



***ADDIS ABABA INSTITUTE OF TECHNOLOGY***

***Department of Electrical and Computer Engineering***

***(Industrial Control)***

***MSc THESIS (ECEg 7909)***

***AN INTELLIGENT AUTOMATIC GENERATION CONTROL***

***FOR A HYDRO-POWER SYSTEM***

***By***

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# **ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**Department of Electrical and Computer Engineering**

**(Industrial Control)**

**A Thesis entitled “AN INTELLIGENT AUTOMATIC GENERATION CONTROL FOR A HYDRO-POWER SYSTEM”, in partial fulfillment of the award of degree of Master of Engineering in Industrial Control submitted to Electrical and Computer Engineering Department of Addis Ababa Institute of Technology, Addis Ababa, Ethiopia.**

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**❖ Certificate**

I hereby certify that the work which is being presented in the Thesis entitled “AN INTELLIGENT AUTOMATIC GENERATION CONTROL FOR HYDRO-POWER SYSTEM”, in partial fulfillment of the award of degree of Master of Engineering in Industrial Control submitted to Electrical and Computer Engineering Department of Addis Ababa Institute of Technology, Addis Ababa, Ethiopia, is an authentic record of my own work carried out under the supervision of **Dr. Dereje S.**

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

**Adane Leul** .....

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

**Dr. Dereje S.** .....

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## ❖ **Abstract**

In an interconnected power system, any sudden small load perturbation in any of the interconnected areas causes the deviation of area frequency and tie line power. Automatic generation control (AGC) plays a very important role to maintain system frequency and tie line power flow at their scheduled values during any load perturbation. Classical controllers like PI and PID controllers are very simple for implementation and give better dynamic response. But, they have larger response time, lack of efficiency, poor handling of system nonlinearities and are not suitable for complex, uncertain, high order and time delay systems. Intelligent controllers can provide a high adaptation to changing conditions and have ability to make decisions quickly by processing imprecise information. They can also perform effectively even with nonlinearities.

This thesis work presents the application of an intelligent AGC such as artificial neural networks (ANN) and fuzzy logic controller (FLC) for a hydropower system. The ANN techniques are used for AGC of interconnected hydro power systems. The feed forward neural network controllers are developed and trained using Lavenberg-Marquardt (LM) back propagation algorithm under supervised training method with adequate amount of data that are generated by using optimal control strategies.

The programming was done in MATLAB and the result shows an improved performance in terms of rise time, settling time, steady state error and overshoot. The designed FLC gave a response with settling time 45 sec and a frequency deviation of 2.3 per unit (p.u). This is a better result than that of a PID controller with settling time and frequency deviation of 125 sec and 2.6 p.u respectively. The designed ANN controller also gave a performance that is close to optimal controller and superior to the integral controller as expected.

## **Key Words**

- Automatic Generation Control (AGC)
- Artificial Neural Networks (ANN)
- Fuzzy Logic Controller (FLC)
- Lavenberg-Marquardt (LM)
- Proportional Integral Derivative (PID)

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## ***Chapter 1***

### ***INTRODUCTION***

#### ***1.1- Automatic Generation Control Problem***

Power systems perform generation, transmission and distribution of electricity to factories and houses to satisfy all kinds of power demand. To optimize performance of electrical equipment, it is important to ensure the quality of the electric power. It is well known that three-phase alternating current (AC) is generally used to transmit electricity. During transmission, both the active power balance and the reactive power balance must be maintained between generating and utilizing the AC power. [3]

Those two balances correspond to two equilibrium points: frequency and voltage. When either of the two balances is broken and reset at a new level, the equilibrium points will float. A good quality of an electric power system requires both the frequency and voltage to remain at standard values during operation. For Ethiopia, the standard values for the frequency and voltage are 50 Hz and 220 V respectively. [4]

However, the users of the electric power change the loads randomly and momentarily. This makes it impossible to maintain the balances of both the active and reactive powers without control. As a result of the imbalance, the frequency and voltage levels will vary with load change. Thus a control system is essential to cancel the effects of random load changes and to keep the frequency and voltage at the standard values.[6-7]

The objective of control strategy in power system is to generate and deliver power in an interconnected systems as reliably and economically as possible while maintaining the frequency and voltage within permissible limits.

Thus real and reactive powers are controlled separately in different part. As demand deviates from its normal value with small amount, the state of the system will change. The automatic control system must sense or detect these changes and initiate a set of counter control action which will eliminate the state deviation as quickly as possible. Load frequency control is to control the real power and frequency for the power system.[8]

Under steady state condition, the total real power generated in the system equals the total MW demand plus real power losses. Automatic Generation Control (AGC) is a scheme that is responsible to automatically adjust the generation as the load changes. It also ensures that each generator provides the allocated shares and system frequency is always maintained close to the nominal value.[13-15]

An interconnected power system consists of control areas which are connected to each other by tie lines. In a control area, all the generators speed up or slow down together to maintain the frequency and relative power angles to scheduled values in static as well as dynamic conditions. In an interconnected power system, any sudden small load perturbation in any of the interconnected areas causes the deviation of frequencies of all the areas and also of the tie line powers.[5]

The main objectives of Automatic Generation Control (AGC) are:

- To maintain the desired megawatt output and the nominal frequency in an interconnected power system.
- To maintain the net interchange of power between control areas at predetermined values.

A perturbation like adding a block of load in a single area power system operating at nominal value of frequency creates the power mismatch in generation and demand. This mismatch is initially compensated by an extraction of kinetic energy from the system, which causes a declining system frequency. As the frequency decreases, the power taken by old load will also decrease.[16]

In large power systems, the equilibrium may be obtained inherently by themselves at a point when the new load is compensated by the reduction in power taken by old load plus the power corresponding to kinetic energy extracted from the system. Consequently, this equilibrium is obtained at the cost of a reduction in frequency. This equilibrium is self-managed by the system and it does not require any governor action. The frequency decline under such a condition is quite large.[21]

However, if the mismatch is large enough, the governors will come into action and the output of generators will increase. Here, the equilibrium is obtained at a point when the new load is compensated with the reduction in the power taken by old load plus the increased generation due to governor action. [23]

Thus, amount of kinetic energy extracted from the system is reduced to a greater extent, although not totally. Hence for this type of equilibrium, the decline in frequency still exists. But it is quite smaller than the case mentioned above. Such equilibrium is normally obtained within 10-12 seconds after the addition of load. The action of governor is thus a primary control.

Despite the action of the governor, the frequency is still different than nominal value and it is further needed to bring the frequency back to nominal value by another precise control strategy. This is done classically with the help of Integral Controllers. It is a secondary control (which operates after allowing the primary control to act) which brings the frequency back to nominal or very close to nominal value. However, the classical integral controllers are basically slow in action. [24-27]

In case of an interconnected power system having two or more areas connected through tie lines, each area supplies its control area and tie lines allow electric power to flow among the areas. However, a load perturbation in any of the areas affects output frequencies of all the areas as well as power flow on the tie lines. [28]

Hence, the control system of each area needs information about transient situation in all other areas to restore the nominal values of area frequency and tie line power. The information about each area is found in its output frequency and the information about other areas is in the deviation of tie line powers.

For example in a two area interconnected power system, this information is taken as  $B_i \Delta f_i + \Delta P_{tie}$  (i = 1, 2, ...), where B = tie line frequency bias, f = nominal frequency and  $P_{tie}$  = tie line power. This is called as the area control error (ACE) and the same is fed as input to the integral controller of corresponding area. [29-31]

Thus, an AGC scheme for an interconnected power system basically incorporates suitable control system which can bring area frequencies and tieline powers back to nominal or very close to nominal values effectively after the load perturbations.[28]

## **1.2- Interconnected Power System**

From a practical viewpoint, problems of frequency control of an interconnected areas are more important than those of isolated (single) areas. However, for understanding the theory and concept of an interconnected system the knowledge of single area is equally important. Practically all power systems today are tied together with neighboring areas and the problem of automatic generation control becomes a joint undertaking.[32]

Following are basic operating principles of an interconnection;

- Under normal operating conditions each control area should strive to carry its own load.
- Each control area must agree upon adopting and regulating control strategies.[35]

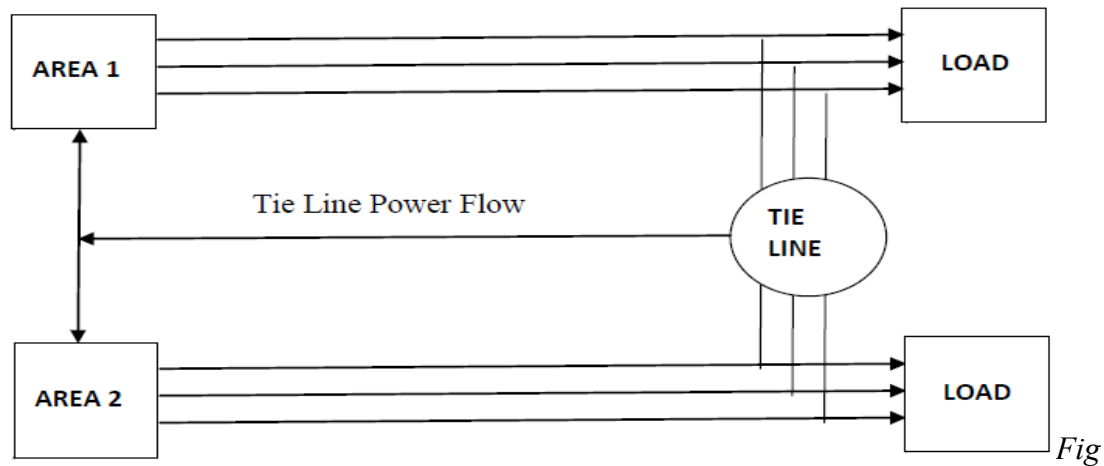
Advantages of interconnection are;

- **Effect of size:** This is major advantage of interconnected systems. As soon as a block of load is added, the required energy is borrowed temporarily from the kinetic energy of the system. Obviously, larger systems will have more available energy.
- **Reduced need of reserve capacity:** Since the peak demands can occur at various hours of the day in various areas, the ratio between peak and average load for a large system is smaller than that of smaller systems.

It is therefore obvious that, all the interconnected areas can benefit from a reduced need of reserve capacity by a scheduled arrangement of energy interchange.[33]

### **A Two Area Interconnected Power System**

A two area interconnected power system in which the two areas are connected through a tie line is shown in Fig 1.1. Each area feeds its control area and tie line allows electric power to flow between the areas.



1.1 - A two area interconnected power system[30]

A single control area is characterized by same frequency throughout. In other words, the area network is ‘rigid’ or ‘strong’. But, in case of a two area system, it is assumed that each area is individually ‘strong’ and the two areas are connected by a ‘weak’ tie line. An interconnected power system may consist of any number of subsystems or areas.[30]

### **1.3- Classical Vs Intelligent Controllers**

#### **Major Draw Backs of Classical Controllers**

- They are slow in action.
- Since they are linear controllers, they do not consider system nonlinearities like governor dead band effects and generation rate constraints (GRCs).
- They have limited capacity of set-point tracking when there is continuous variation of operating point which is caused by continuous load variation.

For a better result, the integrator gain has to be changed frequently as per the changes in operating point. It should also ensure that the gain value is highly compromised between low overshoot in dynamic response and fast transient recovery. [38]

This is quite difficult to achieve practically because an integral controller is basically a fixed controller which is optimal under one condition and ineffective at another operating point. The control rule must cope up with the dynamics of a power system. Therefore, a controller based on intelligent system would therefore be suitable for controlling the system.[41]

### ***Need of Intelligent Control Techniques***

Intelligent control techniques give a great help in implementing AGC for power systems. Today's power systems are more complex and require operation in uncertain and less structured environment. Consequently, secure, economic and stable operation of a power system requires improved and innovative methods of control. [37]

Intelligent control techniques provide a high adaptation to changing conditions and have ability to make decisions quickly by processing imprecise information. Some of these techniques are rule based logic programming, model based reasoning and computational approaches (like fuzzy sets, artificial neural networks, evolutionary programming and genetic algorithms).

In this research work fuzzy logic controller and artificial neural network (ANN) technique is used for AGC of interconnected power systems. [38]

### ***Advantages of ANN over Classical Controllers***

- It quickly adapts to changing operating points and calculates optimal control commands.
- It can perform effectively even with nonlinearities.
- System parameters are not required during starting.
- It can function even system inputs are temporarily lost or errors are introduced.
- If telemetry failure occurs, ANN controller continues to function without needing any decision support software.

### ***Advantages of FLC over Classical Controllers***

- Fuzzy logic controllers are not dependent on accurate mathematical models.
- Parallel or distributed control multiple fuzzy rules – complex nonlinear system.
- Fuzzy logic controllers are based on heuristics and therefore able to incorporate human intuition and experience.
- Robust control. More than 1 control rules – an error of a rule is not fatal [48]

## **1.4- Statement of the problem**

Modern power system network consists of a number of utilities connected together and power is exchanged between utilities over tie-line by which they are connected. In such systems, when there is a load change there will be a steady state frequency deviation depending up on the governor droop characteristics and frequency sensitivity of the load. All generating units on speed governing will contribute to the overall change in frequency irrespective of the location of the load.

In actual power system operation the load is changing continuously and randomly. As the ability of the generation to track the changing load is limited due to physical/technical considerations, there results in an imbalance between the actual and the scheduled generation quantities. This imbalance leads to a frequency error or change that is the difference between the actual and the synchronous frequency. Hence the above stated problems can be solved in this thesis by using an intelligent controllers like fuzzy logic controller (FLC) and artificial neural network (ANN).

## **1.5- Objective of the study**

### ***General objective***

The general objective of this thesis work is to investigate the application of an intelligent automatic generation control by modeling and simulation to regulate the power output of the hydroelectric power generation system with in an area in response to change in system frequency and tie line loading.

### ***Specific Objectives***

- To develop the dynamic model of AGC for a hydropower system.
- To design an Integral as well as Optimal control for AGC of a hydro-power system.
- To design a fuzzy logic controller and artificial neural network for AGC system.
- To compare classical controllers with the intelligent ones using MATLAB simulation.

## **1.6- Significance and Delimitation**

### ***Significance of the study***

In all electrical power generation systems, there is a need to keep the operating frequency at the desired and scheduled value. The change in frequency is due to the change in load level of the system. This frequency variation can be controlled and regulated using an automatic load frequency control. Therefore modeling and designing an appropriate load frequency controller is significant.[8]

Therefore the main contribution of this theses work is to explore and propose the appropriate intelligent controller for automatic generation control for a hydro-power system. The thesis can be used as a reference for future studies that can be done on AGC problems.

In addition, anyone who is going to implement an intelligent AGC in different hydropower systems can also use it as a reference. The thesis work can also be used as a basis for further improvement on the system.

### ***Delimitation Of the study***

Basically this thesis work is delimited to design of AGC for a hydro-power system, design of integral and optimal control for AGC, design of intelligent controllers (FLC and ANN) and finally comparison of classical controllers with intelligent controllers using a MATLAB simulation.

## **1.7- Organization of the thesis**

**Introduction** part includes a brief description of automatic generation control problem, introduction to interconnected power systems, drawbacks of conventional integral controllers, need of intelligent control systems, advantages of ANN and fuzzy logic controllers over classical integral controllers, the problems addressed in the thesis, the general and specific objective of the thesis with significance and delimitation of the study.

**Literature review** deals with comprehensive & critical survey and review of literature on AGC studies related to power system models, control techniques, control strategies, digital control, adaptive and self-tuning schemes. It also has literatures on artificial intelligence (AI) techniques including AGC with ANN and fuzzy logic controller.

**Modeling** part deals with the modeling of different blocks of automatic generation control (AGC) necessary to model the complete closed loop AGC of a hydro-power system, modeling of interconnected hydro-hydro power systems with integral control, state space modeling of these power systems with optimal control strategy, design of optimal controllers and stability studies of these power system models. The discrete versions of these models are also obtained.

**Design** part deals with the design and development of intelligent controllers, development of proposed ANN controllers with their specifications, their interface with power systems in training and controller modes. It also has a step by step procedure adopted with the help of programs in MATLAB for i) generating the training data ii) training of controllers with full state and iii) obtaining performances of neural, optimal and integral controllers under same load disturbance conditions. The design of fuzzy logic controller is also included in this chapter.

**Result and Discussion** part gives simulation results with discussion on performance improvements for both fuzzy logic controller and ANN controllers. Comparison of intelligent controllers with classical controllers is also included here.

**Conclusion and Recommendations** of the research work are also included. And finally for the completeness of the thesis, **references** and an **appendix** showing the nominal values of power system parameters and list of symbols are given at the end.

## **Chapter 2**

### **REVIEW OF LITERATURE**

#### ***2.1- Background***

The AGC problem has been augmented with the valuable research contributions from time to time like AGC regulator designs incorporating parameter variations/uncertainties, load characteristics, excitation control and parallel ac/dc transmission links. The microprocessor-based regulator, self-tuning regulator and adaptive regulator designs is also presented. The most recent advancement in this area is the application of artificial intelligence techniques such as neural networks, fuzzy logic and genetic algorithms to tackle the difficulties associated with the design of regulators with nonlinear models and/or insufficient knowledge about the system. [1]

The major part of the work reported so far are by considering linearized models of multi-area power systems. Later the effect of generation rate constraint (GRC) was included in these types of studies considering both continuous and discrete power system models. However, the implementation of AGC strategy based on a linearized model on an essentially nonlinear system did not necessarily ensure the stability of the system. [2-4]

Hence attention was paid to consider the system nonlinearities. The destabilizing effect of governor dead-band non-linearity on classical AGC system was studied and it was shown that governor dead-band non-linearity tends to produce continuous oscillations in the area frequency and tie-line power transient response.

The successful operation of interconnected power systems requires the matching of total generation with total load demand and associated system losses. The operating point of a power system changes with time and hence these systems may experience deviations in nominal system frequency and scheduled power exchanges to other areas which may yield undesirable effects. There are two variables of interest. i.e. frequency and tie-line power exchanges. Their variations are weighted together by a linear combination to a single variable called the area control error (ACE).

Apart from advances in control concepts, there have been many changes during the last decade or more. These include deregulation of power industry and use of superconducting magnetic energy

storage (SMES), wind turbines and photovoltaic cells as other sources of electrical energy to the system. [5]

Due to these, the control philosophies associated with AGC have changed to accommodate their dynamics and effects on overall system dynamic performance. The critical review of literature about a wide range of methodologies of AGC regulator designs with their salient features is described next.

## **2.2- Review of AGC Schemes**

The first attempt in the area of AGC was to control frequency of a power system via the governor of synchronous machine. This technique was subsequently found to be insufficient and a supplementary control was included to the governor with the help of a signal that is directly proportional to the frequency deviation plus its integral. This scheme constitutes the classical approach to the AGC of power systems. Cohn has done very early works in this important area of AGC. Concordia et al [1] and Cohn [2] have presented basic important works on tie-line power and frequency control and tie line bias control in interconnected systems.

The standard definitions of the terms for AGC on electric power systems were approved by the IEEE standards Committee in 1968 [3]. Following that, suggestions for dynamic modeling of LFC were discussed thoroughly by IEEE PES working groups [4-5]. Based on the experiences with actual implementation of AGC schemes, modifications to the definition of ACE were suggested from time to time to come up with the changing power system environment [6-9].

The Current Operational Problems (COPs) working group has discussed the problems and requirements of regulation of generation on an interconnected power systems in four short notes. Namely, regulation requirement imposed on operators beyond the considerations of long term planners, NAPSIC organization and regulation performance criteria, operating problems of system regulation and factors influencing interconnected operations [6]. The IEEE SGC task force committee report has described about what AGC might be expected to do and what may not be possible or expedient for it to do [7].

R. K. Green [8] presented a new formulation on principles of AGC. He suggested the concept of transformed AGC which could eliminate the need for bias settings by directly controlling the nominal frequency set-point of each unit.

### **2.3- Literature Related to Power System Models**

The AGC problem has been dealt with extensively for more than three decades. The major part of the work reported so far has been performed by considering linearized models of two/multi-area power systems [2, 10, 11, and 12]. K. C. Divya et al [11] has discussed the simulation model of hydro-hydropower systems. They showed that the difficulty in extending the traditional approach for such systems was overcome by assuming all areas in the system operate at the same frequency. They obtained the model by ignoring frequency difference between the control areas.

E. C. Tacker et al [12] have presented formulation of AGC of an interconnected system and investigations via linear control theory. They compared three relative to their ability to influence the transient response of important system variables. Later on, the effect of generation rate constraint (GRC) was included in these types of studies considering both continuous and discrete power system models. Small signal analysis is justified for studying system response for small perturbations. However, the implementation of AGC strategy based on a linearized model on an essentially nonlinear system does not necessarily ensure the stability of the system. Considerable attention was paid by researchers to consider the system nonlinearities [13–15].

In February 1984, the Union Electric in America began implementation of a test to identify the improvement to electric system automatic generation and tie line control that could be achieved by the application of a variable that is non-linear tie line frequency bias. The test showed that when tie line frequency bias is better matched to system response, the area control error performance would be improved and generating unit regulation would be reduced. In addition, the interconnection reliability was enhanced. This work has been discussed by T. Kennedy et al [14].

S. C. Tripathy et al [15] presented a systematic method of choosing the frequency bias parameter and integrator gain of the sampled data supplementary control by using discrete version of the Lyapunov technique.

Heat effect of the steam turbine was considered in the state space model. The effect of governor dead band non-linearity was also considered by using the describing function approach and

including the linearized equations in the state space model. It was shown that the governor dead band non-linearity has a destabilizing effect on the transient response with deterministic and random load disturbances for a purely integral control.

## **2.4- Literature Related to Control Techniques and Strategies**

The pioneering work by number of control engineers has established links between the frequency response of a control system and its closed-loop transient performance in time domain. The investigations carried out using classical control approaches revealed that it would result in relatively large overshoots and transient frequency deviation [16].

Moreover, the settling time of system frequency deviation is comparatively long and is about 10–20 s. AGC regulator design techniques using modern optimal control theory enable power engineers to design an optimal control system with respect to given performance criterion. Fosha and Elgerd [17] were the first to present their pioneering work on an optimal AGC regulator design using this concept. A two-area interconnected power system consisting of two identical power plants of non-reheat thermal turbines was considered for investigations.

R. K. Cavin et al [18] considered LFC problem for interconnected system from the viewpoint of optimal stochastic system theory. A control algorithm was developed which provided improved power system performance in both large and small signal modes of operation. An especially attractive feature of their proposed control scheme was that it required only the currently used variables, frequency deviations and scheduled interchange deviations as inputs.

The feasibility of an optimal AGC scheme requires the availability of all state variables for feedback. However, these efforts seem unrealistic since it is difficult to achieve this. Then, the problem is to reconstruct the unavailable states from the available outputs and controls using an observer. Considering state reconstruction, many significant contributions have been made. Rubaai and Udo [19] presented a hierarchical control scheme for LFC of a multi-area power system. The strategy decomposed a given control problem into multilevel-multilayer hierarchical sub-problems and used the minimum variance stochastic model to represent each sub-problem.

They showed that control strategy could handle unpredictable load changes of random magnitude and duration. The technique was provided for realtime parallel processing that could use only locally available measurements for each entity controller.

Due to practical limitations in the implementation of regulators based on feedback of all state variables, suboptimal and near optimal AGC regulator designs were suggested by many researchers. Moorthy and Aggarawal [20] presented a sub optimal and near-optimal LFC concept using modern control theory. Apart from optimal/suboptimal control concepts, modal control theory was also used to design AGC regulators for power systems.

In the early days, AGC problem of power systems was dealt using control strategies based on centralized control strategy [10, 17]. Many control strategies were proposed on the basis of classes of disturbances.

Elgerd and Fosha [10-17] suggested a feedback and loop gain to eliminate the disturbance. They also suggested different feedback form to develop optimal controllers for an electrical energy system. They assumed the load disturbances to be deterministic. They proposed a proportional controller disregarding the steady state requirements and compensation of load disturbances.

The main limitation of works presented on AGC considering centralized control strategy is the need to exchange information from control areas spread over distantly connected geographical territories along with their increased computational and storage complexities. The decentralized AGC concept appeared in the power system control scenario to deal with such problems very effectively.

Various AGC schemes based on multilevel control and variable structure control strategies were reported in this literature. Bengiamin and Chan [21-22] have discussed about multilevel load frequency control of interconnected power system. They have also discussed about variable frequency control of electric power generation.

They developed a control scheme to reduce mismatch in power generation and consumption of electric power systems. This scheme was introduced to refine the dynamic properties of the integral controller which was originated in accordance with a steady state concept. This controller could change its structure according to certain logic which resulted into distinct advantageous properties.

In most of AGC studies, it is assumed that there is no interaction between the power/frequency and reactive-power/voltage control loops. It may be permissible only when the speed of the excitation systems is much faster than that of the LFC system. But, in practical systems during dynamic perturbations, some interaction between these two control channels does exist [15].

Pan and Liaw [23] suggested an adaptive controller for LFC which used a PI adaptation to satisfy the hyper stability condition for taking care of parameter changes. Only the available information of states and output of the model as well as plant output were required for the control and no explicit parameter identification was required.

## ***2.5- Literature Related to Artificial Intelligent Techniques***

In practice, many nonlinear processes are approximated by reduced-order models possibly linear that are clearly related to the underlying process characteristics. However, these models may be valid only within certain specific operating ranges and a different model may be required in the wake of changed operating conditions or the control system should adopt the new system model parameters.

The advent of artificial intelligence (AI) techniques such as fuzzy logic controller and neural networks has solved this problem to a great extent. The fuzzy logic and neural network technologies offer many more benefits in the area of nonlinear control problems particularly when the system is operating over the nonlinear operating range. The applications of fuzzy logic controller and neural networks in power system control are witnessed in the following literatures.

### ***Literature on Fuzzy Logic Controllers***

According to J. Nanda and A. Mangla in paper ‘Automatic Generation Control of an Interconnected Hydro-Thermal System Using Conventional Integral and Fuzzy Logic Controller’, the presence of FLC (Fuzzy Logic Controller) in both areas and small step perturbation in either area or in both areas simultaneously provide a better dynamic response than integral controller. Nominal parameter of hydrothermal system (R) is investigated.

With FLC like in integral controller, higher sampling period than the practically used is permissible without deteriorating dynamic responses for all practical purposes. The number of

triangular Membership Functions has an impact on dynamic responses and hence needs to be properly selected [24].

Indulkar and Baldevraj introduce a paper that describes the application of fuzzy logic to design a fuzzy controller for automatic generation control (AGC) problem in power system studies. A two area power system has been considered in this work. Frequency deviation for step load increase in one area is plotted as a function of time and is compared with available response using the classical integral controller.

The shortcoming of this work was that it do not compare their results with those from conventional PID controller. The authors only compared their work with classical integral controller. Besides they only used one step load increase for two area system. [25]

G.A. Chown and R C. Hartman described the design, implementation and operational performance of a fuzzy controller as part of Automatic Generation Control (AGC) system in Eskom’s National Control Centre. Fuzzy controller was implemented in the ACE calculation which determines the shortfall or surplus generation that has to be corrected. [26]

EnginYesil, AysenDemiroren and ErkinYesil presents a method based on fuzzy logic controllers (FLCs) for automatic generation control (AGC) of a power system including three areas having two steam turbines and one hydro turbine tied together through power lines. The results obtained by using FLCs proposed in this paper outperform than those of classical controllers. [27]

M. G. Rabbani, M. F. Hossain, M. R. I. Sheikh and M. S. Anower describes the application of fuzzy logic control in an Automatic Generation Control (AGC) of an isolated power system that uses a 12-pulse bridge converter associated with Superconducting Magnetic Energy Storage Unit. A systematic approach for designing the fuzzy logic controller (FLC) was proposed in this paper. [28]

D.M. Vinod Kumar presented a novel approach of Artificial Intelligence (AI) techniques viz., Fuzzy logic, Artificial Neural Network (ANN) and Hybrid Fuzzy Neural Network (HFNN) for Automatic Generation Control (AGC). The limitations of classical controls viz., Proportional, Integral and Derivative (PID) are slow and lack of efficiency in handling system non-linearities.

The primary purpose of the AGC is to balance the total system generation against system load and losses so that the desired frequency and power interchange with neighboring systems are maintained. [29]

M.S.Anower, MG.Rabbani, M.F.Hossain, M.R.I Sheikh and M Rakibul Islam in paper ‘Fuzzy frequency controller for the improvement of power systems dynamics’ proposed a Fuzzy Frequency Controller (FFC) to improve the dynamic performance of a single-area power system. This paper represents the implementation of Fuzzy Frequency Controller for an AGC in single-area power system. The aim of the proposed controller is to restore the frequency to its nominal value in the smallest possible time whenever there is any change in the load demand etc. [30]

H.D. Mathur and H.V. Manjunath proposed a fuzzy logic controller for load frequency control problem of electrical power system. The fuzzy controller was constructed as a set of control rules and the control signal is directly deduced from the knowledge base and the fuzzy inference. The study has been designed for a two area interconnected power system. [31]

A K Swain discussed in paper ‘A Simple Fuzzy Controller for Single Area Hydro Power System Considering Generation Rate Constraints’. The performance of the simplest fuzzy controller which resembles a variable gain nonlinear proportional integral (PI) controller is compared with an implicit self-tuning controller (STC) with integral feature considering a single area hydro-power system with generation rate constraint. The robust feature of these controllers against certain significant parameter variations such as the inertia constant (H) and the self regulation parameter (R) of the governor was investigated. [32]

‘M.F. Hussein T. Takahashi M.G. Rabbani M.R.I. Sheikh T M.S. Anower in the work,’ Fuzzy-Proportional Integral Controller for an AGC in a Single area power system’ presented intelligent load frequency controllers to regulate power output and system frequency by controlling speed of the generator with the help of fuel rack position control. This paper presented an implementation of Fuzzy-Proportional Integral controller (FPIC) for controlling AGC in a single area power system. [33]

### ***Literature on Artificial Neural Networks***

B. Franoise et al [34] have described the application of layered neural networks to nonlinear power system control. They have suggested a feed-forward neural network controller for a two-area system which can minimize frequency transients and obtain zero steady state frequency error. They trained the controller with back-propagation through time algorithm.

A. P. Birch et al [35] have investigated the use of neural networks to act as the control intelligence in conjunction with a standard adaptive LFC scheme. They have shown various advantages of neural network controller over even more advanced adaptive control techniques.

L. D. Douglas et al [36] presented a new AGC scheme to incorporate the non-conforming load problem in which an effort was undertaken to develop algorithms capable of discriminating between non-controllable short-term excursions and controllable long-term excursions. Out of the two techniques described, one was developed using a neural network algorithm for pattern recognition of controllable signals and the other technique was based on detection of the controllable signal in the presence of a noisy random load using a random signal probability model. Test results revealed that neural network-based AGC implementation had a significant improvement over the modern AGC implementation.

D. K. Chaturvedi et al [37] presented the work that deals with the development of non-linear neural network controller using a generalized neural network. They showed drawbacks of neural networks existing at that time was overcome in the generalized neuron structure which was developed to control deviations in frequency.

A. Demiroren et al [38] have investigated an application of layered artificial neural network for AGC of the two-area system. With the help of computer simulations on the interconnected power system with two areas (thermal-thermal) that include reheater effect and also governor dead band effect. They showed that the ANN control scheme is effective in damping out oscillations resulted by load perturbations.

H. Shayeghi et al [39] have proposed a nonlinear ANN controller based on  $\mu$ -synthesis for AGC of power systems. With the simulations on the two-area system, they have showed that the proposed ANN controller was effective and gave good dynamic responses even in the presence of

GRCs. They also showed that the proposed controller was superior to the classical PI and  $\mu$ -based robust controllers.

H. L. Zeynelgil et al [40] have presented an application of layered ANN controller to study AGC problem in a four area interconnected system that had three thermal and one hydro area. They also considered the nonlinearities like reheat effect of steam turbine and upper and lower constraints for generation rate nonlinearity of hydro turbine.

They proposed only one ANN controller, which controlled the input of each area. The controller was trained with back propagation through time (BPTT) algorithm. They showed that the performance of the ANN controller was better than the conventional controllers.

A. Demiroren et al [41] have discussed the application of layered ANN controller to study LFC problems in power systems. They discussed the control scheme with three interconnected areas with two thermal and one hydro area. They have showed that the performance of the ANN controller was better than conventional integral controller.

K. P. Wong [42] has reviewed the applications of artificial intelligence and neural networks in power engineering. He has reported the areas in power systems that artificial intelligence had been applied to. He has also summarized the AI techniques, which had been employed and made suggestions for the improvement of the then existing AI tools.

D. Rerkpreedapong et al [43] proposed two robust decentralized control design methodologies for load frequency control. The first one was based on control design using linear matrix inequalities (LMI) technique in order to obtain robustness against uncertainties. The second controller had a simpler structure and it was tuned by a novel robust control design algorithm to achieve the same robust performance as the first one.

More specifically, genetic algorithm optimization is used to tune the control parameters of the proportional-integral (PI) controller subject to the constraints in terms of LMI. Both proposed controllers were tested on a three-area power system with three scenarios of load disturbances to demonstrate their robust performances.

## **Chapter 3**

### **MODELING**

#### **3.1- Introduction**

One of the most important components in daily operation of an electrical power system is the scheduling and control of generation. This function is the primary concern of the Energy Control Centre and is largely provided by an Automatic Generation Control (AGC) program implemented as part of the Energy Management System (EMS).[41]

In general, electrical power systems are interconnected to provide secure and economical operation. The interconnection is typically divided into *control areas*, with each consisting of one or more power utility companies. Control areas are connected by transmission lines commonly referred to as *tie-lines* and the power flowing between control areas is called *tie-line interchange power*. One of the main responsibilities of each control area is to supply sufficient generation to meet the load demand of its customer either with its own generation source or with power purchased from other control areas.[39]

An essential part of an interconnected system is that all generators in the system respond to changes in frequency via their governor speed control. When the load increases in a particular control area, it is supplied initially by the kinetic energy stored in the rotating masses of the turbine generators. The result is a drop in the system frequency throughout the interconnected system. All generators in the interconnection respond to the speed change and adjust generation to return the frequency to a new steady-state value, thereby establishing a balance between the total system generation and the total system load. It is the function of AGC in the disturbed control area to readjust its generation in an economical manner such that any tie-line interchange power deviation that is resulted from the load change is returned to zero, and the new steady-state frequency is brought back to the scheduled value.[51]

For an isolated power system, the tie-line interchange power is zero and it is the sole responsibility of the isolated control area to meet its own load demand and maintain the system frequency at its scheduled value. For a large system in which the total inertia of the on-line generators is large, regulating the frequency is a challenging task even for the AGC function.

As a result, the accumulated time error is typically much greater in an isolated system since the frequency error tends to be sustained for longer periods of time while the AGC process operates. Understanding the characteristics of power system equipment is a key in the study of AGC. Fig 3.1 depicts the basic control structure of an electrical power system. The primary components to consider are the synchronous generators, the prime movers(turbines), the speed-governing system which includes the governor and the load reference actuator (speed changer), the unit controller and the AGC system.

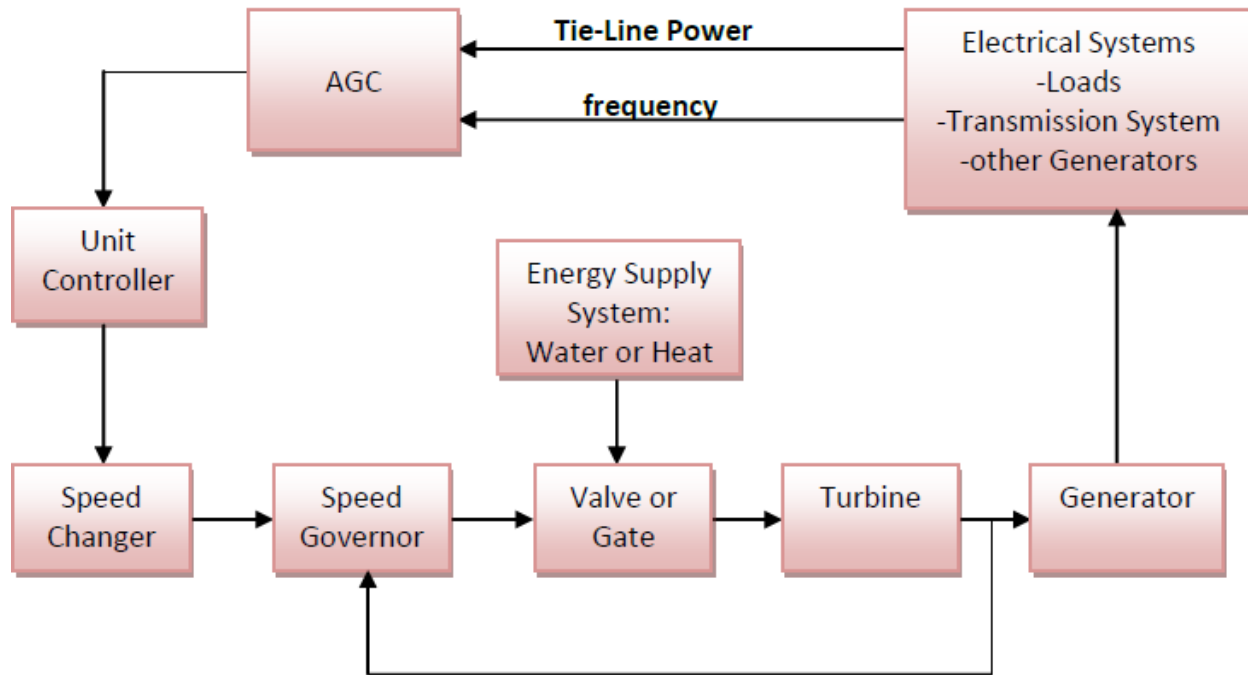


Fig 3.1 - Basic power system control structure[58]

The speed-governing system provides a primary control function that responds quickly to frequency changes caused by a change in the active power balance between generation and load. For governors with speed-droop characteristics, a steady-state frequency deviation from the desired system frequency remains following the primary control action. This deviation is corrected using the AGC function. Compared to the primary control process, this control is slower to respond to changes in the load demand.[62]

Automatic generation control has been utilized by power utilities for several decades. The approach used today generally provides acceptable levels of performance based primarily upon AGC operation criteria. Of course, problems with AGC do exist since operating conditions are continually changing.

These problems are related to the performance of AGC (such as the accumulation of time error and the inadvertent interchange of power) and the *cost* associated with it (such as maintenance of generating units and the availability of the energy source). [56]

### 3.2- Turbine speed governing system model

Speed governors are the units that are used in power system to sense the frequency bias caused by the load change and cancel it by varying the input of the turbine. That is a speed governor senses a speed deviation or a power change command and converts it in to appropriate value control. Since the governor itself does not generate enough force to operate the water or steam valves, we also consider the operation of a single hydraulic servo motor interposed between the governor and the valve.

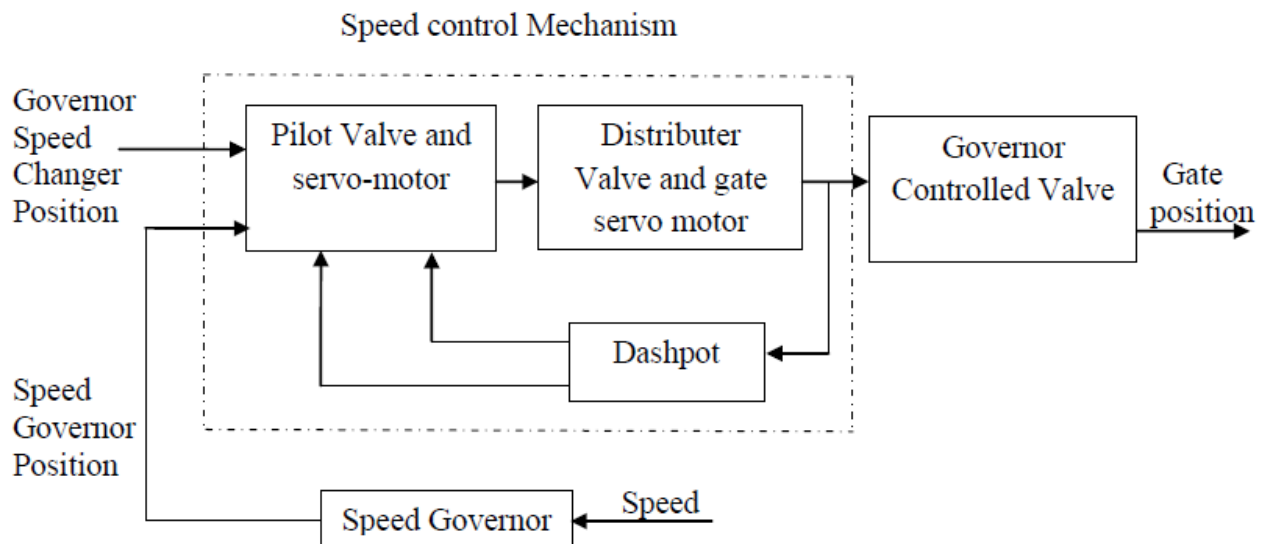


Fig 3.2 - Block diagram of a hydro governor[63]

In the block diagram of the speed governor in Fig 3.2, the speed governor senses the speed and it gives a position which is proportional to the speed deviation. The governor speed changer position which is a signal comes from the automatic generation control of the speed.

The two servo-motors are used to amplify the power which is required to move the gates and the dashpot provide a feedback signal and this feedback is a deviation feedback to realize the deviation signal. The non-linear function is used to relate the gate position with the hydraulic

servomotor position. The transfer function of the dashpot is a derivative gain which can be given

$$\text{by: } \frac{\delta s T_R}{1 + s T_R} \quad (3.1)$$

Where  $\delta$  is called tangent droop

The other feedback is through  $\sigma$  (permanent droop which is sometimes represented by R) to determine the net droop. The transfer function of the various building blocks of the water turbine speed governor can be drawn as below.

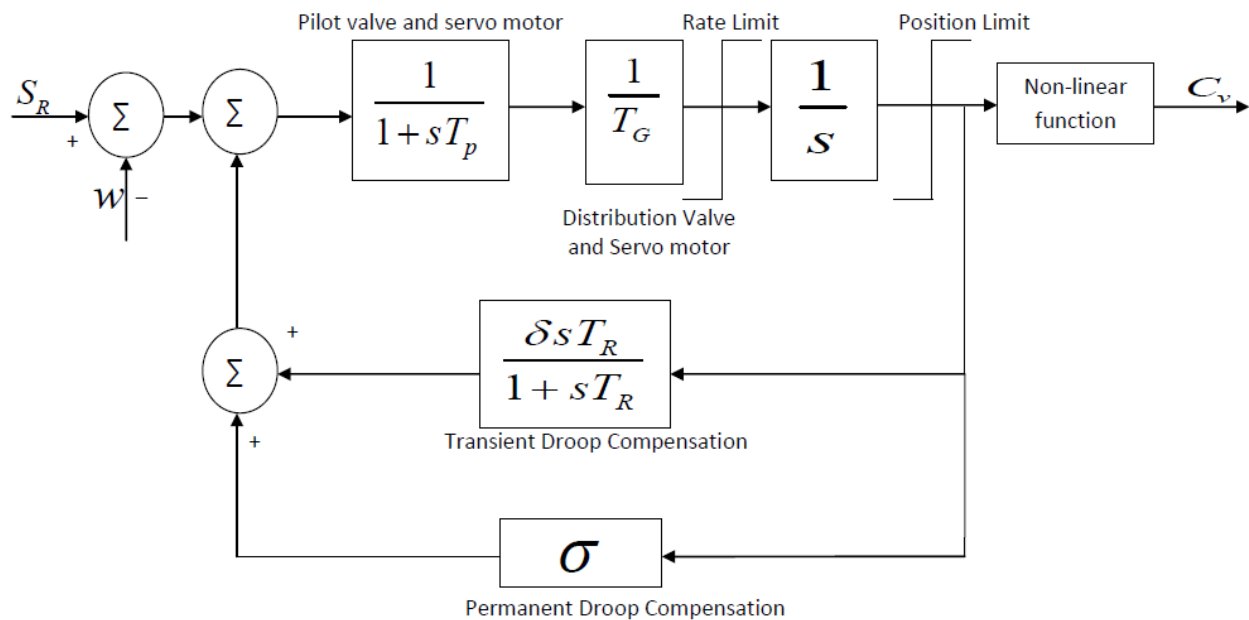


Fig 3.3 - Transfer function block diagram of hydro-governor[49]

The typical parameters for speed governing systems for a hydro turbine are given below;

Parameter	Typical values	Range	
$T_R$ (speed governor rest time)	5sec		2.5-25
$T_G$ (time constant of distribution valve)	0.2sec		0.2-0.4
$T_P$ (time constant of pilot valve and servo motor)	0.04		0.03-0.05
$\delta$ (Tangent droop)	0.3		0.2-1
$\sigma$ (R) -permanent droop	0.05		0.03-0.06

Table 3.1 – parameters of a speed governing system

The time constant  $T_R$  depends on the motor starting time constant which is given by:

$$T_R = 5T_w \quad (3.2)$$

$$\delta = \frac{2.5T_w}{H} \quad (3.3)$$

Where H is the inertia of the turbine

The general transfer function model for speed governing system for a hydro-power can be summarized as below:

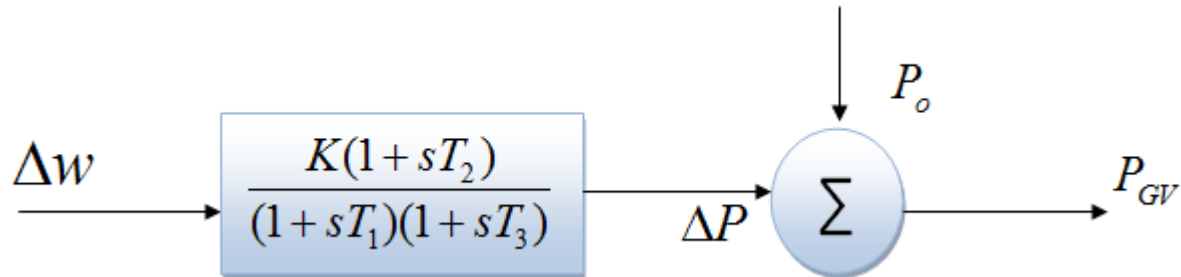


Fig 3.4 - Block diagram of speed governor system

Where;

$\Delta w$  - Input Speed Deviation

$\Delta P$  - Change in Power

$K$  - Gain of the Governor

$P_o$  - Reference Power Setting

$P_{GV}$  - Gate Valve

$T_1$  - Transient droop time constant

$T_2$  - speed governor rest time and

$T_3$  - main servo time constant

### 3.3- Hydro- turbine Model

Consider the penstock-turbine system shown in Fig 3.5 having an effective length of L discharging water to the turbine at a velocity, V feet per second operating at a head of H.

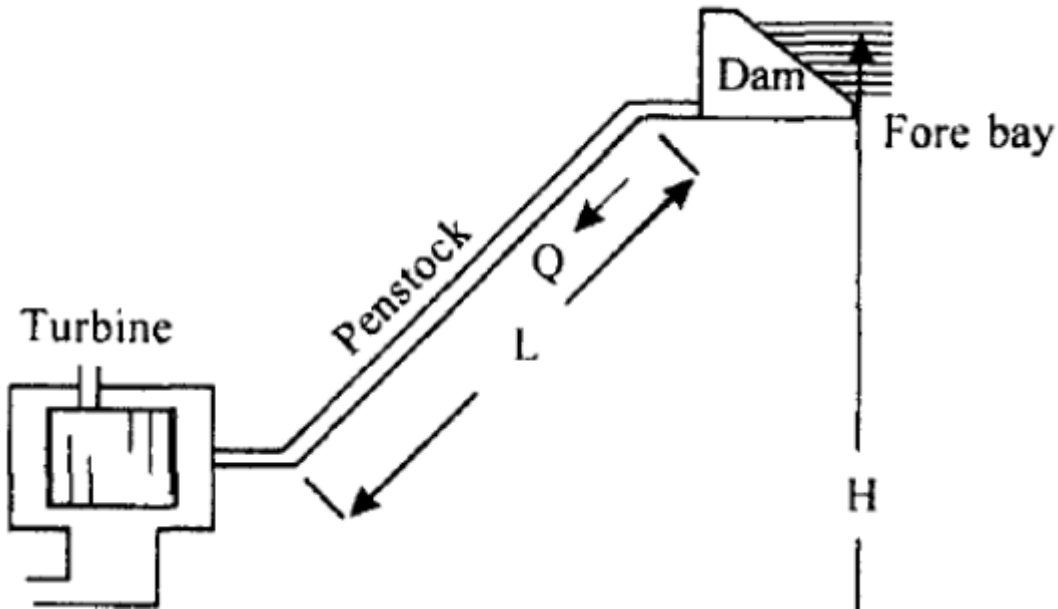


Fig 3.5 - Penstock hydro-turbine model [56]

The penstock is the one in which the water flows from storage tank to the hydro turbine. The tangent characteristic of a hydro turbine is determined by the dynamics of water flow in the penstock and we shall determine the transfer function of the hydro turbine. When we consider a small perturbation about a steady state condition the turbine may be represented by the following linearized equations:

$$\begin{aligned} q &= a_{11}h + a_{12}n + a_{13}g \\ m &= a_{21}h + a_{22}n + a_{23}g \end{aligned} \quad (3.4)$$

Where:

q - per unit deviation in flow

h - per unit deviation in head

n - per unit deviation in speed

g - per unit deviation in gate position

m - per unit deviation in torque

The above two equation are an algebraic equation which relates the water flow following changes in height and gate position similarly the change in torque produced following small change in head, speed and gate position.

Using these equations and the dynamics of the water flow in the penstock a transfer function model of the hydro-turbine can be obtained. The transfer function relating the mechanical power output of the hydro turbine to the gate position can be expressed as below:

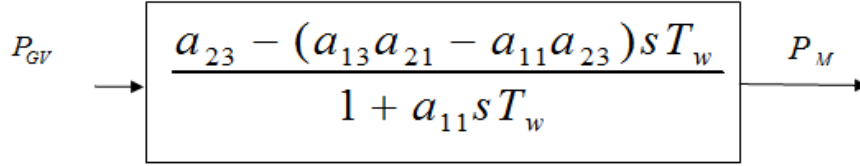


Fig 3.6 – Block diagram of hydro turbine

Where;

$P_{GV}$  -gate position

$P_M$  - mechanical time constant

$T_w$  - water time constant

The coefficient in the two algebraic equations can be interpreted as prior derivatives of deviation in flow (q) respect to head, speed and gate position. Similarly derivatives of torque (m) with respect to head, speed and gate position as described as below:

$$\begin{aligned} a_{11} &= \frac{dq}{dh}, a_{12} = \frac{dq}{dn}, a_{13} = \frac{dq}{dg} \\ a_{21} &= \frac{dm}{dh}, a_{22} = \frac{dm}{dn}, a_{23} = \frac{dm}{dg} \end{aligned} \tag{3.5}$$

For the design purpose let us consider an ideal turbine at rated speed and head (loss less turbine);

$$\begin{aligned} a_{11} &= 0.5 & a_{12} &= 0 & a_{13} &= 1 \\ a_{21} &= 1.5 & a_{22} &= -1 & a_{23} &= 1 \end{aligned}$$

If we make use of these values and substituting in the above block diagram it can be reduced to a block diagram below:

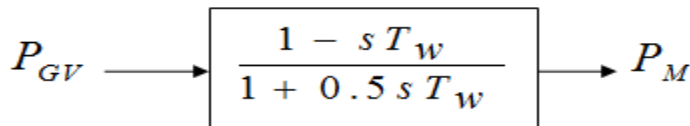


Fig 3.7 – Reduced block diagram of hydro turbine

### 3.4- Synchronous Generator Model

In an electrical power system, the principal source of electric energy is the synchronous generator. Related to the mechanical rotation of the synchronous generator's rotor is the electrical frequency. This electrical frequency depends on achieving a balance in the active power (electrical and mechanical torques), or a match between the electrical power output of the generator and the system load. When a load change does occur, there is an instantaneous change in the electrical torque of the generator and unbalance between the mechanical and electrical torques. This is reflected as a net accelerating (decelerating) torque.

$$T_a = T_m - T_e \quad (3.6)$$

Where;  $T_a$  is accelerating torque (N.m)

$T_m$  is mechanical Torque (N.m)

$T_e$  is Electrical Torque (N.m)

For a generator, the mechanical and electrical torques are both positive. The combined inertia of the generator and the prime mover is accelerated by the unbalance in the applied torques. This gives us the equation of motion described as:

$$J \frac{dw_m}{dt} = T_a = T_m - T_e \quad (3.7)$$

Where;  $J$  - the combined moment of inertia of generator and turbine ( $\text{Kg.m}^2$ )

$w_m$ - angular velocity of the rotor (mech.rad/sec)

$T$ -time (sec)

Defining the inertia constant  $H$  as the kinetic energy in watt-seconds divided by the VA base, or

$$H = \frac{1}{2} \frac{J w_{m0}^2}{VA_{base}} \quad (3.8)$$

$J$  may be written in terms of  $H$  as

$$J = \frac{2H}{w_{om}^2} VA_{base} \quad (3.9)$$

Substituting eq. (3.9) on eq. (3.7)

$$\frac{2H}{w_{om}^2} VA_{base} \frac{dw_m}{dt} = T_m - T_e \quad (3.10)$$

Using  $T_{base} = \frac{VA_{base}}{W_m}$  the per unit form of eq. (3.10)

$$2H \frac{d \bar{w}_r}{dt} = \bar{T}_m - \bar{T}_e \quad (3.11)$$

$$\bar{w}_r = \frac{W_m}{W_{om}} = \frac{W_r}{W_o}$$

Where ;

$W_r$  - angular velocity of rotor [elec. Rad/s], andat rated speed

$W_o$  - rated angular velocity [elec. Rad/s].

Here the super bar notation denotes a per unit quantity. Next setting the mechanical starting time M to be:

$$M=2H [s] \quad (3.12)$$

The equation of motion may be written as:

$$M \frac{d \bar{w}_r}{dt} = \bar{T}_m - \bar{T}_e \quad (3.13)$$

Note that the term inertia constant will be used for both M and H interchangeably

For the study of automatic generation control (AGC), it is preferable to express the relationship given in Eq. (3.13)in terms of mechanical and electrical power rather than torque. The relationship betweenpower P and torque T is given by:

$$P = w_r T \quad (3.14)$$

Since we are considering small deviations (denoted by the prefix  $\Delta$ ) from initial values (denoted by subscript), we may write;

$$\begin{aligned} P &= P_o + \Delta P \\ T &= T_o + \Delta T \\ w_r &= w_o + \Delta w_r \end{aligned} \quad (3.15)$$

Substituting Eq. (3.15) into Eq. (3.14) gives

$$P_o + \Delta P = (w_o + \Delta w_r)(T_o + \Delta T) \quad (3.16)$$

Neglecting higher order terms and considering only the relationship between perturbed values yields;

$$\Delta P = w_o \Delta T + T_o \Delta w_r \quad (3.17)$$

Therefore;

$$\Delta P_m - \Delta P_e = w_o (\Delta T_m - \Delta T_e) + (T_{mo} - T_{eo}) \Delta w_r \quad (3.18)$$

Now, in steady state, electrical and mechanical toques are equal,  $T_m = T_e$  and with speed expression in per unit,  $w_o = 1$  we have;

$$\Delta P_m - \Delta P = \Delta T_m - \Delta T \quad (3.19)$$

Hence, the equation of motion may now be rewritten as:

$$M \frac{dw_r}{dt} = P_m - P_e \quad (3.20)$$

Where M is in units of seconds and all other quantities are in per unit. For analysis of power system dynamic performance, Eq. (3.15) is expressed in the Laplace domain such that the transfer function is:

$$Ms \Delta w_r = \Delta T_m - \Delta T_e \quad (3.21)$$

Solving for the frequency change,

$$\Delta w_r = \frac{1}{Ms} (\Delta T_m - \Delta T_e) \quad (3.22)$$

Next to account for the resistive (frequency independent) and motor (frequency dependent) loads, the change in electrical power is expressed as:

$$\Delta P_e = \Delta P_L + D \Delta w_r$$

Where;

$\Delta P_L$  = Non frequency sensitive load change

$D \Delta w_r$  = Frequency sensitive load change

$D$  = Load damping constant

Here the damping constant is expressed as a percent in load for one percent change in frequency.

Substituting Eq. (3.22) into Eq. (3.21) and solving for the frequency change gives:

$$\Delta w_r = \frac{1}{Ms + D} (\Delta T_m - \Delta T_L) \quad (3.23)$$

This equation describes the dynamics of the synchronous generator by giving the frequency deviation those results from a mismatch between the MW generation and the load demand. It also takes into account the total inertia of the power system as well as the frequency dependent and independent components of the load. For a power system with more than one generating unit, we may write:

$$\Delta w_r = \frac{1}{M_{eq}s + D} (\Delta T_{mi} - \Delta T_L) \quad (3.24)$$

Where:  $\Delta T_{mi}$  =Mechanical power change for generating unit  $i$

$$M_{eq} = \sum M_i [s],$$

$M_i$  =Inertia constant of generating unit  $i$

This assumes that all generators respond coherently to changes in system load enabling them to be represented by an equivalent generator. Then the block diagram representation of the synchronous generator can be expressed as:

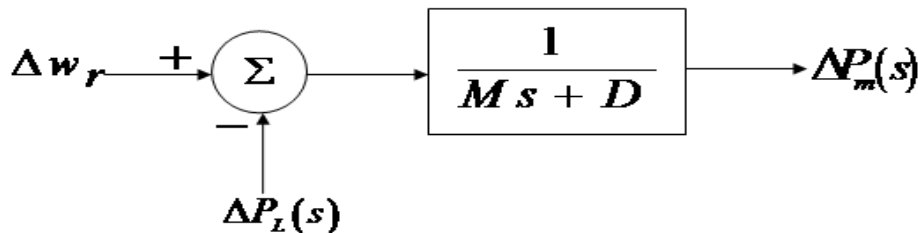


Fig 3.8 -Block diagram of synchronous generator

### 3.5- The Unit Controller

The unit controller provides the control signal to activate the load reference actuator. This control signal known as the unit control error (UCE) is the difference between the unit MW output and the desired generation (economic basepoint plus the AGC control signal). Its main function is to regulate the UCE to zero by issuing raise/lower commands or a desired generation signal to the load reference actuator. This process changes the unit's actual MW output to match the desired MW generation. The unit controller inputs include its economic basepoint (which is the most economic desired unit MW generation as determined from the economic dispatch action), its actual MW output and the portion of the AGC control signal assigned to the particular generating unit. If the unit is not AGC-controlled, the AGC control signal is zero.

### 3.6- Automatic Generation Control in a Single Area System

In the previous sections models for turbine - generator, power system and speed governing systems are obtained. In practice, rarely a single generator feeds a large area. Several generators connected in parallel, located also at different places will supply the power needs of a geographical area. Quite normally, all these generators may have the same response characteristics for changes in load demand.

In such a case, it is possible to define a control area, grouping all the generators in the area together and treating them as a single equivalent generator. For small load changes all these generators swing in unison. Putting together, the various models derived so far a single control area or simply an area can be conceived as shown in Fig 3.9 below;

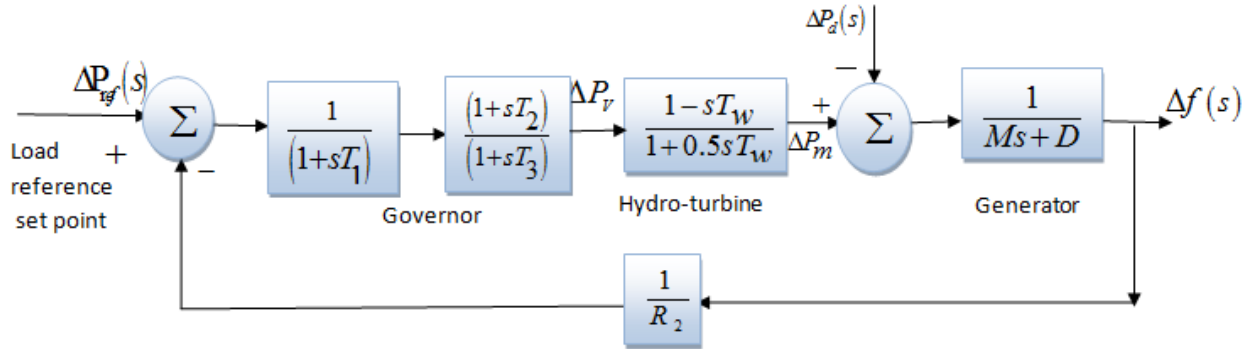


Fig 3.9 -Block diagram of a single area load frequency control

### 3.7- Double Area (Inter-Connected) Power System

#### Tie-Lines

Tie-line bias control is a control philosophy developed for load frequency control in a power system. It is widely used in AGC and was proved efficient in maintaining interconnection reliability and its simplicity in control implementation. The concept allows each control area to operate its generation and to fulfill areas control obligation independently by monitoring and control the area’s ACE.

In an interconnected power system, different areas are connected with each other via tie-lines. When the frequencies in two areas are different, a power exchange occurs through the tie-line that connected the two areas. The tie-line connections can be modeled as shown in Fig 3.10. The Laplace transform representation of the block diagram in Fig 3.10 is;

$$\Delta P_{tieij}(s) = \frac{1}{s} T_{ij} \left( \Delta F_i(s) - \Delta F_j(s) \right) \quad (3.25)$$

Where:  $\Delta P_{tieij}$  - Tie line exchange power between areas  $i$  and  $j$

$T_{ij}$  - Tie line synchronizing torque coefficient between areas  $i$  and  $j$

From Fig 3.10, we can see that the tie-line power error is the integral of the frequency difference between the two areas.

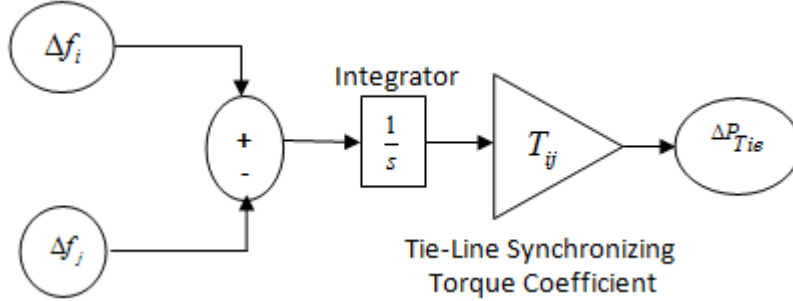


Fig 3.10 -Block diagram of tie lines

### Area control error (ACE)

The goals of LFC are not only to cancel frequency error in each area, but also to drive the tie-line power exchange according to the schedule. Since the tie-line power error is the integral of the frequency difference between each pair of areas, if we control frequency error back to zero any steady state errors in the frequency of the system would result in tie-line power errors. Therefore we need to include the information of the tie-line power deviation into our control input. As a result, an area control error (ACE) is defined as:

$$ACE_i = \sum_{j=1, \dots, n, j \neq i} \Delta P_{tieij} + B_i \Delta f_i [1] \quad (3.26)$$

Where  $B_i$  is the frequency response characteristic for area  $i$  and

$$B_i = D_i + \frac{1}{R_i} \quad (3.27)$$

For two area system the area control error ACE can be calculated as:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_1 \quad (3.28)$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta f_2$$

This ACE signal is used as plant output of each power generating area. Driving ACEs in all areas to zeros will result in zeros for all frequency and tie-line power errors in the system. With the power generating units and the tie-line connections of interconnected areas introduced before, a complete form of one-area power generating unit can be constructed as Fig 3.11.

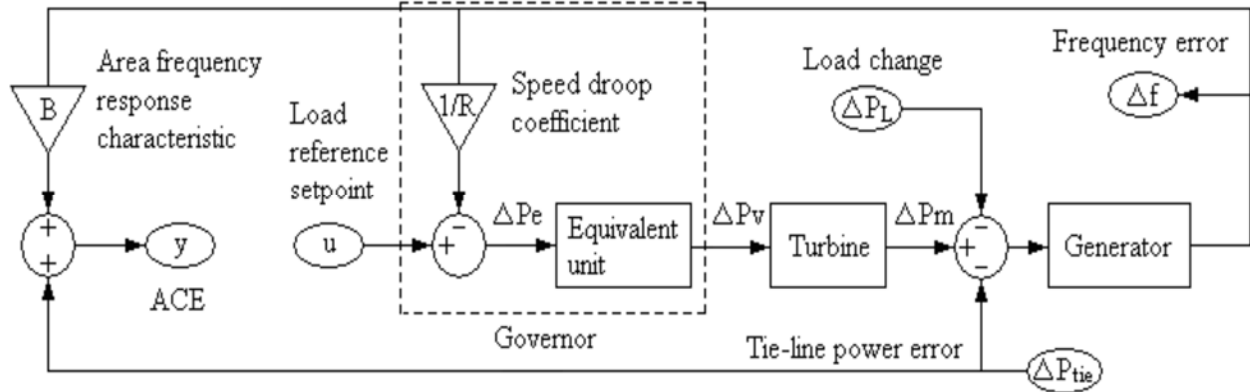


Fig 3.11 - Schematic of one-area power generating unit with tie line[65]

In Figure 3.11, there are three inputs (the controller input  $U(s)$ , load disturbance  $\Delta PL(s)$  and tie-line power error  $\Delta P_{tie}(s)$ ), one ACE output  $Y(s)$  and one generator output  $\Delta f$ . The detailed block diagram modeling of two area hydro-hydropower system for load frequency control investigated is shown in fig 3.12. An extended power system can be divided into a number of load frequency control areas interconnected by means of tie lines. Without loss of generality one can consider a two- area case connected by single tie line.

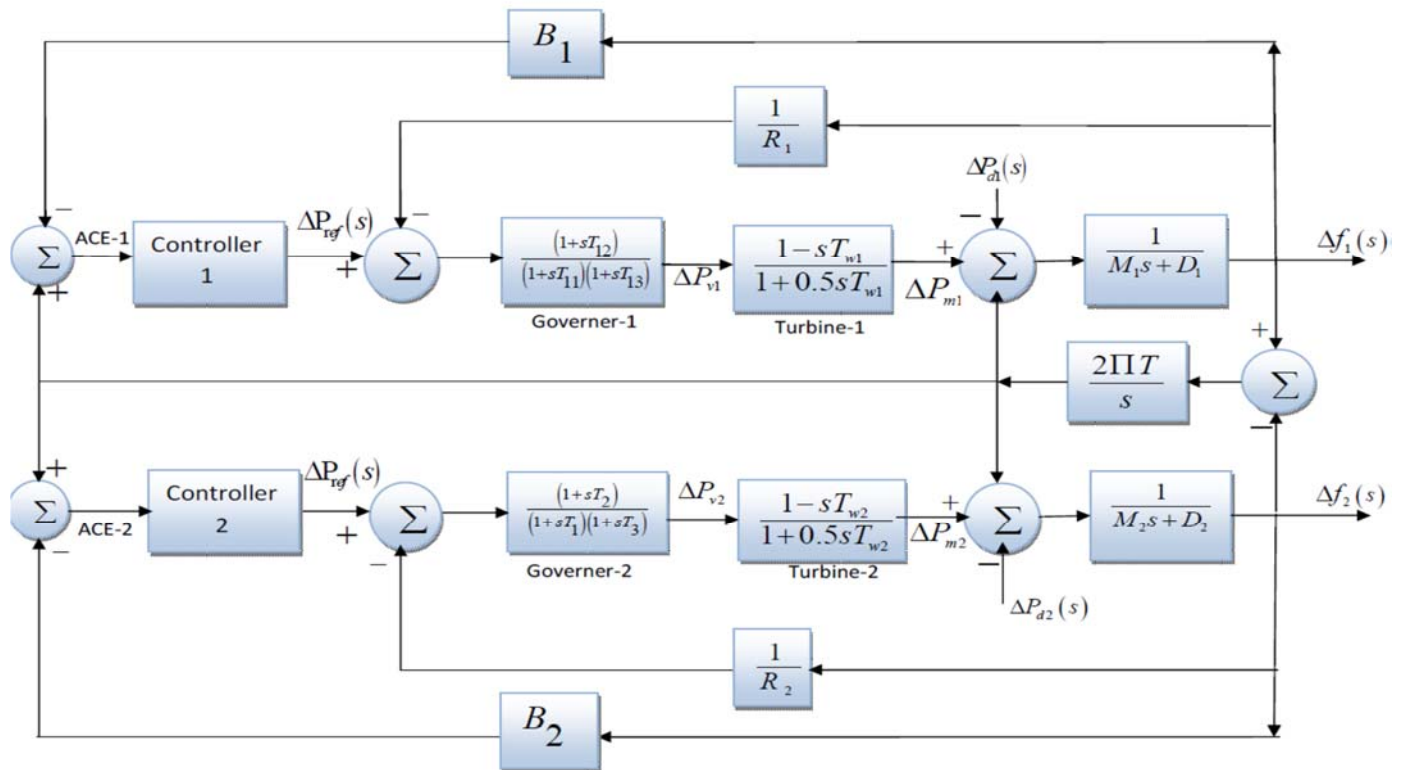


Fig 3.12 -Transfer function model of a two area interconnected system

The control objectives are;

- As far as possible, each control area should supply its own load demand and power transfer through tie line should be on mutual agreement.
- Both control areas should contribute to the frequency control.

For a total change in load of  $\Delta P_D$ , the steady state deviation in frequency in the two areas is

$$\text{given by } \Delta f = \Delta w1 = \Delta w2 = \frac{-\Delta P_D}{B_1 + B_2} \text{ Where; } B_1 = D_1 + \frac{1}{R_1} \text{ } B_2 = D_2 + \frac{1}{R_2} .$$

### 3.8- Modeling with integral and optimal control

For AGC studies it is necessary to obtain appropriate models of the interconnected power systems. In present research work, models of the hydro power systems were considered for AGC study which was modeled in the previous section and shown below:

The models of above mentioned interconnected power system with integral control scheme, state space modeling of these power systems to design optimal controllers and stability studies of this power system model are dealt within this portion. The discrete versions of these power system models have also been obtained.

#### Model of A two area hydro-hydropower system with integral control

The Perturbed model of a two area hydro-hydropower system with conventional integral controller scheme is shown in the Fig. below;

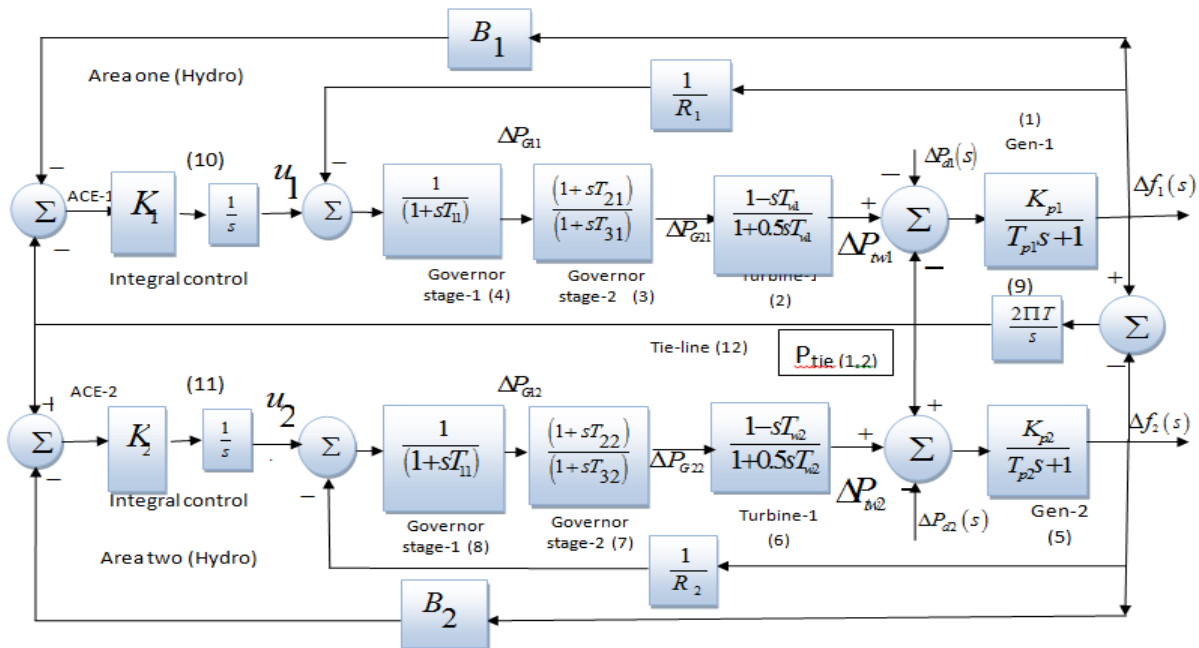


Fig 3.13 -Two area hydro-hydropower system with integral controller

The system state equations with reference to transfer function blocks from 1 to 11 can be used to drive the state equations model for  $\dot{x}_1$  to  $\dot{x}_9$  of the power system. With integral control, the equations for control inputs  $\dot{u}_1$  &  $\dot{u}_2$  are as given below:

- **Area 1 (Block 10):**

$$\dot{u}_1 = -K_1(ACE_1) = -K_1(B_1x_1 + x_9)$$

- **Area 2 (Block 11):**

$$\dot{u}_2 = -K_2(ACE_2) = -K_2(B_2x_5 - x_9)$$

**State Space Representation of Power System Models for Optimal Control**

For the two area hydro-hydropower system, the state space model with full state feedback (11 state feedbacks) has been developed as shown in Fig 3.14 below;

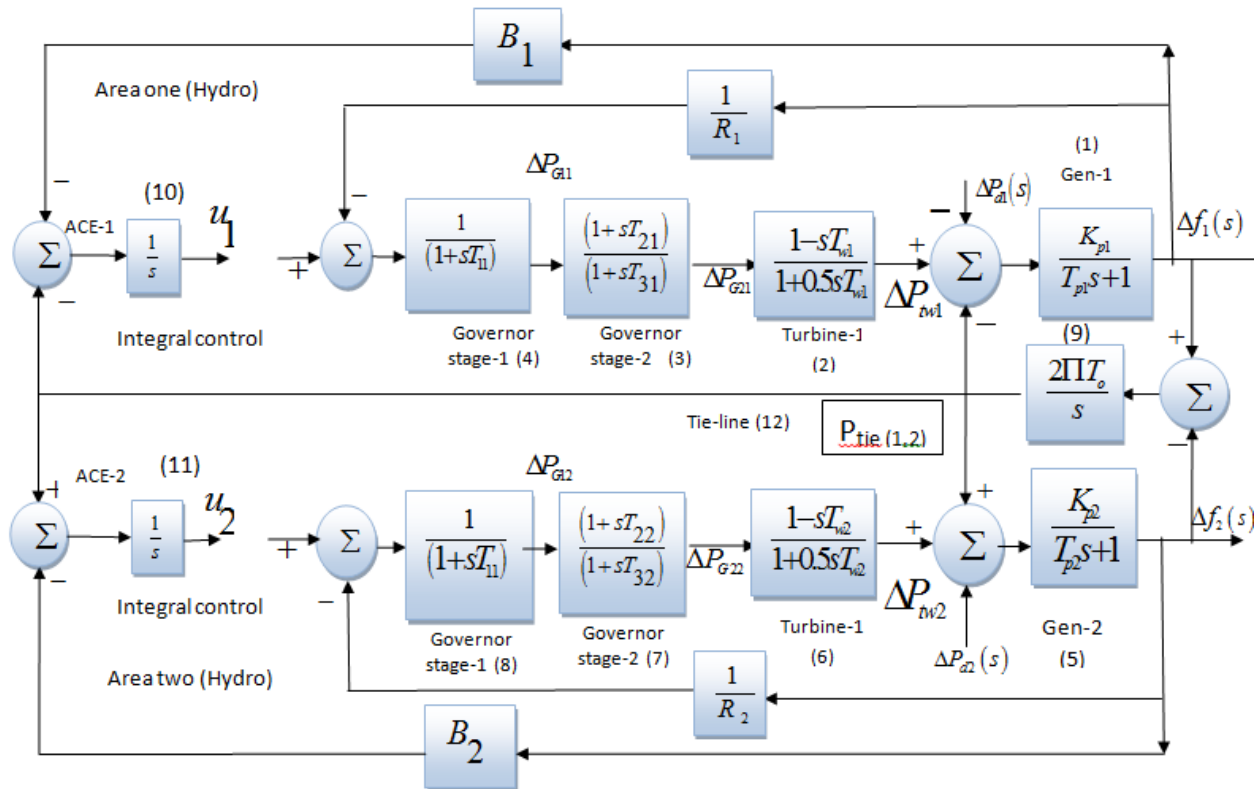


Fig 3.14 -Two area hydro-hydropower system with optimal controller

The Different variables can be defined as:

**State Variables:**

$$x_1 = \Delta f_1 \quad x_2 = \Delta P_{tw1} \quad x_3 = \Delta P_{G21} \quad x_4 = \Delta P_{G11} \quad x_5 = \Delta f_2$$

$$x_6 = \Delta P_{tw2} \quad x_7 = \Delta P_{G22} \quad x_8 = \Delta P_{G12} \quad x_9 = P_{tie(1,2)}$$

$$x_{10} = \int ACE_1 dt \quad x_{11} = \int ACE_2 dt$$

**Control inputs:**  $u_1$  and  $u_2$

**Disturbance inputs:**  $d_1 = \Delta P_{d2}$  and  $d_2 = \Delta P_{d1}$

**State equations:** From the transfer function blocks labeled from 1 to 11 given in bracket of Fig 3.14 above;

• **For block 1:**

$$x_1 + T_{p1} \dot{x}_1 = K_{p1}(x_2 - x_9 - d_1)$$

$$\text{i.e., } \dot{x}_1 = -\frac{1}{T_{p1}}x_1 + \frac{K_{p1}}{T_{p1}}x_2 - \frac{K_{p1}}{T_{p1}}x_9 - \frac{K_{p1}}{T_{p1}}d_1$$

• **For block 2:**

$$x_2 + 0.5T_{w1} \dot{x}_2 = x_3 - T_{w1} \dot{x}_3$$

$$\text{i.e. } \dot{x}_2 = -\frac{2}{T_{w1}}x_2 + \frac{2}{T_{w1}}x_3 - 2\dot{x}_3$$

$$\therefore \dot{x}_2 = -\frac{2}{T_{w1}}x_2 + \frac{2}{T_{w1}}x_3 - 2\left[-\frac{T_{21}}{R_1 T_{11} T_{31}}x_1 - \frac{1}{T_{31}}x_3 + \left(\frac{1}{T_{31}} - \frac{T_{21}}{T_{11} T_{31}}\right)x_4 + \frac{T_{21}}{T_{11} T_{31}}u_1\right]$$

$$\therefore \dot{x}_2 = \frac{2T_{21}}{R_1 T_{11} T_{31}}x_1 - \frac{2}{T_{w1}}x_2 + \left(\frac{1}{T_{w1}} + \frac{2}{T_{31}}\right)x_3 - \left(\frac{2}{T_{31}} - \frac{2T_{21}}{T_{11} T_{31}}\right)x_4 - \frac{2T_{21}}{T_{11} T_{31}}u_1$$

• **For block 3:**

$$x_3 + T_{31} \dot{x}_3 = x_4 + T_{21} \dot{x}_4$$

$$\text{i.e. } \dot{x}_3 = -\frac{1}{T_{31}}x_3 + \frac{1}{T_{31}}x_4 + \frac{T_{21}}{T_{31}}\dot{x}_4$$

$$\therefore \dot{x}_3 = -\frac{1}{T_{31}}x_3 + \frac{1}{T_{31}}x_4 + \frac{T_{21}}{T_{31}}\left[-\frac{1}{R_1T_{11}}x_1 - \frac{1}{T_{11}}x_4 + \frac{1}{T_{11}}u_1\right]$$

$$\therefore \dot{x}_3 = -\frac{T_{21}}{R_1T_{11}T_{31}}x_1 - \frac{1}{T_{31}}x_3 + \left(\frac{1}{T_{31}} - \frac{T_{21}}{T_{11}T_{31}}\right)x_4 + \frac{T_{21}}{T_{11}T_{31}}u_1$$

• **For block 4:**

$$x_4 + T_{11}\dot{x}_4 = u_1 - \frac{1}{R_1}x_1$$

$$\text{i.e. } \dot{x}_4 = -\frac{1}{R_1T_{11}}x_1 - \frac{1}{T_{11}}x_4 + \frac{1}{T_{11}}u_1$$

• **For block 5:**

$$x_5 + T_{p2}\dot{x}_5 = K_{p2}(x_6 - x_9 - d_2)$$

$$\text{i.e. } \dot{x}_5 = -\frac{1}{T_{p2}}x_5 + \frac{K_{p2}}{T_{p2}}x_6 - \frac{K_{p2}}{T_{p2}}x_9 - \frac{K_{p2}}{T_{p2}}d_2$$

• **For block 6:**

$$x_6 + 0.5T_{w2}\dot{x}_6 = x_7 - T_{w2}\dot{x}_7$$

$$\text{i.e. } \dot{x}_6 = -\frac{2}{T_{w2}}x_6 + \frac{2}{T_{w2}}x_7 - 2\dot{x}_7$$

$$\therefore \dot{x}_6 = -\frac{2}{T_{w2}}x_6 + \frac{2}{T_{w2}}x_7 - 2\left[-\frac{T_{22}}{R_2T_{12}T_{32}}x_5 - \frac{1}{T_{32}}x_7 + \left(\frac{1}{T_{32}} - \frac{T_{22}}{T_{12}T_{32}}\right)x_8 + \frac{T_{22}}{T_{12}T_{32}}u_2\right]$$

$$\therefore \dot{x}_6 = \frac{2T_{22}}{R_2T_{12}T_{32}}x_5 - \frac{2}{T_{w2}}x_6 + \left(\frac{1}{T_{w2}} + \frac{2}{T_{32}}\right)x_7 - \left(\frac{2}{T_{32}} - \frac{2T_{22}}{T_{12}T_{32}}\right)x_8 - \frac{2T_{22}}{T_{12}T_{32}}u_2$$

• **For block 7:**

$$x_7 + T_{32} \dot{x}_7 = x_8 + T_{22} \dot{x}_8$$

$$\text{i.e. } \dot{x}_7 = -\frac{1}{T_{32}}x_7 + \frac{1}{T_{32}}x_8 + \frac{T_{22}}{T_{32}}\dot{x}_8$$

$$\therefore \text{i.e. } \dot{x}_7 = -\frac{1}{T_{32}}x_7 + \frac{1}{T_{32}}x_8 + \frac{T_{22}}{T_{32}} \left[ \dot{x}_8 = -\frac{1}{R_2 T_{12}}x_5 - \frac{1}{T_{12}}x_8 + \frac{1}{T_{12}}u_2 \right]$$

$$\therefore \dot{x}_7 = -\frac{T_{22}}{R_2 T_{12} T_{32}}x_5 - \frac{1}{T_{32}}x_7 + \left( \frac{1}{T_{32}} - \frac{T_{22}}{T_{12} T_{32}} \right) x_8 + \frac{T_{22}}{T_{12} T_{32}}u_2$$

• **For block 8:**

$$x_8 + T_{12} \dot{x}_8 = u_2 - \frac{1}{R_2}x_5$$

$$\text{i.e. } \dot{x}_8 = -\frac{1}{R_2 T_{12}}x_5 - \frac{1}{T_{12}}x_8 + \frac{1}{T_{12}}u_2$$

• **For block 9:**

$$\dot{x}_9 = 2\pi T_o x_1 - 2\pi T_o x_5$$

• **For block 10:**

$$\dot{x}_9 = B_1 x_1 + x_9$$

• **For block 11:**

$$\dot{x}_9 = B_1 x_1 - x_9$$

Above equations are arranged in vector matrix form called ‘**State Equation**’ with a form;

$$\dot{x} = Ax + Bu + \Gamma d,$$

Where, A (11×11) is **State Matrix**, B(11×2) is **Control Matrix**&  $\Gamma$  (11×2) is **Disturbance Matrix**. The matrices A, B and  $\Gamma$  are shown below.

$$A = \begin{bmatrix} \frac{1}{T_{p1}} & \frac{K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{K_{p1}}{T_{p1}} & 0 & 0 \\ \frac{2T_{21}}{R_1 T_{11} T_{31}} & -\frac{2}{T_{w1}} \left( \frac{1}{T_{w1}} + \frac{2}{T_{31}} \right) & -\left( \frac{2}{T_{31}} - \frac{2T_{21}}{T_{11} T_{31}} \right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{T_{21}}{R_1 T_{11} T_{31}} & 0 & -\frac{1}{T_{31}} & \left( \frac{1}{T_{31}} - \frac{T_{21}}{T_{11} T_{31}} \right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1 T_{11}} & 0 & 0 & -\frac{1}{T_{11}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0 & 0 & 0 & -\frac{K_{p2}}{T_{p2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2T_{22}}{R_2 T_{12} T_{32}} & -\frac{2}{T_{w2}} \left( \frac{1}{T_{w2}} + \frac{2}{T_{32}} \right) & -\left( \frac{2}{T_{32}} - \frac{2T_{22}}{T_{12} T_{32}} \right) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{T_{22}}{R_2 T_{12} T_{32}} & 0 & -\frac{1}{T_{32}} & \left( \frac{1}{T_{32}} - \frac{T_{22}}{T_{12} T_{32}} \right) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{R_2 T_{12}} & 0 & 0 & -\frac{1}{T_{12}} & 0 & 0 & 0 & 0 \\ 2\pi T_o & 0 & 0 & 0 & 2\pi T_o & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & B_2 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{2T_{21}}{T_{11} T_{31}} & 0 \\ \frac{T_{21}}{T_{11} T_{31}} & 0 \\ \frac{1}{T_{11}} & 0 \\ 0 & 0 \\ 0 & \frac{2T_{22}}{T_{12} T_{32}} \\ 0 & \frac{T_{22}}{T_{12} T_{32}} \\ \frac{1}{T_{12}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}; \quad \Gamma = \begin{bmatrix} -\frac{K_{p1}}{T_{p1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{K_{p2}}{T_{p2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The **State Vector** ‘ $x$ ’ (11×1), **Control Vector** ‘ $u$ ’ (2×1) and the **Disturbance Vector** ‘ $d$ ’ (2×1) are:

$$x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} \end{bmatrix} \quad u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

### 3.9- Design of Optimal Control

In optimal control, the control inputs are chosen as a linear combination of feedback from all the eleven system states  $X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} \end{bmatrix}$  as given below;

$$u_1 = k_{11}x_1 + k_{12}x_2 + k_{13}x_3 + k_{14}x_4 + k_{15}x_5 + k_{16}x_6 + k_{17}x_7 + k_{18}x_8 + k_{19}x_9 + k_{1-10}x_{10} + k_{1-11}x_{11}$$

$$u_2 = k_{21}x_1 + k_{22}x_2 + k_{23}x_3 + k_{24}x_4 + k_{25}x_5 + k_{26}x_6 + k_{27}x_7 + k_{28}x_8 + k_{29}x_9 + k_{2-10}x_{10} + k_{2-11}x_{11}$$

Where:  $K = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} & k_{17} & k_{18} & k_{19} & k_{1-10} & k_{1-11} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} & k_{27} & k_{28} & k_{29} & k_{2-10} & k_{2-11} \end{bmatrix};$

The system State Equation is;

$$\dot{x} = Ax + Bu \dots\dots\dots \text{(For a step load change of a constant magnitude, } \Gamma d = 0)$$

The output equation is;

$$Y = Cx + Du$$

However, for a feedback control system, the matrix D is assumed to be zero.

Hence;  $Y = Cx$

Where: C (2 × 11) is the **Output Matrix**.

Finally, the state space model of the system under consideration takes a form as;

$$\dot{x} = Ax + Bu \quad \text{And} \quad Y = Cx$$

The control inputs are linear combinations of system states given by;

$$u = -Kx$$

#### **Determination of the Feedback Gain Matrix (K)**

The design of an optimal controller is to determine the feedback matrix ‘K’ in such a way that a certain Performance Index (J) is minimized while transferring the system from an initial arbitrary state  $x(0) \neq 0$  to the origin in an infinite time i.e.,  $x(\infty) = 0$ .

Generally, the performance index J is chosen in quadratic form as;

$$J = \frac{1}{2} \int_0^{\infty} (x^T Qx + u^T Ru) dt$$

Where, ‘**Q**’ is a real, symmetric and positive semi-definite matrix called as ‘**state weightingmatrix**’ and ‘**R**’ is a real, symmetric and positive definite matrix called as ‘**control weightingmatrix**’.

The matrices Q and R are determined on the basis of following system requirements.

- The excursions (deviations) of area control errors (ACEs) about steady state values are minimized. In this model, these excursions are determined as;

$$ACE_1 = B_1 \Delta f_1 + P_{Tie(1,2)} = B_1 x_1 + X_9 \text{ And } ACE_2 = B_2 \Delta f_2 + P_{Tie(1,2)} = B_2 x_5 - X_9$$

- The excursions of  $\int (ACE) dt$  about steady values are minimized. In this model, these excursions are  $X_{10}$  and  $X_{11}$ .
- The excursions of control inputs  $u_1$  and  $u_2$  about steady values are minimized.

Under these considerations, **J** takes a form;

$$J = \frac{1}{2} \int_0^{\infty} [(B_1 x_1 + x_9)^2 + (B_2 x_5 - x_9)^2 + (x_{10})^2 + (x_{11})^2 + (u_1)^2 + (u_2)^2] dt$$

$$i.e. J = \frac{1}{2} \int_0^{\infty} [(B_1^2 x_1^2 + 2B_1 x_1 x_9 + 2x_9^2) + B_2^2 x_5^2 - 2B_2 x_5 x_9 + 2x_9^2 + x_{10}^2 + (x_{11})^2 + u_1^2 + u_2^2] dt$$

This gives the matrices Q (11×11) and R (2×2) as:

$$Q = \begin{bmatrix} B_1^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & B_2^2 & 0 & 0 & 0 & -B_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & -B_2 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Therefore the matrices A, B, Q & R are known. But the optimal control is given by

$$u = -Kx$$

‘**K**’ is the feedback gain matrix given by

$$K = R^{-1} B^T S$$

Where ‘**S**’ is a real, symmetric and positive definite matrix which is the unique solution of matrix **Riccati** Equation given by:

$$A^T S + SA - SBR^{-1}B^T S + Q = 0$$

The closed loop system equation is;

$$\dot{x} = Ax + B(-Kx) = (A - BK)x = A_c x$$

The matrix  $A_c = (A - BK)$  is the closed loop system matrix. The stability of closedloop system can be tested by finding Eigenvalues of the matrix  $A_c$ .

### **System Analysis with MATLAB**

After substituting values of parameters as taken from literatures (which will be written in the appendix), the state equations and the matrices A, B, Q & R are expressed as;

$$\dot{x}_1 = -0.05x_1 + 6(x_2 - x_9 - d_1)$$

$$\dot{x}_2 = 0.000877823x_1 - 2x_2 + 2.2x_3 - 0.197893223x_4 - 0.002106776u_1$$

$$\dot{x}_3 = -0.004389117x_1 - 0.1x_3 + 0.098946611x_4 + 0.001053388u_1$$

$$\dot{x}_4 = -0.008555784x_1 - 0.02053388x_4 + 0.02053388u_1$$

$$\dot{x}_5 = -0.05x_5 + 6(x_6 + x_9 - d_2)$$

$$\dot{x}_6 = 0.000877823x_5 - 2x_6 + 2.2x_7 - 0.197893223x_8 - 0.002106776u_2$$

$$\dot{x}_7 = -0.004389117x_5 - 0.1x_7 + 0.098946611x_8 + 0.001053388u_2$$

$$\dot{x}_8 = -0.008555784x_5 - 0.02053388x_8 + 0.02053388u_2$$

$$\dot{x}_9 = 0.444222x_1 - 0.44422x_5$$

$$\dot{x}_{10} = 0.425x_1 + x_9$$

$$\dot{x}_{11} = 0.425x_5 - x_9$$

$$A = \begin{bmatrix} -0.05 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & -6 & 0 & 0 \\ 0.000877823 & -2 & 2.2 & -0.197893223 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.004389117 & 0 & -0.1 & 0.098946611 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.008555784 & 0 & 0 & -0.02053388 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.05 & 6 & 0 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.000877823 & -2 & 2.2 & -0.197893223 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.004389117 & 0 & -0.1 & 0.098946611 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.008555784 & 0 & 0 & -0.02053388 & 0 & 0 & 0 \\ 0.44422 & 0 & 0 & 0 & -0.44422 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.425 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -0.0062106776 & 0 \\ 0.001053388 & 0 \\ 0.02053388 & 0 \\ 0 & 0 \\ 0 & -0.0062106776 \\ 0 & 0.001053388 \\ 0 & 0.02053388 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad Q = \begin{bmatrix} 0.180625 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.425 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.180625 & 0 & 0 & 0 & -0.425 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.425 & 0 & 0 & 0 & -0.425 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

**MATLAB program to obtain S, K & Ac:**

(‘MATLAB R2008a’ software is used to design the optimal controllers).

$A = [-0.05 \ 6 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ -6 \ 0 \ 0; -0.00877823 \ -2 \ 2.2 \ -0.197893223 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; -0.004389117 \ 0 \ -0.1 \ 0.098946611 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; -0.008555784 \ 0 \ 0 \ -0.02053388 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ -0.05 \ 6 \ 0 \ 0 \ 6 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ -0.00877823 \ -2 \ 2.2 \ -0.197893223 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ -0.004389117 \ 0 \ -0.1 \ 0.098946611 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ -0.008555784 \ 0 \ 0 \ -0.02053388 \ 0 \ 0 \ 0; 0.44422 \ 0 \ 0 \ 0 \ -0.44422 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0.425 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0.425 \ 0 \ 0 \ 0 \ -1 \ 0 \ 0];$

$B = [0 \ 0; -0.0062106776 \ 0; 0.001053388 \ 0; 0.02053388 \ 0; 0 \ 0; 0 \ -0.0062106776; 0 \ 0.001053388; 0 \ 0.02053388; 0 \ 0; 0 \ 0; 0 \ 0].$

$Q = [0.180625 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0.425 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0.180625 \ 0 \ 0 \ 0 \ -0.425 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0; 0.425 \ 0 \ 0 \ 0 \ -0.425 \ 0 \ 0 \ 0 \ 2 \ 0 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0; 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1]$

$R = [1 \ 0; 0 \ 1]$

$S = care(A, B, Q, R)$

$K = inv(R) * B' * S$

$Ac = A - B * K$

$eig(S)$

$eig(A)$

$eig(Ac)$

**Output of the MATLAB program:**

$S = \begin{bmatrix} 0.0169 & 0.0463 & 0.3197 & 0.0408 & 0.0130 & 0.0404 & 0.3074 & 0.0331 & -0.0011 & 0.0096 & 0.0066 \\ 0.0463 & 0.1355 & 0.9693 & 0.1269 & 0.0404 & 0.1179 & 0.9174 & 0.1047 & -0.0165 & 0.0274 & 0.0187 \\ 0.3197 & 0.9693 & 9.1417 & 1.7232 & 0.3074 & 0.9174 & 8.3817 & 1.3214 & -0.0521 & 0.2119 & 0.1092 \\ 0.0408 & 0.1269 & 1.7232 & 0.6611 & 0.0331 & 0.1047 & 1.3214 & 0.3096 & -0.0147 & 0.0461 & 0.0001 \\ 0.0130 & 0.0404 & 0.3074 & 0.0331 & 0.0169 & 0.0463 & 0.3197 & 0.0408 & 0.0011 & 0.0066 & 0.0096 \\ 0.0404 & 0.1179 & 0.9174 & 0.1047 & 0.0463 & 0.1355 & 0.9693 & 0.1269 & 0.0165 & 0.0187 & 0.0274 \\ 0.3074 & 0.9174 & 8.3817 & 1.3214 & 0.3197 & 0.9693 & 9.1417 & 1.7232 & 0.0521 & 0.1092 & 0.2119 \\ 0.0331 & 0.1047 & 1.3214 & 0.3096 & 0.0408 & 0.1269 & 1.7232 & 0.6611 & 0.0147 & 0.0001 & 0.0461 \\ -0.0011 & -0.0165 & -0.0521 & -0.0147 & 0.0011 & 0.0165 & 0.0521 & 0.0147 & 0.0511 & -0.0070 & 0.0070 \\ 0.0096 & 0.0274 & 0.2119 & 0.0461 & 0.0066 & 0.0187 & 0.1092 & 0.0001 & -0.0070 & 0.0142 & -0.0032 \\ 0.0066 & 0.0187 & 0.1092 & 0.0001 & 0.0096 & 0.0274 & 0.2119 & 0.0461 & 0.0070 & -0.0032 & 0.0142 \end{bmatrix}$

Matrix 'S' is found to be real, positive definite & symmetric. All of the Eigenvalues are real and positive: 0, 0, 0.0002, 0.0002, 0.0010, 0.0034, 0.0046, 0.0115, 0.0459, 0.1028 and 1.8294.

$$K = \begin{bmatrix} 0.8877 & 2.7859 & 38.9946 & 14.6020 & 0.7525 & 2.3831 & 30.2641 & 7.1000 & -0.2551 & 1.0000 & 0.0000 \\ 0.7525 & 2.3831 & 30.2641 & 7.1000 & 0.8877 & 2.7859 & 38.9946 & 14.6020 & 0.2551 & 0.0000 & 1.0000 \end{bmatrix}$$

Now we can express the equation of the control inputs  $u_1$  and  $u_2$  as:

$$u_1 = 0.8877x_1 + 2.7859x_2 + 38.9946x_3 + 14.6020x_4 + 0.7525x_5 + 2.3831x_6 + 30.2641x_7 + 7.1000x_8 - 0.2551x_9 + 1.0000x_{10}$$

$$u_2 = 0.7525x_1 + 2.3831x_2 + 30.2641x_3 + 7.1000x_4 + 0.8877x_5 + 2.7859x_6 + 38.9946x_7 + 14.6020x_8 - 0.2551x_9 + 1.0000x_{11}$$

And also the closed loop system matrix 'Ac' is given as below:

$$A_c = \begin{bmatrix} -0.0500 & 6.0000 & 0 & 0 & 0 & 0 & 0 & 0 & -6.0000 & 0 & 0 \\ -0.0033 & -1.9827 & 2.4422 & -0.1072 & 0.0047 & 0.0148 & 0.1880 & 0.0441 & -0.0016 & 0.0062 & 0.0000 \\ -0.0053 & -0.0029 & -0.1411 & 0.0836 & -0.0008 & -0.0025 & -0.0319 & -0.0075 & 0.0003 & -0.0011 & -0.0000 \\ -0.0268 & -0.0572 & -0.8007 & -0.3204 & -0.0155 & -0.0489 & -0.6214 & -0.1458 & 0.0052 & -0.0205 & -0.0000 \\ 0 & 0 & 0 & 0 & -0.0500 & 6.0000 & 0 & 0 & 6.0000 & 0 & 0 \\ 0.0047 & 0.0148 & 0.1880 & 0.0441 & -0.0033 & -1.9827 & 2.4422 & -0.1072 & 0.0016 & 0.0000 & 0.0062 \\ -0.0008 & -0.0025 & -0.0319 & -0.0075 & -0.0053 & -0.0029 & -0.1411 & 0.0836 & -0.0003 & -0.0000 & -0.0011 \\ -0.0155 & -0.0489 & -0.6214 & -0.1458 & -0.0268 & -0.0572 & -0.8007 & -0.3204 & -0.0052 & -0.0000 & -0.0205 \\ 0.4442 & 0 & 0 & 0 & -0.4442 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.4250 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.4250 & 0 & 0 & 0 & -1.0000 & 0 & 0 \end{bmatrix}$$

The Eigen values of the open loop system matrix (i.e. the state matrix) 'A' are:

$$0; 0; -0.0280 + 2.3173i; -0.0280 - 2.3173i; -0.0280 - 2.3173i; -1.9935; -1.9844; -0.0013 + 0.1790i; -0.0013 - 0.1790i; -0.1835; -0.1008 \text{ and } -0.0203$$

From the result we can see that two Eigenvalues are zero and remaining have negative real parts which indicate that the system is marginally stable before applying the optimal control strategy.

And also the Eigen values of closed loop system matrix 'Ac' are obtained as:

$$-0.0283 + 2.3173i; -0.0283 - 2.3173i; -1.9844; -1.9935; -0.1007 + 0.2699i; -0.1007 - 0.2699i; -0.2356 + 0.0893i; -0.2356 - 0.0893i; -0.0700 + 0.0978i; -0.0700 - 0.0978i; -0.0700 - 0.0978i \text{ and } -0.1411.$$

Now we can observe that all the eigen values of the closed loop matrix 'Ac' have negative real parts indicating that the system is asymptotically stable after applying optimal control strategy.

### **3.10 - Discrete Equations For Integral and optimal Control**

The State equations and control equations for power system models of two area hydro-hydro system were obtained in the above sections for integral and optimal control. For the development of ANN controllers with MATLAB programming, the power system equations are required in discrete time form and they are given below. The sampling time is 0.01 second and ‘k’ denotes the sample number (iteration number).

#### ***Discrete Equations for Integral Control***

$$x_1(k+1) = 0.9995x_1(k) + 0.06(x_2(k) - x_9(k) - d_1(k))$$

$$x_2(k+1) = 0.00000877823x_1(k) + 0.98x_2(k) + 0.022x_3(k) - 0.001979x_4(k) - 0.00002106u_1(k)$$

$$x_3(k+1) = -0.0000439x_1(k) + 0.999x_3(k) + 0.000989x_4(k) + 0.00001053u_1(k)$$

$$x_4(k+1) = -0.00008555x_1(k) + 0.9997947x_4(k) + 0.0002053u_1(k)$$

$$x_5(k+1) = 0.9995x_5 + 0.06(x_6(k) + x_9(k) - d_2(k))$$

$$x_6(k+1) = 0.00000877823x_5(k) + 0.98x_6(k) + 0.022x_7(k) - 0.001979x_8(k) - 0.00002106u_2(k)$$

$$x_7(k+1) = -0.0000439x_5(k) + 0.999x_7(k) + 0.000989x_8(k) + 0.00001053u_2(k)$$

$$x_8(k+1) = -0.00008555x_5(k) + 0.9997947x_8(k) + 0.0002053u_2(k)$$

$$x_9(k+1) = 0.0044422x_1(k) - 0.0044422x_5(k) + x_9(k)$$

$$x_{10}(k+1) = 0.00425x_1(k) + 0.01x_9(k) + x_{10}(k)$$

$$x_{11}(k+1) = 0.00425x_1(k) - 0.01x_9(k) + x_{11}(k)$$

$$u_1(k+1) = -0.000085x_1(k) - 0.0002x_9(k) + u_1(k)$$

$$u_2(k+1) = -0.000085x_5(k) + 0.0002x_9(k) + u_2(k)$$

#### ***Discrete Equations for Optimal Control***

$$x_1(k+1) = 0.9995x_1(k) + 0.06(x_2(k) - x_9(k) - d_1(k))$$

$$x_2(k+1) = 0.00000877823x_1(k) + 0.98x_2(k) + 0.022x_3(k) - 0.001979x_4(k) - 0.00002106u_1(k)$$

$$x_3(k+1) = -0.0000439x_1(k) + 0.999x_3(k) + 0.000989x_4(k) + 0.00001053u_1(k)$$

$$x_4(k+1) = -0.00008555x_1(k) + 0.9997947x_4(k) + 0.0002053u_1(k)$$

$$x_5(k+1) = 0.9995x_5 + 0.06(x_6(k) + x_9(k) - d_2(k))$$

$$x_6(k+1) = 0.00000877823x_5(k) + 0.98x_6(k) + 0.022x_7(k) - 0.001979x_8(k) - 0.00002106u_2(k)$$

$$x_7(k+1) = -0.0000439x_5(k) + 0.999x_7(k) + 0.000989x_8(k) + 0.00001053u_2(k)$$

$$x_8(k+1) = -0.00008555x_5(k) + 0.9997947x_8(k) + 0.0002053u_2(k)$$

$$x_9(k+1) = 0.0044422x_1(k) - 0.0044422x_5(k) + x_9(k)$$

$$x_{10}(k+1) = 0.00425x_1(k) + 0.01x_9(k) + x_{10}(k)$$

$$x_{11}(k+1) = 0.00425x_1(k) - 0.01x_9(k) + x_{11}(k)$$

$$u_1(k+1) = 0.8877x_1(k) + 2.7859x_2(k) + 38.9946x_3(k) + 14.6020x_4(k) + 0.7525x_5(k)$$

$$+ 2.3831x_6(k) + 30.2641x_7(k) + 7.1x_8(k) - 0.2551x_9(k) + x_{10}(k)$$

$$u_2(k+1) = 0.7525x_1(k) + 2.3831x_2(k) + 30.2641x_3(k) + 7.1x_4(k) + 0.8877x_5(k)$$

$$+ 2.7859x_6(k) + 38.9946x_7(k) + 14.6020x_8(k) - 0.2551x_9(k) + x_{11}(k)$$

### **3.11-Concluding Remarks**

Models of hydro-hydro power systems were developed with integral as well as optimal control strategies. The optimal controllers were designed and the control equations in continuous time were obtained for the power system model under consideration. This model was studied for system stability and it was ensured that they are asymptotically stable with parameters values as given in specification (Appendix) after applying optimal control strategy. Also for the power system model under consideration, the discrete time equations for system states as well as control inputs are obtained for both integral control and optimal control strategies. These equations were used for development of ANN controllers.

## **Chapter 4**

# **CONTROLLER DESIGN**

### **4.1- PID Controller Design**

The portion of integral control in an Automatic Generation Control (AGC) will be substituted by a new controller which is PID controller. A PID controller is a generic control loop feedback mechanism widely used in an industrial control systems.

A PID controller attempts to correct error between a measured process variable and a desired set point by calculating and then producing a corrective action that can adjust the process accordingly and rapidly to keep the error to minimal.

The proportional value determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors and the derivative value determines the reaction based on the rate at which the error has been changing.

By tuning three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. Response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of PID algorithm for control does not guarantee optimal control of the system or system stability.

In order to design PID Controller, the value of  $K_p$ ,  $K_i$  and  $K_d$  was determined by using trial and error method. The value of  $K_p$ ,  $K_i$  and  $K_d$  was varied in order to see the best performance. The input for PID controller is frequency error for single area system and ACE for two area system. The output is change in control power setting for both. Single input and single output system was implemented in this controller. Therefore, using the above method and tuning values of the proportional-integral-derivative controller gains are found to be;

- $K_p=20$
- $K_i=4$
- $K_d=20$

## **4.2- Fuzzy Logic controller Design**

For Fuzzy Logic Controller, it was slightly different in terms of input output criteria. For Fuzzy Logic Controller modeling, it is done using two inputs and one output. For single area system, the inputs are frequency error and change of frequency error. For two area system, the inputs are area control (ACE) and change in area control error (dACE). The output for both systems is change in control power setting.

Fuzzy logic is used to calculate area control error ACE (out) i.e. control signal in the form of area control error that will be provided to both areas to generate according to change in total load in order to maintain system frequency within permissible limits. Area control error and change in frequency of the system are used as inputs for FLC.

### ***Algorithm for fuzzy logic application to AGC problem***

Calculation of control action in fuzzy logic controller algorithm consists of the following four basic steps.

- Calculate frequency error/area control error (ACE) and change of frequency error (dACE)/change in area control error (dACE).
- Convert the error and change of frequency into fuzzy variables i.e. linguistic variables such as Positive Large (PL), Positive Small (PS), Zero (ZE) etc., as given below.
- Evaluate the decision rules shown in rule base given below using the compositional rule of inference.
- Calculate the deterministic input required to regulate the process.

Control rules are formulated in linguistic terms using fuzzy sets to describe the magnitude of error, frequency deviation and magnitude of the appropriate control action.

### ***Rule base (with 5 membership functions)***

The rules may use several variables both in the condition and conclusion of the rules. The controllers can therefore be applied to both multi input multi output (MIMO) and single input and single output (SISO) problems. But in this project, MIMO was used because there are two inputs and one output. Rule format basically is a linguistic controller that contains rules in the if-then format, but they can also be represented in different format. In AGC for single area and two area systems, the rules are presented to the end-user in a format similar to the one below.

- If error is NL and change in error is NL then output is NL
- If error is NL and change in error is NS then output is NL
- If error is NL and change in error is ZE then output is NS
- If error is NL and change in error is PS then output is NS
- If error is NL and change in error is PL then output is ZE
- If error is NS and change in error is NL then output is NL
- If error is NS and change in error is NS then output is NS
- If error is NS and change in error is ZE then output is NS
- If error is NS and change in error is PS then output is ZE
- If error is NS and change in error is PL then output is PS
- If error is ZE and change in error is NL then output is NS
- If error is ZE and change in error is NS then output is NS
- If error is ZE and change in error is ZE then output is ZE
- If error is ZE and change in error is PS then output is PS
- If error is ZE and change in error is PL then output is PS
- If error is PS and change in error is NL then output is NS
- If error is PS and change in error is NS then output is ZE
- If error is PS and change in error is ZE then output is PS
- If error is PS and change in error is PS then output is PS
- If error is PS and change in error is PL then output is PL
- If error is PL and change in error is NL then output is ZE
- If error is PL and change in error is NS then output is PS
- If error is PL and change in error is ZE then output is PS
- If error is PL and change in error is PS then output is PL
- If error is PL and change in error is PL then output is PL

The error in the rule may be frequency error and change infrequency error for single area system or area control error and change in area control error for two area system. It is also possible to write the rule base in table form as below;

Frequency error/change infrequency error	NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL

Table 4.1 - Rule base for single area system

ACE/ $\Delta$ ACE	NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL

Table 4.2 - Rule base for Double area system

Where:

NL = negative large, NS = negative small, ZE = zero, PS = positive small & PL = positive large

**Note:** The Membership function used is the triangular and the Method used for De-fuzzification is centroid method.

**Fuzzy Logic controller in Single Area System**

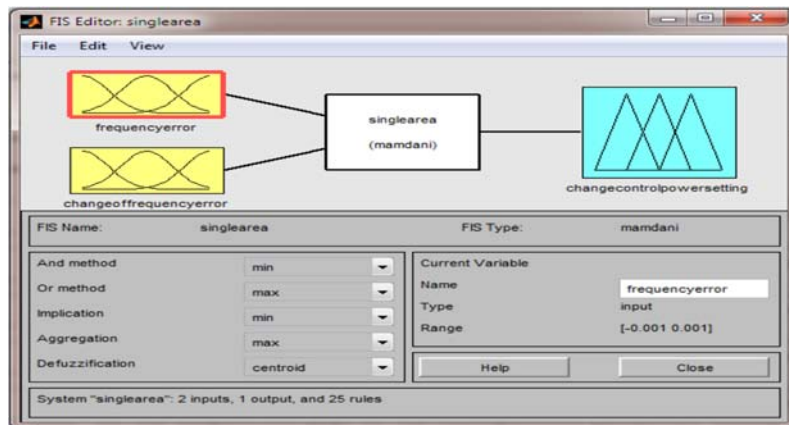


Fig 4.1 -Fuzzy Interference System Editor

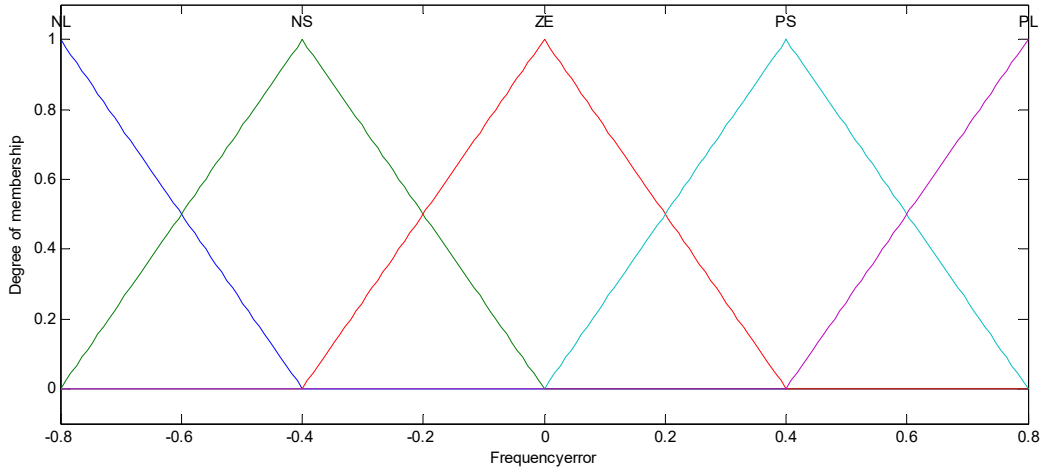


Fig 4.2 -Membership function editor for input 1-frequency error

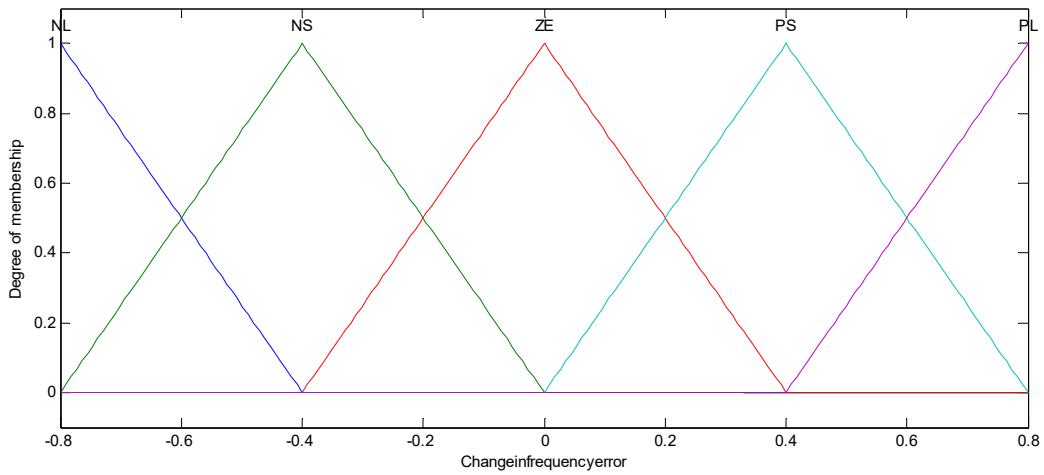


Fig 4.3 -Membership function editor for input 2-change of frequency error

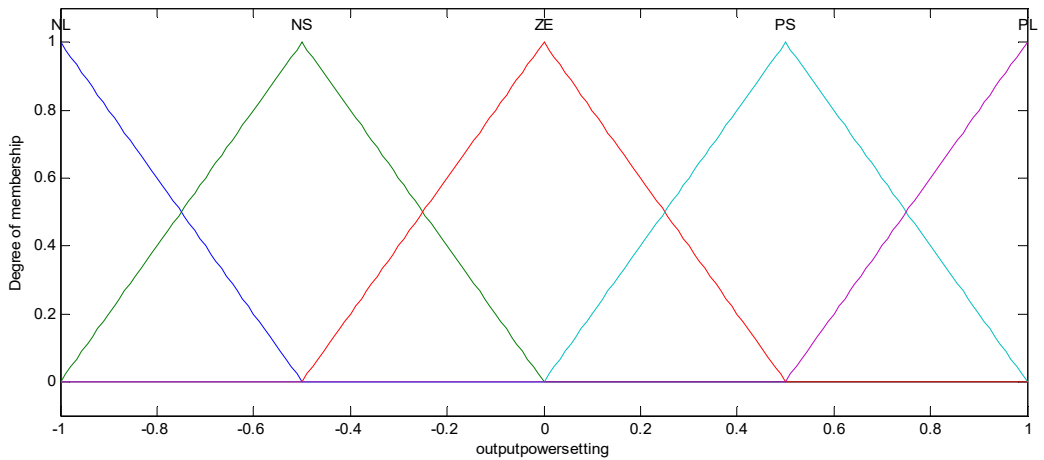


Fig 4.4 -Membership function editor for output -change in control power setting

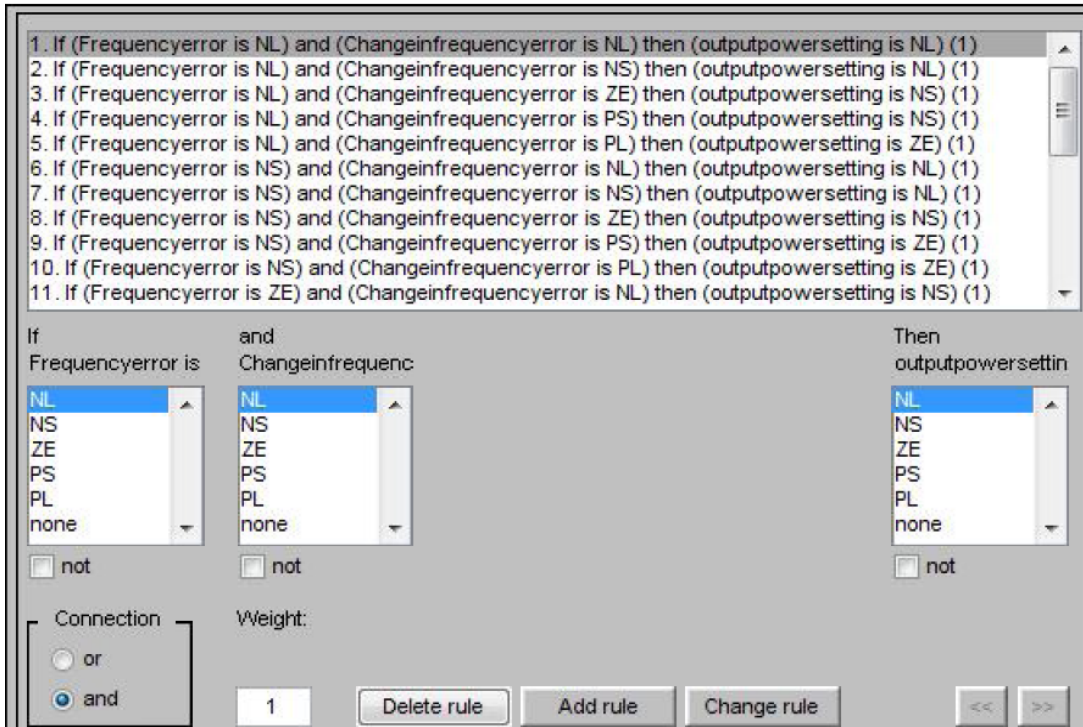


Fig 4.5 -Rule Editor

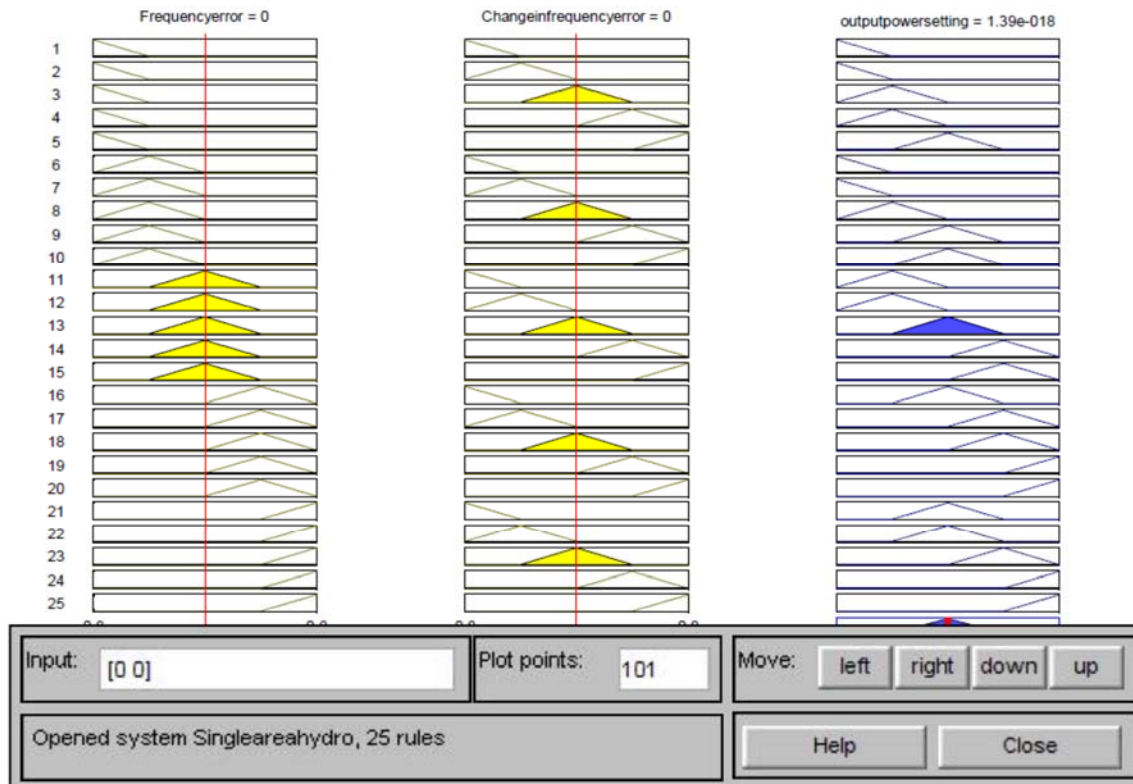


Fig 4.6 - Rule Viewer

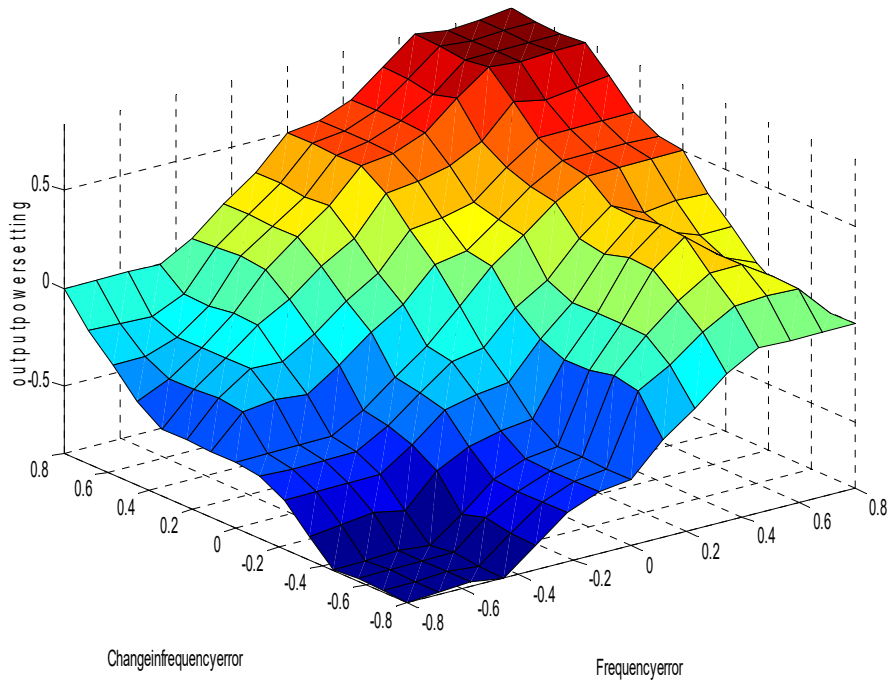


Fig 4.7 -Surface Viewer

**Fuzzy Logic controller in Double Area Systems**

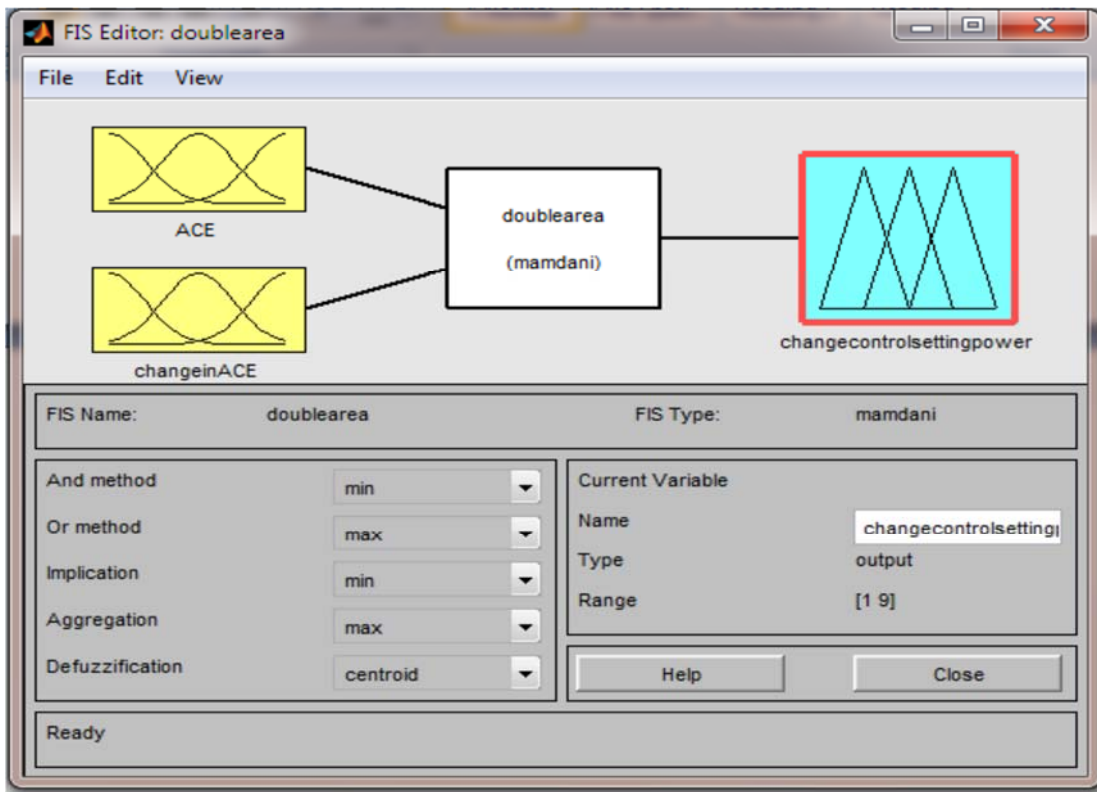


Fig 4.8 -Fuzzy Inference System Editor

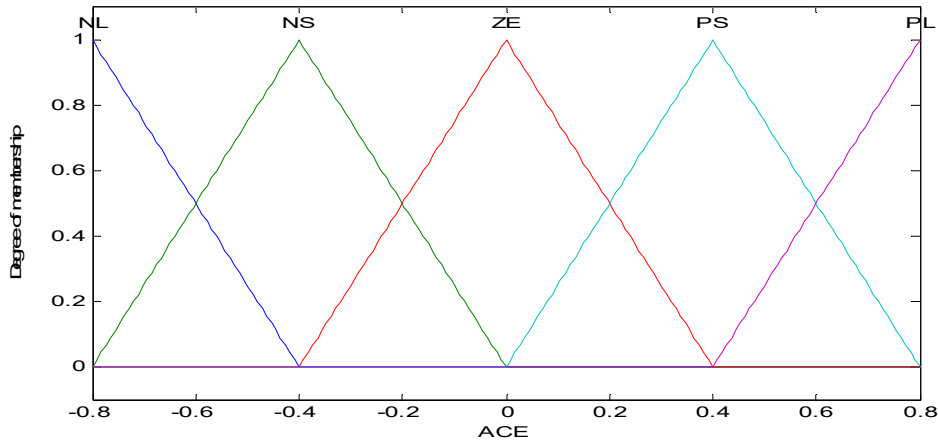


Fig 4.9 - Membership function editor for input 1-ACE

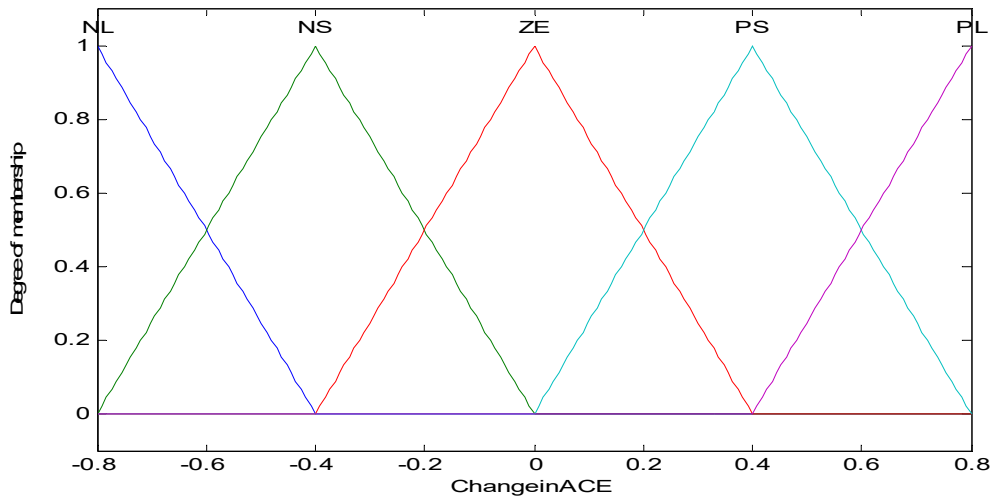


Fig 4.10 - Membership function editor for input 2-Change in ACE

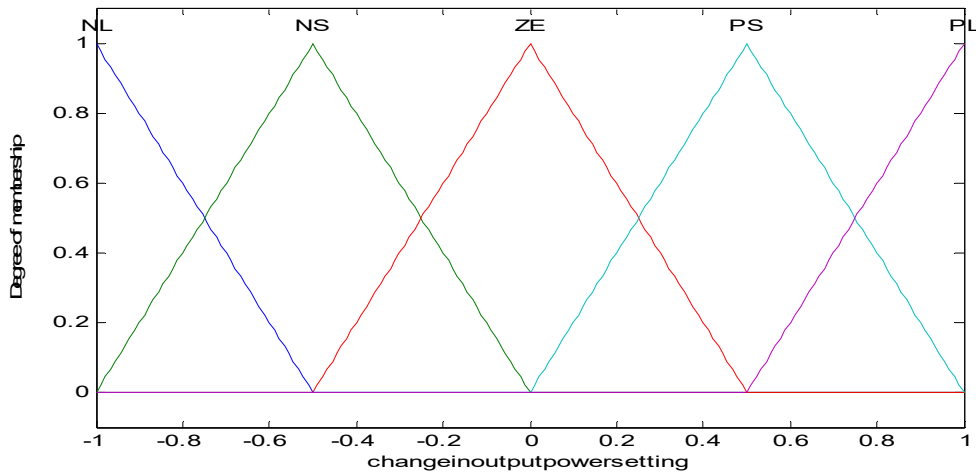


Fig 4.11 - Membership function editor for output -change in control power setting

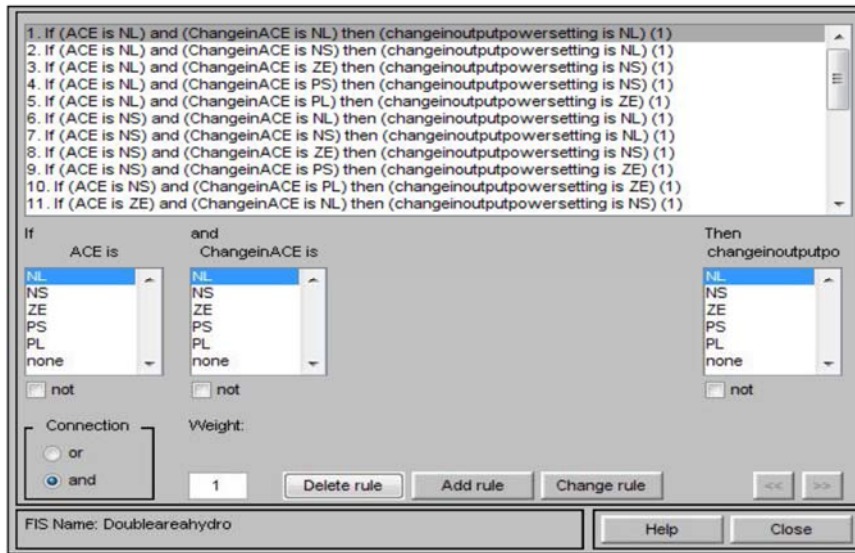


Fig 4.12 - Rule Editor



Fig 4.13 - Rule Viewer

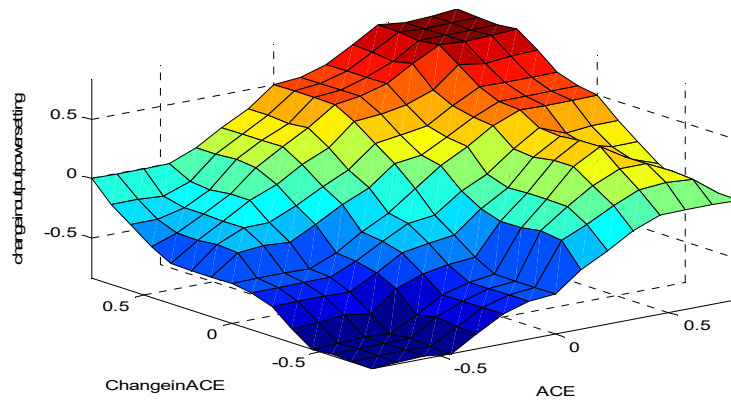


Fig 4.14 - Surface Viewer

### 4.3- Neural Network Controller Design

#### Specifications of Proposed Neural Network Controller

- Type of Neural Network: Feed Forward back propagation network
- Number of layers: 3
- Neurons: 20 in 1st layer (input), 10 in 2nd layer (hidden) and 2 or 3 in 3rd layer (output)
- Activation functions: Logarithmic Sigmoid for 1st and 2nd layers, Linear for 3rd layer
- Training algorithm: Lavenberg-Marquardt (LM) back propagation
- Training method: Supervised training

#### Proposed Scheme of Training and using the ANN Controller for AGC

Neural network with power system in training mode:As an Illustration, the proposed scheme of training and using the ANN controllers for AGC is demonstrated here for the hydro-hydro power system models. Fig 4.15 shows interface of neural network with the power system in training mode for a two area hydro-hydro power system (11 system states).

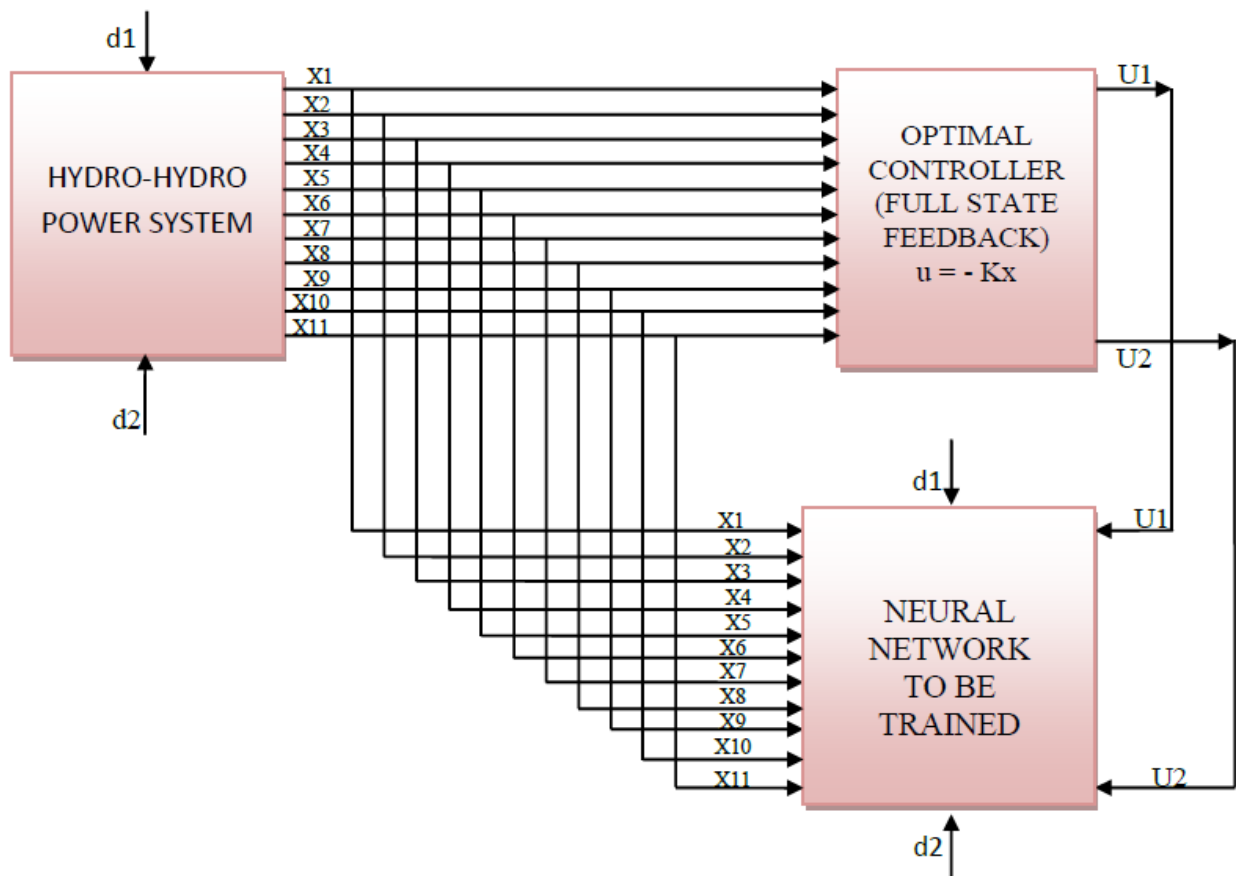


Fig 4.15 - Interface of neural network with power system in training model

**Trained neural network with power system as controller:**

The interface of trained neural network with the power system as a real time controller is shown in Fig 4.16.

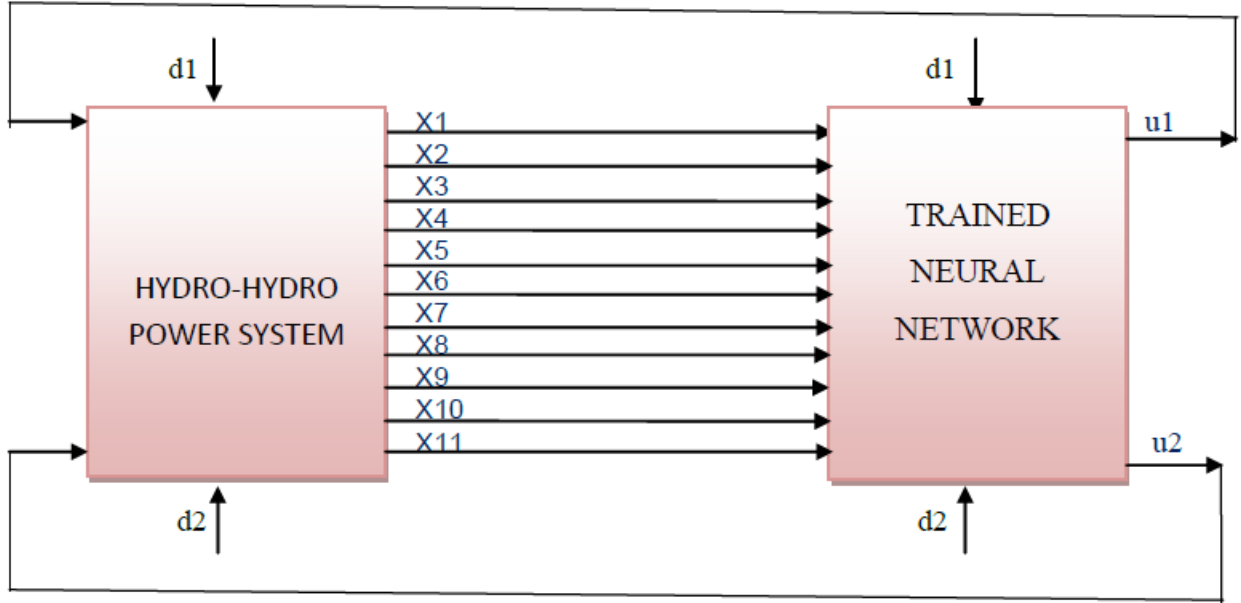


Fig 4.16 - Interface of neural network with power system in controller mode

**Development of ANN Controller with Programming using MATLAB**

The programming using MATLAB for developing a neural network controller for the hydro-hydro power system is described here.

➤ **Step 1: Generation of training data**

The system state equations (equations for  $x_1$  to  $x_{11}$ ) and control input equations (equations for  $u_1$  &  $u_2$ ) in discrete form for a two area Hydro-hydro power system were given in previous section. These equations are used to generate the training data.

A program has been executed using MATLAB which generates values of load disturbances in two areas ( $d_1$  &  $d_2$ ) randomly in the range of 0 to 1 percent per unit i.e. between 0 to 0.01 per unit. The program evaluates equations and stores the values of all variables after each iteration. Since the time of study and sampling time are chosen to be 15 sec and 0.01 sec respectively, a total of 1501 samples are collected for each variable for one pair of load disturbance. These all variables are stored in workspace and make one data set.

Thus, one data set comprises of 15 variables ( $x_1$  to  $x_{11}$ ,  $u_1$ ,  $u_2, d_1, d_2$ ). For  $d_1$  or  $d_2$ , all the 1501 values in one data set are equal (since we assume load disturbances of constant magnitude). About 60 to 100 such data sets at different combinations of load disturbances were collected and saved for the power system model under consideration. Following MATLAB program generates and saves the data sets.

```
i=1;
j=1500;
d1(i)=abs(randn)/200,
d2(i)=abs(randn)/200,
for n=1:71,
x1(i)=0,
x2(i)=0,
x3(i)=0,
x4(i)=0,
x5(i)=0,
x6(i)=0,
x7(i)=0,
x8(i)=0,
x9(i)=0,
x10(i)=0,
x11(i)=0,
u1(i)=0,
u2(i)=0,
for k=i:j,
x1(k+1)=0.9995*x1(k)+0.06*[x2(k)-x9(k)-d1(k)],
x2(k+1)= 0.000008778*x1(k)+0.98*x2(k)+0.022*x3(k)-0.001979*x4(k)-0.00002106*u1(k),
x3(k+1)=-0.00000439*x1(k)+0.999*x3(k)+0.0009894*x4(k)+0.00001053*u1(k),
x4(k+1)=-0.00008555*x1(k)+0.9997947*[x4(k)+0.0002053* u1(k)],
x5(k+1)= 0.9995*x5(k)+0.06*[x6(k)+x9(k)-d2(k)],
x6(k+1)= 0.000008778*x5(k)+0.98*x6(k)+0.022*x7(k)-0.001979*x8(k)-0.00002106*u2(k),
x7(k+1)= -0.00000439*x5(k)+0.999*x7(k)+0.0009894*x8(k)+0.00001053*u2(k),
x8(k+1)= -0.00008555*x5(k)+0.9997947*[x8(k)+0.0002053* u2(k)],
x9(k+1)=0.0044422*x1(k)-0.0044422*x5(k)+x9(k),
x10(k+1)=0.00425*x1(k)+0.01*x9(k)+x10(k),
x11(k+1)=0.00425*x1(k)-0.01*x9(k)+x11(k),
```

```
u1(k+1)=0.8877*x1(k)+2.7859*x2(k)+38.9946*x3(k)+14.6020*x4(k)+0.7525*x5(k)+2.3831*x6(k)+30.2641*x7(k)
+7.1*x8(k)-0.2551*x9(k)+x10(k),
u2(k+1)=0.7525*x1(k)+2.3831*x2(k)+30.2641*x3(k)+7.1*x4(k)+0.8877*x5(k)+2.7859*x6(k)+38.9946*x7(k)+14
.6020*x8(k)-0.2551*x9(k)+x11(k),
d1(k+1)=d1(k),
d2(k+1)=d2(k),
end
i=i+1501;
j=j+1501;
d1(i)=abs(randn)/200,
d2(i)=abs(randn)/200,
end
```

➤ **Step 2: Training of neural network**

An input vector ‘P’ is defined to be consisted of all system states ( $x_1$  to  $x_{11}$ ) and load disturbances ( $d_1$  &  $d_2$ ). The target vector ‘T’ is defined again to be consisted of control inputs ( $u_1$  &  $u_2$ ) since the supervised training method is chosen. A feedforward neural network was also defined with three layers.

First layer has 20 neurons, second has 10 and the third has 2 neurons. The activation functions are chosen as logarithmic sigmoid for first and second layers and linear for the third layer. The training algorithm is chosen as Lavenberg-Marquardt (LM) backpropagation. Certain number of epochs (between 100 and 200) were also set for training. One epoch corresponds to scanning of all the training data once and the number of epochs is not fixed one.

The specified neural networks have been trained several times with different number of data sets and different number of epochs so that the best trained network was retained and saved. During training, ‘P’ is the input to the network and ‘T’ is the target. During each epoch, the network adjusts the weights of neural connections so that it can give output closer to that of the target ‘T’. The error is backpropagated after each epoch.

The error goal was kept to a very small value of  $1 * 10^{-11}$ . For the best trained network obtained so far for this model after many attempts, the error of about  $1 * 10^{-9}$  was achieved which is quite acceptable. The MATLAB program to get a trained neural network for this model is given below.

```
P=[x1; x2; x3; x4; x5; x6; x7; x8; x9; x10; x11];
T= [u1; u2];
net=newff([minmax(P)],[20,10,2],{'logsig','logsig','purelin'},'trainlm');
sim(net,P);
net.trainParam.show = 1;
net.trainParam.epochs = 100;
net.trainParam.goal = 1e-11;
net.trainParam.mem_reduc = 10;
[net,tr]=train(net,P,T);
sim(net,P)
```

➤ **Step 3: Obtaining performance of ANN controller for random load disturbances**

The trained network is now ready to work as a controller. For any values of load disturbances, the appropriate outputs are given by the network which act as the control inputs of the power system. The performance of trained neural network was tested for many pairs of load disturbances and the network gave a superior control as compared to integral control and quite matching control as compared to optimal control.

The MATLAB program to obtain neural network controller performance is given below for sample values of load disturbances. e.g.,  $d_1 = 0.0014$ ,  $d_2 = 0.0068$ . All variables i.e., system states, control inputs and load disturbances are suffixed with ‘\_N’ to identify them as variables corresponding to ANN control strategy. The time of study is 15 seconds (1501 samples).

```
x1_N(1)=0,
x2_N(1)=0,
x3_N(1)=0,
x4_N(1)=0,
x5_N(1)=0,
x6_N(1)=0,
x7_N(1)=0,
x8_N(1)=0,
x9_N(1)=0,
x10_N(1)=0,
x11_N(1)=0,
u1_N(1)=0,
u2_N(1)=0,
d1_N(1)=0.0014,
```

```
d2_N(1)=0.0068,
for k=1:1500,
x1_N(k+1)=0.9995*x1_N(k)+0.06*[x2_N(k)-x9_N(k)-d1_N(k)],
x2_N(k+1)=0.000008778*x1_N(k)+0.98*x2_N(k)+0.022*x3_N(k)-0.001979*x4_N(k)-0.00002106*u1_N(k),
x3_N(k+1)=-0.00000439*x1_N(k)+0.999*x3_N(k)+0.0009894*x4_N(k)+0.00001053*u1_N(k),
x4_N(k+1)=-0.00008555*x1_N(k)+0.9997947*[x4_N(k)+0.0002053*u1_N(k)],
x5_N(k+1)=0.9995*x5_N(k)+0.06*[x6_N(k)+x9_N(k)-d2_N(k)],
x6_N(k+1)=0.000008778*x5_N(k)+0.98*x6_N(k)+0.022*x7_N(k)-0.001979*x8_N(k)-0.00002106*u2_N(k),
x7_N(k+1)=-0.00000439*x5_N(k)+0.999*x7_N(k)+0.0009894*x8_N(k)+0.00001053*u2_N(k),
x8_N(k+1)=-0.00008555*x5_N(k)+0.9997947*[x8_N(k)+0.0002053*u2_N(k)],
x9_N(k+1)=0.0044422*x1_N(k)-0.0044422*x5_N(k)+x9_N(k),
x10_N(k+1)=0.00425*x1_N(k)+0.01*x9_N(k)+x10_N(k),
x11_N(k+1)=0.00425*x1_N(k)-0.01*x9_N(k)+x11_N(k),
d1_N(k+1)=d1_N(k),
d2_N(k+1)=d2_N(k),
R=[x1_N(k+1); x2_N(k+1); x3_N(k+1); x4_N(k+1); x5_N(k+1); x6_N(k+1); x7_N(k+1);
x8_N(k+1); x9_N(k+1); d1_N(k+1); d2_N(k+1)];
b=sim(net,R),
u1_N(k+1)=b(1,:),
u2_N(k+1)=b(2,:),
end
```

➤ **Step 4: Obtaining performances of optimal and integral controllers**

For the purpose of comparison, response of system states for the sameload disturbances was obtained by optimal control strategy and integral control strategy with following MATLAB program. The suffixes ‘\_O’ (for optimal) and ‘\_I’ (for integral) is attached to the variables to identify them separately.

**Program for obtaining optimal control performance**

```
x1_O(1)=0,
x2_O(1)=0,
x3_O(1)=0,
x4_O(1)=0,
x5_O(1)=0,
x6_O(1)=0,
x7_O(1)=0,
x8_O(1)=0,
```

```
x9_O(1)=0,
x10_O(1)=0,
x11_O(1)=0,
u1_O(1)=0,
u2_O(1)=0,
d1_O(1)=0.0014,
d2_O(1)=0.0068,
for k=1:1500,
x1_O(k+1)=0.9995*x1_O(k)+0.06*[x2_O(k)-x9_O(k)-d1_O(k)],
x2_O(k+1)= 0.000008778*x1_O(k)+0.98*x2_O(k)+0.022*x3_O(k)-0.001979*x4_O(k)-0.00002106*u1_O(k),
x3_O(k+1)=-0.00000439*x1_O(k)+0.999*x3_O(k)+0.0009894*x4_O(k)+0.00001053*u1_O(k),
x4_O(k+1)=-0.00008555*x1_O(k)+0.9997947*[x4_O(k)+0.0002053*u1_O(k)],
x5_O(k+1)= 0.9995*x5_O(k)+0.06*[x6_O(k)+x9_O(k)-d2_O(k)],
x6_O(k+1)= 0.000008778*x5_O(k)+0.98*x6_O(k)+0.022*x7_O(k)-0.001979*x8_O(k)-0.00002106*u2_O(k),
x7_O(k+1)=-0.00000439*x5_O(k)+0.999*x7_O(k)+0.0009894*x8_O(k)+0.00001053*u2_O(k),
x8_O(k+1)=-0.00008555*x5_O(k)+0.9997947*[x8_O(k)+0.0002053* u2_O(k)],
x9_O(k+1)=0.0044422*x1_O(k)-0.0044422*x5_O(k)+x9_O(k),
x10_O(k+1)=0.00425*x1_O(k)+0.01*x9_O(k)+x10_O(k),
x11_O(k+1)=0.00425*x1_O(k)-0.01*x9_O(k)+x11_O(k),
u1_O(k+1)=0.8877*x1_O(k)+2.7859*x2_O(k)+38.9946*x3_O(k)+14.6020*x4_O(k)+0.7525*x5_O(k)+2.3831*x6
_O(k)+30.2641*x7_O(k)+7.1*x8_O(k)-0.2551*x9_O(k)+x10_O(k),
u2_O(k+1)=0.7525*x1_O(k)+2.3831*x2_O(k)+30.2641*x3_O(k)+7.1*x4_O(k)+0.8877*x5_O(k)+2.7859*x6_O(k
)+38.9946*x7_O(k)+14.6020*x8_O(k)-0.2551*x9_O(k)+x11_O(k),
d1_O(k+1)=d1_O(k),
d2_O(k+1)=d2_O(k),
end
```

**Program for obtaining integral control performance**

```
x1_I(1)=0,
x2_I(1)=0,
x3_I(1)=0,
x4_I(1)=0,
x5_I(1)=0,
x6_I(1)=0,
x7_I(1)=0,
x8_I(1)=0,
x9_I(1)=0,
u1_I(1)=0,
u2_I(1)=0,
```

```
d1_I(1)=0.0014,  
d2_I(1)=0.0068,  
for k=1:1500,  
x1_I(k+1)=0.9995*x1_I(k)+0.06*[x2_I(k)-x9_I(k)-d1_I(k)],  
x2_I(k+1)= 0.000008778*x1_I(k)+0.98*x2_I(k)+0.022*x3_I(k)-0.001979*x4_I(k)-0.00002106*u1_I(k),  
x3_I(k+1)=-0.00000439*x1_I(k)+0.999*x3_I(k)+0.0009894*x4_I(k)+0.00001053*u1_I(k),  
x4_I(k+1)=-0.00008555*x1_I(k)+0.9997947*[x4_I(k)+0.0002053*u1_I(k)],  
x5_I(k+1)= 0.9995*x5_I(k)+0.06*[x6_I(k)+x9_I(k)-d2_I(k)],  
x6_I(k+1)= 0.000008778*x5_I(k)+0.98*x6_I(k)+0.022*x7_I(k)-0.001979*x8_I(k)-0.00002106*u2_I(k),  
x7_I(k+1)=-0.00000439*x5_I(k)+0.999*x7_I(k)+0.0009894*x8_I(k)+0.00001053*u2_I(k),  
x8_I(k+1)=-0.00008555*x5_I(k)+0.9997947*[x8_I(k)+0.0002053*u2_I(k)],  
x9_I(k+1)=0.0044422*x1_I(k)-0.0044422*x5_I(k)+x9_I(k),  
u1_I(k+1)=-0.00085*x1_I(k)-0.0002*x9_I(k)+u1_I(k),  
u2_I(k+1)=-0.00085*x5_I(k)+0.0002*x9_I(k)+u2_I(k),  
d1_I(k+1)=d1_I(k),  
d2_I(k+1)=d2_I(k),  
end
```

➤ **Step 5: Plotting the graphs of system states**

The power system performance with neural network controller was compared with results of optimal control strategy and integral control strategy by plotting graphs of system states on same scale with the help of following MATLAB program.

```
epochs=1:1501;  
plot(epochs,x1_I,epochs,x1_O,epochs,x1_N);  
plot(epochs,x2_I,epochs,x2_O,epochs,x2_N);  
plot(epochs,x3_I,epochs,x3_O,epochs,x3_N);  
plot(epochs,x4_I,epochs,x4_O,epochs,x4_N);  
plot(epochs,x5_I,epochs,x5_O,epochs,x5_N);  
plot(epochs,x6_I,epochs,x6_O,epochs,x6_N);  
plot(epochs,x7_I,epochs,x7_O,epochs,x7_N);  
plot(epochs,x8_I,epochs,x8_O,epochs,x8_N);  
plot(epochs,x9_I,epochs,x9_O,epochs,x9_N);  
plot(epochs,x10_O,epochs,x10_N);  
plot(epochs,x11_O,epochs,x11_N);  
plot(epochs,u1_I,epochs,u1_O,epochs,u1_N);  
plot(epochs,u2_I,epochs,u2_O,epochs,u2_N);
```

## Chapter 5

### RESULT and DISCUSSION

In this work, a single and an interconnected power systems are developed with Classical, optimal, fuzzy logic and ANN controllers to illustrate performance of load frequency control using MATLAB/SIMULINK package. The parameters used for simulation are given in the appendix.

#### 5.1- AGC without PID and Fuzzy Logic Controller

Simulation was carried out to see the performance of AGC. This entire block is built in MATLAB/SIMULINK software. These entire block diagrams are executed in this software and the results were obtained in the form of graph frequency deviation versus time.

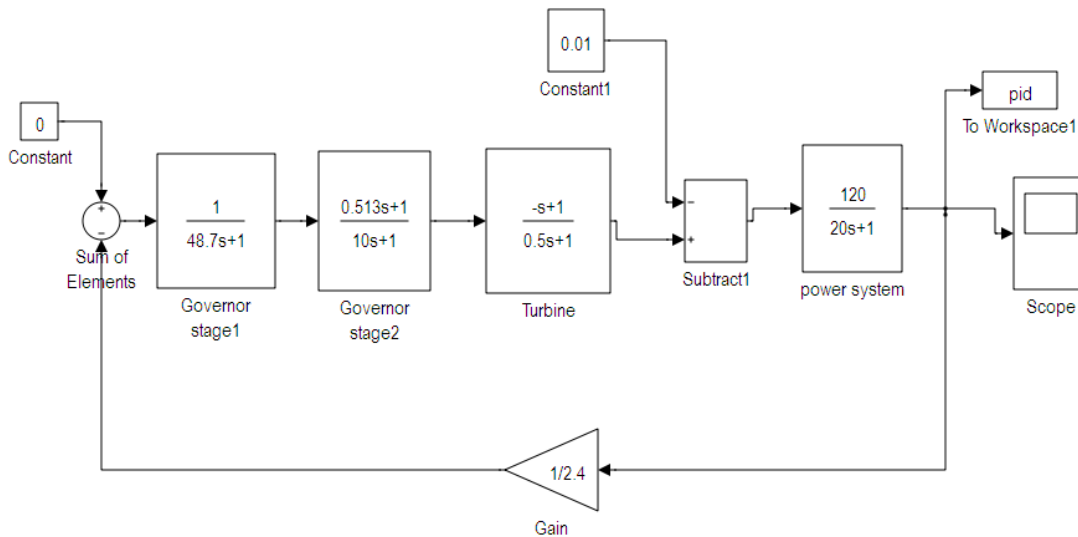


Fig 5.1 -single area Hydro power systems without PID and Fuzzy Logic

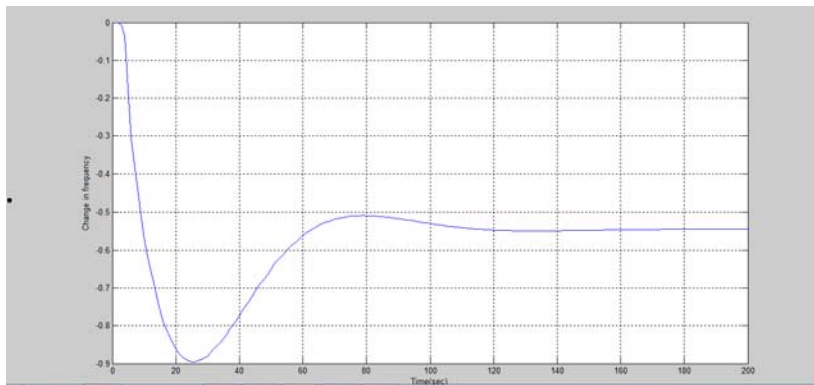


Fig 5.2 -change in Frequency for Single Area System without PID and Fuzzy Logic Controller

### 5.2- Single Area using PID Controller

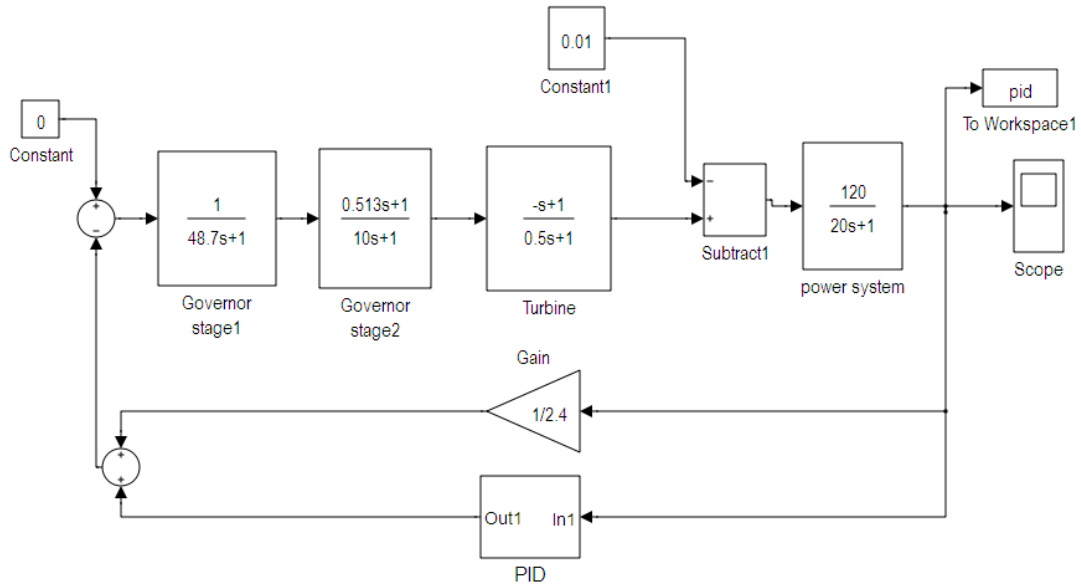


Fig 5.3 -single area Hydro power systems by using PID

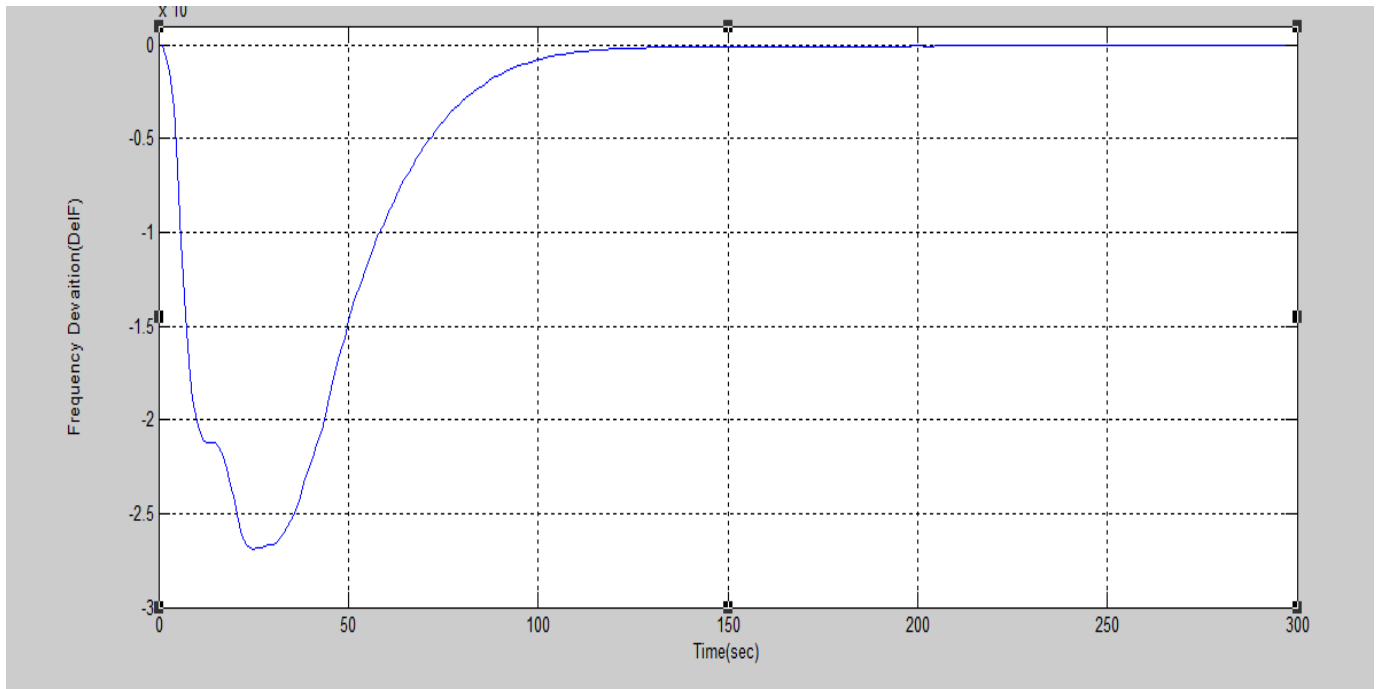


Fig 5.4 -Frequency Response for PID in Single Area Hydro System

### 5.3- Single Area Using Fuzzy Logic Controller

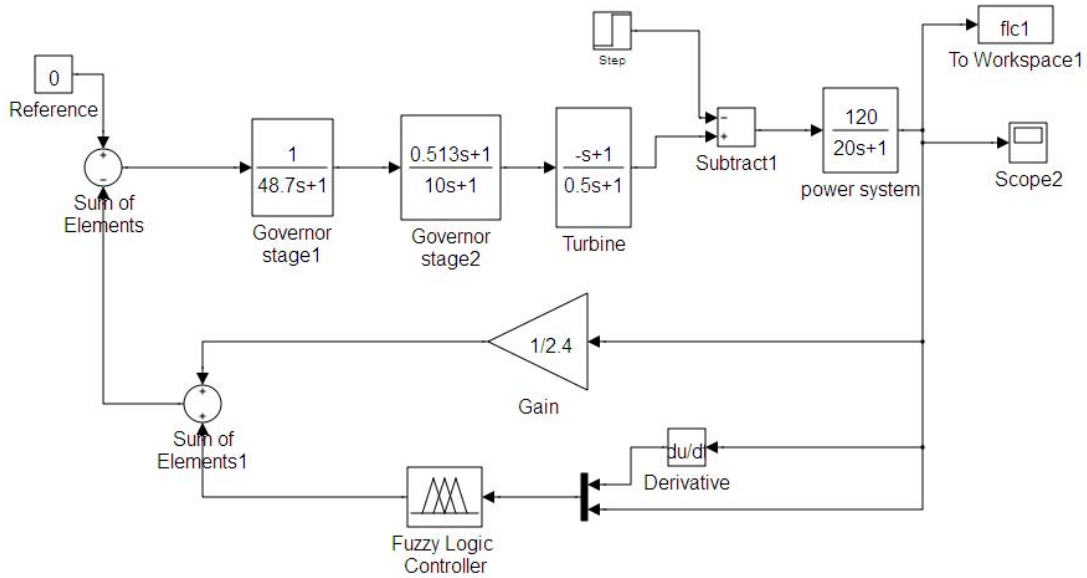


Fig 5.5 -single areas Hydro Power System by using Fuzzy Logic Controller

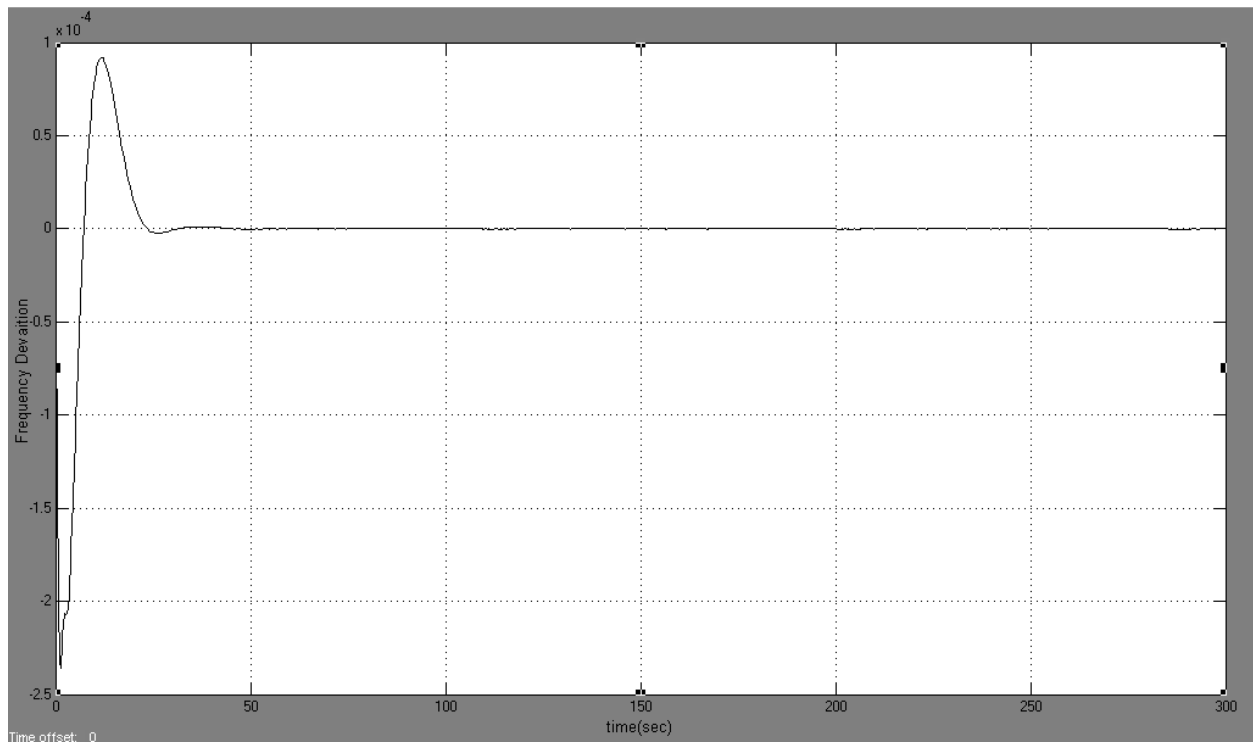


Fig 5.6 -Frequency Responses for Fuzzy Logic in Single Area Hydro System

**Analysis of Single area system:**

This a performance comparison of PID and FLC based on their settling time and frequency deviation.

<b>Controller</b>	<b>Settling Time (Ts)</b>	<b>Frequency Deviation (p.u)</b>
PID	125sec	-2.6
Fuzzy Logic Controller	45sec	-2.3

Table 5.1 -Comparison of PID and Fuzzy Logic in single area system

In terms of oscillation, the dynamic response of AGC using PID Controller in single area hydro power systems is high compare to AGC using Fuzzy Logic Controller. It can be proved that the performance of AGC systems using Fuzzy Logic Controller in single area system is better than using PID Controller in single area system.

**5.4- Double Area using PID Controller**

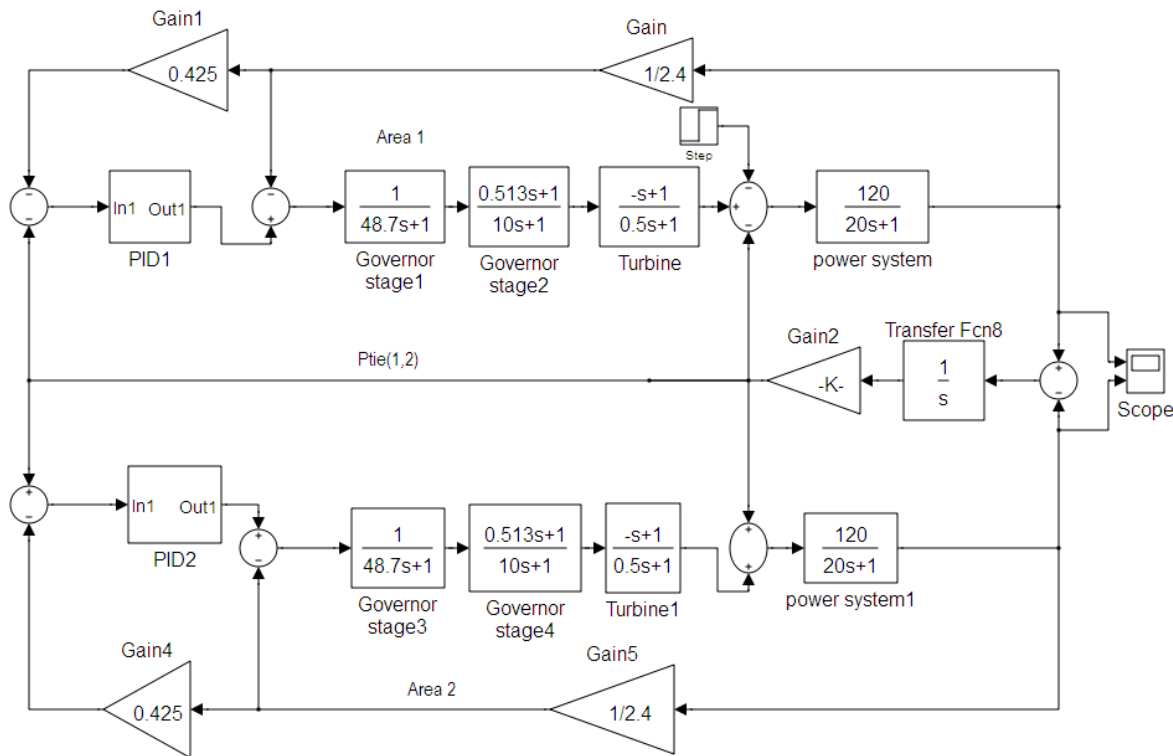


Fig 5.7 -Double Area Hydro-Hydro Power System by using PID

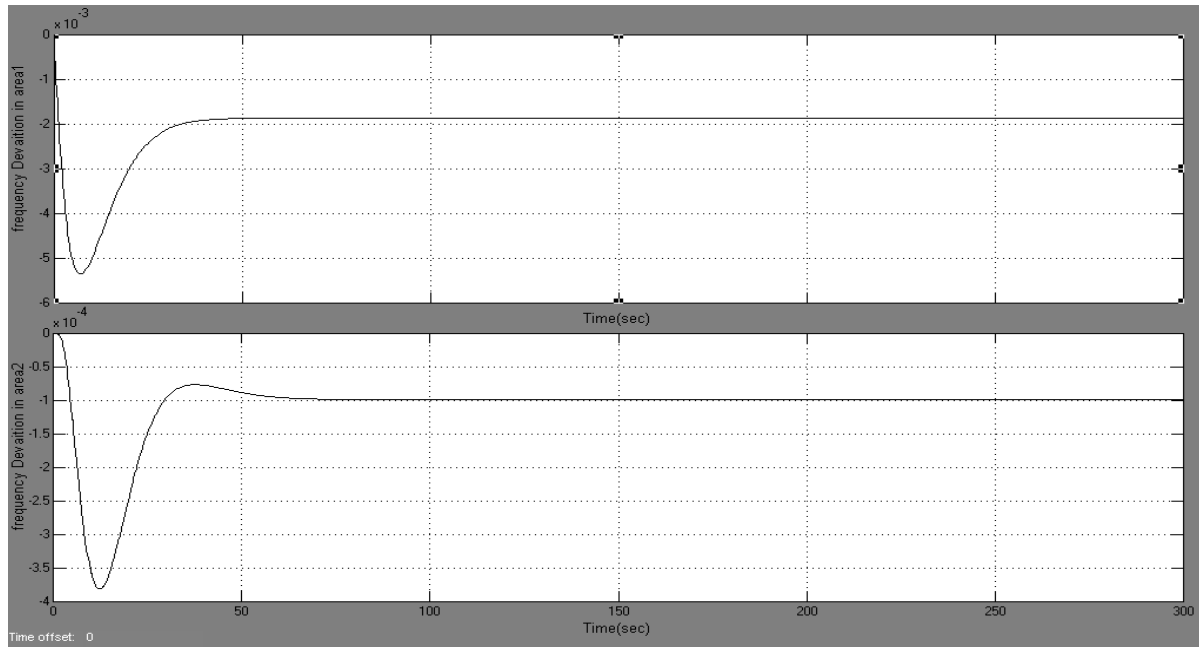


Fig 5.8 - Frequency Responses for PID in Double Area Hydro-Hydro Power System

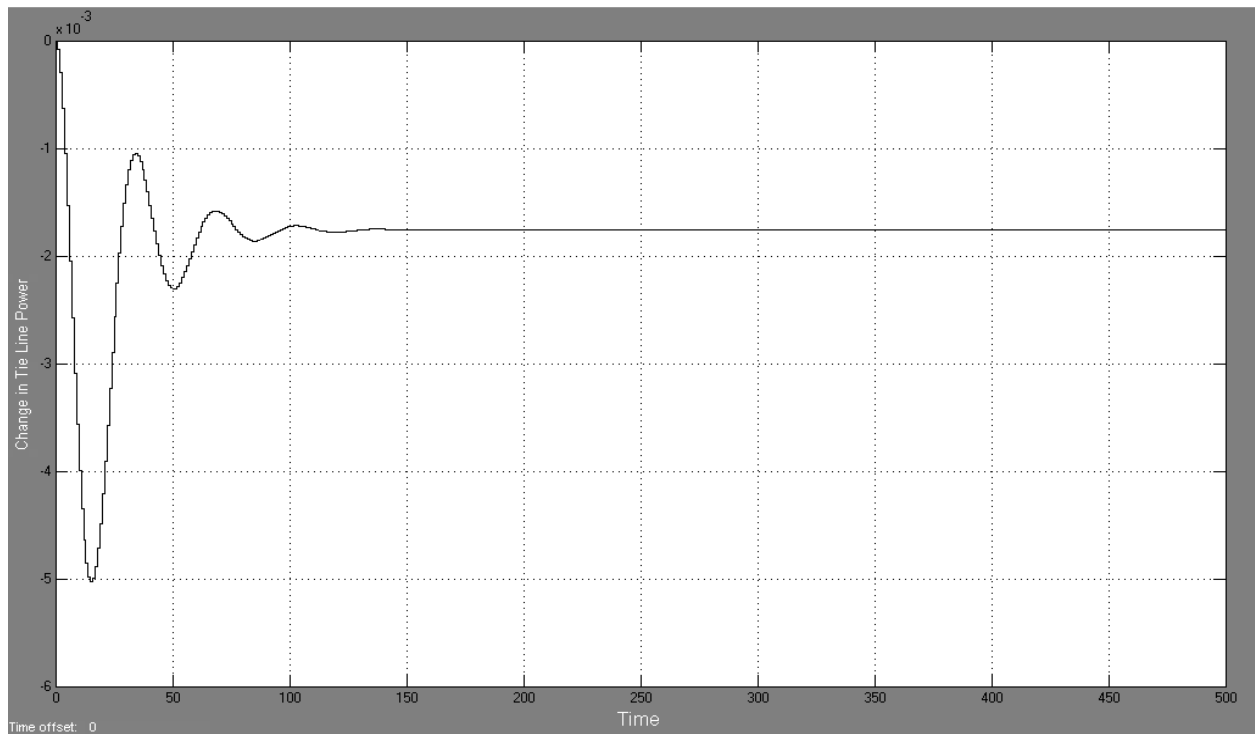


Fig 5.9 - Tie line power Deviation for PID in Double Area Hydro-Hydro Power System

### 5.5- Double Area using Fuzzy Logic Controller

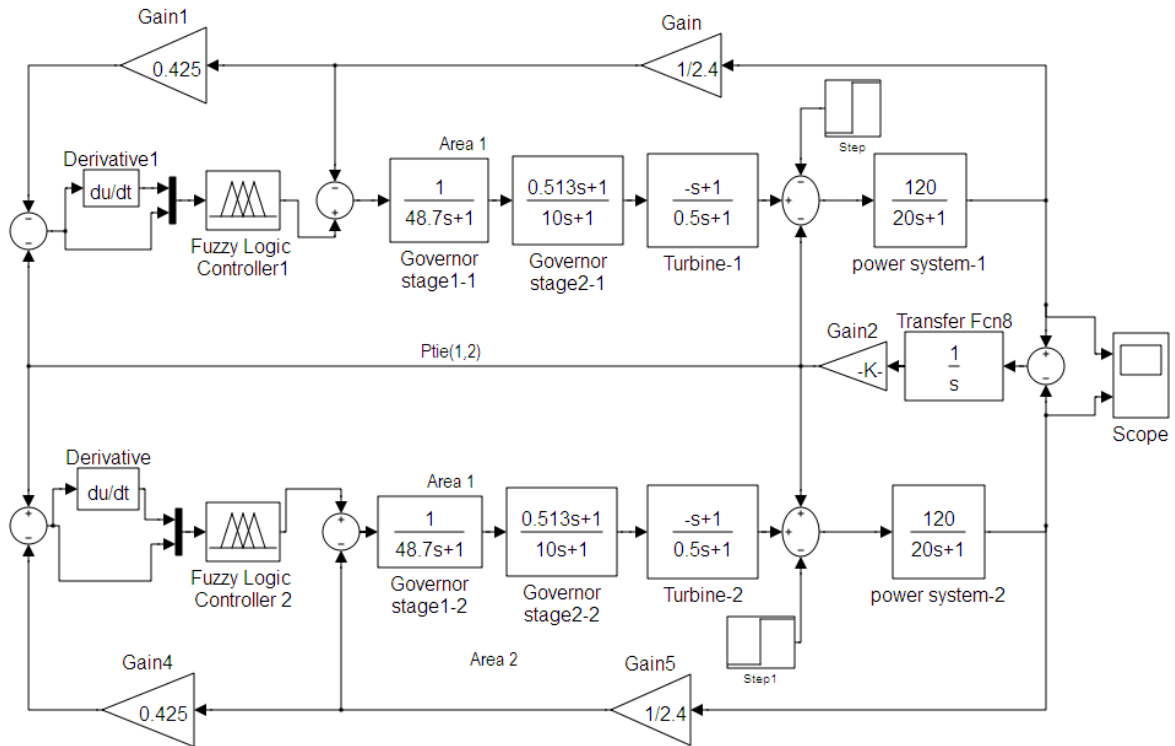


Fig 5.10 - Double Area Hydro-Hydro Power Systems Using Fuzzy Logic Controller

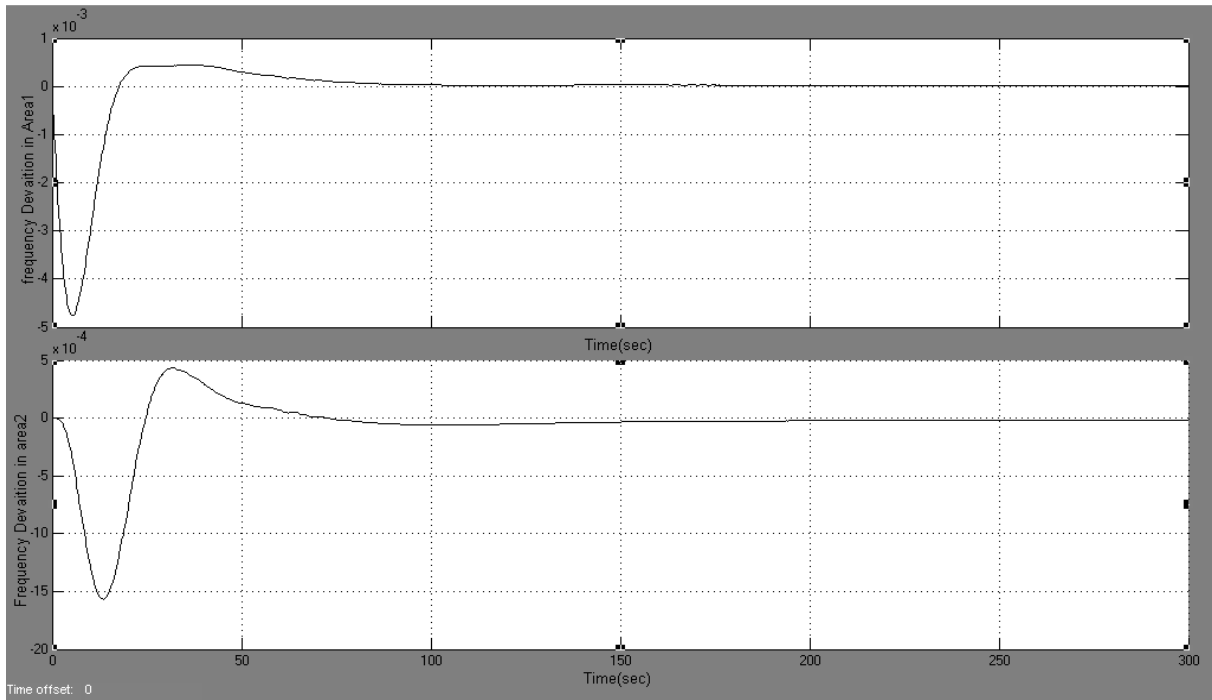


Fig 5.11 -Frequency Responses for Fuzzy Logic Controller in Double Area Hydro-Hydro Power System

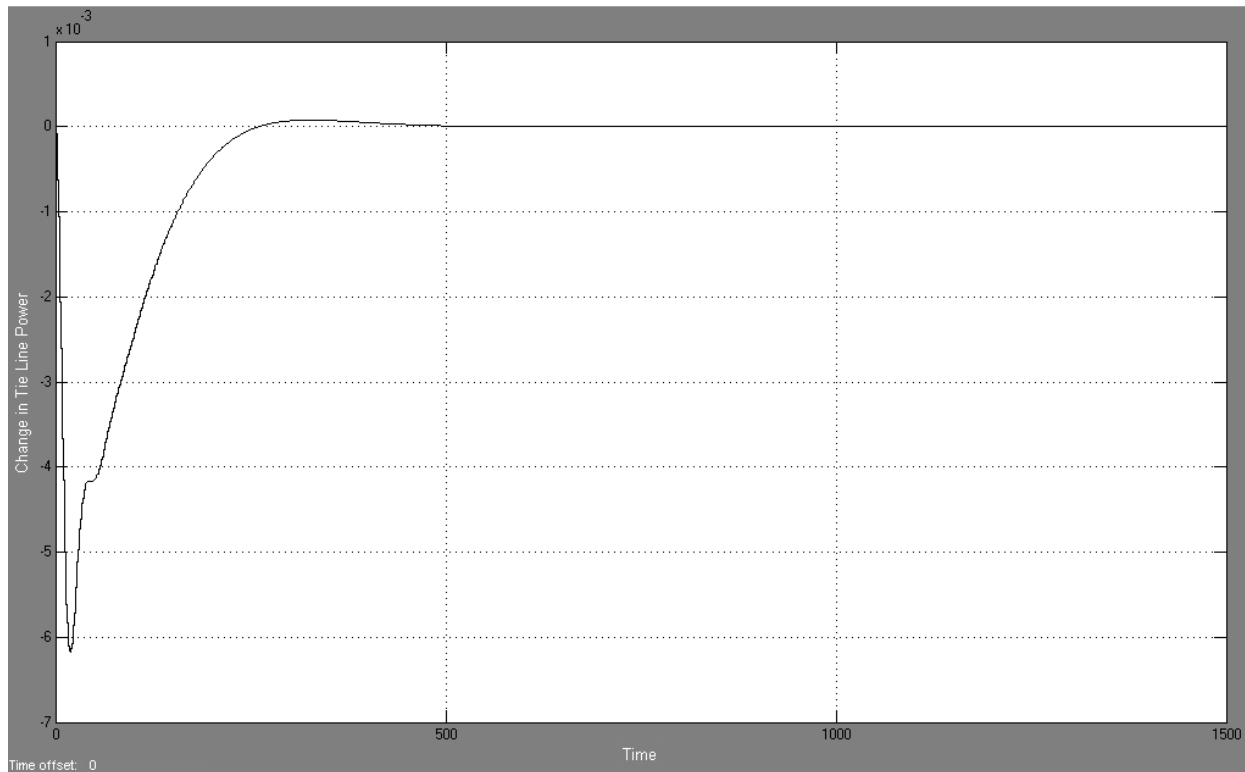


Fig 5.12 -Tie line power Deviation for FLC in Double Area Hydro-Hydro Power System

## 5.6- AGC with integral, optimal and ANN Controller

In this section, the performance of ANN controllers with full state feedback along with the performances of optimal and integral controllers is shown in the form of dynamic responses of area frequencies for the hydro-hydro power system model under consideration.

In this study, the data sets needed for training the neural network are generated by using optimal control strategy. The trained neural network was therefore expected to give the performance closer to that of the optimal control. The range of load disturbance in different areas was chosen to be from 0 to 1 percent per unit (i.e. 0 to 0.01 per unit).

The neural network controller was trained with full state feedback. The number of data sets used for training the neural network was varied from about 50 to 100. It was observed that, the neural network may not be successfully trained in first attempt but a large number of attempts have to be made with different number of data sets and different number of epochs. Finally for the hydro-hydro power system model, the best trained network was retained as the controller and it was permanently saved as a MATLAB file.

### Results for Two Area Hydro-Hydro Power System

Fig 5.13 and Fig 5.14 show the dynamic responses of frequency deviations in two areas (i.e.  $\Delta f_1$  and  $\Delta f_2$ ) for the two area Hydro-Hydro power system for sample values of area load disturbances ( $d_1 = 0.0014\text{pu}$  and  $d_2 = 0.0068\text{pu}$ ). These figures show the performance of ANN controller trained with full state feedback in comparison with optimal and integral controllers on same scale. It is evident that, the neural network controller has given the performance that is very close to that of optimal controller and quite superior to that of integral controller.

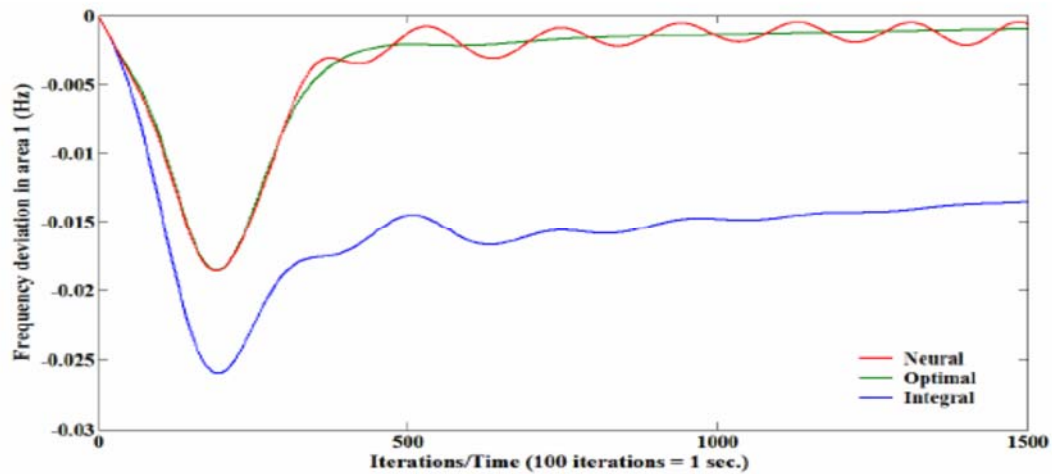


Fig 5.13 - Frequency Responses for Integral, Optimal and ANN Controller in Double Area Hydro-Hydro Power System in area 1

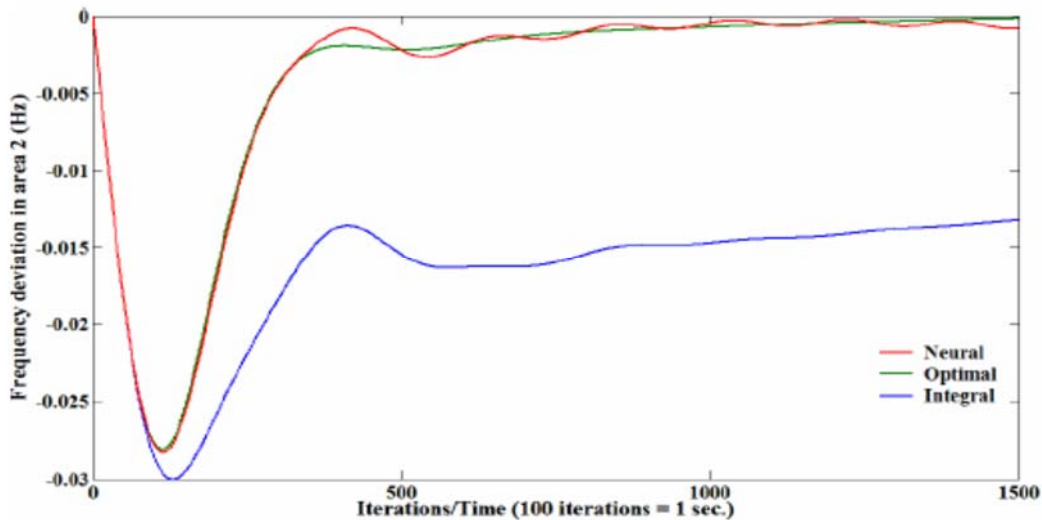


Fig 5.14 - Frequency Responses for Integral, Optimal and ANN Controller in Double Area Hydro-Hydro Power System in area 2

## **CHAPTER 6**

### **CONCLUSION and RECOMMENDATION**

#### **6.1- CONCLUSION**

As described on the objective part, the main objective of this thesis work is to apply an intelligent controllers like Fuzzy Logic Controller (FLC) and Artificial Neural Network (ANN) Controller to Automatic Generation Controller (AGC) of a hydro-power system. For this purpose both classical controllers (Integral and PID) as well as intelligent controllers (FLC and ANN) are designed so that their performance would be compared.

From the MATLAB simulation result it is shown that the designed FLC gave a response with settling time 45 sec and a frequency deviation of 2.3 per unit (p.u). This is a better result than that of a PID controller with settling time and frequency deviation of 125 sec and 2.6 p.u respectively.

Again frequency response for Integral, Optimal and ANN controllers is shown on same scale and it is observed from the figure that the designed ANN controller gave a response that is too close to Optimal controller response and superior to the Integral controller. This is expected and desired result since the ANN controllers are developed and trained with a data sets that are obtained from the optimal control.

The ANN controllers developed in present work offer the following benefits over classical integral controllers;

- Fast transient recovery
- Low overshoot in dynamic response of system state variables
- Less time to settle the excursions of system state variables within acceptable limits
- Ability to give satisfactory performance under simultaneous load perturbations

Generally speaking, this thesis work full fills its objective by applying intelligent controllers (FLC and ANN) to AGC of a hydro-power system. The designed intelligent controllers also gave a frequency response that is better than classical controllers. So, finally I conclude that this thesis work is a complete success.

## **6.2- RECOMMENDATION**

Future works that can be pursued related to this research area can add the following points;

- Expanding the number of system areas to larger.
- AGC system used can be investigated and implemented for each type of Generator.
- In the present work, the load disturbances  $d_1$  and  $d_2$  considered are of deterministic nature. The work can be extended to dynamic (time varying) load disturbances.
- The ANN controllers can be developed with unsupervised training method for implementation of dynamical systems.
- Comparison of the proposed ANN controller with fuzzy logic controller is subject to the future work.
- The controller that is used for AGC is recommended using hybrid fuzzy neural network or any other controller that can give better performance of AGC systems.

## ❖ **References**

- [1] C. Concordia and L.K. Kirchmayer, ‘Tie line power and frequency control of electric power systems,’ Amer. Inst. Elect. Eng. Trans., Pt. II, Vol. 72, pp. 562-572, Jun. 1953.
- [2] N. Cohn, ‘Some aspects of tie-line bias control on interconnected power systems,’ Amer. Inst. Elect. Eng. Trans., Vol. 75, pp. 1415-1436, Feb. 1957.
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**❖ APPENDIX**

***Nominal Values of Parameters Used In Power System Models***

<b><i>Parameters</i></b>	<b><i>Description</i></b>	<b><i>Values</i></b>	<b><i>Unit</i></b>
$R_1$ and $R_2$	<i>Regulations of Governors in Areas 1 and 2</i>	2.4	<i>Hz/pu MW</i>
$K_1$ and $K_2$	<i>Integral Controller Gain for Hydro Area 1 and 2</i>	0.02	<i>pu MW/Hz Sec</i>
$K_{P1}$ and $K_{P2}$	<i>Power System Constants in Areas 1 and 2</i>	120	<i>Hz/pu MW</i>
$T_{P1}$ and $T_{P2}$	<i>Power System Time Constants in Areas 1 and 2</i>	20	<i>Second</i>
$B_1$ and $B_2$	<i>Tie Line Frequency Bias in Areas 1 and 2</i>	0.425	<i>pu MW/Hz</i>
$T_0$	<i>Synchronizing Coefficient for Tie Line for Two Area Systems</i>	0.0707	<i>MW/radian</i>
$T_{11}$ and $T_{12}$	<i>Hydro Governor (Stage 1) Time Constant for Hydro Area 1 and 2</i>	48.7	<i>Second</i>
$T_{21}$ and $T_{22}$	<i>Hydro Governor (Stage 2) Time Constant for Hydro Area 1 and 2</i>	0.513	<i>Second</i>
$T_{31}$ and $T_{32}$	<i>Hydro Governor (Stage 3) Time Constant for Hydro Area 1 and 2</i>	10	<i>Second</i>
$T_{w1}$ and $T_{w2}$	<i>Water Starting Time for Water Turbine in Hydro Area 1 and 2</i>	1	<i>Second</i>
$T$	<i>Sampling Time in Discrete Equations of Power System</i>	0.01	<i>Second</i>

## **List of symbols**

$a_{11}, a_{12}$  and  $a_{13}$  = derivatives of deviation in flow ( $q$ ) respect to head, speed and gate position

$a_{21}, a_{22}$  and  $a_{23}$  = derivatives of torque ( $m$ ) with respect to head, speed and gate position

$B_1$  and  $B_2$  =Tie Line Frequency Bias in Areas 1 and 2

$B_i$  = tie line frequency bias factors in area  $i$

$D$  =Load damping constant

$D\Delta\omega_r$  =Frequency sensitive load change

$f_i$  = nominal frequency in area  $i$

$g$  = the per unit deviation in position

$H$  = inertia of the turbine

$h$  = the per unit deviation in head

$J$  = the combined moment of inertia of generator and turbine ( $\text{Kg.m}^2$ )

$K$  =Gain of the Governor

$k$  = Sample Number (Iteration Number) in Discrete Time Equations

$m$  = the per unit deviation in torque

$M_{eq} = \sum M_i [s]$ , =the total inertia of the power system

$M_i$  =Inertia constant of generating unit  $i$  [s]

$n$  = the per unit deviation in speed

$P_o$  =Reference Power Setting

$P_{GV}$  =Gate Valve

$P_M$  = mechanical time constant

$q$  =the per unit deviation in flow

R1 & R2 = Regulations of Governors in Areas 1 & 2

$t$  = time (sec)

$T_a$  = accelerating torque (N.m)

$T_e$  =Electrical Torque (N.m)

$T_m$  =mechanical Torque (N.m)

$T_R$  = speed governor rest time

$T_P$  = time constant of pilot valve and servo motor

$T_G$  = time constant of distribution valve

$T_w$  = Water starting time constant

T1 = Hydro Governor (Stage 1) Time Constant for Hydro Area (Transient droop time constant)

T2 =Hydro Governor (Stage 2) Time Constant for Hydro Area (speed governor rest time)

T3 =Hydro Governor (Stage 2) Time Constant for Hydro Area (main servo time constant)

$T_o/T_{ij}$  = Synchronizing Coefficient for Tie Line for Two Area Systems  $i$  and  $j$

T =Sampling Time in Discrete System Equations

$V_j$  = sum of the weights to the neuron at layer  $j$

$V_k$  = sum of the weights to the neuron at layer  $k$

$w_{ji}$  =synaptic weight between layer  $j$  and layer  $i$  neurons

$w_{ki}$  = synaptic weight between layer  $j$  and layer  $k$  neurons

$W_m$  = angular velocity of the rotor (mech.rad/sec)

$W_r$  = angular velocity of rotor [elec. Rad/s], and at rated speed

$\omega_o$  = rated angular velocity [elec. Rad/s].

$Y_j$  = output of a neuron at layer  $j$

$Y_k$  = output of a neuron at layer  $k$

$\Delta f(s)$  = Frequency Deviations in Areas

$\Delta P$  =Change in Power

$\Delta P_L$  =Non frequency sensitive load change

$\Delta P_d(s)$  = Load Disturbances in Areas

$\Delta P_{ref}(s)$  =Load reference set point

$\Delta P_{tie}$  = tie line power in area  $i$

$\Delta T_{mi}$  =Mechanical power change for generating unit  $i$  [pu]

$\Delta \omega$  =Input Speed Deviation

$\delta$  = tangent droop

$\sigma(R)$  = permanent droop or Regulation of Governor

$\Sigma$  = summation

$\eta$  =Learning rate