Chapter 1

Introduction

1.1 Introduction

The development of electrical power was envisaged in the nineteenth century, and in the late nineteenth century electrical power generating units were installed throughout the world. The fast growth of these units was witnessed in the twentieth century. In India at the time of independence, the total generating capacity of electrical power was around 1362 MW. In early stages, the electric-power generating stations were installed around big cities, and the need for commissioning transmission systems was not given due consideration at that time. Under the five-year plans, a huge volume of industrial units was planned, and consequently the need for development of more electric power coupled with a large network of transmission systems at a faster rate was evident. The schemes for this have been implemented first at the state level and then at regional levels. The power industry is trying hard to meet the load demands on the system. In the new millennium much more efforts will be needed to meet the requirements of load demands, not by generating electrical power according to our load demands, but also by meeting the economical and environmental standards set up through legislation from time to time.

Presently the total installed capacity of electrical power in India is around 128,000 MW. The break up of this power according to different types of generating modes is hydro 32,326 MW; thermal 81,207 MW; nuclear 3360 MW; non-conventional 6,190 MW [1]. In India, due to various technical, economical, and environmental considerations, the electric power generating units have been installed at remote locations from load centers. However, they have to operate in an interconnected fashion to share the benefits of utilizing variability in generation mixes and load patterns and other technological advantages. Therefore, there is a requirement of such transmission links which are capable of exchanging large chunks of electrical power between widely spread power pools effectively and efficiently. A huge transmission network has already been laid in India to cater to the energy needs at reasonably good cost and in a human-friendly environment.

In a normal power system, it is expected that both active and reactive power demands will vary from time to time. In order to cope up with this accordingly, it is essential that system inputs, namely mechanical power and field voltage are to be increased or decreased. This will ensure quality of supply to be standard in terms of its frequency and level of voltage. Therefore, it can be stated that electricity is a unique commodity whose production and consumption must be matched instantaneously and continuously.

The electric power grid has only the rotational kinetic energy of the connected synchronous generators to help balance production and consumption: enough energy storage to sustain the grid for cycles to seconds (depending on the amount of imbalance). It is not possible to maintain a perfect generation vs. load balance although active control systems attempt to do this by constantly adjusting the generator's power input.

The restructuring process of the electricity market that is now taking place will affect all business aspects of the power industry as it exists today from generation to transmission, distribution, and consumption. Transmission circuits, in particular, will be stretched to their thermal limits exceeding their existing stability limits due to the fact that building of new transmission lines is difficult, if not impossible, from environmental and /or political aspects. With deregulation comes the need for tighter control strategies to maintain the level of reliability that consumers not only have taken for granted but expect even in the event of considerable structural changes, such as a loss of a large generating unit or a transmission line, and loading conditions, due to the continuously varying power consumption.

The main aim of computer control in power system is the matching of the active power generation to the load demand at any given point of time. The most important generation sources are synchronous generators. Typically generators are present at only about 5% of the network buses. At the generator buses both active and reactive power can be controlled. The real power is controlled by the turbine torque and the reactive power via the exciter and field winding. The change in area generation to bring the frequency back to its nominal values is termed as area requirement.

Each generator is equipped with two separate automatic feedback control loops. The automatic voltage regulator (AVR) loop maintains control of the bus voltage by means of reactive power output. The load frequency control or automatic generation control (latter name has come up with the present day system where manual regulation is not possible) loop maintains a constant frequency by manipulation of the real power output. The continuous operation of electric power system requires system operators to constantly balance the energy demanded by consumers. Changes in demand and/or supply can be observed by measuring the system frequency. Increase in demand will result in a frequency below the specified value and a decreased demand would result in a frequency above specified. It is the system operator’s job to balance the system’s frequency as close as possible to specified value. This balancing process is known as load frequency control [2]-[5].

The management and control of a power system from the power system control centre is a complex process and needs interaction between many levels of the command hierarchy and on vastly varying time scales. Table 1.1 shows the time scale of various hierarchical control problems.

Earlier most of the slower control functions were carried out manually while faster control functions were achieved using analogue automatic control system. In recent times the availability of large scale process control computers at the energy centre resulted in an increasing use of digital computers instead of the manual or automatic analogue control systems. In automatic load frequency control, there are two feedback loops- primary and secondary. The purpose of these loops is to achieve real power balance or load tracking in the system. The automatic load frequency control loops are designed to maintain power balance by an appropriate adjustment of the turbine torque. By means of the primary loop a relatively fast but coarse frequency control is achieved. The secondary control automatic load frequency control loop works in a slow reset mode to eliminate the remaining small frequency errors [6]-[8].

Table 1.1: Time scale of various hierarchical control problems

Time scale	Control problems
Milliseconds	Local control: relaying and system voltage control and excitation control
Few seconds	Load frequency control, state estimation and energy logging.
5-10 minutes	Economic dispatch
Few minutes – an hour	Security analysis
Few hours –1 week	Unit commitment
Yearly	Maintenance scheduling
1 year – 10 years	System planning

1.2 Primary Control

The electric frequency in the network (the system frequency *f*) is a measure for the rotation speed of the synchronized generators. By increase in the total demand the system frequency (speed of generators) will decrease, and by decrease in the demand the system frequency will increase. Regulating units will then perform automatic primary control action and the balance between demand and generation will be re-established. The frequency deviation is influenced by both the total inertia in the system, and the speed of primary control. Under undisturbed conditions, the system frequency must be maintained within strict limits in order to ensure the full and rapid deployment of control facilities in response to a disturbance. Figure 1.1 shows the the block diagram of overall system control stages.

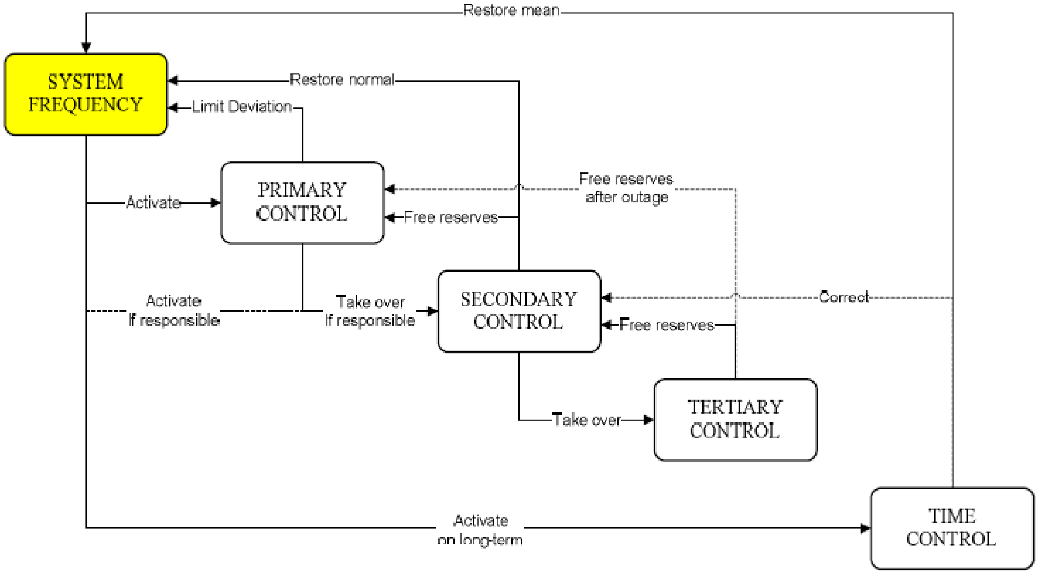

Figure 1.1: Block diagram of overall system control stages

The load frequency control is handled collectively by a unison effort by all generator units within a so-called control area, usually; the boundaries of the control areas coincide with those of the individual power systems belonging to the pool. In the strictest sense, all the generators in a control area should constitute a coherent group. In the analysis to follow, coherency is assumed. Even in case of a major frequency deviation / offset, each control area will maintain its interconnections with adjoining control areas, provided that the secure operation of its own system is not jeopardized.

1.2.1 Primary Control Basics

Various disturbances or random deviations which impair the equilibrium of generation and demand will cause a frequency deviation, to which the primary controller of generating sets involved in primary control will react at any time. The proportionality of primary control and the collective involvement of all interconnection partners are such that the equilibrium between power generated and power consumed will be immediately restored, thereby ensuring that the system frequency is maintained within permissible limits. In case that the frequency exceeds the permissible limits, additional measures out of the scope of primary control, such as (automatic) load-shedding, are required and carried out in order to maintain interconnected operation.

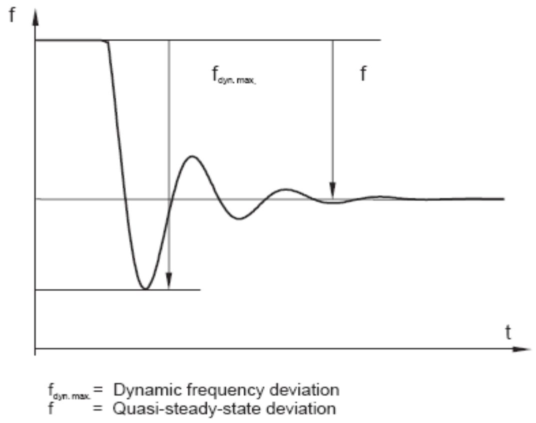

Figure 1.2: Dynamic frequency deviation

This deviation in the system frequency will cause the primary controllers of all generators subject to primary control to respond within a few seconds. The controllers alter the power delivered by the generators until a balance between power output and consumption is re-established. As soon as the balance is re-established, the system frequency stabilizes and remains at a quasi-steady-state value, but differs from the frequency set-point because of the droop of the generators which provide proportional type of action. Consequently, power cross-border exchanges in the interconnected system will differ from values agreed between generation utilities. Now, secondary control will take over the remaining frequency and power deviation after few seconds. The function of secondary control is to restore power cross-border exchanges to their (programmed) set-point values and to restore the system frequency to its set-point value at the same time.

The magnitude $\Delta f_{dyn.max}$, shown in the figure 1.2, of the dynamic frequency deviation is governed mainly by the following:

- the amplitude and development over time of the disturbance affecting the balance between power output and consumption;
- the kinetic energy of rotating machines in the system;
- the number of generators subject to primary control, the primary control reserve and its distribution between these generators;
- the dynamic characteristics of the machines (including controllers);
- the dynamic characteristics of loads, particularly the self-regulating effect of loads.

1.3 Secondary Control

Any imbalance between electric power generation and consumption will result (in real-time) in a frequency change within the complete network of the synchronous area. As a result over time, a frequency deviation occurs. At system frequency below specified value, the total demand has been larger than the total generation, at frequency above the specified one the total demand has been less than the total generation. In practice, the demand varies continuously, even without having forecast errors, so that secondary control on a real-time basis is required on a continuous basis. A deviation Δf of system frequency, from its set-point value, will activate primary control power throughout the synchronous area. Primary control allows a balance to be re-established at a system frequency other than the frequency set-point value (at a quasi-steady-state frequency deviation Δf), in response to a sudden imbalance between power generation and consumption (incident) or random deviations from the power equilibrium. Since all control areas contribute to the control process in the interconnected system, with associated changes in the balance of generation and consumption in these control areas, an imbalance between power generation and consumption in any control area will cause power interchanges between individual control areas to deviate from the agreed / scheduled values (power interchange deviations ΔP_i).

The function of secondary control is to keep or to restore the power balance in each control area and, consequently, to keep or to restore the system frequency f to its set-point value and the power interchanges with adjacent control areas to their programmed scheduled values, thus ensuring that the full reserve of primary control power activated will be made available again. In addition, secondary control may not impair the action of the primary control. These actions of secondary control will take place simultaneously and continually, both in response to minor deviations (which will inevitably occur in the course of normal operation) and in response to a major discrepancy between production and consumption. In order to fulfill these requirements in parallel, secondary control needs to be operated whereas all control areas provide mutual support by the supply of primary control power during the primary control process, only the control area affected by a power unbalance is required to undertake secondary control action for the correction. Consequently, only the controller of the control area, in which the imbalance between generation and consumption has occurred, will activate the corresponding secondary control power within its control area. Parameters for the secondary controllers of all control areas need to be set such that, ideally, only the controller in the zone affected by the disturbance concerned will respond and initiate the deployment of the requisite secondary control power. Within a given control area, the demand should be covered at all times by electricity produced in that area, together with electricity imports (under purchase contracts and / or electricity production from jointly operated plants outside the zone concerned). In order to maintain this balance, generation capacity for use as secondary control reserve must be available to cover power plant outages and any disturbances affecting production, consumption and transmission. Secondary control is applied to selected generator sets in the power plants comprising the control loop. Secondary control operates for periods of several minutes, and is therefore timely dissociated from primary control. Secondary control makes use of measurements of the system frequency and active power flows on the tie lines of the control area, a secondary controller that computes power set point values of selected generation sets for control and the transmission of these set-point values to the respective generation sets. When consumption exceeds production on a continuous basis, immediate action must be taken to restore the balance between the two (by the use of standby supplies, contractual load variation or load-shedding or the shedding of a proportion of customer load as a last resort). Sufficient transmission capacity must be maintained at all times to accommodate reserve control capacity and standby supplies. Since it is technically impossible to guard against all random variables affecting production, consumption or transmission, the volume of reserve capacity will depend upon the level of risk which is deemed acceptable. These principles will apply, regardless of the division of responsibilities between the parties involved in the supply of electricity to consumers [6], [9], [10].

1.3.1 Principle of the Secondary Controller

In order to determine, whether power interchange deviations are associated with an imbalance in the control area concerned or with the activation of primary control power, the network characteristic method needs to be applied for secondary control of all control areas in the synchronous area. Each control area is equipped with one secondary controller to minimize the area control error (ACE) in real-time:

$$\mathrm{ACE} = \mathrm{P}_{\mathrm{meas}} - \mathrm{P}_{\mathrm{sched}} + \mathrm{B}\,(f_{\mathrm{mean}} - f_0)$$

With $\mathrm{P}_{\mathrm{meas}}$ being the sum of the instantaneous measured active power transfers on the tie lines, $\mathrm{P}_{\mathrm{sched}}$ being the scheduled exchange power with all the neighboring / adjacent control areas, B is know as area frequency bias constant (MW/Hz) set on the secondary controller, and $(f_{\mathrm{mean}} - f_0)$ being the difference between the instantaneous measured system frequency and the set-point frequency. The ACE is the control area's unbalance ($\mathrm{P}_{\mathrm{meas}} - \mathrm{P}_{\mathrm{sched}}$) minus its contribution to the primary Control. The power transits are considered positive for export and negative for import. Hence, a positive (respectively a negative) ACE requires a reduction (respectively an increase) of the secondary control power. The ACE must be kept close to zero in each control area. The purpose is twofold:

- **Control area balance**.

If the measured system frequency f_{mean} is equal to the set-point frequency f_0, the ACE is the unbalance of the control area, i.e. the difference between the measured power exchanges P_{meas} and the scheduled exchanges P_{sched}.

- **Non detrimental effect on primary control**.

The power developed by primary control in the control area under consideration has to be subtracted from the power unbalance in order not to neutralize the primary control action. Due to the uncertainty on the self regulating effect of the load, B may be chosen such that the secondary control will accentuate the effect of the primary control and not counteract it.

1.3.2 Control Hierarchy and Organization

The synchronous area consists of multiple interconnected control areas, each of them with centralized secondary control. Each control area may be divided into sub-control areas that operate their own underlying secondary control, as long as this does not jeopardize the interconnected operation. The hierarchy of secondary control consisting of the synchronous area with control blocks and (optionally) included control areas is shown in figure 1.3.

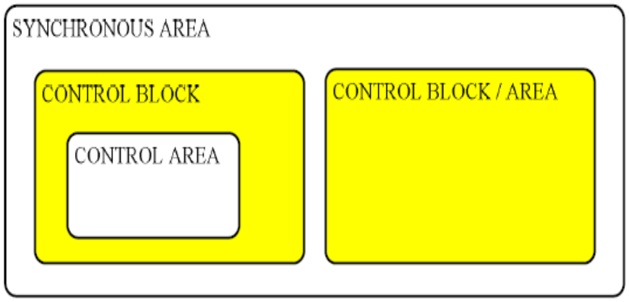

Figure 1.3: Control hierarchy and organization

1.4 Tertiary Control

Tertiary control is any automatic or manual change in the working points of generators or loads participating, in order to:

- guarantee the provision of an adequate secondary control reserve at the right time;
- distribute the secondary control power to the various generators in the best possible way, in terms of economic considerations;

Typically, operation of tertiary control (in succession or as a supplement to secondary control) is bound to the time-frame of scheduling, but has in principle same impact on interconnected operation as secondary control. The power which can be connected automatically or manually under tertiary control, in order to provide / restore an adequate secondary control reserve, is known as the tertiary control reserve. This tertiary control reserve must be used in such a way that it will contribute to the restoration of the secondary control range when required.

1.5 Measures for Emergency Conditions

The direct measures for emergency conditions are based to a certain extent on the philosophy that in the event of a major disruption, selective restrictions in the energy supply are more acceptable than the consequences of an extended network breakdown resulting in a power cut lasting for several hours.

The system frequency as a global parameter is the main criterion that signalizes emergency situations in the system. Due to its equal value in the interconnected system, all partners are automatically participating at problem solving by the automatic action of the primary controllers. Local indicators that inform about possible emergency situations, are “overloading of the interconnecting tie-lines” that can result in action of automatic protection situation are also “decreasing of the transmission voltage” causing voltage collapse due to abnormally high flow of reactive power in the transmission system. Counteraction of the secondary controller and the measures for emergency conditions shall be avoided in a coordinated way.

1.6 Various Techniques to tackle LFC Problem

The need for modern control system theory has achieved an importance in affecting the dynamic response of large interconnected system in the last two decades such as optimal control, adaptive control, pole placement approach and intelligent techniques. A brief description of these techniques is given below.

1.6.1 Optimal Control

The controller design problem is specified by: the process, the criterion that is formulated in the performance index and the admissible control signal. A discrete time model can describe the process, while the performance index is written as a mathematical function to express the cost (cost function). This describes the requirements made for the behavior of the plant. The optimal design procedure minimizes this cost function to get the optimal solution of control design. This controller is one of the centralized types of controllers where each state of the system is communicated between the subsystem and controllers.

1.6.2 Adaptive Control

The adaptive controller is a controller that can modify its behavior in response to changes in the dynamics of the process and in the magnitude and characteristics of disturbances. Adaptive controllers also have their own parameters, which must be chosen. Controllers without any externally adjusted parameters can be designed for specific applications in which the purpose of control can be stated a priory.

1.6.3 Pole Placement Technique

In the pole placement technique the closed loop poles of the system may be placed anywhere in the complex plane in order to stabilize the system and satisfy requirement of any stability margin or damping ratio.

Normally the parameters of the conventional controllers (fixed-gain, lead-lag and PID) are determined off-line at a nominal operating point to give good performance. However, the system dynamic response may regress when the operating point changes. The controllers such as optimal and adaptive controllers are always very hard to implement in real power systems due to the extensive number of feedback variables to be communicated over long distances. In addition, it is extremely difficult to measure most of the feedback variables required by both optimal and adaptive controllers. It is also difficult to find the optimal solution when the system size is large as Riccati equation of the system order is solved iteratively and the adaptive control requires model identification in real time, that is, time consuming. For pole placement technique, many cautions are to be considered, e.g., the closed loop poles may require large stabilizing gains, which are limited by physical constraints.

1.6.4 Intelligent Techniques

New techniques such as fuzzy logic, artificial neural networks, genetic algorithm and expert system have been used in power system applications. The thriving of artificial intelligent which utilizes the human experience in a more relaxed form than the conventional mathematical approach has recently attracted more attention to many artificial intelligent techniques.

1.6.4.1 Fuzzy Logic

Fuzzy logic is the application of logic to imprecision and has found application in control system design in the form of Fuzzy Logic Controllers (FLCs). Fuzzy logic controllers facilitate the application of human expert knowledge, gained through experience, intuition or experimentation, to a control problem. Such expert knowledge of a system’s behavior and the necessary intervention required to adequately control that behavior is described using imprecise terms known as “linguistic variables”. The imprecise value of linguistic variables reflects the nature of human observation and judgment of objects and events within our environment, and their use in FLCs thus allows the mapping of heuristic, system-related information to actions observed to provide adequate system control. In this way, FLCs obviate the need for complex mathematical descriptions of non-linear behavior to the nth degree and thus offer an alternative method of system control. Figure 1.4 illustrates the constituent blocks of a FLC and the general concept of fuzzy control.

The rule base of a FLC consists of a set of behavior/action constructs that describe the action to be taken on the occurrence of particular observed/measured system behavior or state. The constructs consist of a premise (i.e. system behaviour/state) and the associated consequent (i.e. the action to be taken in order to achieve adequate system control under the observed system behaviour/state) used in an '*if* premise *then* consequent' form.

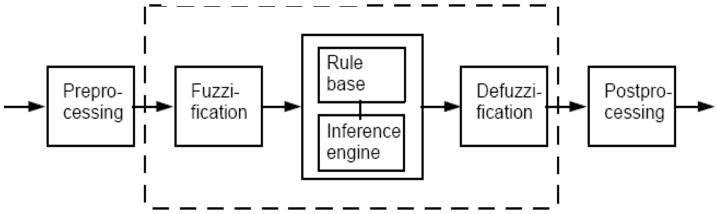

Figure 1.4: Architecture of fuzzy logic controller

Combinations of multiple premises and consequents are possible which enhance the precision of the rule -base. The rule base of a FLC must adequately cover all possible system behavior in respect of applied actions. The above descriptions of linguistic variables and rule -bases do not in themselves render the controller 'fuzzy', since, as defined, they could be adequately used in a boolean-based system. What makes the controller 'fuzzy' is the use of membership functions (MFs) to quantify to what degree of certainty each rule is true in respect of the system state at any particular time. The 'shapes' and relative spacing of the MFs form a critical element of the FLC and describe expert understanding of the meaning of the linguistic variables. Typical MF shapes are triangular, trapezoidal, sigmoid or custom-based, with several MFs used to partition the domain of the numeric value under consideration (i.e. the universe of discourse UOD). The use of MFs ensures that certainty, as defined within a FLC, is based upon the *subjective interpretation* of an expert rather than upon a probability distribution. Degrees of certainty (i.e. degree of membership of a fuzzy set) range from 0 to 1 in value and hence partial membership is possible. The FLC aggregates the levels of certainty for the entire rule -base to obtain an aggregate fuzzy output set, which is subsequently used to obtain a crisp (i.e. numerically valued), control action. The combination of the rule -base (RB), and associated membership functions (MF), constitute the controller knowledge base (KB), which in effect represents the embedded expert system knowledge. In general, two forms of FLC are defined,

- Mamdani
- Sugeno

Both of these architectures are similar in all respects except for the formulation of the output crisp value. In the Mamdani FLC, the output is formulated using fuzzy sets whereas the Sugeno type FLC uses single -spike output.

1.7 Objectives of the Thesis

This thesis addresses a major issue in power system control i.e. load frequency control of interconnected power systems. The principle objectives of the study are to systematically analyze the two area and three area power systems and develop models and algorithms for different control strategies. The main research topics of the thesis are summarized as follows:

(a) Mathematical Modeling of Interconnected Power systems:

Mathematical models of interconnected (two area and three area) systems are formulated. Models for generator, load, speed governor, turbine, and reheat turbine are devised in transfer function form.

(b) Linear Quadratic Regulator Design for Load Frequency Control for Two area interconnected System:

Linear quadratic regulator design for two area interconnected system for minimizing quadratic performance index to find optimized value of feedback gain matrix is obtained to achieve dynamic response of frequency variation and tie line variations when system is subjected to sudden disturbance.

(c) Fuzzy Controller Design for LFC problem:

Fuzzy logic is used to design a controller for LFC which is implemented on two area, and three area power systems. Fuzzy inference systems of Mamdani and Sugeno type with different type of membership functions and set of rules have been used to synthesize the control strategy. This fuzzy controller has given responses that compare favorably with the responses obtained through classical controllers, and other intelligent controllers. In addition to AC tie-line connection between any two areas, HVDC link is connected in parallel to AC tie line in another study of dynamic performance of interconnected system.

(d) Testing Robustness of Fuzzy Controller:

The issue of robustness is achieved by testing fuzzy controller with varying three parameters: frequency bias constant, tie-line constant, and power system time constant to ± 30 % of their nominal values

1.8 Arrangement of the Thesis

- Chapter 1 discusses the introduction of load frequency control problem of interconnected electrical power system. This chapter describes various control levels and control strategies of this major problem of power system control.

- Chapter 2 presents a comprehensive literature survey on load frequency control problem. Different methods adopted by researchers to tackle this problem so far have been thoroughly analyzed.
- Chapter 3 deals with problem identification and development of mathematical model of two area interconnected and three area interconnected power systems. Transfer functions of various components used in order to make final and most appropriated block diagram for the suitable solution of this problem are evolved.
- Chapter 4 is about the control strategies employed in this thesis. Linear quadratic regulator design for optimal solution and fuzzy logic based intelligent integral control schemes to solve problem of two and three area interconnected power system have been discussed in this chapter.
- Chapter 5 and Chapter 6 present results and analysis of implementation of proposed control schemes on two area and three area systems respectively. Simulations results are presented in a very elaborative manner to understand the importance and usefulness of proposed control strategies. Different cases of two and three areas are taken in order to analyze the dynamic performance of the multi-area systems and robustness of the controller developed.
- Chapter 7 concludes and proposes future scope of presented work.