2)$ to $\approx 90\%$ $(1.8\,m^2)$ in 4 sec. This increase in gate 1 position has caused a deviation of $\approx 26\%$ in the output power of neighbouring turbine units. This simulation proved that the hydraulically coupled turbines are interacting. Therefore, if the turbines are individually controlled (one PID governor each), disturbance signals caused by neighbouring turbines are permanently available on each controller causing unbounded deviation errors which make the plant unstable and lead to hydraulic mass oscillations in the conduit system and transferable oscillations to the power grid.

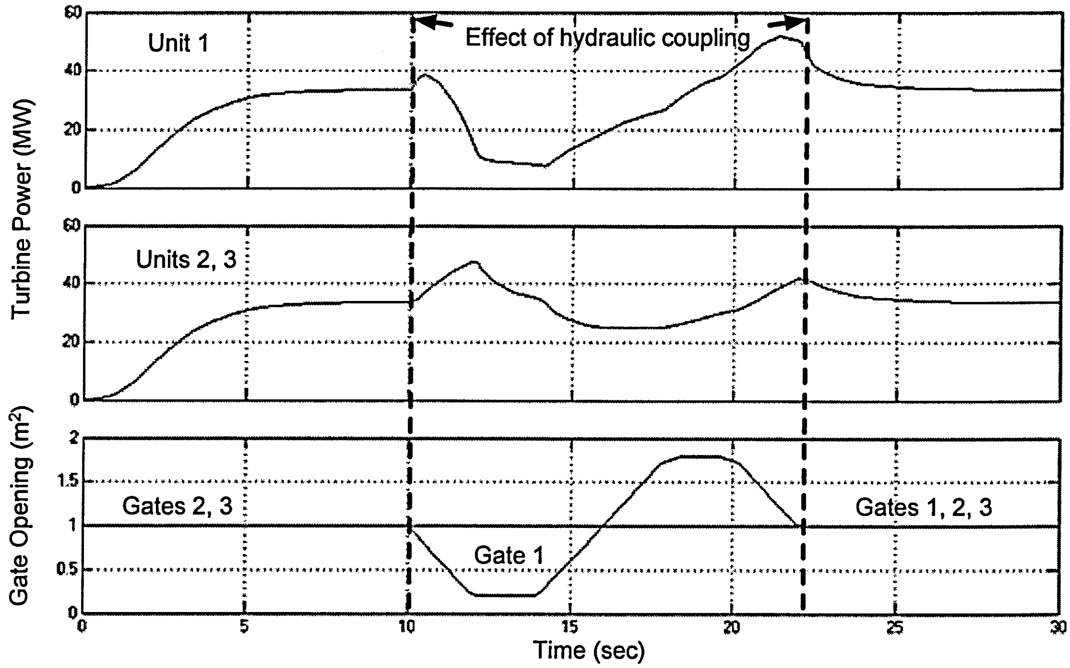


Figure 3.17 Simulation results of three hydraulically coupled turbines

3.4 Conclusions

- The cascaded hydropower plant is a complex nonlinear system that involves interacting input and output nonlinear parameters, nonlinear flow rates, and nonlinear dynamical hydraulic heads. The plant's optimal operational point is time variant dependent on the reservoirs' initial conditions and changes in their inputs conditions. The losses in hydraulic heads due to friction are a key player in the plant's efficiency. The plant would be sensitive to changes in the climate temperature and changes in water density. The hydraulic coupling between the turbines of a power house makes the disturbances in one turbine transferable to neighbouring turbine units which may make the plant unstable and lead to hydraulic mass oscillations in the conduits and may transfer oscillations to the power grid where the other power houses on the same grid will see those oscillations as changes in the load demand.

- In the light of the above, the cascaded hydropower plant is not particularly suitable to be controlled by a single control system or to be controlled by classical PID controllers. It has to be decomposed into decoupled dynamical subsystems and a new control system should be designed that successfully addresses the problems of each subsystem *(local plant levels, local control systems)* with the design of a new supervisory control system that monitors and revises the control strategies of each subsystem *(global plant level, supervisory control system).* Therefore, a new fuzzy logic turbine governor is designed and implemented in Chapter 4, that may replace the classical PID turbine governors and be capable of controlling the hydraulic turbine together with its penstock under nonlinear process conditions. A new fuzzy logic controller is designed and implemented in Chapter 5, that is capable of controlling together three hydraulically coupled interacting turbines with their penstocks under nonlinear process conditions. A new fuzzy logic supervisory control and optimization system is designed and implemented in Chapter 6 that is capable of controlling and optimising the cascaded reservoirs hydropower plant at the global level.

Chapter 4. FUZZY LOGIC GOVERNOR DESIGN AND IMPLEMENTATION

4.1 Introduction

In this chapter a fuzzy logic turbine governor is designed and implemented for the control of a hydraulic turbine together with its penstock under nonlinear process conditions that can be used in the local control loops of the cascaded hydropower plant, and may replace the classical PID turbine governors that are commonly used in hydropower plant control which can cause instability problems. The fuzzy logic governor is designed according to an "expert knowledge base" which is gathered by the intensive literature review of Chapter 2 and the modelling and simulation results of Chapter 3.

4.2 The Design Methodology

In order to design the fuzzy logic turbine governor, the following tasks were formulated and implemented.

- To formulate an "expert knowledge base" on hydraulic turbine governing control, its nonlinear dynamics and its operational modes. Presented in section 4.3.

- To select an appropriate turbine model that represents its nonlinear dynamics, and to create a control strategy. Presented in section 4.4.

- To identify the inputs and outputs of the fuzzy controller and to formulate their scaling factors and their fuzzy linguistic variables. Presented in section 4.5.

- To create suitable fuzzy membership functions for both the inputs and outputs in the light of the turbine's nonlinear characteristics and to satisfy its control strategy. Presented in section 4.6.

- To construct the rule base that converts the "expert knowledge base" into control actions covering all of the turbine's operational modes and executing its control strategy. Presented in section 4.7.

- Implement the fuzzy turbine governor in Matlab and carry out simulations to obtain results. Presented in section 4.8.

4.3 Formulation of Expert Knowledge Base

To design a fuzzy logic turbine governor reliable and smart enough to service a nonlinear process, the design has to rely not only on accurate turbine modelling but also on an "expert knowledge base". The expert knowledge base is technical information on hydraulic turbine operation and control gathered from expert people who work in this field, reported and or published articles, field trials, simulation and predictions. It may also cover some hidden dynamics not modelled. The gathered expert knowledge supporting the design of a fuzzy hydraulic turbine governor can be summarised as follows:

1. It should keep the rotational speed of the turbine-generator unit stable and constant at any grid load and prevailing conditions in the water conduit. It should automatically control the speed of the generator shaft by controlling water through the turbine. A hydraulic system opens and closes gates.

Governors consist of speed sensing, gate positioning and stabilizing equipment.

2. At load rejections or emergency stop the turbine admission has to be closed down according to acceptable limits of the rotational speed rise of the unit and the pressure rise in the water conduit.

3. Alterations of the grid load cause deviations between turbine power output and the load. For a load decrease the excess power accelerates the rotating masses of the unit to a higher rotational speed, the following governor reduction of the turbine admission means deceleration of the water masses in the conduit and a corresponding pressure rise.

4. Hydro turbines because of their initial inverse response characteristics of power to gate changes require provision of transient droop features in the speed controls for stable control performance. The term "transient droop" implies that for fast deviations in frequency, the governor exhibits high regulation (low gain) while for slow changes and in the steady state the governor exhibits the normal low regulation (high gain).
5. The turbine control loop gain is nonlinearly varying with the gate opening which makes the PID turbine governors need to be re-tuned for each operational mode; otherwise oscillations that lead to instability of the turbine will take place.
6. For high frequency deviation while the power deviation is small do not respond as for a "transient frequency drop".
7. Permanent droop settings: the variation of the load as a function of the change in frequency is dependent on the permanent droop setting which determines the speed regulation under steady conditions. It is defined as the speed droop in percent or per unit required to drive the gate from min to max opening without change in speed reference.
8. PID governors: rotational speed is dependent on the load for power/load equilibrium conditions. Higher rotational speed occurs at zero loads than at

max load. This dependency is linear-proportional control. For units delivering power to a grid system, the frequency has to be constant at any load (integral control). Groups of governors are also provided with a derivative function utilized for improvement of the phase angle of the frequency response. The purpose of the derivative is to extend the crossover frequency beyond the constraints imposed on the PI governors. When a PID governor is properly tuned, the transient gain will be increased by a value higher than normal PI values, and this may result in roughly the same increase in crossover frequency beyond the constraints imposed on the PI governors and thereby in governor response speed.

9. Dead band: a feature of modern governors designed to desensitize the governor to small frequency changes in order to reduce mechanical wear (a parameter set in the governor control system).

10. Operational considerations: each turbine is normally designed for best efficiency near rated power output. The efficiency at low power levels (<50%) is much lower. A "rough zone" is a an operational zone where the unstable flow levels lead to high pressure shock waves which can cause mechanical damage. This occurs mostly at low power levels, with flows of lower efficiency levels. Plant operators avoid running in these operational zones.

11. Hydraulic transients may result from changes in valve settings, changes in power demand for turbines, changes in reservoir elevation (flood and rain falls), or a turbine governor "hunting".

12. For controlling hydraulic transients, the gate operation should be limited to operation to slow changes. For Francis turbines the principle is to set the closing rate of the guide vanes to a value which satisfies the rotational speed rise limits. Divert some of the discharge through a controlled by-pass valve so that the pressure rise in the conduit is kept below the prescribed level.

13. During load rejection: to keep the rise of the rotational speed below a prescribed limit at load rejections, the admission closing rate must be equal to or higher than a certain value. For the pressure rise in the water conduit the condition is opposite, the closing rate of the admission must be equal to or lower than a certain value to keep the pressure rise as low as prescribed. For power plants where these two demands are not fulfilled by one single control, the governors are provided with dual control functions, one for controlling the rotational speed rise and the other for controlling the pressure rise.

14. Frequency and load regulation: the governor shall be able to maintain stability of the generating unit when running on an isolated grid. Load regulation on a rigid system is the most common operational mode. The variation of the load as a function of the change in frequency is dependent on the permanent droop setting.

15. Start and stop sequence control: during the period of startup the unit shall be run up to nominal speed as quickly as possible and as smoothly as possible. This can be carried out manually or automatically, but the admission must be opened only when permitted by all overriding start conditions. In shutdown mode the admission shall be closed as quickly as possible but limited by the magnitude of the pressure rise in the tunnel and pressure shaft system.

16. The friction losses in water heads increase with higher flow rates which may limit a turbine from reaching its rated power output. Therefore, the friction losses should not be ignored in turbine modelling while designing or setting up its control system.

4.4 The Control Strategy

The hydraulic turbine is represented by the nonlinear model developed in section 3.2.2 and shown in Figure 3.5, which combines the turbine-penstock dynamics with the head at turbine admission, turbine flow rate and the losses in water head due to friction. According to the formulated "expert knowledge base" in section 4.3, it was decided to follow a multilayered control strategy that is illustrated in Figure 4.1 and may be classified as follows:

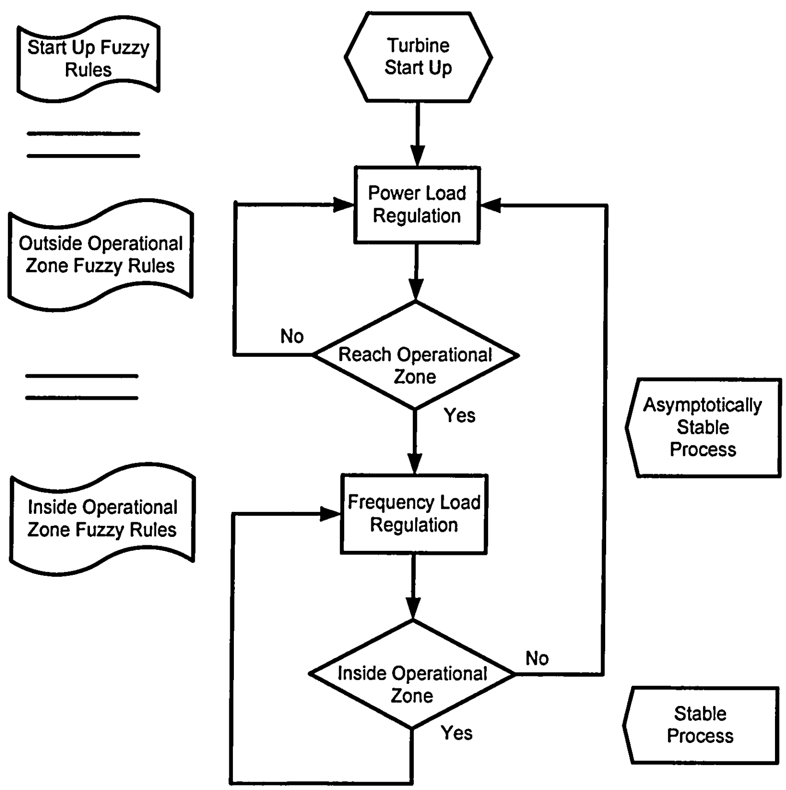


Figure 4.1 Fuzzy governor control strategy

- *Start up from initial conditions:* based on the fact that nonlinear systems are sensitive to initial conditions and to limit a false turbine gate opening when starting up from initial conditions, some exclusive start-up fuzzy rules are added to form the first layer of control.

- *Reaching the operational zone:* once the turbine is started up, the system immediately responds to load demands by evaluating the power error signal and temporarily neglecting the frequency error signal until what is called the "operational zone" is reached. Picking up the load demand as quickly as possible by positioning the gate until the power error is minimised to a preset value, is thus achieved. The operational zone is a virtually defined area on the universe of discourse set between the two membership functions of "*Power Error Positive Small Small*" and "*Power Error Negative Small Small*" and surrounding the zero power error value by a membership function "OZ", as presented in Section 4.5 and illustrated in Figure 4.2. Therefore a resultant crisp turbine operational zone will always be the zone bounded by $\pm 5\%$ power error margins with a central value (*optimal operational zone crisp values*) bounded by $\pm 1.75\%$. The boundaries of the operational zone are based on the desired permanent droop setting which is defined in sections 2.4 and 4.3, it is normally from 0-6%, in this design the 5% permanent droop setting is used. As long as the fuzzy governor is taking action to keep the turbine operating or steadily oscillating within the operational zone, the controlled process becomes asymptotically stable (In the sense of Liapunov second method of stability analysis of nonlinear systems [Dutton 1997 et al. Ogata1997]). Once the fuzzy governor has reached the "operational zone" it will start, if a frequency error exists, to carry out frequency regulation and it will continue control efforts to keep the turbine operating or steadily oscillating within its optimal operational zone defined above. Here, the controlled process becomes stable. This task is handled by an exclusive set of fuzzy rules and an output signal called "gate control" which will form the second layer of control.

- *Inside the operational zone:* once the turbine has reached the "operational zone", the system will verify the frequency error signal and convert it into corrections to the present gate position through a partial output control signal called "gate control delta". As long as the frequency error is always corrected while the turbine is still operating inside the "operational zone", the controlled process becomes stable. This task is handled by an exclusive set of fuzzy rules and the output control signal called "gate control delta" which will form the third layer of control.

- *Gate-power nonlinear relationship:* the nonlinear relationship between the turbine's gate and its output power as illustrated in Figure 2.8, is accounted for in section 4.5 by scaling factors shown in Figure 4.2 and the "reaching operational zone" fuzzy rules.

- *Fuzzy inference system:* Mamdani fuzzy inference method is the one selected for the development of the fuzzy turbine governor, as it provided more flexibility to implement the control strategy down the finest details.

4.5 Inputs and Outputs of Fuzzy Turbine Governor

The inputs and outputs of fuzzy governor scaling with their fuzzy linguistic variables are shown in Figure 4.2. The fuzzy linguistic variables are defined in Table 4.1.

Three inputs of the fuzzy governor are formulated as follows:

- *Power error signal:* this is the deviation between the power set point (desired value) and the generated power feed back signal (load demand), its scaling factor is from -100% to +100%.

- *Frequency error signal:* this is the deviation between the frequency set point (desired value) and the grid frequency feedback signal (frequency demand normally from 49-50 Hz), its scaling factor is from -5% to +5%.

- *Gate position:* this is the turbine gate position feed back signal by which the fuzzy controller always knows the present gate position, its scaling factor is from 0% to +100%.

Two outputs of the fuzzy governor are formulated as follows:

- *Gate control:* this is the turbine gate control signal, its scaling factor is from 0% to +100%.

- *Gate control delta:* this is a partial turbine's gate control signal which only corrects the gate position when the turbine's "operational zone" has been reached where only frequency regulation is allowed, its scaling factor is from -10% to +10%.

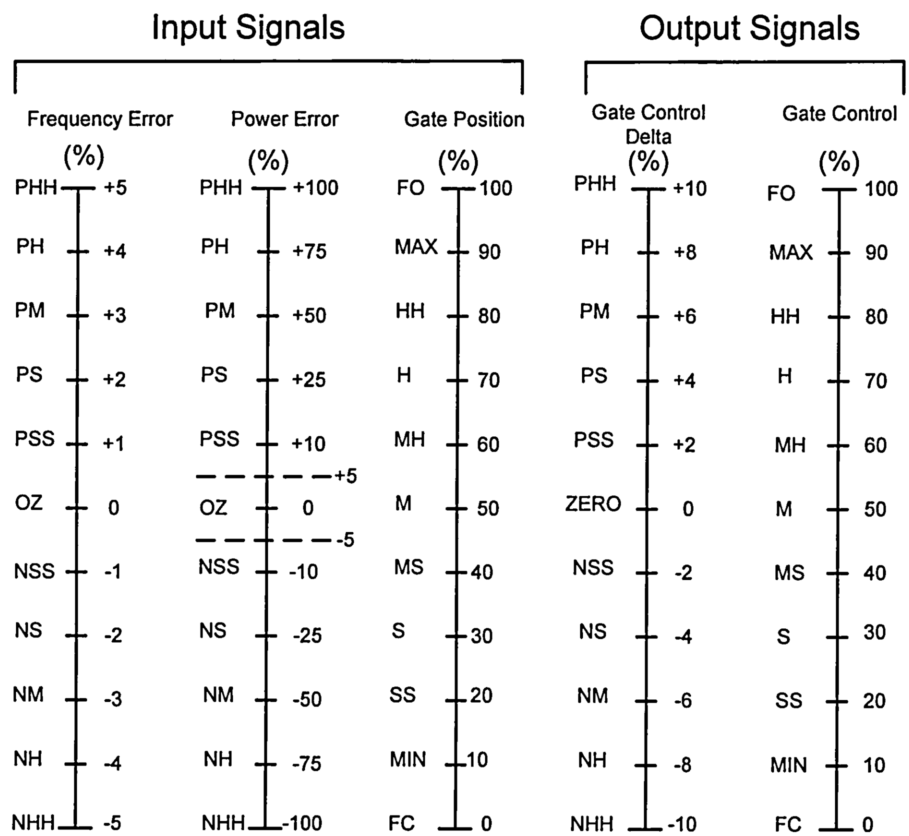


Figure 4.2 Scaling of the fuzzy governor inputs and outputs

Linguistic Variable	*Definition*
PHH	Positive High High
PH	Positive High
PM	Positive Medium
PS	Positive Small
PSS	Positive Small Small
ZERO	0
NHH	Negative High High
NH	Negative High
NM	Negative Medium
NS	Negative Small
NSS	Negative Small Small
OZ	Operational Zone
FO	Fully Open
MAX	Maximum
HH	High High
H	High
MH	Medium High
M	Medium
MS	Medium Small
S	Small
SS	Small Small
MIN	Minimum
FC	Fully Closed

Table 4.1 Fuzzy governor linguistic variable definitions

4.6 Fuzzy Turbine Governor Membership Functions

Upon testing some numbers of Gaussian and trapezoidal membership functions for this application, it was found that the fuzzification of all inputs and outputs in this application could each be based on eleven triangular membership functions of sharp transitions with small intersection areas. This achieved better results in terms of faster response and reduced oscillations. This is because the nonlinear process under control is highly sensitive to small changes such as the present gate position versus the present error value. Fewer membership functions with wider intersection areas gave approximated values only, and did not detect these small changes which led to high overshoot oscillations that destabilized the system. Using a higher number of triangular membership functions with small intersection areas can better track the error trajectory of the nonlinear process under control. The triangular input and output membership functions of the fuzzy governor are formulated as follows:

- *Input 1 - Power error signal*: as shown in Figure 4.3, comprises eleven triangular membership functions with the operational zone "OZ" indicated in the middle.

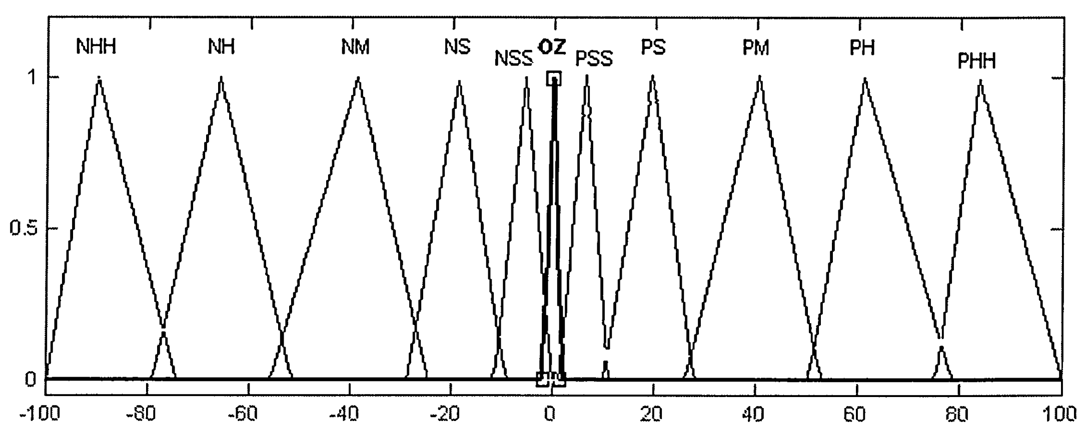


Figure 4.3 Power error- input membership functions

- *Input 2 - Frequency error signal:* as shown in Figure 4.4, comprises eleven triangular membership functions with a frequency operational zone "OZ" indicated in the middle.

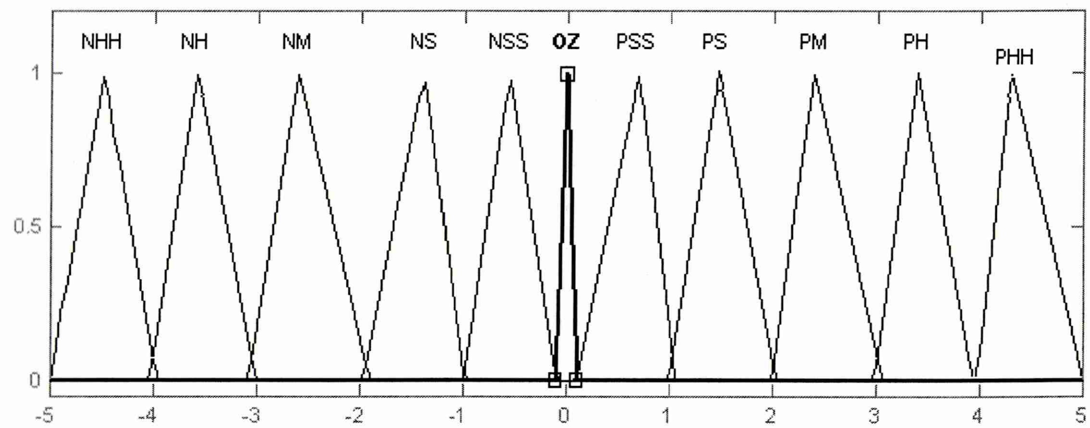


Figure 4.4 Frequency error- input membership functions

- *Input 3- Gate position:* As shown in Figure 4.5, comprises eleven triangular membership functions. It represents the nonlinear characteristic of the turbine gate where the effective operational zone of the gate is from the position "MIN" to the position "MAX" which is ≈ 5-90%. The fully open position "FO" is used to indicate to the fuzzy governor that the gate exceeded it maximum operational zone and no control is carried out beyond this point so that saturation and winding up can be avoided. The fully closed position "FC" is kept very tight so that false and small gate opening can be detected.

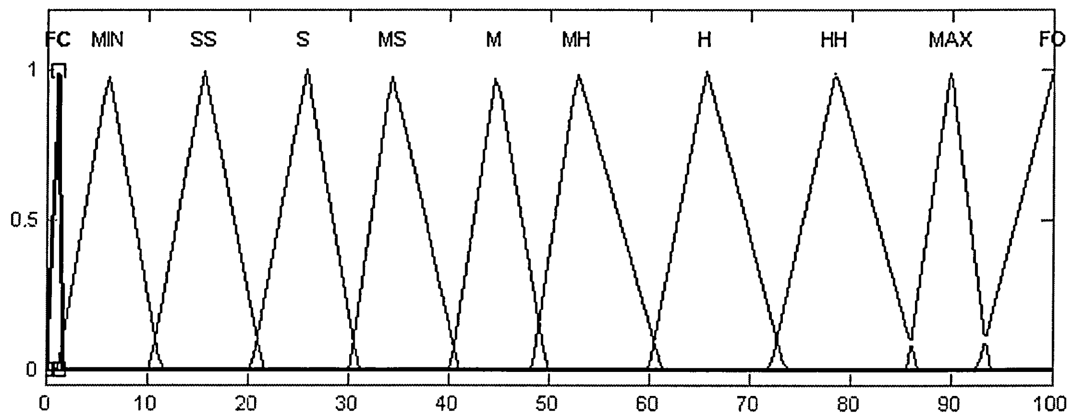


Figure 4.5 Gate position-input membership functions

- *Output 1 - Gate control:* as shown in Figure 4.6, comprises eleven triangular membership functions. As will be noted the fully closed gate opening "FC" is different from the one in Figure 4.5. This is to prevent false gate opening.

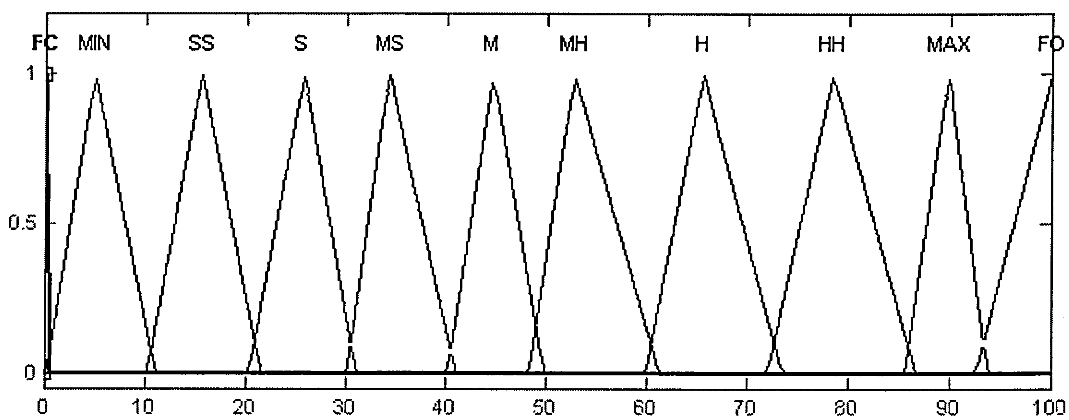


Figure 4.6 Gate control- output membership functions

- *Output 2 - Gate control delta:* As shown in Figure 4.7, comprises eleven triangular membership functions.

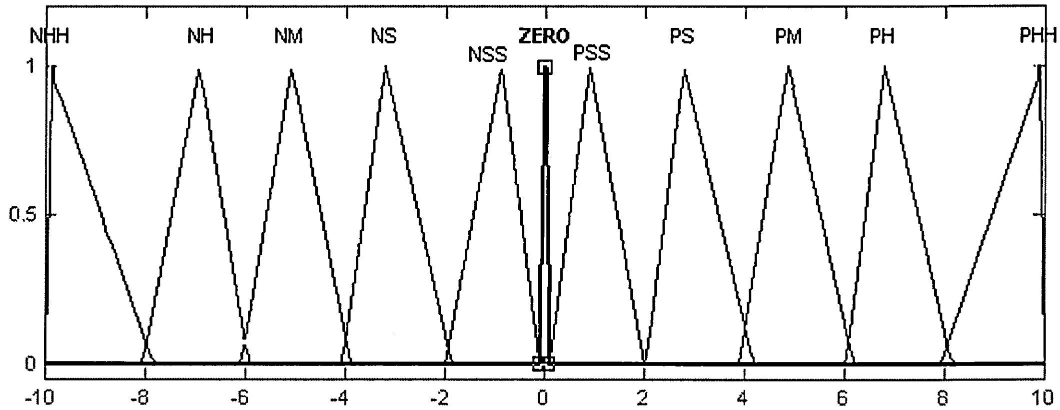


Figure 4.7 Gate control delta-output membership functions

4.7 Fuzzy Governor Rule Base

In the light of the "expert knowledge base" in section 4.3 and the control strategy of section 4.4, a fuzzy rule base comprising a total of 226 rules is constructed. The resultant fuzzy governor control surfaces that represent the controller dynamics are shown in Figures 4.8- 4.10. The 226 constructed control rules are listed in Appendix E and are classified in sections 4.7.1- 4.7.3. The shape of the control surface reflects the linearity or the nonlinearity of the process under control. As an example, the nonlinear relationship between the turbine gate's position and its generated power can be seen in Figure 4.8, while the same nonlinear relationship can be seen nonlinearly variant in Figure 4.9 dependent on the value of the gate position feedback signal. The peaks in the middle of the control surface shown in Figure 4.10 represent the "operational zone" which was defined in section 4.4, where only frequency regulation is allowed.

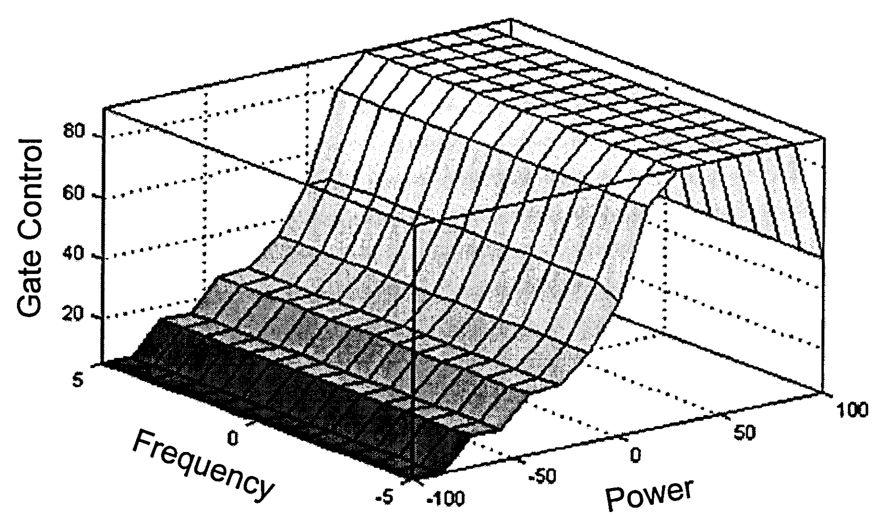


Figure 4.8 Fuzzy governor control surface power-frequency-gate control

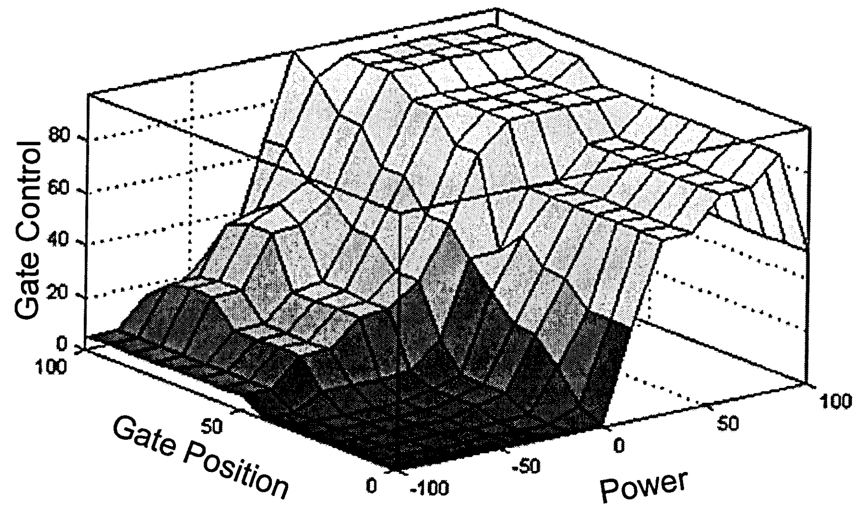


Figure 4.9 Fuzzy governor control surface power-gate position-gate control

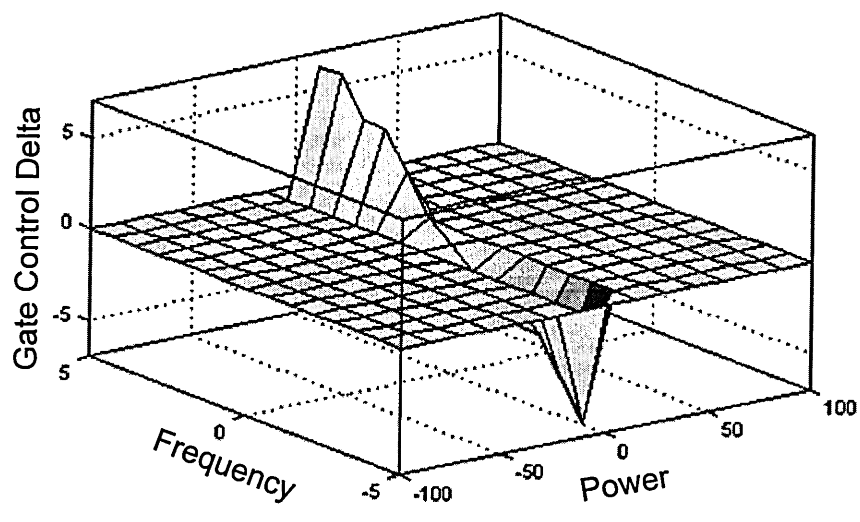


Figure 4.10 Fuzzy governor control surface power-frequency-gate control delta

4.7.1 Start Up From Initial Conditions Fuzzy Rules

The function of the *Start up from initial conditions* rules is to detect some combined unique conditions of the gate position and the power error which are exclusively available at the turbine start up and cannot be available in any of the other operational modes, and to establish a quick response as soon as the turbine has started. Examples are a "Positive High High" power error value and a "Fully Closed" gate position, and a "Negative High High" power error value and a "Fully Open" gate position. A total of 15 rules are constructed to handle the start up from initial conditions, some examples are as follows:

IF *Power Error* is **PHH** AND *Gate Position* is **FC THEN** *Gate Control* is **MAX**

IF *Power Error* is **PHH** AND *Gate Position* is **MIN THEN** *Gate Control* is **MAX**

IF *Power Error* is **PSS** AND *Gate Position* is **FC THEN** *Gate Control* is **SS**

IF *Power Error* is **NHH** AND *Gate Position* is **FO THEN** *Gate Control* is **MIN**

IF *Power Error* is **NSS** AND *Gate Position* is **FO THEN** *Gate Control* is **HH**

4.7.2 Reach the Operational Zone Fuzzy Rules

The function of the *reach the operational zone* fuzzy rules is to pick up the load demand as quickly as possible by positioning the gate while temporarily neglecting the frequency error until the power error signal reaches and remains within the so-called "operational zone". Total 98 rules are constructed to handle this task, some examples are as follows:

IF *Power Error* is **PHH** AND *Gate Position* is **SS THEN** *Gate Control* is **MAX**

IF *Power Error* is **PM** AND *Gate Position* is **S THEN** *Gate Control* is **H**

IF *Power Error* is **PSS** AND *Gate Position* is **FC THEN** *Gate Control* is **SS**

IF *Power Error* is **NHH** AND *Gate Position* is **H THEN** *Gate Control* is **MIN**

IF *Power Error* is **NS** AND *Gate Position* is **H THEN** *Gate Control* is **M**

4.7.3 Inside the Operational Zone Fuzzy Rules

Once the turbine is inside the "operational zone", the function of the *inside the operational zone* fuzzy rules is to verify the frequency error signal and convert it to a correction in the present gate position through a partial output control signal called "gate control delta". A total of 112 rules are constructed to handle this task, some examples are as follows:

IF *Power Error* is **OZ** AND *Frequency Error* is **NHH** AND *Gate Position* is **MS THEN** *Gate Control* is **MS** AND *Gate Control Delta* is **NH**

IF *Power Error* is **OZ** AND *Frequency Error* is **NSS** AND *Gate Position* is **MH THEN** *Gate Control* is **MH** AND *Gate Control Delta* is **NSS**

IF *Power Error* is **OZ** AND *Frequency Error* is **OZ** AND *Gate Position* is **HH THEN** *Gate Control* is **HH**

IF *Power Error* is **OZ** AND *Frequency Error* is **PSS** AND *Gate Position* is **S THEN** *Gate Control* is **S** AND *Gate Control Delta* is **PSS**

IF *Power Error* is **OZ** AND *Frequency Error* is **PHH** AND *Gate Position* is **H THEN** *Gate Control* is **H** AND *Gate Control Delta* is **PH**

4.8 Simulation of Fuzzy Turbine Governor

The design of the fuzzy governor was implemented in Matlab and fuzzy governor-hydraulic turbine simulation models were produced. The aim of this simulation work was to demonstrate the performance of the fuzzy governor compared with a PID governor under nonlinear process conditions. The Matlab simulation models with their physical parameters are attached in Appendix B.

4.8.1 Performance of Fuzzy Governor Versus PID Governor

A simulation model was implemented in Matlab based on the turbine nonlinear model which developed in section 3.2.2 and shown in Figure 3.5, the designed fuzzy governor, and a PID governor are connected to a typical turbine model. The PID governor were tuned according to refrences [Sanathanan1987 et al. IEEE1992]. The simulation results are shown in Figures 4.11 – 4.12 and presented as follows:

- Figure 4.12 shows the characteristics of the power error signal for both of the fuzzy and PID governors in response of a load demand of 50% at steady state head conditions. The fuzzy governor shows much faster response, it has quickly reached its operational zone as designed, and reached steady state conditions and remained inside the operational zone awaiting a frequency error regulation, if any, which leads to a stable power generation as shown in Figure 4.11.
- The PID governor shows higher overshoots before reaching steady state conditions with much slower settling time. These are reflected in the generated power as shown in Figure 4.11.

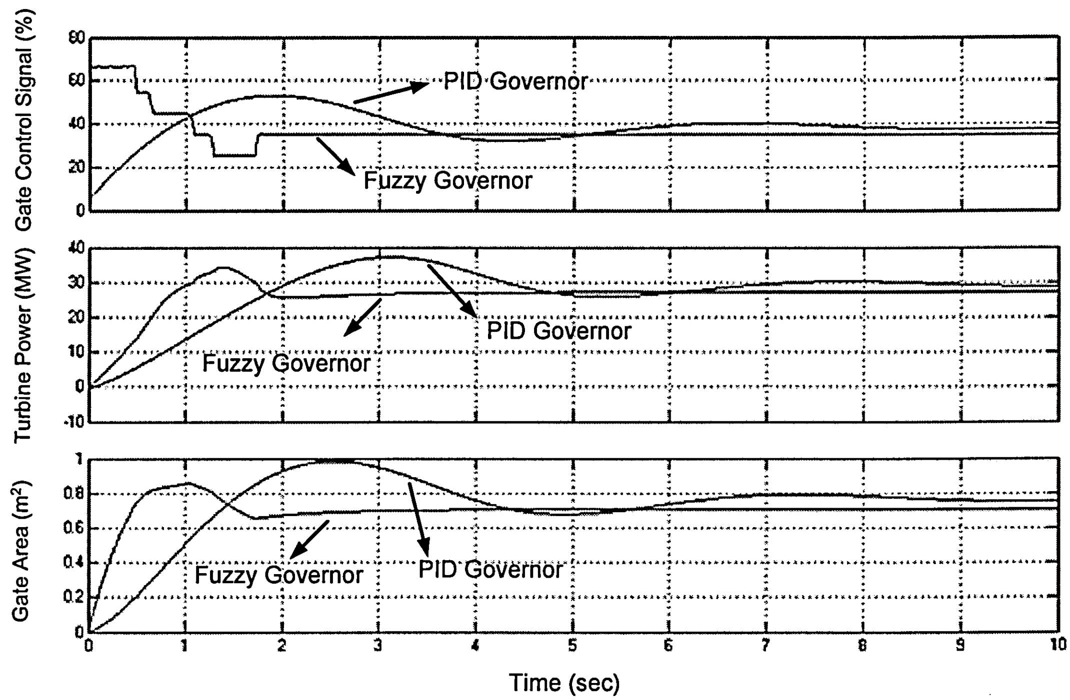


Figure 4.11 Performance of fuzzy governor versus PID governor

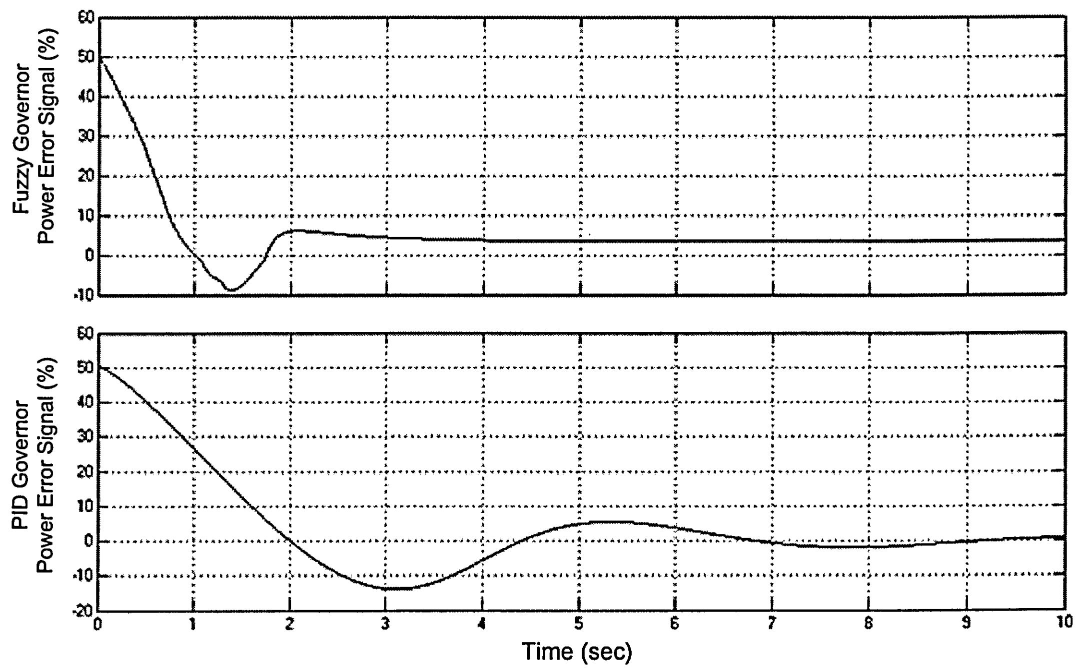


Figure 4.12 Fuzzy and PID governors' power error signal characteristics

4.8.2 Response to Disturbance

In this simulation, the fuzzy and PID governors are subjected to a disturbance signal (water hammer) under dynamical head conditions. The simulation results are shown in Figures 4.13 – 4.15 and presented as follows:

- Figure 4.14 shows the characteristics of the power error signal for both the fuzzy and PID governors in response to a load demand of 65% at dynamical head conditions and in response to a disturbance signal (water hammer). Again, the fuzzy governor shows much faster response, it has quickly reached its operational zone as designed and responded to water hammer by steady oscillations but remained inside the operational zone without overshoots awaiting a frequency error regulation, if any, which leads to steady power generation with much fewer oscillations around the set point as shown in Figure 4.13.

- The PID governor shows continuous oscillations with higher overshoots and did not reach steady state conditions, which are reflected on the turbine's highly disturbed head and flow rate as shown in Figure 4.15 and the generated power as shown in Figure 4.13.

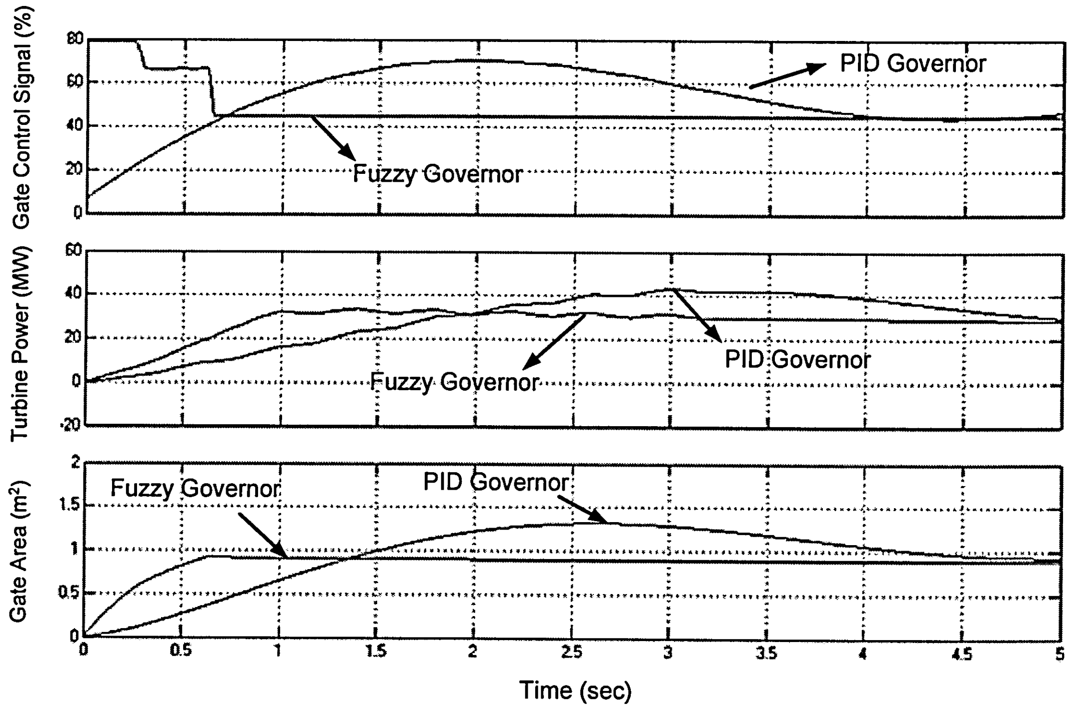


Figure 4.13 Fuzzy and PID governors' response to a disturbance signal

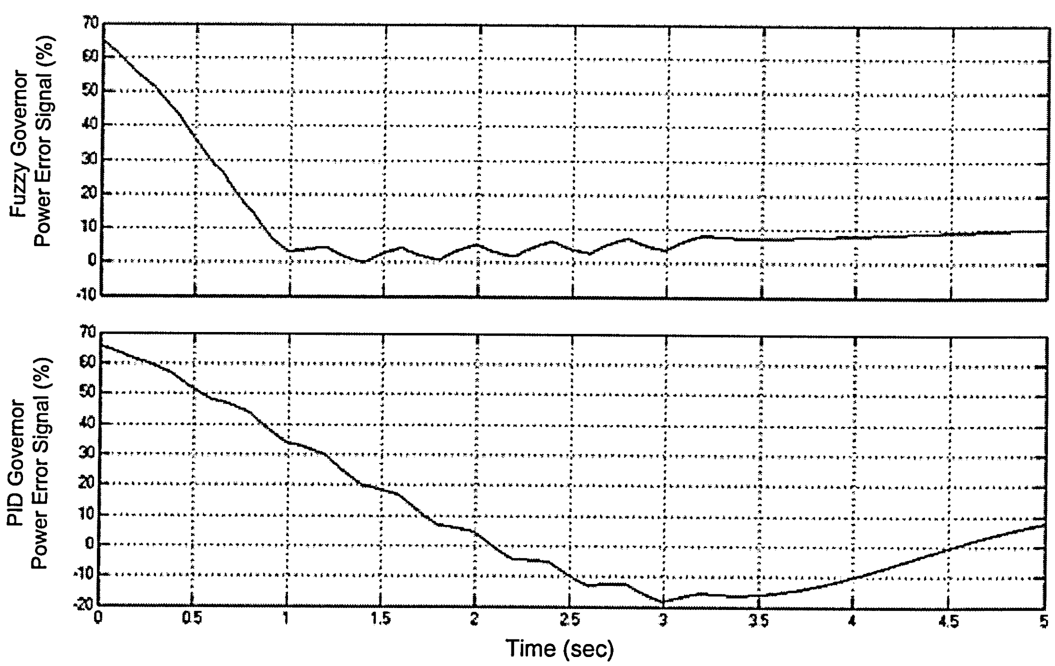


Figure 4.14 Fuzzy and PID governors' power error signal characteristics under disturbance

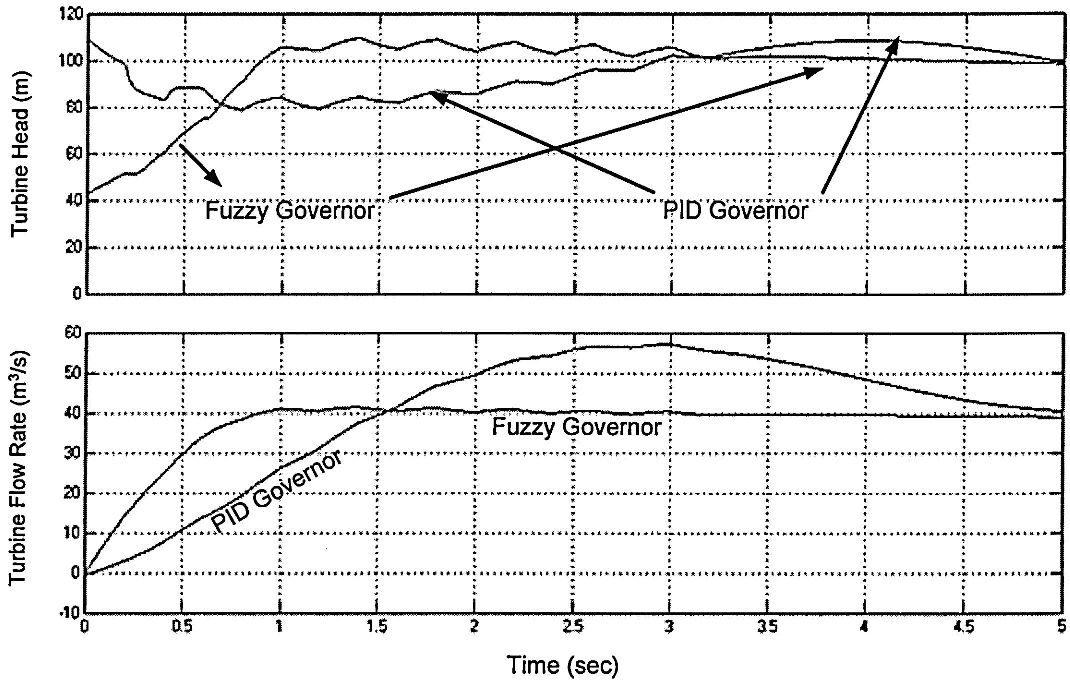


Figure 4.15 Turbine head and flow rate under disturbance for both Fuzzy and PID governors' control

4.9 Conclusions

- A new fuzzy logic turbine governor is designed and simulated that may replace the classical PID turbine governors and be capable of controlling the hydraulic turbine, together with its penstock, under nonlinear process conditions. The fuzzy governor comprises three inputs and two outputs, and 226 control rules distributed between three control layers.

- The fuzzy governor shows faster response and settling times. It shows more stable performance under both the steady state head and variable dynamical head conditions. It can achieve asymptotic stability under disturbances.

CHAPTER 5 FUZZY CONTROLLER FOR THREE HYDRAULICALLY COUPLED TURBINES

5.1 Introduction

In the light of the modelling and simulation work presented in sections 3.2.3 and 3.3.6, the hydraulic coupling between the turbines of a power house makes the disturbances in one turbine transferable to neighbouring turbine units. This may destabilize the power plant and transfer oscillations to the power grid, where the electrically coupled power houses will see those oscillations as changes in the load demand which may destabilize the cascaded hydro power plant. In this chapter a single fuzzy controller is designed and implemented exclusively to control together three hydraulically coupled turbines under nonlinear process conditions. It is able to compensate the deviation errors due to the hydraulic interaction. The fuzzy controller can be used as a local control system for any of the power houses within the cascaded hydropower plant. It is designed according to an "expert knowledge base" which was gathered by the intensive literature review of Chapter 2 and the modelling and simulation results of Chapter 3. A governing control fuzzy rule set of a turbine is constructed based on the expert knowledge base presented in section 4.3. Therefore, each fuzzy rule set is a fuzzy governor by itself as per the one designed and implemented in Chapter 4. That's why some parts of Chapter 4 are repeated in this Chapter in order to keep the sequence of the design methodology.

5.2 The Design Methodology

In order to design the fuzzy controller, the following tasks are formulated and implemented.

- To formulate an "expert knowledge base" on hydraulic turbine governing control, its nonlinear dynamics and its operational modes and the effect of hydraulic coupling. Presented in section 5.3.

- To select an appropriate model of hydraulically coupled turbines, and to create its control strategy. Presented in section 5.4.

- To identify the inputs and outputs of the fuzzy controller and to formulate their scaling factors and their fuzzy linguistic variables. Presented in section 5.5.

- To create the fuzzy membership functions for the inputs and outputs which satisfy the hydraulically coupled turbines' control strategy. Presented in section 5.6.

- To construct the rule base that converts the "expert knowledge base" into control actions covering all of the turbines' operational modes and executing their control strategy. Presented in section 5.7.

- Implement the fuzzy controller in Matlab and carry out simulations to obtain results. Presented in section 5.8.

5.3 Formulation of Expert Knowledge Base

To design a fuzzy controller reliable and smart enough to service simultaneously three hydraulically coupled turbines under nonlinear process conditions, the design has to rely not only on accurate turbine modelling, but also on an "expert knowledge base". The expert knowledge base comprises technical information on hydraulic turbine operation and control gathered from expert people who work in this field, reported and or published articles, field trials, simulation and predictions. It may also cover some hidden dynamics not modelled. The formulated expert knowledge supporting the design of the fuzzy controller may be summarised as follows:

1. The fuzzy rules are evaluated and processed in parallel; therefore, the fuzzy controller of the three hydraulically coupled turbines may contain three built in fuzzy rule sets working in parallel, one set for each turbine unit governing control. A governing control fuzzy rule set of a turbine is constructed based on the expert knowledge base presented in section 4.3. Therefore, each fuzzy rule set is a fuzzy governor by itself as per the one designed and implemented in Chapter 4.

2. The deviation error due to hydraulic coupling is caused by the gate positioning of one turbine which may rapidly increase or decrease the head at the other hydraulically coupled turbines' admissions. Accordingly, these turbines' control systems will respond by correcting their own gate positions which in turn may re-affect the other hydraulically coupled turbines. These actions if not accounted for, may destabilize the hydropower plant.

3. The fuzzy control system should respond quickly to load demand for each turbine unit and compensate deviation errors due to the hydraulic interaction from neighbouring turbine units, and quickly reach steady state conditions for each turbine.

4. The turbines may be subject to different load demands and may operate at different individual set points.

5. To design a control strategy that exclusively compensates for the deviation errors due to hydraulic coupling, a plant trial should be undertaken to determine the deviation error values on each turbine due to the gate positions of other turbines, or alternatively a simulation test can be undertaken as presented in section 3.3.6.

6. For the control system to be able to detect a rapid change in a gate's position, new inputs will be added to the system which are the gate rate of change (dG/dt) for each turbine in the plant.

5.4 The Control Strategy

The three hydraulically coupled turbines are represented by the nonlinear model developed in section 3.2.3 and shown in Figure 3.7 which combines all of the three turbines'-penstocks' dynamics with the heads at turbines' admissions, turbines' flow rates and the losses in water heads due to friction. In accordance with the "expert knowledge base" presented in section 5.3, it was decided to follow a multilayered control strategy comprising four control layers and illustrated in Figure 5.1 that may be classified as follows:

- *Start up from initial conditions:* Based on the fact that nonlinear systems are sensitive to initial conditions and to limit a false turbine gate opening when starting up from initial conditions, exclusive start up fuzzy rules are added for each turbine to form the first layer of control.

- *Reaching the operational zone:* Once the turbines are started up, the system immediately responds to load demands by evaluating the power error signal for each turbine and temporarily neglects the frequency error signal until the so called "Operational Zone" has been reached for each turbine. This picks up the load demand as quickly as possible by positioning the gate until the power error is minimised to a preset value, for each turbine. The operational zone is a virtually defined area on the universe of discourse, set between the two membership functions of "*Power Error Positive Small Small*" and "*Power Error Negative Small Small*" and surrounding the zero power error value by a membership function "OZ". So, the resultant crisp operational zone for each turbine will always be the zone bounded by $\pm 5\%$ power error margins with a central value (*optimal operational zone crisp value*) bounded by $\pm 1.75\%$. The boundaries of the operational zone are set according to the desired permanent droop setting which is defined in sections 2.4 and 4.3, it is normally from 0-6%, and in this design the 5% permanent droop setting is considered. As long as the fuzzy controller is carrying out control to keep each turbine operating or steadily oscillating within the operational zone, the controlled process becomes asymptotically stable (In the sense of Liapunov second method of stability analysis of nonlinear systems [Dutton 1997 et al. Ogata1997]). Once the fuzzy controller has reached the "Operational Zone" it will start, if a frequency error exists, the frequency regulation and it will continue carrying out efforts to keep each turbine operating or steadily oscillating within its optimal operational zone defined above. Here, the controlled process becomes stable. This task is handled for each turbine by an exclusive set of fuzzy rules and an output signal called "Gate Control" which will form the second layer of control.

- *Inside the operational zone:* Once each turbine is operating inside its "Operational Zone", the system will verify the frequency error signal and convert it into corrections in the present gate position of each turbine through a partial output control signal called "Gate Control Delta". As long as the frequency error is always corrected while each turbine is still operating inside its "Operational Zone", the controlled process becomes stable. This task is handled by an exclusive set of fuzzy rules for each turbine and an output signal called "Gate Control Delta" which will form the third layer of control.

- *Hydraulic interaction compensation:* The control system expects to see the deviation errors caused by other hydraulically coupled turbine units as changes in the dynamical head and according to the second control layer above, the control system will correct those errors. However, large deviation errors due to hydraulic coupling may take place during the start up or shutdown of a turbine, due to a large change in a turbine's operational set point, or a rapid and large change in a turbine's load demand; which all lead to large and rapid changes in a turbine's gate position that affect the other hydraulically coupled turbines in the plant. Therefore, a feed forward error compensator would be required for each turbine control exclusively available for rapid compensation of deviation errors caused only by large and rapid changes in a turbine gate's position. This is achieved by constructing an exclusive and parallel fuzzy rule set, and by modifying the output signal "Gate Control Delta" for each turbine to include two new fuzzy membership functions called "Compensation Negative" and "Compensation Positive" which are set to release a maximum ±15% gate position correction signal if and only if a large and rapid gate position change is detected at any of the plant's turbine units. To detect a large and rapid gate position change, three input signals are added to the fuzzy controller, which are the gate rates of change (dG/dt) for each turbine. As soon as a large and rapid change in the gate position at any of the turbines is detected, the fuzzy controller will issue immediate compensation signals (feed forward) to the neighbouring gates that will help reduce the disturbance time cycle until the power regulation fuzzy rules pick up the new changes, regulate them and reach steady state conditions. This task forms the fourth layer of control.

- *Gate-power nonlinear relationship:* The nonlinear relationship between the turbine's gate and its output power as illustrated in Figure 2.8, is accounted for in section 5.5 by exclusive scaling factors shown in Figure 5.2 and the "Reaching Operational Zone" fuzzy rules.

- *Fuzzy inferences system:* The Mamdani fuzzy inference method is the one selected for the development of the fuzzy turbine governor, as it provided more flexibility to implement the control strategy down the finest details.

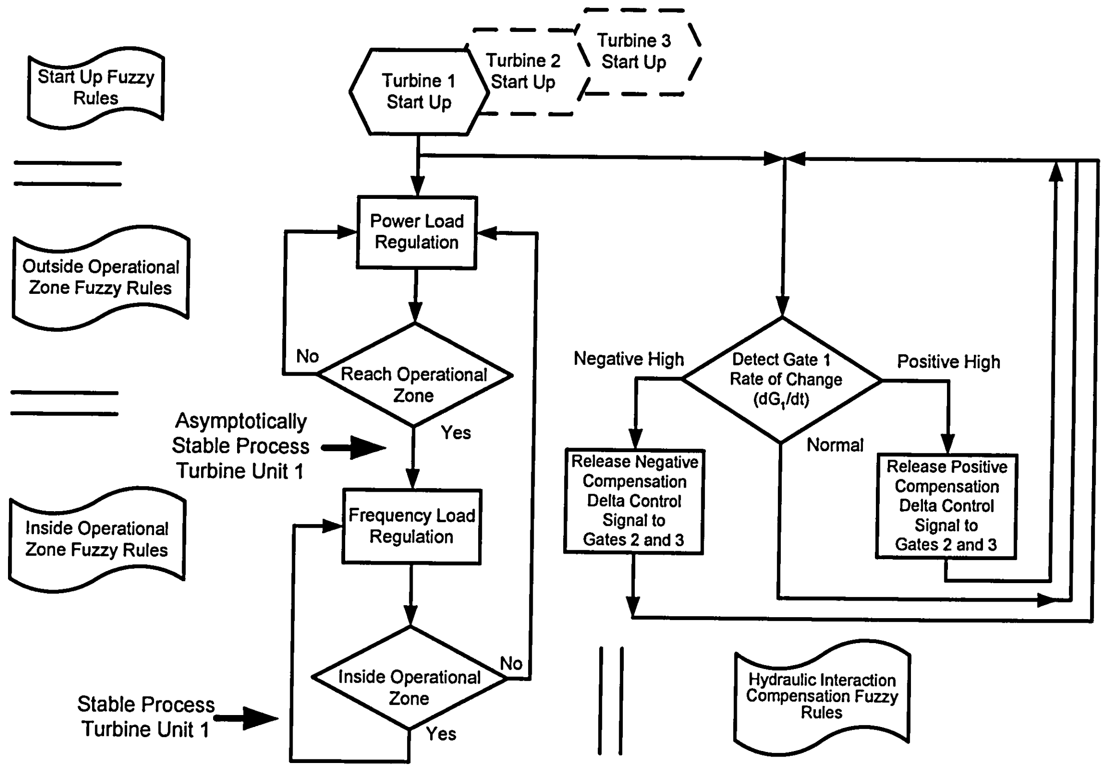


Figure 5.1 Control strategy of the three turbines' fuzzy controller

5.5 Inputs and Outputs of The Fuzzy Controller

A total of twelve inputs of the fuzzy controller is distinguished into three similar sets, one set for each turbine. Each set is formulated as follows:

- *Power error signal:* This is the deviation between the power set point (desired value) and the generated power feed back signal (load demand), its scaling factor is from -100% to +100%.
- *Frequency error signal:* This is the deviation between the frequency set point (desired value) and the grid frequency feed back signal (frequency demand normally from 49-50 Hz), its scaling factor is from -5% to +5%.
- *Gate position:* This is the turbine gate position feed back signal so that the fuzzy controller always knows the present gate position, its scaling factor is from 0% to +100%.
- *Gate rate of change (dG/dt):* This is the turbine gate position rates of change signal so that the fuzzy controller can detect rapid and large changes in a gate's position, its scaling factor -2 to +2 (m/s).

A total of six outputs of the fuzzy controller is distinguished into three similar sets, one set for each turbine. Each set is formulated as follows:

- *Gate control:* This is the turbine gate control signal; its scaling factor is from 0% to +100%.
- *Gate control delta:* This is a turbine's partial gate control signal which has two functions. Firstly, it corrects the gate position when a turbine's "Operational Zone" has been reached where only frequency regulation is allowed. Secondly, it is used as feed forward "Compensation Positive" and "Compensation Negative" signals. Its scaling factor is from -15% to +15%.

The scaling of the inputs and outputs of the fuzzy controller is shown in Figure 5.2; their fuzzy linguistic variables are defined in Table 5.1.

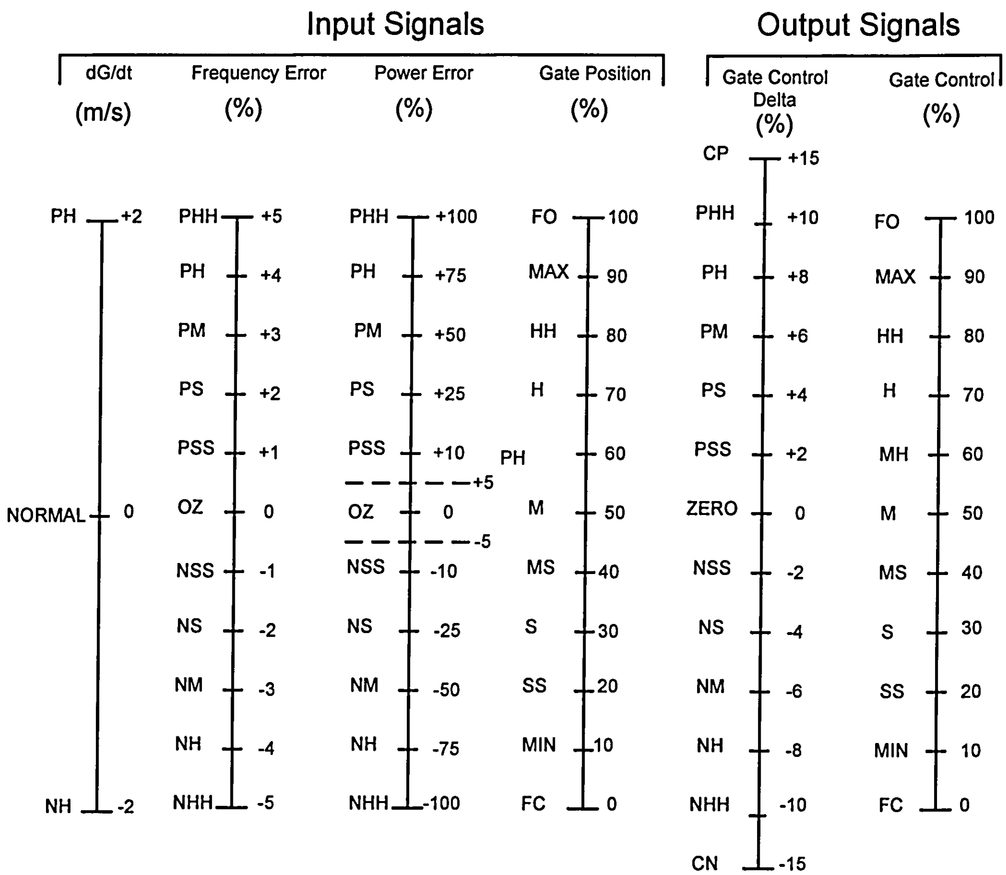


Figure 5.2 Scaling of the fuzzy controller inputs and outputs for each turbine

Linguistic Variable	*Definition*
PHH	Positive High High
PH	Positive High
PM	Positive Medium
PS	Positive Small
PSS	Positive Small Small
ZERO	0
NHH	Negative High High
NH	Negative High
NM	Negative Medium
NS	Negative Small
NSS	Negative Small Small
OZ	Operational Zone
FO	Fully Open
MAX	Maximum
HH	High High
H	High
MH	Medium High
M	Medium
MS	Medium Small
S	Small
SS	Small Small
MIN	Minimum
FC	Fully Closed
CP	Compensate Positive
CN	Compensate Negative

Table 5.1 Fuzzy controller linguistic variables' definitions

5.6 Fuzzy Controller Membership Functions

As explained in section 4.6, upon testing some numbers of gaussian and trapezoidal membership functions for this application, it was found that the fuzzification of all inputs and outputs in this application, each based on eleven triangular membership functions of sharp transitions with small intersection areas, achieved better results in terms of faster response and reduced oscillations. The exception is the new input *"Gate Position Rate of Change"*, for which trapezoidal membership functions are used in order to give an approximated indication of the present state of the rate of change signal. Also two trapezoidal membership functions "Compensation Negative" and "Compensation Positive" have been added to the "Gate Control Delta" in addition to the existing triangular ones in order to release an approximated feed forward compensation value of ± 12-15 %. The input and output membership functions of the fuzzy controller for each turbine control are formulated as follows:

- *Input 1 - power error signal*: As shown in Figure 5.3, this comprises eleven triangular membership functions with the operational zone "OZ" indicated in the middle.

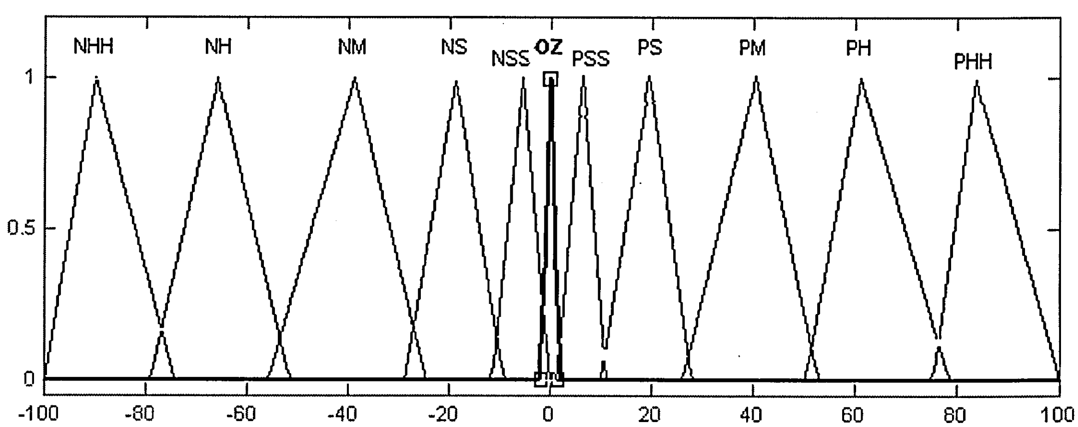


Figure 5.3 Power error- input membership functions

- *Input 2 - frequency error signal:* As shown in Figure 5.4, this comprises eleven triangular membership functions with a frequency operational zone "OZ" indicated in the middle.

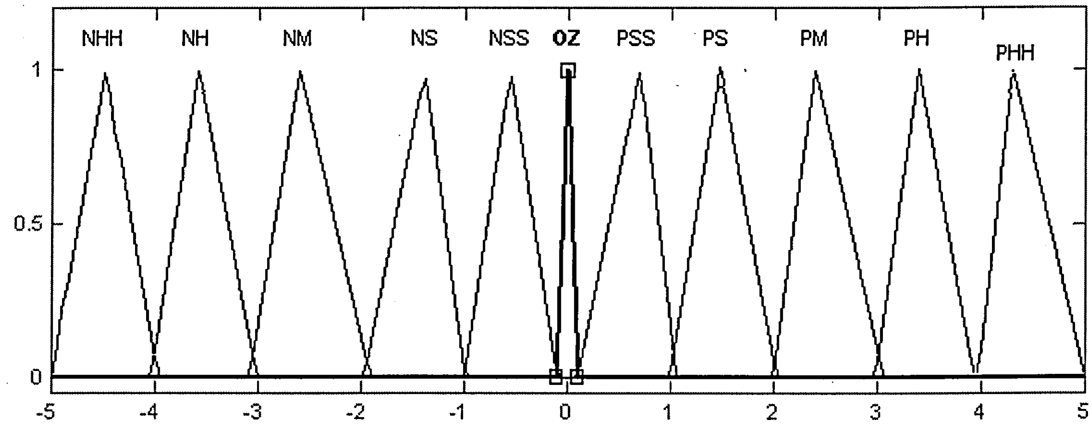


Figure 5.4 Frequency error- input membership functions

- *Input 3 - gate position:* As shown in Figure 5.5, this comprises eleven triangular membership functions. It represents the nonlinear characteristic of the turbine gate where the effective operational zone of the gate is from the position "MIN" to the position "MAX" which is ≈ 5-90%. The fully open position "FO" is used to indicate to the fuzzy governor that the gate exceeded it maximum operational zone. No control is allowed beyond this point so that saturation and winding up can be avoided. The fully closed position "FC" is kept very tight so that false and small gate opening can be detected.

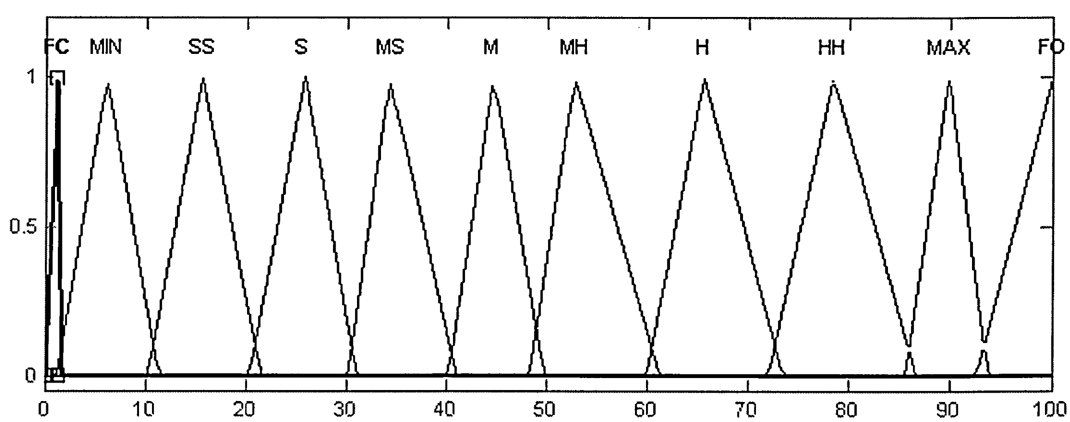


Figure 5.5 Gate position-input membership functions

- *Input 4 - gate position rate of change (dG/dt):* As shown in Figure 5.6, this comprises three trapezoidal membership functions. It distinguishes the detection of the gate position rate of change into three detection zones which are "Negative High" which means that the gate is rapidly closing, "Normal" which means that the gate position rate of change is within its predefined and allowed limits, and "Positive High" which means that the gate is rapidly opening.

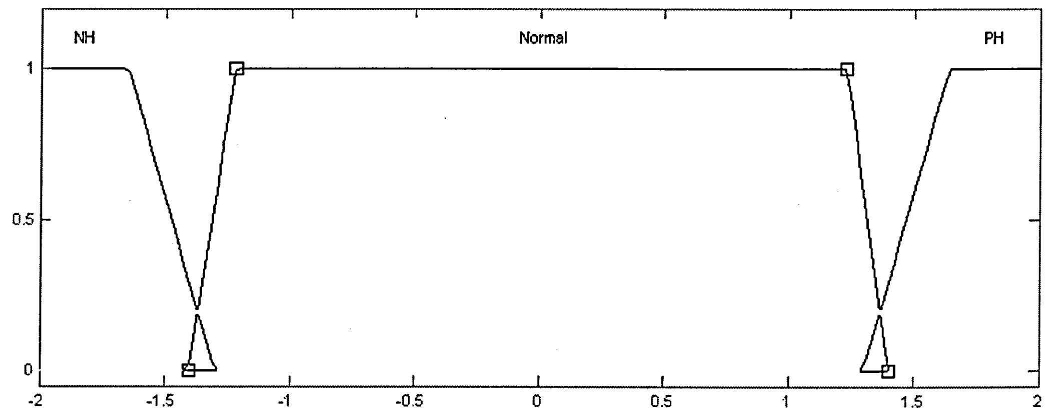


Figure 5.6 Gate position rate of change (dG/dt)

- *Output 1 - gate control:* As shown in Figure 5.7, this comprises eleven triangular membership functions. As will be noted the fully closed gate opening "FC" is different from the one in Figure 5.5. This is to prevent false gate opening.

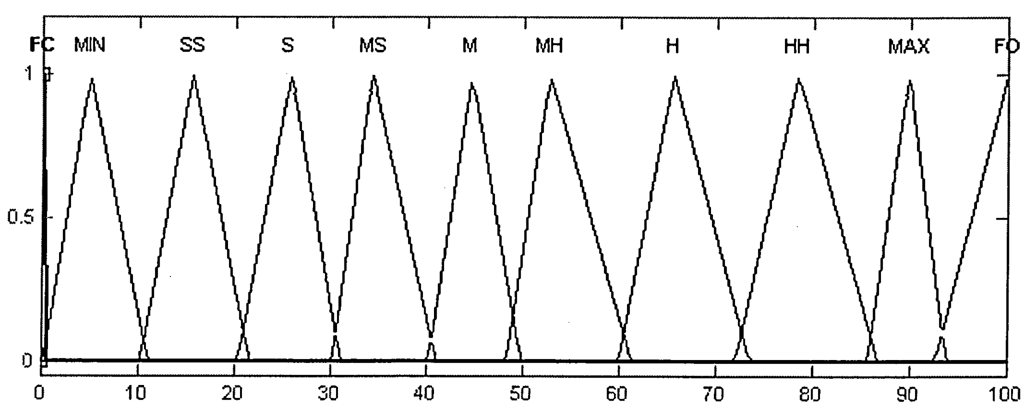


Figure 5.7 Gate control- output membership functions

- *Output 2 - gate control delta:* As shown in Figure 5.8, this comprises 13 membership functions, 11 triangular membership functions are exclusively used for frequency regulation and 2 trapezoidal ones are used for feed forward compensation.

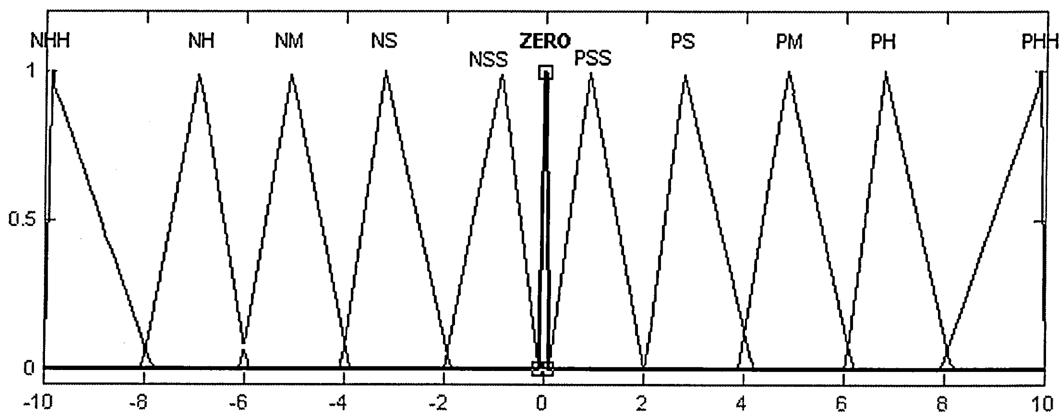


Figure 5.8 Gate control delta-output membership functions

5.7 Fuzzy Controller Rule Base

In the light of the "expert knowledge base" in section 5.3 and the control strategy of section 5.4, a fuzzy rule base comprising a total of 699 rules was constructed. The resultant fuzzy governor control surfaces that represent the controller dynamics are shown in Figures 5.9- 5.13. The constructed 699 control rules are listed in Appendix E and are classified in sections 5.7.1- 5.7.4.

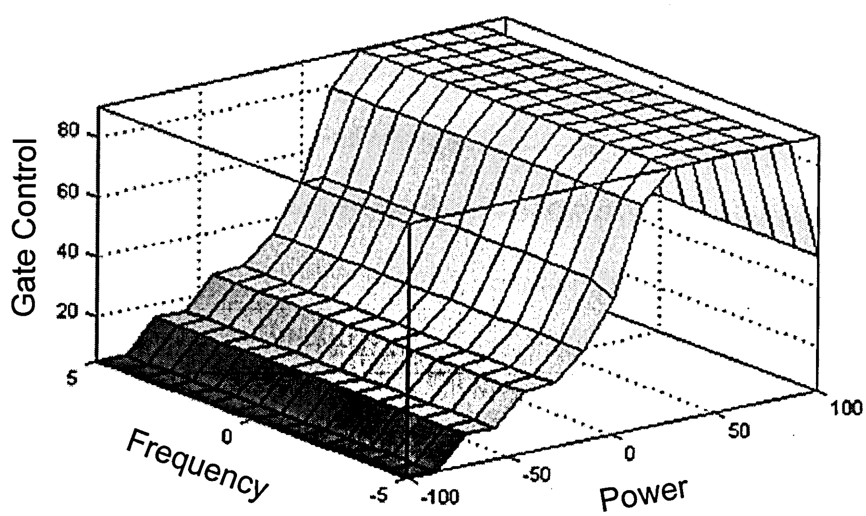


Figure 5.9 Fuzzy control surface power-frequency-gate control

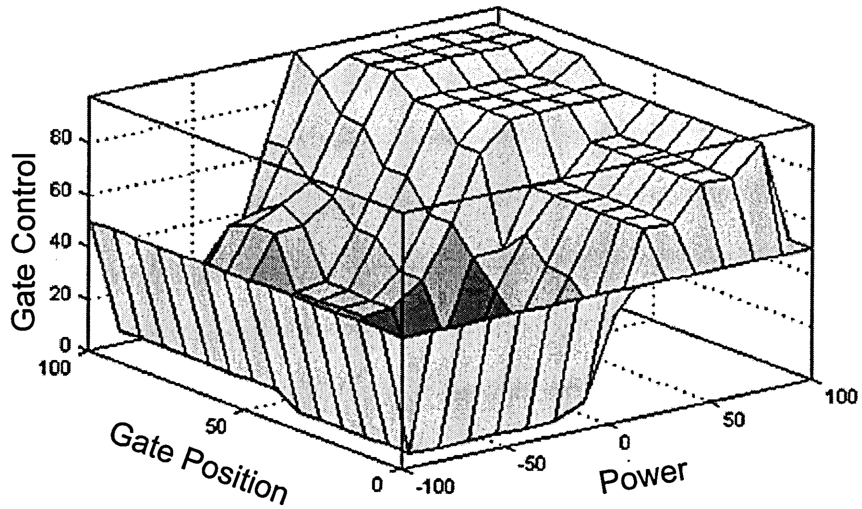


Figure 5.10 Fuzzy control surface power-gate position-gate control

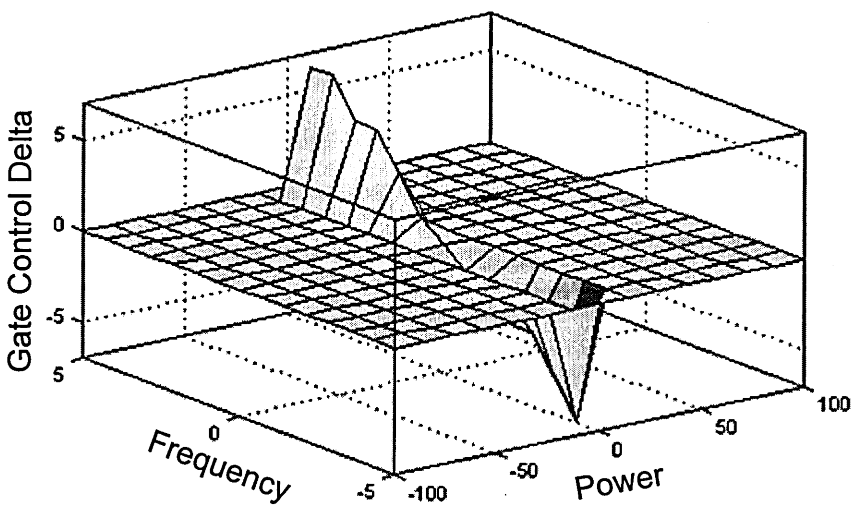


Figure 5.11 Fuzzy control surface power-frequency-gate control delta

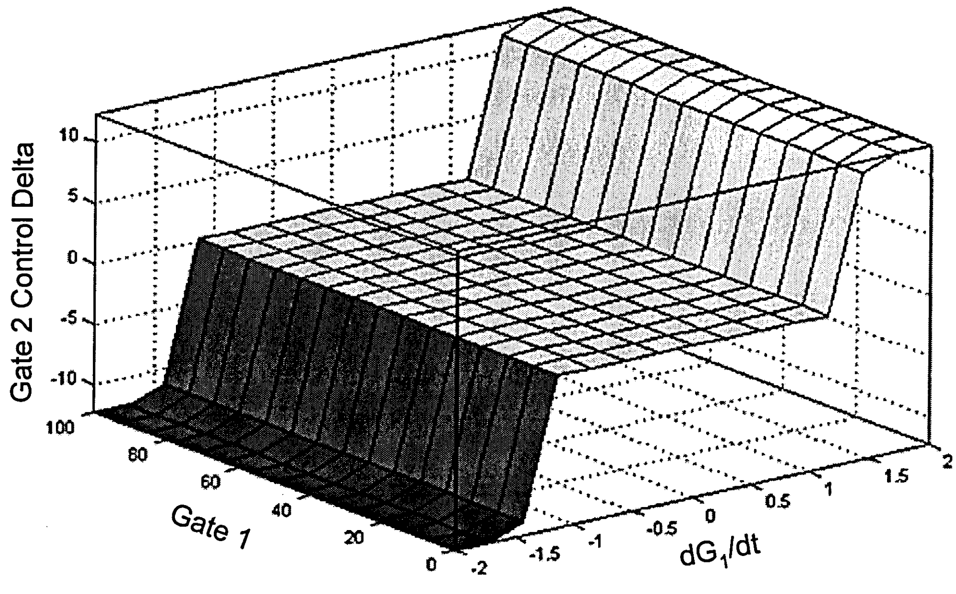


Figure 5.12 Fuzzy control surface gate 1 position - (dG_1/dt) - gate control delta 2

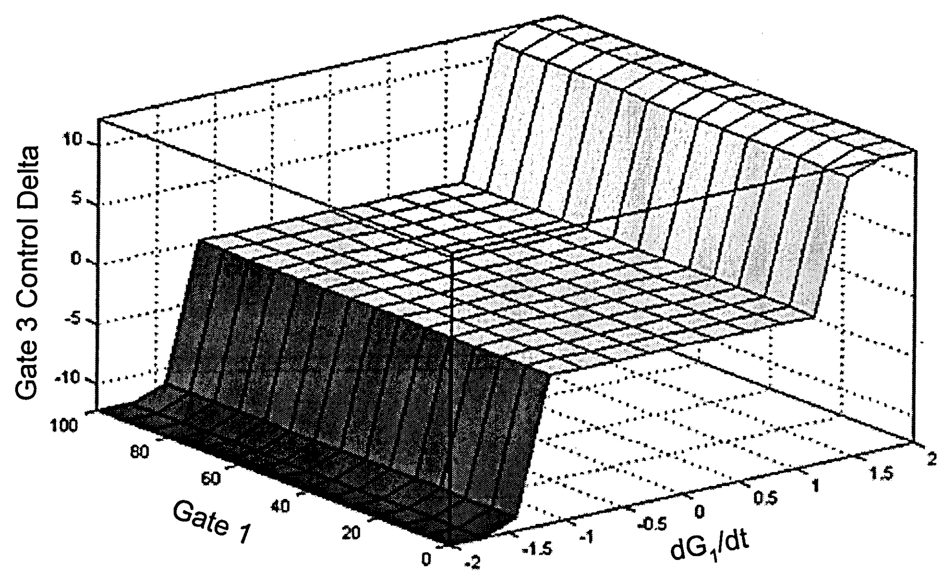


Figure 5.13 Fuzzy control surface gate 1 position - (dG_1/dt) - gate control delta 3

5.7.1 Start Up From Initial Conditions Fuzzy Rules

The function of the *start up from initial conditions* rules is to detect some combined unique conditions of the gate position with the power error which are exclusively available at the turbine start up and can not be available in any of the other operational modes, and to establish a quick response as soon as the turbine has started. One possibility is a "Positive High High" power error value and a "Fully Closed" gate position, or a "Negative High High" power error value and a "Fully Open" gate position. A total of 15 rules are constructed for each turbine to handle the start up from initial conditions, some examples are as follows:

IF *Power Error* is **PHH** AND *Gate Position* is **FC THEN** *Gate Control* is **MAX**

IF *Power Error* is **PHH** AND *Gate Position* is **MIN THEN** *Gate Control* is **MAX**

IF *Power Error* is **PSS** AND *Gate Position* is **FC THEN** *Gate Control* is **SS**

IF *Power Error* is **NHH** AND *Gate Position* is **FO THEN** *Gate Control* is **MIN**

IF *Power Error* is **NSS** AND *Gate Position* is **FO THEN** *Gate Control* is **HH**

5.7.2 Reach the Operational Zone Fuzzy Rules

The function of the *reach the operational zone* fuzzy rules is to pick up the load demand as quickly as possible by positioning the gate while temporarily neglecting the frequency error until the power error signal reaches and remains within the so called "Operational Zone". A total of 98 rules are constructed for each turbine to handle this task, some examples are as follows:

IF *Power Error* is **PHH** AND *Gate Position* is **SS THEN** *Gate Control* is **MAX**

IF *Power Error* is **PM** AND *Gate Position* is **S THEN** *Gate Control* is **H**

IF *Power Error* is **PSS** AND *Gate Position* is **FC THEN** *Gate Control* is **SS**

IF *Power Error* is **NHH** AND *Gate Position* is **H THEN** *Gate Control* is **MIN**

IF *Power Error* is **NS** AND *Gate Position* is **H THEN** *Gate Control* is **M**

5.7.3 Inside the Operational Zone Fuzzy Rules

Once the turbine is operating inside the "Operational Zone", the function of the *inside the operational zone* fuzzy rules is to verify the frequency error signal and convert it to a correction to the present gate position through a partial output control signal called "Gate Control Delta". A total of 112 rules are constructed for each turbine to handle this task, some examples are as follows:

IF *Power Error* is **OZ** AND *Frequency Error* is **NHH** AND *Gate Position* is **MS THEN** *Gate Control* is **MS** AND *Gate Control Delta* is **NH**

IF *Power Error* is **OZ** AND *Frequency Error* is **NSS** AND *Gate Position* is **MH THEN** *Gate Control* is **MH** AND *Gate Control Delta* is **NSS**

IF *Power Error* is **OZ** AND *Frequency Error* is **OZ** AND *Gate Position* is **HH THEN** *Gate Control* is **HH**

IF *Power Error* is **OZ** AND *Frequency Error* is **PSS** AND *Gate Position* is **S THEN** *Gate Control* is **S** AND *Gate Control Delta* is **PSS**

IF *Power Error* is **OZ** AND *Frequency Error* is **PHH** AND *Gate Position* is **H THEN** *Gate Control* is **H** AND *Gate Control Delta* is **PH**

5.7.4 Hydraulic Interaction Compensation Fuzzy Rules

As soon as a rapid and large gate position rate of change is detected from one of the turbines, the compensation fuzzy rules will issue the feed forward compensation signals to the other turbines' gates. Total 6 rules are constructed to handle this task as follows:

IF *(dG_1/dt)* is **PH THEN** *Gate Control Delta 2* is **CP** AND *Gate Control Delta 3 is* **CP**

IF *(dG_1/dt)* is **NH THEN** *Gate Control Delta 2* is **CN** AND *Gate Control Delta 3 is* **CN**

IF *(dG_2/dt)* is **PH THEN** *Gate Control Delta 1* is **CP** AND *Gate Control Delta 3 is* **CP**

IF *(dG_2/dt)* is **NH THEN** *Gate Control Delta 1* is **CN** AND *Gate Control Delta 3 is* **CN**

IF *(dG_3/dt)* is **PH THEN** *Gate Control Delta 1* is **CP** AND *Gate Control Delta 2 is* **CP**

IF *(dG_3/dt)* is **NH THEN** *Gate Control Delta 1* is **CN** AND *Gate Control Delta 2 is* **CN**

5.8 Simulation of Fuzzy Controller

The design of the fuzzy controller was implemented in Matlab and Simulink, and the fuzzy controller-three hydraulically coupled turbines' simulation models were produced. The aim of this simulation work was to present the performance of the fuzzy controller and demonstrate its response to the hydraulic coupling problem under nonlinear process conditions. The Simulink models with their physical parameters are attached in Appendix C.

5.8.1 Performance of the Fuzzy Controller

A simulation model was implemented in Matlab connecting the fuzzy controller to the three hydraulically coupled turbines based on their nonlinear models developed in section 3.2.3 and shown in Figure 3.7. The simulation results are shown in Figures 5.14 – 5.18 and presented as follows:

- The turbines are set at different operational set points (Turbine 1 at 60%, Turbine 2 at 50%, and Turbine 3 at 45%). Figure 5.14 shows the characteristics of the power error signal for each turbine where the fuzzy controller has successfully operated each turbine at its designated set point and the steady state condition has rapidly been reached for each turbine, this is done via the built in "Reach Operational Zone" parallel turbines' fuzzy rules. As expected, the settling time and overshoots are different for each turbine because they are operating at different set points, and due to the hydraulic coupling compensation, especially at start up conditions. This is reflected in the generated power from each turbine as shown in Figure 5.15, in the turbines' heads as shown in Figure 5.16, and in the turbines' flow rates as shown in Figure 5.17.

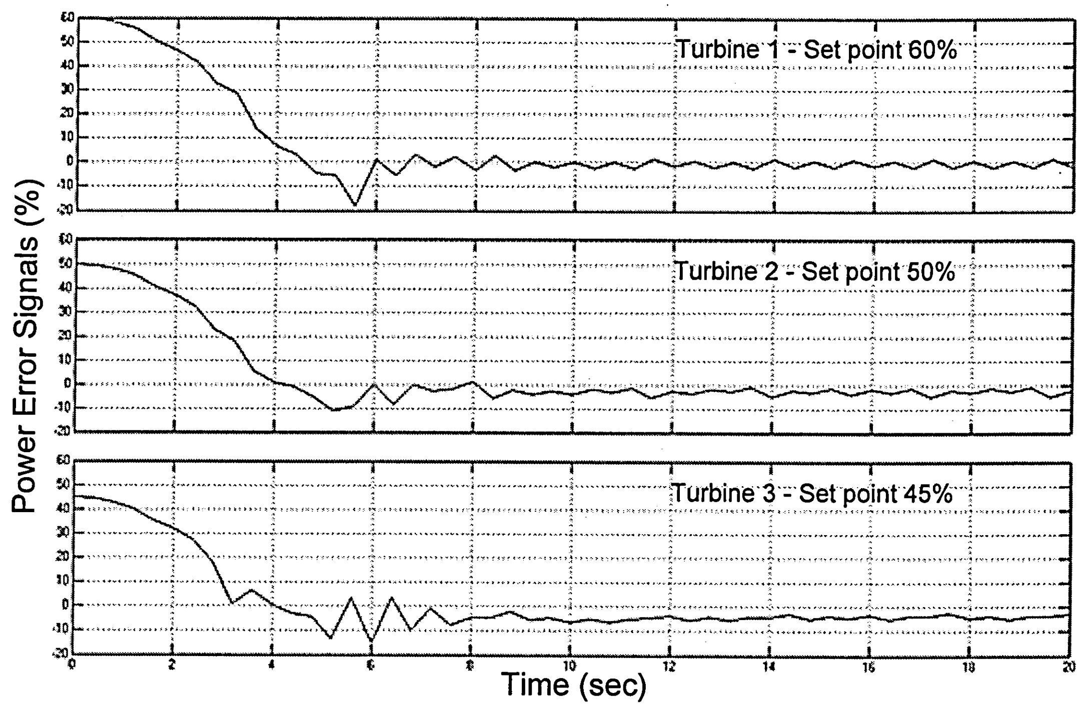


Figure 5.14 The three hydraulically coupled turbines' power error signals under fuzzy control

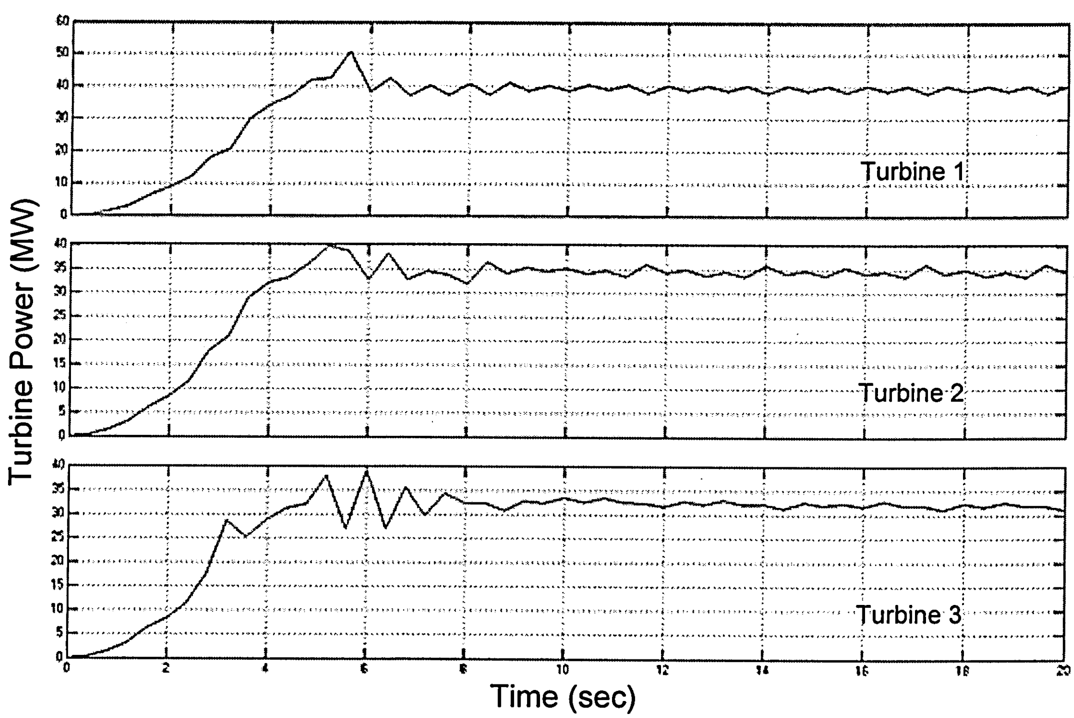


Figure 5.15 The three hydraulically coupled turbines' output powers under fuzzy control

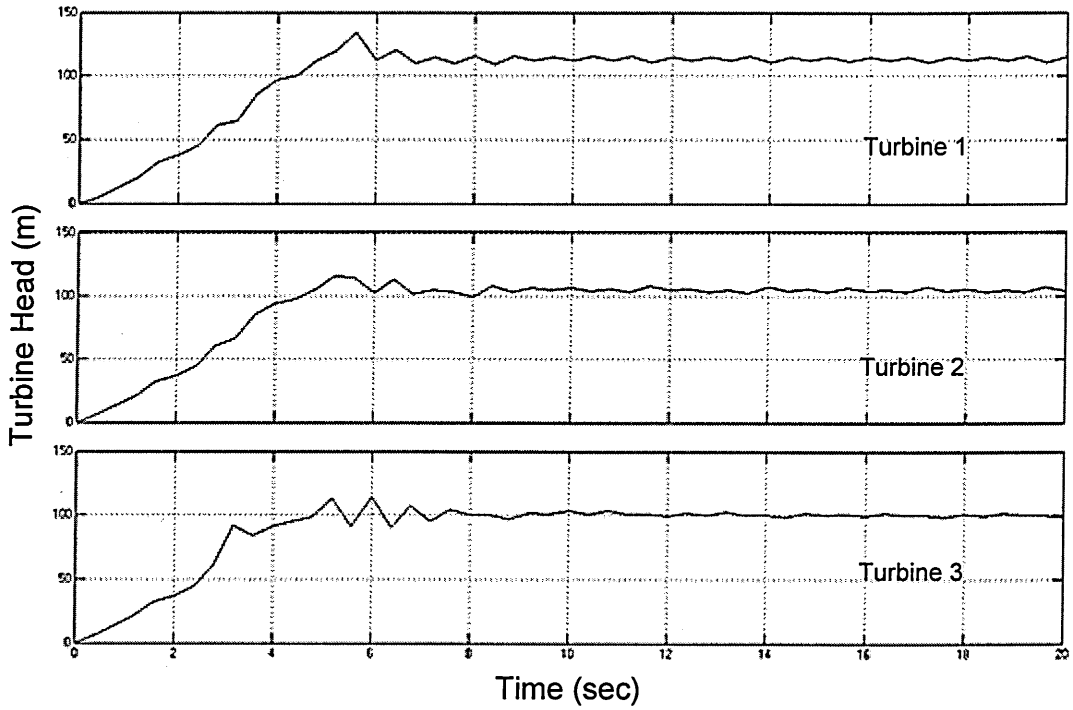


Figure 5.16 The three hydraulically coupled turbines' heads under fuzzy control

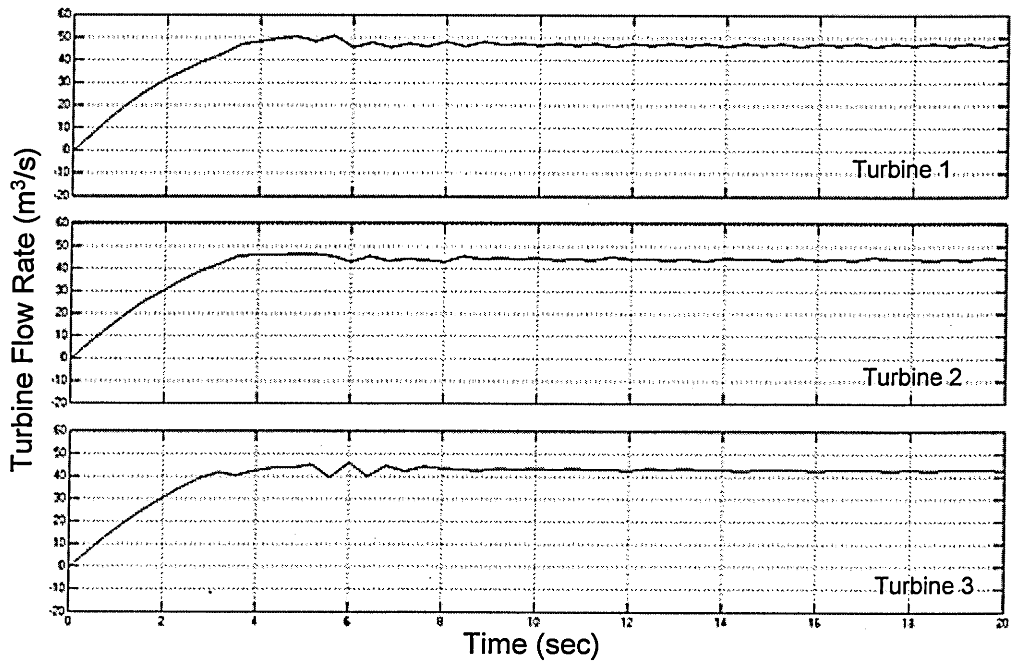


Figure 5.17 The three hydraulically coupled turbines' flow rates under fuzzy control

- Figure 5.18 shows the detected gate position rate of change for each turbine which is highest at start up, decreasing afterwards until it reaches and remains at zero at the steady state conditions.

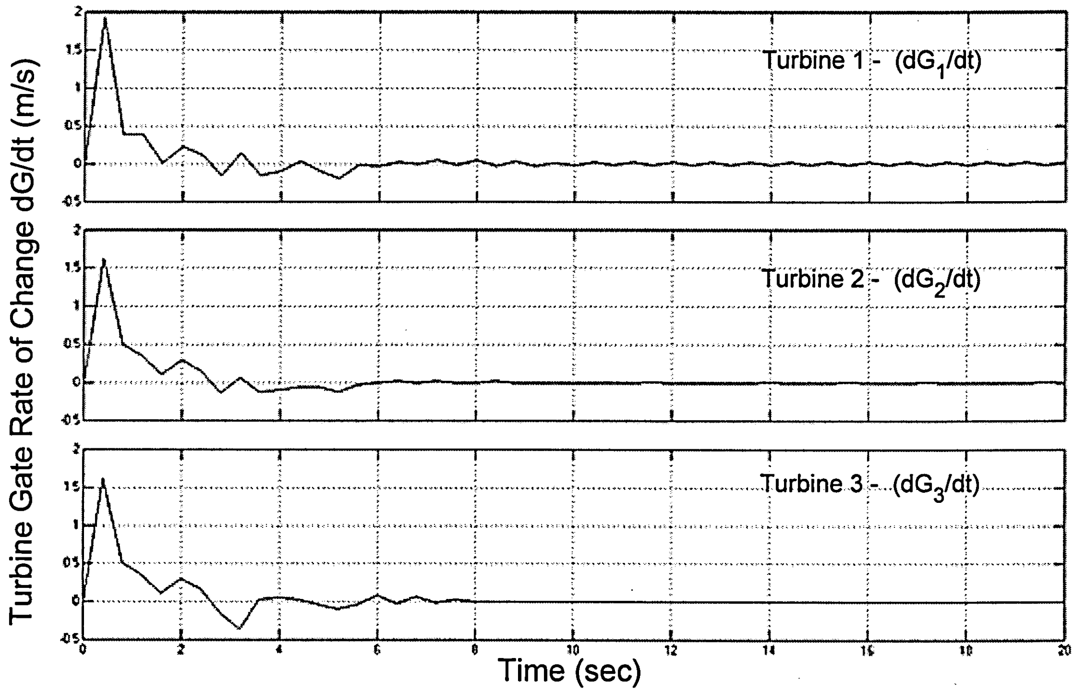


Figure 5.18 The three hydraulically coupled turbines' gates rate of change

5.8.2 Hydraulic Coupling Compensation

In this simulation, turbine 2 has been subjected to a disturbance signal (its operational set point has rapidly dropped from 60% to 20 %) under dynamical head conditions. The simulation results are shown in Figures 5.19, 5.20 where the fuzzy controller has successfully compensated the deviation errors due to hydraulic coupling on both of turbines 1 and 3, and has reached the steady state condition for all of the three turbines. As indicated in Figure 5.20, the effect of the feed forward compensation at turbines 1 and 3 is obvious as turbine 2 set point has dropped rapidly from 60% to 20%, and according to the "Reach Operational Zone Rules" a rapid power regulation has taken place, accordingly its gate position has rapidly dropped towards the close position which decreases the head at the turbine admission while increasing the heads on turbine 1 and 3 admissions. Here, and according to the "Reach Operational Zone Fuzzy Rules" of turbines 1 and 3, the normally expected actions of gates 1 and 3 are to rapidly move towards the close position in order to cope with the rapid increase in water heads which will normally lead to a drop in their (turbines 1 and 3) output powers. But, due to the successful feed forward compensation actions of the "Hydraulic Coupling Compensation Fuzzy Rules", as shown in figure 5.20, we see a moderate increase in turbine 1 and 3 output powers instead of a decrease during a so called *compensation cycle*, followed by a so called *regulation cycle.* Then normal operation continues.

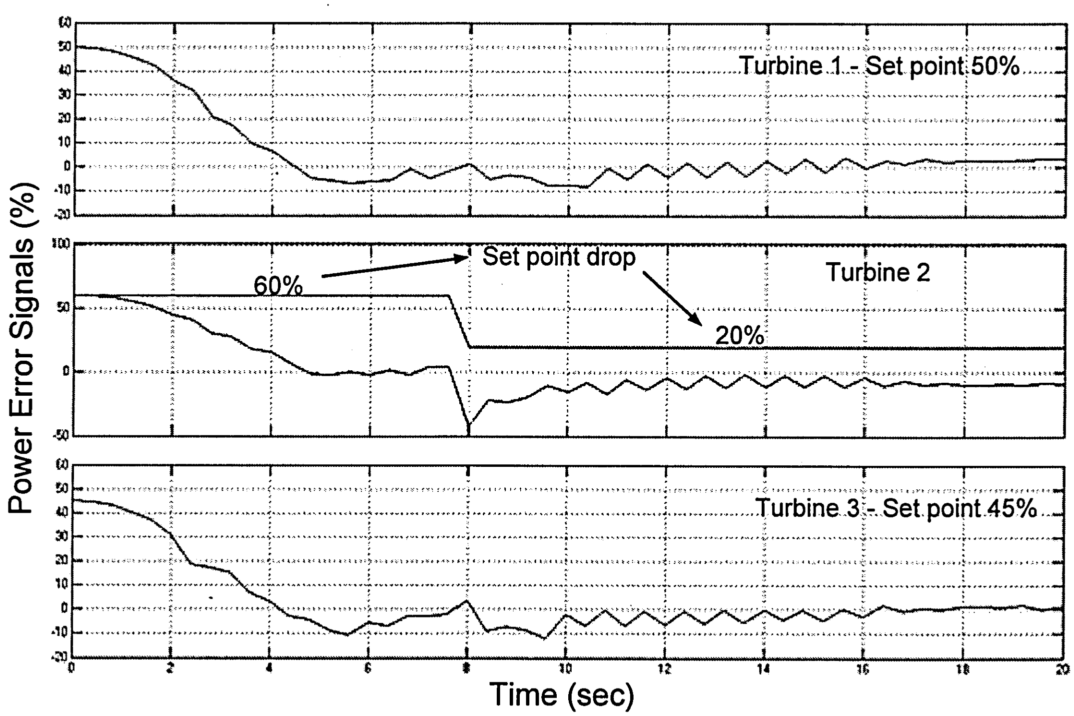


Figure 5.19 Fuzzy controller-Turbines' error signals under hydraulic coupling disturbance

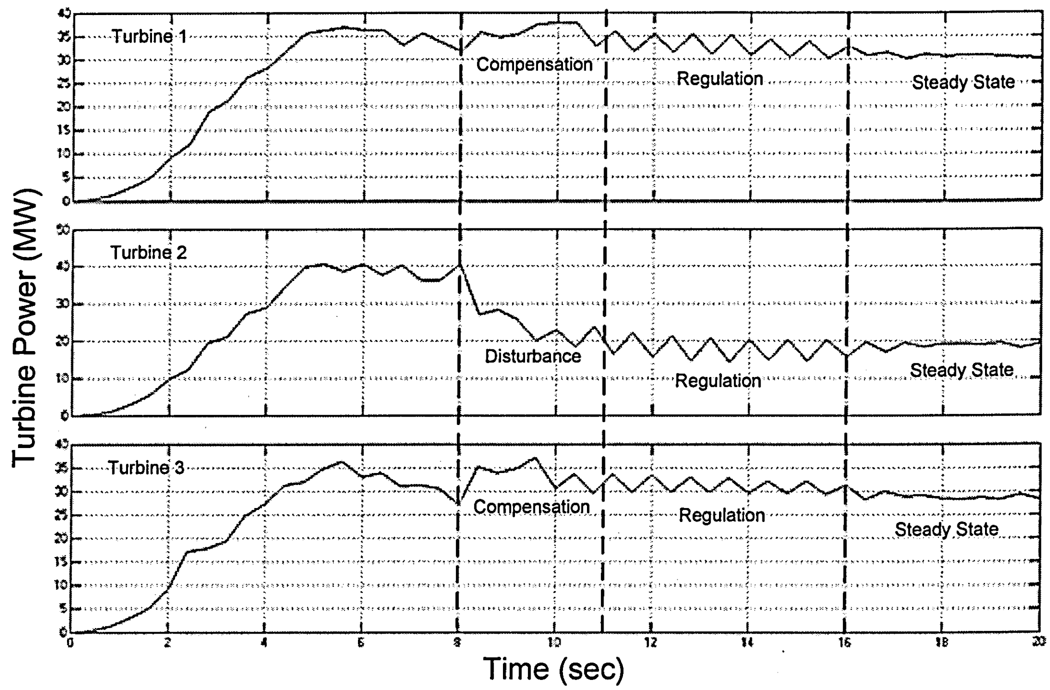


Figure 5.20 Fuzzy controller-Turbines' powers under hydraulic coupling compensation

5.9 Conclusions

- A new fuzzy logic controller has been designed and implemented, that is capable of controlling together three hydraulically coupled turbines under nonlinear process conditions, and is capable of compensating deviation errors due to hydraulic interactions between the plant's turbines. The fuzzy controller comprises 12 inputs and six outputs, and 699 control rules distinguished into four control layers.

- The fuzzy controller shows fast response and settling times. It shows a reasonably stable performance under dynamical head conditions. It can operate the three hydraulically coupled turbines at different operational set points, and successfully compensates the deviation errors due to hydraulic interactions between turbines.

- The fuzzy controller can be used as a local control system for any of the power houses within the cascaded hydropower plant.

CHAPTER 6 FUZZY SUPERVISORY CONTROL AND OPTIMIZATION SYSTEM

6.1 Introduction

In Chapter 4 a new fuzzy hydro turbine governor was designed and simulated, and in Chapter 5 a new fuzzy controller for three hydraulically coupled turbines was designed and simulated. Both of the new designs may solve the local control problems of a hydropower sub-system within a cascaded reservoirs hydropower plant, in terms of improved performance and stability. However, as presented in section 2.2.3, a cascaded reservoirs hydropower plant may spread over widely-separated geographical locations and different ground elevations, which makes the plant subject to a wide variety of physical constraints and time-varying parameters such as rain falls, floods, changes in climate conditions and any other uses of water that might be available such as irrigation or utilities. The cascaded reservoirs are also feeding the water to each other. Also any extra water increases the hydropower value which in turn decreases the use of fossil fuel power plants which in turn will reduce carbon pollution. Therefore the cascaded reservoirs hydropower plant's water resources have to be optimized to get a reasonable yet maximized hydropower operating pattern. In this Chapter, a fuzzy supervisory control and optimization system is designed and implemented. The new fuzzy system monitors the reservoirs' rates of discharge/accumulation and alters the operational set points of the local fuzzy controllers which control the hydropower plant sub-systems, in real time, so that a maximized power plant operational envelope is always maintained.

6.2 The Design Methodology

In order to design the fuzzy supervisory control and optimization system, the following tasks are formulated and simulated.

- To formulate an "expert knowledge base" on the optimization and scheduling of the hydropower plants that are cascaded and sharing the same water resources. Presented in section 6.3.

- To develop a control and optimization strategy based on a cascaded reservoirs hydropower plant model which comprises three reservoirs and three power houses. Each power house has three hydraulically coupled turbines controlled by the fuzzy controller developed in Chapter 5. Presented in section 6.4.

- To identify the inputs and outputs of the fuzzy supervisory control and optimization system and to formulate their scaling factors and their fuzzy linguistic variables. Presented in section 6.5.

- To create the fuzzy membership functions for the inputs and outputs which satisfy the control and optimization strategy. Presented in section 6.5.

- To construct the rule base that will execute the control and optimization actions. Presented in section 6.6.

- Implement the fuzzy controller in Matlab and carry out simulations to obtain results. Presented in section 6.7.

6.3 Formulation of Expert Knowledge Base

Generally, the scheduling of the cascaded reservoirs hydropower systems has been one of the principal and most difficult optimization problems in economic operation and control of those plants. The gathered expert knowledge supporting the design and implementation of the fuzzy supervisory control and optimization system is as follows:

1. The optimization function is to minimize the non hydraulic power production expenses over a scheduling period (week/day ahead planning) by releasing water from each reservoir and through each power house over all the planning time intervals, so as to minimize the total cost of non hydraulic energy, whilst satisfying diverse hydraulic and load balance constraints. This optimization task is currently carried out by off-line numerical analysis via a wide variety of optimization techniques to produce an optimized hydropower plant operational schedule which is not interfaced to the hydropower plant real time control systems. The plant operators manually alter the operational set points of the plant and change its operational policy according to the optimized schedule.

2. The aim is one of minimizing the non hydraulic power production expenses by means of maximizing the hydropower plant's operational envelope.

3. Any unforeseen changes in the hydropower plant water inputs or a power house shutdown in a cascaded system, would require an immediate re-scheduling which makes the off-line optimization numerical analyses inefficient.

4. In the light of the above, a smart supervisory control and optimization system that is capable of altering the operational set points of the cascaded reservoirs hydropower plant's subsystems, in real time, according to the present water

input conditions, in such a way as to continuously maximize the plant operational envelope would be a highly desirable solution.

5. Based on the modelling and simulation work undertaken in Chapter 3, a cascaded hydropower system exclusively working from its initial conditions would have its own *optimal operational set point* at certain gate positions not necessarily the *maximum positions* but we may say the *optimal positions.* The *optimal operational set point* would also be time variant as long as new changes in the reservoirs' inputs are taking place.

6.4 The Control and Optimization Strategy

To formulate the control and optimization strategy, a cascaded reservoirs hydropower plant design model as illustrated in Figure 6.1, is considered. It comprises three reservoirs and three power houses; each power house has three hydraulically coupled turbines controlled by the fuzzy controllers (FLC's 1-3) which were developed in Chapter 5. The three hydraulically coupled turbines are represented by the nonlinear model developed in section 3.2.3 and shown in Figure 3.6 which combines the three sets of turbine-penstock dynamics with the heads at the turbines' admissions, the turbines' flow rates and the losses in water heads due to friction.

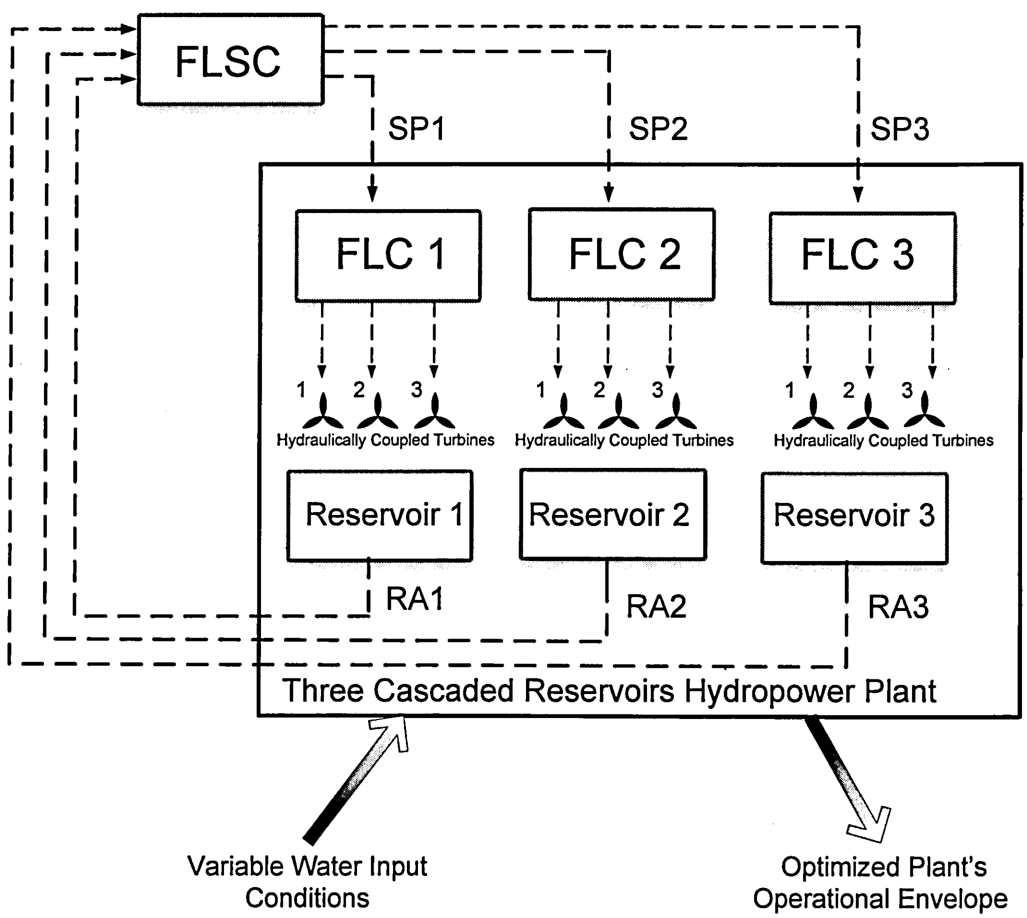


Figure 6.1 Cascaded reservoirs hydropower plant real time control and optimization model

The signals RA 1-3 are the inputs of the fuzzy supervisory control and optimization system (FLSC) and are the rates of change in head (dH/dt) for each reservoir. The signals SP 1-3 are the output signals of the fuzzy supervisory control and optimization system (FLSC) which are the operational set points of the fuzzy controllers (FLC's 1-3).In accordance to the "expert knowledge base" presented in section 6.3 and the simulation and modeling work in Chapters 3-5, it was decided to use the following fuzzy control and optimization strategy:

- *Reservoir's differential flow rate real time monitoring:* A reservoir's differential flow rate signal is the difference between the reservoirs's input flow rate and output flow rate. When its value is negative, it means the reservoir is discharging, when it is positive, it means the reservoir is accumulating. When its value is near zero i.e. positive very small or negative very small (in terms of fuzzy membership functions as per Table 6.1), it means that the reservoir and consequently the hydropower plant are operating near steady state flow conditions. By substituting the differential flow rate value for the value $(Q_i - Q_o)$ in equation 3.6, the rate of change in head (dH/dt) for each reservoir, is always obtained. Feeding these head rate of change signals to the inputs of the FLSC, a real time monitoring of the cascaded reservoirs' states is achieved. Hence, the FLSC can decide which operational set point value is required for each power house within the cascaded reservoirs hydropower plant, according to its reservoir state and in real time.

- *Optimization policy:* It is always required to maximize the cascaded hydropower plant operational envelope as much as possible at all water input conditions that may vary from one reservoir to another. This achieved by formulating the *fuzzy optimization rules.*

- *Fuzzy optimization rules:* The function of the fuzzy optimization rules is to alter the operational set point of each power house according to its reservoir differential flow state so that it reaches steady state flow conditions where the differential flow state is close to zero, and operating each power house as long as possible at its optimal operational set point. As an example, when a reservoir's differential flow state is negative high, the operational set point of this power house will be reduced to lowest. When it is negative medium, the operational set point of this power house will be reduced to low. When it is negative small, the operational set point of this power house will be set to the optimal one - which is a medium operational set point- for this plant model. When it is negative very small or positive very small, no action is taken and the present operational set point of this power house is kept the same until the reservoir's state changes. When it is positive high, the operational set point of this power house will be increased to highest. When it is positive medium, the operational set point of this power house will be increased to high. When it is positive small medium, again the operational set point of this power house will be set to the optimal one - which is a medium operational set point for this plant model. This optimization process is continuous until it is overridden -if necessary- by a load demand and continues thereafter, leading to an optimized cascaded reservoirs hydropower plant operational envelope which is proved by the simulations presented in Section 6.7.

- *Fuzzy Inference System:* Mamdani fuzzy inference method is the one selected for the development of the fuzzy turbine governor, as it provided more flexibility to implement the control strategy down the finest details.

6.5 Inputs and Outputs of Fuzzy Supervisory Control and Optimization System

There are three inputs of the fuzzy supervisory control and optimisation system, one from each reservoir (RA 1-3), each one is formulated and scaled as follows:

- *Reservoir's Head State:* This is the rate of change in the reservoir's head (dH/dt). When its value is negative, it means the reservoir is discharging. When it is positive, it means the reservoir is accumulating, this is in accordance with equation 3.6. Its scaling factor is from -100% to +100%. The fuzzification of this input signal is based on two trapezoidal membership functions and six triangular membership functions, as shown in Figure 6.2.

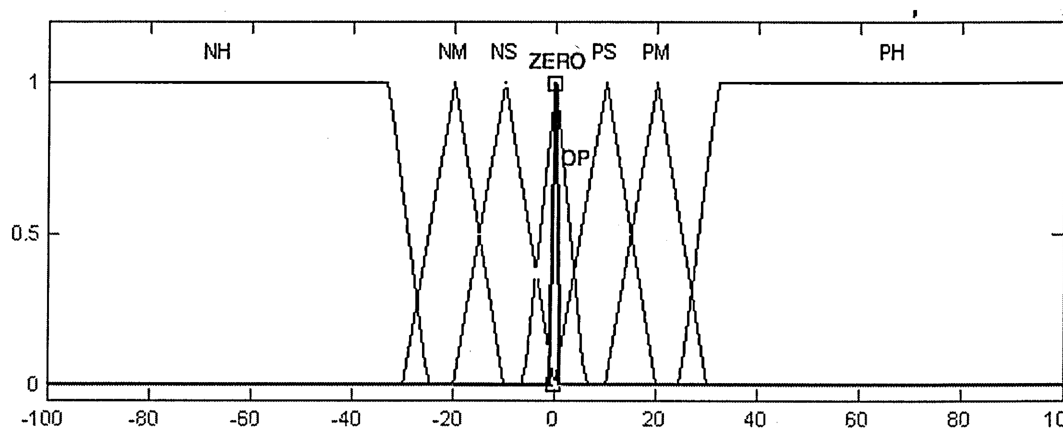


Figure 6.2 FLSC input membership functions

There are three outputs of the fuzzy supervisory control and optimisation system, one to each power house fuzzy controller (SP 1-3), each one is formulated and scaled as follows:

- *Power House Operational Set Point:* This is the control signal that enables the fuzzy supervisory control and optimization system to alter the operational set point of each power house's fuzzy controller; its scaling factor is from 0% to +100%. For more smoothness in changing the operational set point of each power house, the defuzzification of this output signal is based on five Gaussian membership functions, as shown in Figure 6.3.

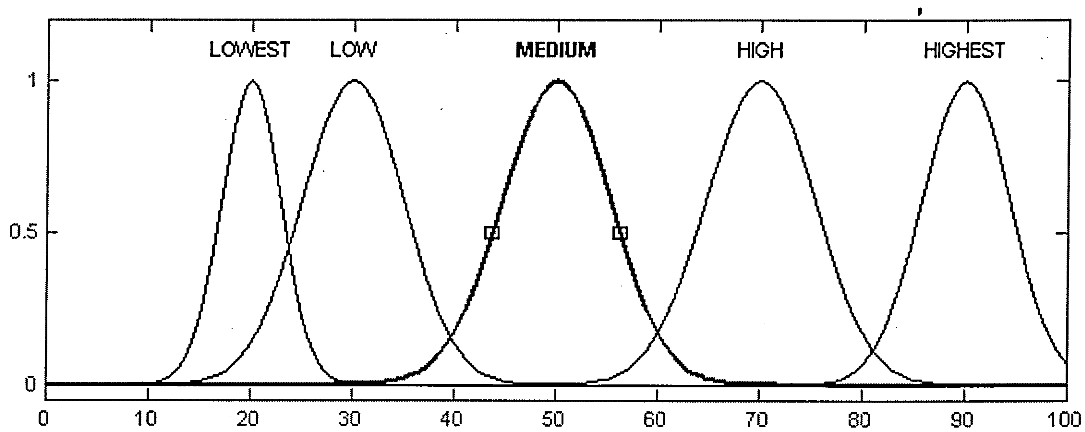


Figure 6.3 FLSC output membership functions

The fuzzy linguistic variables of this system are defined in Table 6.1.

Linguistic Variable	*Definition*
PH	Positive High
PM	Positive Medium
PS	Positive Small
ZERO	0
NH	Negative High
NM	Negative Medium
NS	Negative Small
OP	Optimal Set Point
LOW	Low
LOWEST	Lowest
HIGH	High
HIGHEST	Highest
MEDIUM	Medium

Table 6.1 Definition of fuzzy linguistic variables

6.6 Fuzzy Control and Optimization Rule Base

As per the presented control and optimization strategy of Section 6.4, the function of the fuzzy optimization rules is to alter the operational set point for each power house according to its reservoir's differential flow state so that it reaches steady state flow conditions where the differential flow state is close to zero, and operating each power house as long as possible at its optimal operational set point. This leads to an optimized cascaded reservoirs hydropower plant operational envelope. The formulated rule base comprises the following fuzzy rule sets:

- *Rules for Reservoir 1:*

IF *RA1* is **NH** THEN *SP1* is **LOWEST**

IF *RA1* is **NM** THEN *SP1* is **LOW**

IF *RA1* is **NS** THEN *SP1* is **MEDIUM**

IF *RA1* is **PS** THEN *SP1* is **MEDIUM**

IF *RA1* is **PM** THEN *SP1* is **HIGH**

IF *RA1* is **PH** THEN *SP1* is **HIGHEST**

- *Rules for Reservoir 2:*

IF *RA2* is **NH** THEN *SP2* is **LOWEST**

IF *RA2* is **NM** THEN *SP2* is **LOW**

IF *RA2* is **NS** THEN *SP2* is **MEDIUM**

IF *RA2* is **PS** THEN *SP2* is **MEDIUM**

IF *RA2* is **PM** THEN *SP2* is **HIGH**

IF *RA2* is **PH** THEN *SP2* is **HIGHEST**

- *Rules for Reservoir 3:*

IF *RA3* is **NH** THEN *SP3* is **LOWEST**

IF *RA3* is **NM** THEN *SP3* is **LOW**

IF *RA3* is **NS** THEN *SP3* is **MEDIUM**

IF *RA3* is **PS** THEN *SP3* is **MEDIUM**

IF *RA3* is **PM** THEN *SP3* is **HIGH**

IF *RA3* is **PH** THEN *SP3* is **HIGHEST**

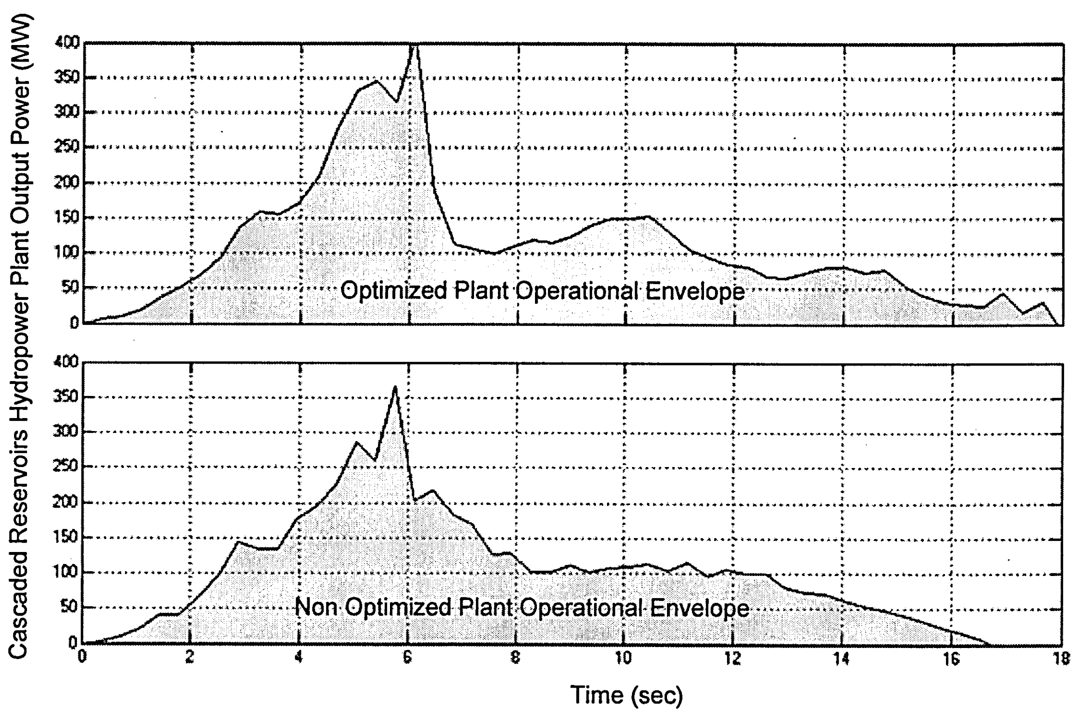
6.7 Simulation of the Fuzzy Supervisory Control and Optimization System

The design of the fuzzy supervisory control and optimization system was implemented in Matlab and simulation models for the cascaded reservoirs hydropower plant shown in Figure 6.1 were produced. The aim of this simulation work is to present the performance of the fuzzy supervisory control and optimization system and demonstrate its real optimization capabilities. The Simulink simulation models with their physical parameters are attached in Appendix C. In the following sections and based on Equation 3.6, the simulation time is dependent on the value of A which is the reservoir's area (m^2). It is the real area of a reservoir of symmetrical geometry, or an approximated value for an asymmetrical reservoir, or a selected value for simulation purposes that can reflect the actual water capacity of the reservoir thus affecting only the simulation time. The reservoir static water head is the same in the three cases. Therefore, the time scale that is expressed in seconds in those simulations would be rescaled to reflect the same dynamics in an actual time horizon of hours/days/weeks/months simply by changing the value of A. The small value of A was chosen purely to speed up the simulation runs (which could take tens of hours otherwise). The 18 seconds time scale was adequate to reflect the actual water capacity used in those simulations.

6.7.1 Cascaded Hydropower Plant Optimization from Initial Conditions

A simulation model was implemented in Simulink for a cascaded reservoirs hydropower plant model as shown in Figure 6.1. It comprises three reservoirs and three power houses. Each power house has three hydraulically coupled turbines controlled by the fuzzy controllers (FLC's 1-3) which were developed in Chapter 5. The three hydraulically coupled turbines are represented by the nonlinear model developed in section 3.2.3 and shown in Figure 3.6, which combines the three sets of turbine-penstock dynamics with the heads at turbines' admissions, turbines' flow rates and the losses in water heads due to friction. To prove the optimization capabilities of the developed system, two identical plant simulation models are used. The only difference between them is that only one model is connected to the developed fuzzy supervisory control and optimization system. The other model is based on individual power house operational set point fixed settings, which are the optimal operational set point of 50% (In the light of the simulation results of Chapter 3). The simulation results are shown in Figures 6.4 – 6.7 which are presented as follows:

- Figure 6.4 shows the resultant optimized plant's operational envelope compared to the non optimized one. The fuzzy supervisory control and optimization system is successfully maximizing the cascaded reservoirs hydropower plant's operational envelope from initial conditions. This is evident from the peak values of the plant output power which are higher than the ones of the non optimized case, and the operational horizon of the optimized plant is longer than the one of the non optimized case. This is because of the plant's nonlinear time variant friction loss dynamics. In the non optimized case, the plant's local control systems are working individually towards a fixed power generation for each plant and according to a preset operational set point, where the turbines' flow rates are being controlled according to the head condition at the turbines' inlets only, regardless of the reservoirs' head states. This makes the friction losses in the hydraulic conduits higher than the optimized case. In the optimized case the operational set points are simultaneously varying in such a way that they are dependent only on the reservoirs' head states and aim towards a steady state discharge flow rate for each reservoir before the water reaches the turbines' inlets, thus, the friction losses in the hydraulic conduits are minimized and accordingly the generated power is maximized. This means that the optimized system is extracting more energy from the same volume of water more than the non optimized system.



Figures 6.4 Cascaded reservoirs hydropower plant's real time optimization

o Figure 6.5 shows the output control signals of the fuzzy supervisory control and optimization system to each power house. These are produced by the fuzzy optimization rule base that is continuously altering the operational set point for each power house in the plant in real time according to its reservoir's state so that a maximized operational envelope of the total plant is achieved.

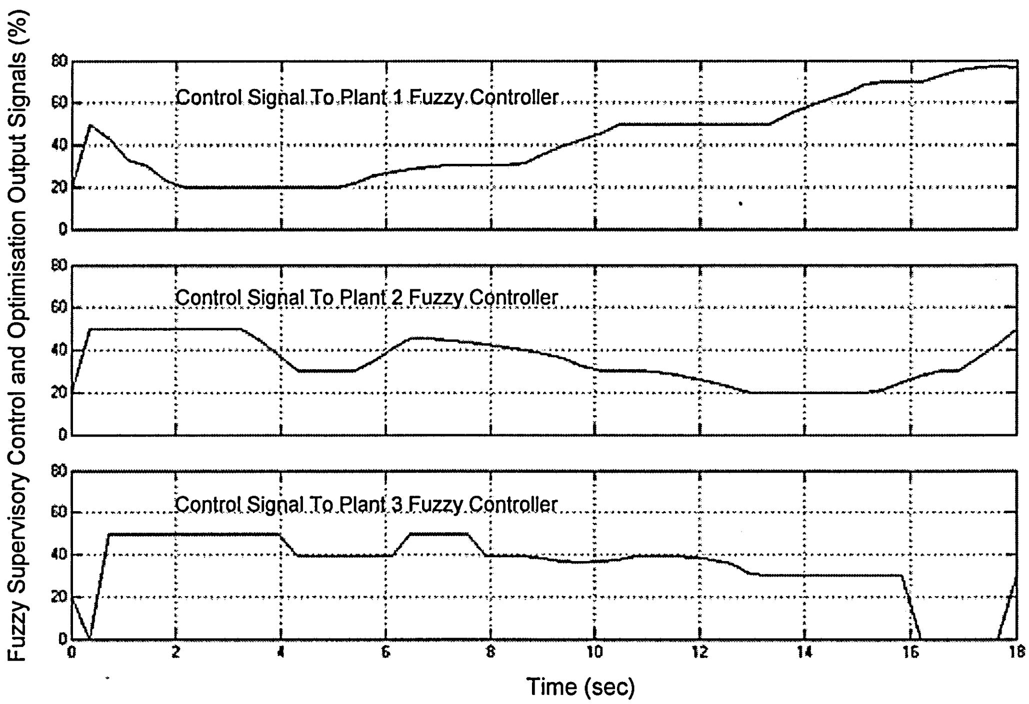


Figure 6.5 Fuzzy supervisory control and optimization system- output control signals

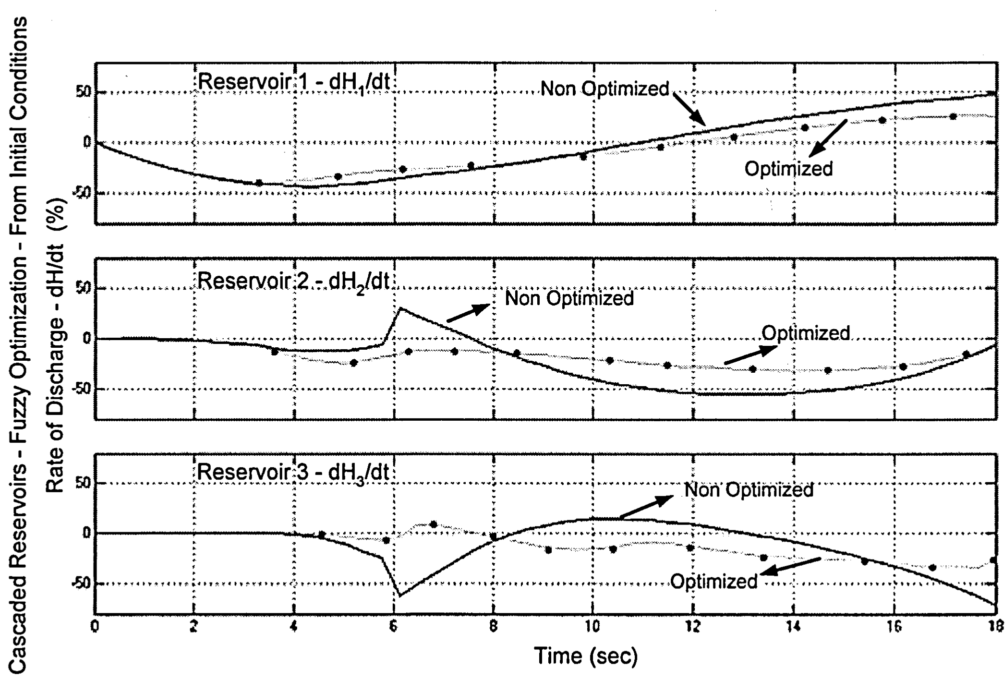


Figure 6.6 Reservoirs' head states for both the optimized and non optimized cases

- Figure 6.6 shows the head states of the three reservoirs for both the optimized and non optimized cases. This is more smoothly varying in the optimized case. Figure 6.7 shows the trajectories of the three reservoirs' head states for both the optimized and non optimized cases where the formulation of knots is much less in the optimized case.

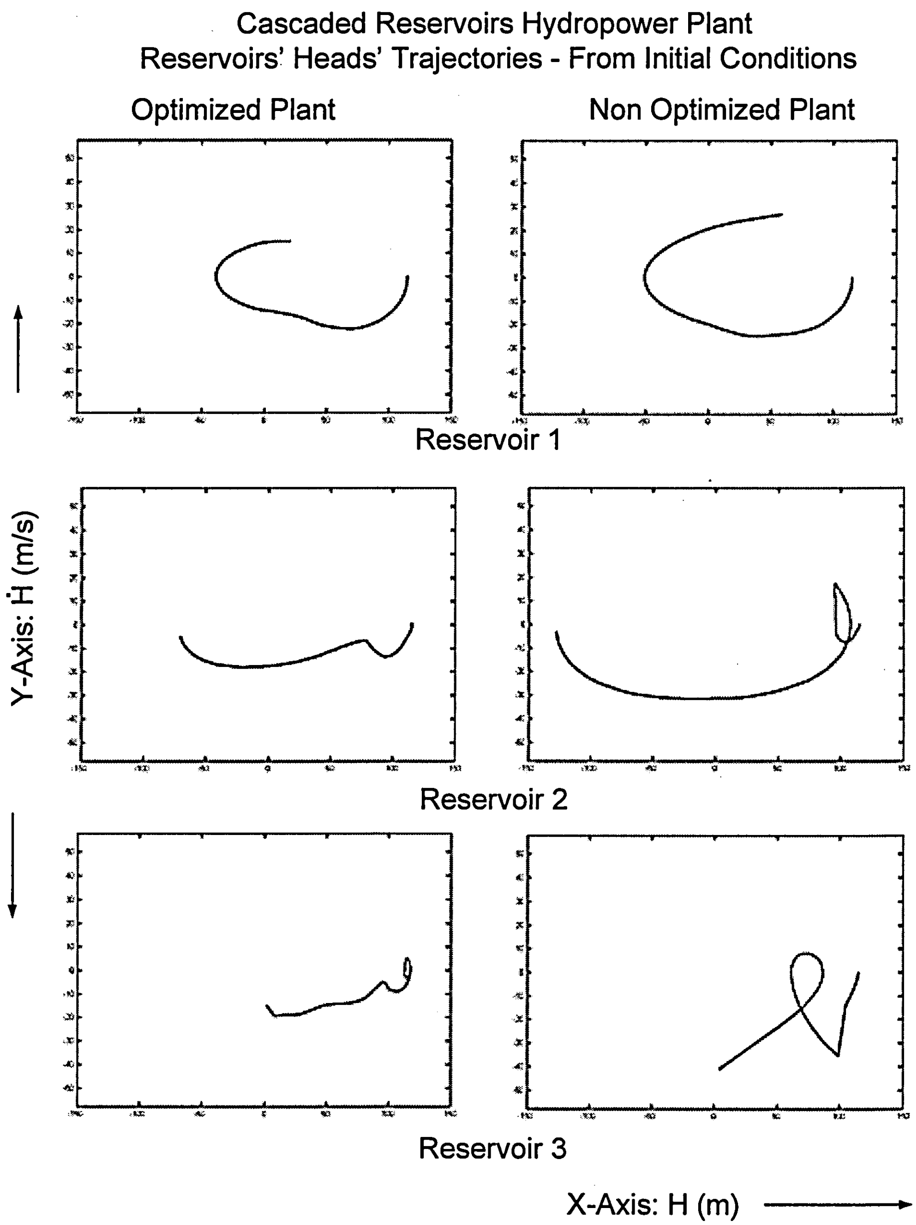


Figure 6.7 Trajectories of the three reservoirs' head states for both the optimized and non optimized cases

6.7.2 Cascaded Hydropower Plant Optimization from Random Input Conditions

A simulation model was implemented in Simulink for the cascaded reservoirs hydropower plant model of Figure 6.1 which comprises three reservoirs and three power houses. Each power house has three hydraulically coupled turbines controlled by the fuzzy controllers (FLC's 1-3) which were developed in Chapter 5. The three hydraulically coupled turbines are represented by the nonlinear model developed in section 3.2.3 and shown in Figure 3.7, which combines the three sets of turbine-penstock dynamics with the heads at turbines' admissions, turbines' flow rates and the losses in water heads due to friction. This simulation is showing the optimization performance of the fuzzy supervisory control and optimization system in response to random water input conditions for each reservoir. The simulation results are shown in Figures 6.8 – 6.10 which are presented as follows:

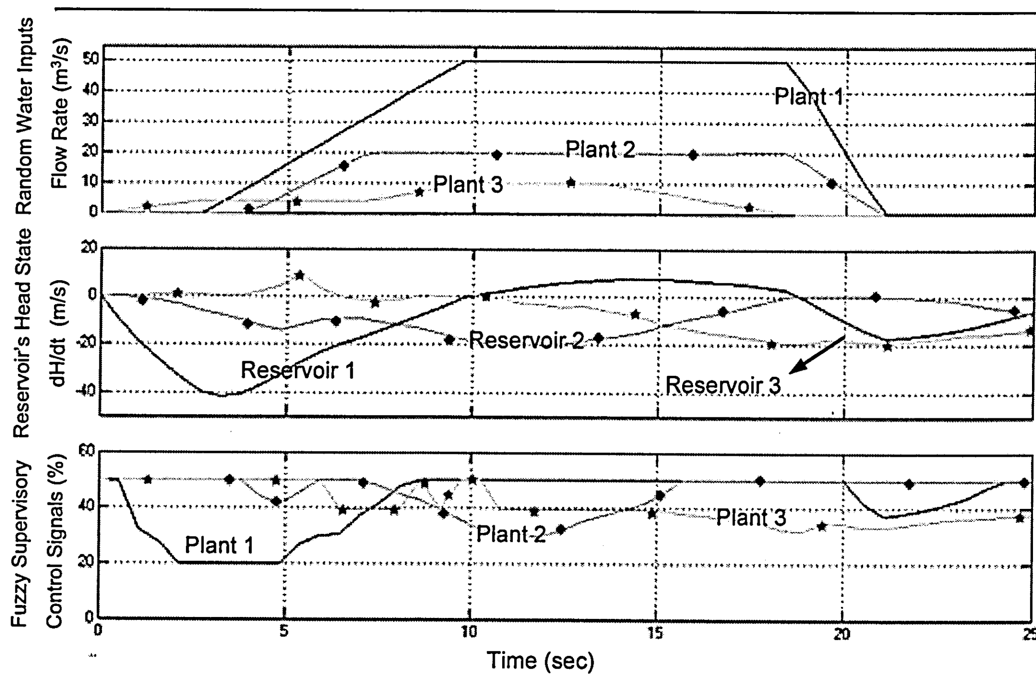


Figure 6.8 FLSC control signals and the reservoirs' head states subject to random water input conditions

- Figure 6.8 shows the random water input to each reservoir which may represent rainfall or a flood. It also shows each of the three reservoirs' head states (dH/dt), and the control signal of the fuzzy supervisory control and optimization system for each power house. The resultant optimized operational envelope of the total cascaded plant is shown in Figure 6.9; also it shows the optimized operational envelope for each of the plant's sub-systems. Compared to the performance of the non optimized plant (without the FLSC) of Figure 6.10, the fuzzy supervisory control and optimization system is successfully maximizing the cascaded reservoirs hydropower plant's operational envelope under random input conditions, although the non optimized plant simulation is set to a higher operational set point of 65%. Figure 6.11 shows the trajectories of the three reservoirs' head states for both the optimized and non optimized cases where the formulation of knots is much less in the optimized case.

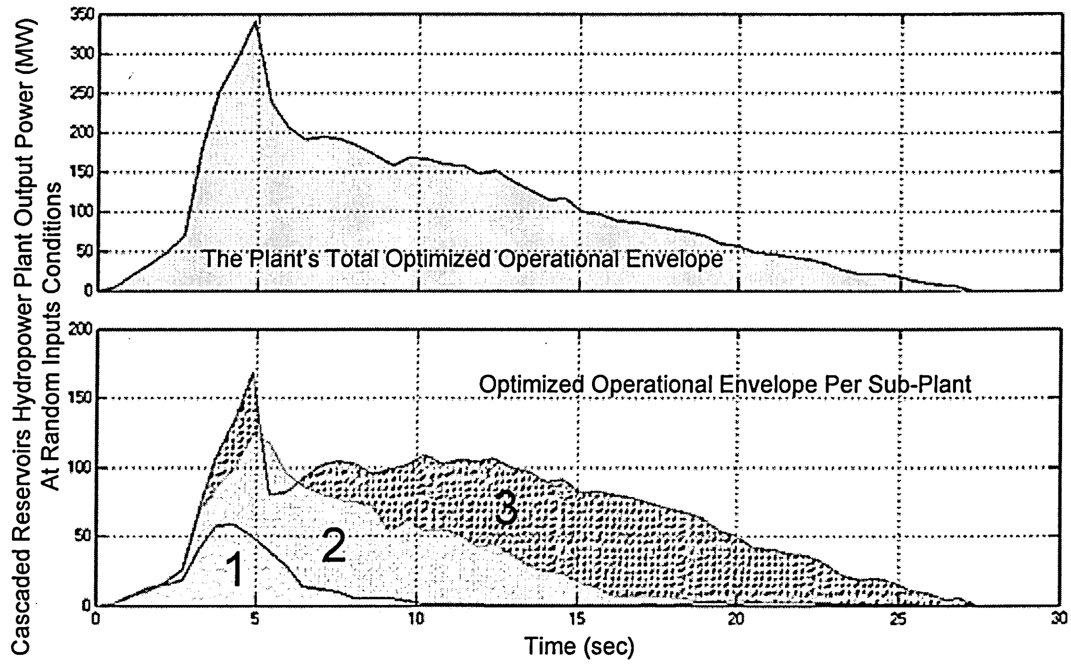


Figure 6.9 Optimized plant's operational envelope subject to random water input conditions

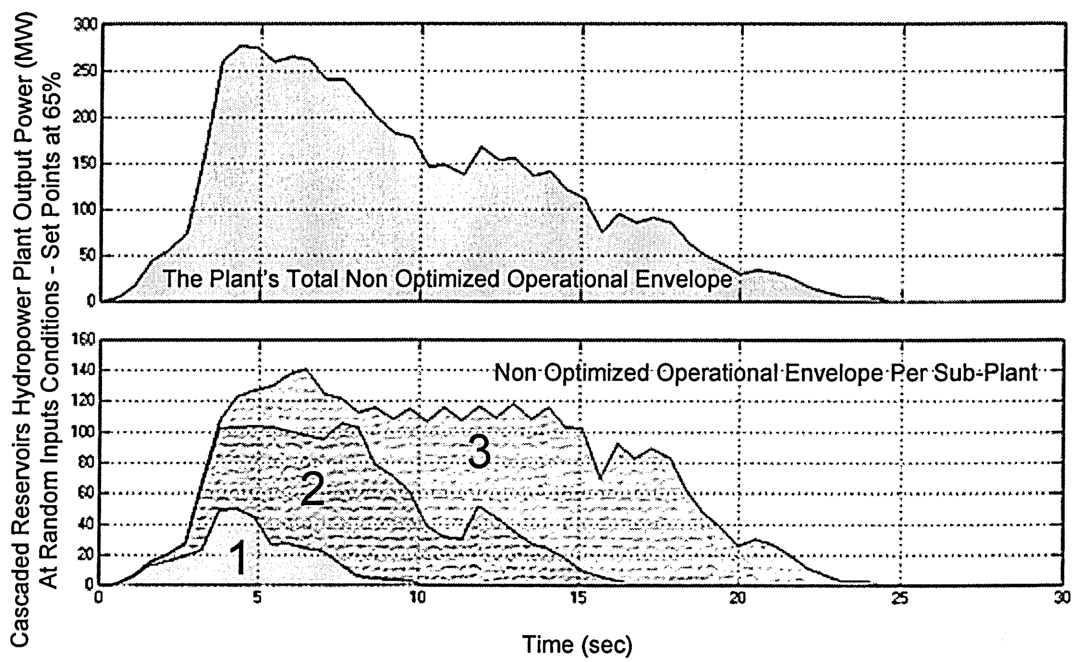


Figure 6.10 Non optimized plant's operational envelope subject to random water input conditions and set to 65% operational set points

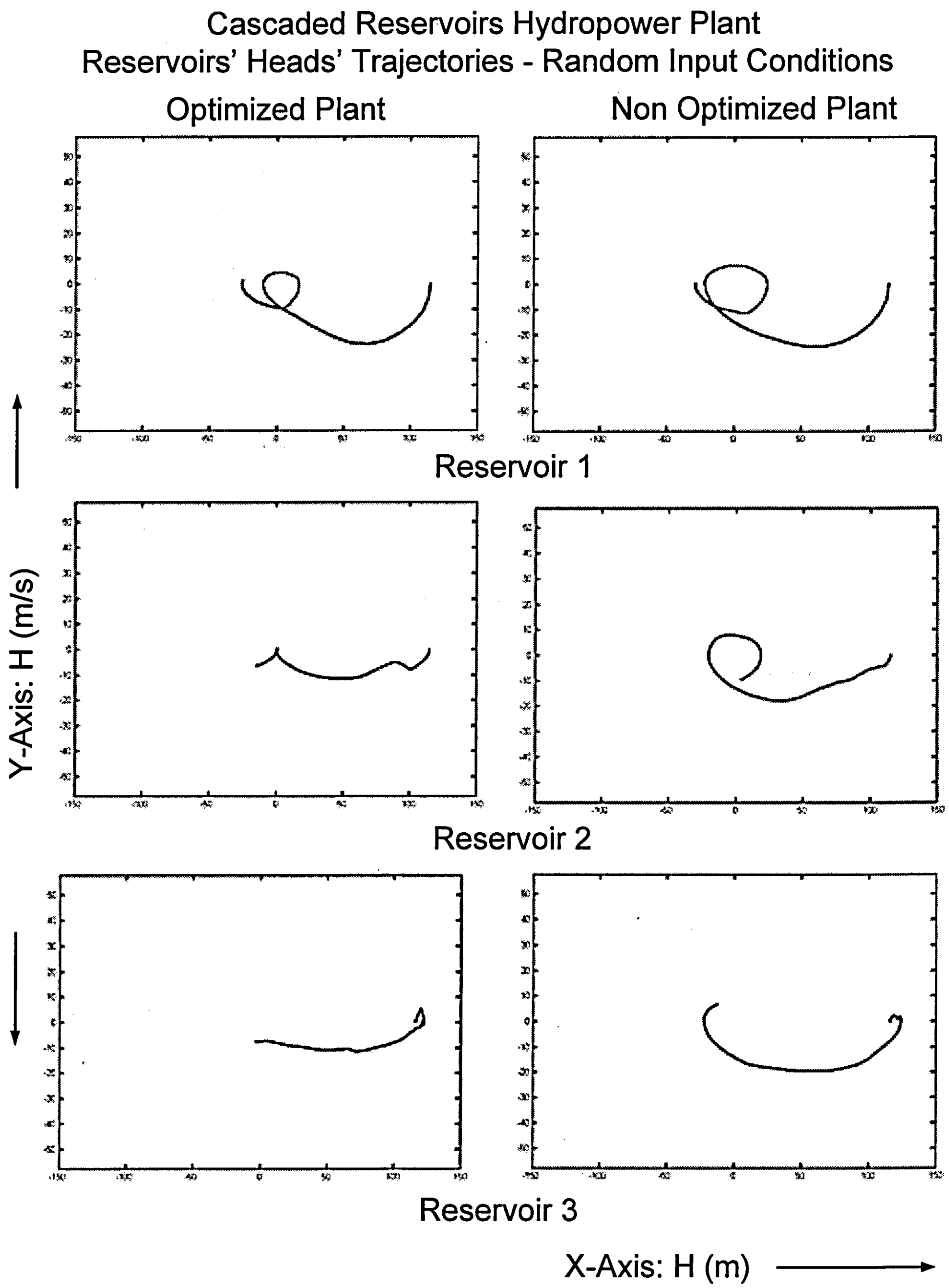


Figure 6.11 Trajectories of the three reservoirs' head states for both the optimized and non optimized cases-subject to random water input conditions

6.7.3 Prediction of the Hydropower Plant Operational Pattern Based on a Water Input Forecast

The model of the cascaded reservoirs hydropower plant shown in Figure 6.1 can be used to predict the optimized operational pattern over long calendar periods, based on long term forecasting of rainfalls or floods. A simulation model was implemented in Simulink for the cascaded reservoirs hydropower plant model of Figure 6.1 which comprises three reservoirs and three power houses. Each power house has three hydraulically coupled turbines controlled by the fuzzy controllers (FLC's 1-3) which were developed in Chapter 5. The three hydraulically coupled turbines are represented by the nonlinear model developed in section 3.2.3 and shown in Figure 3.7 which combines the three sets of turbine-penstock dynamics with the heads at turbines' admissions, turbines' flow rates and the losses in water heads due to friction. As per the results shown in Figure 6.12, by entering long term forecast water inputs to the plant simulation model, an optimized and long term predicted operational pattern of the plant is obtained.

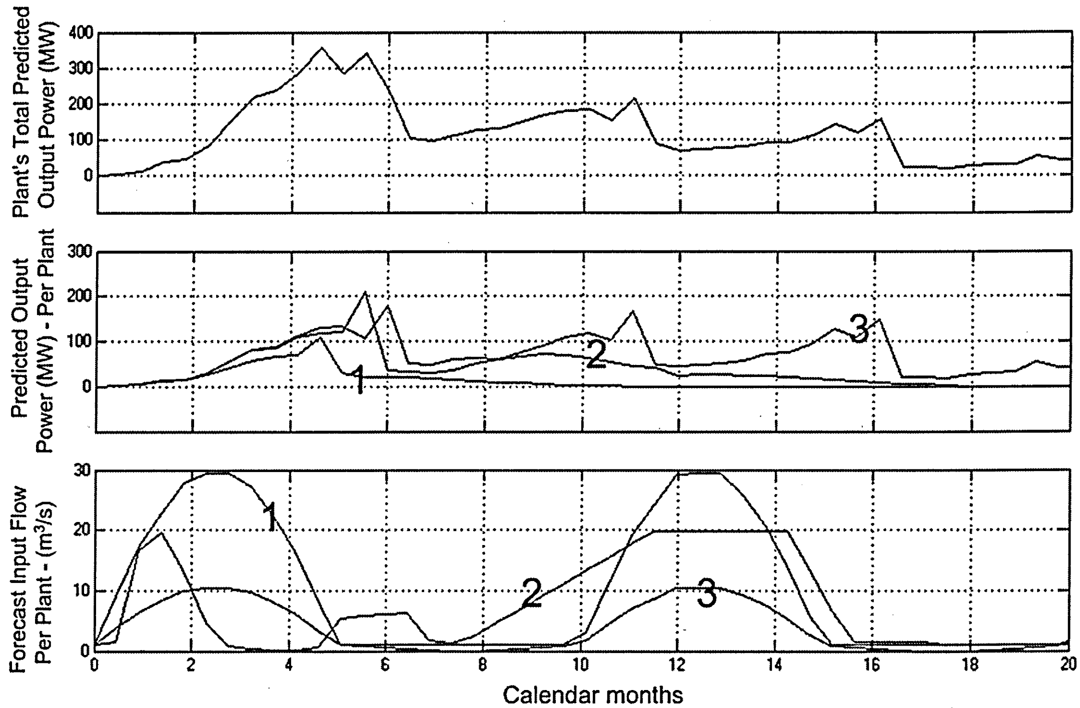


Figure 6.12 Prediction of the Hydropower Plant Operational Pattern Based on a Water Input Forecast

6.8 Conclusions

A new fuzzy supervisory control and optimization system has been designed and simulated which is capable of altering the operational set points of the cascaded reservoirs hydropower plant's subsystems in real time according to the present water input conditions so that it is continuously maximizing the plant operational envelope. It is extracting more energy from the same volume of water more than the non optimized system.

Chapter 7. OBSERVATIONS ON THE STABILITY OF FUZZY CONTROL SYSTEMS

7.1 INTRODUCTION

In the lights of the fuzzy logic control systems development and simulation intensive work undertaken in this thesis, a new methodology to carry out stability analysis of fuzzy logic control systems may be achieved, it is reported in the following sections.

7.2 Fuzzy Control Systems Stability Criteria

These points arise from the work in this thesis after intensive simulation runs and trials of different approaches.

- A fuzzy logic control system (FLC) is stable if and only if it drives the feedback error of a nonlinear unstable plant model to a bounded and reasonable operational zone and drives the feedback error to zero for a linear model of the same plant.

- It must enforce finite boundary conditions on all of its outputs, and should posses enough rules to start up the plant from maximum and minimum initial conditions.

- A stable fuzzy logic control system (FLC) should have three types of rules:

- Start up from initial conditions rules; these rules are exclusively for start up from minimum or maximum initial condition and will not be effective thereafter.

- To "operational zone" rules that drive the system to asymptotic stability; these rules are exclusively for the normal operational mode of the plant after it has been started up and where the feedback error signals are in the range 5-95 %. These rules will not be effective otherwise.

- Inside "operational zone" rules that drive the system to complete stability; these rules are exclusively for the optimum operational mode of the plant where the feedback error signals are in the range 0-5 %, and will not be effective otherwise.

- The total number of rules of a stable fuzzy logic control system (FLC) is subject to the following condition:

$MFNO >> n$, subject to the constraint of $D_{FLC} > D_P$ [7.1]

where; $MFNO$ is the total number of membership functions for a single input or output of the FLC and n is the order of the plant. As example for a 5th order nonlinear plant model the number of membership functions of a single input or output should be much higher than 5. This reduces oscillations and maximum overshoots and eliminates limit cycles, providing that the dynamics of the FLC (D_{FLC}) are faster than the dynamics of the plant (D_P).

- A stability test can be carried as follows: on a simulation model of the FLC and plant and at a set point of "Zero", the error signal should follow the "zero" line for a stable FLC. For an unstable FLC the error signal would be expected to asymmetrically deviate from the "Zero" line. Here, the membership functions are to be calibrated until the deviation is symmetrical and reaches or becomes close to the "Zero" line, especially the "operational zone" membership function. This is illustrated in Figure 7.1.

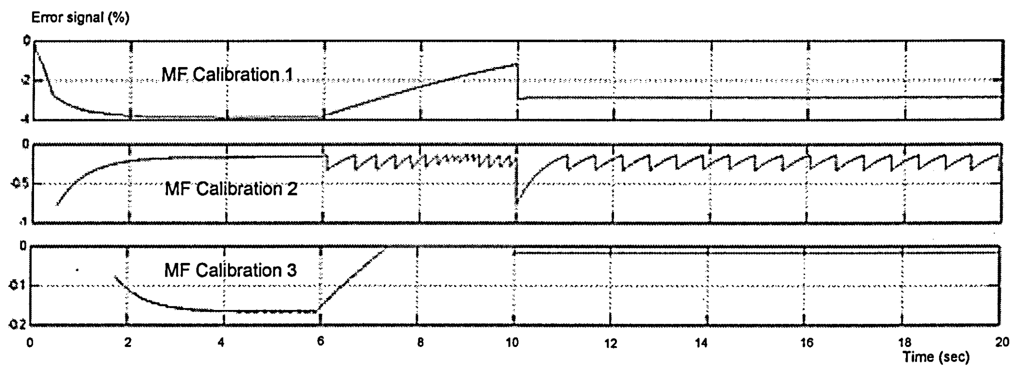


Figure 7.1 Stabilizing FLC by membership function calibration at "Zero" set point.

- For a stable FLC and a nonlinear plant model, the feedback signal membership functions should not be identical to the membership functions of the control signal. An intentional difference between them may reduce the steady state errors. For example Figure 7.2 illustrates the membership functions of the turbine guide vane position feedback signal; Figure 7.3 illustrates the membership functions of the guide vane control signal. Note the different versions of the membership function FC between the two figures.

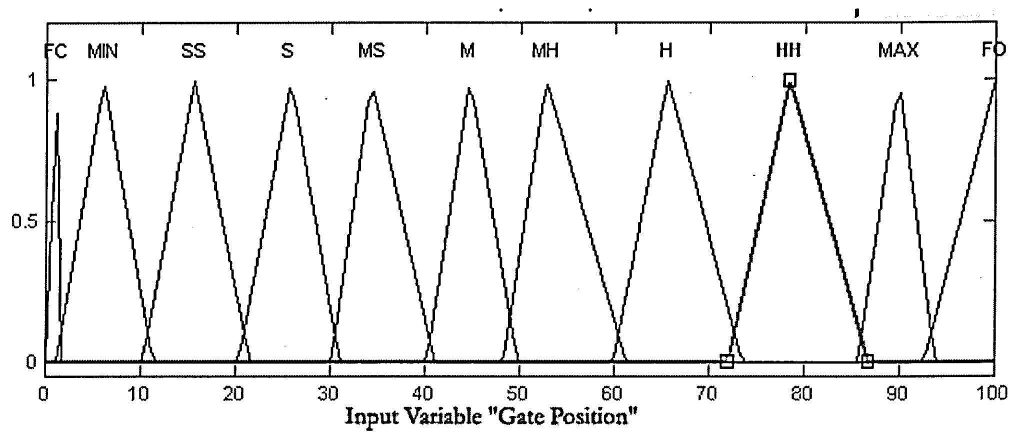


Figure 7.2 FLC Membership functions – Input Variable

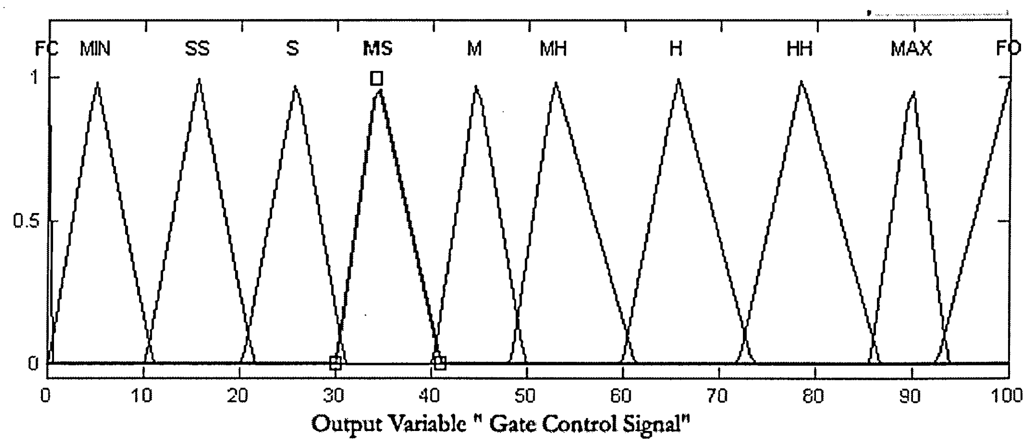


Figure 7.3 FLC Membership functions – Output Variable

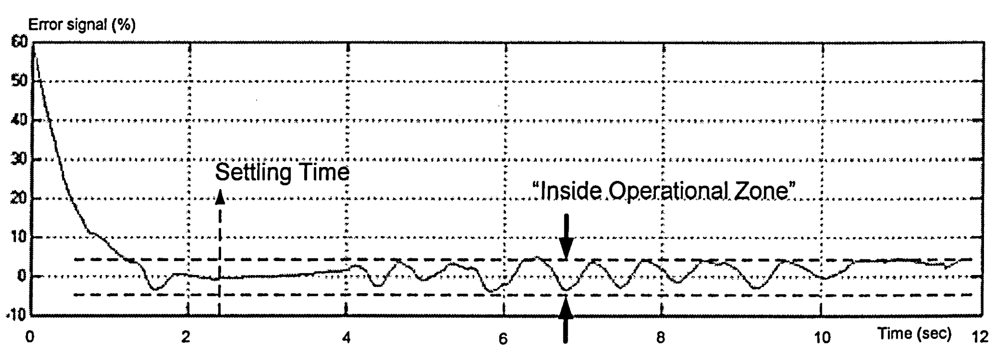


Figure 7.4 Feedback error signal of a stable FLC

- As illustrated in Figure 7.4, the FLC settling time is the time required for an output to reach steady state conditions or oscillate within the "operational zone".

7.3 Conclusions

Generally, a standard stability analysis for fuzzy logic control systems is one of the pending problems, it is a new research area which needs to be investigated and further developed [Zadeh1996]. The observations on the stability of fuzzy logic control systems has been introduced and reported in this Chapter. It is based on intensive mathematical modelling, computer simulations undertaken in this research work.

CHAPTER 8. CONCLUSIONS AND DISCUSSIONS

This thesis has reported the development of a nonlinear mathematical model of a cascaded reservoirs hydropower plant. The developed model was accurate enough to represent and simulate the plant nonlinear dynamics and to design and test three fuzzy control systems addressing three major cascaded reservoirs hydropower plant problems. The first one is a fuzzy turbine governor replacing the classical PID controller, the second is a fuzzy controller for a number of hydraulically coupled turbines under nonlinear and interacting process conditions, and the third is a fuzzy supervisory control and optimization system.

1. In Chapter 3, the cascaded reservoirs hydropower plant was decomposed into a collection of decoupled subsystems, a nonlinear mathematical model for each subsystem was derived. The development and simulation work in this chapter started with a new cascaded reservoirs hydropower plant nonlinear model presented in section 3.2 which involved the development of a mathematical model for each of the hydraulic reservoir dynamics presented in section 3.2.1, turbine dynamics presented in section 3.2.2, three hydraulically coupled turbines' dynamics in section 3.2.3, pressure wave dynamics in section 3.2.4, and generator dynamics in section 3.2.5. Finally the simulation of the cascaded reservoirs hydropower plant was presented in section 3.6:
2. The cascaded hydropower plant is a complex nonlinear system that involves interacting input and output nonlinear parameters, nonlinear flow rates, and nonlinear dynamical hydraulic heads.
3. The plant's optimal operational point is time variant, dependent on the reservoirs' initial conditions and changes in their inputs conditions.

4. The losses in hydraulic heads due to friction are a key player in the plant's efficiency.

5. The plant would be sensitive to changes in the climate temperature and changes in water density.

6. The hydraulic coupling between the turbines of a power house makes the disturbances in one turbine transferable to neighbouring turbine units which may make the plant unstable and lead to hydraulic mass oscillations in the conduits. It may also transfer oscillations to the power grid where the other power houses on the same gird will see those oscillations as changes in the load demand.

7. The cascaded hydropower plant is not particularly suitable for control by a single control system or to be controlled by classical PID controllers. The thesis describes how the system can be decomposed into decoupled dynamical subsystems and how a new control system may be designed that successfully addresses the problems of each subsystem *(local plant levels, local control systems).* The design of a new supervisory control system that monitors and revises the control strategies of each subsystem has also been presented *(global plant level, supervisory control system).*

8. In Chapter 4, a new fuzzy logic turbine governor is designed and implemented that may replace the classical PID turbine governors and be capable of controlling the hydraulic turbine, together with its penstock, under nonlinear process conditions. The fuzzy governor comprises three inputs and two outputs, and 226 control rules distributed between three control layers.

9. The fuzzy governor shows faster response and settling times. It shows more stable performance under both steady state head and variable dynamical head conditions. It can achieve asymptotic stability under disturbances.

10. In Chapter 5, a new fuzzy logic controller was designed and simulated that is capable of controlling together three hydraulically coupled turbines under nonlinear process conditions and capable of compensating deviation errors due to

hydraulic interactions between the plant's turbines. The fuzzy controller comprises 12 inputs and six outputs, and 699 control rules distributed between four control layers.

11. The fuzzy controller shows fast response and settling times. It shows a reasonably stable performance under dynamical head conditions. It can operate the three hydraulically coupled turbines at different operational set points, and successfully compensate the deviation errors due to hydraulic interactions between turbines. The fuzzy controller can be used as a local control system for any of the power houses within the cascaded hydropower plant.

12. In Chapter 6, a new fuzzy supervisory control and optimization system was designed and simulated. It is capable of altering the operational set points of the cascaded reservoirs hydropower plant's subsystems in real time according to the present water input conditions so that it is continuously maximizing the plant operational envelope. It is extracting more energy from the same volume of water more than the non optimized system.

13. In Chapter 7, observations on the stability of fuzzy logic control systems were introduced and reported. A fuzzy logic control system (FLC) is stable if and only if it drives the feedback error of a nonlinear unstable plant model to a bounded and reasonable operational zone and drives the feedback error to zero for a linear model of the same plant. It must enforce finite boundary conditions on all of its outputs, and should posses enough rules to start up the plant from maximum and minimum initial conditions. A stable fuzzy logic control system (FLC) should have three types of rules: start up from initial conditions rules, to "operational zone" rules that drive the system to asymptotic stability, and inside "operational zone" rules that drive the system to complete stability.

14. Fuzzy logic control is highly effective for complex nonlinear systems and may provide a higher contribution in the hydroelectric industry, especially for the cascaded reservoirs hydropower systems. The designed fuzzy logic controllers in this thesis are nonlinear multiple inputs and multiple outputs controllers where

any hydraulic turbine's nonlinear power-gate relationship can be fitted and accounted for while the other classical control systems need to be re-tuned for each operational mode in order to cope with the hydraulic turbine's nonlinear power-gate relationship. The designed fuzzy logic controllers were intensively tested and simulated over a wide range of large and small, positive and negative inputs systems, satisfactory results were obtained. As might be generally expected, the integral term in the PID regulator results in zero steady–state error. The fuzzy governor exhibits a non-zero steady state error but it is within the specified tolerance of the set point. In principle a zero steady-state error can be achieved by adding an integrator after the fuzzy controller, but this has the usual destabilising effect and is therefore omitted as results are satisfactory.

15. The importance of cascaded reservoirs hydropower systems compared to others is that a single bounded mass of water generates electric energy multiple times instead of once, this is because the water is continuously passed between multiple reservoirs at different elevations until it reaches the bottom or end reservoir. This thesis, therefore, aimed to enhance the existing cascaded reservoirs hydropower systems and future ones by new designs of control and optimisation systems based on fuzzy logic.

16. Accuracy of Modelling and Simulations: The literature review carried out in this thesis could not find any published research work that developed a dynamical model of a cascaded reservoirs hydropower plant to start with, and hence a new dynamical model was developed and introduced in Chapter 3. However, the cascaded reservoirs hydropower system's modelling carried out by decomposing the system into a collection of decoupled subsystems; a nonlinear mathematical model for each subsystem was derived. Each dynamical subsystem model represents all the nonlinear dynamics that normally destabilize the subsystem and that lead to disturbance and instability of the main system. Here, it is possible to compare the modelling of decoupled subsystems with others. The most important comparison is between the turbines' coupling model developed in this thesis in section 3.2.3 and the models developed in references [IEEE1992 et al.

Vouranos1993 et al. Hannett1994]. A common methodology of this thesis and the others uses the law of momentum to yield a relationship between the flow, head, and the hydraulic conduit dimensions for each turbine, and uses the continuity equation to yield the turbines' coupling relationship as per Equations 3.35–3.37. However, references [IEEE1992 et al. Vouranos1993 et al. Hannett1994] used those equations to yield a relational matrix comprising so called water starting times and mutual water starting times. This is based on expressing the turbines' heads and flows in per unit representation by dividing each of them by the rated head and rated flow for each turbine respectively. Whilst their models may be suitable for simulating the turbines' coupling effects based on individual steady state conditions, they are not suitable for dynamical modelling and simulations where the hydraulic coupling effect can be seen under all dynamical head conditions. These include dynamical friction losses and flow rates, and the turbines' control systems dynamics. This is because of the fact that the water starting times (which represent the acceleration time of water in conduits defined as $T_w = LQ / gHA_c$) are used in those references are dealt with as constant algebraic values, whereas actually they are dynamical variables whose values are dependent on both dynamical head and flow values for each turbine, as is well explained in references [Chaudhry1987 et al. Streeter1982]. To revise the developed relational matrices of those references to comprise dynamical water starting times, instead, is not possible. The developed model in this thesis which is shown in Fig. 3.7, allows the simulation of both steady state and dynamical head conditions as per the simulation models of Chapters 3-6. Also, a control system can be added to the same model at inputs G1-G3 (turbines' gates) and the turbines can be set to any different and individual load conditions, thus enabling the simulation of any desired plant's operational mode and the investigation of the turbines' coupling effects for each mode. Also, the reservoir dynamics as per Equation 3.6 are included in the developed model of Fig. 3.7, which is simultaneously deducting both the sum of the turbines' volume flow rates from the reservoir's water and the head losses due to friction in the main tunnel, so that a net value of the dynamical head is always obtained. This enables the continuous monitoring of the turbines' performances with their control systems all over the hydropower plant's operational envelope, starting from any desired reservoir's water initial condition. Based on Equation 3.6, the simulation time is dependent on the value of A which is the reservoir's area (m^2). It is the real area of a reservoir of symmetrical geometry, or an approximated value for an asymmetrical reservoir, or a selected value for simulation purposes that can reflect the actual water capacity of the reservoir thus affecting only the simulation time. The reservoir static water head is the same in the three cases. Therefore, the time scale that is expressed in seconds in those simulations would be rescaled to reflect the same dynamics in an actual time horizon of hours/days/weeks/months simply by changing the value of A. The small value of A was chosen purely to speed up the simulation runs (which could take tens of hours otherwise). Also, Equations 3.35–3.37 can be easily revised to include both various tunnel and penstock lengths, and cross sectional areas. These equations can be extended further to include more turbine units too.

CHAPTER 9. FURTHER WORK

A futuristic cascaded reservoirs hydropower solution may use any accumulated rain falls, sustained water, and waste recycled water of community areas that have various elevations by constructing a collecting reservoir for each area. The United Kingdom is one of the potential locations for such futuristic cascaded hydropower solutions; a good example would be the city of Sheffield that has (for example) four different community areas at four various elevations: Crookes, Upper Walkley, Lower Walkley and Hillsborough with a river at the bottom. This would be a small-scale scheme, but the fuzzy control and optimization systems developed in this thesis, may be used for any of the small to large scale cascaded reservoirs hydropower plants. It is recommended to further expand and improve these new fuzzy control and optimization systems designs so that completely unmanned cascaded reservoirs hydropower plant can be achieved which may increase the hydropower contribution in electricity generation. Some of the recommended expansions and improvements could be to increase the inputs and outputs of the fuzzy control systems in order to cover emergency shutdowns, bypass valve control, and to change the turbine-gate-hydraulic servo system's speed.

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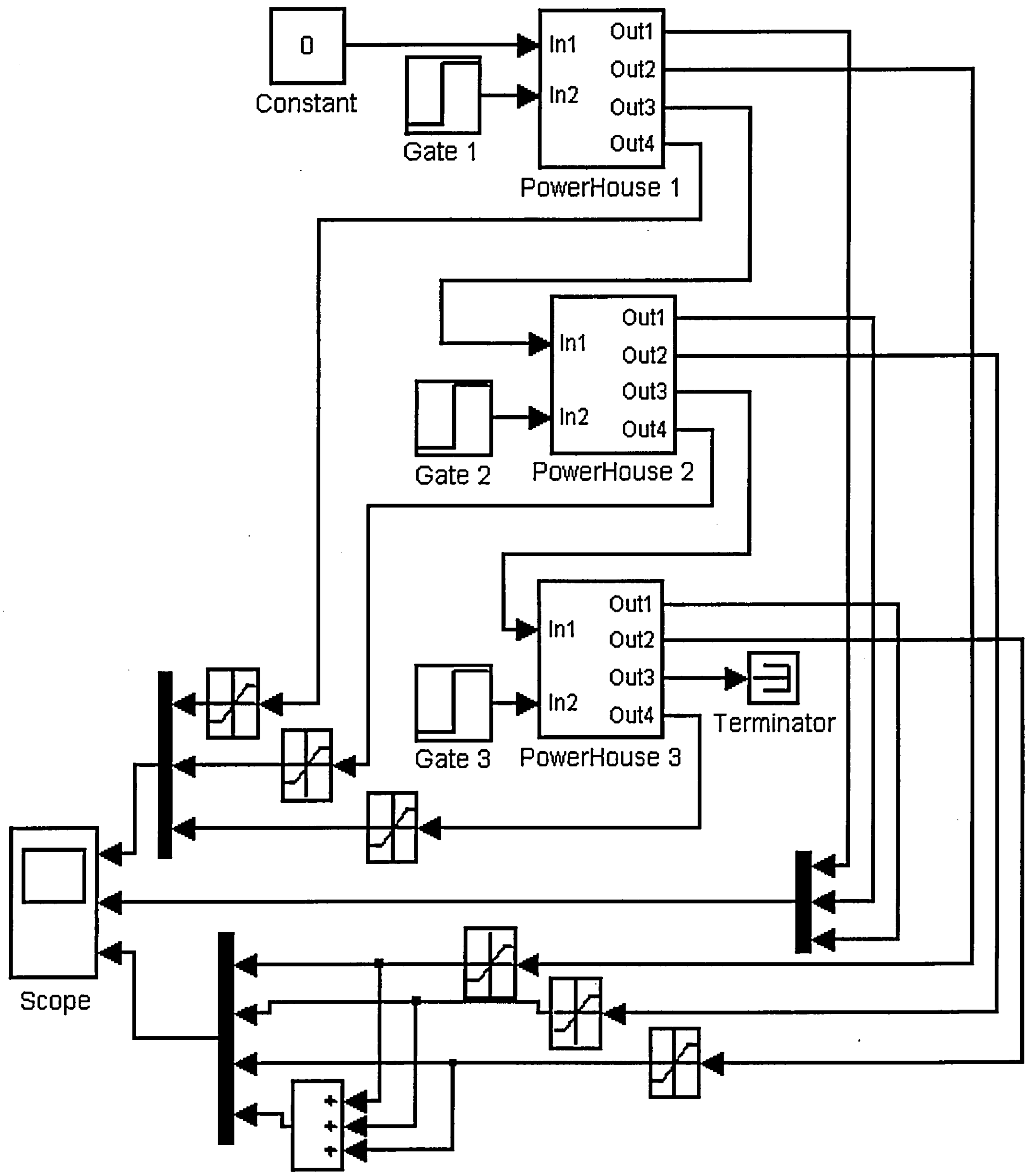
APPENDIX- A CHAPTER 3 SIMULATION MODELS

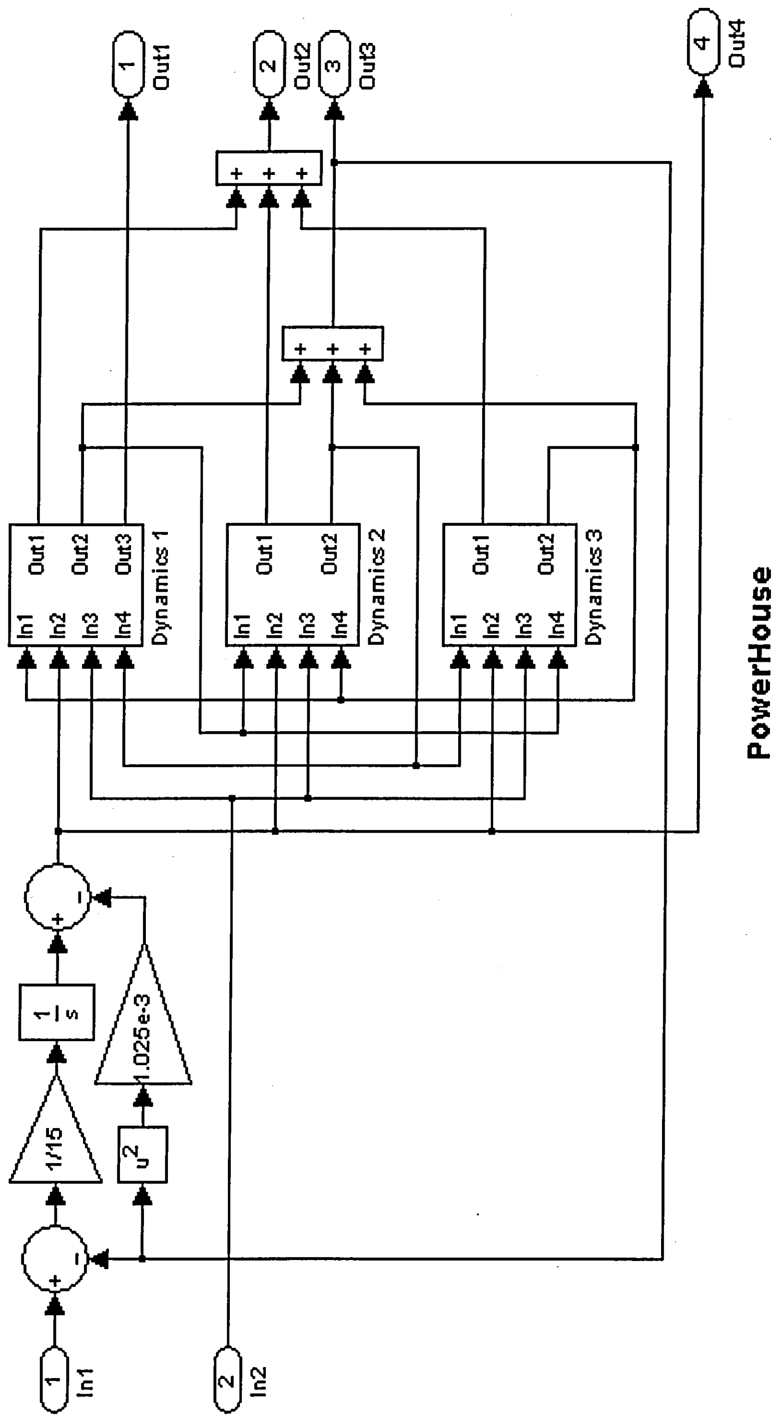
A.1 Cascaded Reservoirs Hydropower Plant Physical Parameters:

L	100 m	H_D	115 maximum
L_1,L_2,L_3	20 m	A_{c1},A_{c2},A_{c3}	2 m^2
Ac	6 m^2	K	1.7
K_1,K_2,K_3	2.72	η	*0.76*
f_T	1.025×10^{-3}	$f_{P1},\ f_{P2},\ f_{P3}$	3.186×10^{-3}
Ω	0	δ	1
f	0.02	g	9.81 $m\ .s^{-2}$
ρ	1000 $kg.m^{-3}$	Reservoir Height	15 m

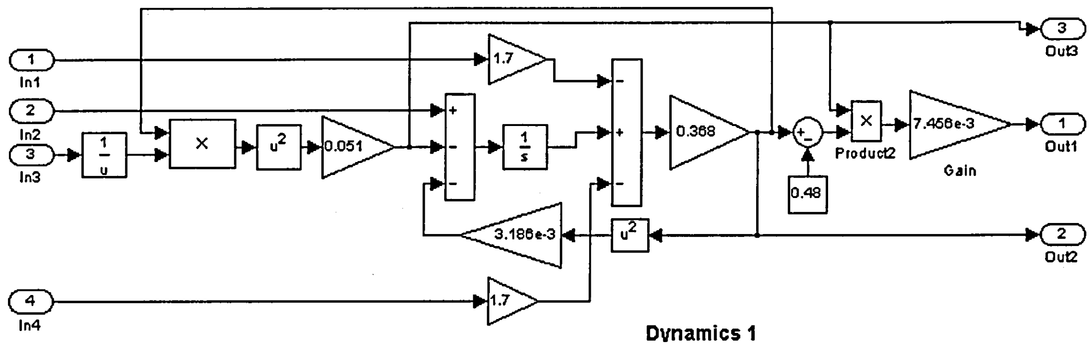
A.2 Simulink Model of Sections 3.3.1-3.33:



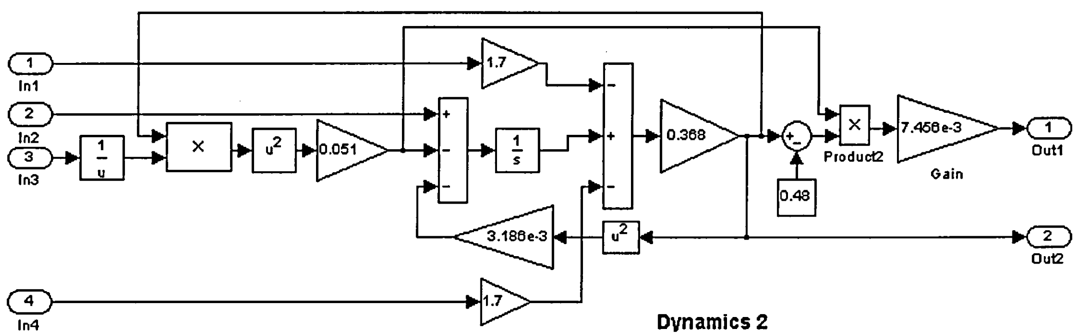
Simulation model of a cascaded reservoirs hydropower system comprises three power houses, without control systems. Each power house simulation subsystem is presented in the following sections.



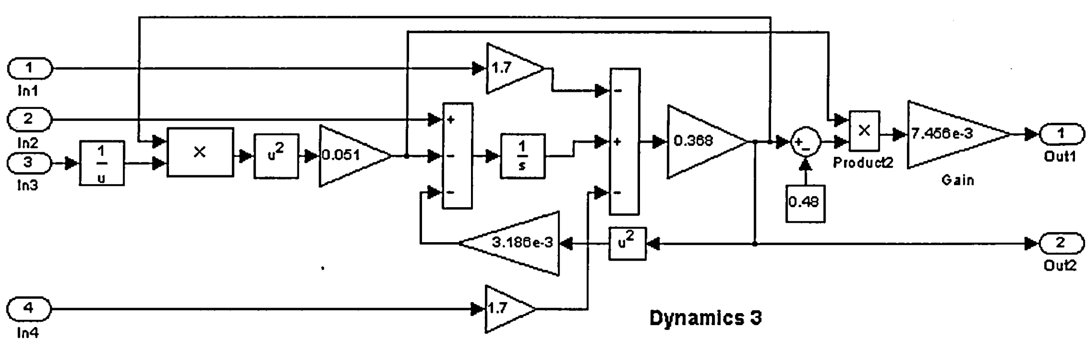
Power house subsystem simulation model, it comprises three hydraulically coupled turbines (Dynamics 1-3). Each turbine simulation model subsystem is presented in the following sections.



Dynamics 1



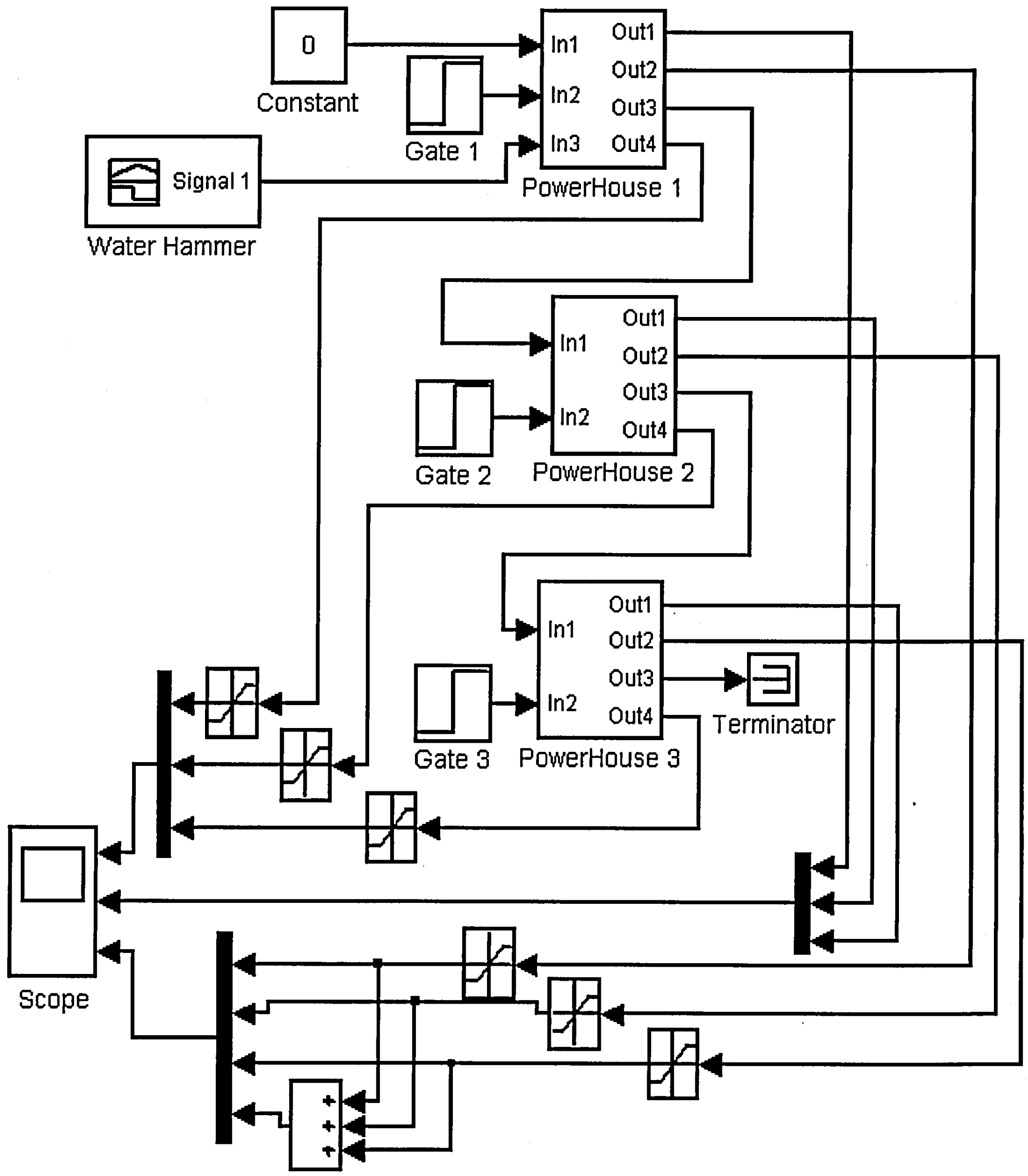
Dynamics 2



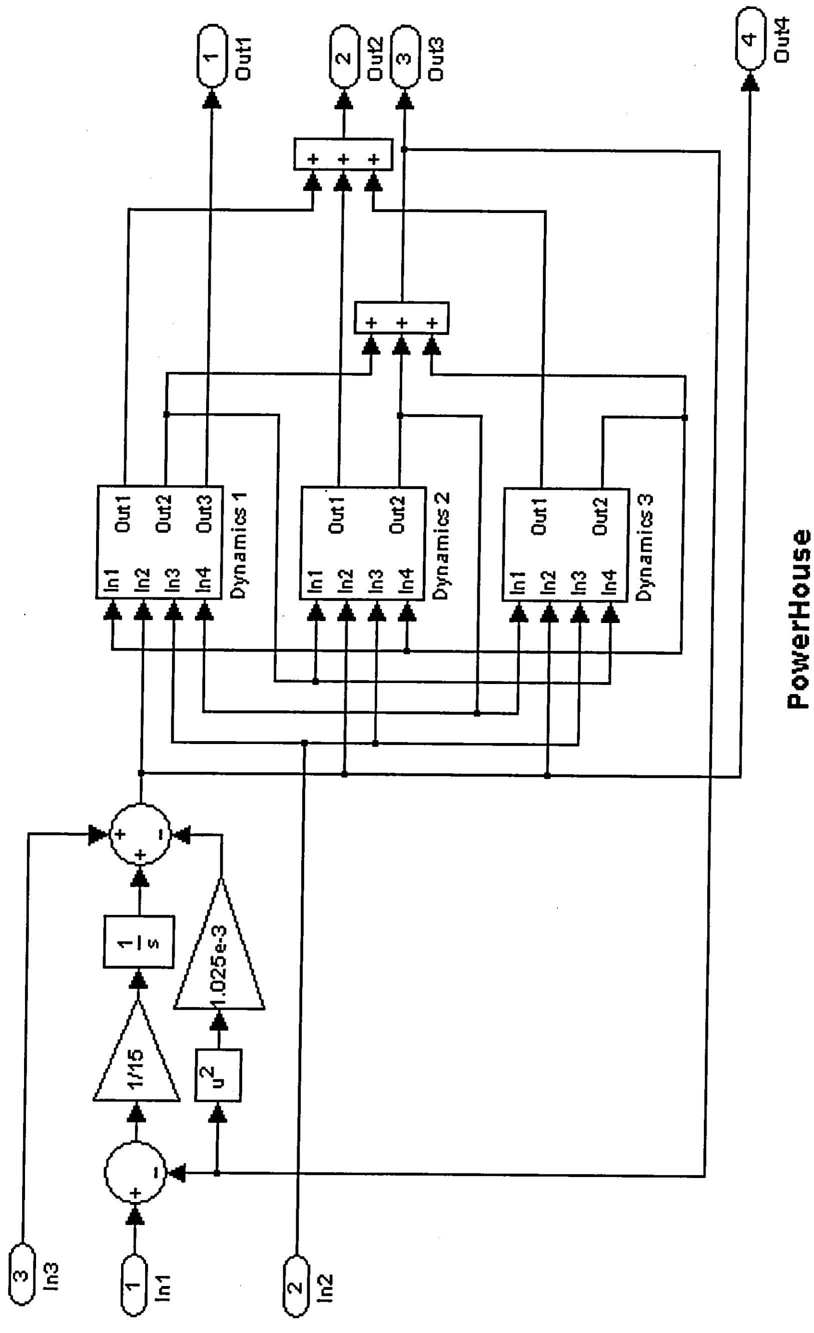
Dynamics 3

Hydraulic turbine simulation model subsystem

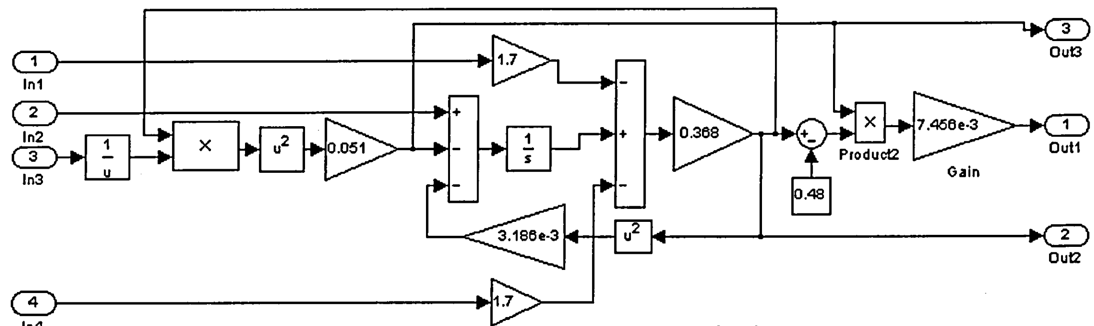
A.3 Simulink Model of Section 3.3.5:



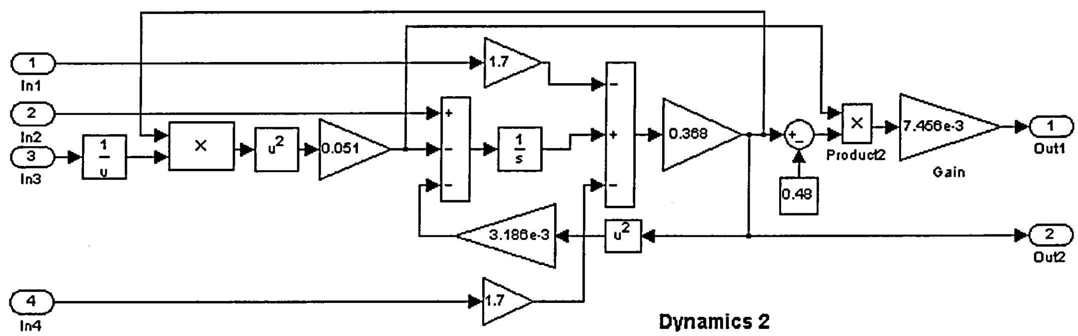
Simulation model of a cascaded reservoirs hydropower system comprises three power houses, without control systems, and with water hammer disturbances. Each power house simulation subsystem is presented in the following sections.



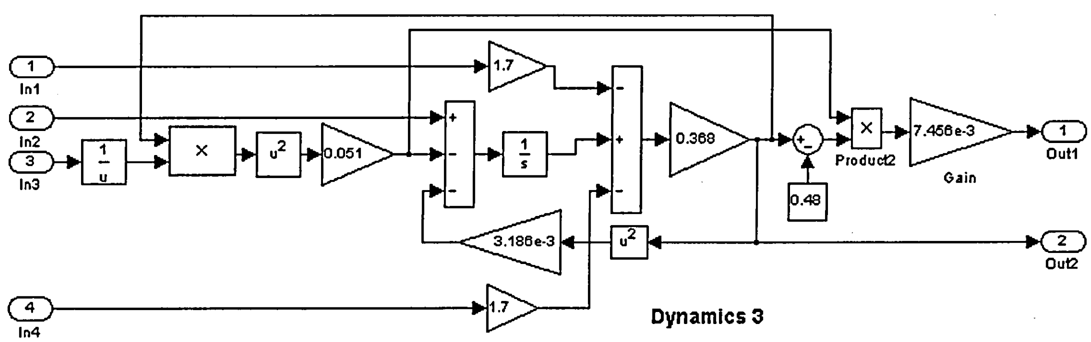
Power house subsystem simulation model, it comprises three hydraulically coupled turbines (Dynamics 1-3). Each turbine simulation model subsystem is presented in the following sections.



Dynamics 1



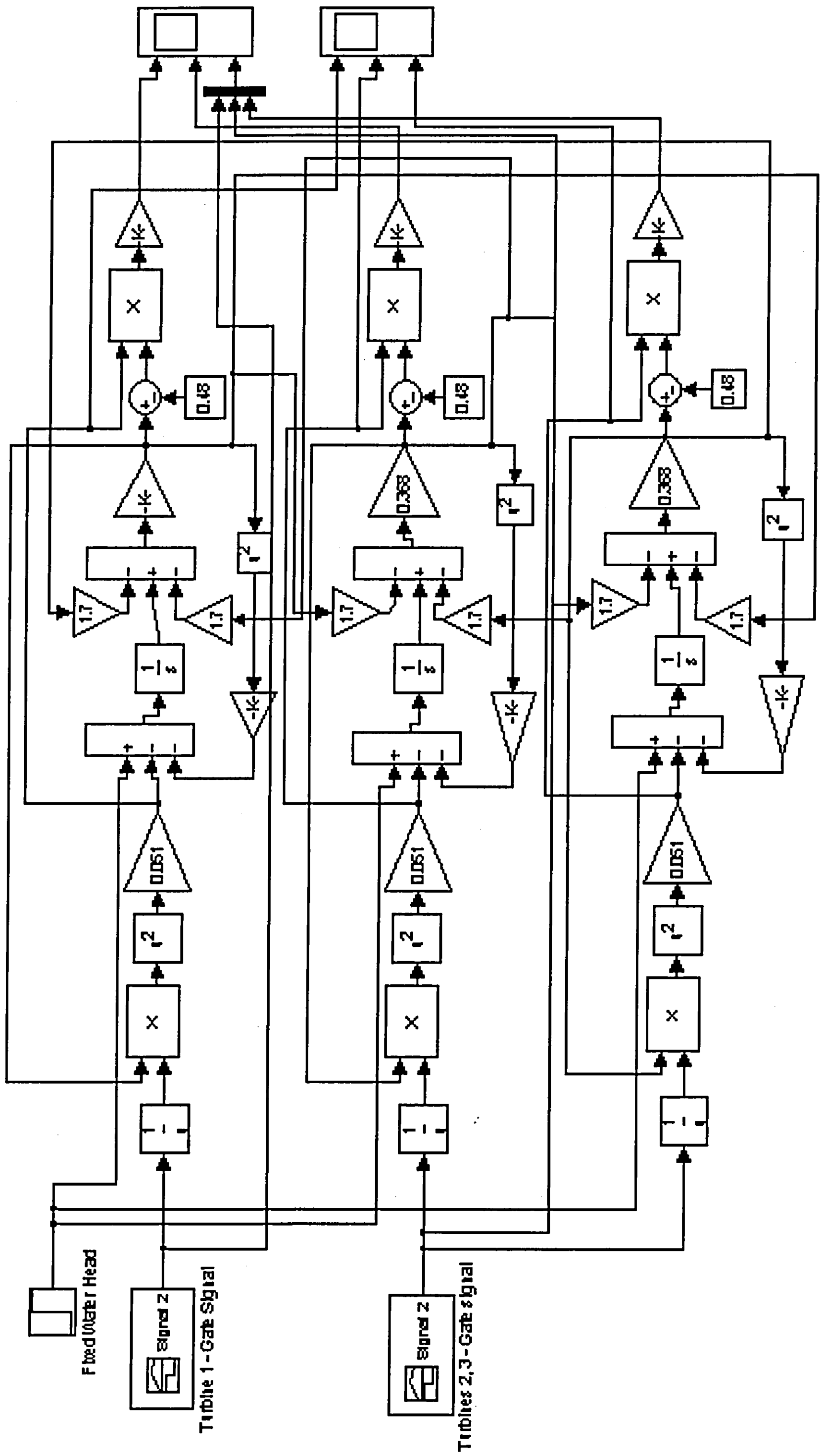
Dynamics 2



Dynamics 3

Hydraulic turbine simulation model subsystem

A.4 Simulink Model of Section 3.3.6:



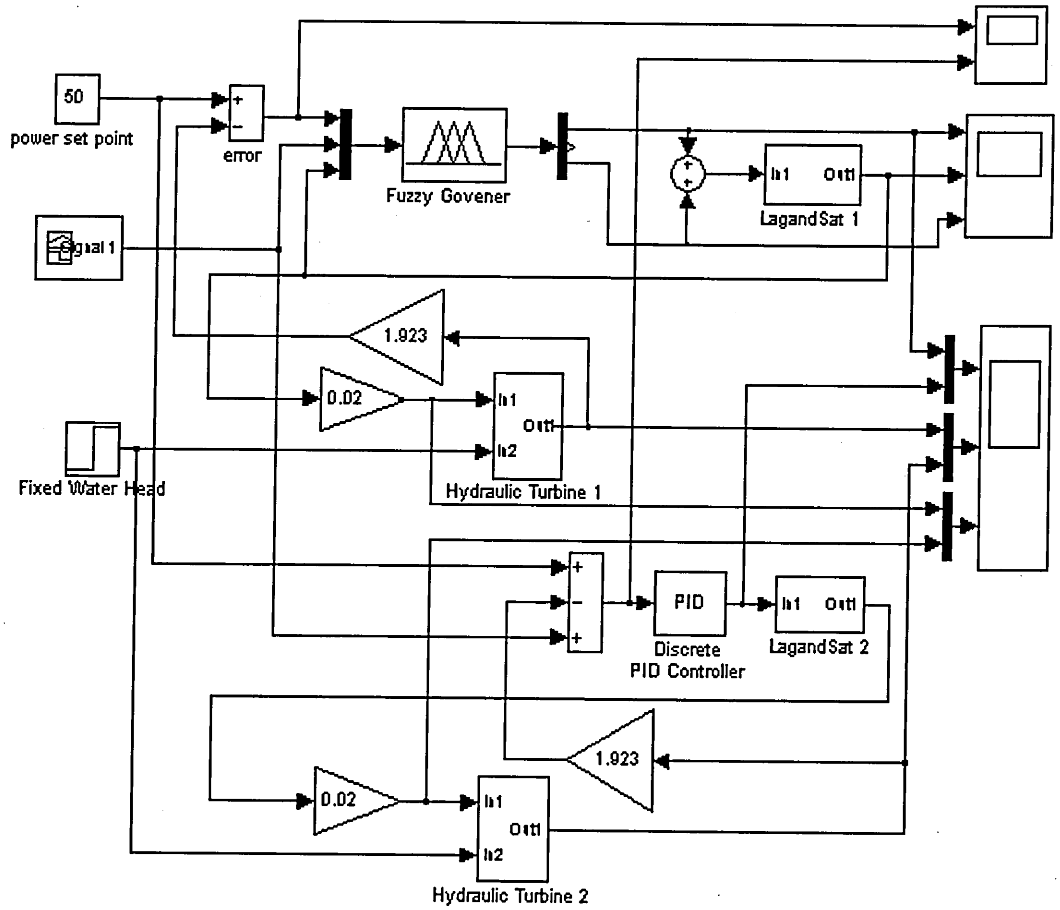
Simulation model of three hydraulically coupled turbines

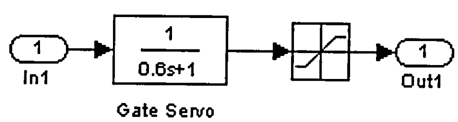
APPENDIX- B CHAPTER 4 SIMULATION MODELS

B.1 Cascaded Reservoirs Hydropower Plant Physical Parameters:

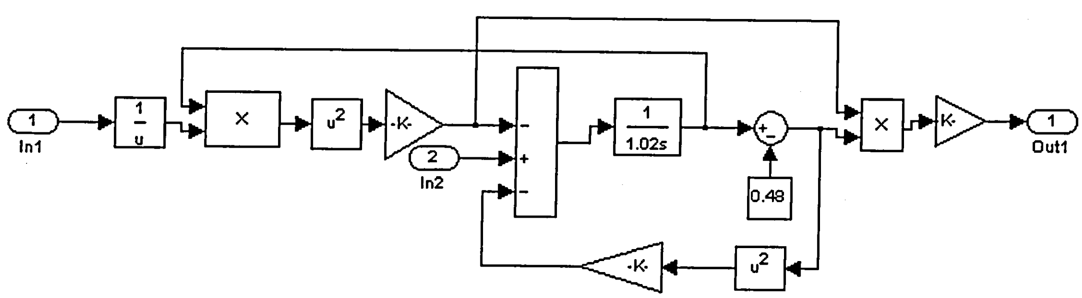
L	100 m	H_D	115 maximum
L_1,L_2,L_3	20 m	A_{c1},A_{c2},A_{c3}	2 m^2
Ac	6 m^2	K	1.7
K_1,K_2,K_3	2.72	η	*0.76*
f_T	1.025×10^{-3}	f_{P1}, f_{P2}, f_{P3}	3.186×10^{-3}
Ω	0	δ	1
f	0.02	g	9.81 $m.s^{-2}$
ρ	1000 $kg.m^{-3}$	Reservoir Height	15 m

B.2 Simulink Model of Section 4.8.1:





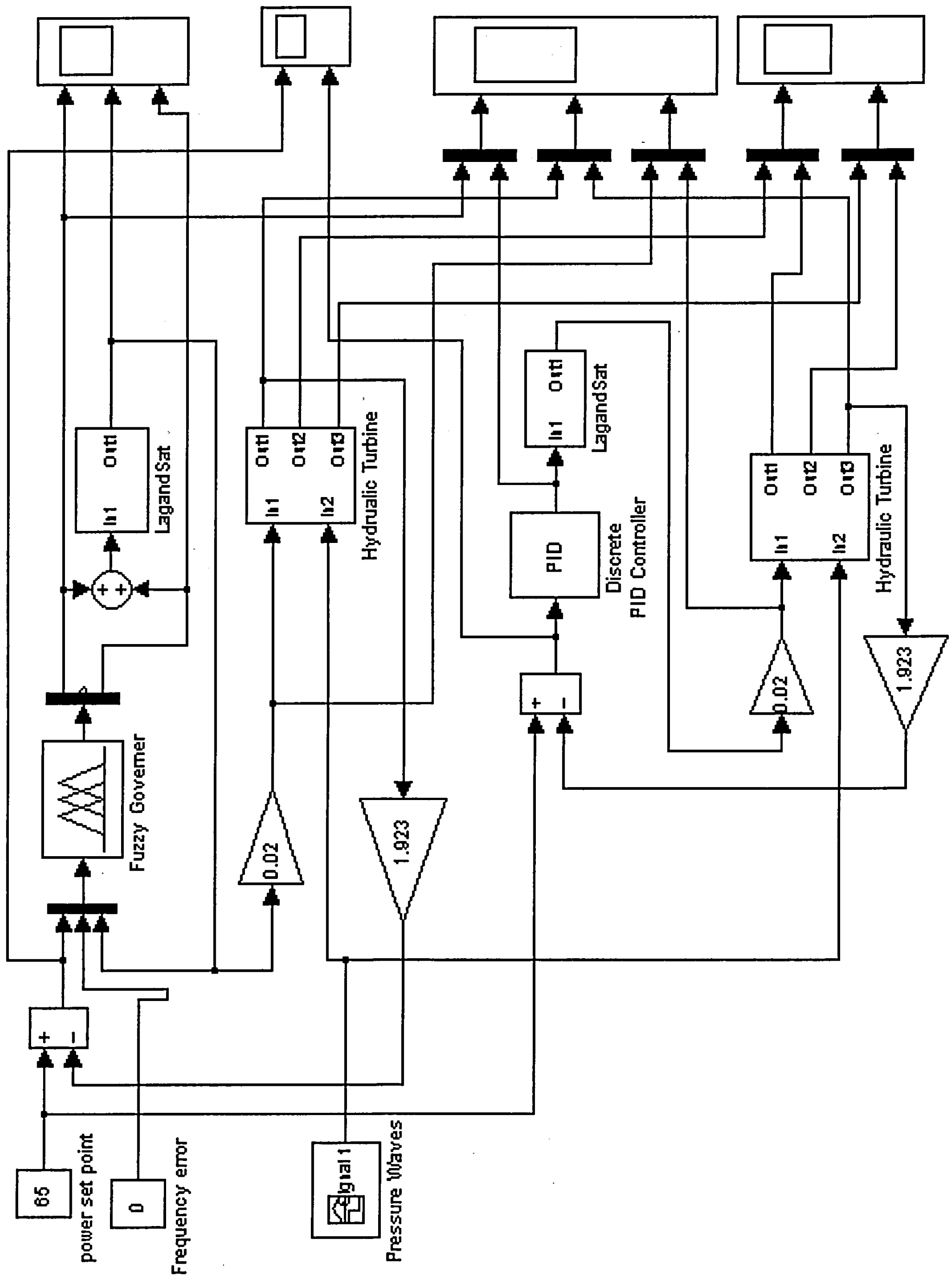
LagandSat 1



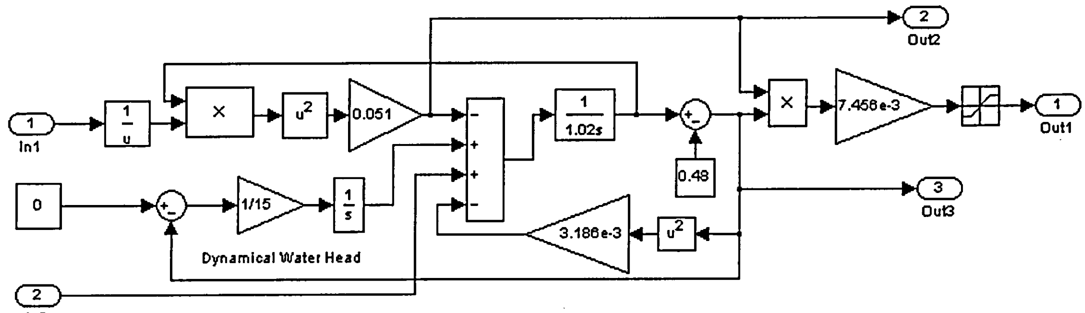
Hydraulic Turbine 1, 2

Simulation model of the hydraulic turbine controlled by the fuzzy governor and the PID governor.

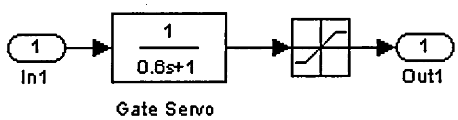
B.3 Simulink Model of Section 4.8.2:



Simulation model of the hydraulic turbine, controlled by the fuzzy governor and the PID governor with disturbances.



Hydraulic Turbine



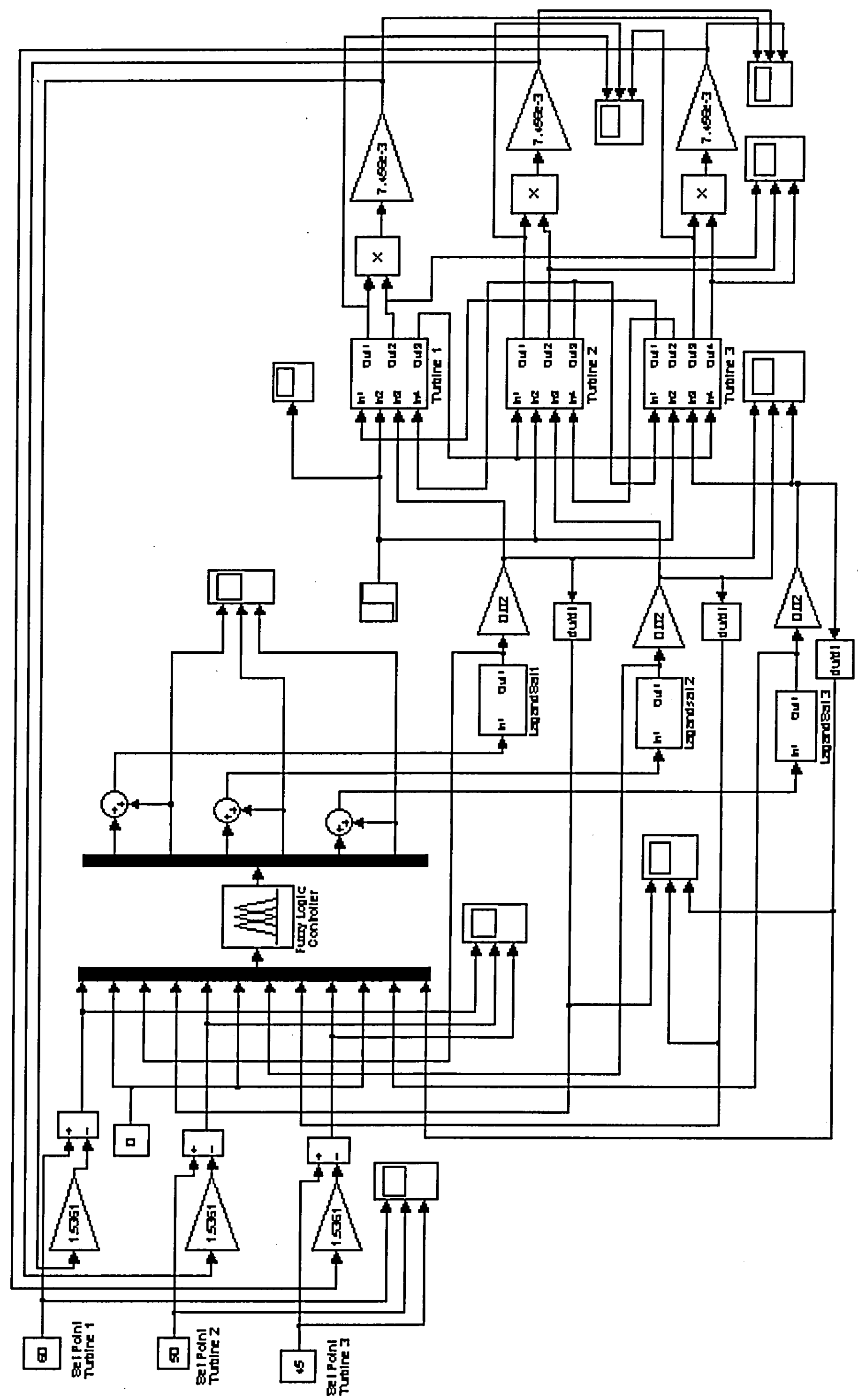
LagandSat

APPENDIX- C CHAPTER 5 SIMULATION MODELS

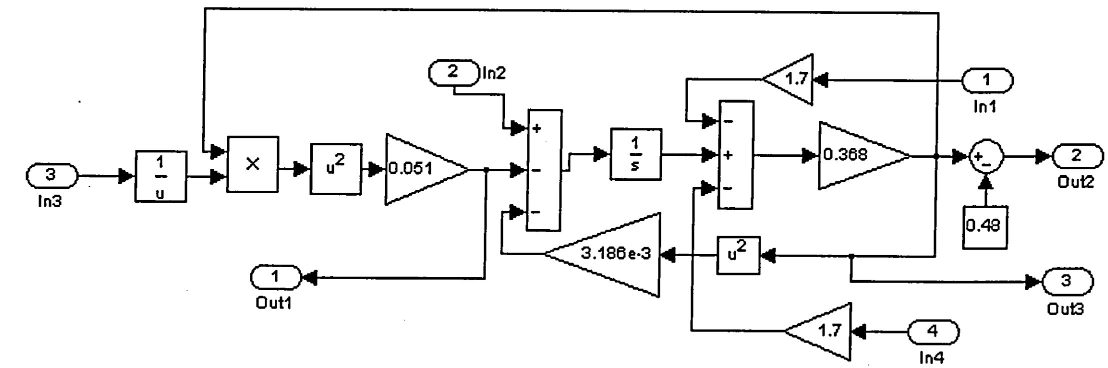
C.1 Cascaded Reservoirs Hydropower Plant Physical Parameters:

L	100 m	H_D	115 maximum
L_1, L_2, L_3	20 m	A_{c1}, A_{c2}, A_{c3}	2 m^2
Ac	6 m^2	K	1.7
K_1, K_2, K_3	2.72	η	*0.76*
f_T	1.025×10^{-3}	f_{P1}, f_{P2}, f_{P3}	3.186×10^{-3}
Ω	0	δ	1
f	0.02	g	9.81 $m.s^{-2}$
ρ	1000 $kg.m^{-3}$	Reservoir Height	15 m

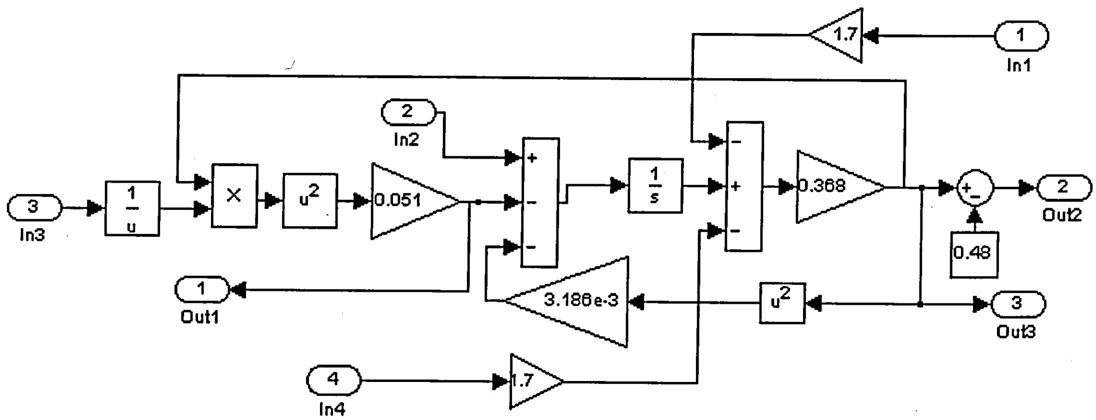
C.2 Simulink Model of Sections 5.8.1:



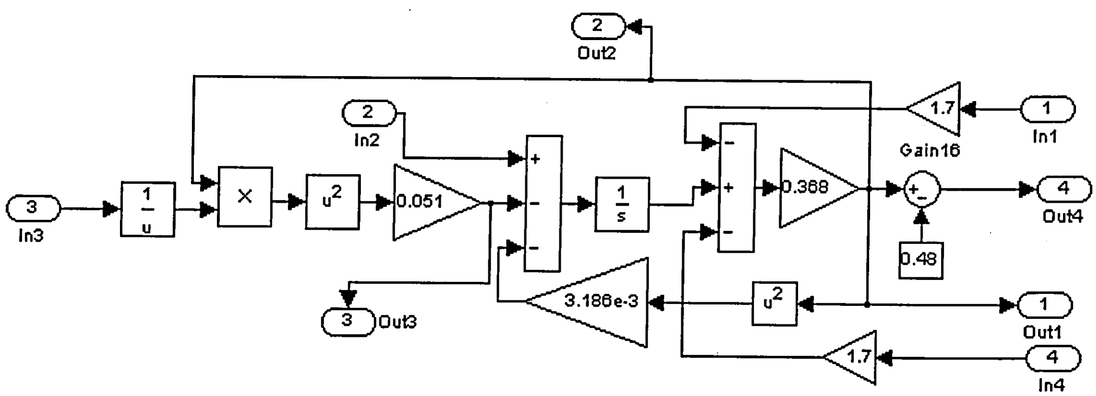
Simulation model of the fuzzy controller with three hydraulically coupled turbines.



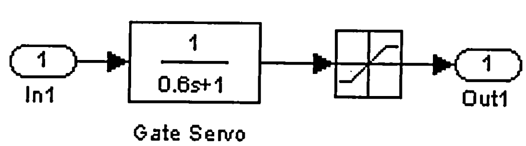
Turbine 1



Turbine 2

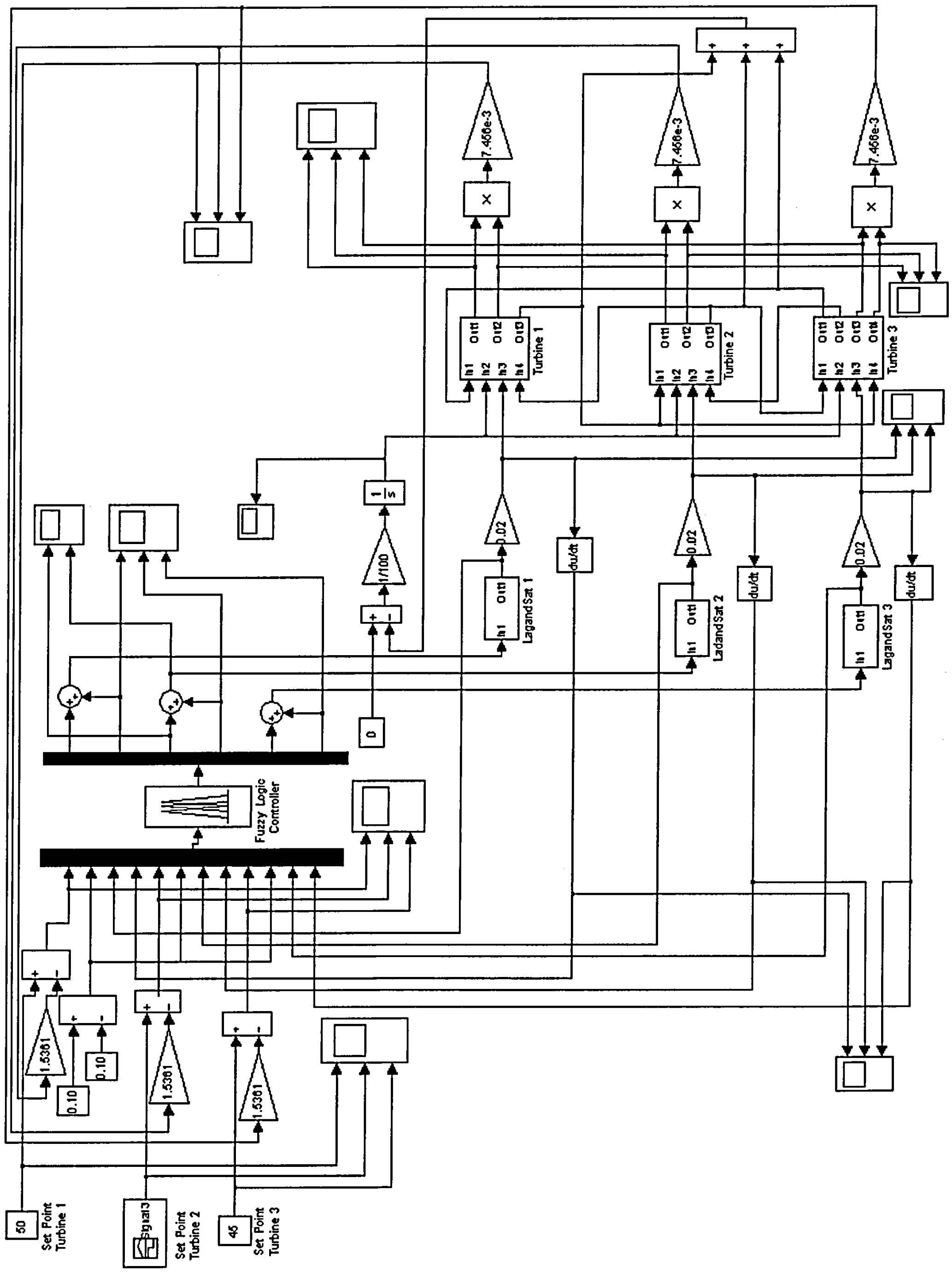


Turbine 3

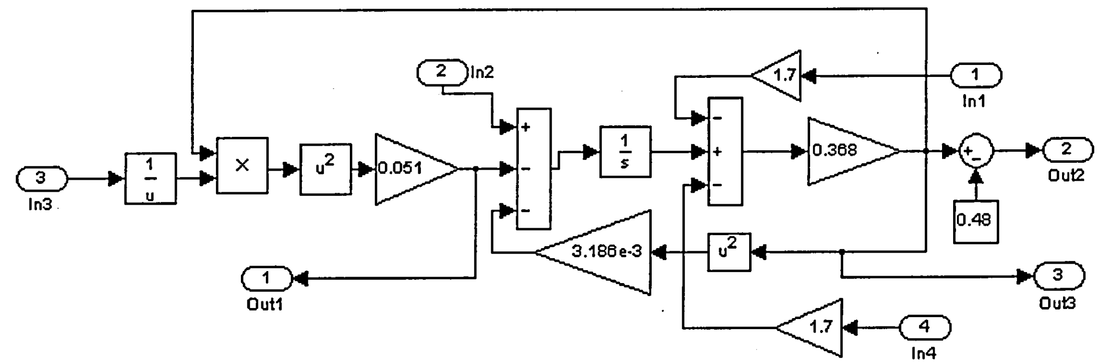


LagandSat

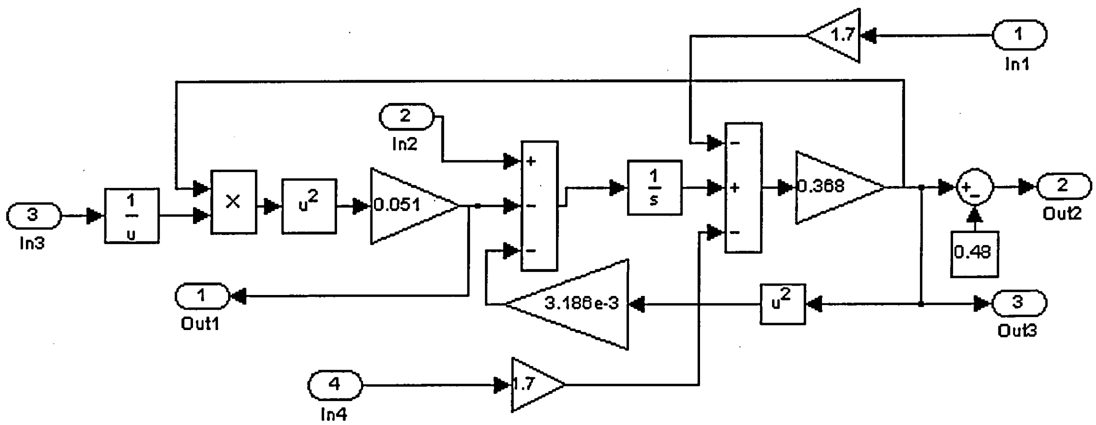
C.3 Simulink Model of Sections 5.8.2:



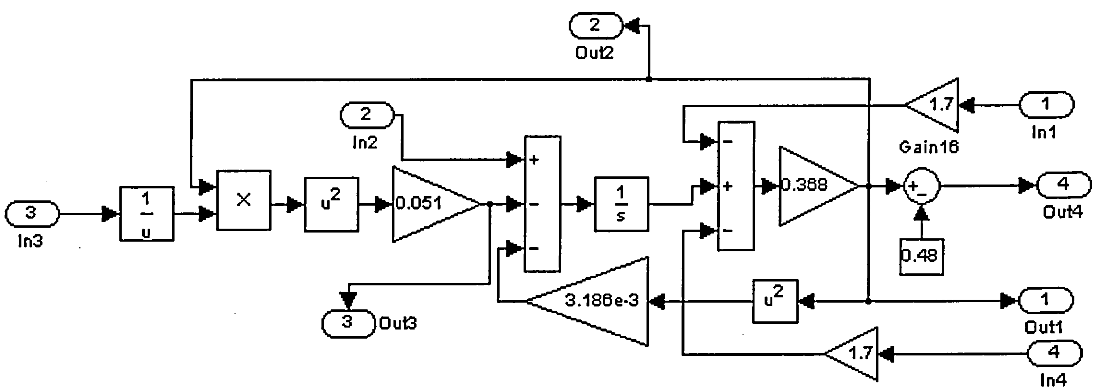
Simulation model of the fuzzy controller with three hydraulically coupled turbines with disturbances.



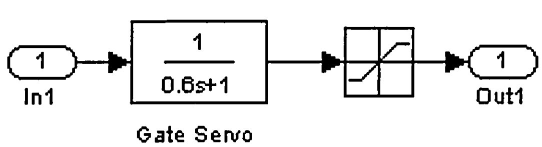
Turbine 1



Turbine 2



Turbine 3



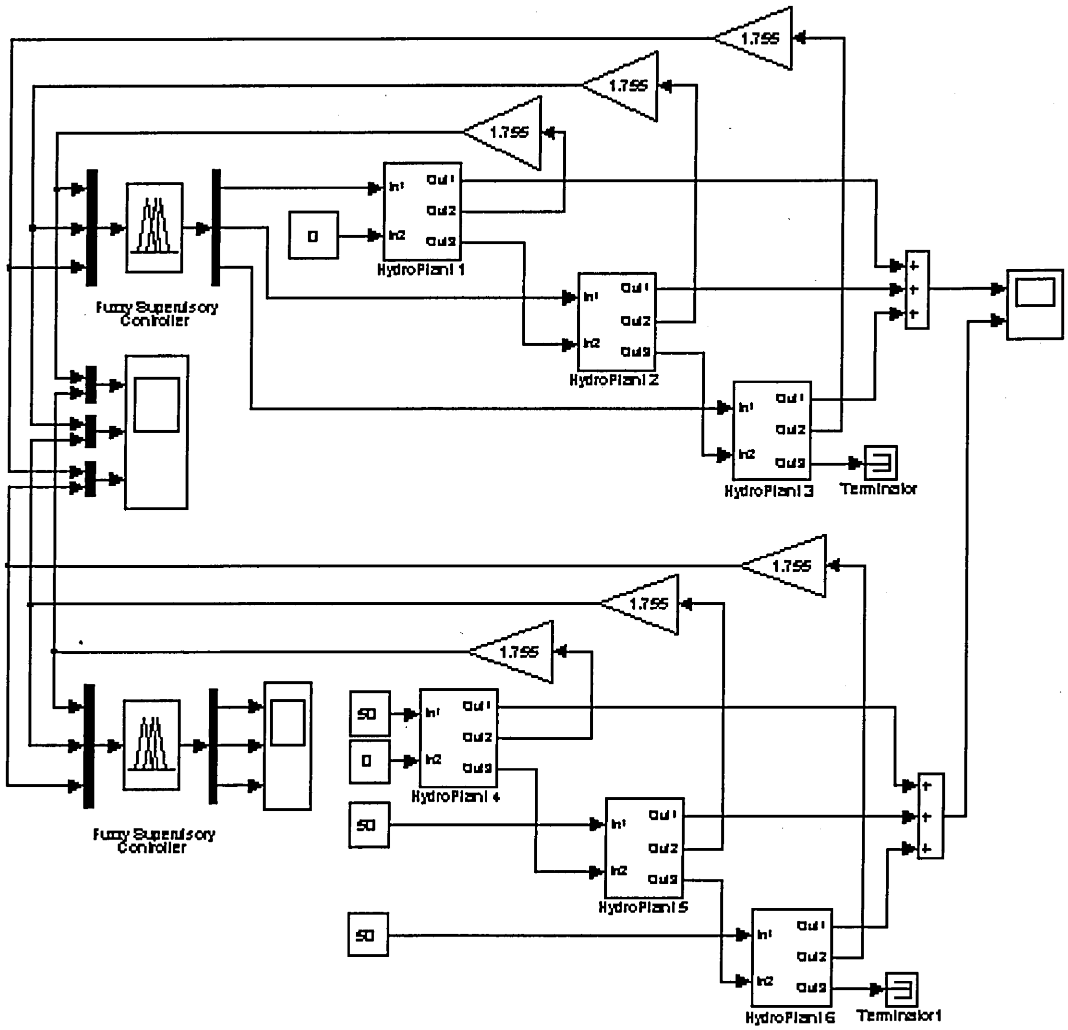
LagandSat

APPENDIX- D CHAPTER 6 SIMULATION MODELS

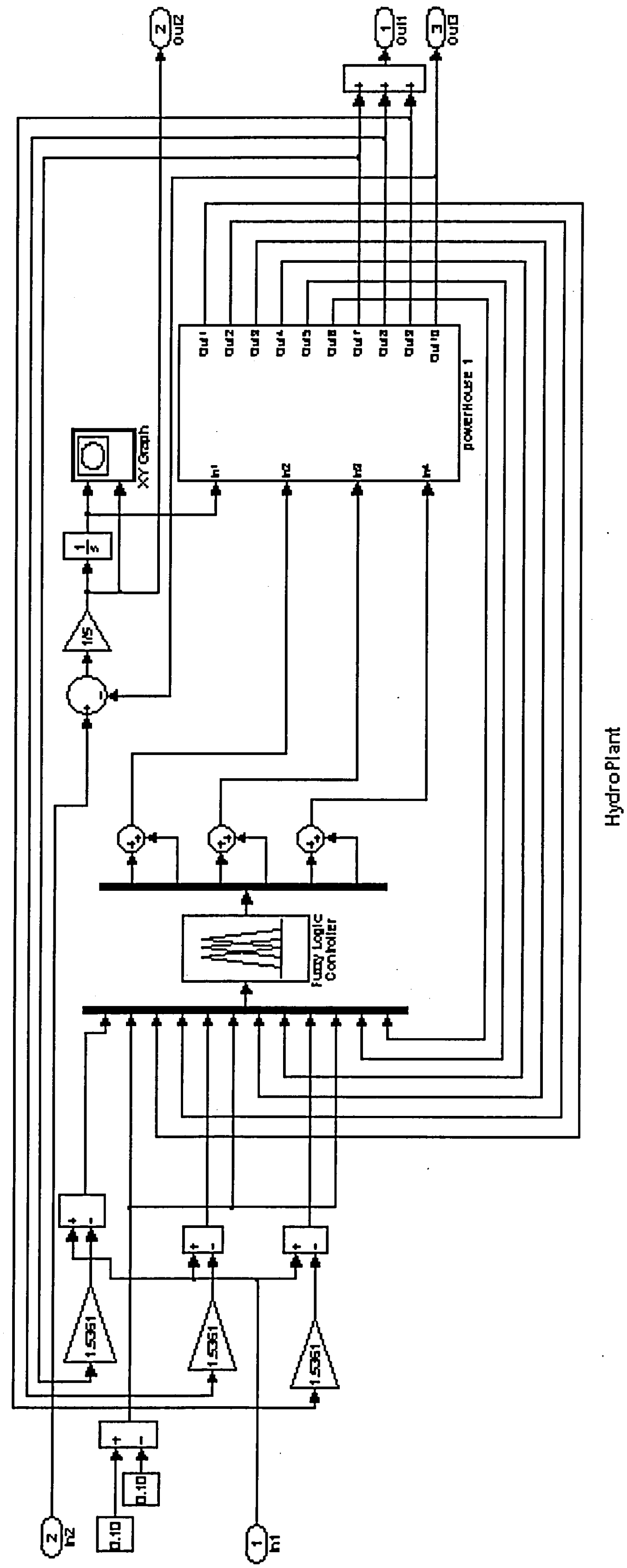
D.1 Cascaded Reservoirs Hydropower Plant Physical Parameters:

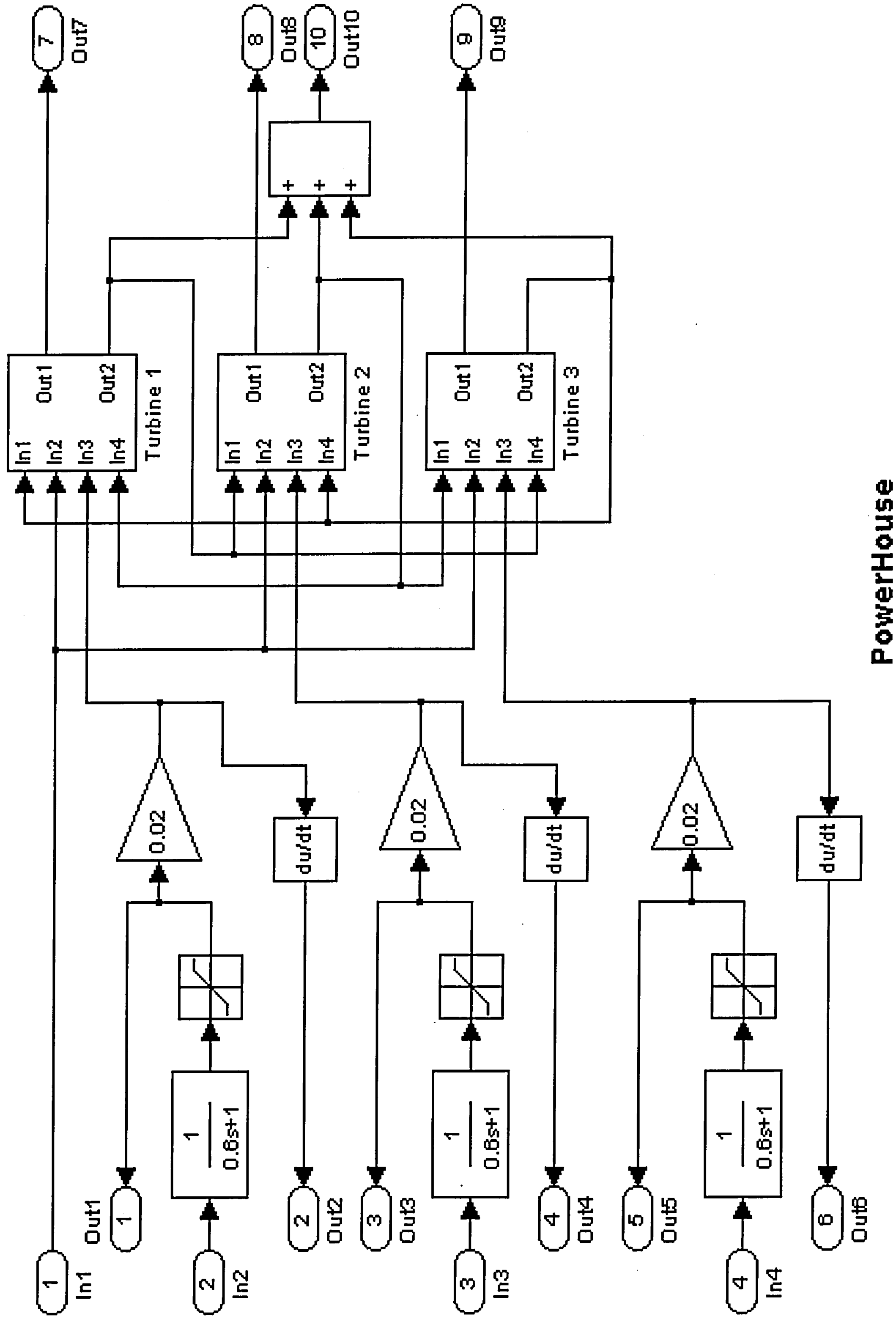
L	100 m	H_D	115 maximum
L_1,L_2,L_3	20 m	A_{c1},A_{c2},A_{c3}	2 m^2
Ac	6 m^2	K	1.7
K_1,K_2,K_3	2.72	η	*0.76*
f_T	1.025×10^{-3}	f_{P1}, f_{P2}, f_{P3}	3.186×10^{-3}
Ω	0	δ	1
f	0.02	g	9.81 m .s^{-2}
ρ	1000 kg.m^{-3}	Reservoir Height	15 m

D.2 Simulink Model of Sections 6.3.1- 6.3.3:

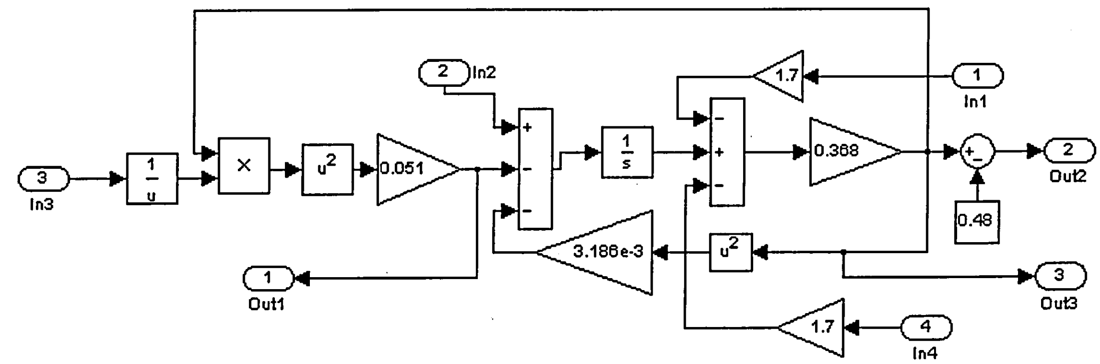


Simulation model of a cascaded reservoirs hydropower system comprises three hydropower subsystems (HydroPlant 1-3) with the fuzzy supervisory control and optimization system. Each hydropower subsystem simulation model is presented in the following sections.

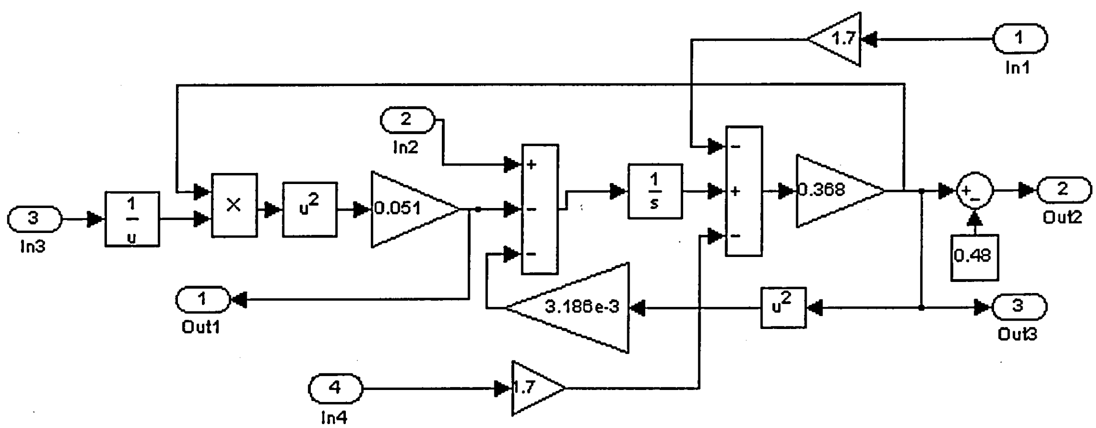

Out2
Out1
Out3
XY Graph
powerHouse 1
Fuzzy Logic Controller
HydroPlant
1.5361
1.5361
1.5361
0.10
0.10
In2
In1



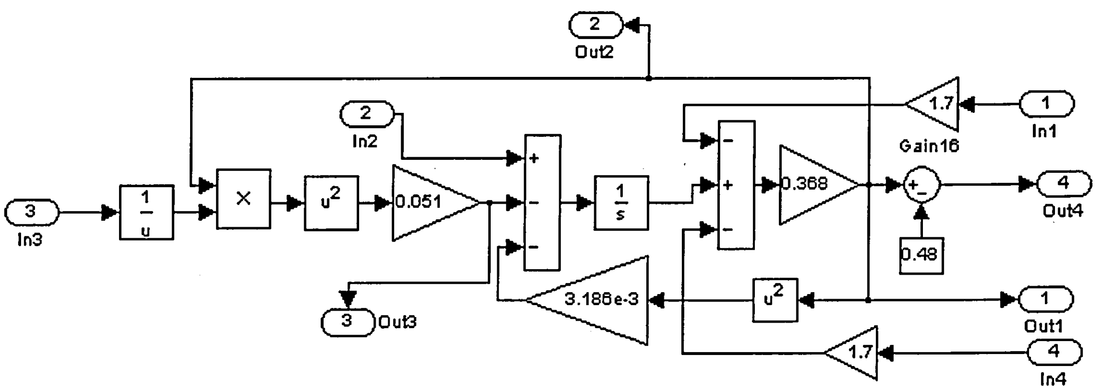
PowerHouse
Turbine 1
Turbine 2
Turbine 3
In1
In2
In3
In4
Out1
Out2
0.02
du/dt
1
0.6s+1
Out1
Out2
Out3
Out4
Out5
Out6
Out7
Out8
Out9
Out10



Turbine 1



Turbine 2



Turbine 3

APPENDIX- E FUZZY RULES

E.1 Start up From Initial Conditions Fuzzy Rules:

IF	Power Error	&	Frequency Error	&	Gate Position	*THEN*	Gate Control	&	Gate Delta
	PHH		ANY		FC		MAX		ZERO
	PHH		ANY		MIN		MAX		ZERO
	PH		ANY		FC		HH		ZERO
	PH		ANY		MIN		HH		ZERO
	PM		ANY		FC		H		ZERO
	PM		ANY		MIN		H		ZERO
	PS		ANY		FC		MS		ZERO
	PS		ANY		MIN		MS		ZERO
	PSS		ANY		FC		SS		ZERO
	PSS		ANY		MIN		SS		ZERO

E.2 Reach the Operational Zone Fuzzy Rules:

IF	Power Error	&	Frequency Error	&	Gate Position	*THEN*	Gate Control	&	Gate Delta
	PHH		ANY		SS		MAX		ZERO
	PH		ANY		SS		HH		ZERO
	PM		ANY		SS		H		ZERO
	PS		ANY		SS		MS		ZERO
	PSS		ANY		SS		S		ZERO
	OZ		ANY		SS		SS		ZERO
	PHH		ANY		S		MAX		ZERO
	PH		ANY		S		HH		ZERO
	PM		ANY		S		H		ZERO
	PS		ANY		S		M		ZERO
	PSS		ANY		S		MS		ZERO
	OZ		ANY		S		S		ZERO
	PHH		ANY		MS		MAX		ZERO
	PH		ANY		MS		HH		ZERO
	PM		ANY		MS		H		ZERO
	PS		ANY		MS		MH		ZERO
	PSS		ANY		MS		M		ZERO
	OZ		ANY		MS		MS		ZERO
	PHH		ANY		M		MAX		ZERO
	PH		ANY		M		HH		ZERO
	PM		ANY		M		H		ZERO
	PS		ANY		M		M		ZERO
	PSS		ANY		M		MH		ZERO
	OZ		ANY		M		M		ZERO
	PHH		ANY		MH		MAX		ZERO
	PH		ANY		MH		MAX		ZERO
	PM		ANY		MH		MAX		ZERO
	PS		ANY		MH		HH		ZERO
	PSS		ANY		MH		H		ZERO
	OZ		ANY		MH		MH		ZERO
	PHH		ANY		H		FO		ZERO
	PH		ANY		H		MAX		ZERO
	PM		ANY		H		MAX		ZERO
	PS		ANY		H		MAX		ZERO
	PSS		ANY		H		HH		ZERO
	OZ		ANY		H		H		ZERO
	PHH		ANY		HH		FO		ZERO
	PH		ANY		HH		FO		ZERO
	PM		ANY		HH		FO		ZERO
	PS		ANY		HH		FO		ZERO
	PSS		ANY		HH		MAX		ZERO
	OZ		ANY		HH		HH		ZERO
	PHH		ANY		MAX		FO		ZERO
	PH		ANY		MAX		FO		ZERO
	PM		ANY		MAX		FO		ZERO
	PS		ANY		MAX		FO		ZERO
	PSS		ANY		MAX		FO		ZERO
	OZ		ANY		MAX		MAX		ZERO

IF	Power Error	&	Frequency Error	&	Gate Position	*THEN*	Gate Control	&	Gate Delta
	NHH		ANY		MAX		MIN		ZERO
	NH		ANY		MAX		S		ZERO
	NM		ANY		MAX		M		ZERO
	NS		ANY		MAX		H		ZERO
	NSS		ANY		MAX		HH		ZERO
	NHH		ANY		HH		MIN		ZERO
	NH		ANY		HH		S		ZERO
	NM		ANY		HH		M		ZERO
	NS		ANY		HH		MH		ZERO
	NSS		ANY		HH		H		ZERO
	NHH		ANY		H		MIN		ZERO
	NH		ANY		H		SS		ZERO
	NM		ANY		H		S		ZERO
	NS		ANY		H		M		ZERO
	NSS		ANY		H		MH		ZERO
	NHH		ANY		MH		MIN		ZERO
	NH		ANY		MH		SS		ZERO
	NM		ANY		MH		S		ZERO
	NS		ANY		MH		MS		ZERO
	NSS		ANY		MH		M		ZERO
	NHH		ANY		M		FC		ZERO
	NH		ANY		M		MIN		ZERO
	NM		ANY		M		MIN		ZERO
	NS		ANY		M		SS		ZERO
	NSS		ANY		M		MS		ZERO
	NHH		ANY		MS		FC		ZERO
	NH		ANY		MS		FC		ZERO
	NM		ANY		MS		FC		ZERO
	NS		ANY		MS		MIN		ZERO
	NSS		ANY		MS		S		ZERO
	NHH		ANY		S		FC		ZERO
	NH		ANY		S		FC		ZERO
	NM		ANY		S		FC		ZERO
	NS		ANY		S		MIN		ZERO
	NSS		ANY		S		SS		ZERO
	NHH		ANY		SS		FC		ZERO
	NH		ANY		SS		FC		ZERO
	NM		ANY		SS		FC		ZERO
	NS		ANY		SS		FC		ZERO
	NSS		ANY		SS		FC		ZERO
	NHH		ANY		MIN		FC		ZERO
	NH		ANY		MIN		FC		ZERO
	NM		ANY		MIN		FC		ZERO
	NS		ANY		MIN		FC		ZERO
	NSS		ANY		MIN		FC		ZERO
	NHH		ANY		FC		FC		ZERO
	NH		ANY		FC		FC		ZERO
	NM		ANY		FC		FC		ZERO
	NS		ANY		FC		FC		ZERO
	NSS		ANY		FC		FC		ZERO

E.3 Inside the Operational Zone Fuzzy Rules:

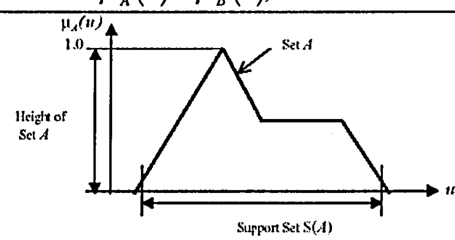
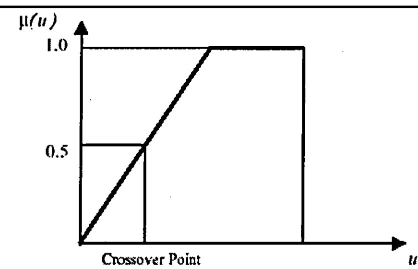
IF	Power Error	&	Frequency Error	&	Gate Position	*THEN*	Gate Control	&	Gate Delta
	OZ		NHH		FO		FO		NH
	OZ		NHH		MAX		MAX		NH
	OZ		NHH		HH		HH		NH
	OZ		NHH		H		H		NH
	OZ		NHH		MH		MH		NH
	OZ		NHH		M		M		NH
	OZ		NHH		MS		MS		NH
	OZ		NHH		S		S		NH
	OZ		NHH		SS		SS		NH
	OZ		NHH		MIN		MIN		NH
	OZ		NHH		FC		FC		NH
	OZ		NH		FO		FO		NM
	OZ		NH		MAX		MAX		NM
	OZ		NH		HH		HH		NM
	OZ		NH		H		H		NM
	OZ		NH		MH		MH		NM
	OZ		NH		M		M		NM
	OZ		NH		MS		MS		NM
	OZ		NH		S		S		NM
	OZ		NH		SS		SS		NM
	OZ		NH		MIN		MIN		NM
	OZ		NH		FC		FC		NM
	OZ		NM		FO		FO		NS
	OZ		NM		MAX		MAX		NS
	OZ		NM		HH		HH		NS
	OZ		NM		H		H		NS
	OZ		NM		MH		MH		NS
	OZ		NM		M		M		NS
	OZ		NM		MS		MS		NS
	OZ		NM		S		S		NS
	OZ		NM		SS		SS		NS
	OZ		NM		MIN		MIN		NS
	OZ		NM		FC		FC		NS
	OZ		NS		FO		FO		NSS
	OZ		NS		MAX		MAX		NSS
	OZ		NS		HH		HH		NSS
	OZ		NS		H		H		NSS
	OZ		NS		MH		MH		NSS
	OZ		NS		M		M		NSS
	OZ		NS		MS		MS		NSS
	OZ		NS		S		S		NSS
	OZ		NS		SS		SS		NSS
	OZ		NS		MIN		MIN		NSS
	OZ		NS		FC		FC		NSS
	OZ		NSS		FO		FO		NSS
	OZ		NSS		MAX		MAX		NSS
	OZ		NSS		HH		HH		NSS
	OZ		NSS		H		H		NSS

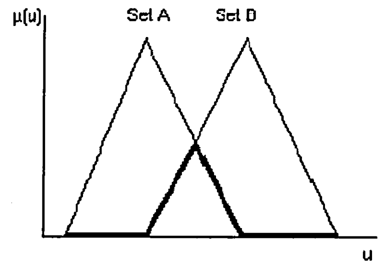
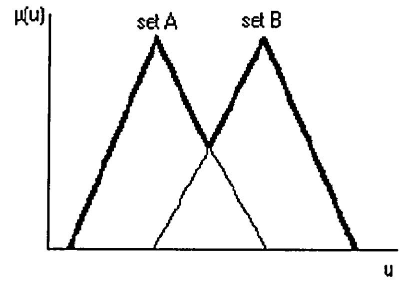
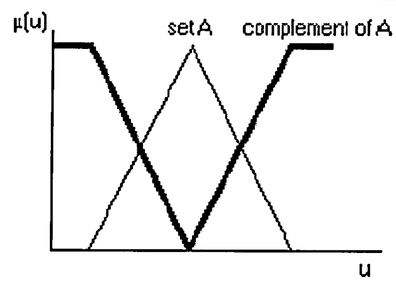
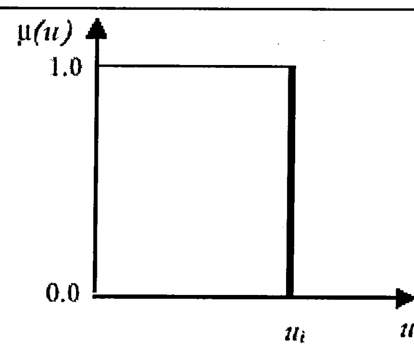
IF	Power Error	&	Frequency Error	&	Gate Position	*THEN*	Gate Control	&	Gate Delta
	OZ		NSS		MH		MH		NSS
	OZ		NSS		M		M		NSS
	OZ		NSS		MS		MS		NSS
	OZ		NSS		S		S		NSS
	OZ		NSS		SS		SS		NSS
	OZ		NSS		MIN		MIN		NSS
	OZ		NSS		FC		FC		NSS
	OZ		OZ		FO		FO		------
	OZ		OZ		MAX		MAX		------
	OZ		OZ		HH		HH		------
	OZ		OZ		H		H		------
	OZ		OZ		MH		MH		------
	OZ		OZ		M		M		------
	OZ		OZ		MS		MS		------
	OZ		OZ		S		S		------
	OZ		OZ		SS		SS		------
	OZ		OZ		MIN		MIN		------
	OZ		OZ		FC		FC		------
	OZ		PSS		FO		FO		PSS
	OZ		PSS		MAX		MAX		PSS
	OZ		PSS		HH		HH		PSS
	OZ		PSS		H		H		PSS
	OZ		PSS		MH		MH		PSS
	OZ		PSS		M		M		PSS
	OZ		PSS		MS		MS		PSS
	OZ		PSS		S		S		PSS
	OZ		PSS		SS		SS		PSS
	OZ		PSS		MIN		MIN		PSS
	OZ		PSS		FC		FC		PSS
	OZ		PS		FO		FO		PS
	OZ		PS		MAX		MAX		PS
	OZ		PS		HH		HH		PS
	OZ		PS		H		H		PS
	OZ		PS		MH		MH		PS
	OZ		PS		M		M		PS
	OZ		PS		MS		MS		PS
	OZ		PS		S		S		PS
	OZ		PS		SS		SS		PS
	OZ		PS		MIN		MIN		PS
	OZ		PS		FC		FC		PS
	OZ		PM		FO		FO		PM
	OZ		PM		MAX		MAX		PM
	OZ		PM		HH		HH		PM
	OZ		PM		H		H		PM
	OZ		PM		MH		MH		PM
	OZ		PM		M		M		PM
	OZ		PM		MS		MS		PM
	OZ		PM		S		S		PM

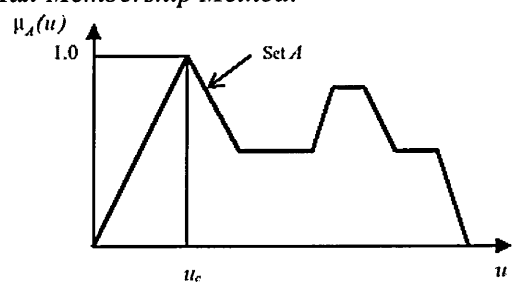
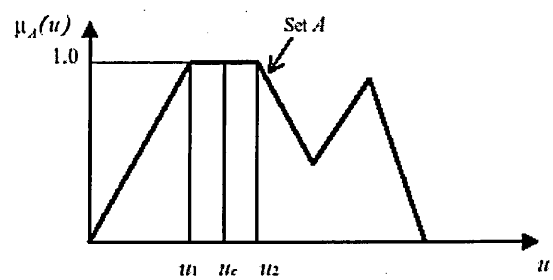
IF	Power Error	&	Frequency Error	&	Gate Position	*THEN*	Gate Control	&	Gate Delta
	OZ		PM		SS		SS		PM
	OZ		PM		MIN		MIN		PM
	OZ		PM		FC		FC		PM
	OZ		PH		FO		FO		PH
	OZ		PH		MAX		MAX		PH
	OZ		PH		HH		HH		PH
	OZ		PH		H		H		PH
	OZ		PH		MH		MH		PH
	OZ		PH		M		M		PH
	OZ		PH		MS		MS		PH
	OZ		PH		S		S		PH
	OZ		PH		SS		SS		PH
	OZ		PH		MIN		MIN		PH
	OZ		PH		FC		FC		PH
	OZ		PHH		FO		FO		PHH
	OZ		PHH		MAX		MAX		PHH
	OZ		PHH		HH		HH		PHH
	OZ		PHH		H		H		PHH
	OZ		PHH		MH		MH		PHH
	OZ		PHH		M		M		PHH
	OZ		PHH		MS		MS		PHH
	OZ		PHH		S		S		PHH
	OZ		PHH		SS		SS		PHH
	OZ		PHH		MIN		MIN		PHH
	OZ		PHH		FC		FC		PHH

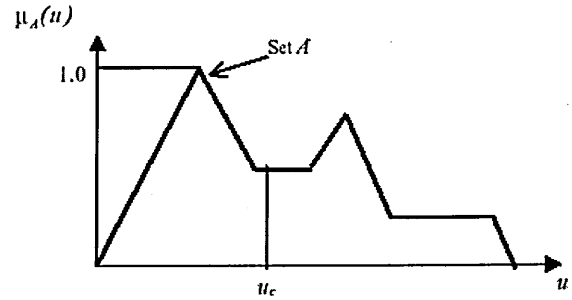
APPENDIX- F FUZZY TERMS, OPERATORS AND MEMBERSHIP TYPES

The fuzzy terms and operators are defined and summarized as follows:

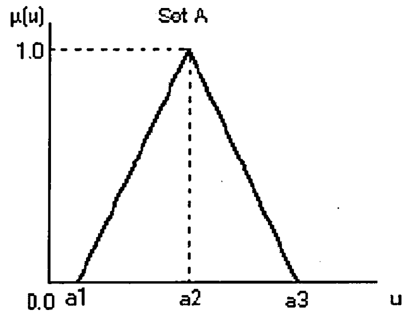
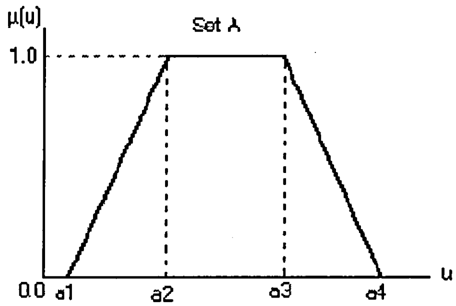
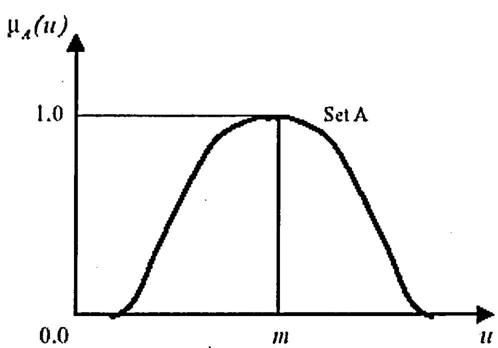
Term	*Definition*
Empty Fuzzy Set	A fuzzy set A is empty if: $\mu_A(u)=0, \forall u \in U$
Normal Fuzzy Set	A fuzzy set A is called normal if there is at least one element u_o that has a membership function equal to one: $\mu_A(u_o)=1$
Equality of Fuzzy Sets	Two fuzzy sets A and B are said to be equal if their membership functions are equal for every element u: $\mu_A(u)=\mu_B(u), \forall u \in U$
Height of Fuzzy Set	 It is the maximum value of the membership function for all $u \in U$.
Fuzzy Crossover Point	 It is the element in the universe of discourse that has a membership function with a value of 0.5.
Concentration "VERY"	The concentration of a fuzzy set A is obtained by squaring its membership function over the universe of discourse: $\mu_{CON(A)}(u) = (\mu_A(u))^2$
Dilation	The dilation of a fuzzy set A produces a new fuzzy set with membership function equal to the square root of the membership function of A: $\mu_{DIL(A)}(u) = \sqrt{\mu_A(u)}$

Intersection "AND"	 The intersection of two fuzzy sets A and B whose membership functions are μ_A and μ_B respectively, is defined as: $\mu_{A\cap B}(u) = \min(\mu_A(u), \mu_B(u))$; or $\mu_{A\cap B}(u) = \mu_A(u) \cdot \mu_B(u)$
Union "OR"	 The union of two sets A and B is defined as: $\mu_{A\cup B}(u) = \max(\mu_A(u), \mu_B(u))$; or $\mu_{A\cup B}(u) = [\mu_A(u) + \mu_B(u)] - [\mu_A(u).\mu_B(u)]$
Complement "NOT"	 For a fuzzy set A with a membership function $\mu_A(u)$, the complement of A is defined as: $\overline{\mu_A(u)} = 1 - \mu_A(u)$
Fuzzification	

	This is the process of converting a crisp quantity into a fuzzy quantity. Fuzzification maps a crisp input $u_i \in U$ into a fuzzy set A_{ui} which may take the form of a singleton: $$\mu_{A_{ui}}(u) = \begin{Bmatrix} 1, u < u_i \\ 0, Otherwise \end{Bmatrix}$$ Or may take the form of any of the membership function as shown in Table(2), it is defined as follows: $$\mu_{A_{ui}}(u) = \begin{Bmatrix} 1, u = u_i \\ decreases\ from\ 1\ as\ u\ moves\ from\ u_i \end{Bmatrix}$$
Defuzzification	This is the process that maps a fuzzy quantity to a crisp quantity which can be achieved by using any of the following three methods: *1) Max-Membership Method:*  The crisp value is the one with the highest degree of membership, i.e. u_c is chosen such that: $\mu_A(u_c) \geq \mu_A(u) \forall u \in U$ 2) *Mean of Maxima Method*  It is used when there is more than one peak value in the membership shape. In this method, u_c is the mean value of all peaks present in the shape, as follows: $$u_C = \frac{u_1 + u_2}{2}$$

	3) Centre of Gravity Method  Here, u_C is chosen to give an approximation of the geometrical centre of a closed curve, i.e. it is the value that splits the area under $\mu_A(u)$ curve into two equal parts: $u_C = \dfrac{\int \mu_A(u).u.du}{\int \mu_A(u).du}$

The fuzzy membership types are defined and summarized as follows:

Fuzzy Membership Type	*Definition*
Triangular 	The triangular membership function has a sharp transition, its value may be written as follows: $$\mu_A(u)=\begin{cases}0, u<a_1\\ \dfrac{u-a_1}{a_2-a_1}, a_1\le u<a_2\\ \dfrac{a_3-u}{a_3-a_2}, a_2\le u<a_3\\ 0, u\ge a_3\end{cases}$$
Trapezoidal 	The trapezoidal membership function is similar to the triangular membership function but with more than one peak value, its value may be written as follows: $$\mu_A(u)=\begin{cases}0, u<a_1\\ \dfrac{u-a_1}{a_2-a_1}, a_1\le u<a_2\\ 1, a_2\le u<a_3\\ \dfrac{a_3-u}{a_3-a_2}, a_2\le u<a_4\\ 0, u\ge a_4\end{cases}$$
Gaussian 	The gaussian membership function is used when extra smoothness in transitions is required, its value may be written as follows: $$\mu_A(u)=e^{-\left\{\frac{u-m}{\sigma}\right\}^2}$$

APPENDIX- G LIST OF PUBLISHED JOURNAL PAPERS

Paper Title	Journal Name	Status
Design of a Fuzzy Logic Hydraulic Turbine Governor	Control and Intelligent Systems	Submitted on 4/6/2003 Accepted for publication on 15/10/2003 Copy is attached
Dynamical Modelling of Three Hydraulically Coupled Turbines	Power and Energy Systems	Submitted on 11/6/2003 Accepted for publication on 9/12/2003 Copy is attached
Fuzzy Controller for Three Hydraulically Coupled Turbines	ISA Transactions	Submitted on 18/6/2003 Under Review
Dynamical Modelling and Simulation of a Cascaded Reservoirs Hydropower Plant	Electric Power Systems Research	Submitted on 27/6/2003 Under Review
Fuzzy Supervisory Control and Optimization System for a Cascaded Reservoirs Hydropower Plant	European Journal of Control	Submitted on 24/7/2003 Under Review

From: "journals" <journals@iasted.org>
To: <M.Mahmoud@shu.ac.uk>
Sent: 15 October 2003 22:41
Subject: Final Acceptance - Paper 201-1434REV

Re: Revised Paper Number 201-1434

Dear Dr. Mahmoud:

I am very pleased to inform you that the above-mentioned paper, entitled "DESIGN OF A FUZZY LOGIC
HYDRAULIC TURBINE GOVERNOR", has been accepted for publication in the international journal,
Control and Intelligent Systems. This paper has passed peer review, and final approval by a member of the Editorial Board.

Your paper will be copy edited by our staff and formatted for publication using LaTeX. When processing of your paper is complete, a galley proof will be sent to you to check over. I will schedule your paper to be published in the next issue, if possible. Page charges may apply: for papers exceeding eight (two-column) printed pages, including illustrations, there is a mandatory page charge of US $100 per page, which is a prerequisite for publication.

Thank you very much for helping us maintain the consistent high quality of this publication.

Yours very truly,

Carmen Kam
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December 9, 2003

M. Mahmoud
School of Engineering
Sheffield Hallam University
Pond Street
Sheffield S1 1WB
United Kingdom

RE: "Dynamical Modelling and Simulation of a Cascaded Reserevoirs Hydropower Plant"

Dear Professor Mahmoud:

It is my pleasure to inform you that the above-referenced paper has been accepted for publication in *EPSR*. Your paper will appear in an upcoming issue of the Journal. Any further correspondence concerning your paper will be from the publisher in Ireland.

Thank you for your interest in the Journal. Through *EPSR,* your technical contributions will be broadly disseminated and will benefit the power engineering profession worldwide.

Very truly yours,

B. Don Russell, Ph.D., P.E.
Editor-in-Chief

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