CHAPTER- 1

INTRODUCTION

The successful operation of interconnected power systems requires the matching of total generation with total load demand and associated system losses. With time, the operating point of a power system changes, and hence, these systems may experience deviations in nominal system frequency and scheduled power exchanges to other areas, which may yield undesirable effects. In actual power system operations, the load is changing continuously and randomly. The ability of the generation side to track the changing load is limited due to physical / technical consideration, causing imbalance between the actual and the scheduled generation quantities. This action leads to a frequency variation. The difference between the actual and the synchronous frequency causes mal operation of sophisticated equipments like power converters by producing harmonics.

1.1 Electric Power Regulation

Power systems consist of control areas representing a coherent group of generators i.e. generators which swing in unison characterized by equal frequency deviations. In addition to their own generations and to eliminate mismatch between generation and demand these control areas are interconnected through tie-lines for providing contractual exchange of power under normal operating conditions. One of the control problems in power system operation is to maintain the frequency and power interchange between the areas at their rated values. Automatic generation control is to provide control signals to regulate the real power output of various electric generators within a prescribed area in response to changes in system frequency and tie-line loading so as to maintain the scheduled system frequency and established interchange with other areas.

Many control strategies for Load Frequency Control in electric power systems have been proposed by researchers over the past decades. This extensive research is due to fact that LFC constitutes an important function of power system operation where the main objective is to regulate the output power of each generator at prescribed levels while keeping the frequency fluctuations within pre-specifies limits.

The mechanical power is produced by a turbine and delivered to a synchronous generator serving different users. The frequency of the current and voltage waveform at the output of the generator is mainly determined by the turbine steam flow. It is also affected by changes in user power demands that appear, therefore, as electric perturbations. If, for example, the electric load
on the bus suddenly increases, the generator shaft slow down, and the frequency of the generator decreases. The control system must immediately detect the load variation and command the steam admission valve to open more so that the turbine increases its mechanical power production, counteracts the load increases and brings the shaft speed at the rated value which result generator frequency back to its nominal value.

1.1.1 Load-frequency control (LFC)

For large scale electric power systems with interconnected areas, Load Frequency Control (LFC) is important to keep the system frequency and the inter-area tie power as near to the scheduled values as possible. The input mechanical power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. A well designed and operated power system must cope with changes in the load and with system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits. Load frequency control is basic control mechanism in the power system operation. Whenever there is variation in load demand on a generating unit, there is a momentarily an occurrence of unbalance between real-power input and output. This difference is being supplied by the stored energy of the rotating parts of the unit.

Load Frequency Control (LFC) is being used for several years as part of the Automatic Generation Control (AGC) scheme in electric power systems. One of the objectives of AGC is to maintain the system frequency at nominal value (50 Hz).

1.1.2 Automatic generation control (AGC)

Automatic generation control (AGC) is defined as, the regulation of power output of controllable generators within a prescribed area in response to change in system frequency, tie-line loading, or a relation of these to each other, so as to maintain the schedules system frequency and / or the established interchange with other areas within predetermined limits. The two basic inter-area regulating responsibilities are as follows:-

(i) When system frequency is on schedule, each area is expected automatically to adjust its generation to maintain its net transfer with other areas on schedule, thereby absorbing its own load variations. As long, all areas do so; scheduled system frequencies as well as net interchange schedules for all area are maintained.

(ii) When system frequency is off-schedule, because one or more areas are not fulfilling their regulating responsibilities, other areas are expected automatically to shift their respective net transfer schedules proportionally to the system frequency deviation and in direction to assist the deficient areas and hence restore system frequency. The extent of each area’s shift of net
interchange schedule is programmed by its frequency bias setting. Therefore, a control strategy is needed that not only maintains constancy of frequency and desired tie-power flow but also achieves zero steady state error and inadvertent interchange. Numbers of control strategies have been employed in the design of load frequency controllers in order to achieve better dynamic performance.

1.1.3 Control Strategy

The objective of the control strategy in a power system is to generate and deliver power in an interconnected system as economically and reliably as possible while maintaining the frequency and voltage within permissible limits. The power system control has a hierarchical structure. The control system consists of a number of nested control loops that control different quantities in the system. In general, the control loops on lower system levels, e.g. locally in a generator, are characterized by smaller time constants than the control loops active on a higher system level. For example, the automatic voltage regulator (AVR), which regulates the voltage of the generator terminals, responds typically in a time scale of a second or less. While, the secondary voltage control (SVC), which determines the reference values of the voltage controlling devices among which the generators, operates in a time scale of tens of seconds or minutes. That means these two control loops are virtually de-coupled. As another example, AVR (which controls the reactive power and voltage magnitude) and LFC (which controls the real power and frequency) loops can considered. The excitation system time constant is much smaller than the prime mover time constant and its transient decay much faster, which does not affect the LFC dynamic. Thus, the cross-coupling between the LFC loop and the AVR loop is negligible. This is also generally true for the other control loops. As a result, a number of de-coupled control loops operating in power system in different time scales for protection, voltage control, turbine control, tie-line power and frequency control. Although the overall control system is complex, in most cases it is possible to study the different control loops individually due to the de-coupling. Depending on the loop nature, the required model, important variables, uncertainties, objectives, and possibly control strategy will be different.

1.1.4 Time Scales of the Power System Controllers

A schematic diagram showing the current different time scales of the power system controllers and devices is shown in Fig. 1.1. The protection devices are in the first level. To protect the systems and other important devices they must be fast as possible. The second level is mainly related to power system stabilizers (PSS) and reactive power controllers such as AVRs,
flexible ac transmission systems (FACTS), energy storages, and HVDC systems. At the highest level, the tie-line power and frequency controllers are in place (Hassan Bevrani, 2004).

![Diagram of different time scales of power system controls]

1.1.5 LFC problem in Single Area Power System

Basically, single area power system consists of a governor, a turbine, and a generator with feedback of regulation constant. System also includes step load change input to the generator. This work mainly, related with the controller unit of a single area power system. The load frequency control strategies have been suggested based on the conventional linear Control theory. These controllers may be unsuitable in some operating conditions due to the complexity of the power systems such as nonlinear load characteristics and variable operating points. To some authors, variable structure control maintains stability of system frequency. However, this method needs some information for system states, which are very difficult to know completely. Also, the growing needs of complex and huge modern power systems require optimal and flexible operation of them. The dynamic and static properties of the system must be well known to design an efficient controller.

Under normal operating condition controller are set for small changes in load demand without voltage and frequency exceeding the pre specified limits. If the operating condition changes by any cause, the controller must be reset either manually or automatically. The objective of load frequency controller is to exert the control off frequency and at the same time real power exchange via outgoing transmission line.
The frequency is sensed by frequency sensor. The change in frequency and tie line real power can be measured by change in rotor angle $\delta$. The load frequency controller amplify and transform error signal, i.e., $(\Delta f_i$ and $\Delta P_{tie})$ in to real power command signal $\Delta P_{ci}$ which is sent to the prime mover via governor (that control the valve mechanism). To call for an increment or decrement in torque the prime mover balances the output of governor which will compensate the value of error signal that is $\Delta f_i$ and $\Delta P_{tie}$. The process continues till deviation in form of $\Delta f_i$ and $\Delta P_{tie}$ as well as the specified tolerance.

The LFC problem in power systems has a long history. In a power system, LFC as an ancillary service acquires an important and fundamental role to maintain the electrical system reliability at an adequate level. It has gained the importance with the change of power system structure and the growth of size and complexity of interconnected systems. The well-known conventional LFC structure for a given control area and a multi area power system (includes N area) is shown in Fig. 1.3.
Fig. 1.3 A control area equipped with LFC

### 1.1.6 Conventional LFC Structure

The LFC model given in Fig. 1.3 uses three simple (first order) transfer functions for modeling the turbine, generator and power system (load and rotating mass). The effects of local load changes and interface with other areas are properly considered as two input signals. Each control area monitors its own tie-line power flow and frequency at the area control center. The area control error (ACE) which is a linear combination of tie-line and frequency errors is computed and allocated to the controller \( K(s) \). Finally, the resulted control action signal or a percentage of it is applied to the turbine-governor unit. The operation objectives of the LFC are summarized to maintain system frequency close to nominal value, to control the tie-line interchange schedules, and to divide the load between generator units. Commonly, a simple integral or proportional-integral control law is used as controller \( K(s) \) to perform LFC task. A multi-area power system is comprised of areas that are interconnected by high-voltage transmission lines or tie-lines. The trend of frequency measured in each control area is an indicator of the trend of mismatch power in the interconnection and not in the control area alone. Therefore, following a load disturbance within a control area or an occurred mismatch power on tie-lines, the frequency of that control area experiences a transient change. The feedback mechanism comes into play and generates the appropriate signal to the turbine for tracking the load variation and compensates the mismatch power.
Depending on the type of generating units, and constraints on their range and rate of response to the LFC signals, the actual response time (for example for a steam unit) takes a few to several tens of seconds. In LFC practice, rapidly varying components of system signals are almost unobservable due to filters involved in the process. That is why further reduction in the response time of LFC is neither possible nor desired. Practically, the design and performance of an LFC system highly depend on how generation units respond to control signal. Such control strategies are useful as they are able to maintain a sufficient level of reserved control range and a sufficient level of control rate. In light of this fact, although the present dissertation uses some academic examples (and data) in which the assumed parameters (and in result, dynamics of the simplified models) are not completely matched to real ones, and gives the impression that the output of the models can be changed quickly, however the proposed control strategies are flexible enough to set a desired level of performance to cover the practical constraint on the control action signals. Since the 1970s, the described LFC scheme in Fig. 1.3 is widely used by researchers for the LFC analysis and synthesis.

The performance of the automatic generation control depends upon how various power generating units respond to these signals. The speed of their response is limited by natural time lags of the various turbine dynamics and the power system itself. In other words the design of automatic generation controller depends upon various energy source dynamics involved in the AGC of the area. But in real situations each control area may have large number of various sources of power generation such as hydro, thermal, gas, nuclear etc. The various generations are connected by a stiff network that is why the frequency deviations are assumed to be equal in an area. The load over a day varies which is evident from a daily load curve. Therefore the contributions of generations from various sources in an area are adjusted to meet the load variations. The performance of the Automatic Generation Control may also vary in respect to the changes in the share of different type of power generations to the total generation of the area. In order to obtain the optimum realistic AGC performance, the automatic generation controller parameters have to be optimized for various nominal loading conditions. In practice, it is not necessary that all types of power generating units having speed governors may take part in the area AGC activity. Due to the lower power production cost a typical generation in an area may be contributing to its maximum by running at its rated load capacity while others may not be. In such case the typical generation is regulated by the speed governor alone but its dynamics will also play a role in the selection of the automatic generation controller parameters for other generations in the area. Large scale power systems are normally composed of control areas or regions representing coherent group of generators.
1.2 Need of Load Frequency Control

The active and reactive power demands are never steady and they continuously changes with the rising or falling trend of load demand. There is a change in frequency with the change in load which causes problems such as:

1. Most AC motors run at speeds that are directly related to frequency. The speed and induced electro motive force (e.m.f) may vary because of the change of frequency of the power circuit.
2. When operating at frequencies below 49.5 Hz; some types of steam turbines, certain rotor states undergo excessive vibration.
3. The change in frequency can cause mal operation of power converters by producing harmonics.
4. For power stations running in parallel it is necessary that frequency of the network must remain constant for synchronization of generators.

1.3 Concept of Load Frequency Control

In the steady state operation of power system, the load demand is increased or decreased in the form of Kinetic Energy stored in generator prime mover set, which results the variation of speed and frequency accordingly. Therefore, the control of load frequency is essential to have safe operation of the power system.

Neglecting resistances

\[ P = \frac{E.V}{X} \sin \delta \]  \hspace{1cm} (1.1)

If \( \delta \) changes to \( \delta + \Delta \delta \), then \( P \) changes to \( P + \Delta P \)

\[ P + \Delta P = \frac{E.V}{X} \sin(\delta + \Delta \delta) = \frac{E.V}{X}[\sin \delta \cos \Delta \delta + \cos \delta \sin \Delta \delta] \]  \hspace{1cm} (1.2)

Since \( \Delta \delta \) is very small,
\[ \cos \Delta \delta \approx 1 \] and \[ \sin \Delta \delta \approx \Delta \delta \]

\[ P + \Delta P = \frac{E.V}{X} \sin \delta + \frac{E.V}{X} \cos \delta \cdot \Delta \delta \]
\[ \Delta P = \frac{E.V}{X} \cos \delta \cdot \Delta \delta \]
\[ \Delta P \approx \Delta \delta \]  \hspace{1cm} (1.3)

Small power changes mainly depends on \( \Delta \delta \) or \( \Delta f \).

Moreover, frequency is also a major stability criterion for large-scale stability in multi area power systems. To provide the stability, a constant frequency is required which depends on active power balance. If any change occurs in active power demand/ generation in power systems, frequency cannot be hold as its rated value. Hence, oscillations increase in both power and frequency. Thus, the system is subjected to a serious instability problem. To improve the stability
of the power networks, it is necessary to design load frequency control (LFC) systems that control the power generation and active power at tie lines of interconnected system. In interconnected power networks with two or more areas, the generation within each area has to be controlled to maintain the scheduled power interchange. Load frequency control scheme has two main control loops. These are primary control and secondary control loops. This action has been realized by using a turbine-governor system in the plant.

1.4 Primary and secondary control

In the primary control action, only active power is balanced. However, maintaining the frequency at scheduled value (e.g. 50 Hz) cannot be provided. Therefore, steady state frequency error can occur forever and control action is not enough for interconnected system. In interconnected power systems, frequency must be equal at all areas at nominal value. The second level of generation control is called secondary or supplementary control. This secondary control is in large power systems which include two or more areas of interconnected power system. Active power is controlled at the tie line between neighboring areas of central and local load control along with distribution center.

In modern large inter-connected systems, manual regulation is not feasible so automatic generation and voltage regulation equipment is installed in each Generator. The proportional integral (PI) controllers do the regulation by taking care of small changes in load demand without frequency and voltage exceeding the prescribed limit.

![Diagram of load frequency and excitation voltage regulator of a turbo-generator](image)

Fig. 1.4: Schematic diagram of load frequency and excitation voltage regulator of a turbo-generator
The schematic diagram of load frequency and excitation voltage regulators of a turbo generator is shown in Fig.1.4. The controllers are set for a particular operating condition and they take care of small changes in load demand without frequency and voltage exceeding the prescribed limits. With the passage of time, as the change in active load demand becomes large, the controllers must be reset either manually or automatically.

The small changes in active power is dependent on internal machine angle $\delta$ and is independent of bus voltage; while bus voltage depends on machine excitation (therefore on reactive generation $Q$) and is independent of machine angle $\delta$. Change in the angle $\delta$ is caused by momentary change in generator speed. Therefore load frequency and excitation voltage controls are not interactive for small changes and can be modeled and analyzed independently. Furthermore, excitation voltage control is fast acting in which the major time constant encountered is that of a generator field; while the power frequency control is slow acting with major time constant contributed by the turbine and generator moment of inertia. This time constant is much larger than that of the generator field. Thus the transients in excitation voltage control vanish much faster and do not affect the dynamics of power frequency control. Change in load demand can be identified as:

1. Slow varying changes in mean value of load demand.
2. Fast random variations around the mean value of load demand. The regulators must be designed to be insensitive to fast random changes otherwise the system will be prone to hunting resulting in excessive wear and tear of rotating machines and control equipment.

1.5 Basic Generator Control Loops

The automatic voltage regulator (AVR) loop controls the magnitude of the terminal voltage $V$. The latter voltage is continuously sensed, rectified, and smoothed. This dc signal, being proportional to $|V|$, is compared with a dc reference $|V|_{\text{ref}}$. The resulting “error voltage” after amplification and signal shaping, serves as the input to the exciter which finally delivers the voltage $V_f$ to the generator field wingding. The automatic load-frequency control (AFLC) loop regulates the megawatt output and frequency (speed) of the generator.
The loop is not a single one as in the case of the AVR. A relatively fast primary loop responds to a frequency signal which is an indirect measure of megawatt balance. Via the speed governor and the control valves, the steam (or hydro) flow is regulated with the intent of matching the megawatt output to relatively fast load fluctuations. Thus, tending to maintain a megawatt balance, this primary loop performs indirectly a coarse speed or frequency control.

1.6 Isochronous Control

A slower secondary loop maintains the fine adjustment of the frequency, and also by ‘reset’ action maintains proper megawatt interchange with other pool members. This loop is insensitive to rapid load and frequency changes but focuses instead on drift like changes which take place over periods of minutes. To obtain better accuracy, the speed changer position should be adjusted in such a manner that the steady state error be zero. This is referred as isochronous control. To obtain this, the speed changer should be commanded by a signal obtained by first amplifying and then integrating the frequency error.
1.7 Concept of Two Area Control

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 two-area case connected by tie-line is considered. The control objectives are as follows:

(1) Each control area as far as possible should supply its own load demand and power transfer through tie line should be on mutual agreement.

(2) Both control areas should controllable to the frequency control.

A two area system consists of two single area systems connected through a power line called tie-line. Each area feeds its user pool, and the tie line allows electric power to flow between the areas, because both areas as well as the power flow on the tie-line. For the same reason, the control system of each area needs information about the transient situation in both areas to bring the local frequency back to its steady state value. Information about the local area is found in the tie line power fluctuations. Therefore, the tie-line power is sensed, and the resulting tie-line power signal is fed back into both areas. It is conveniently assumed that each control area can be represented by an equivalent turbine, generator and governor system. Symbol used with suffix 1 refer to area 1 and those with suffix 2 refer to area 2. A complete diagram is given in Fig. 1.6.

In an isolated control area case the incremental power \( (\Delta P_G - \Delta P_D) \) was accounted for by the rate of increase of stored kinetic energy and increase in area load caused by increase in frequency. Since a tie line transports power in or out of an area, this fact must be accounted for in the incremental power balance equation of each area.

![Fig.1.6 Conventional Two Area System: Basic Block Diagram](image-url)
1.8 Intelligent Hybrid Controllers

In this thesis the performance evaluation based on different conventional controllers (PI & PID) and intelligent controllers (like Fuzzy, ANN and ANFIS) with different gain scheduling has been carried out. The fuzzy controller offers better performance over the conventional controllers, especially, in complex and nonlinearities associated system. Among the various types of load frequency controllers, the most widely employed is the conventional proportional integral (PI) controller. The PI controller is simple for implementation but generally gives large frequency deviations. The performance of PI and PID controllers deteriorates as the complexity of the system increased due to the nonlinearity and boilers dynamics in the interconnected power system. In order to keep the system performance near its optimum, it is desirable to track the operating conditions and use updated parameters to compute the control.

Fuzzy technique has been applied to the Load Frequency Control problems with rather promising results. The salient feature of these techniques is that they provide a model-free description of control systems and do not require model identification. Whereas fuzzy control technique also has some limitations of selecting proper membership functions and defuzzification problem. Then it has been thought of a controller which can even work with nonlinearities and can give fast response. The Artificial Neural Network came in existence. By training the neurons, multiplying with weight and applying a suitable activation function, the output can be obtained. The ANN controller works better for large power system or unstructured system. But this ANN controller also has some limitation of training of neural network and activation function. There is a need of such controller which has both properties fuzzy and neural then a hybrid neuro-fuzzy controller is sought. The ANFIS is having capability of training of data and application of membership function for error and change in error, fuzzy inference system and defuzzification. In multi area power system like two area, three area and four areas interconnected hydro thermal-reheat power system ANFIS controller give better settling performance than the other four types of controller discussed. Therefore hybrid intelligent control approach using ANFIS controller is better than the conventional (PI and PID) controller and intelligent (Fuzzy, ANN and ANFIS) controller. Details of intelligent controllers are given in the preceding sections.

1.9 Fuzzy Logic Control

Fuzzy logic is a thinking process or problem-solving control methodology incorporated in control system engineering, to control systems when inputs are either imprecise or the mathematical models are not present at all. Fuzzy logic can process a reasonable number of
inputs but the system complexity increases with the increase in the number of inputs and outputs, therefore distributed processors would probably be easier to implement. It is an idea or problem-solving methodology to control non-linear systems. The conventional control systems that work on the basic approximation of systems to be linear systems failed drastically when the range of application of such linear models was increased and therefore the need of control logic that could work even with linear systems was born. The phenomenon which brought non-linearities to linear systems are columbic forces, friction backlash etc and therefore owing to these factors the linear systems were either unstable or poor in their performance transient.

Fuzzy logic originated in the United States some 30 years ago but most of the researchers there scoffed it off by stating it merely as ‘probability’ but it was the mental acumen of the Japanese that helped them manifest fuzzy logic not only in complex systems but even in systems like cameras, washing machine, etc. One breathtaking success of fuzzy logic was the complete automation of railway drive system in Japan and it was then that the research on fuzzy logic gained momentum. The systems that looked impossible to manifest and facilitate worked remarkably well after the application of fuzzy logic to them. If the dynamics of the system and input parameters are imprecise or missing, then fuzzy logic works by exploiting its tolerance for imprecision of input parameters. As the father of fuzzy logic Lofti A Zadeh puts it, “because precision is costly, it makes sense to minimize the precision needed to perform a task”. The applicability of fuzzy logic is indeed promising.

1.10 Fuzzy Logic Vs Conventional Controls

Humans are conditioned to think and work on precise and accurate data and it is only after the knowledge of this data that to design control systems. It is often found that control systems designed even after the knowledge of such precise input data and intricate mathematical models fail drastically when used in real world because our world is too complex for the mathematical models to cope with, whereas in such cases fuzzy logic tolerates the imprecision of input data and equations and yet produces desired results.

Fuzzy logic incorporates a very simple algorithm that is “IF X AND Y THEN Z.” Let me explain it with the example of temperature of the water with which I will bathe. Suppose it is a chilly winter and I want to take bath. Water will obviously be too cold for me to handle. What will I do next is add some warm water and check whether this time the temperature is of my liking. If not, I will add some more warm water. This time temperature is of my liking and therefore I can take bath. This is how fuzzy logic works. You can observe that the above
example is indeed a temperature control than anything else. You can also observe that no mathematical models were used and even then I was able to control the temperature to my liking. Therefore, in a nutshell “If water is cold or warm or vice-versa”. The quantity of water which needs to be added depends upon whether water is “very cold,” cold,” ‘very warm’ or ‘warm’.

1.10.1 How It Is Used?

1. Define the control objectives and criteria: What you are trying to control? What do you have to do to control the system? What sort of response do you need? What are possible system failure modes?
2. Define and determine the input and output relationships and choose minimum number of variables for input to the fuzzy logic engine (typically error and rate-of-change-of-error).
3. Using rule-based structure of fuzzy logic, break the control problem down into a series of “IF X AND Y THEN Z” rules that define the desired system output response for given system input condition.
4. Create fuzzy logic membership functions that define the meaning (values) of input and output terms used in rules.
5. Create the necessary pre- and post-processing fuzzy logic routines if implementing in software. Otherwise, program the rules in the fuzzy logic hardware engine.
6. Test the system performance, and tune the rules and membership functions and retest until satisfactory results are obtained.

1.10.2 Why Use Fuzzy Logic?

Fuzzy logic provides many unique features that make it a good choice for many control problems. Some are as follows:

1. It is very robust and does not require precise, noise-free inputs. The output control is a smooth function despite a wide range of input variations.
2. Since the fuzzy logic controller uses user-defined rules (IF X AND Y THEN Z) for governing the target control system and can be easily modified at will, the system performance can be apparently changed.
3. Fuzzy controllers are not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change of parameters for implementations. Any sensor data providing information for system action or reaction is sufficient. This allows the sensor’s data to be imprecise, thus keeping the system complexity low.
4. Because fuzzy logic incorporates rule-based operations, any reasonable number of inputs can be processed and numerous outputs generated although defining the rule base for too many
inputs and outputs becomes more complicated since rules defining their interrelation must also be defined. It would be better to break the control system into smaller segments and use several smaller fuzzy logic controllers distributed on the system, each with more limited responsibility.

5. Fuzzy logic can control non-linear systems that would be difficult or impossible to model mathematically.

1.11 Neural Network

Neural networks are adaptive statistical models based on an analogy with the structure of the brain. They are adaptive because they can learn to estimate the parameters of some population using a small number of exemplars (one or a few) at a time. They do not differ essentially from standard statistical models. For example, one can find neural network architectures akin to discriminate analysis, principal component analysis, logistic regression, and other techniques. In fact, the same mathematical tools can be used to analyze standard statistical models and neural networks. Neural Networks are used as statistical tools in a variety of fields, including psychology, statistics, engineering, econometrics, and even physics. They are used also as models of cognitive processes by neuro and cognitive scientists. Basically, neural networks are built from simple units, sometimes called neurons or cells by analogy with the real thing. These units are linked by a set of weighted connections. Learning is usually accomplished by modification of the connection weights. Each unit codes correspond to a feature or a characteristic of a pattern. These networks usually organize their units into several layers. The first layer is called the input layer, the last one the output layer. The intermediate layers (if any) are called the hidden layers. The information to be analyzed is fed to the neurons of the first layer and then propagated to the neurons of the second layer for further processing. The result of this processing is then propagated to the next layer and so on until the last layer. Each unit receives some information from other units (or from the external world through some devices) and processes this information, which will be converted into the output of the unit. The goal of the network is to learn or to discover some association between input and output patterns, or to analyze, or to find the structure of the input patterns. The learning process is achieved through the modification of the connection weights between units. In statistical terms, this is equivalent to interpreting the value of the connections between units as parameters (e.g., like the values of ‘a’ and ‘b’ in the regression equation, by = a + bx) to be estimated. The learning process specifies the “algorithm” used to estimate the parameters.
1.12 Artificial Neural Networks

Artificial neural networks (ANN) have been developed as generalizations of mathematical models of biological nervous systems. A first wave of interest in neural networks (also known as connectionist models or parallel distributed processing) emerged after the introduction of simplified neurons. The basic processing elements of neural networks are called artificial neurons, or simply neurons or nodes. In a simplified mathematical model of the neuron, the effects of the synapses are represented by connection weights that modulate the effect of the associated input signals, and the nonlinear characteristic exhibited by neurons is represented by a transfer function. The neuron impulse is then computed as the weighted sum of the input signals, transformed by the transfer function. The learning capability of an artificial neuron is achieved by adjusting the weights in accordance to the chosen learning algorithm.

A typical artificial neuron and the modeling of a multilayered neural network are illustrated in Figure 1.7. Referring to this figure, the signal flow from inputs $x_1, \ldots, x_n$ is considered to be unidirectional, which are indicated by arrows, as is a neuron’s output signal flow ($O$). The neuron output signal $O$ is given by the following relationship:

$$O = f(\text{net}) = f\left(\sum_{j=1}^{n} w_j x_j\right)$$

(1.4)

Where $w_j$ is the weight vector, and the function $F(\text{net})$ is referred to as an activation (transfer) function. The variable net is defined as a scalar product of the weight and input vectors,

$$\text{net} = w^T x = w_1 x_1 + \cdots + w_n x_n$$

(1.5)

Where, $T$ is the transpose of a matrix, and, in the simplest case, the output value $O$ is computed as:

$$O = f(\text{net}) = \begin{cases} 1 & \text{if } w^T x \geq \theta \\ 0 & \text{otherwise} \end{cases}$$

(1.6)

Where $\theta$ is called the threshold level; and this type of node is called a linear threshold unit.

1.13 Artificial Neural Architectures

The basic architecture consists of three types of neuron layers: input, hidden, and output layers. In feed-forward networks, the signal flow is from input to output units, strictly in a feed-forward direction. The data processing can extend over multiple (layers of) units, but no feedback
connections are present. Recurrent networks contain feedback connections. Contrary to feedforward networks, the dynamical properties of the network are important. In some cases, the activation values of the units undergo a relaxation process such that the network will evolve to a stable state in which these activations do not change anymore. In other applications, the changes of the activation values of the output neurons are significant, such that the dynamical behaviour constitutes the output of the network. There are several other neural network architectures (Elman network, adaptive resonance theory maps, competitive networks, etc.) depending on the properties and requirement of the application. A neural network has to be configured such that the application of a set of inputs produces the desired set of outputs. Various methods to set the strengths of the connections exist. One way is to set the weights explicitly, using a prior knowledge. Another way is to train the neural network by feeding it teaching patterns and letting it change its weights according to some learning rule. The learning situations in neural networks may be classified into three distinct sorts. These are supervised learning, unsupervised learning, and reinforcement learning. In supervised learning, an input vector is presented at the inputs together with a set of desired responses, one for each node, at the output layer. A forward pass is done, and the errors or discrepancies between the desired and actual response for each node in the output layer are found. These are then used to determine weight changes in the net according to the prevailing learning rule. The term “supervised” originates from the fact that the desired signals on individual output nodes are provided by an external agent.

![Artificial neuron and multilayered neural network](image)

**Fig. 1.7** Architecture of an artificial neuron and a multilayered neural network

The artificial neural network (ANN), often called the neural network, is the most generic form of AI for emulating the human thinking process compared to the rule-based Expert system.
and Fuzzy Logic. The cerebral cortex of a human brain is said to contain around 100 billion nerve cells or biological neurons, which are interconnected to form a biological neural network. The memory and intelligence of the human brain and corresponding thinking process are generated by the action of this neural network. Although the structure of a biological neuron is known, the way they are interconnected is not well known. An ANN tends to emulate the biological nervous system of the human brain in a very limited way by an electronic circuit or computer program. However inferior the ANN model of the biological nervous system, it tends to solve many important problems. An ANN (also defined as a neuro-computer or connectionist system in the literature) is particularly suitable for solving pattern recognition and image processing type problems that are difficult to solve by conventional digital computer. On the other hand, a digital computer is very efficient in solving Expert system problems and somewhat less efficient in solving Fuzzy logic problems. Pattern recognition or input/output mapping constitutes the core of neuro computation. Basically, this mapping is possible by the associative memory property of the human brain. This property helps us to remember or associate the name of a human brain remembers and learns, an ANN is normally trained (not programmed) to learn by example input/output, associating patterns. This is like teaching alphabet characters to a child, where the characters are shown and their names are pronounced repeatedly. Broadly, the ANN technology has been applied in process control, identification, forecasting, diagnostic, robot vision, and financial problems, just to name a few. There is a very old and fascinating history behind the ANN Technology. After reviewing neural network concept it is mainly emphasized on applications in power electronics, power system and the drives area will be described from the literature. The structure of an artificial neuron is shown in Fig. 1.8.

![Fig. 1.8 Structure of Artificial Neuron](image)
1.14 HYBRID NEURO-FUZZY CONTROL

1.14.1 Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS stands for Adaptive Neuro-Fuzzy Inference System. The ANFIS controller combines the advantages of fuzzy controller as well as quick response and adaptability nature of ANN. Fundamentally, ANFIS is about taking a fuzzy inference system (FIS) and tuning it with a back propagation algorithm based on some collection of input-output data. This allows your fuzzy systems to learn. A network structure facilitates the computation of the gradient vector for parameters in a fuzzy inference system. Once the gradient vector is obtained, a number of optimization routines is applied to reduce an error measure (usually defined by the sum of the squared difference between actual and desired outputs). This process is called learning by example in the neural network literature.

Some Constraints are as follows:-

Since ANFIS is much more complex than the fuzzy inference systems discussed so far, all the available fuzzy inference system options cannot be used. Specifically, ANFIS only supports Sugeno systems subject to the following constraints:

• First order Sugeno-type systems.
• Single output derived by weighted average defuzzification.
• Unity weight for each rule.

An error occurs if your FIS matrix for ANFIS learning does not comply with these constraints. Moreover, ANFIS is highly specialized for speed and cannot accept all the customization options that basic fuzzy inference allows, that is, one cannot make own membership functions and defuzzification functions; that to make do with the ones provided.

The fuzzy inference system that has been considered is a model that maps:

– Input characteristics to input membership functions,
– Input membership function to rules,
– Rules to a set of output characteristics,
– Output characteristics to output membership functions, and
– The output membership function to a single-valued output, or
– A decision associated with the output.

• Only membership functions has been considered that have been fixed, and somewhat arbitrarily chosen. Also, only fuzzy inference is applied for modeling systems whose rule structure is essentially predetermined by the user’s interpretation of the characteristics of the variables in the
model. In general the shape of the membership functions depends on parameters that can be adjusted to change the shape of the membership function. The parameters can be automatically adjusted depending on the data that has been tried to model.

1.14.2 Model Learning and Inference through ANFIS

(i) Suppose already it have been collected input/output data and would like to build a fuzzy inference model/system that approximate the data.
(ii) Such a model would consist of a number of membership functions and rules with adjustable parameters similarly to that of neural networks.
(iii) Rather than choosing the parameters associated with a given membership function arbitrarily, these parameters could be chosen so as to tailor the membership functions to the input/output data in order to account for these types of variations in the data values.
(iv) The Neuro-Adaptive learning techniques provide a method for the fuzzy modeling procedure to learn information about a data set, in order to compute the membership function parameters that best allow the associated fuzzy inference system to track the given input/output data.
(v) Using a given input/output data set, the toolbox function ANFIS constructs a fuzzy inference system (FIS) whose membership function parameters are tuned (adjusted) using either a back propagation algorithm alone, or in combination with a least squares type of method.
(vi) This allows fuzzy systems to learn from the data they are modeling.

1.15 Objective of the Thesis

The objective of the research on load frequency control of interconnected power system based on Hybrid Intelligent Controller is as follows:

(1) To develop the transfer function model of two areas, three areas and four areas hydro thermal reheat power system interconnected by tie-lines for Load Frequency Control.
(2) To Design intelligent controllers based on the following techniques:
   (a) Fuzzy Logic Control and Artificial Neural Network.
   (b) Adaptive Neuro-fuzzy Inference System.
(3) To evaluate the performance of the designed controllers with existing conventional controllers (PI and PID) by simulating both the designed and existing controllers.
1.16 Organization of Thesis

The thesis has been organized into five chapters.

- **Chapter 1: Introduction**: The chapter discusses about the Automatic Generation Control, Load Frequency control, Concepts of Load Frequency Control and its expressions and Load Frequency Control in single area and multi area power systems in brief and objective of the thesis is also included in this chapter.

- **Chapter 2: Review of Literature**: This chapter discusses about the various research works done by various persons all over the countries. The development in load frequency control by them has been discussed in brief with their publication details. The literature survey is arranged as per the year published. The oldest work is placed first and then preceded by the latest work.

- **Chapter 3: Materials and Methodology**: This chapter discusses about the all the theories and concepts of Load Frequency Control in single area, two areas, three areas and four areas interconnected hydro thermal power system with their modeling derivations and block diagrams. This also includes the transient responses, formulas of automatic controllers, and the concepts and theory of the Neural Networks, Fuzzy logic controller and ANFIS controllers and their models.

- **Chapter 4: Simulation and Results**: This chapter discusses about the simulation carried out with the developed model of LFCs of two areas, three areas and four areas interconnected power system. It also includes the comparison of the responses obtained by simulating the LFCs with conventional (PI, PID) and intelligent (ANN, Fuzzy and ANFIS) controllers.

- **Chapter 5: Summary and Conclusion**: This chapter includes the summary of the research work and conclusion of the whole simulation and dynamic responses by the controllers and its future scope is also added.

- **Appendix A**: This includes the transient response specifications of second order system.

- **Appendix B**: This Appendix includes the detailed models of fuzzy sets and membership function, types and defuzzification methods.

- **Appendix C**: This appendix includes the details of artificial neural network and ANN controllers.
• **Appendix D:** This includes the hybrid neuro-fuzzy (HNF) controller and the architecture of the ANFIS and related equations.

• **References:** This includes the list of references cited in the thesis and arranged in alphabetical order of the names of the Authors.