AUTOMATIC GENERATION CONTROL OF INTER-CONNECTED POWER SYSTEM

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CERTFICATE

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ABSTRACT

In Practical situation of the power system, the overall generation is produced by the combination of thermal, hydro and /or nuclear power plants. Among them, the thermal and hydro power plants participate in automatic generation control (AGC).The purpose of control strategy is successful implementation on the system concern having varying characteristics. Also, many research papers available in the power system area reveal the fact that it is worthwhile to use HVDC transmission link which has a stabilizing effect on the system dynamics. Day by day increasing HVDC projects motivate us to investigate the effect of using parallel combination of EHVAC transmission link for system interconnection of the power system areas on the systems dynamic performance.

Thus, the aim of the present dissertation is to study **“AUTOMATIC GENERATION CONTROL OF INTERCONNECTED POWER SYSTEMS”**. For that purpose, investigations have been done with 2-area interconnected power system consisting of non-heat and reheat thermal – thermal plant having similar characteristics. Further the system interconnection has been considered in three different ways i.e EHVAC transmission link only, HVDC transmission link only and EHVAC transmission in parallel with HVDC transmission link. More over, HVDC link has been assume to be operated in constant current control mode. To check out effectiveness of incorporating HVDC link, simulation has been done and time response plot of frequency deviation, EHVAC tie line flow deviation, HVDC incremental power flow deviation and area control error foe both area have been obtained by implementing optimal AGC regulator design with full state vector feedback control strategies in the wake of 1% step load disturbance in either area (Here area -2). Thus, on the basis of this response is, the dynamic performance of the system has been studied .Beside this to study the close loop system stability, the closed loop system Eigen value have been computed.

Moreover, a comparative study of proportional and Proportional plus integral control strategy on the basis of the response is obtained has also be done in present report.

Load frequency Control (LFC) is used for many years as part of Automatic Generation Control (AGC) in power system around the world. In a mixed power system, it is usual to find an area regulated by thermal generation or gas generation or in combination of both .A detailed literature search shows that there is a great need to improve the control strategy to achieve good performance of the mixed system in the transient mode.

By investigating the results we observe that the Proportional plus integral control strategies provide the better dynamic performance of the system as compared to that obtained in proportional control strategies case. Also incorporating the incremental power flow through HVDC transmission link (ΔPdc) in the interconnected power system model improves the system stability. By using ΔPdc as an additional state variable we get improve dynamic performance of system has compare to that obtained in the case study where it has not been consider . The dynamic performance of system further gets improved if we considered ΔPdc is considered as an additional control variable with the conventional turbine controller. We also observe that dynamic performance of the interconnected power system is better in case of reheat thermal-thermal identical plant as compare to non-reheat thermal-thermal identical plants.

How ever it is not always feasible to measure all the state variable of the interconnected power system as considered above. Thus, the investigation has also been carried out with sub-optimal AGC regulator design with output vector feedback control strategy. The frequency deviation, EHVAC tie-line power flow, incremenral power flow through HVDC link and area control error are easy to access therefore , have been selected as output variables. To study the close loop system stability and the system dynamic performance, the close loop system Eigen values ant the time response plots of the selected output variables have been obtained. The result obtained indicate that although, the close loop stability of the system is maintained but stability margin reduce here. The dynamic performance responses obtained shows a reduction in first overshoot but oscillatory mode have increase greatly here as compared to that obtained in optimal AGC design with full state vector feedback control strategy.

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CHAPTER1

1.1 INTRODUCTION

Electric energy is one of the significant components for the growth and development of any country. It is the backbone of industry and all-around development of the country. It is a coveted form of energy as it can be generated centrally in bulk and transmitted economically over long distances. The per capita energy consumption is an indicator of the overall development of a country. The per capita figure has been raised from (22400 to 25295 for Norway), (10336 to 10457 for US), (6599 to 11446 for Australia), (4944 to 8212 for Japan), (5022 to 6755 for UK) and (173 to 594 for India) in KWhr from the year 1980 to 2003. With the ever increasing per capita energy consumption and exponentially rising population, the demand for electrical energy has been increasing enormously over the years. Technologists have already come to conclusion that the earth's non-replenish able fuel resources are near to its end. The oil crisis of 1970's has already taken attention towards it. A coordinated worldwide action plan is needed to ensure that energy supply to people at large is assured for a longer time, economically and also, ecologically. Hence, continuous motivation is being provided for power engineers to install increasingly large capacity generating stations and higher size if generating units to cope with these situations. In this accordance, individual power systems are organized in the form of electrically connected areas or regional grids for economical as well as technical reason. This regional grid operates technically and economically independently. But these independent grids are eventually interconnected to form a national grid and may further form an international grid. This is done so that each area is contractually tied to other areas in respect to certain generation and scheduling features. The rapid industrial development and the growth in the interconnections have created the necessity of improved quality and continuity of service. To achieve this, an electric energy system supposes to maintain a desired level characterized by nominal frequency, voltage profile and load flow configuration. It can be kept in this nominal state by closed control of the real and reactive powers generated in the controllable sources of the system.

1.2 Power System Engineers and Power System Studies

The power system engineers of the first decade of the twenty-first century have to face a variety challenging tasks. This can be met by keeping an eye over recent scientific advances and the latest technology available. In the planning operation, the decisions of generating electricity-where when and by what fuel, have to be taken. The engineer has to face the problem of planning and coordinated operation of a gigantic and a complex power network to make to make it economic and reliable. In our country, the engineer has to solve an additional dilemma of power cuts load mismanagement.

To make operation, improvement and expansion of power system planning, the engineers must have a sound knowledge of load flow studies, short circuit studies stability studies. The knowledge of economic load dispatch and frequency control is always desired. The engineers have to take help of digital computers and microprocessors to take over the above problems. Table 1 shows the time to scale of various hierarchical control problems to be solved by computers and microprocessors.

1.3 Power System Operating States

The operational and control philosophies of present time power systems have greatly changed over last few decades from their earlier approaches to the modern control approaches. Modern ECC have to be designed to perform a broad range of control function for an efficient, economic and reliable operation of the system. The main objective for operation is to keep the normal state as long as possible by satisfying the condition that the load demands are met and the load flow equations are satisfied, the frequency is constant the bus voltage magnitudes are with in narrow prescribed limits and no power system element is overloaded. The actual operation condition of a power system may lie among the four operating states discussed below which have been shown in Fig 1.1

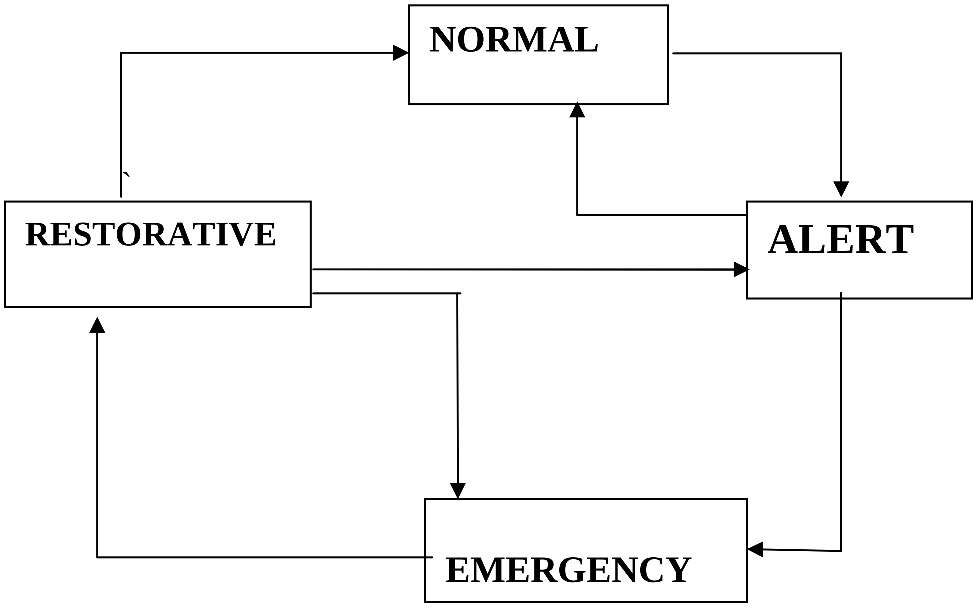


Fig 1.1 Operating System of a Power System

- **Normal**
- **Alert**
- **Emergency**
- **Restorative**

Generally a power system remains in the normal operating state. But at anytime, during its normal operating condition, it may face a contingency condition like outage of generating unit, short circuit, tripping of a line, loss of a transformer etc. Because of these type of contingencies, the system security level become reduced which can lead the system in one of the two states namely, alert pr emergency states. In the first type i.e. alert state, the systems remain stable and the operating constraints are satisfied. Some of the operating constraints like voltage and frequency may violate but that can be tolerated for a certain period. Hence the system may therefore be brought back to the normal operating state by some preventive control methods. However, during the alert states, if some other or the same type of contingency occurs, then the system's state become emergency state. This may cause overloading of the line and it has to be prevented by means of emergency controls, if in case, emergency controls fails, tripping of the overloaded line has to be done and it may become necessary to shut down system completely. Up to some extent, the system can be restored by load shedding. If system collapses, the restoration involves rescheduling if active and reactive power unit constraints, resynchronization and gradual load pickup. In the restorative state, corrective action is taken so that the system goes back to a new normal state or to the previous normal state. It may be noted that during the restoration process of the system in normal state, the system may deviate from its economic generation criterion, Restoration process should be kept as fast as possible.

1.4 Power System Control Problem

Table1.1 shows the time scale of various hierarchical control problems to be solved by computers/ microprocessors. In this table main elements of the control hierarchy and the approximate time on which it operates are shown.

(Table1.1)Time hierarchy of Power System Control Problems

Time-scale	Control Problems
Milliseconds	Relaying, system voltage control and excitation control
2sec-5minutes	Automatic Generation Control(AGC)
5-10 minutes	Economic dispatch
Few minutes-1 hour	Security analysis
Few hours- 1 week	Unit Commitment(UC)
1month-6month	Maintenance scheduling
1year-10year	System planning

From the table, it is observable that manual control is much slower that the automatic control. Many control schemes which were controlled manually or by analog method in past have been replaced by highly efficient digital computers and microprocessors. The very first level control is the local control. It is at the lowest level of time horizon and has a great importance of power engineers. Local control deals with fast control of fault isolation, voltage regulation and the excitation control. It is desirable to keep the system frequency within prescribed limit. To achieve this turbine governors adjust input power to the system in response to frequency deviation. This type of control is feasible for isolated system; more than one generator is required for one frequency stabilization. As the participating units have different dynamic characteristics, it causes oscillations in the network leading to the system instability that's why each unit is provided with a regular in which frequency deviation is fed back only by means of a proportional regular. It is to be noted that many base load units do not participate in system frequency control and for these units only the produced power is fed back.

AGC is the second level control. Its main function is to match the generated active power to the varying load demand. Also, its keep the system frequency and net power exchanges close to the scheduled values. In the wake of disturbance due to load increase, the system frequency goes down which initiates the operation of the local frequency control. Hence, a new study states is reached after a short time and new value of frequency and power exchange are set. At this moment operation of AGC is being initiates to regain the original set values. Effective implementation of AGC is dependent on the power system mode which is functionally related to the type, magnitude and location of disturbance occurred in the system. Normally the three types of disturbance are identified in power system: small(less than 2% of relate area capacity), moderately large (2% to 5%) and large (more than 5%). In the mode of operation the load disturbances are such that each area is capable of taking care of load various by itself. These small load variations are said class 1 type disturbances. The control action required by AGC is to change the generation meeting of ED objective. However, the moderately large disturbances are said class2 type disturbances. If load disturbances of this type are occurring in base area than from the security and economic point of view the control action required by is essentially needed. Also there are some instants when control action is required for disturbance in the areas other then area of disturbance. In case of large disturbances said as class III type disturbance occurred in base area, the control objective is the allocation of the spinning reserve. In this type of disturbance, allocation of spinning reserve has to be done on-line in advance ahead of time thereby adapting the generation to varying load demand and associated contingencies.

Economic dispatch is third level control adopted for economic operation of power system. In ED, the optimal output allocation for each unit is calculated so that the overall fuel cost is minimized within operating constraints. As one of the objectives of optimal AGC is to share the generation economically, hence to meet this criteria economic dispatch has to be carried out in conjunction with AGC within system constraints.

Security analysis is the fourth level control. During an abnormal operating condition in the power system some preventive action like generating shifting or security dispatch or increased reserves are required. The common strategy is generation scheduling which may offer a generation pattern for generating unit for secure system operation that may be different form that guided by economic generation criterion. Hence economic and secured co-ordination appears as an operational problem for such systems. Thus in general we can say that control strategy have to minimize the cost of generation power while maintaining its quality and satisfying the security system constraints.

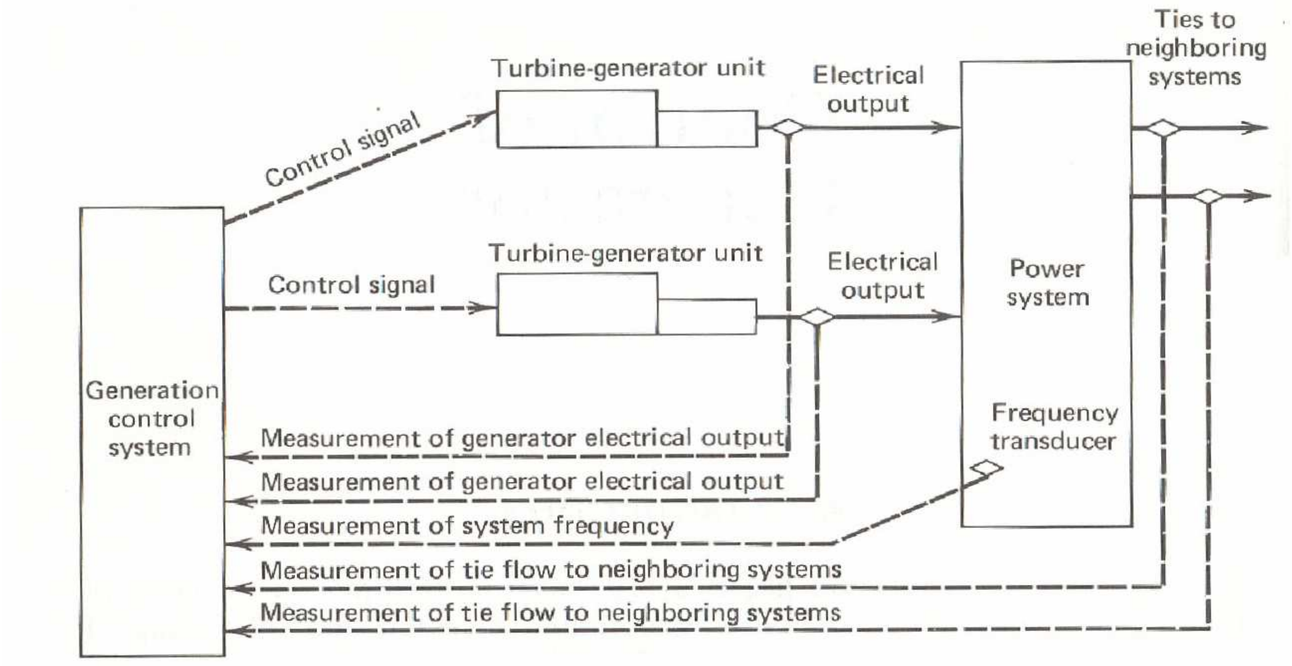
Next level control is unit commitment (UC). As is evident, it is not economical to run all the units available all the time. To determine the units of a plant that should operate for a particular load is the problem of UC. However, this problem is of importance for thermal plants as for other type of generation like hydro; their operating cost and start-up times are negligible so that their on off status is not important.

The basic concept of the control problem of a system is to achieve the specific objectives for which the system is meant while operating the system within the constraints imposed by physical and technical system. The conventional classical control techniques primarily based on the frequency domain analysis are usually reserved for linear time-invariant SISO systems and allow the designer greater freedom for intuition and experience. The modern control theory applies the time domain approach for the problem formulation rather than frequency domain approach which is well known as state space approach. Using this approach linear time-invariant controllable and observable system can be designed to achieve any target to a great degree of accuracy by state feedback control methods. The design of system regulators based on the classical control theory, in general may not give optimal system performance, where as the regulator designed using optimal control theory on the other hand, enables the designers to have optimal system design with respect to given performance criteria.

1.5 Automatic Generation Control

Automatic Generation Control (AGC) is defined by IEEE [9] as "**The regulation of the power output of electric generators within a prescribed are in response to changes in system frequency, tie-line loading or the regulation of these to each other, so as to maintain the scheduled system frequency or the established interchange with other areas within predetermined limits**". AGC has evolved rapidly from the time when the function was performed manually, through the days of analog systems to the present application of sophisticated direct digital control systems. The AGC problem has been extensively studied during the last four decades. Most of the work concentrates on the net interchange tie-line bias control strategy making use of the area control error (ACE). The existence of ACE means that there is excess or deficient of spinning stored energy in an area and a correction to stored energy is required to restore the system frequency to scheduled value.

Many authors have reported the early work on AGC. Cohn [5] has extensively studied the static aspect of the net interchange tie line bias control strategy. On the static analysis basis Cohn has inferred that, for the minimum interaction between control areas, the frequency bias setting of a control area should be matched to the combined generation and load frequency response of the areas. However, no analysis has been made regarding deciding the magnitude of gain settings for the supplementary controllers.



Figs 1.2 BLOCK DIAGRAM OF AGC

Work reported in literature on AGC pertains to either two-area thermal-thermal or hydro-hydro or combination of these two but there is no or very little work on AGC for multi generation thermal system, hydro system and gas system. In a mixed power system, it is usual to find an area regulated by hydro generation or gas generation or in combination of both.

In the present work, Integral controller and optimal control design are used to restore the frequency to its nominal value and their dynamic responses are compared for system consisting of thermal, hydro and gas based generation.

1.5.1 Objectives of AGC

The basic role if AGC is to maintain the desired Megawatt output of a Generator unit and assist in controlling the frequency of larger interconnection. The AGC also helps to keep the net interchange of power between the pool members at predetermined values. Control action applied should be such that the different Characteristics of units of various types (thermal, hydro, nuclear etc.) are taken into Account. The AGC plays an important role in an interconnected power system to carry out the following objectives:

- Each area must regulate its own load disturbances, if possible.
- Each area must be contributed to the control of the system frequency.
- In steady state, frequency and net tie-line interchanges must return to scheduled values in all areas.

AGC earlier called as LFC (Load Frequency Control), is essentially a Controlling link between the dispatch offices of an area. The last two of the above Objectives are achieved by designing an efficient load frequency control (LFC) System. The first function involves another set of control session namely active Power dispatch. These two sets of control action help to maintain the active power generation in the system at economically optimum levels. There is also a need to maintain a balance between the reactive power generation and the reactive power demand on the system and to ensure a proper dynamic stability of the system operation. The various generators are generally usually equipped with automatic voltage regulators (AVR) in order to meet these two requirements.

1.5.2. LOAD FREQUENCY CONTROL (SINGLE AREA CASE)

The most common power system control objectives are regulation, optimization and stabilization. The power system control analysis depends on simulation of system dynamic behavior. Simulation implies the existence of mathematical models for specific power systems. The mathematical model generally includes the components of the power system that influence the electrical and mathematical powers of the machines. Automatic Generation Control (AGC) was developed to both maintain a (nearly) constant frequency and to regulate tie line flows. This is done through the Load-Frequency Control (LFC). Load Frequency Control in electric power system represents the first realization of a higher-level control system. It has made the operation of interconnected systems possible and today it is still the basis of any advanced concept for guidance of large systems. A peculiarity of LFC lies in the fact that each partner in the interconnection has equal rights and possibilities being limited only by the installed power in the area and the capability of the tie-lines: thus it is not a centralized control system when total interconnection is considered.

Before moving into the interconnection system let's first consider the single area network. To understand the model we should know the turbine speed governing system as frequency changes depend on speed.

1.5.3 Load Frequency or Real Power Control

Real power control is also referred to as Megawatt frequency or p.f. control. The aim of this control is to maintain real power balance in the system through control of system frequency. Whenever the real power demand changes, a frequency change occurs. This frequency error is amplified, mixed and changed to a command signal which is sent to the turbine governor. The governor operates to restore the balance between the input and output by changing the turbine input. Load frequency control (LFC) has gained in importance with the growth of Interconnected systems and has made the operation of interconnected system Possible. Today, it is still the basis of many advanced concepts for the control of large systems.

1.5.4 Automatic Voltage or Reactive Power Control

Reactive power control is also referred to as MegaVar voltage or QV Control. The aim of the control is to maintain the system voltage between limits by adjusting the excitation of machines. The automatic voltage regulator senses the differences between a rectified voltage derived from stator voltage and a reference voltage. This error signal is amplified and fed to excitation circuit. The change of excitation maintains the Vars balance in the network.

The above two control channels operate more or less independent of each Other. Moreover the p.f. loop is rather slow in action due to inertia of mechanical parts whereas the QV loop is very fast. The methods developed for control of individual generators, and eventually control of large interconnections, play a vital role in modern energy control centers (ECC). Modern ECC are equipped with on-line computers performing all signal processing through the remote acquisition systems known as supervisory control and data acquisition (SCADA) systems.

1.6 Objective of the Dissertation

We have the following objectives in the present report.

- We have to study the dynamic performance of an interconnected power system The system to be considered is a 2-area interconnected power system with non-reheat and reheat thermal-thermal identical power plants having 1% step load disturbance in either area and optimal AGC regulator design using full state vector feedback control strategy has to be considered. The effectiveness of the considered optimal regulator design has to be demonstrated
- We have to study the effect of incorporating HVDC link on the system Performance. System interconnection has to be considered as EHVAC link Only, HVDC link only and EHVAC link in parallel with HVDC transmission Link. Also, the HVDC link power flow (ΔPdc) has to be considered as a state Variable and as an additional control variable.

1.7 Conclusion

In this chapter, the role of power system engineers, operating states and control problem associated with power system has been introduced. Further, role and objectives of automatic generation control (AGC) has been illustrated.

Chapter 2

Literature Review

2.1 Introduction

The industrial growth of a nation requires increased consumption of energy, particularly electrical energy. This has led to increase in the generation and transmission facilities to meet the increasing demand. In U.S.A., till the early seventies, the demand doubled every ten years. In developing countries, like India, the demand doubles every seven years which requires considerable investment in electric power sector.

The imperative of supplying energy at reasonable costs coupled with the depleting reserves of non- renewable energy has led to the establishment of remote generation stations- predominantly fossil- fuel fired thermal stations. Environmental considerations also sometimes dictate the sitting of power stations at remote locations. Large hydro stations are invariably at distances of hundred of kilometers from load center. The need to economize on costly investments in generation mixes and load patterns have given rise to interconnection of neighboring system and development of large power grids.

Remote generation and system interconnection lead to a search for efficient power transmission at increasing power transmission levels. The increase in voltage level is not always feasible. The problem of ac transmission particularly in long distance transmission particularly in long distance transmission, has led to the development of DC transmission .However, as generation and utilization of power remain at alternating current, the DC requires conversion at two ends, from AC TO DC at the receiving end. This converter are static- using high power thyristors connected in series to give the required voltage ratings .The physical process of conversion is such that the same station can switch from rectifier to inverter by simple control action, thus facilitating power reversal.

2.2 EHVAC Ring

The highest existing EHVAC transmission system consists of a fairy strong network of 400kv lines and associated substations. It is possible, and is being attempted, to interconnect adjoining regional grids by building rather short 400 kV lines at boundaries. At present, it is not possible to operate regions interconnected in this fashion as uncontrolled power flow takes place on such links due to difference in operating frequency of the interconnected grids. Since the existing RLDCs are not equipped to bring about effective grids control and discipline, practically it seems impossible to achieve the objective. Moreover, due to limited power carrying capacity of 400kV lines, it is impossible to realize a reliable ring -main system.

There is another possibility of having a national ring main system comprising 735/765/800 kV lines. As a matter of fact, there are few 765 kV lines under construction and some of which initially are to be operated 400 kV. But the extent of 765kv network required forming a kind of national ring main on regional basis.

2.3 HVDC Ring

There are number of bulk power HVDC transmission system in operation, under medium and long term planning. These systems are very strong and involve long intra and regional distances. One attractive could be to transform the existing and upcoming HVDC system into a backbone national ring - main system by adding a few missing links, modern control and communication systems.

The HVDC ring will become a kind of overlay EHV transmission system for 400 kV AC network .There will be some definite advantages of an HVDC ring - main system, such as

- Short circuit level will be contained, thereby obviating the need for either replacement of existing 400 kV equipment rated for 40 KA, or putting series reactors.
- Full control over power flow, which can be exercised either through individual HVDC link control system and /or form RLDCs and national load dispatch centre (NLDC).
- Possibility of forced stabilization of the national grid in the event of disturbance through various ' defence plans’; Isolation of regional grids will be possibly by safe blocking , in case of proliferation of a grid distribution.

2.4 Hybrid Ring

After the different regional grids stabilize in term or there operating parameters, the interconnection through 400 kV AC lines at the regional boundaries can be done smoothly without creating any problem in the operation of the concerned grids. Such a regional interconnection can co- habit with an HVDC ring -main .During the period when such an interconnection is not possible, already implemented HVDC back -to -back links will serve the purpose of interconnection on a small -scale power exchange basis.

2.5 POWER SYSTEM INTERCONNECTIONS USING HVDC Links

2.5.1 Introduction

There are many reasons for the interconnection of power systems, including differences in demand (daily or seasonal), generation versus load imbalances, optimization of generating capacity reserves, CO2 credits and differences, in energy prices. In the early days the small generally vertically integrated utilities connected with their neighbors, using extension of the AC systems, to better utilize their resources. Such interconnections were of limited geographical extent 1950’s and 1960's transmission technologies development that allowed longer distance and higher power interconnections. These technologies, mainly higher HVDC voltages, coupled with series compensation, and HVDC were to a large extent developed for the connection of remote hydro- electric generation, but they also served for the interconnection of power system including the use of submarine cables. Development at that was most concentrated in North America and Europe. But followed in many parts of the world John Graham, Geir Biledt and Jon Johansson [23] have given the following reasons for using HVDC for transmission

Interconnections; however it is important to remember that this interconnection operate in an environment of predominantly AC transmission. HVDC interconnections are employed both within and to connect synchronous areas, and so complete with EHVAC, which has modern devices available to ensure satisfactory performance. One notable

AC interconnection is the Brazilian North-south link, which connects two large areas and uses a high degree of series compensation, including thyristors controlled series capacitors.

2.5.2 WHY HVDC?

Keeping in mind that the majority of power system transmission is using EHVAC and that this is undoubtedly very successful, we need to ask under which circumstances we should use HVDC. In case of long distance, over land or submarine, an issue is economic, the question of saving on lines or cables to cover increased station costs. However this often secondary to other consideration such as environmental impact or the controllability of HVDC. This advantage can be used for solving any of a number of challenges by the use of HVDC:

- Interconnection of systems employing power/frequency regulating characteristics not compatible with synchronous connection.
- Avoiding undesirable loop flows in parallels AC transmission lines.
- Control of interchanges, possibly with additional signal, to ensure system stability margins are kept.
- Controlling the power flow and avoiding overloading to prevent cascading trips, thus limiting system break-up under severe contingencies.
- Limit short circuit increase.
- Give controllable reactive power support for long AC lines in case of capacitor commutated converters or voltage source converters.
- Avoid voltage collapse by dynamic support to increase stability margins in case of HVDC lights.

The above technical advantages, when combined with the economical or environmental advantages given by less costly lines or cables, reduced right-of-ways and lower level of electromagnetic fields, conclude that HVDC gives many benefits for transmission interconnections.

2.6 Automatic Generation control strategy

The history of automatic generation control strategy has started with the control strategy has started with the control of frequency of a power system, via the flywheel governor of the synchronous machine. When this technique was subsequently found to be insufficient, a supplementary control was joined to the governor with the help of a signal directly proportional to the frequency deviation plus it's integral. Conventional AGC techniques were based on tie-line bias control which was based on two variables are weighted together by a linear combination to a single variable called area control error. The feedback gains selected in conventional control scheme are not based on any specific, but are calculated on the basis of operating experience. The study of the AGC schemes can be classified based on the

2.6.1 Types of power system models

- **Linear models**
- **Non- linear models**
- **Continuous and discrete models**

Over the last two three decades, most of the work carried out on AGC problem has been to considered a linearized two or multi area power system model. Elgerd and Fosha[2] presented work on AGC of a two year power system using a linearized two area power system model consisting of none reheat thermal power plants a considerable work has been done by other researchers on AGC of two area interconnected power systems consisting reheat /non reheat thermal plants. A number of research articles have also been reported regarding AGC regulator designs and dynamic system performer’s assessment of hydro thermal plants. the frequency and tie-line power responses of a two area hydro thermal systems with fixed gain settings of conventional integral controller where investigated by Kirchmayer[36] .P.kumar and co – workers[8] have comprehensively investigated the feasibility of suboptimal AGC regulators for a two areas hydro thermal power system using output vector feedback as well as limited state feedback control strategy.

However, only a limited number of research papers can be found for AGC of interconnected power system with system models including non linearity has compared to those that considered linear models of the power system. Although small signals analysis is justified for studying system response for small perturbations, it is essential to compensate for system non -linearity when operating over a wide range of operating conditions. More over, the implementation of control strategy design by considering linearized model on an essentially non-linear system do not insure of the system under large perturbations. E.B. Shahrodi and A. Morched [9] have studied the dynamic behavior of AGC system incorporating the effect of system non-linearity .They highlighted the assessment of the effects of non linearity according to the position in the control loops. It was revealed that the advisor effects on the non-linearity are pronounced than the linear model at operating point as lightly damped critical modes. The effect of non - linearities can be minimized by increasing the damping of these modes.

Most of the work reported so far concerning AGC of interconnected power Systems involve continuous times power system models. The development of Digital computers motivated the researches to used digital control schemes, which are inherently discontinuous processes. For this an AGC regulator designers has to resort to the discrete time analysis for optimism of the AGC strategies. The area control error representing generation mismatch in an area can be derived in discrete mode by sampling the tie-line power and systems frequency and then transferring over the telemetering links. Unlike the continuous – time system, the control vector in the discrete mode constrained to remain constant between the sampling instant. BOHN and MINIESY [6] have analyzed effect of the sampling period on the system dynamic performance using discrete model of a single area power system. Later on M.L.KOTHARI and co workers [11] have study the AGC in discrete mode of two area reheat thermal system with new area control error.

2.6.2 Control technique

- **Classical Control technique**
- **Optimal/sub optimal control technique**
- **Modal Control technique**

The amount of work reported the AGC interconnected power systems using the classical Control theory is limited. The regulators designs based on Classical Control theory is limited to its systems having single input and single output formulation. Elgerd and Fosha[2] and others had presented their work on AGC which were essentially concerned with the classical approach to determine the optimum integrator gain for area Control errors. M.L.Kothari and co workers [11] have studied some aspects of sample data AGC of two area power system with the controller based on classical control approach. The investigations carried out reveal that this will result in relatively large overshoot and transient frequency deviation.

The Classical Control theory which uses frequency response methods such as Nyquist, bode and root locus methods, leads to the system that are stable and satisfy a set of more or less arbitrary performance requirement. Such systems are in general, not optimal in any meaningful sense. As modern MIMO power system more and more complex, the classical control theory, which deals with SISO systems, become entirely power less for MIMO system. How ever, the approach using modern control theory permits to cop with the increased complexity of modern plants. The recent developments in modem control theory are in the direction of the application of optimal Control theory to the power system control problems. The design of AGC regulators based on classical theory is generally based on trail and error procedure, which is general, will not yield an optimal system performance. A wide range of research papers are available on optimal controller designs. The optimal controllers are based on the control law which is a function of all states of the system, and since all the system states are not accessible and measurable, the implementation of such regulators imposes the practical problems. The idea of suboptimal controllers design came about to overcome this problem imposed by optimal controllers. An AGC regulator design technique based on the output vector feedback control strategy has been used, treating the problem as a output zeroing problem and making use of matrix minimum principle by K.Venkateswarlu and A.K .Mahalananbis [7].

The regulator designs using models control theory have also been proposed for analyzing the AGC systems. Based on the state -augmentation approach of Tripathy and Davison [4], the AGC regulator designs have been proposed using modal control theory and the performance of these regulators was compared with those obtained with regulator design using optimal control theory .A non-linear optimization technique has been applied to achieve the desired location for AGC problem of a multi area power system incorporating a dc link.

2.6.3 AGC implementation strategies

- **Centralized control strategy**
- **Decentralized control strategy**
- **Multilevel control strategy**

In the early days, the tie line bias control used to be implemented by assuming that area may be considered in isolation so that the area control could be decided on the basis of the response characteristics of the area decoupled from the other areas.Elgerd and Fosha [3] assume the load disturbances to be known and deterministic. They proposed a proportional controller disregarding the steady state requirements and compensation of load disturbances. Many control strategies have been proposed on the basis of types of disturbances. The main limitation of the work presented small disturbances has been emphasized. The main limitation of the presented on AGC considering 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.

In view of the increasing power demands, modern power systems are growing in size to cope with the increasing power demands. Hence, in view of the limitations mentioned power earlier, it is difficult to implement the AGC algorithm in a centralized manner. There is a wide range of research papers available on the decentralized AGC control strategy for large scale continuous and discrete time systems. Decentralized AGC control strategies have been proposed by reconstructing measurement matrix for a two area hydrothermal power systems by P.Kumar and his fellows [8]. An appreciable amount of research work has been contributed by M.Aldeen [12] relating the decentralized LFC of interconnected power systems considering the different aspects of the problem.

A multilevel system approach has been applied to design AGC strategies. Using singular perturbation theory a linear optimal AGC regulator design based on multi-time scale approach has been reported. A two-level sub-optimal controller has been proposed by Bohn and Miniesy [5].However, this approach does not ensure zero steady errors. Later, a multilevel finite optimal controller design has been reported which ensures zero steady errors.

2.7 Automatic Generation Control focused on Unit Control

When the concepts of automatic generation control (AGC) were the first developed, the only control loops was for the control area. Driving the measured control area net interchange to a given scheduled value scheduled values was the control objective and raise and lower contact closures actuating governor speed changer motors was simultaneously broadcast to each unit on control even through the duration of each pulse could be manually adjusted to recognize individual unit size and/or ability to regulate. Generation was blindly raised or lowered to force net interchange to the desired value.

To complete the design of this early area controller, a frequency dependent bias for the scheduled net interchange was developed that modeled the change in area actual net interchange caused by area governor response and load change due to deviation from normal system frequency. This allowed AGC (supplemental control) to position unit governor speed changers so that when system frequency returned to the proper level via governor control; i.e., without supplemental control. This area tie-line bias control mechanism has been in constant use ever since with slight modification for continuous time error correction.

Through the years, unit output control loops were added to AGC and power plant computers that control unit output and digital governors were added to the overall control scheme (sometimes unsuccessfully) but the basic of performing area closed loop control has remained unchanged.

The paper presented by R.K Green [14] takes the basic objective of area control recognizes the availability of unit control mechanisms, and transforms ACG into a form that allows the focus to be on unit control rather than area control. The approach taken is to define a typical AGC process, simplify it to its most fundamental elements, redistribute terms within the basic equations and then add back features to the transformed process. The resultant AGC adheres to the same fundamental principles as classic AGC but from a different view point.

The advantages that transformed AGC has over conventional AGC are summarized as: Current AGC use global interconnected system frequency (which a single control area cannot control) as a driving force for both the area and unit control loops. This often causes unit response to response to frequency deviations that are unnecessary and undesirable. Transformed AGC eliminates the need for frequency as an input variable, using only local area measurements and schedules to drive the proportional control. Integrated system frequency and tie-line measurement errors are handled as after -the-fact correction terms. By eliminating frequency (and bias estimates) from the control loop, transformed AGC provides steadier system frequency and smoother unit control. A governor set point or coordinated controller set point is a 60 Hz set point by design. Conventional AGC often sends the wrong set point value (a target for actual generation) to the unit 60 Hz set value, thereby improving the AGC/plant interface and enhancing system control. Transformed AGC is compatible with conventional AGC while others use conventional AGC. For system frequency to have significant portion of interconnect would need to use the new process.

2.8 Automatic Generation Control in Deregulated Power system

Load frequency control (LFG) is used for many years as part of the automatic generation control (AGC) in the power stations around the world in the synchronous Nordic power system however; this function (termed secondary control) has so far been handled with manual control actions. Increased operational strain due to new HVDC connections in the next decade (1998) will make it increasingly difficult to maintain the current manual control system. In the paper presented by B.John, H Backen and ove S.Grade [16], a model of the interconnected power system of Norway and Sweden is used to show how introduction of AGC might aid the system operator in handling the increase strain. However, the classical LFC based on the area control error (ACE) is difficult to implement in a deregulated environment. An alternative concept is thus introduced where selected unit are automatically following load changes on the HVDC connections.

2.9 .Automatic Generation Control for DC Link Power System

This paper has been presented by G.Fujita; G. Shirai and R.Yokoyama [21].The paper discusses load frequency control (LFG) with HVDC. So far, automatic generation control (AGC) has been focused on economic dispatch control and load frequency control especially the latter is mainly on frequency stabilization for AC-link network systems. However the upcoming power electronics based HVDC transmission system of new aspects for the improvement of frequency control.

In the present paper, 2 area and 3-area network have been used to discuss how a HVDC interconnected system works to improve frequency fluctuation for random load disturbance. Because DC interconnection provides an adequate if the control gain is tuned properly. However, it has been observed that the effect differs by geometrical differences. To discuss the effectiveness of HVDC link for frequency control (LFC), the HDVC link has been used for designed for Hokkatdo-Honshu link in Japan and also proposed for Minami-Fukumitsus link in Japan. The simulated load fluctuation model has been constructed to demonstrate actual loads behavior.

It has been observed that in AC interconnected power systems, the HVDC link connecting two of the local systems does not provide frequency improvement since power exchange has been already achieved on the links. However, if two isolated power systems are interconnected, the HVDC link will make the important role to sustain the frequency deviation within regular tolerance even if the capacity is very small compared to those of two systems, these acts as a single system and the disturbance to the smaller system is cancelled as a tiny disturbance of the whole system.

2.10 Recent philosophies of AGC

Modem power generation control areas consist of large power plants and many industrial customers. High quality supplies of the electricity increases the demand for automatic generation control in electric power network. For quickly satisfying the large load changes or other disturbances and enhancing the safely of the power system, the feed for ward strategy and the non-linear governor-boiler model in automatic generation control are investigated by Li Pingkang and Mayongzhen [17]. Some new concepts some as developing new algorithm for more effectively control; considering the whole boiler-turbine-generator model instead only the governor- boiler model for the load disturbances; understanding interaction between the fast area control error loop and slow governor boiler inner loop, have been discussed. Simulations of the automatic generation control with feed forward PI controller have shown that these ideas are helpful to the automatic generation control realization. Various control aspect concerning the AGC problem have been highlighted by Ibraheem, P.Kumar and co workers [26]. AGC schemes based on parameters, such as linear & non-linear power system models, classical and optimal control, centralized & decentralized, and multi level control, has been discussed by them. AGC strategies based on digital, self tuning control, adaptive, VSS systems, and intelligent/soft computing control have been shown. Finally, the investigations on AGC systems incorporating BES/SMES, wind turbines, FACTS devices, and PV systems have also been discussed.

The fuzzy controller was integrated in to the existing off the shelf AGC system with only a few modifications. The operational performance over two years showed an overall improvement of 50% in the reduction of control compared to the original AGC controller and an initial improvement of 20% in the quality of control of the optimized original controller. A novel approach of artificial intelligence (AI) techniques viz., fuzzy logic, artificial neural network (ANN)and hybrid fuzzy neutral network (HFNN) for the AGC has been presented by D.M.Vinod Kumar [18] .The result shows that hybrid fuzzy neutral network (HFNN) controller has a better dynamic response i.e. quick in response , reduced error magnitude and minimized frequency transients.

Conclusion

A review of the literature available in the area of power system operation and control has been taken. The various aspects of HDVC and its needs in the interconnected power system have been shown. Feasibility of HVDC transmission ring in India has been discussed. Later on, AGC strategy and some recent trends in its area have been emphasized.

Chapter 3

Problem formulation & Modeling

3.1 Description of the Problem

Automation Generation Control (AGC), earlier called as load frequency control (LFC), is essentially a controlling link between the dispatch offices of an area. AGC is necessary for proper operation of an interconnected power system. In modern large interconnected power system networks automatic generation control equipments installed on each generator. The AGC system is feedback control whose task is to control or maintain the net interchange and frequency at scheduled values. The generator outputs, tie-line flows and frequency are measured with set point and adjusted to correct the errors in the control quantities accordingly. In an interconnected power system, the role of AGC is to divide the leads among system stations, and generators so as to achieve maximum economy and correctly control the scheduled interchanges of tie-line power while maintaining a reasonably uniform frequency.

Here, we have to study "**Automatic Generation Control of interconnected Power system**". The study incorporates the investigations with two area interconnected consisting of identical plants with non-reheat and transmission link, HVDC transmission link with Pdc as state Variable as well as Control Variable and EHVAC/HVDC transmission link with Pdc as state Variable as well as Control Variable. The HVDC transmission links considered to be operated in constant current control mode. The time response plot for frequency deviation, EHVAC tie-line power, HVDC tie-line power and control error of both the areas have to be obtained by implanting optimal AGC regulator using full state vector feedback 1% step load disturbance has to be taken in one of two areas. Two types of controllers proportional (P) and proportional plus integral (PI), have to be incorporated. The dynamic performance of the system has to be observed on basics response obtained. Also closed loop system Eigen values have to be computed to study the closed loop system stability. After investigating the control strategy which produces the better dynamic performance of the system. Same responses have to be obtained for the suboptimal AGC case using output vector feedback. In this case to, 1% Step load disturbance in one of the two areas has to be considered.

3.2 Modeling –An Introduction

The widespread application of automatic voltage regulators and fast acting governors is posing many problems for successful operation of power system. In spite of the considerable number of simplifying assumptions & approximations, the mathematical analysis of such complex system is a difficult matter. The difficulties are encountered both in setting up the initial differential equations & in their solution and the resulting calculation are very tedious to obtain the desired solution.

The method of all small oscillations when applied to check the steady state stability of a system containing several stations with automatic excitation system required the solution of equations involving many unknowns resulting time consuming calculations connected with transient process initiated by sudden change of operational conditions require much care full work when a step by step methods used to solve the non-linear equations. Even an experienced calculator may take 400 to 500 hours to carry out an analysis of transient stability of simple system containing two controlled stations and a load.

The complexity of calculations increase so much with a large number of stations that it becomes impossible to apply the analytical methods by ordinary/ annual computation. Still great difficulties are faced when newly designed components are to be added to an installation.

Nevertheless, such problem arises and requires an engineering solution. The out lies in the application of models which are of great value in helping to formulate the equations describing the process under investigation. Mathematical models, in their turn, remove many difficulties arising in the solution of such equation by ordinary mean.

Mathematical model gives the mathematical description of the dynamic characteristics of the system. After mathematical model has been completed; the control engineering simulates the model on a computer to test the behavior of resulting system in response to various singles and disturbances. Here in our project work we have used mathematical modeling to analyze automatic generation control strategies.

3.2.1 Governor – Turbine Control

The prime sources of electrical energy supplied by utilities are the kinetic energy of water and thermal energy derived from fossil fuels. The prime movers convert these sources of energy into mechanical energy that is, in turn, converted to electrical energy by synchronous generators. The prime mover governing systems provide a means of controlling power and frequency, a function commonly referred to as load frequency control.

In a steam turbine the stored energy of high temperature and high-pressure steam is converted into mechanical (rotating) energy, which then is converted into electrical energy in the generator. The original source of heat can be a furnace fired by fossil fuel (coal gas, or oil) or biomass, or it can be a nuclear reactor. It is the task of the turbine governor to control the control valve such that the generator in question produces the desired power. The turbine governor and the dynamic properties of the turbine determine the power produced by a generator.

To make more realistic studies, appropriate mathematical models of steam turbines [6, 10, 11] e.g. reheat, non-reheat steam turbines, hydro turbines [11, 20, 21, 26] and gas turbine [15, 16] are to be considered for the dynamic simulation of the system behavior. The important component for controlling the speed of the turbine is the governor. Governor for each system differs from other. Transfer function models for these turbine governors of references are used for the studies undertaken in this report.

This section gives an overview of the modeling of turbines based. Figure2.1 below shows a block diagram how these turbine models that are used in study in the system models.

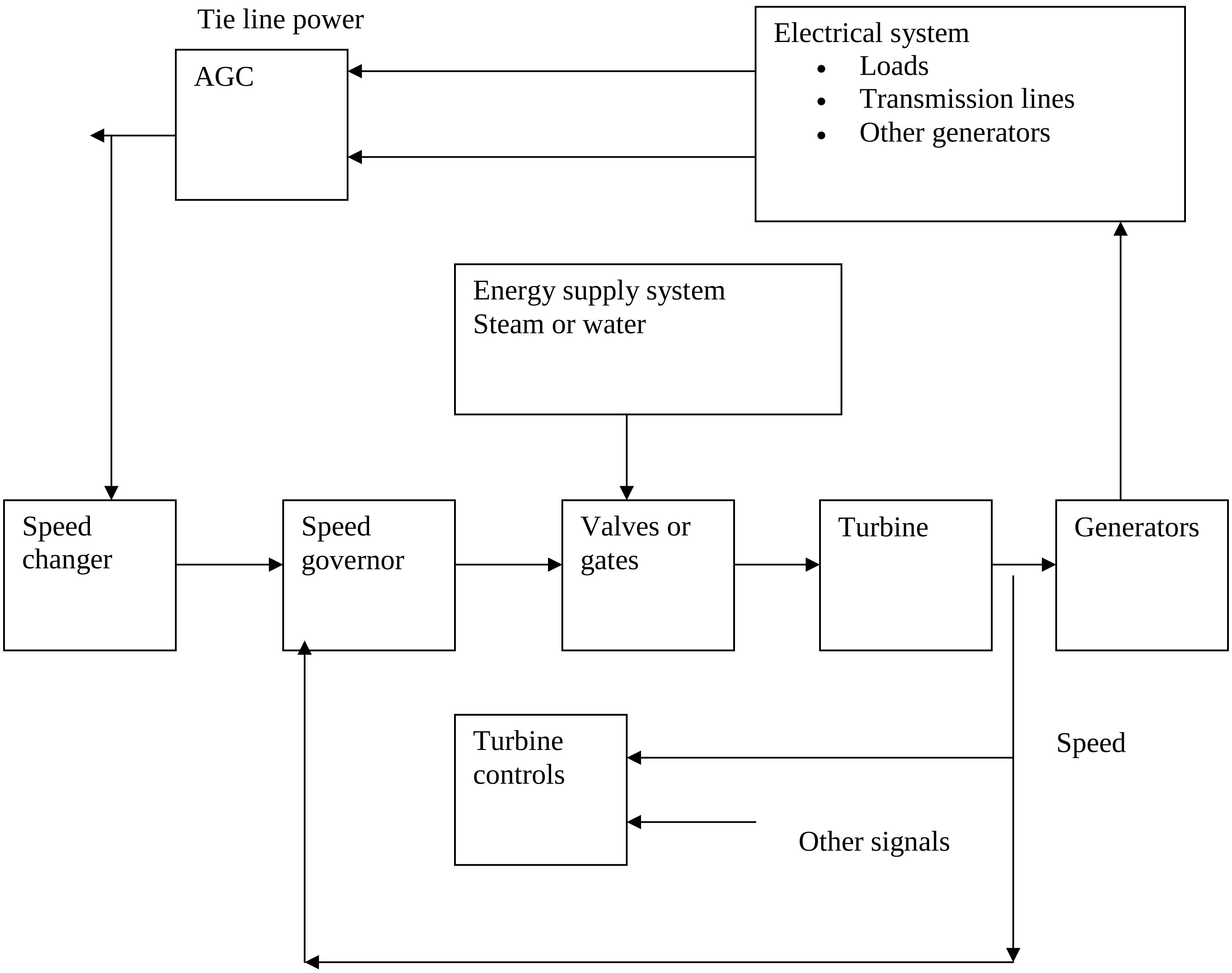


Fig. 3.1 Functional block diagram of power generation and control system

3.2.2 Speed Governor Model

The transfer function of speed governor (see appendix) is given by the equation 3.1 below:

$$\Delta Xg(s) = \left[\Delta Pc(s) - \frac{1}{R} * \Delta F(s)\right] * \left[\frac{Kg}{1 + sTg}\right] \qquad \text{…………………..…………….. (3.1)}$$

Where,

R= Speed regulation of the governor (Hz/p.u.MW)

Kg= Gain of speed governor (typical value 1)

Tg= Time constant of speed governor (typical value 100 milli-secs)

The block diagram representation of the above transfer function is shown in fig 3.1.

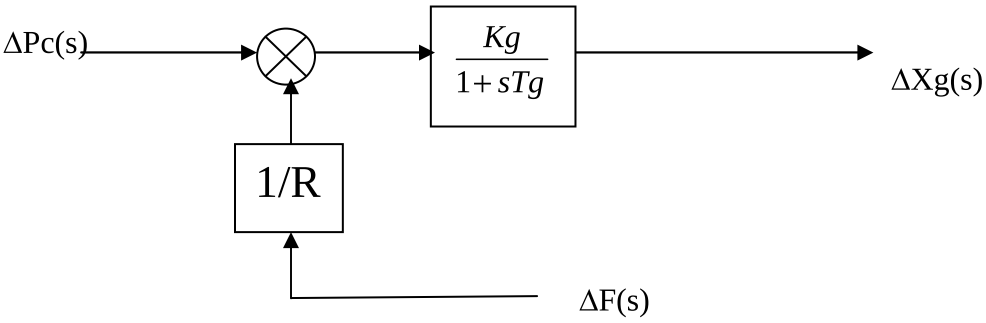


Fig. 3.2 Block Diagram of speed Governor Model

3.2.3 Turbine Model

We can categorize the turbine the turbine in two ways:

i) Non-Reheat Turbine

This type of turbine has only one time constant (as the reheat stage is absent) and its transfer function is given by the equations 3.2 below:

$$\Delta Pg(s)=\Delta Xg(s)*\left[\frac{Kt}{1+sTt}\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.2)$$

Where,

Kt= Gain of the turbine (typical value 1)

Tt =Time constant of turbine (0.2 to 2 secs)

The block diagram representation of the above transfer function is shown in fig 3.2.

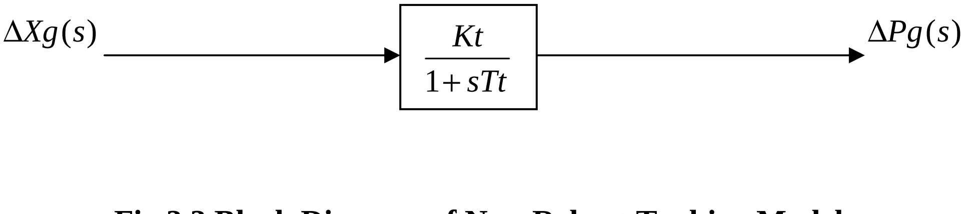


Fig 3.3 Block Diagram of Non-Reheat Turbine Model

ii) Reheat Turbine

This type of has two time constants, one time constant is due to turbine and the other one is due to presence of reheated. The overall transfer function is given by the equation 3.3 below:

$$\Delta Pg(s) = \Delta Xg(s) * \left[\frac{Kt}{1+sTt}\right] * \left[\frac{1+sKrTr}{1+sTr}\right] \quad \text{……………………………….. (3.3)}$$

Where,

Kr=C= Reheat coefficient of the turbine (0.25 to 0.5)

Tr =Time constant of reheater (3 to 10 secs)

The block diagram representation of the above transfer function is shown in fig 3.3.

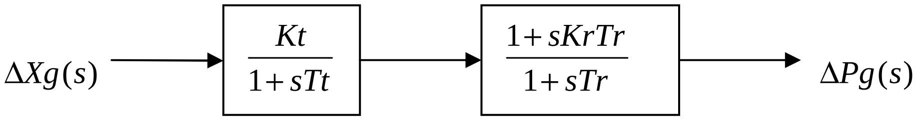


Fig 3.4 Block Diagram of Reheat Turbine Model

3.2.4 Generator Load Model

The transfer function of generator load (see appendix) is given by the equation 3.4 below:

$$\Delta F(s) = [\Delta Pg(s) - \Delta Pd(s)] * \left[\frac{Kp}{1+sTp} \right] \qquad \text{…………..………………………. (3.4)}$$

Where,

Kp=1/D= Gain power system (typical value 100 Hz/p.u.MW)

$Tp = \dfrac{2H}{f^{o} \;*\; D}$ = Time constant of power system (typical value 10 secs)

The block diagram representation of the above transfer function is shown in fig 3.4.

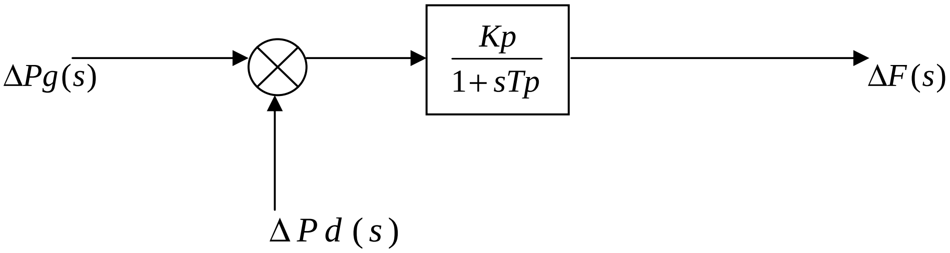


Fig. 3.5 Block Diagram of Generator Load Model

3.3 Transfer Function Model of $\Delta P\,tie$

The expression for total incremental tie-line power exported from area ‘I’ can be given as follows:

$$\Delta P\,tie\,i = \sum_{n=1}^{n} 2\pi T_{in}\left(\int \Delta F\,i - \int \Delta F\,n\,dt\right) \qquad \text{…………………}(3.5)$$

Where, ‘n’ represents the number of control areas.

Thus, for a 2-area case we have the following equations:

$$\Delta Ptie = 2\pi T_{12}\left(\int \Delta F1 - \int \Delta F\,2dt\right) \qquad \text{…………………………………}\ (3.6)$$

$$\frac{d}{dt}\Delta Ptie = 2\pi T_{12}\left(\Delta F1 - \Delta F\,2\right) \qquad \text{…………………………………..}\ (3.7)$$

Where, T_{12} is the synchronizing coefficient between the two areas.

However for the two identical interconnected power system areas we have

$$\Delta Ptie1 = \Delta Ptie \qquad \text{…………………………………..}\ (3.8)$$

$$\Delta Ptie2 = -\left(\Pr 1/\Pr 2\right) = a_{12}\Delta Ptie \qquad \text{…………………………………..}\ (3.9)$$

Considering the integral control actions for the design of optimal AGC regulator, the integrals of areas control error of both the identical areas are given as follows:

$$\left|ACE\right| = \int\left(\Delta Ptie + B_1\Delta F1\right)dt \qquad \text{……………………..……………}\ (3.10)$$

$$\frac{d}{dt}\left(\left|ACE\right|\right)=\left(\Delta Ptie+B_1\Delta F1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.11)}$$

Similarly for area2;

$$1ACE2=\int\left(a_{12}\Delta Ptie+B_2\Delta F2\right)dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.12)}$$

$$\frac{d}{dt}1ACE2=\left(a_{12}\Delta Ptie+B_2\Delta F2\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.13)}$$

In case of system interconnection as EHVAC in parallel with HVDC transmission link integral of area control error of both areas would also consider ΔPdc as shown in the following equations:

$$1ACE1=\int\left[\Delta Ptie+\Delta Pdc+B_1\Delta F1\right]dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.14)}$$

$$\frac{d}{dt}\left(1ACE1\right)=\int\left[\left(\Delta Ptie+\Delta Pdc\right)+B_1\Delta F1\right]dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.15)}$$

Similarly for area 2;

$$1ACE2=\int\left[a_{12}\left(\Delta Ptie+\Delta Pdc\right)+B_2\Delta F2\right]dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.16)}$$

$$\frac{d}{dt}\left(1ACE2\right)=\left[a_{12}\left(\Delta Ptie+\Delta Pdc\right)+B_2\Delta F2\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.17)}$$

Where, B_1 & B_2 are frequency bias constants of area 1 & 2 respectively.

3.4 Transfer Function Model of ΔPdc

The incremental power flow through HVDC link (see appendix) has been taken as a linear first order model with time constant Tdc. The transfer function is given by equation 3.18 below:

$$\Delta Pdc(s) = \left[\frac{Kdc}{1+sTdc}\right] * \left[\Delta F(s)\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.18)$$

Where,

Kdc = Gain of the HVDC link

Tdc = Time constant associated with HVDC link

The block diagram represented of the above transfer function is shown in fig 3.5

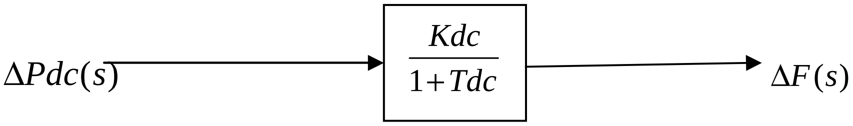


Fig 3.6 Block Diagram of HVDC Link

3.5 Control Area Concept

Let us consider a practical system with a number of generation stations and loads. It is possible to divide an extended power system (say, a national grid) into sub-areas (may be state electricity boards) in which the generators are tightly coupled together to form a coherent groups i.e, all the generators respond in unison to changes in the load or speed changer setting. Such a coherent area is called a “Control Area” in witch the frequency is assumed to be the same throughout in static as well as dynamic conditions. For purpose of developing a suitable control strategy, a control area can be reduced to a single speed governor, turbo generator and load system. The objective of the control strategy is to generate and deliver power in an interconnected system as economically and reliably as possible while maintaining the voltage and frequency within the permissible limits.

3.6 Automatic load Frequency Control Techniques

Depending on whether one or all the system have been assigned the job of maintaining the frequency constant and extent of tie line load required, the following methods are available for load frequency control of interconnected systems.

3.6.1 Flat Frequency Control

The job of maintaining the frequency constant is assigned to one machine or one station. This machine or station absorbs all the changes in the system load while all other machines carry constant load. There is no control on tie-line power and frequency controllers are used on only the master machine. On master machines, the frequency controller can detect a frequency change of the order of 0.005 Hz. Flat frequency control has the advantage that new and more efficient machines can be made to carry the base load and the less efficient machines can act as the master machines for taking up load changes. The main disadvantage of this type of control is that it results in random variations in tie line powers.

3.6.2 Flat Tie-Line Load Control

The aim of this control is keep the tie-line power constant irrespective of the load demands. The increase in demands of an area is met by increase in generation in that area. This control is used when a small and a large system are interconnected through a tie-line. The large system maintains the system frequency and the small system is controlled to keep the lie-line power constant. It is not suitable when two or more large system is interconnected because in such cases the tie-line power frequency deviation has a tendency to swing back and forth following a load change.

3.6.3 Parallel Frequency Regulation

In this mode, all areas of the interconnected power system are involved in the control strategy. All the areas respond to changes in load and regulate to maintain the frequency as a constant.

3.7 Automatic Generation Control Techniques

Automatic equipment permits various types of system control. The various methods discussed above can be performed with the help of automatic control equipments. It is obvious that automatic control is more convenient and efficient method. The following types of technique are commonly used in practical automatic schemes:

3.7.1 Selective Frequency Control

The common method of operation a large interconnected system assigns v control to a control system, are then controlled on the basis of the system frequency and tie-line. The tie-line loading as the basis of automatic control is used in different ways. One of these is known as the selective v control. Here each system in the group takes care of the load changes on its owns system and does not aid the other systems in the groups for changes outside it's owns limits.

3.7.2 Tie-Line Load Bias Control

This is the most commonly used method in which all the power system in the interconnection aid in regulating frequency of where the frequency changes originates. The equipment consists of a master load frequency controller and tie-line recorder measuring the power input on the tie, as for selective frequency control. The tie-line instrument biases the load frequency controller by changing the control point until the desired relationship exists between the tie-line loading and system frequency.

Conclusion

Description of the problems and various models involved has been discussed. Also, some definition regarding load frequency control techniques have been given.

Chapter- 4

AGC with Optimal Control Strategy

4.1 Introduction

It is technically feasible to operate the power system in an interconnected manner. The various areas of power pools are interconnected through tie-lines. These tie-lines are utilized for contractual energy exchange between areas and provides inter areas support in case of abnormal conditions. India has the largest assets of more than 40,000 kms of 400 KV AC lines in the world. Due to numerous merits of DC transmission system over AC, many DC transmission lines have been laid down in the world and many projects are sets for future. In India, trends are towards laying down linear length DC transmission systems for power exchanges between the control areas. The future structure of power systems may be very complex consisting of power pools with generations from hydro , thermal , nuclear and others non- conventional methods with different kinds of area interconnections like AC, DC and parallel AC/DC transmission systems.

The basic concept of the control problem of a system is to achieve the specific objectives for which the system is meant while operating within limitations imposed by physical and technical system constraints. The conventional classical control techniques, primarily based on the frequency domain analysis, are usually reserved for linear time invariant SISO systems are allow the designer greater freedom for intuition and experience. The modern control theory applies the timed domain approach for the problem formation, which is well known as state space approach. This approach is well suited for its real time implementation through digital computers and consists of some minimum set of variables which are essential for completely describing the internal status if the system. The regulator design using optimal control theory enables the designers to have optimal system design with respect to given performance criteria. The important feature of modern optimal control is the establishment of analytic performance index for the system and its optimization makes the system control more meaningful in the sense of its optimality.

4.2 Optimal AGC Regulator Design with Full State Vector Feedback

Let us take an S-area interconnected power system described by a completely controllable and observable linear time-invariant state space representation. The differential equations of the system are can be written as

$$\underline{\dot{X}} = A\underline{X} + B\underline{U} + \Gamma P d$$

$$Y = C\underline{X} + D\underline{U}$$

We find the control [U]opt, so as to minimize the performance index

$$J = \int_0^\infty \frac{1}{2}[X^T Q X + (U_{opt})^T R U_{opt}]dt \qquad \text{-------------4.3}$$

Where,

Q – a positive semi-definite symmetric state cost weighting matrix.

R – a positive definite symmetric control cost weighting matrix.

The right hand side of equation 4.3 accounts for the expenditure of the energy of the control signals. The matrices Q & R determine the relative importance of the error and the expenditure of this energy. In the equation 4.1 above, the term ΓPd is eliminated and the equation becomes as follows:

$$\underline{\dot{X}} = A\underline{X} + B\underline{U} \quad : \quad X(0) = X_0$$

Where, X (0) = X is the initial condition.

However, in equation 4.2, D is normally taken zero. Hence, equation 4.2 becomes,

$$\underline{Y} = C\underline{X}$$

Now, to minimize the performance index given by the equation 4.3, a control law is defined as

$$[\underline{U}]_{opt} = -K^{*}\underline{X}$$

Hence, in order to design optimal regulator so as to minimize the performance index, we have to solve the Matrix- Riccatti (MR) equation given as:

$$A^{T}P + PA - PBR^{-1}B^{T}P + Q = 0$$

By solving this equation, we get positive definite symmetric matrix P such that the optimal control law is calculated as

$$[\underline{U}]_{opt} = -RB^{T}P\underline{X}$$

And hence, the desired optimal feedback gain matrix will be

$$K^{*} = R^{-1}B^{T}P$$

4.3 Power System Model

The power system model selected here in this report is a 2-area interconnected power system consisting of identical thermal plants with non-reheat and reheat turbines. Here, we have taken three types of interconnections (i) only EHVAC transmission link, (ii) only HVDC transmission link, (iii) EHVAC link in parallel with HVDC transmission link as shown in Fig. 4.25. The HVDC link is assumed to be operated in constant current control (CCC) mode. The block diagram with transfer function representation is shown in Fig. 4.26 for parallel EHVAC/HVDC transmission link case. For EHVAC transmission link only, HVDC link has to be removed and similarly for HVDC transmission link only, EHVAC link has to be removed.

4.3.1 Case Studies

The investigations for interconnected power system models with optimal AGC regulators designed based on proportional (P) control strategy is not advisable in comparison to optimal AGC regulators designed based on proportional plus integral (Pl) control strategy. Since as the incorporation of HVDC link in power system model under considerations has resulted in a modified version of power system models which were used in earlier studies. Here, in our report we consider both the control approaches foe the power system model.

We have two categories, one for non-reheat thermal plants and other for reheat thermal plants. Then, k for each category we have two different control strategy proportional (P) and proportional integral (Pl). After this, for each of the above control strategy, we have, three types of interconnections i.e. EHVAC only, HVDC only and parallel EHVAC/HVDC transmission link. Also in HVDC link, ΔPdc (HVDC link power flow) has been considered in two ways i.e. ΔPdc as state variable and Δpdc as control variable. To sum-up, we have 20 different case studies as shown in 4 parts below:

(a) Non-Reheat Proportional (P) Control Cases

a1) System interconnection as EHVAC transmission link only.

a2) System interconnection as HVDC transmission link only, With Pdc as state variable.

a3) System interconnection as HVDC transmission link only, with Pdc as control variable.

a4) System interconnection as parallel EHVAC/HVDC transmission link, with Pdc as state variable.

a5) System interconnection as parallel EHVAC/HVDC transmission link, with ΔPdc as control variable.

(b) Non – Reheat Proportional Integral (Pl) Control Cases

(b1) System interconnection as EHVAC transmission link only.

(b2) System interconnection as HVDC transmission link only, with Pdc as state variable.

(b3) System interconnection as HVDC transmission link only, with Pdc as control variable.

(b4) System interconnection as parallel EHVAC/HVDC transmission link, with Pdc as state variable.

(b5) System interconnection as parallel EHVAC/HVDC transmission link, with ΔPdc as control variable.

(c) Reheat Proportional (P) Control Cases

(c1) System interconnection as EHVAC transmission link only.

(c2) System interconnection as HVDC transmission link only, with Pdc as state variable.

(c3) System interconnection as HVDC transmission link only, with Pdc as control variable.

(c4) System interconnection as parallel EHVAC/HVDC transmission link, with Pdc as state variable.

(c5) System interconnection as parallel EHVAC/HVDC transmission link, with ΔPdc as control variable.

(d) Reheat Proportional Integral (Pl) Control Cases

(d1) System interconnection as EHVAC transmission link only.

(d2) System interconnection as HVDC transmission link only, with Pdc as state variable.

(d3) System interconnection as HVDC transmission link only, with Pdc as control variable.

(d4) System interconnection as parallel EHVAC/HVDC transmission link, with Pdc as state variable.

(c5) System interconnection as parallel EHVAC/HVDC transmission link, with Pdc as control variable.

4.4 State Variable Model

The following assumptions have to be taken for the linear state space model of 2-area interconnected power system:

l. The system model representation is linearized about an operating point.

ll. The interconnection between the two power system areas is weak but within an area is strong.

1ll. The generators operating in area form a coherent group, hence each area is represented by an equivalent generator.

lV. Active power-frequency control loop is completely decoupled from reactive power voltage control loop and the node voltages remain constant.

V. Losses are neglected.

Vl. The HVDC link is considered to be operated in constant current control mode.

The state space representation of the system considered here can be given by differential equations 4.4 & 4.5 respectively. The associated vectors for case studies a1 to d5 are given as follows:

4.4.1 State Vectors

Non-reheat P case

$$[Xa1] = [\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Ptie]'$$

$$[Xa2] = [\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Pdc]'$$

$$[Xa3] = [\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2]'$$

$$[Xa4] = [\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Ptie, \Delta Pdc]'$$

$$[Xa5] = [\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Ptie]'$$

Non-Reheat, PI case

$$[Xb1] = \left[\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Ptie, \int ACE1, \int ACE2\right]'$$

$$[Xb2] = \left[\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Pdc, \int ACE1, \int ACE2\right]'$$

$$[Xb3] = \left[\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \int ACE1, \int ACE2\right]'$$

$$[Xb4] = \left[\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Ptie, \Delta Pdc, \int ACE1, \int ACE2\right]'$$

$$[Xb5] = \left[\Delta f1, \Delta f2, \Delta Xg1, \Delta Xg2, \Delta Pg1, \Delta Pg2, \Delta Ptie, \int ACE1, \int ACE2\right]'$$

Re-heat P Case

$$[Xc1]=[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Ptie]'$$

$$[Xc2]=[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Pdc]'$$

$$[Xc3]=[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2]'$$

$$[Xc4]=[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Ptie,\Delta Pdc]'$$

$$[Xc5]=[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Ptie]'$$

Re-heat PI Case

$$[Xd1]=\left[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Ptie,\int ACE1,\int ACE2\right]'$$

$$[Xd2]=\left[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Pdc,\int ACE1,\int ACE2\right]'$$

$$[Xd3]=\left[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\int ACE1,\int ACE2\right]'$$

$$[Xd4]=\left[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Ptie,\Delta Pdc,\int ACE1,\int ACE2\right]'$$

$$[Xd5]=\left[\Delta f1,\Delta f2,\Delta Xg1,\Delta Xg2,\Delta Pg1,\Delta Pg2,\Delta \Pr 1,\Delta \Pr 2,\Delta Ptie,\int ACE1,\int ACE2\right]'$$

4.4.2 Control Vector

[Ua1]= [ΔPc1, ΔPc2]’;

[Ua1]=[Ua2]=[Ua4]=[Ub1] =[Ub2] =[Ub4]=[Uc1]

[Uc2]= [Uc4] = [Ud1] = [Ud2] = [Ud4]

[Ua3]= [ΔPc1, ΔPc2, Δ Pdc]’;

[Ua3]=[Ua5] =[Ub3]=[Ub5]= [Uc3]=[Uc5] =[Ud3]=[Ud5];

4.4.3 Disturbance Vector

[Pd-a1]= [ΔPd1, ΔPd2]’;

[Pd-a1]=[Pd-a2]=[Pd-a3]=[Pd-a4]=[Pd-a5]=[Pd-b1]=[Pd-b2]=[Pd-b3]=[Pd-b4]=

[Pd-b5]=[Pd-c1]=[Pd-c2]=[Pd-c3]=[Pd-c4]=[Pd-c4]=[Pd-c5]=[Pd-d1]=[Pd-d2]=

[Pd-d3]= [Pd-d4]=[Pd-d5];

4.5 State Matrices

The state matrices in the state space representation can be obtained from the differential equations obtained from the transfer function model .We have shown state matrix for non- reheat, PI case (Table –A1) and reheat –PI case (Table-A2).All other state matrices for non-reheat P and PI case and reheat P & PI cases can be obtained from it by doing some manipulation as shown in Table –A3 and Table A-4 respectively.

4.6 Control Matrices

Similarly, in the same way, here we have shown the control matrix for non-reheat, PI case (B-b4) and reheat, PI case (B-d4). All other control matrices for non-reheat P & PI cases and Reheat p & PI cases can be obtained from it by doing some manipulation.

```
[B-b4]=[0,0,1/tg1,0,0,0,0,0,0,0;

        0, 0, 0, 1/Tg2, 0, 0, 0, 0, 0, 0;

        Kp1/Tp1, (a12*Kp1)/Tp1, 0, 0, 0, 0, 0, 0, 0, 0;]’


[B-d4]=[0,0,1/Tg1,0,0,0,0,0,0,0,0,0;

        0,0,0,1/Tg2,0,0,0,0,0,0,0,0;

        Kp1/Tp1,(a12*Kp1)/Tp1,0,0,0,0,0,0,0,0,0,0]’
```

4.7 Disturbance Matrices

As Discussed above, Here we have shown the disturbance matrix for non-reheat, PI case (Γ-b4) and reheat, PI case (Γ-d4). We have taken the symbol Γ as G. All other disturbance matrices for non-reheat P & PI cases and Reheat P & Pi cases can be obtained from by doing manipulation.

[Γ-b4]=[G-b4]=[-Kp1/Tp1,0,0,0,0,0,0,0,0,0;

0,-Kp2/Tp2, 0, 0, 0, 0, 0, 0, 0, 0]'

[Γ-d4]=[G-d4]=[-Kp1/Tp1,0,0,0,0,0,0,0,0,0,0,0;

0,-Kp2/Tp2,0,0,0,0,0,0,0,0,0,0]'

4.8 State Cost Weighting Matrix 'Q'

We have selected the cost weighting matrix 'Q' as an identity matrix of the proper dimension for each case study considered.

4.9 Control Cost Weighting Matrix 'R'

We have selected the control cost weighting matrix 'R' as an identity matrix. For each of the case study its dimension is taken as 2x2. However, for the cases where ΔPdc is taken as control variable, its dimension is 3x3.

4.10 Input Data

Pr1=Pr2=2000 MW;H1=H2=5 sec;
D1=D2=0.00833 p.u.Mw/Hz;
R1=R2=2.4 Hz/p.u.MW;
B1=B2=0.425 p.u.MW/Hz;
Kg1=Kg2=1.0;Tg1=Tg2=0.08 sec;

Kt1=Kt2=1.0;Tt1=Tt2=0.3 sec;
a12=-1;ΔPd1=0.00;
ΔPd2=0.01;

4.10.1 Data for Reheat Case

Because of the reheat action two more term, Proportional of the Torque produced by the high pressure unit of the turbine (C) and the time lag created by the reheater (Tr), would be included in addition to above data.

Kr1=Kr2=C=0.5;
Tr1=Tr2=10 sec;

4.10.2 Data for AC link

Pmax=200 MW (10% of Rated Power);
A=δ1- δ2=30 degree

4.10.3 Data for Dc Link

Kdc=1.0;
Tdc=0.2 sec;

4.11 Conclusion

The AGC regulator design approach based on optimal control theory has been introduced. Dynamic performance study of a 2 –area interconnected power system consisting of non-reheat & reheat thermal-thermal identical power plants has been carried out. Matlab package has been used for the simulation purpose. All the state, control and disturbance and disturbance vector and their respective coefficient matrix have been obtained for each case study.

CHAPTER -5

RESULTS

5.1 Simulation result

The program for simulation has been developed using Matlab package.The program developed all the 20 different case studies (a1-d5). All the cases can be access by giving proper input choice during the program execution (Program 1). All the state, control and disturbance vectors and their corresponding coefficient matrices can also be obtained. The inbuilt LQR command has been used to solve the Matrix-Rriccatti equation. Thus, Eigen values and optimum feedback gain matrices have been obtained.Also, a check for closed loop system stability has been provided. After obtaining the required matrices. Matlab function have been developed for each case.

5.2 Optimal Feedback Gain Matrices

The Optimal gain matrices obtained by solving Matrix – Riccatti equation through program 1 for all the 20 case studies are given bellow:

[K* -a1]= 0.6329 0.0144 0.6113 -0.0009 1.1180 -0.0054 -0.8648;
0.0144 0.6329 -0.0009 0.6113 -0.0054 1.1180 0.8648;

[K* –a2]= 0.4673 0.2924 0.5826 0.0735 0.9562 0.4004 -0.2055 -0.2114;
0.6421 0.5963 0.0735 0.5966 0.4758 1.0399 0.2052 0.2360;

[K* -a3]= 0.3184 0.3289 0.5455 0.0649 0.7364 0.3762;
0.3289 0.3184 0.0649 0.5455 0.3762 0.7364;
-0.7060 0.7060 0.0042 -0.0042 -0.2682 0.2682 ;

[K* -a4] = 0.4673 0.2924 0.5826 0.0735 0.9562 0.4004 -0.2055 -0.2114;
0.6421 0.5963 0.0735 0.5966 0.4758 1.0399 0.2052 0.2360;

[K* -a5]= 0.3151 0.3322 0.5452 0.0652 0.7349 0.3777 -0.0807;
0.3322 0.3151 0.0652 0.5452 0.3777 0.7349 0.0807;
-0.7385 0.7385 0.0068 -0.0068 -0.2573 0.2573 -0.4096;

[K* –b1] = 0.8855 -0.0291 0.6468 -0.0067 1.3349 -0.0415 -0.7190 1.0000 0.0000;
-0.0291 0.8855 -0.0067 0.6468 -0.0415 1.3349 0.7190 0.0000 1.0000;

[K* –b2] = 0.6918 0.2604 0.6172 0.0634 1.1612 0.3489 -0.2115 0.9975 -0.0704;
0.6097 0.8234 0.0634 0.6307 0.4229 1.2435 0.2592 0.0704 0.9975;

[K* –b3] = 0.4274 0.4290 0.5608 0.0793 0.8292 0.4642 0.5804 0.4196;
0.4290 0.4274 0.0793 0.5608 0.4642 0.8292 0.4196 0.5804;
-0.7442 0.7442 0.0006 -0.0006 -0.2879 0.2879 -0.6979 0.6979;

[K* –b4] = 0.6974 0.2597 0.6196 0.0632 1.1756 0.3469 -0.2531 -0.2275 0.9967 -0.0818
0.6192 0.7953 0.0632 0.6275 0.4230 1.2239 0.3001 0.2506 0.0818 0.9967

[K* –b5] = 0.4274 0.4290 0.5608 0.0793 0.8292 0.4642 0.5804 0.4196
0.4290 0.4274 0.0793 0.5608 0.4642 0.8292 0.4196 0.5804
-0.7442 0.7442 0.0006 -0.0006 -0.2879 0.2879 -0.6979 0.6979

[K* –c1] = 0.4890 0.0426 0.5430 0.0045 1.9970 0.0689 -0.2841 -0.0071 -1.1340;
0.0687 0.6669 0.0045 0.7065 1.1404 3.1237 -0.5425 0.1484 1.2896;

[K* –c2]= 0.3365 0.2959 0.5216 0.0644 1.5207 0.8325 -0.1617 -0.0274
-0.1006;
0.7854 0.5989 0.0644 0.6854 1.6129 2.8647 -0.4211 0.1514
0.0958;

[K* –c3]= 0.2161 0.2682 0.5079 0.0504 1.4198 0.6647 -0.1913 -0.0221
0.4364 0.3375 0.0504 0.6435 1.7298 2.3114 -0.5828 0.1665
-0.7398 0.7057 0.0209 -0.0396 -0.5237 0.1449 0.1318 -0.0281

[K* –c4] = 0.3390 0.2887 0.5225 0.0637 1.5144 0.8234 -0.1531 -0.0276
-0.098 -0.1180;
0.7750 0.5723 0.0637 0.6818 1.8262 2.8154 -0.5318 0.1534
0.0896 0.0893;

[K* –c5] = 0.2140 0.2697 0.5075 0.0506 1.3629 0.6679 -0.1644 -0.0223
-0.0327;
0.4363 0.3382 0.0506 0.6434 1.7817 2.3090 -0.6075 0.1669 -
0.0106;
-0.7684 0.7384 0.0223 -0.0392 -0.2107 0.1308 -0.0154 -0.0230
-0.4138;

[K* –d1] = 0.8078 0.0264 0.5736 0.0017 4.0095 0.0301 -1.1119 -0.0054
-1.2112 0.9943 -0.1067;
0.0512 0.9553 0.0017 0.7400 0.3209 3.5789 -0.1496 0.1376
1.1818 0.1067 0.9943;

[K* –d2] = 0.4549 0.3658 0.5335 0.0701 2.6998 0.9123 -0.6815 -0.0281
-0.1469 0.9579 0.2872;
0.9180 0.8332 0.0701 0.7135 1.4218 3.2445 -0.2857 0.1424

0.1917 -0.2872 0.9579;

[K* –d3] = 0.3223 0.3641 0.5161 0.0630 1.6562 0.8352 -0.2602 -0.0267 0.4447 0.2932;

0.5970 0.5042 0.0630 0.6657 2.0879 2.6072 -0.6858 0.1590 0.5139 0.6903;

-0.7947 0.7263 0.0167 -0.0371 -0.6475 0.1623 0.1727 -0.0266 -0.7335 0.6814;

[K* –d4] = 0.4621 0.3387 0.5357 0.0668 2.8574 0.8687 -0.7482 -0.0273 0.1379 -0.1860 0.8674 0.4976;

0.9429 0.9929 0.0668 0.7327 1.1644 3.5018 -0.1700 0.1366 -0.5989 0.3244 -0.4976 0.8674;

[K* –d5] = 0.3252 0.3619 0.5163 0.0627 1.6538 0.8330 -0.2582 -0.0269 0.0382 0.4408 0.2967;

0.5908 0.5097 0.0627 0.6662 2.0915 2.6111 -0.6888 0.1594 -0.1034 0.5214 0.6836;

-0.8662 0.7947 0.0147 -0.0324 -0.6130 0.1936 0.1481 -0.0217 -1.0535 -0.7306 0.6668;

5.3 Optimal Closed loop system Eigen value

The Optimal Closed loop system Eigen value obtained by solving Matrix – riccatti equation through program 1 for all the 20 case studies are given below:

Case a: Non-Reheat P-Mode

Case a1	Case a2	Case a3	Case a4	Case a5
-17.7868 -17.7821 -2.8590 + 2.1339i -2.8590 - 2.1339i -1.7145 + 2.7126i -1.7145 - 2.7126i -2.3164	-17.7546 -17.7858 -2.1992 + 5.4683i -2.1992 - 5.4683i -4.4834 -3.0851 + 2.2391i -3.0851 - 2.2391i -0.8979	17.7000 -17.7868 -2.8590 + 2.1339i -2.8590 + 2.1339i -5.6210 + 1.1977i -5.6210 + 1.1977i	-17.7546 -17.7858 -2.1992 + 5.4683i -2.1992 - 5.4683i -4.4834 -3.0851 + 2.2391i -3.0851 - 2.2391i -0.8979	17.7868 -17.6976 -5.2549 + 1.8455i -5.2549 - 1.8455i -2.8590 + 2.1339i -2.8590 - 2.1339i -1.0530

Case b: Non-Reheat PI-Mode

Case b1	Case b2	Caseb3	Case b4	Case b5
-17.7868 -17.7821 -2.8482 + 2.1375i -2.8482 - 2.1375i -1.7106 + 2.7331i -1.7106 - 2.7331i -2.3095 -0.5310 -0.3925	-17.7585 -17.7857 -2.5374 + 5.1357i -2.5374 - 5.1357i -3.1771 + 2.2521i -3.1771 - 2.2521i -4.4609 -0.6045 -0.3101	-17.7868 -17.7000 -5.6169 + 1.2114i -5.6169 - 1.2114i -2.8482 + 2.1375i -2.8482 - 2.1375i -0.3925 -0.4009	-17.7546 -17.7858 -2.1987 + 5.4796i -2.1987 - 5.4796i -4.4587 -3.0827 + 2.2394i -3.0827 - 2.2394i -0.9859 -0.5106 -0.2798	-17.7868 -17.7000 -5.6169 + 1.2114i -5.6169 - 1.2114i -2.8482 + 2.1375i -2.8482 - 2.1375i -0.3925 -0.4009

Case c: Reheat P-Mode

Case c1	Case c2	Case c3	Case c4	Case c5
-17.6044	-17.5897	-17.5930	-17.5898	-17.5930
-17.5752	-17.5771	-17.4667	-17.5753	-17.4691
-4.0011	-2.4644 +4.6619i	-6.7449	-2.0308+5.0411i	-5.2767+0.6737i
-3.4593	-2.4644 - 4.6619i	-4.6689	-2.0308-5.0411i	-5.2767-0.6737i
-0.9262+ 2.5933i	-4.3990	-3.7689	-4.4059	-3.7908
-0.9262 - 2.5933i	-3.8872	-1.5995 -1.4113i	-3.9082	-1.6229+1.4057i
-1.4754+ 1.2344i	-1.7605 + 1.6527i	-1.5995 + 1.4113i	-1.7222+1.7007i	-1.6229-1.4057i
-1.4754 - 1.2344i	-1.7605 – 1.6527i	-0.1227	-0.8940	-1.0950
-0.1261	-0.1339		-0.1251	-0.1233

Case d: Reheat PI-Mode

Case d1	Case d2	Case d3	Case d4	Case d5
-17.6044	-17.5897	-17.5930	-17.5898	-17.5930
-17.5752	-17.5771	-17.4667	-17.5752	-17.4691
-4.0015	-2.4642+4.6625i	-6.7278	-2.0307+5.0418i	-5.2701+0.6928i
-3.4637	-2.4642-4.6625i	-4.6760	-2.0307-5.0418i	-5.2701-0.6928i
-0.9329+2.6079i	-4.3991	-3.7711	-4.4062	-3.7929
-0.9329-2.6079i	-3.8887	-1.5872+1.4268i	-3.9095	-1.6115+1.4202i
-1.4667+1.2614i	-1.7518+1.6680i	-1.5872-1.4268i	-1.7088+1.7148i	-1.6115-1.4202i
1.4667-1.2614i	-1.7518-1.6680i	-0.1263	-1.7088-1.7148i	-0.9480+0.4607i
-0.3843	-0.1304+0.0550i	-0.4026	-0.7749+0.3392i	-0.9480-0.4607i
-0.2968	-0.1304-0.0550i	-0.3906	-0.7749-0.3392i	-0.3957
-0.2454	-0.3906		-0.1479+0.0650i	-0.1265
			-0.1479-0.0650i	

5.4 Discussion of Results

In the present chapter, the dynamic system performance with optimal AGC regulator design has been studied. For that purpose, 1% load disturbance in area-2 is considered and area-1 & area-2 (Δf1 and Δf2), EHVAC tie-line power flow deviation (Δ P tie), HVDC tie –line power flow deviation (ΔP dc) and area control error of area 1 & 2 (ACE1 and ACE2) has been taken. The close loop systems Eigen values obtain are listed in table -5.3. From which we examine the close loop system stability of all the case studies concern. We notice the real part of all the Eigen value is negative for all case studies (a1-a5) which ensure the stability of closed loop system. Also, we obtain a higher degree of stability when ΔPdc is considered as an additional state variable as compared to that of case studies in which ΔPdc is not considered the system model for both Proportional and proportional Integral control strategies.

In Case of Non-reheat Proportional case ; it has been observed that dynamic Eigen values of Δf1 for case studies a1 and a2 have oscillatory modes which is eliminated in case study (a3-a5) it has been notice that connecting the two areas as EHVAC in parallel with HVDC and taking ΔPdc as one of the state variable (Case study a4) improves the dynamic performance much better in case of Δf1 and ACE1 responses but in case of Δf2 , ΔPtie and ACE2 responses by considering ΔPdc as one of the control variable (case study a5) gives an overall improve dynamic performance. While in case of ΔPdc response, case study a2 tie line connection as HVDC with ΔPdc as state variable provides improve dynamic performance.

In case of Non-reheat Proportional Integral case; it has been observed that the Eigen values obtained tend to settle down to zero study state value. The system dynamic performance for each case (b1-b5) has been improved greatly as compared to the previous discussed cases (a1-a5). All though oscillatory mode is observed to case b2 but it is present only in this case (i.e tie- line connection as HVDC link with ΔPdc as state variable). Case study b4 (EHVAC in parallel with HVDC, ΔPdc as state variable) provides much better result of dynamic performance for Δf1 response while for Δf2 , ΔPtie and ACE2 responses , it is case study b5 (now ΔPdc has control variable) which comes out to be superior . The case study b2 gives better result of dynamic performance for ΔPdc and ACE1 responses.

In case of Reheat Proportional case; It has been notice that oscillatory mode of system interconnection as EHVAC link only (case c1) remain continue as seen in case a1 the difference is that the peak value has been increase now. Once again here too, EHVAC in parallel with HVDC and ΔPdc as state variable (case study c4) provides better dynamic performance as compared to others for Δf1 and ACE1 responses while in case of Δf2, ΔPtie and ACE2 Eigen values , it is case study c5 which gives better result of system dynamic performance . For ΔPdc case study c2 gives improve system dynamic performance.

The Eigen values of case studies d1-d5 have been obtained by apply proportional control strategy. In this case too, the Eigen values obtained tend to settle down to zero steady state value. The system dynamic performance has been improved as compared to the previous case study. For the case study d1, oscillatory mode is also observed which has been removed by the other case studies d2-d5. The case study d4 (EHVAC in parallel with HVDC and ΔPdc as state variable) provide better dynamic performance Δf1 and ACE1 responses, while Δf2, ΔPtie and ACE2 responses, case study d5 (considering ΔPdc as control variable now) provide improve system dynamic performance.

Thus we can say that in corporation of ∆Pdc in the system dynamic model as a favorable effect on the system dynamic performance. Also, in the proportional Integral control strategy, ∆Pdc has an adding effect in the improvement in the system dynamic performance when it is considered as an additional state as well as control variable with turbine controllers. Hence , by considering all the case studied a1-d5 we can say that for 2-area thermal – thermal identical plant reheat proportional integral control strategy offer a better improve system dynamic performance.

CHAPTER-6

OVER VIEW OF THE WORK

6.1 Conclusion

The present work has been carried out with the objective of "Automatic generation control of 2-Area interconnected power systems". Optimal regulator design with full state vector feedback, for AGC of 2-Area interconnected power system consisting of power plants (Non-reheat/reheat thermal-thermal) of similar characteristics, has been proposed.

The design of AGC regulator using full state vector feedback control strategy for a 2 – area interconnected power system. All the state, control and disturbance vector and their respective co-efficient matrices have been obtained for each case study. Using the Matlab package simulation has been done. Closed loop systems Eigen values for each case study have been obtained. The Investigation carried out for the considered power system model revel that –

- All the closed loop systems Eigen values obtained have negative real part.
- By Eigen value study , closed loop system stability is maintained
- A better system dynamic performance has been obtained when proportional integral strategy is applied as compared to that obtained with proportional control strategy.
- The presence of ΔPdc in the system model produces better results and has a favorable effect on closed loop system.

CHAPTER 7

7.1 Scope for Further Research

1. In the present report, Power system model have been considered to be linear. Thus, system non-linearties like governor dead band, load change rate limiter, backlash etc., may also be considered in the design techniques.

2. Here, only 2-area thermal-thermal (non-reheat and reheat) interconnected power system has been considered with identical plants. Thus, a multi area power system interconnected via EHVAC, HVDC and parallel combination of EHVAC and HVDC transmission links may be considered for further study.

3. Some other combination of generating plant like Hydro-thermal having identical and/or un-identical characteristics may also be taken in to the consideration.

4. Some other software packages and different algorithm techniques may also be chosen for further study. Also, Artificial intelligence (AI) techniques, like fuzzy logic, ANN, HFNN may be used in the place of conventional control techniques used here.

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APPENDIX A

LIST OF SYMBOLS

ΔXgi	Incremental change in governor valve position of ith area
ΔPci	Incremental change in speed changer position of ith area
ΔPgi	Incremental change in Power generation of ith area
ΔF_s	System frequency deviation. Hz
R	Speed regulation of generator
K_G	Gain of speed governor
T_G	Time constant of speed governor
T_T	Time constant of thermal turbine
T_P	Power system Time constant
T_W	Water starting turbine for hydraulic turbine
K_T	Gain of non-reheat turbine
K_P	Power system gain
ΔP_G	Change in generated power
ΔP_D	Change in load demand
ΔP_C	Change in speed governor
ΔP_M	Hydraulic turbine mechanical power
ΔG	Change in gate position
T_1	Fuel system lags constant1 for gas turbine
T_2	Fuel system lags constant2 for gas turbine
T_3	Load limiter constant for gas turbine
L_{max}	Load Limit
V_{max}	Maximum value position for gas turbine
V_{min}	Minimum value position for gas turbine
ΔP_{tie}	Tie-line power deviation
T_{ij}	Synchronizing coefficient for tie-line
$\underline{X}$	Area state vector
$\underline{u}$	Control vector
$\underline{p}$	Disturbance vector
[A]	System matrix
[B]	Control matrix
[r]	Disturbance matrix
K_i	Integral controller gain
K_{Di}	Discrete Integral controller gain
ACE	Area Controller Error
HVDC	High Voltage Direct Current
EHVAC	Extra High Voltage Alternating Current
P	Proportional Control
PI	Proportional Integral Control
s	Laplace operator

Appendix B

Speed Governor Modeling

Let we assume that the system is initially under steady state conditions, i.e. , the linkage mechanism stationary and pilot valve closed, steam valve opened by a definite magnitude , turbine running at constant speed with turbine power output balancing the generator load.

Let the operating condition be characterized by:

f^o =system frequency

Pg^o =generator output (turbine output), neglecting generator loss

$y_E{}^o$ =steam valve setting

Let the point "A" on the linkage mechanism (as shown in fig.) be moved downwards by a small amount by Δy_A . This results in a change in the turbine power output and hence,

$$y_A = k_c \Delta Pc \qquad \text{---------------- (1)}$$

Where, ΔPc is the commanded increase/decrease in output power.

The command signal ΔPc (i.e. Δy_E) sets into motion a sequence of events,i.e. the pilot valve moves upwards, high pressure oil flows on to top of the main piston moving it downwards; the steam valve opening consequently increase the turbine generation increases,i.e. frequency goes up.

Two factors contribute to the movement at point C, (one is ΔPc & other form load side, i.e. frequency)

i) Δy_A Contributes $-\left(\frac{l_2}{l_1}\right)$ or - k_1 Δy_A (i.e. upwards) or $-k_1\, k_c\, \Delta Pc$

ii) Increase in frequency Δf causes the fly balls to move outwards so that B moves downwards by a proportional amount $k'_2 \Delta f$. The consequent movement of C with A remaining fixed at Δy_A is

$$-\left(\frac{l_2+l_1}{l_1}\right)K'_2\Delta f = k_2\Delta f \text{ (i.e. downwards)}$$

Hence, the net movement of C is,

$$\Delta y_c = -k_1 k_c \Delta PC + k_2 \Delta f \qquad \text{------------ (2)}$$

The movement of D (Δy_D) is the amount by which the pilot valve opens. It is contributed by Δy_c and Δy_E and hence, can be written as

$$\Delta y_{D=}\left(\frac{l4}{l_3+l_4}\right)\Delta y_c + \left(\frac{l4}{l_3+l_4}\right)\Delta y_E$$

Or $$\Delta y_D = k_3 \Delta y_C + k_4 \Delta y_E \qquad \text{------ (3)}$$

The movement Δy_D depending upon its sign opens one of the ports of the pilot valve admitting high pressure oil in to the cylinder there by moving the main piston and operating the steam valve by Δy_E .

Let we take the following assumptions,

(1) Inertial reaction forces of main piston and steam valve are negligible compared to the forces exerted on the piston by high pressure oil.

(2) Because of the above said assumption, the rate of oil admitted to the cylinder is proportional to port opening Δy_D .

The volume of oil admitted to the cylinder is thus proportional to the time integral of Δy_D. The movement Δy_E is obtained by dividing the oil volume by the area of the cross – section of the piston. Thus

$$\Delta y_E = k_5 \int_0^t (-\Delta y_D) dt \qquad \text{------------ (4)}$$

Taking the Laplace transform of equation (20,(30 and (4), to get

$$\Delta y_c(s) = -k_1 k_c \Delta P_c(s) + k_2 \Delta f(s) \qquad \text{----------- (5)}$$

$$\Delta y_D(s) = k_3 \Delta y_c(s) + k_4 \Delta y_E(s) \qquad \text{----------- (6)}$$

$$\Delta y_E(s) = \Delta X_g(s) = -k_5 \frac{1}{s} \Delta y_D(s) \qquad \text{------------ (7)}$$

Eliminating $\Delta y_c(s)$ and $\Delta y_D(s)$, from the above equation, to get

$$\Delta y_E(s) = \frac{k_1 k_3 k_c \Delta P_C(s) - k_2 k_3 \Delta f(s)}{k_4 + (s / k_{5)}}$$

$$\Delta X_g(s) = \left[\Delta P_C(s) - \frac{1}{R} * \Delta f(s) \right] * \left[\frac{K_g}{1 + sT_g} \right] \text{------------ (8)}$$

Where

$R = \frac{k_1 k_c}{k_2} =$ speed regulation of the governor (Hz/p.u.MW)

$K_g = \frac{k_1 k_3 k_c}{k_4}$ =gain of speed governor

$T_g = \frac{1}{k_4 k_5}$ =time constant of speed governor (sec)

Equation (8) is represented in the form of a block diagram as shown in fig. given below:

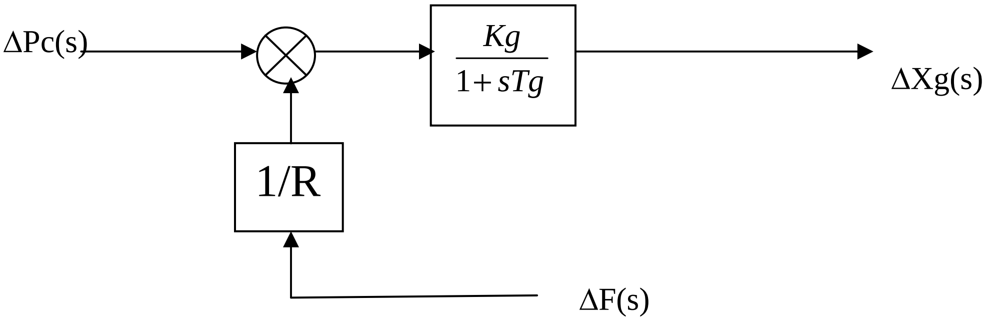

Fig (B1)

Appendix C

Generator Load Modeling

The increment in power input to the generator load system is ΔPg-ΔPd, where ΔPg=ΔPt, incremental turbine power output (assuming generator incremental loss to be negligible) and ΔPd is the load increment. This increment in the power input to the system is accounted for in two ways:

(i) Rate of increase of stored kinetic energy in the generator rotor. At scheduled frequency (f) , the stored energy is

$W^{o}_{ke} = H * P_r$ (kW-sec or Kilojoules)

Where, Pr is the kW rating of the turbo generator and H is defined as its inertia constant.

The Kinetic energy being proportional to square of speed (Frequency), the kinetic energy at a frequency of (fo + Δf) is given by

$$W_{ke} = W^{o}_{ke} * f^{o} + (\Delta f / f^{o})^2$$

$$W_{ke} = W_{ke} = H * P_r * [1 + (2 * \Delta f / f^{o})]$$

Rate of change of Kinetic energy is therefore

D (W_{ke})/dt= $(2 * H * P_r) * d(\Delta f / f^{o}) / dt$

(ii) As the frequency changes , the motor load changes being sensitive to speed, the rate of change of load with respect to frequency ,i.e. ∂Pd/∂f can be regarded as nearly constant or small changes in frequency f and can be expressed as

$$(\partial P_d / \partial f)\Delta f = D\Delta f$$

Where, the constant D can be determined empirically. D is positive for a predominantly motor load.

Writing the power balance equation, we have

$$\Delta P_g - \Delta P_d = (2 * H * P_r) * d(\Delta f \;/\; f^o)/dt + D\Delta f$$

Dividing throughout by Pr and rearranging with speed expressed in per unit

$$\Delta P_g(p.u) - \Delta P_d(p.u) = (2 * H) * d(\Delta f)/dt + D(p.u)\Delta f$$

Taking Laplace Transform, we can write ΔF(s) as

$$\Delta F(s) = [\Delta P_g(s) - \Delta P_d(s)]/[D + 2 * H * s]$$

Or, $\Delta F(s) = [\Delta P_g(s) - \Delta P_d(s)] * \left[\frac{K_p}{1 + sT_p}\right]$

Where, Kp=1/D = gain of the system (Hz/p.u.MW)

Tp=2*H/D=time constant of power system (sec)

Equation (7) is represented in the form of a block diagram as shown in the figure given below:

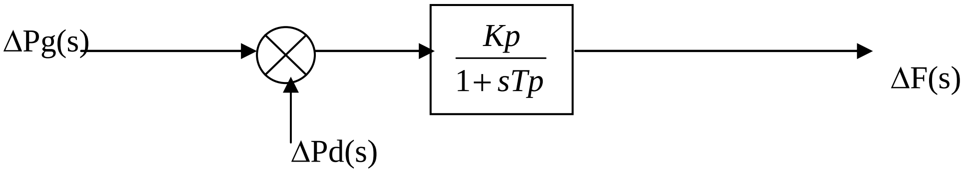

Fig (C1)

Appendix D

Program for HVDC, EHVAC, EHVAC/DC for Reheat and Non-Reheat with P and PI Mode

```
clear;
clc;
%Pr1=2000;Pr2=2000;R1=2.4;R2=2.4;B1=.425;B2=.425;H1=5;H2=5;
%Kt1=1;Kt2=1;Tt1=0.3;Tt2=0.3;Kr1=0.5;Kr2=0.5Tr1=10;Tr2=10;
%Kg1=1;Kg2=1;Tg1=.08;Tg2=.08;D1=.00833;D2=.00833;Kdc=1;
%Tdc=0.2;Pmax=200;p11=.00;p22=.01;a=30;f0=50;
Pr1=input('Enter Pr1\n');
Pr2=input('Enter Pr2\n');
R1=input('Enter R1\n');
R2=input('Enter R2\n');
B1=input('Enter B1\n');
B2=input('Enter B2\n');
H1=input('Enter H1\n');
H2=input('Enter H2\n');
Kt1=input('Enter Kt1\n');
Kt2=input('Enter Kt2\n');
Tt1=input('Enter Tt1\n');
Tt2=input('Enter Tt2\n');
Kr1=input('Enter Kr1\n');
Kr2=input('Enter Kr2\n');
Tr1=input('Enter Tr1\n');
Tr2=input('Enter Tr2\n');
Kg1=input('Enter Kg1\n');
Kg2=input('Enter Kg2\n');
Tg1=input('Enter Tg1\n');
Tg2=input('Enter Tg2\n');
D1=input('Enter D1\n');
D2=input('Enter D2\n');
Kdc=input('Enter Kdc\n');
Tdc=input('Enter Tdc\n');
Pmax=input('Enter Pmax\n');
p11=input('Enter ?Pd1\n');
p22=input('Enter ?Pd2\n');
a=input('Enter angle difference in deg.\n');
fo=input('Enter frequency\n');
a12=-Pr2/Pr1;
T12=(Pmax/Pr2)*cos(a*pi/180.0);
Kp1=1/D1;
Kp2=1/D2;
Tp1=2*H1/(fo*D1);
Tp2=2*H2/(fo*D2);
a11=-1/Tp1;
a15=Kp1/Tp1;
a19=-a15;
a110=-a15;
a22=-1/Tp2;
a26=Kp2/Tp2;
a29=-a12*a26;
a210=a29;
a31=-Kg1/(R1*Tg1);
a33=-1/Tg1;
a42=-Kg2/(R2*Tg2);
a44=-1/Tg2;
```

```
a53=(Kr1*Kt1)/Tt1;
a55=-1/Tr1;
a57=(1/Tr1)-(Kr1/Tt1);
a64=(Kr2*Kt2)/Tt2;
a66=-1/Tr2;
a68=(1/Tr2)-(Kr2/Tt2);
a73=1/Tt1;
a77=-Kt1/Tt1;
a84=1/Tt2;
a88=-Kt2/Tt2;
a91=2*pi*T12;
a92=-a91;
a101=Kdc/Tdc;
a1010=-1/Tdc;
a111=B1;
a119=1;
a122=B2;
a129=a12;
b13=Kg1/Tg1;
b24=Kg2/Tg2;
b31=-a15;
b32=a12*b31;
g11=-a15;
g22=-a26;
disp('Here 2-area Thermal System is Represented.');
Q=input('Enter 1 for Non-Reheat System and 2 for Reheat system\n');
switch Q
case 1

% NON-REHEAT CASE
disp('Enter your choice for control action')
Q1=input('Enter 1 for p contro1, 2 for PI control\n');
A=[a11 0 0 0 a15 0 a19 a110 0 0 ; 0 a22 0 0 0 a26 a29 a210 0 0 ;
   a31 0 a33 0 0 0 0 0 0 0 ; 0 a42 0 a44 0 0 0 0 0 0 ;
   0 0 a73 0 a77 0 0 0 0 0 ; 0 0 0 a84 0 a88 0 0 0 0 ;
   a91 a92 0 0 0 0 0 0 0 0 ; a101 0 0 0 0 0 0 a1010 0 0 ;
   a111 0 0 0 0 0 a119 a119 0 0 ; 0 a122 0 0 0 0 a129 a129 0 0 ];



B=[0 0 b13 0 0 0 0 0 0 0;
   0 0 0 b24 0 0 0 0 0 0;
   b31 b32 0 0 0 0 0 0 0 0]';

Pd= [p11;p22];
G=[g11 0 0 0 0 0 0 0 0 0;
    0 g22 0 0 0 0 0 0 0 0]';

switch Q1
case 1
%PROPORTIONAL CONTROL (NON-REHEAT)
disp('How do you want to connect the two areas?');
Q11=input('Enter 1 for EHVAC, 2 for HVDC Link and 3 for EHVAC/HVDC\n');

switch Q11
case 1
disp('EHVAC WITH P Control (NON-REHEAT)');
% For EHVAC WITH P CONTrol (NON_REHEAT)
```

```
A(8:10,:)=[];
A(:,8:10)=[]
B(8:10,:)=[];
B(:,3)=[]
C=eye(7);
D=zeros(7,2);
Pd
G(8:10,:)=[]
Q=eye(7);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part.');
else
disp('Real part of one of the Eign value is not negative');
end % For eigen values
case 2
disp ('HVDC WITH P Control (NON-REHEAT)');
%For HVDC with P control(Non-Reheat)
Q=input('For Pdc as state variable enter 1 and as control variable
enter 2\n');
switch Q
case 1
A(9:10,:)=[];
A(:,9:10)=[]
B(9:10,:)=[];
B(:,3)=[]
C=eye(8);
D=zeros(8,2);
Pd
G(9:10,:)=[]
Q=eye(8);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part,');
else
disp('Real Part of one of the Eign Value is not negative');
end % For eigen values
case 2
A(8:10,:)=[];
A(:,8:10)=[]
B(8:10,:)=[]
C=eye(7);
D=zeros(7,3);
Pd
G(8:10,:)=[]
Q=eye(7);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('Real part of one of the Eigen Value is not negative');
end % For eigen Values
end
    case 3
```

```
        disp('EHVAC/DC with P-Control(Non-Reheat)');
        %for EHVAC/DC with P Control(non-reheat)
        Q=input('For Pdc as state variable enter 1 and as control
variable enter 2\n');
        switch Q
case 1
A(9:10,:)=[];
A(:,9:10)=[]
B(9:10,:)=[];
B(:,3)=[]
C=eye(8);
D=zeros(8,2);
Pd
G(9:10,:)=[]
Q=eye(8);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
    disp('All eigen values have negative real part.');
else
    disp('Real part of one of the Eigen value is not negative');
end %For Eigen values
  case 2
A(8:10,:)=[];
A(:,8:10)=[]
B(8:10,:)=[]
C=eye(7);
D=zeros(7,3);
Pd
G(8:10,:)=[]
Q=eye(7);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
 disp('All eigen values have negative real part.');
else
    disp('Real part of one of the Eigen value is not negative');
end
        end
otherwise
disp('Invalid choice');
end

case 2
% PROPORTIONAL PLUS INTEGRAL CONTROL (NON-REHEAT)
disp('How do you want to connect the two areas?');
Q11=input('Enter 1 for EHVAC, 2 for HVDC Link and 3 for EHVAC/HVDC\n');

switch Q11
case 1
disp('EHVAC WITH PI Control (NON_REHEAT)');
% For EHVAC WITH PI Control (Non-Reheat)
A(8,:)=[];
A(:,8)=[]
B(8,:)=[];
```

```
B(:,3)=[]
C=eye(9);
D=zeros(9,2);
Pd
G(8,:)=[]
Q=eye(9);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eigen values have negative real part.');
else
disp('Real part of one of the Eigen Value is not negative');
end % For eigen values
case 2
disp('HVDC WITH PI Control (NON-REHEAT)');
% For HVDC With PI Control (Non-Reheat)
Q=input('for Pdc as state variable enter 1 and as control variable
enter 2\n');

switch Q
case 1
A(7,:)=[];
A(:,7)=[]
B(7,:)=[];
B(:,3)=[]
C=eye(9);
D=zeros(9,2);
Pd
G(7,:)=[]
Q=eye(9);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part.');
end %For eign values
case 2
A(7:8,:)=[];
A(:,7:8)=[]
B(7:8,:)=[]
C=eye(8);
D=zeros(8,3);
Pd
G(7:8,:)=[]
Q=eye(8);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part,');
else
disp('Real Part of one of the eigen value is not negative');
end % For eigen values
end
case 3
disp('EHVAC/DC WITH PI Control (NON-REHEAT)');
% For EHVAC/DC With PI Control (Non-Reheat)
```

```
Q=input('for Pdc as state variable enter 1 and as control variable
enter 2\n');

switch Q
case 1
A
B(:,3)=[]
C=eye(10);
D=zeros(10,2);
Pd
G
Q=eye(10);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part.');
end %For eign values
case 2
A(7:8,:)=[];
A(:,7:8)=[]
B(7:8,:)=[]
C=eye(8);
D=zeros(8,3);
Pd
G(7:8,:)=[]
Q=eye(8);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part,');
else
disp('Real Part of one of the eigen value is not negative');
end % For eigen values
case 2
A(8,:)=[];
A(:,8)=[]
B(8,:)=[]
C=eye(9);
D=zeros(9,3);
Pd
G(8,:)=[]
Q=eye(9);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part,');
else
disp('Real Part of one of the eigen value is not negative');
end % For eigen values
end
otherwise
disp('Invalid choice');
end
otherwise
disp('Invalid choise');
```

```
end %For Por PI of NON-REHEAT

% REHEAT CASE
case 2
disp('Enter your choice for control action')
Q1=input('Enter 1 for P contro1, 2 for PI control\n');

A=[a11,0,0,0,a15,0,0,0,a19,a110,0,0;
0,a22,0,0,0,a26,0,0,a29,a210,0,0;
   a31,0,a33,0,0,0,0,0,0,0,0,0;        0,a42,0,a44,0,0,0,0,0,0,0,0;
   0,0,a53,0,a55,0,a57,0,0,0,0,0;      0,0,0,a64,0,a66,0,a68,0,0,0,0;
   0,0,a73,0,0,0,a77,0,0,0,0,0;        0,0,0,a84,0,0,0,a88,0,0,0,0;
   a91,a92,0,0,0,0,0,0,0,0,0,0;        a1010,0,0,0,0,0,0,0,0,a1010,0,0;
   a111,0,0,0,0,0,0,0,a119,0,0,0;      0,a122,0,0,0,0,0,0,a129,0,0,0];
B = [0 0 b13 0 0 0 0 0 0 0 0 0;
   0 0 0 b24 0 0 0 0 0 0 0 0;
   b31 b32 0 0 0 0 0 0 0 0 0 0]';
Pd= [p11;p22];
G=[g11 0 0 0 0 0 0 0 0 0 0 0; 0 g22 0 0 0 0 0 0 0 0 0 0]';
switch Q1
case 1
% PROPORTIONAL CONTROL (REHEAT)
disp('How do you want to connect the two areas?');
Q11=input('Enter 1 for EHVAC, 2 for HVDC Link and 3 for EHVAC/HVDC\n');

switch Q11
case 1
disp('EHVAC WITH P Control (REHEAT)');
% For EHVAC WITH P CONTROL (REHEAT)
A(10:12,:)=[];
A(:,10:12)=[]
B(10:12,:)=[];
B(:,3)=[]
C=eye(9);
D=zeros(10,2);
Pd
G(10:12,:)=[]
Q=eye(9);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part.');
else
disp('Real part of one of the Eign value is not negative');
end % For eigen values
case 2
disp ('HVDC WITH P Control (REHEAT)');
% For HVDC WIth P Control (Reheat)
Q=input('For Pdc as state variable enter 1 and as control variable
enter 2\n');

switch Q
case 1
A([9,11,12],:)=[];
A(:,[9,11,12])=[]
B(10:12,:)=[];
```

```
B(:,3)=[]
C=eye(9);
D=zeros(9,2);
Pd
G(10:12,:)=[]
Q=eye(9);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part,');
else
disp('Real Part of one of the Eign Value is not negative');
end % For eigen values
case 2
A(9:12,:)=[];
A(:,9:12)=[]
B(9:12,:)=[]
C=eye(8);
D=zeros(8,3);
Pd
G(9:12,:)=[]
Q=eye(8);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eigen values have negative real part.');
else
disp('Real part of one of the Eigen Value is not negative');
end % For eigen Values
end
case 3
disp('EHVAC/DC WIth P Control (Reheat)');
% For EHVAC/DC With P Control (Reheat)
Q=input('for Pdc as state variable enter 1 and as control variable
enter 2\n');

switch Q
case 1
disp('EHVAC WITH P CONTROL (REHEAT)');
% For EHVAC WITH P CONTROL (REHEAT)
A(11:12,:)=[];
A(:,11:12)=[]
B(11:12,:)=[];
B(:,3)=[]
C=eye(10);
D=zeros(10,2);
Pd
G(11:12,:)=[]
Q=eye(10);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part.');
else
disp('Real part of one of the Eign value is not negative');
```

```
end % For eigen values
case 2
A(10:12,:)=[];
A(:,10:12)=[]
B(10:12,:)=[];
C=eye(9);
D=zeros(9,3);
Pd
G(10:12,:)=[]
Q=eye(9);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part.');
else
disp('Real part of one of the Eign value is not negative');
end % For eigen values
end
otherwise
disp('Invalid choice');
end

case 2
% ehvacrpi PROPORTIONAL PLUS INTEGRAL CONTROL (REHEAT)
disp('How do you want to connect the two areas?');
Q11=input('Enter 1 for EHVAC, 2 for HVDC Link and 3 for EHVAC/HVDC\n');

switch Q11
case 1
disp('EHVAC WITH PI Control (REHEAT)');
% For EHVAC WITH PI Control (Reheat)
A(10,:)=[];
A(:,10)=[]
B(10,:)=[];
B(:,3)=[]
C=eye(11);
D=zeros(11,2);
Pd
G(10,:)=[]
Q=eye(11);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eigen values have negative real part.');
else
disp('Real part of one of the Eigen Value is not negative');
end % For eigen values
case 2
disp('HVDC WITH PI Control (REHEAT)');
% For HVDC With PI Control (Reheat)
Q=input('for Pdc as state variable enter 1 and as control variable
enter 2\n');

switch Q
case 1
```

```
A(9,:)=[];
A(:,9)=[]
B(9,:)=[];
B(:,3)=[]
C=eye(11);
D=zeros(11,2);
Pd
G(9,:)=[]
Q=eye(11);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eign values have negative real part.');
else
disp('Real Part of one of the eigen value is not negative');
end % For eigen values
case 2
A(9:10,:)=[];
A(:,9:10)=[]
B(9:10,:)=[];
C=eye(10);
D=zeros(10,3);
Pd
G(9:10,:)=[]
Q=eye(10);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('All eign values have negative real part,');
else
disp('Real Part of one of the Eign Value is not negative');
end % For eigen values
end
case 3
disp('EHVAC/DC WITH PI Control (REHEAT)');
% For EHVAC/DC With PI Control (Reheat)
Q=input('for Pdc as state variable enter 1 and as control variable
enter 2\n');

switch Q
case 1
A
B(:,3)=[]
C=eye(12);
D=zeros(12,2);
Pd
G
Q=eye(12);
R=eye(2);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part.');
else
disp('Real part of one of the Eigen Value is not negative');
end %For eign values
```

```
case 2
A(10,:)=[];
A(:,10)=[]
B(10,:)=[]
C=eye(11);
D=zeros(11,3);
Pd
G(10,:)=[]
Q=eye(11);
R=eye(3);
[K,P,E]=lqr(A,B,Q,R)
eigr=real(E);
if eigr<0
disp('all eigen values have negative real part,');
else
disp('Real Part of one of the eigen value is not negative');
end % For eigen values
end
otherwise
disp('Invalid choise');
end
otherwise
disp('Invalid choice');
end
otherwise
disp('Invalid choise');
end
```