AUTOMATIC GENERATION CONTROL OF MULTI-AREA MULTI-SOURCE SYSTEM USING OPTIMIZED TID CONTROLLER

DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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Submitted by:

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CANDIDATE'S DECLARATION

I hereby certify that the work which is presented in the Major Project – II entitled **"Automatic Generation Control of Multi-Area Multi-Source System Using Optimized TID Controller"** in fulfilment of the requirement for the award of the Degree of Master of Technology in Power System and submitted to the Department of Electrical Engineering, Delhi Technological University, Delhi is an authentic record of my own, carried out during a period from January to May 2022, under the supervision of Prof. Narendra Kumar.

Place: Delhi **DEEPESH SANGWAN**

Date: 30/05/2022

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CERTIFICATE

This is to certify that the thesis work entitled **"Automatic Generation Control of Multi-Area Multi-Source System Using Optimized TID Controller"**, submitted by Mr. Deepesh Sangwan, Roll No. 2K20/PSY/07, a student of Master of Technology in the Department of Electrical Engineering at Delhi Technological University (formerly Delhi College of Engineering), is a work carried out by him under my guidance during 2020-2022 towards the partial fulfilment of the requirement of the award of degree of Master of Technology and is an original contribution with existing knowledge and faithful record of research work carried out by him under my guidance and supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date: 30/05/2022

Prof. Narendra Kumar

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ABSTRACT

In today's world, electricity demands of every household and industry is increasing day by day. Electricity Blackouts, Frequency deviation and voltage imbalance can wreak havoc affecting industries whose work is solely based on electricity and affecting our day to day lives. For a stable and reliable power system, some type of control strategy is required. If frequency not maintained at optimal level, it could result in high magnetizing currents in transformers and induction motors. To tackle the problem of frequency imbalance, Automatic Generation Control was introduced to control the frequency deviations and inter-area power exchanges. Method of regulating the real power output of the generators to match the sudden load changes happening on the demand side is termed as Automatic Generation Control. It is implemented when two or more than two areas are interconnected. Primary control is provided using governor. Supplementary control is provided using some type of controller like I, PI, PID etc.

This project work presents the design and analysis of TID controller optimized using TLBO and PSO optimization techniques for Automatic Generation Control (AGC) of an interconnected two area power system with Multi source in each area. Initially the TLBO based PID controller is being used to optimize the system. After that TID controller is being used with two optimization techniques for comparison purpose. Non linearities like Governor Deadband (GDB), Boiler Dynamics (BD) and Generation Rate Constant (GRC) is also being implemented to make the system as realistic as possible with real world scenarios.

This two-area system is being simulated in MALTAB Simulink and run for multiple times with each time running for 100 iterations considering 50 as population size. A 0.1 per unit of step load perturbation is enforced in a specific area and different gain parameters of TID controller are properly tuned using TLBO considering Integral Time Absolute Error (ITAE) as the objective function. Multiple objective functions are being considered but the best results are obtained using ITAE as an objective function. In the formulated approach the objective function consists of combination of deviations in frequency and tie line power. Superiority of TLBO based TID controller over PSO based TID controller is observed and as well as over TLBO based PID controller.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbols	Name of the parameter/constant
GW	Giga-Watts
AGC	Automatic Generation Control
ΔF	Frequency deviation
$\Delta Ptie$	Tie-line power deviation
ACE	Area Control Error
UFLS	Under Frequency Load Shedding
ED	Economic Dispatch
UC	Unit Commitment
TFM	Transfer Function Model
T_{12}	Synchronizing Coefficient
GRC	Generation Rate Constraint
BD	Boiler Dynamics
GDB/DZ	Governor Dead Band/Dead Zone
pu	Per Unit
TLBO	Teaching Learning Based Optimization
PSO	Particle Swarm Optimization
lb	Lower Bound
ub	Upper Bound
TID	Tilt-Integral-Derivative
PID	Proportional-Integral-Derivative
T	Number of iterations
N_P	Population Size
w	Inertia Weight
K_P	Proportional Gain
K_I	Integral Gain
K_D	Derivative gain
ITAE	Integral Time Absolute Error

CHAPTER-1

INTRODUCTION

1.1. General

Power is one of key pillars for economic growth and welfare of nations. It is a one of the major components of infrastructure. For consistent growth of the Indian economy, the existence and development of adequate power infrastructure is essential. The challenge of supplying reliable and good quality of electrical energy at a reasonable cost to the consumers is one of the prime objectives of the planners of the nation. The electric power system is one of the oldest infrastructures. The quality, reliability and the cost are important features which provide the basis of attracting consumers in a country. The per capita consumption of electrical energy has been considered as the prime index to evaluate the overall development of any country. In developing countries like India, there has been a wide gap between the electric energy demand and its production. The power engineers and the government agencies along with public sectors are continuously putting their best efforts to improving infrastructure and minimize this gap. Due to best efforts, this gap has been narrowed down to great extent, but still a gap exists.

India's power sector is one of the most diverse sectors in the world. Sources of power generation are basically divided into two types conventional (Coal, Hydro, lignite, Oil, Natural gas and nuclear power) and Non-conventional (Solar, Wind, Tidal, Energy from Urban Waste). Addition to the installed generating capacity is required to meet the increasing demands of electricity in the nation. The installed capacity in India and annual electricity generation has increased by multiple folds in more than seventy years after independence. The distribution and transmission network in India have also expanded to the population accordingly. Still electrical supply is not consistent in large section of Indian people living in rural areas. According to The Central Electricity Authority (CEA), India's power requirement to grow to reach 817 GW by 2030 i.e., even more than double of current requirement [1]. The important reasons for this are exponential growth of population and the continuous all-round development in the country. Therefore, the power engineers, planners, economists and technologists are visualizing the challenges to come in future and searching out the means to meet these challenges effectively. The installation of electric power generating stations in the country are associated with technological, economic, social, regional, eco-friendly and most importantly the political considerations. Therefore, the power generating stations are located at remote locations from the load centers. However, for technical and economic reasons, power systems are electrically interconnected into huge power grids which are further divided into regional operating groups called power pools. Although every member in pool operates independently, they are dependent on other pool members in respect to generation and scheduling aspects because of the mutual contract. There are numerous advantages associated with operating in interconnected or pool fashion like; provision of construction of larger and more economical generating units and the transmission of large blocks of energy from the generating sources to major loads, reduced reserves requirements by sharing of capacity between areas and sectors, capacity savings from time zone and random diversity, capacity savings by seasonal exchange of capacity between areas which have opposing winter and summer needs, transmission facility of off-peak energy, flexibility to meet unforeseen emergency demands and importantly to have technical benefits out of the uses of the variability in generation mixes and load patterns[2].

The operation of power system in an interconnected fashion system usually leads to improved system security also. These benefits have been recognized from the beginning and hence, interconnections between the power pools continue to grow. Interconnected systems serve to handle large demands of power. The energy can be transferred in both the directions which serves the best technical objective. Via interconnection, transfer of energy can take place to or from other power systems belonging to the same power pool. For successful, stable and reliable operation of interconnected power system, a technically compatible transmission system to act as pool interconnection is essentially required [3].

1.2. Automatic Generation Control

An electrical power system is a large-scale complex interconnected system with many system constraints and non-linearities. There has been a higher demand of electrical power loads both on domestic and industrial scale as our dependency on electricity is increasing day by day. A Power system must be kept at the optimum operating level which is identified by load flow configuration, Voltage profile and nominal frequency. For a stable and reliable power system, it is important to manage the load properly to avoid any mismatch between the load and generation as shown in Fig.1.1 since a failure to do so results in frequency fluctuation and voltage drops. Both reactive and active power demand are never constant, and they constantly vary with the changing demand on load side.

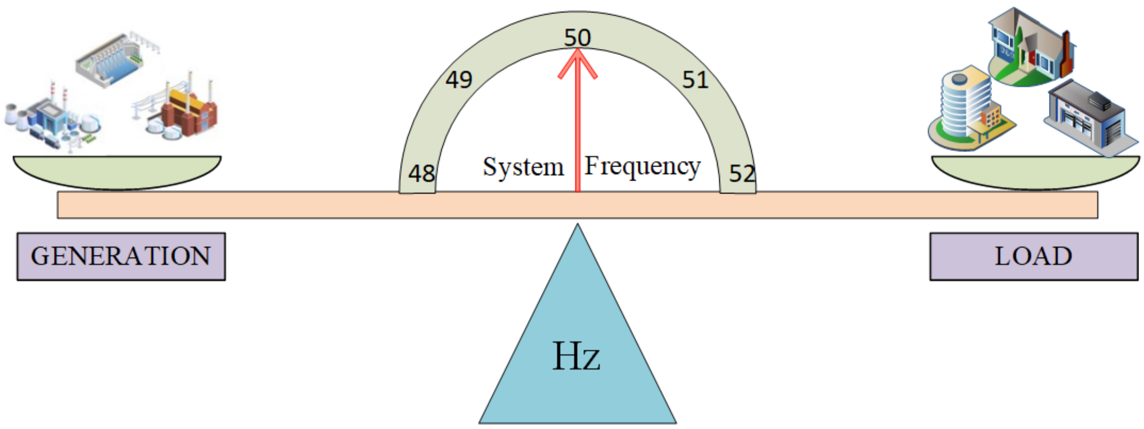

Fig.1.1. Frequency Balance in Power System

Generation must be consistently regulated to meet the ever-changing load demand otherwise machine speed will change along with deviations in frequency which is not desirable. To maintain voltages at the system buses within prescribed limits, excitation of the generators must be continuously modulated to meet reactive power demand with reactive power generation [4]. In today's modern world where everything is interconnected, it is not possible to regulate these changes manually. An effective control strategy is required to manipulate the generation to meet the continuously changing load demands. Therefore, each generator is equipped with Automatic Generation equipment to provide some form of control to modulate the generation.

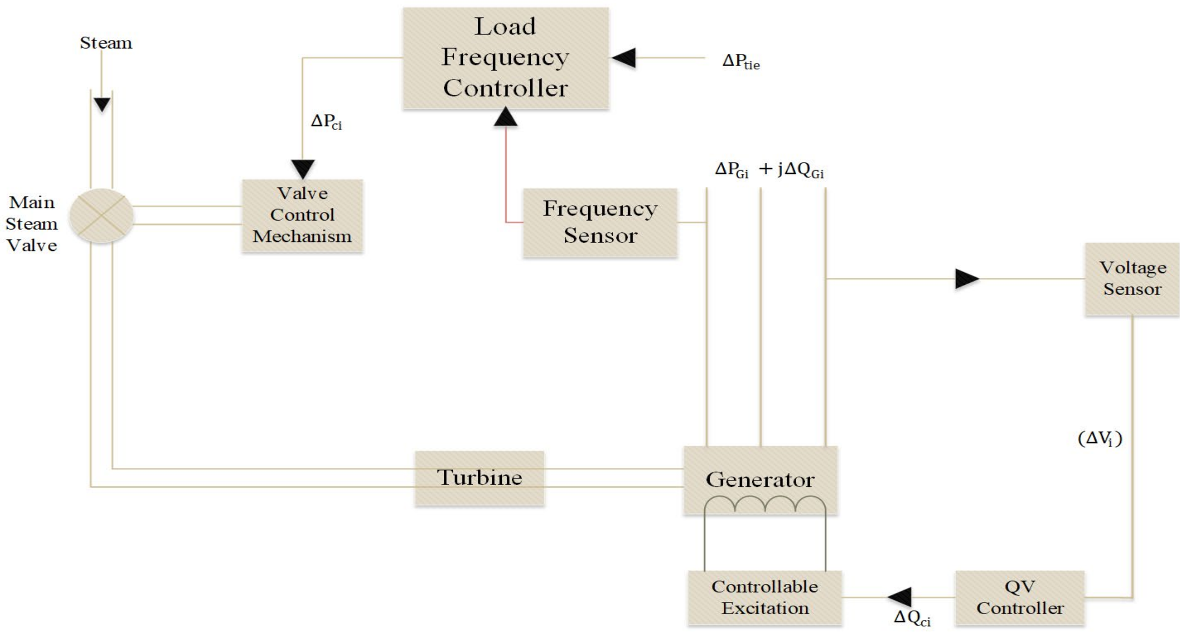

Fig. 1.2. Automatic Generation Control Block diagram

In modern large, intertwined power system, it is a prudent feature to preserve optimal frequency and tie-line power deviations at desired level regardless of load perturbations in any area. If frequency not maintained at optimal level, it could result in high magnetizing currents in transformers and induction motors [5]. To maintain stability, it becomes obligatory to accordingly change the position of hydro-gates (or main steam valves) by opening or closing them depending on load changes in line with appropriate control strategy. This method of regulating the real power output of generators is termed as Automatic Generation Control. Fig. 1.2 represent the block diagram of AGC. It is implemented when two or more than two areas are interconnected. Primary control is provided using governor. Supplementary control is provided using some type of controller like I, PI, PID etc. [6].

There are various control loops in AGC as shown in Fig 1.3. The responsibility of primary AGC loop is to modulate the speed of the generator and real power output.

It comprises of speed governing system mounted on prime mover. It makes use of feedback of real power output of the generator and generator speed or frequency. The supplementary AGC loop regulates the real power output, tie-line power exchange and frequency. It comprises of a signal being fed back into the speed governor. The signal, referred to as the Area Control Error. The combination of frequency deviation (ΔF) and tie-line power deviation (ΔPtie) is termed as ACE. The supplementary loop gives feedback via ACE and incremental change (U_S) adds it to the primary control loop through a suitable controller. The incremental change in power generation function (U_{GS}) is obtained from the generator by using its input signals from primary (U_P) and supplementary (U_S) control loops.

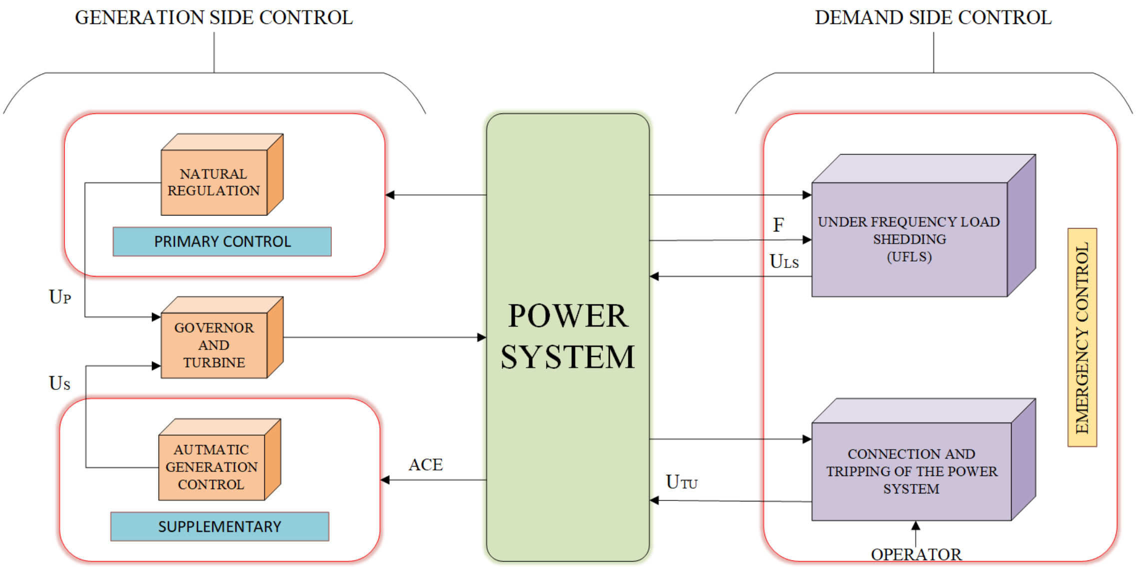

Fig. 1.3. Control Loops in AGC System

Following a significant fault, there is a serious demand generation imbalance associated with rapid frequency changes. Supplementary control loop of AGC might fail in maintaining the frequency change at optimum level. Under these circumstances, emergency control and frequency load shedding (UFLS) are to be initiated to eliminate the risk of cascaded contingencies which may lead to interruption of power supply. In case of emergency control, UFLS and protection system act as a tertiary control. Whenever supplementary controller fails to regulate unwanted change in operating condition, the UFLS control system senses the signals

(frequency and its derivative) and produces an appropriate increment function (U_{LS}) for load shedding while protection unit produces an increment change (U_{TU}) for tripping of the power system network to get the power system in nominal state.
The time hierarchy of execution of control functions in power system arises because of the extremely wide range of response time intrinsic in power system operation and control. Time decomposition is always carried out to subdivide a difficult problem into smaller sub-problems [7]. The overall operation and control of a power system on time scale may be clubbed in four major groups as described in Table 1.1. In this table, there are still some slower and faster functions than the time decomposition which are not mentioned here. For example, maintenance scheduling has a time scale of days while relay action is faster than governor action.

Table 1.1 Time Hierarchy of control functions in power system

Sr. No.	Control functions	Time scale
1.	Governor action	Few seconds
2.	Automatic generation Control (AGC)	Many Seconds
3.	Economic dispatching (ED)	Minutes
4.	Unit Commitment (UC)	Hours

It often happens that control function at higher level take place with a slower time scale than control function at a lower level. An example of this is that UC control action take place at interconnected power system levels while EDC, AGC and governor action take place at individual plants level. However, this is not a general rule. For example, boiler control action done at the power plant level can be slower than AGC done at system level [7]. Apart from that, control functions for governor action and AGC are executed as on-line functions while UC and other slower functions (i.e., maintenance, planning etc.) are considered to be executed as off-line functions. The economic dispatch is carried out as on-line and off-line function depending upon the situation.

1.3. Objectives of AGC

Automatic generation control (AGC) is the name given to a control system having three major objectives [5]: -

- To maintain frequency of the system at or very close to optimum value.
- To manage power interchange between control areas at correct value.
- To maintain each unit's generation at the most economic value.

1.4. Components of AGC

1. **Primary Control**
    - To preserve the balance between generation and load demand.
    - In control theory, the primary control correlate with proportional controller.
    - Instant (automatic) action to sudden deviations in load.
    - E.g. Reaction to frequency change

2. **Secondary Control**
    - To maintain the tie-line power flow between interconnected areas.
    - Counteractive control actions are done by operators.

3. **Economic Dispatch**
    - Most economical way of scheduling all the units.

1.5. Advantages of AGC

Automatic Generation Control or also known Load Frequency Control offers a great deal of advantages in Pool flow of power: -

- It offers a stable and reliable power system.
- Maintains the frequency at the optimal level.

- Maintains exchange of tie-line power at optimal level
- Capacity savings from time zone and random diversity
- Avoid machine damages
- Avoid blackouts
- Limits the variations happening in the power system

1.6. Outline of Dissertation

This dissertation consists of:

Chapter 1: In this chapter introduction to the term Automatic Generation Control is done along with its objectives, advantages and challenges.

Chapter 2: This shows the literature review done for the project "Automatic Generation Control of Multi-Area using Optimized TID Controller". This chapter demonstrates the findings of different controllers using different optimization techniques.

Chapter 3: This chapter focuses on system modelling explaining the system transfer Function, system constraints which have been considered. Along with the simulation in MATLAB.

Chapter 4: This chapter focus on understanding of different optimization techniques and their comparison. Along with two optimization techniques namely TLBO and PSO which have been used in this work.

Chapter 5: This chapter focus on design and analysis of TID controller. along with its basic structure, it also focuses on application, advantages, and comparison with other controllers.

Chapter 6: This chapter summarizes the result obtained through the models and acknowledges the future work that can be done.

CHAPTER-2

LITERATURE REVIEW

2.1. Introduction

The literature review shows an immense amount of progress and work done in the field of AGC in the past few decades. Apart from Design and implementation of AGC strategies using conventional methods, intelligent methods are gaining more interest from the scholars in past few years. These concepts are helping the power engineers to handle the power system becoming more complex, nonlinear, and uncertain year by year. Despite advances in control concepts, many operating structural changes have taken place during last three decades. Deregulation of power industry is one of the most imperative changes witnessed by the power industry worldwide. In the subsequent sections, these schemes are reviewed expansively. In this chapter, research papers related to Automatic Generation control using different types of sources in multi-area systems are being reviewed. Research Papers which use different controllers based on different meta-heuristic optimization techniques are being discussed.

2.2. Literature Survey

The very early developments in AGC shows the use of flywheel governor of synchronous machine to control the change in frequency in power system. Subsequently, supplementary control was incorporated to the governor with the help of Area Control Error (ACE) signal which is directly proportional to integral of summation of deviation in frequency and tie-line power i.e., area control area (ACE). This scheme is the classical approach for AGC of electrical power system.

2.2.1. Overview of AGC

Very early works in classical AGC were based on tie-line bias control approach [8, 9]. The examinations with large signal dynamics of AGC systems by using an optimization technique based on nonlinear programming might be a maiden attempt [10]. During literature survey it is observed AGC was put forward by Cohn [11]. With the advent of modern control theory and its revolutionary applications by Fosha and Elgerd [12] in power system control, there has been an incessant effort to suggest optimal AGC schemes to circumvent many limitations of classical methods during 1970. Kumar and Kothari shed some light on past control techniques formulated for AGC [13]. The design of linear optimal PI regulator for a two and three-area power systems was presented by Calovic [14]. Some recent applications of optimal AGC regulators are available in the literature [14, 15,16]. Though optimal AGC schemes offered purposely improved dynamic performance of the system, they are analogous with all system states being measured which is not practically feasible sometimes. Dynamic performance of the AGC system can be improved under operating conditions and changeable system parameters, variable structure controller has offered better potential Since digital control is more accurate, reliable, flexible compact and fewer vulnerable to drift and noise, different scholars have suggested discrete or digital or sampled data AGC control schemes in AGC of power system.

Over the last decades, intelligent techniques have emerged in a big way to deal with the problems associated with successful design and implementation of control methods for large and complex electrical power system. Their potential applications in the area of AGC of power system have continuously been witnessed in the literature for more than last two decades [17,18,19]. Various intelligent techniques like, fuzzy logic [20-23], ANN based controllers [24-28], Genetic algorithm [33-37], Particle swarm optimization [38-40], Hybrid-PSO-PS [41], Pattern Search [42], Artificial bee colony [43], Bacterial foraging optimization algorithm [51,52], JAYA algorithm [41,42], Bat Algorithm [53-55], Firefly algorithm [44-47], Grey Wolf optimization [47], bang-big crunch optimization (BB-BCO) [48], Teaching Learning Based Optimization [56,57], Moth Flame Optimization [59,60]etc.

2.2.2. AGC classification based on control methods

Since the dawn of AGC, various controls methos have been introduced and developed. Over time these methods have been modified, rectified and replaced with new methods. This section discusses those controls methods and overview the details, advantages and major drawbacks. Different control approaches are proposed for AGC which are divided into four types:

1. Classical Control Methods

The very early developments in AGC shows the use of flywheel governor of synchronous machine to control the change in frequency in power system. But as the time progressed this method was not sufficient enough to maintain the balance of power system. Subsequently, supplementary control was incorporated to the governor with the help of Area Control Error (ACE) signal which is directly proportional to integral of summation of deviation in frequency and tie-line power i.e., area control area (ACE). This scheme is the classical approach for AGC of electrical power system. Some examples of classical control approaches are Bode Plots, Root Locus and Nyquist. Main advantage of these methods being very simple and easy to implement. They require low initial cost and plan structure. They are mainly based on conventional controllers. AGC problem in a multi-variable system based on the pole placement technique is addressed in the literature [52]. The authors in [53] provided a comparison of different classical controllers including I, PI, ID, PID, and ID used in two, three, and five area power systems considering reheat turbine power plants with appropriate non-linearities Although, they quickly provide transient and stability information but they are not very accurate and are of poor quality. They usually result in poor dynamic performance and provide low resistance to sensor and actuator faults. Being only valid for LTI and SISO systems are the major drawbacks associated with this approach.

2. Modern Controls Methods

Modern control approach made the way for implementation of optimal or suboptimal control methods in the power system frequency control approach.

A detailed analysis of optimal control methods in the AGC system of an interconnected power system is presented in study [70]. An optimal PI regulator is used, which utilizes a performance index minimization criterion and employing a full feedback control strategy. The sensitivity analysis is conducted to ensure that the optimum controller is capable of operating effectively in the presence of abrupt load shifts and system parameter variations. Transient analysis is used to determine the dynamic response of a system, taking into consideration the settling period, over and undershooting, and damping parameters. The complexities of solving non-linear matrix equations in an optimal-AGC system are reduced by designing the sub-optimal AGC, which is based on the constrained feedback control technique and requires the feedback of only available states [71]. Major drawback with this approach is requirement of large storage space, complex structures and special configuration for a problem.

3. Intelligent Control Methods

In recent years, intelligent methods, such as artificial neural networks (ANNs), fuzzy logic, various optimization algorithms and hybrid intelligent techniques have been applied to evade the problems which were not solved via conventional techniques. These methods are found very capable and reliable in synthesis and analysis of AGC schemes in power system. The intelligent techniques due to their inherent salient features have been gained a due space for AGC schemes in restructured power systems since more than last two decades. Some of the important intelligent methods for AGC of restructured power systems are reviewed in the following subsections.

- **Fuzzy logic based AGC schemes**

Due to simplicity, robustness and reliability, fuzzy logic is used in almost all fields of science and technology, including solving AGC problems in restructured power systems. It offers instinctive design. Controllers are set up through practice and use of novel rules. Rules usually demonstrate control action. Contrasting the traditional control approaches, which are essentially based on the linearized mathematical models of the systems, the fuzzy logic control (FLC) technique tries to establish the controller directly based on the measurements, long term knowledge and experiences of domain experts. Various types of possible FLC structures are available in the literature. These structures are derived by considering various numbers and types of inputs and outputs, fuzzy sets, membership functions (mfs), control rules, inference engine (fis), and defuzzification methods. Some recent fuzzy logic-based controllers optimized using suitable optimization techniques are explored in [20-23]. Some major pitfalls are large number of tuning parameters, stability is not certain, use of trial and error for optimization and problems associated with comprehensive rules and their durability.

- **ANN based AGC schemes**

Artificial neural networks (ANNs) promote great interest due to their potential to learn better approximation of any arbitrary nonlinear function and their aptitude for use in parallel processing and multivariable systems. Power systems are imagined to be highly nonlinear as a whole and it is very difficult to model them mathematically for the analysis purpose. The ANNs works well for a system with non-linearities and uncertainties solving this problem to a great extent. The neural technology offers many more benefits in the area of nonlinear control problems, particularly when the system is operating over the nonlinear operating range. It is ideally suitable for multivariable and complex systems. Numerous types of topologies exist for ANN in deep learning algorithms that can be applied to both supervised and unsupervised learning approaches. The applications of neural networks in power system for solving AGC problem are witnessed in [24-28]. Moreover, a deep forest RL algorithm is designed in [28] as a preventive strategy for the dual and triple areas AGC problems. The flexibility of the ANN has been increased over time using the flexible sigmoid functions. The resultant network is called a flexible neural network (FNN) used for the design of the AGC system.an artificial FNN based AGC for a three-area integrated power grid network under a restructured environment is proposed in the literature [25] to attain the minimum acceptable regulation in the area frequency and to eradicate the effect of the disturbance during the heavy loading conditions and line disturbances.

- **ANFIS based AGC schemes**

The adaptive neuro-fuzzy inference system (ANFIS) is used as a supplementary controller which perform better compared to fuzzy and ANN controllers [29,30]. In [29], an ANFIS controller is designed for a three-area hydrothermal gas multi-source restructured power system which outperforms various intelligent controllers. In [30], an ANFIS controller designed for a two-area hydrothermal restructured power system with SMES–TCPS combination outperforms conventional PI and FLC controllers. In [31] ANFIS Based Controller is designed for AGC of a Hydro-hydro Power System with UPFC to improve dynamic performance of the system and Hydrogen Electrolyzer Units in series UPFC and tie-line. In [32] ANFIS based controller is designed for a four-area interlinked power system considering GRC and its superiority is shown when compared with PID and Fuzzy controllers.

4. Soft Computing control approaches:

- **Genetic Algorithm (GA)**

The genetic algorithm (GA) is a searching algorithm that uses the mechanism of natural selection and natural genetics. GA operates without the knowledge of the task domain and utilizes only the fitness of evaluated individuals. From the random initial population, GA starts a loop of evolution processes consisting of selection, crossover and mutation in order to improve the average fitness function of the whole population. The GA has been used to adjust parameters for different AGC controllers like I, PI, PID, sliding mode or variable structure controller etc. In the recent past, many studies exploiting GA dealing different restructured power systems have been appeared in the literature [33,34]. A GA tuned PI controller show improved results compared to a $H\infty$ controller in traditional and restructured power systems. Bhateshvar et al., presents GA based fuzzy controllers in [34]. An Adaptive PI-GA Based Technique for Automatic Generation Control with Renewable Energy

Integration is shown in [36]. Fuzzy logic-based GA optimized controller for a two-area system is shown in [37].

- **Particle Swarm Optimization (PSO)**

Kennedy and Eberhart proposed Particle Swarm Optimization technique in 1995. It is formulated using the social behavior of animal groups like bird flocking or fish schooling. They basically proposed that sharing information among the group increases the chances of survival of the group. For e.g., a flock of bird has better chances of finding the food than an individual bird. Advantage lies in sharing the mutual information with the group which would eventually help in discovering the best place to hunt.

It is a bio-inspired swarm based meta-heuristic optimization technique which used the concept of sharing information with the group to achieve the best solution possible. It uses flock of birds (particles or agents) which consists of swarm exploring the search space, looking for optimal solution. Each particles alters its velocity depending on its own and its group members' flying experiences and contributes by sharing its positional coordinates in solution space which are correlated with the best solution that has been attained by the particle so far [39].. In restructured environment PSO has been applied for tuning AGC controllers as stated in [38-40]. In [39] 2-DOF PID Controller is designed for a Wind turbine and Synchronous Generator for Load Frequency Control Optimization by PSO. In [40] Banaja Mohanty used a hybrid chemical reaction-PSO technique for AGC in two area power system considering GDB, GRC and BD.

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- **Firefly Algorithm (FA)**

The firefly algorithm (FA) is a nature-inspired metaheuristic optimization technique which is based on the socia (flashing) activities of fireflies in the summer sky in the tropical temperature regions. Its major benefit is the fact that it employs mainly real random numbers and is based on the global communication among the swarming particles i.e., fireflies and consequently, it appears further effective in multi objective optimization. The use of FA in AGC under deregulated environment is available in the literature [44,45,46,47]. Gorripotu et al., in reference [44] proposed a FA optimized fuzzy PID controller with derivative filter for AGC of restructured four-area reheat thermal power system with GRC and GDB. In [45] fuzzy PID controller optimized using FA for AGC of multi-area multi-source power systems with UPFC and SMES is being proposed. Results are being compared with GSA and DE based controller for same power system.

- **Differential Evolution (DE) Algorithm**

Differential evolution (DE) algorithm, a search heuristic algorithm, is a simple, efficient, reliable algorithm with simple coding. The major advantage of DE over GA is that GA uses crossover operator for evolution while DE relies on mutation act. Different types of controllers optimized via DE are available in the literature for restructured power systems [48]. Shaik et al., in [48] presents a DE based PID controller for solving AGC problem in nonlinear restructured two-area hydrothermal power system with doubly fed induction generator (DFIG) based wind turbine. DE based PID outperforms PSO based PID controller. In [50] PID controller is designed suing modified Differential evolution algorithm for AGC in two area power system. DE is modified by varying the value of mutation dynamically to increase its searching ability in both exploitation and exploration stage.

- **Bacterial Foraging optimization algorithm**

The bacterial foraging optimization algorithm (BFOA) is a fresh evolutionary technique in which the number of parameters used for searching the total solution space is much higher compared GA. The BFOA is inspired by the natural selection which tends to get rid of the animals with poor foraging strategies and favor those having triumphant foraging strategies. This optimization technique has been successfully implemented to solve AGC problems under deregulated environment [51,52]. Thirunavukarasu et al., proposed a PI2 controller tuned using BFOA for restructured two-area reheat thermal power system with RFB and unified power flow controller (UPFC) [51]. Yogendra Arya in [52] proposed Design and analysis of

BFOA-optimized fuzzy PI/PID controller for AGC of multi-area traditional/restructured electrical power systems.

- **Bat- Inspired Algorithm**

Bat search algorithm is a powerful swarm based meta-heuristic technique proposed by Xin-She yang in 2010 which is used for solving optimization problems. It is inspired by the echolocation behavior of swarm of bats which they use to search for food. Bats are extraordinary animals. They are the only mammals with wings and have advanced ability of echolocation. Bats navigate and find insect prey using this ability. They produce sound waves at frequencies above human hearing, called ultrasound. They emit sound waves which bounces of the neighboring objects and helps them in evading the obstacles. This also help them in locating their roosting crevices in dark. In [53] a novel design approached is used to propose a PID controller using Bat inspired algorithm to improve load frequency control and AVR. In [55] Magdy A. S. Aboelela implemented Bat inspired algorithm for AGC using traditional PID controller and hybrid fractional order and Brain Emotional Intelligent controller.

- **Teaching Learning-Based Optimization (TLBO)**

TLBO was proposed by R.V. Rao et al. and Rao and Patel in 2011. TLBO only requires control of common control parameters which are given by-size of population and Number of generations. It doesn't consist of algorithm specific parameters. TLBO is basically a population-based optimization technique that replicates the environment of a classroom teaching experience to optimize a specific objective function. This algorithm consists of two phases: (i) Teacher phase: -Imitates teaching of students through teacher. (ii) Learner phase: -Interaction of Students (Learners) amongst them to share their knowledge. In this algorithm every population member tries to gain something new from other population member to improve themselves. In a classroom, teacher teaches the students (Learners) to make them educated. Then the students interact with themselves to further alter and enhance their gained knowledge. Population is represented by the group of students (Learners) and different subjects offered in class is analogous to various design parameters of optimization problem. The fitness value of a specific optimization problem is represented by learner's result. Teacher is regarded as the best solution in the entire population. R.K. Sahu proposed a hybrid of TLBO and pattern search algorithm for a deregulated environment to overcome the drawbacks of TLBO. In [57] a Fractional order PID controller is optimized using TLBO in interconnected power system for AGC.

- **Water Cycle Algorithm**

It is one of recent optimization technique use by many researchers for solving difficult problems in various engineering fields. The provided algorithm has also developed interest in the field of AGC for gaining optimal values. This technique was proposed by proposed by Eskandari et.al in the year 2012 for solving many complex problems. The algorithm is population-based searching technique enthused from the movement of water cycle. The initial population is taken to be rivers and global best solution is the sea. The raindrops occurring after rain will act as the solution for finding the solution for the given problem. The proposed algorithm is presented in the recent paper with 3DOF-PID controller for improving the performance of the system [58].

- **JAYA**

Jaya algorithm is a newly published meta-heuristic optimization algorithm developed by R. Venkata Rao (Rao 2016) and that means victory. Jaya algorithm is enthused by TLBO algorithm and in TLBO we required two phases but in Jaya we work upon only single phase that makes Jaya algorithm a very advanced and simpler technique . In this paper the Jaya algorithm is being modified for optimizing the parameters of the PID controller. Jaya Algorithm's working principle is based on the fact that the obtained numerical solution that has been attained must move towards the best solution and avoid the solutions that are inferior for the given optimization problem. Traditional Jaya algorithm has many benefits and very easy implementation for solving various optimization problems as tuning of the particular parameters are not required. As, the Jaya algorithm works on simpler notion that is it approaches towards the best solution and avoids worst solution. Nidhi Gupta proposed a PID controller based on JAYA algorithm and compared that with Bat algorithm for generation control strategy in diverse source power system with varying participation factor [53].

- **Moth flame Optimization**

This algorithm is a nature-inspired optimization technique and is inspired from the action of moths. The navigation method of moths present in nature is the main inspiration for performing this technique. This navigation method is defined as transverse orientation. As these moths fly in night and uses the moon direction for the movement at a fixed angle and this is the very effective technique used by moths to travel along a straight line for a longer distance. The same navigation method is used by humans. In the proposed algorithm it is supposed that the provided moths are represented as the candidate solution and problem variables are the moth's position in the given search space. In the stated paper the novel MFO technique is used for a hydro system in AGC [59,60].

- **Improved Artificial Electric Field**

In the physical world the electrostatic force is one of the major fundamental forces. The idea of charge particles and electric field gives a theory related to charge particles and the force of attraction or repulsion between two charged particles. This optimization technique is also a nature-based algorithm that works on the natural phenomena and is also inspired from the Coulomb's law of electrostatic force. Artificial electric field algorithm has been designed in such a way that it works as a population-based optimization technique. In population the charge is treated as fitness value. In recent researches a novel improved Artificial Electric Field Algorithm has been used in AGC for minimizing area control error and to find the optimal solution [61].

- **AGC with ESD and FACTS**

The researchers over the world wide have proposed various control strategies for various types of restructured power system to control the governor action so that the system frequency and tie-lie power deviations are kept minimal and GENCOs may generate the required electrical power in the most effective manner. The effectiveness of these novel control strategies can further be enhanced in the presence of energy storage devices (ESD) and flexible AC transmission systems (FACTS) devices. Energy storage units such as battery energy storage (BES), capacitive energy storage (CES), redox flow battery (RFB) and superconductive magnetic energy storage (SMES) can successfully damp oscillations in a power system because they offer storage capacity in addition to the kinetic energy of the generator rotor, which can share the sudden alterations in power requirement. The incorporation of CES [62], RFB [63] and SMES [62] in AGC of restructured system is available the literature Different FACTS devices are thyristor-controlled phase shifter (TCPS), static synchronous series compensator (SSSC), interline power flow controller (IPFC), thyristor-controlled series compensator (TCSC), unified power flow controller (UPFC), gate-controlled series capacitor (GCSC) etc. Numerous studies have been explored the prospective of using FACTS devices for enhanced power system control since they provide more flexibility.

2.2. Conclusion

A comprehensive and critical review of the published literature in the area of AGC of traditional/restructured power systems has been presented in this chapter. Though, the more emphasis is paid on the review of the literature on AGC schemes in multi-source multi-area power systems. The literature on recent developments like AGC schemes based on the concepts of intelligent strategies including fuzzy logic, neural networks, mixed fuzzy-neural and various soft computing techniques like GA, PSO, BFOA, ABC, FA, DE etc., have been reviewed significantly. Various AGC strategies, types of multi-area single/multi-source systems with and without energy storage units, FACTS devices and AC/DC tie-line have also been reviewed.

Considering the above work done, the following are the main objectives of this paper:

(1) To design a TID controller with TLBO and PSO optimization technique for interconnected multi-area multi- source power system. i.e., thermal, hydro, and gas power sources in each control area.

(2) The superiority of TLBO will be seen by comparing with PSO based controller and traditional PI controller for the same system at 0.1 per unit SLP in control area-1 in terms of performance index value, performance parameters in terms of settling time, and dynamic response in terms of deviation in frequency and tie -line power.

CHAPTER-3

SYSTEM MODELLING

3.1. Power System

Commonly utilized energy sources in the power generating plants consists of coal, oil, nuclear energy and falling water. Therefore, in current scenario, the control areas are supposed to have various types of generating sources. In this chapter, mathematical models of two-area interconnected power systems are developed which consists of power plants having multi-source like hydrothermal and thermal gas sources. The two-areas are interconnected in traditional as well as restructured configurations. The transfer function models of the systems in state variable form are developed for each component of the system.

3.1.1. System Transfer Function

In a power system, the synchronous generators are normally driven by prime mover getting energy from sources like hydro, thermal and gas. These prime movers are used to convert energy obtained from these sources into mechanical energy. Then synchronous generators convert this mechanical energy into electrical energy. The prime mover governing systems provide a means of controlling power and frequency, a function commonly referred to as load-frequency control or automatic generation control (AGC) [5].

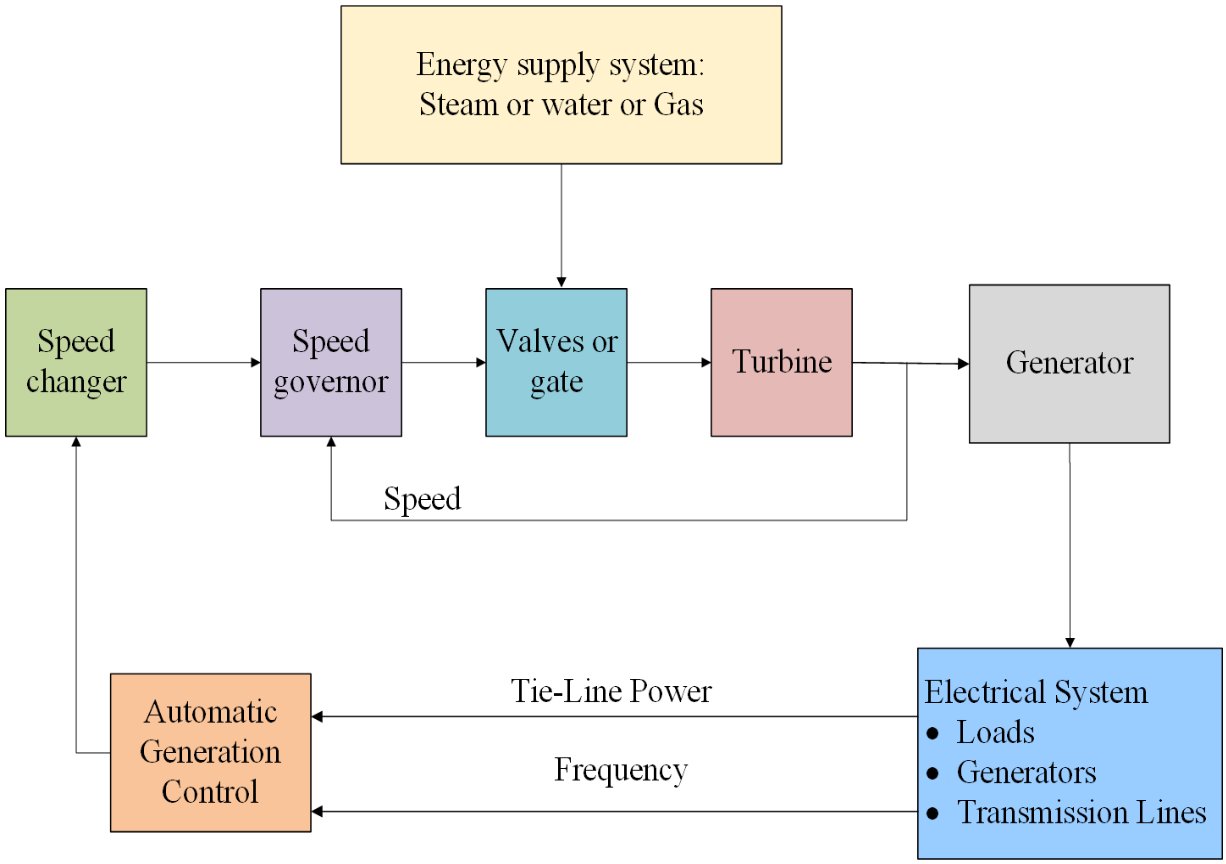

Fig. 3.1. Functional relationship between the basic elements associated with power system operation and control.

When there is a load change, it is reflected instantaneously as a change in the electrical torque output of the generator. This causes a mismatch between the mechanical torque and the electrical torque which in turn results in speed variations [4]. Governor then adjusts the turbine valve/gate to bring the frequency back to the nominal or scheduled value. Fig. 3.1 represent the speed governing mechanism associated with power system operation and control. The measured rotor speed is compared with reference speed. The error signal (equal to speed deviation) is amplified and integrated to produce a control signal which actuates the main steam supply valves in the case of a steam turbine, or gates in the case of a hydraulic turbine. Because of the reset action of this integral controller, will reach a new steady state only when the speed error is zero [5].

- **Modelling of Thermal Power Plant**

The coal based thermal power plant contains fuel and the energy associated with this is used for generating high temperature and pressure steam in the reservoir. In axial flow steam turbines, the generated steam energy is then converted into mechanical energy. The turbine is having number of rotating and stational blades that are concentrated into various assemblies. Whenever the steam passes through the stationary blades it starts accelerating and attains an increase in kinetic energy. The steam then experiences a change in direction and momentum when it is directed on to the rotating blades of the turbine. Therefore, a tangential force is exerted on the blades of the turbine and the torque output on the shaft of the turbine. Then the steam tends to pass axially along the shaft of the turbine this will lead to increase in volume, reduction in pressure and increase in the blade length from the ingress of the steam. In thermal power plant the steam turbine is distinguished into three phases, in which each phase is linked on a mutual shaft. The turbine is classified into multiple phases so to make steam reheat between stages to enhance and continuously increment the complete efficiency of the steam cycle. In this present work the main focused classification of the steam turbine is as follows: reheat and non-reheat turbines.

The non-reheat turbines are constructed for the units less than 100 MW and have one turbine phase. The steam flow in the turbine is controlled by the governing system. In this there is a speed measurement device for governing the speed signal. The foremost amplifies of the valve mover and governing system is an oil servomotor that is regulated with the help of pilot valve. During emergency conditions the emergency stop valves are required to halt the generator and mostly used to regulate the primary start-up of the turbine whenever the generator is synchronized [5].

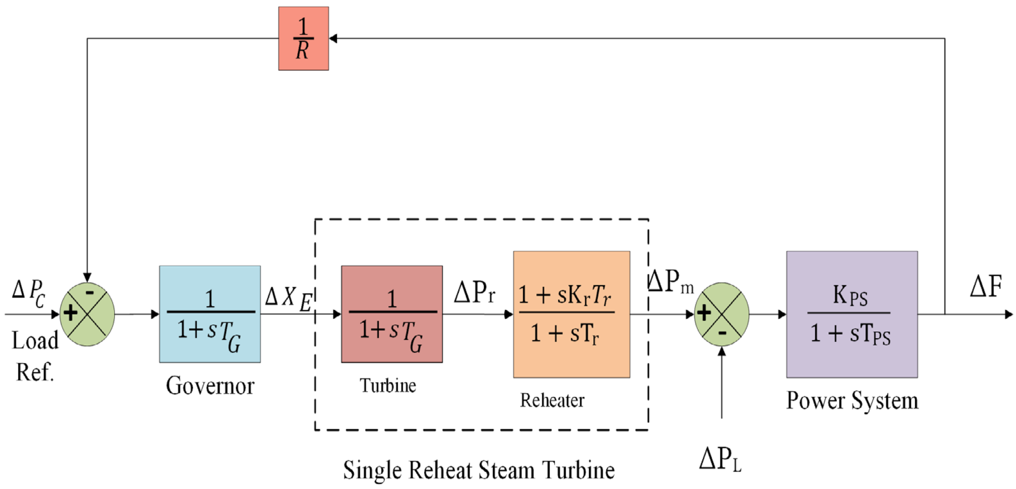

Fig. 3.2. Block Diagram of reheated steam turbine with speed governing system.

Fig. 3.2 shows its approximate linear transfer function model (TFM). Equation 3.1 represents single reheat steam turbine which is given below as

$$\Delta P_m(s) = \frac{1+sK_rT_r}{(1+sT_G)(1+sT_r)}\Delta X_E(s) \tag{3.1}$$

Where, Kr is the reheat coefficient which is the fraction of the power generated in the high-pressure cylinder. The deviation in output power of single reheat steam turbine in response of change in governor setting is represented by Equation 3.2.

$$\Delta X_E(s) = \left(\frac{1}{1+sT_G}\right)\left(\Delta P_c(s) - \frac{\Delta F}{R}\right) \tag{3.2}$$

- **Modelling of Hydro Power Plant**

In Hydro power plant, the hydraulic turbine uses the force applied by the water when it falls on the lower reservoir from the upper reservoir. The upright distance between level of the tank and the upper reservoir is defined as head. The different categories of hydraulic power plants are lower head, medium head and higher head that are categorized by the size of the head, however there is no such harsh delineation line. The hydraulic turbines actually are of two basic types, the impulse turbines and reaction turbines. The impulse turbines (or Pelton Wheel) are mostly used for high heads that is 300m or more. In this the runner is at the atmospheric pressure and the complete pressure drop takes place in the nozzles that are stationary. These help in converting it into kinetic energy from the potential energy. The jets with the high velocity of water interrupt the spoon-shaped buckets on the runner this tends to rebound the water at axially about 160 degrees. The variation in momentum offers the torque to drive the runner as the supplied energy being completely kinetic [5].

Low and medium head hydro plants are built employing reaction turbines such like a Francis turbine. The pressure inside the reaction turbine is above atmospheric and the energy provided by the water is both potential as well as kinetic and that is the pressure head forms, right, both kinetic and potential forms. The reaction turbines generally use large water passage, need large volume of water and functions at low speed because of the comparatively low-pressure head. The generator is having a larger diameter due to the less revolving speed.

The features of the water column feeding the turbine are influencing the performance of the hydraulic turbine. This comprises of water compressibility, pipe wall elasticity in the penstock and effects of water inertia. The effect of water inertia is produced due to the variations in turbine flow to lag behind fluctuations in gate openings of the turbine. So, effect of elasticity in travelling waves causes flow and pressure inside the pipe and this phenomenon is known as water hammer effect. The detailed modelling of hydraulic turbines entails enclosure of transmission line such as reflection that occurs in the elastic walled pipe carrying compressible fluid. Fig 3.3 represents the block diagram of hydro power plant. The simplest transfer function of the hydraulic turbine is given by:

$$\frac{\Delta P_{Gh}}{\Delta X_E} = \frac{1-sT_W}{1+0.5sT_W} \quad (3.3)$$

And for mechanical hydraulic governor is:

$$G_{HG}(s) = \left(\frac{1}{1+sT_{RH}}\right)\left(\frac{1+sT_R}{1+sT_{GH}}\right) \quad (3.4)$$

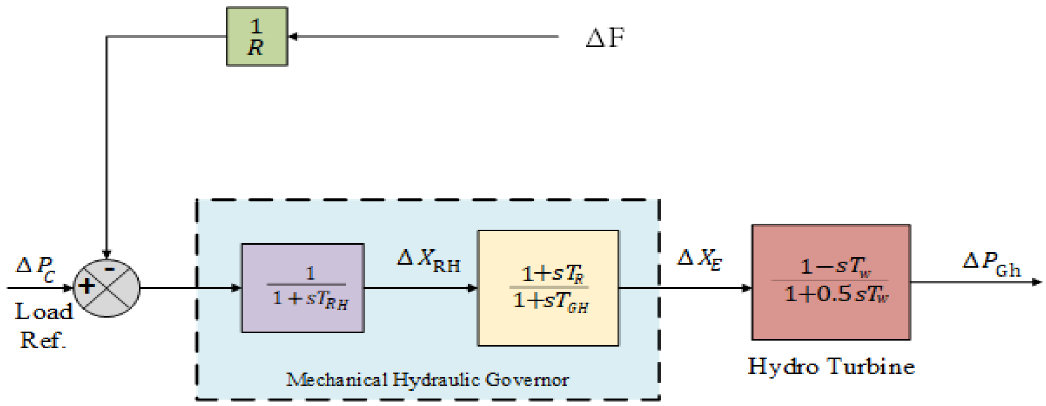

Fig. 3.3. Block diagram of Hydro power plant

- **Modelling of Gas Power Plant**

In gas power plant the gas turbines do not require transitional working fluid and in this thermal energy is being transformed into mechanical energy employing the burning turbine consumed gases. In this the air is used as the working fluid with the fuel being heavy, medium fuel oil or natural gas. The furthermost prevalent system for gas turbines is the open regenerative cycle and it is comprised of a turbine, combustion chamber and compressor. The fuel is then supplied to the combustion chamber from the governor valve to be burnt in the existence of air provided by the compressor. The hot and compressed air is then mixed with the burning products which is further directed into the turbine where it transfers and expands its energy to the moving blades as that of steam turbine[5]. The consumed gases are then used to heat the air distributed by the compressor. Fig. 3.4 represent all the components mentioned in gas power plant with speed governing system. There are also other, more complex cycles that use either inter-cooling or compressor inter-cooling with reheating or regeneration.

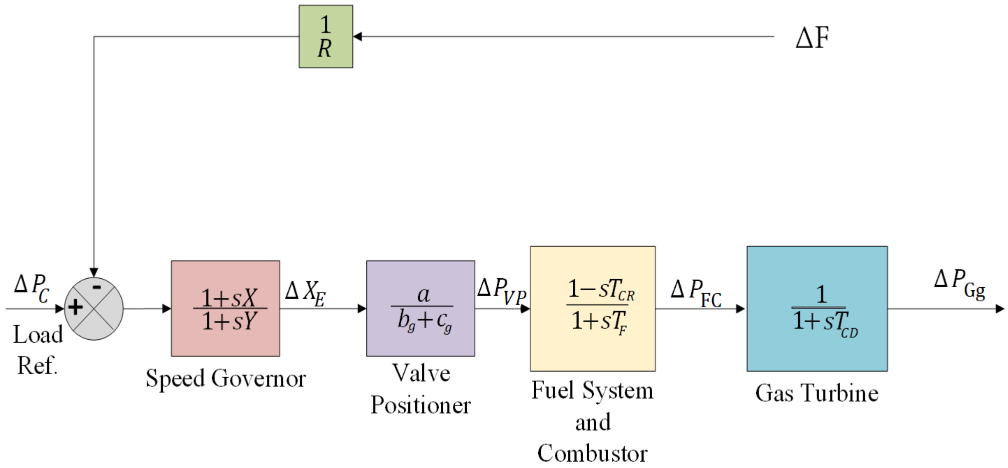

Fig. 3.4. Block diagram of Gas power plant

For small load perturbation, the change in setting of gas turbine governor (ΔX_E), valve positioner (ΔP_{VP}), fuel and combustor system (ΔP_{FC}) and gas turbine power output (ΔP_{Gg}) are given by subsequent mathematical relations**.**

$$\Delta X_E = \left(\frac{1+sX}{1+sY}\right)\left(\Delta P_c - \frac{\Delta F}{R}\right) \quad \textbf{(3.5)}$$

$$\Delta P_{VP} = \left(\frac{a}{c_g+sb_g}\right)\Delta X_E \quad (3.6)$$

$$\Delta P_{FC} = \left(\frac{1-sT_{CR}}{1+sT_F}\right)\Delta P_{VP} \quad (3.7)$$

$$\Delta P_{Gg} = \left(\frac{1}{1+sT_{CDi}}\right)\Delta P_{FC} \quad (3.8)$$

The overall transfer function model for gas turbines can be given by uniting Eqns. (3.5) to (3.8).

- **Modelling of Tie-Line**

When two control areas of a power system are interconnected via AC tie-line, the synchronizing coefficient (T_{12}) is given by: -

$$T_{12} = P_{12max} \cos(\delta_1 - \delta_2) \tag{3.9}$$

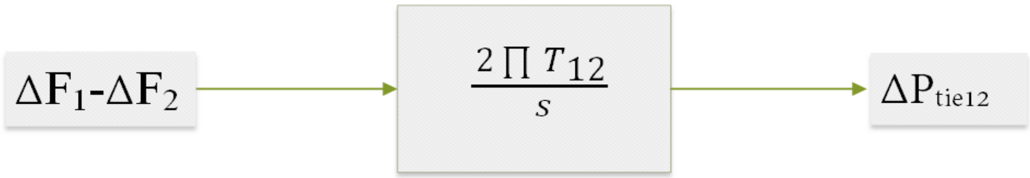

Fig. 3.5. Block diagram of AC Tie-Line

For small load perturbation, the deviation in tie-line power flow (ΔP_{tie12}) is given by Fig. 3.5 and mathematical expression is given below

$$\Delta P_{tie12} = \frac{2\prod T_{12}}{s}(\Delta F_1 - \Delta F_2) \tag{3.10}$$

The ratio of area power rating (α_{12}) can be defined as:

$$\alpha_{12} = -\frac{P_{r1}}{P_{r2}} \tag{3.11}$$

3.2. Non Linearities

Practical power systems are nonlinear in nature having a variety of nonlinearities and physical constraints. Consequently, for studying the problems occurring in an AGC system, it is necessary to comprise the main intrinsic limitations and nonlinearities in the described power system model. The chief constraints that influence the system performance significantly are generation rate constraint (GRC) [64,65], boiler dynamics (BD) [65,66] and governor dead band or dead zone (DZ) nonlinearity [66,67] as described following in brief.

3.2.1. Generation Rate Constraint

In real world because of the boundations of mechanical and thermal movements, electric power generation plants cannot modify their power outputs too quickly which can be defined as generation rate constraint (GRC). GRC is given in a percentage of the rated output of the generator per unit of time. It offers big challenge to the control approaches employed because they radically persuade the system dynamic performance. In a pragmatic AGC study, GRC impacts must be integrated. Under the nonappearance of GRC, undesirably, generators are anticipated to chase large temporary disturbances that may turn power generation network to unstable [64]. The time results of the given power system in the existence of GRC show bigger overshoots and longer settling time in comparison to the system having no GRC. Further, if the parameters of the controller are not optimized properly, the power system may turn unstable in the presence of GRC [64].

3.2.2. Boiler Dynamics

In this, Boiler is used to produce steam under pressure. It receives feed water warmed in the economizer and gives the outputs in the form of saturated steam. Recirculation boiler uses a drum to isolate steam from the recirculation water aiming to proceed it to the superheater as a heatable vapour [65]. Thus, the recirculation boilers are denoted to as drum type boiler.

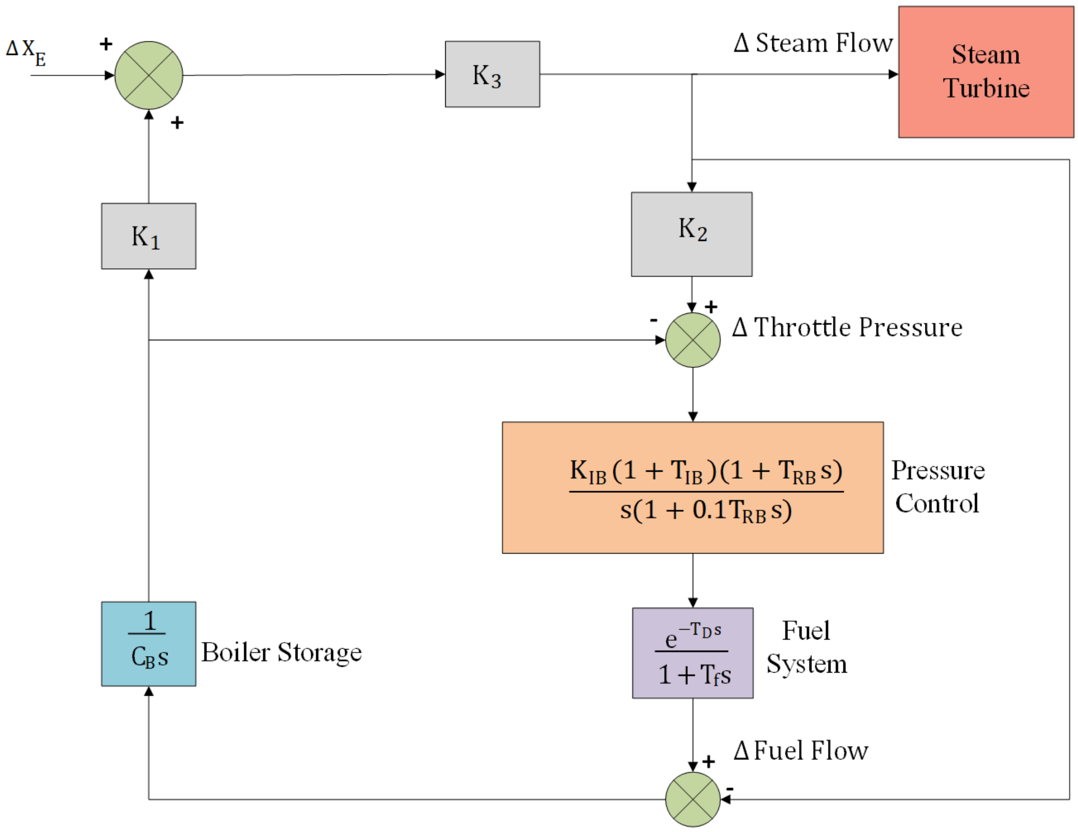

Fig. 3.6. Block diagram representing Boiler Dynamics in Thermal Turbine.

The change in generation is started by turbine control valves and the boiler controls respond with essential control action, variations in steam flow and variations in throttle pressure, the combustion rate and hence output of the boiler [66]. To launch long-term dynamics of fuel and steam flow on the boiler drum pressure, boiler dynamics (BD) are incorporated in thermal units. Fig. 3.6 shows the boiler dynamics model of a coal fired well-tuned drum type boiler. The transfer function models of pressure control unit and fuel system are given in Equations:

$$G_{PC} = \frac{K_{IB}(1+sT_{IB})(1+sT_{RB})}{s(1+0.1sT_{RB})} \tag{3.12}$$

$$G_{FS} = \frac{e^{-sT_D}}{1+sT_f} \tag{3.13}$$

Employing 2nd order Pade approximation method, e^{-sT_D} can be approximated as specified in Equation (3.14)

$$e^{-sT_D} = \frac{1-\frac{sT}{2}+\frac{s^2T^2}{2}}{1+\frac{sT}{2}+\frac{s^2T^2}{2}} \tag{3.14}$$

The linear transfer function model of BD is derived using signal flow graph technique as:

$$G_{BD} = \frac{K_3(1+G_1G_2)}{1-K_1K_2K_3G_1G_2 + G_1G_2 + K_1K_3G_2} \tag{3.15}$$

Where, $G_{BD} = G_{PC} \times G_{FS}$ This contains the long-term dynamics of steam and fuel flow on boiler drum pressure. Demonstrations for combustion controls are also included. Although, the model is principally a boiler that is drum type, comparable responses are noticed for once through pressurized water reactors and boilers. The model is effective to learn about the coal fired units with weakly tuned (oscillatory) combustion controls, coal fired units with fine-tuned controllers and well-tuned gas or oil-fired components [65]. In conventional thermal units, generation changes are instigated by valves in turbine control and the boiler controls counter with obligatory prompt control action after observing deviations in pressure and changes in steam flow. The BD nomenclatures and parameters are specified in Nomenclature section and Appendix 2, respectively.

3.2.3. Governor Deadband

Governor Deadband is one of the key concerns in power system's dynamic performance as it makes the system more oscillatory. The GDB is the total magnitude of a sustained speed change where in there is no resulting change in valve position [66]. It can be defined as the range of speed after which governor action starts. There should only be a limited percentage of Deadband in system to avoid hunting of governor and for stable operation. Response of governor is sluggish if Deadband is high. It is usually given in per cent of rated speed. In traditional power system operating environment, the effect of GDB on performance of AGC regulator has been investigated in [66,67].

3.3. Objective Function

Objective function is defined as the system objective expressed as a function of the decision variables. Optimization technique makes use of an objective function to find the value of decision variables in a manner in which objective function is being maximized or minimized. It is an approach to achieve best solution possible. It is a real valued function to be optimized under some constraints and it defines the relationship between input and output of a system which is represented by the function. A minimization problem has been used in this work to minimize the deviations in frequency and tie line power. The fitness is inversely proportional to the objective function in minimization problems. General mathematical expression of objective function is given by: -

$$Maximize\ or\ Minimize = \sum c_i X_i \tag{3.16}$$

Where

- c_i is the coefficient that matches the i^{th} variable
- X_i is the i^{th} decision variable

Performance of the controllers is studied based on different performance indices. There are four types of indices which are given by: -

1. Integral of Square Error
2. Integral of Time multiplied Square Error
3. Integral of Absolute Error
4. Integral of Time multiplied Absolute Error

Their Mathematical representation is shown as below: -

- $ISE = \int e(t)^2 . dt$ (3.17)
- $ITSE = \int e(t)^2 . t . dt$ (3.18)
- $IAE = \int e(t) . dt$ (3.19)
- $ITAE = \int e(t) . t . dt$ (3.20)

Upon analysing the different performance indices, it has been found that the system performs better using ITAE. Objective Function consists of amalgamation of fluctuations in frequency and tie line power and its mathematical expression can be shown as below: -

$$ITAE = \int_0^{tsim}(|\Delta F| + |\Delta Ptie_{12}|).t.dt \quad (3.21)$$

3.4. Modelling and Simulation

In present work, two area Multi Source system is taken into consideration. Area 1 contains two sources-Thermal unit with Reheat Turbine and other being Hydrothermal plant. Area 2 contains one thermal unit using reheat turbine and other being Gas Power Plant. Area 1 and Area 2 are interconnected via AC tie-line. For regulating tie line power as well as frequency deviations, TID controller is being used in each area. Area Control Error comprises of Sum of fluctuations in frequency and tie line power which is being fed to implemented controller whose gains are optimized using TLBO algorithm. TID controller minimizes ACE signal. The ACE in each area is explained as follows: -

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_1 \quad (3.22)$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta f_2 \quad (3.23)$$

Where ΔP_{12} and ΔP_{21} represent the tie-line power changes in both areas respectively. Δf_1 and Δf_2 are the frequency variations in each area. B_1 and B_2 represent the frequency bias coefficient of each area. When a sudden load deviation occurs in the system, area controller errors being fed to the TID controllers are minimized to attain stability in tie line power and frequency deviations.

The system considered is a restructured two-area multi-source with area capacities of 2000 MW. The thermal areas are equipped with Reheat turbine, mechanical governor based hydro turbine plants and gas power plant. Hence, each area consists of two sources. The GRC for Reheat thermal unit is considered 10%/min

(0.0017 pu/s) and for hydro power plant, it is considered 360%/min for lowering generation (−0.06 pu/s) and 270%/min for raising generation (+0.045 pu/s) [53]. The boiler dynamics (BD) are considered in between governor and turbines of each thermal GENCO. The standard magnitude or maximum limit value of dead zone (DZ) for governors of steam turbines is taken as ±0.0006 pu or ±0.06% (±0.036 Hz) and for hydro governors, a DZ of ±0.0002 or ±0.02% (±0.012 Hz) is considered [68]. The block diagram of SIMULINK model of system is shown in Fig. 3.7.

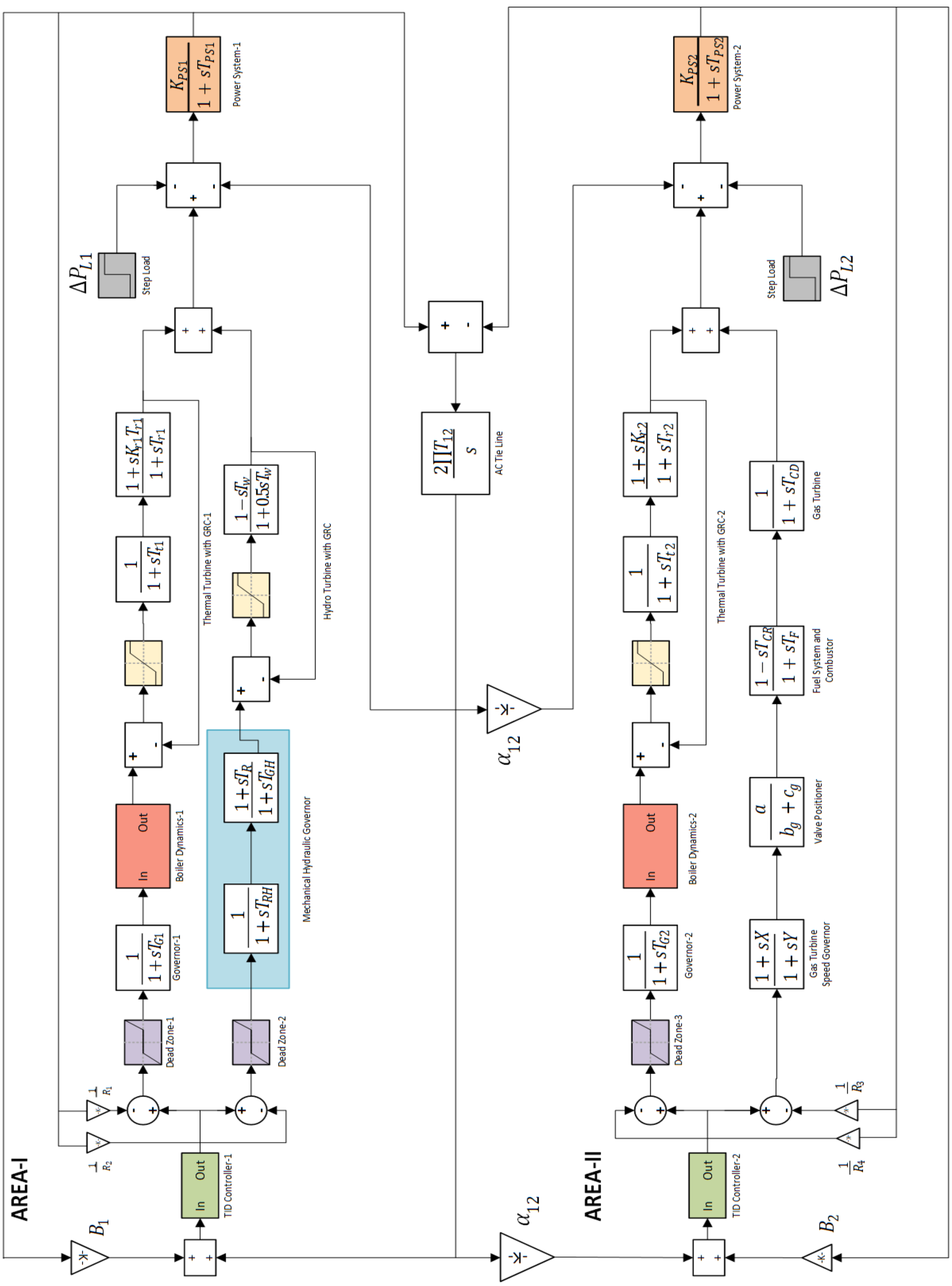

Fig. 3.7. Block diagram of SIMULINK model

CHAPTER-4

OPTIMIZATION TECHNIQUES

4.1. Introduction

Optimization is a collection of methods and mathematical principles used for solving quantitative problems in many disciplines like engineering, biology, business and physics. Mathematical elements in different disciplines are common when it comes to solving quantitative problems and this commonality led to the growth of optimization in vastly different fields but the main crux of using them remains the same which is to obtain the best solution possible under pre-defined constraints and assumptions. The development of optimization techniques is not limited only to computer science but also in control theory, mathematical economics, numerical analysis, operations research, numerical analysis and game theory.

Basically, Optimization problems consists of three fundamental elements: -

- **Objective Function**- Depending on the nature of problem, It needs to be maximized or minimized.
- **Variables**- Quantities whose values needs to be altered in order to optimize the objective.
- **Constraints**- Boundations on the values of variables which they can attain.

Optimization algorithm is a process which is implemented recursively by comparing many feasible solutions till an optimum solution is obtained. With the advancement in the field of computers, it has become an integral part of computer-aided design courses. Optimization algorithms are basically of two different types: -

(a) **Deterministic Algorithms**-It is an algorithm which is purely dependent on its inputs. Specific set of rules are followed every time to obtain the result without incorporating any randomness in the model. They are also called as reliable algorithms because for a particular set of input instructions the machine will always give the same output. These algorithms have been successfully applied for many engineering design problems.

(b) **Stochastic Algorithms**-As the name suggests these optimization techniques involves some kind of randomness in the model. These algorithms use their stochastic nature as part of search procedure. This search procedure increases the probability of finding the global optima. It also allows the algorithms to avoid getting trapped in a loop and attain results far better than deterministic algorithms in case of high dimensional non-linear objective problems.

Further classification with different types of optimization techniques has been given in Fig. 4.1 below:

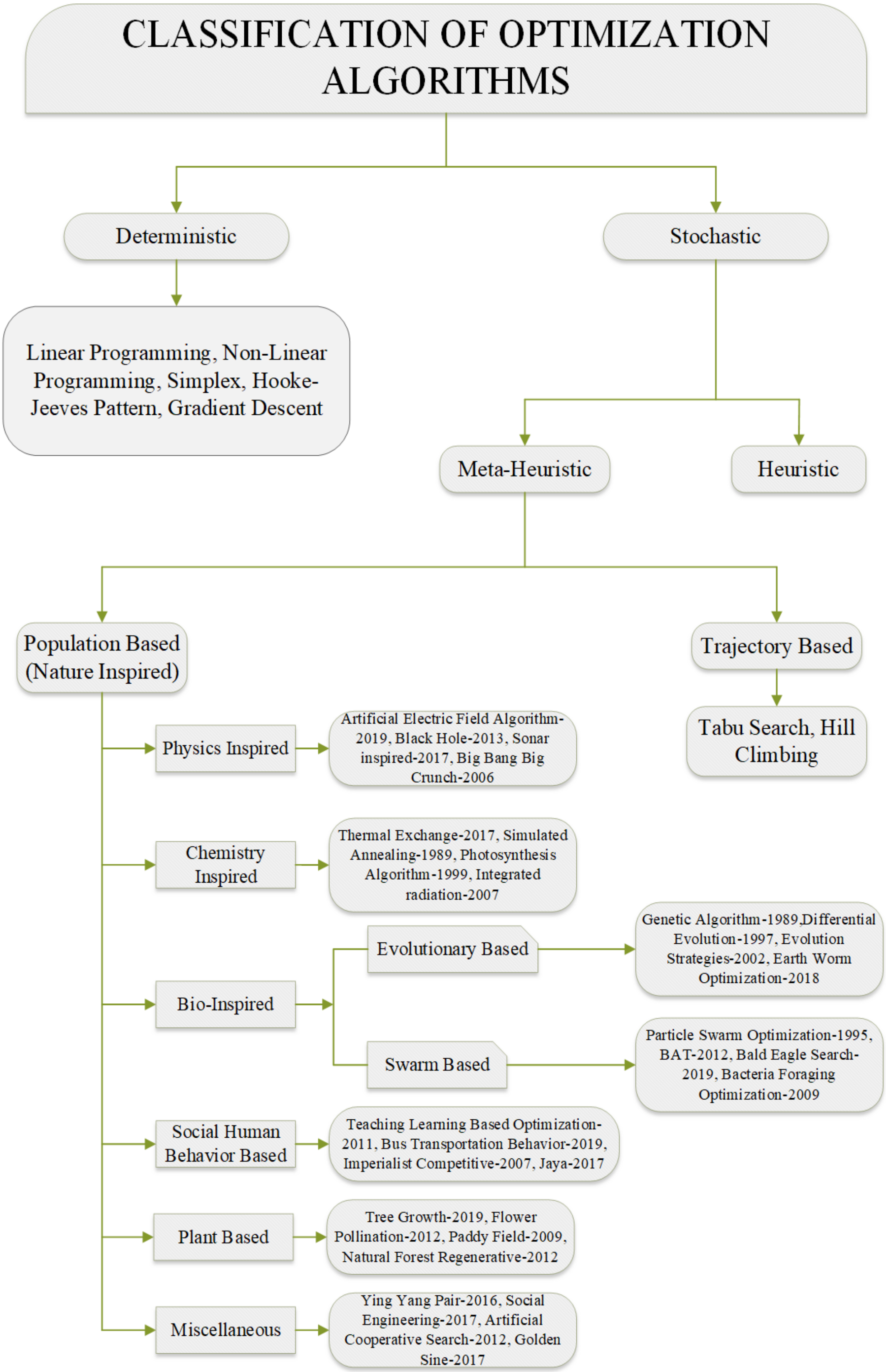

Fig. 4.1. Classification of optimization techniques

Formulation of optimization problem: -

In this process, A prominent design is acquired when comparing the solutions achieved iteratively using former knowledge of problem. First, we need to investigate the feasibility of each solution by choosing optimal design variables. Best solution is attained by comparing each solution with respect to minimization or maximization of objective function. Fig. 4.2 shows an outline of the steps usually involved in an optimal design formulation. Objective of formulation is to create a mathematical model of the optimal design problem, which then can be solved using an optimization algorithm.

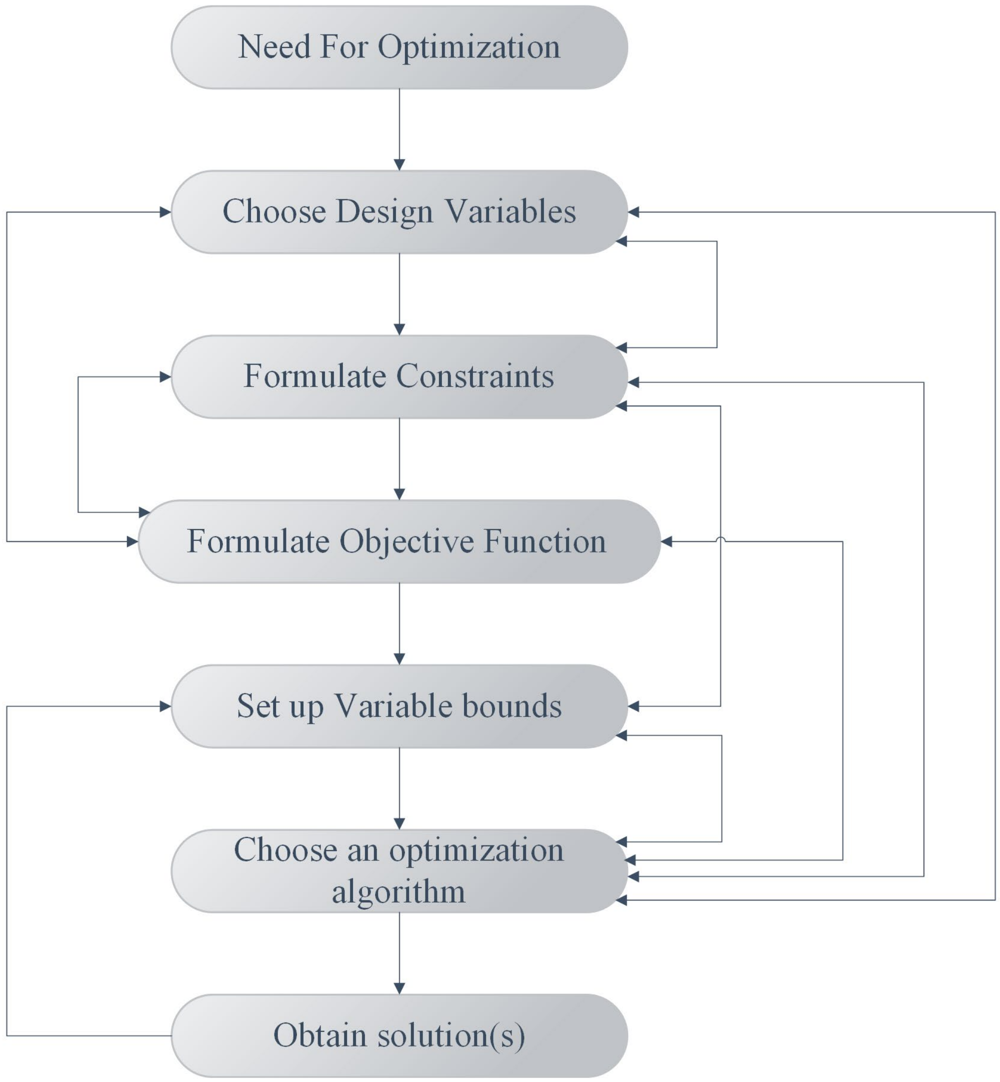

Fig. 4.2. Flowchart of the optimal design procedure

Design variables: The first step begins with finding the design variables which are modified during optimization process. An optimization problem consists of many design variables/parameters out of which some parameters can be highly sensitive to the proper functioning of algorithm. Other less important parameters usually remain fixed. Thumb rule is to keep the number of design variables to as minimum as possible. After this, the outcome of the problem will decide whether new variables need to be incorporated in the formulation or replace the old ones.

Constraints: It's a set of restrictions applied on the values of design variables which they can attain. User decides the number and nature of constraints which need to be incorporated into the system. Constraints may or may not have an exact mathematical expression. This depends on the type of problem, objective function and system which is being considered. Basically, there are two types of constraints which emerge from most considerations:

1. *Inequality type constraints*- states that the functional relationships among variables are either active, ε-active, violated or inactive to a resource value

2. *Equality type constraints*- state that functional relationships should exactly match a resource value

Objective functions: The next step is to find the objective function in terms of problem parameters and design variables. Optimization algorithm involves minimization or maximization of objective function to achieve the best solution possible.

Variable bounds: The final step is to set the upper bounds and lower bounds of each design variables which restricts the values in a certain range and objective function doesn't attain arbitrary values. In case of any design variables violating the upper bounds or lower bounds, chosen bounds can be modified or variables can attain that limiting value and optimization algorithm may be simulated again.

4.2. Teaching-Learning Based Optimization

To find optimal solutions to the problems, several modern meta-heuristic algorithms have been proposed. These algorithms basically depend on common control parameters and algorithm-dependent control parameters. It is very important to regulate the control parameters which are algorithm-dependent otherwise the performance of the optimization will not be optimal. Inappropriate tuning can result in more computational efforts and getting trapped in local optimal solution. Keeping in mind all these problems, TLBO was proposed by R.V. Rao et al. and Rao and Patel in 2011. TLBO only requires control of common control parameters which are given by-size of population and Number of generations. It doesn't consist of algorithm specific parameters. TLBO is basically a population-based optimization technique that replicates the environment of a classroom teaching experience to optimize a specific objective function**.** Inspiration for this algorithm is knowledge transfer in a classroom environment. Required parameters for this optimization technique is-Population size and number of iterations. In this algorithm every population member tries to gain something new from other population member to improve themselves. In a classroom, teacher teaches the students (Learners) to make them educated. Then the students interact with themselves to further alter and enhance their gained knowledge. Population is represented by the group of students (Learners) and different subjects offered in class is analogous to various design parameters of optimization problem. The fitness value of a specific optimization problem is represented by learner's result. Teacher is regarded as the best solution in the entire population [69]. Schema chart of TLBO is presented through Fig. 4.3.

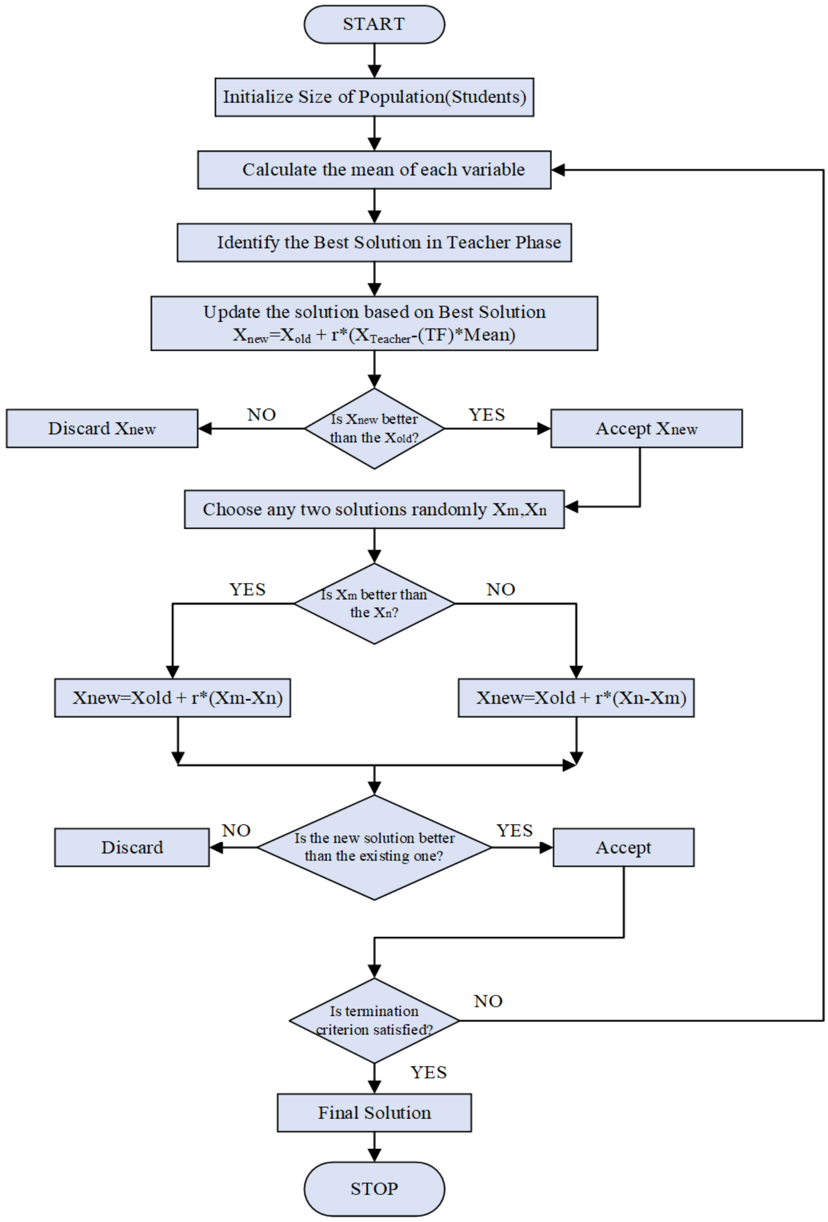

Fig. 4.3. Flowchart OF TLBO

This algorithm consists of two phases:

(i) Teacher phase: -Imitates teaching of students through teacher.

- New solution is generated using best solution and mean of the population(class).
- Greedy Selection: New solution will be accepted if better than the current solution.
- Teacher: Solution corresponding to the best fitness value.

- After selecting the teacher, we have to generate a new solution using equation given below. Each variable in a solution(X) is modified as

$$X_{new} = X + r(X_{best} - T_f X_{mean}) \quad (4.1)$$

- Where

  X=Current solution

  X_{new}= New solution

  X_{best}=Teacher

  X_{mean}= Mean of the population

  T_f= Teaching factor, either 1 or 2

  r= Random number between 0 and 1

  T_f =is same for all variables of a solution

  r=to be selected for each variable
- Selection of solution-Evaluate fitness (f_{new}) of the new solution (X_{new}) generated in teacher phase. Perform greedy selection to update the population.

$$\left.\begin{aligned} X &= X_{new} \\ f &= f_{new} \end{aligned}\right\} \text{If } f_{new} < f \quad (4.2)$$

X and f remains the same if $f_{new} > f$.

(ii) Learner phase: -Interaction of Students (Learners) amongst them to share their knowledge

- New Solution is generated using a partner solution
- Greedy selection
- Partner solution: Randomly selected solution from the population. Each variable of solution is modified as

$$X_{new} = X + r(X - X_p) \text{ if } f < f_p \tag{4.3}$$

$$X_{new} = X - r(X - X_p) \text{ if } f \geq f_p \tag{4.4}$$

- Where

  X=Current solution

  X_{new}= New solution

  X_p=Partner solution

  f = Mean of the population

  f_{new}= fitness of partner solution

  r= Random number between 0 and 1

- Learner phase: Bounding and selection of solution. Bound the newly generated variables, if required

  x= lb if x<lb

  x=ub if x>ub

- Evaluate fitness of new solution (f_{new}) generated using learner phase equation. Perform greedy selection to update the population member

$$\left.\begin{aligned} X &= X_{new} \\ f &= f_{new} \end{aligned}\right\} \text{ If } f_{new} < f \tag{4.5}$$

X and f remain the same if $f_{new} > f$.

Each solution undergoes teacher phase followed by learner phase as shown in Fig. 4.4.

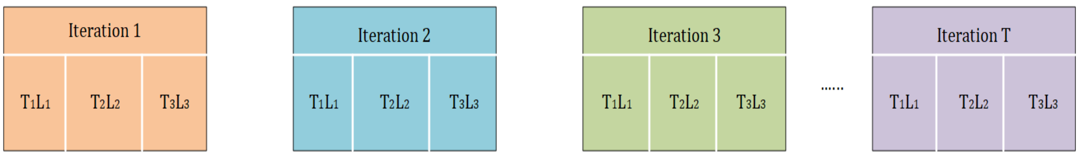

Fig. 4.4. Block diagram representing iterations in Teacher and Learner phase of TLBO

4.3. Particle Swarm Optimization

Kennedy and Eberhart proposed Particle Swarm Optimization technique in 1995. It is formulated using the social behavior of animal groups like bird flocking or fish schooling. They basically proposed that sharing information among the group increases the chances of survival of the group. For e.g., a flock of bird has better chances of finding the food than an individual bird. Advantage lies in sharing the mutual information with the group which would eventually help in discovering the best place to hunt.

It is a bio-inspired swarm based meta-heuristic optimization technique which used the concept of sharing information with the group to achieve the best solution possible. It uses flock of birds (particles or agents) which consists of swarm exploring the search space, looking for optimal solution. Each particles alters its velocity depending on its own and its group members' flying experiences and contributes by sharing its positional coordinates in solution space which are correlated with the best solution that has been attained by the particle so far [39]. This is known as Personal Best or $P_{Best.}$ The other parameter which is of great significance in PSO is Global Best or $G_{Best.}$ This is basically the best value attained so far by any particle. A problem can have more than one local minimum and maxima, but it can only have one global minima and minima. This technique is Heuristic in nature because it can't reach the exact global maximum or minimum. It gets very close to a Global optimal solution. Flowchart of the PSO is given below in Fig. 4.5.

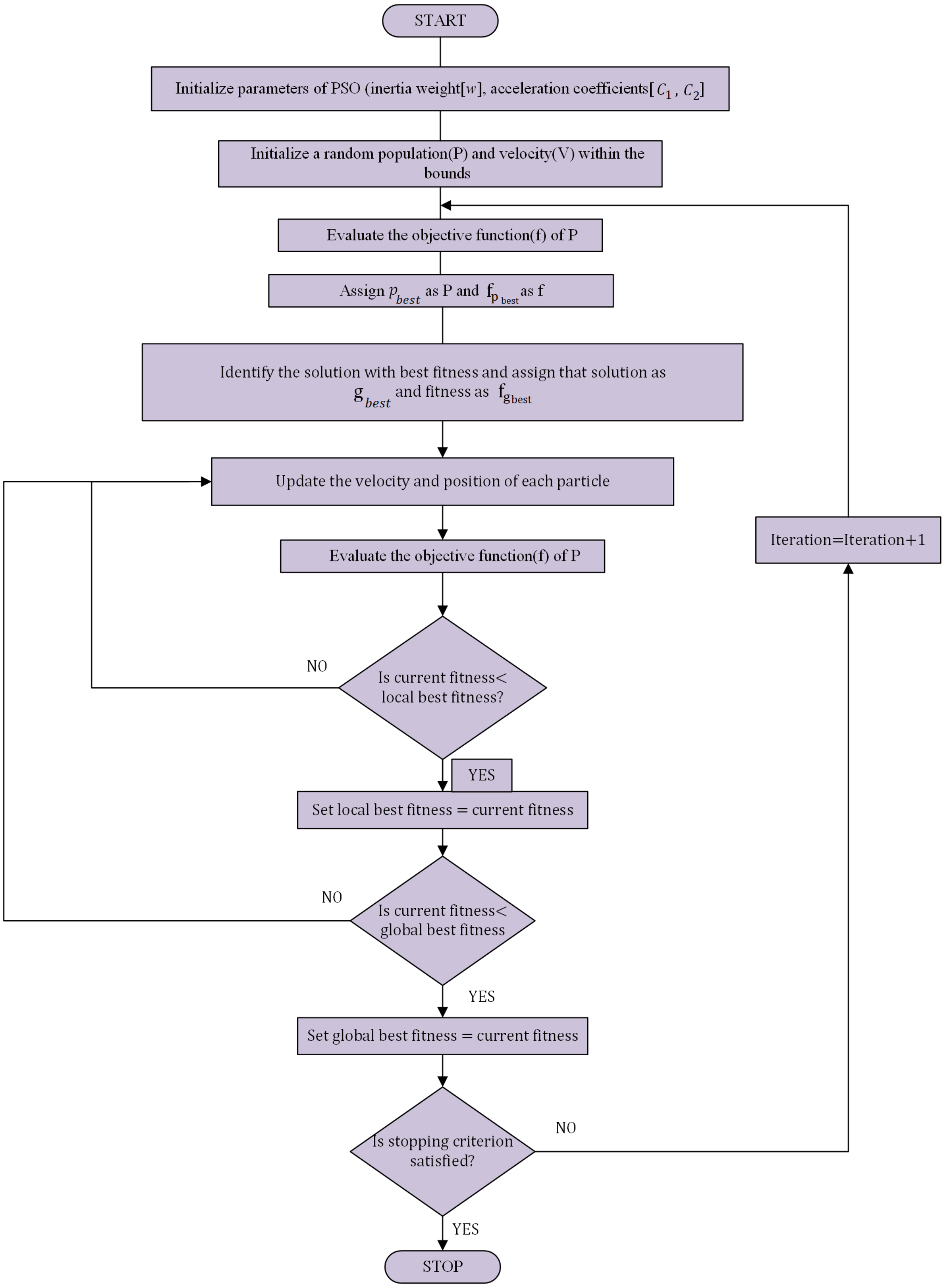

Fig. 4.5. Flowchart of PSO

Each particle/bird has two characteristics analogous to it-position and velocity. Particles modify their position by altering their velocity to:

- Avoid predators
- Seek food
- Identify optimized environmental parameters.

Each particles memorizes the best location identified by it. Particles communicate the information regarding the best location explored by them [33]. Velocity of the particles are modified by using: Flying experience of the particle and flying experience of the group [34]. Initial Position an velocity of the particles are generated randomly within search space. Particle velocity (v) is determined as

$$v_i = wv_i + c_1 r_1 (p_{best,i} - X_i) + c_2 r_2 (g_{best} - X_i) \qquad (4.6)$$

Position of a particle is modified as

$$X_i = X_i + v_i \qquad (4.7)$$

Evaluate the objective function f_i and update the population, irrespective of the fitness. Next step is to update the pbest and gbest if

$$\left.\begin{aligned} p_{best,i} &= X_i \\ f_{p_{best,i}} &= f_i \end{aligned}\right\} \text{If } f_i < f_{p_{best,i}} \qquad (4.8)$$

$$\left.\begin{aligned} g_{best} &= p_{best,i} \\ f_{g_{best}} &= f_{g_{best,i}} \end{aligned}\right\} \text{If } f_{p_{best,i}} < f_{g_{best}} \qquad (4.9)$$

4.4. Comparison between TLBO and PSO

Comparative analysis between TLBO and PSO on the basis of various criterion has been done in Table 4.1. It clearly shows TLBO is much superior to PSO.

Table 4.1 Difference between TLBO and PSO

Criterion	TLBO	PSO
Phases	Teacher, Learner	No phases (Position and Velocity update)
Convergence	Monotonic	Monotonic (with g_{best} and p_{best})
Parameters	Population size, termination criteria	Population size, termination criteria, inertia weight, acceleration coefficients
Generation of new solution	Only using other solutions, mean and best solution (part of population)	Using velocity vector, personal best and global best (need not to be the part of population)
Solution update in one iteration	Twice	Once
Selection	Greedy	New solution is always accepted (μ, λ)
Number of function evaluations	$N_P + 2N_P T$	$N_P + N_P T$

4.5. Conclusion

Algorithm specific parameters do have an impact on the performance of the algorithm. Number of tuning parameters in TLBO (2) is less compared to PSO (5). This is one of the advantages of TLBO, user doesn't need to spend time tuning the parameters, there are only two and termination criteria is fairly straight like it can be terminated based on the number of iterations or based on the amount of time that they have to solve that particular optimization problem. Though PSO is simpler than TLBO in its implementation but tuning of these actors can become very difficult for many problems.

CHAPTER-5

Tilt-Integral-Derative Controller

5.1. Introduction

Controllers are used to obtain the desired performance specifications. The controllers are used for comparing the measured values with the required values and if there is a deviation or error from the required value the necessary control action to correct it will be implemented by the controller. The obligatory set point can be attained when the controller transfers the output after the improvement to the final control element. In a given power system the controller plays a vital role in controlling various parameters associated to it. Thus, the controllers are further used to customize the parameters of the system in the process plant and also used to make the system stable. Basic block representing the functioning of a controller is shown in Fig. 5.1.

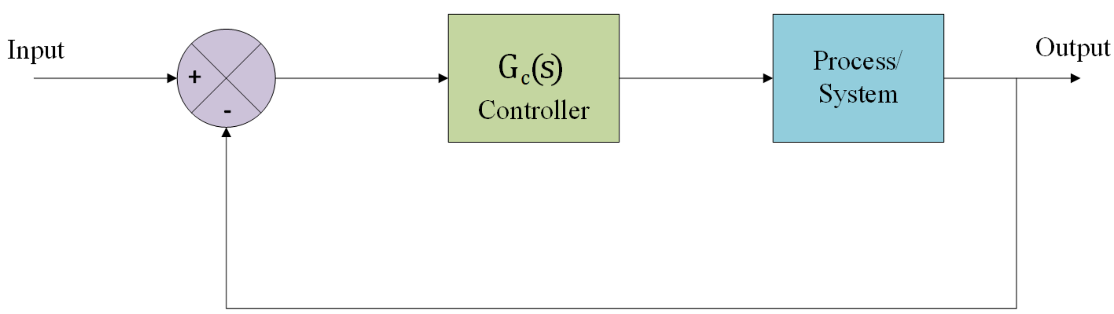

Fig. 5.1. Basic Controller diagram

After receiving the output from the feedback system, the controller compares the given value from the output to the required value and in case if the obtained value gets deviated from the required value, then the controller will do the specific actions to obtain the required value. There is a sensor that helps in sensing the output in the feedback system and converts it into proper feedback signal. The set point value is given by the reference input and the given error detector will compare the feedback value to the reference value.

There are two types of controllers: -

1. Continuous--- Proportional Control
   - Integral Control
   - Derivative Control.

2. Discontinuous-
   - On-Off Controller
   - Multi-Position Controller.

1. ***Proportional Controller***: It is used to vary the transient response of a system. Proportional controller is usually amplifier with gain K_P. Transfer function of proportional controller is given by

$$G_c(s) = K_P \quad (5.1)$$

2. ***Integral Controller***: It is used to decrease the steady state error by increasing the type of system. Stability decreases because of increase in type of system. Transfer function of integral controller is given by

$$G_c(s) = {}^{K_I}/_{s} \quad (5.2)$$

3. ***Derivative Controller***: It is used to increase the stability of the system. Stability of the system is increased by adding zeros. Steady state error

increases since the type of system decreases. Transfer function of proportional controller is given by

$$G_c(s) = K_D s \tag{5.3}$$

4. ***Proportional Integral Controller***: It is used to decrease the steady state error without affecting stability, because a pole at origin and zero are added. Bandwidth decreases and rise time, increases i.e., transient response becomes slower. It also improves damping and filters out high frequency noise. Transfer function of proportional integral controller is given by

$$G_c(s) = K_P + K_I/s \tag{5.4}$$

$$G_c(s) = K_P\left(1 + \frac{1}{T_I s}\right) \tag{5.5}$$

where $T_I = \frac{K_P}{K_I}$ is known as integral or reset time.

5. ***Proportional Derivative Controller:*** It is used to increase the stability without affecting steady state error, because a type is not changed and zero are added. Bandwidth increases and reduces rise time and settling time i.e., transient response is improved. It also improves damping but noise enters at high frequency. Transfer function of proportional integral controller is given by

$$G_c(s) = K_P + K_D s \tag{5.6}$$

$$G_c(s) = K_P(1 + T_D s) \tag{5.7}$$

where $T_D = \frac{K_D}{K_P}$.

6. ***PID Controller***: It is used to decrease the steady state error and to increase the stability, because pole at origin and two zeros are added. One zero compensate the pole and other zero will increase the stability.

$$G_c(s) = K_P + K_I/s + K_D s = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{5.8}$$

5.2. Tilt-Integral-Derivative Controller

TID Controller was proposed by Boris J. Lurie in 1973. The general design of a TID controller is analogous to PID controller but instead of proportional component, a tilted component is used. Transfer function of the titled part is represented by 's' raise to the power of (-1/n) whose value lies preferably between 2 and 3. 'n' is a non-zero real number. The term tilt means that it can provide a feedback gain which is tilted in regard to gain frequency of traditional controller. Its Transfer function equation is given by:

$$G_C(s) = K_T s^{(-\frac{1}{n})} + {K_I}/{s} + K_D s \quad (5.9)$$

Although PID controllers can be tuned easily, and their stability analysis is easy to carry but the performance achieved is not optimal. TID compensator is less prone to effect of variations in plant's parameters, allows for simpler tuning, better feedback control and better disturbance rejection ratio. Overall response achieved with TID controller is very close to optimal one [69]. In present study TID controller is used in each area and structure of TID is given below in Fig. 5.2.

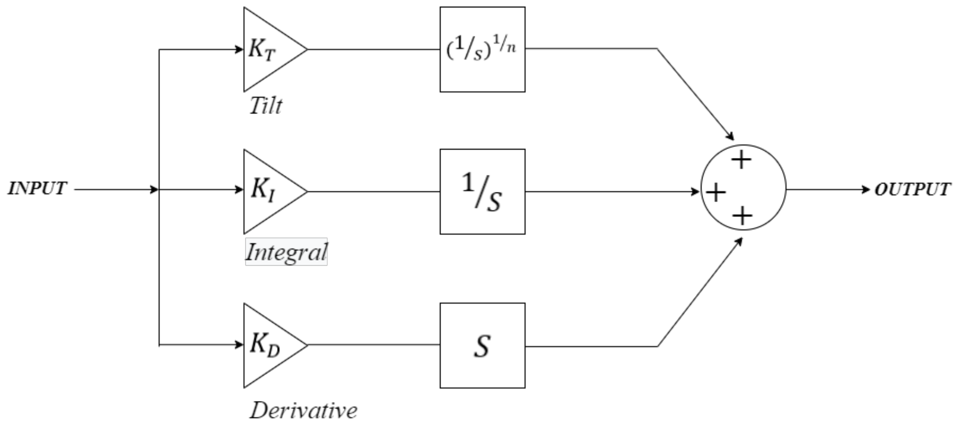

Fig. 5.2. Block diagram of Tilt-Integral-Derivative Controller

It is very analogous to a feedback control system compensator of the PID type but instead of using a proportional gain, it employs a titled midfrequency gain. The TID controller of the invention allows for a closer approximation of Bode optimal response than PID controllers, which results in about 4 dB better disturbance rejection at a frequency one-half the crossover frequency [69]. Tuning and designing TID controllers is as easy or easier and as fast or faster than designing and tuning PID controllers. TID controller is robust in nature and ratio of transient response to command input remains pretty good over wide range of variations in plant parameters.

5.3. Comparison with Traditional Controller

Performance criterion of TID controller is being compared with traditional PID controller. The comparison is shown in Table 5.1. which clearly shows the simpler tuning and much closer optimal response is achieved with TID controller.

Table 5.1. Comparison between Controllers

Tilt-Integral-Derivative Controller	**Proportional-Integral-Derivative Controller**
Better feedback control	Good feedback control
Better Disturbance Rejection ratio	Good Disturbance Rejection Ratio
Simpler Tuning	Good Tuning
Less prone to effect of variations in plant's parameters	More prone to effect of variations in plant's parameters
Response is very close to optimal one	Performance achieved is not optimal

CHAPTER-6

RESULTS AND CONCLUSION

6.1. Introduction

TLBO optimization technique is employed in this present research work for optimizing gain parameters of the proposed controller considering 0.1 per unit step load disturbance in Area-I of interconnected system using ITAE. Results of simulation are acquired by running simulations in MATLAB Simulink model as shown in Fig 6.1. Simulation data for TLBO and PSO has been provided below

Table 6.1 Simulation Data

Parameter Name	TLBO	PSO
No of Iterations(T)	100	100
Population Size(N_P)	50	50
Upper Bound(ub)	2	2
Lower Bound(lb)	-2	-2
Inertia Weight(w)	-	0.8
Acceleration Coefficients	-	C_1=C_2=1.5

Initially the analysis is performed using traditional PID controller which is optimized using TLBO. Then interconnected system is being simulated using PSO based TID controller for the comparison purposes. Then TLBO based TID controller is being used in this system. The different parameters of controllers are estimated by executing these three different cases and results obtained are given in Table 6.2 which shows the gain parameters of TLBO and PSO based TID controller, settling time and performance index ITAE. Data present in table evidently exhibits the superiority of TLBO based controller over the later ones. Minimum settling time is attained with TLBO based TID controller in comparison to PSO based TID controller and TLBO based PID controller.

Table 6.2 Controller Parameters

Parameters	TLBO Based TID	PSO Based TID
K_{T1}	0.1016	0.0214
K_{I1}	-0.6697	-0.7545
K_{D1}	0.0101	0.0106
n_1	2.2066	2.4000
K_{T2}	0.3519	0.1152
K_{I2}	-0.3009	-0.1906
K_{D2}	0.1506	0.0696
n_2	2.2409	2.4000

Table 6.3 Performance parameters in case of ΔF

Criterion	TLBO-TID	PSO-TID	**TLBO-**PID
Settling Time	16.9347	24.2	36.48
Peak Overshoot	0.004075	0.006631	0.006897
Peak Undershoot	0.008738	0.009493	0.01132

Table 6.4 Performance parameters in case of ΔP_{Tie}

Criterion	TLBO-TID	PSO-TID	**TLBO-**PID
Settling Time	17.85	39.4429	46.68
Peak Overshoot	0.04258	0.0445692	0.0367304
Peak Undershoot	0.11789	0.124867	0.153735

Table 6.4 Performance Index

Controller	ITAE
TLBO-TID	0.0013
PSO-TID	0.0315
TLBO-PID	0.1979

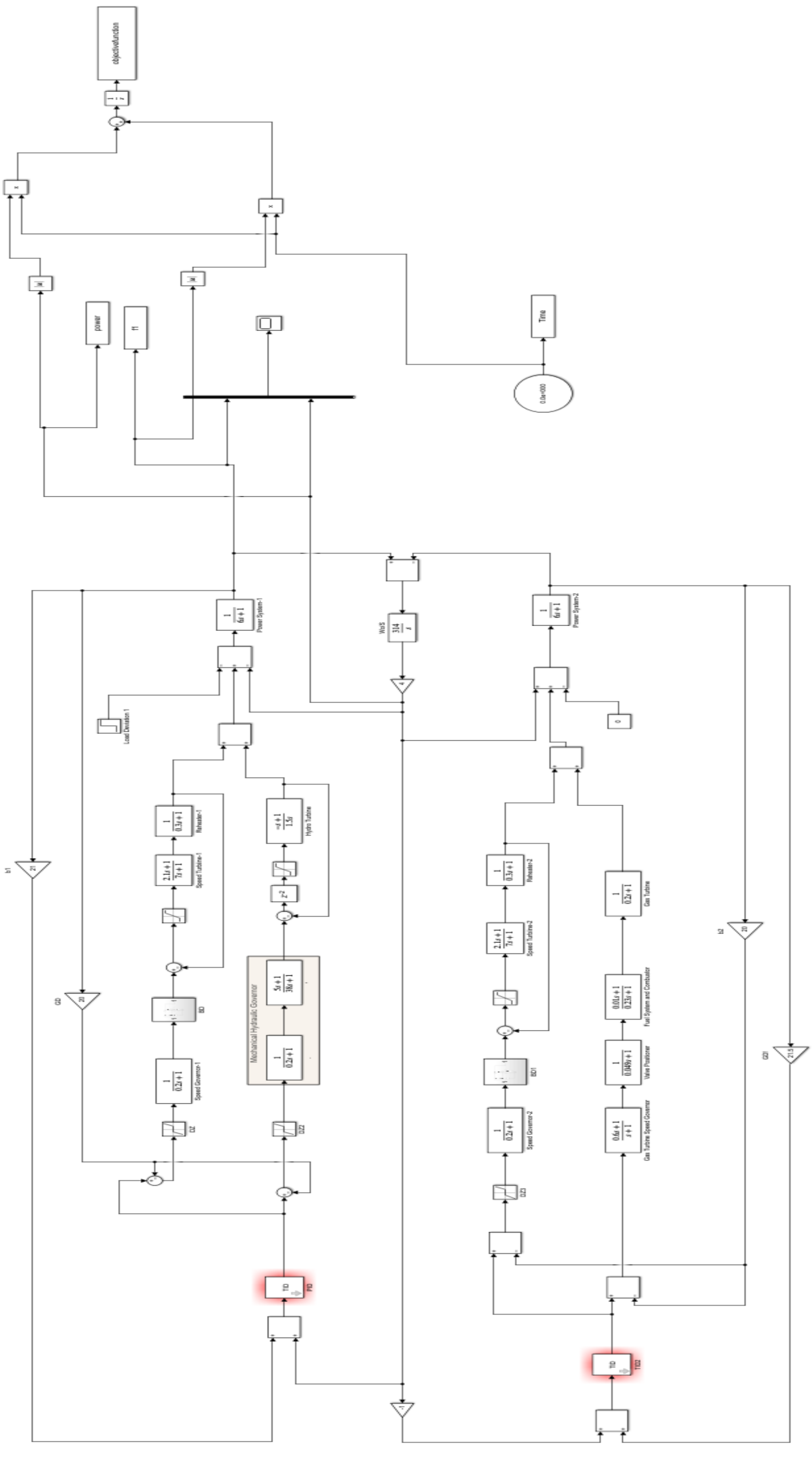

Fig. 6.1. SIMULINK Model

6.2. Frequency Deviation and Tie-Line Power Change Plots

Figures [6.2-6.7] shown below exhibits the superior performance of TLBO based controller over controllers. Plots are obtained after running the simulation for 50 seconds are given below: -

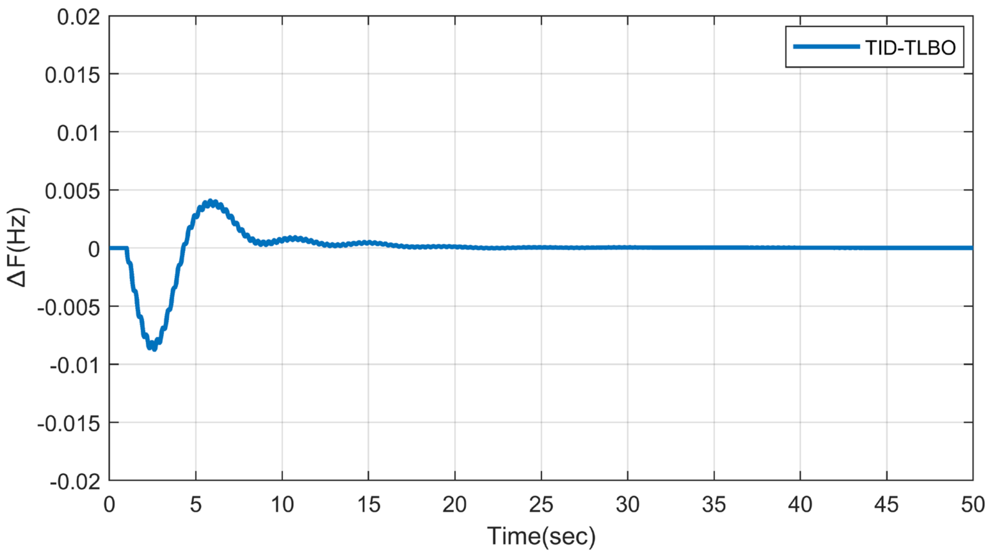

Fig. 6.2. Frequency deviation in case of TLBO based TID controller

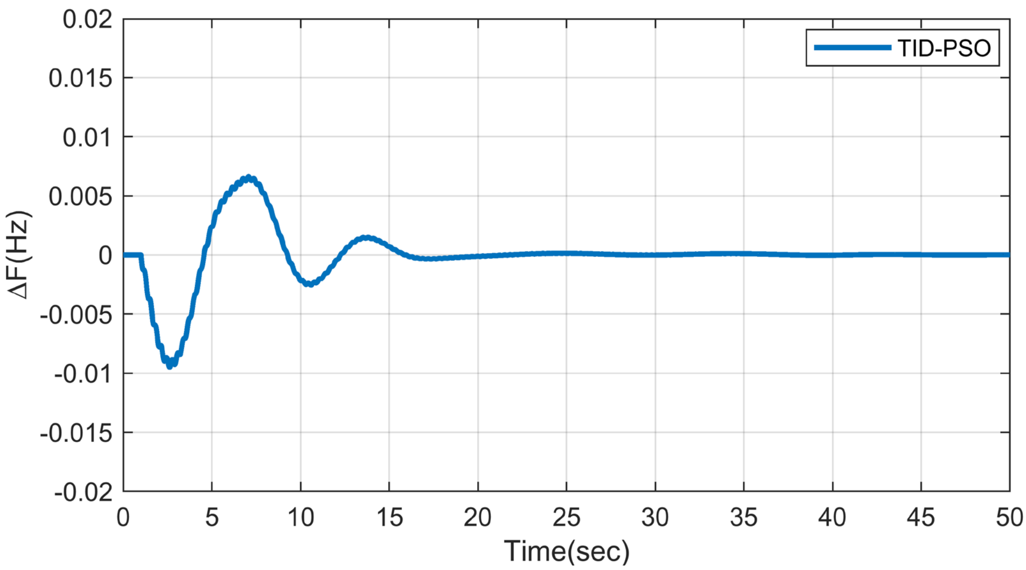

Fig. 6.3. Frequency deviation in case of PSO based TID controller

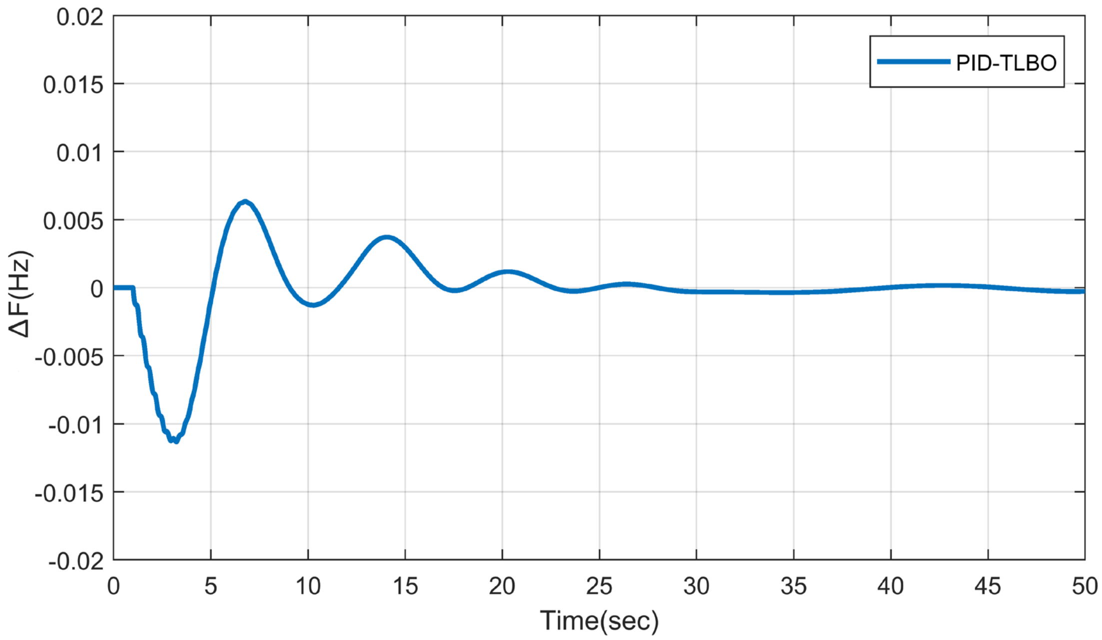

Fig. 6.4. Frequency deviation in case of TLBO based PID controller

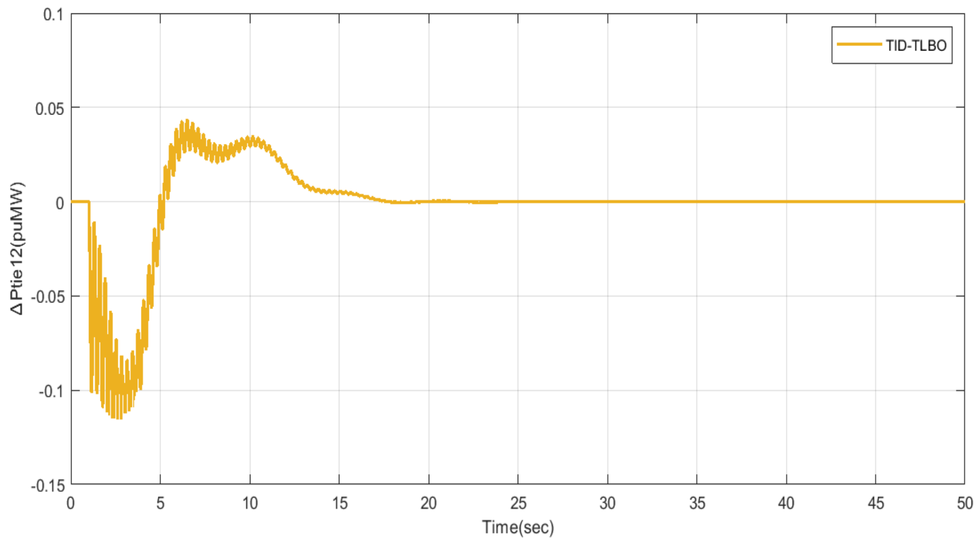

Fig. 6.5. Deviation in Tie-line power using TLBO tuned TID controller

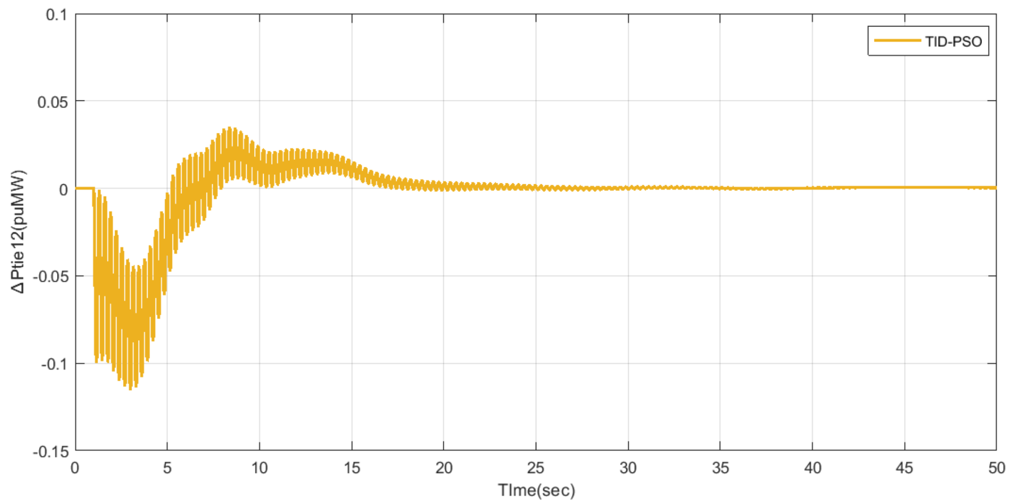

Fig. 6.6. Deviation in Tie-line power using PSO tuned TID controller

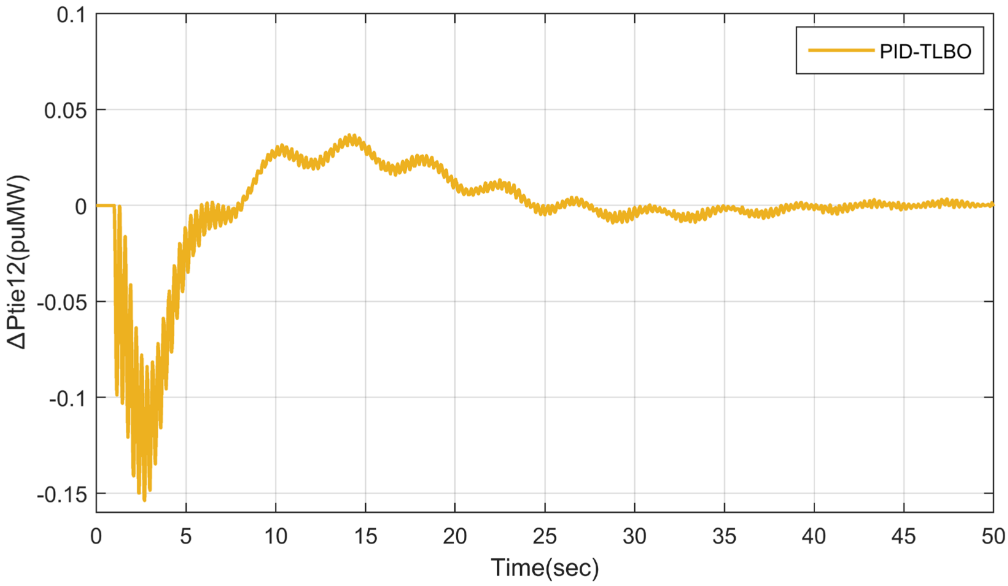

Fig. 6.7. Deviation in Tie-line power using TLBO based PID controller

It can be inferred from Figures. (6.2-6.7) that TLBO optimized TID controller provides better dynamic performance for both frequency and tie-line power deviation when it comes to settling times, peak undershoot, peak overshoot, ITAE objective function value.

6.3. Conclusion

In this work, SLP of 0.1 per unit is applied to multi-area multi-source interconnected power system considering appropriate GRC/DZ/BD system. Controller designed and optimized employing TLBO technique for linear system is implemented on the same system with GRC/DZ/BD/TD physical constraints. Tuning of the different gain criterion of TID controller for the Multi-Area System using TLBO algorithm has been done to obtain optimal values and performance index has been measured with respect to PSO based TID controller and TLBO based PID controller. Plots of fluctuations in frequency and Tie line Power have been observed for all three cases (TLBO tuned TID, PSO tuned TID and TLBO tuned PID) that are used in this work, and it is noticed that TLBO based TID controller produces the most desirable performance resulting in less settling time and peak overshoot in comparison to its counterparts.

6.4 Future Scope

- The current study is limited only for two-area interconnected power system but this work can further be extended for three/four-area power systems.
- In the present study, it is assumed that control areas of power system have multi-sources of power generations like thermal, hydro or gas in each area. However, further studies may be done by considering diverse sources like gas, wind, diesel, nuclear etc. in each control area of multi-area power system.
- Fractional order controller, Fuzzy controllers or cascaded controllers can be used.

- More recent optimization techniques like Bald Eagle search (2019), Bus Transportation Behavior (2019), Earth Worm Optimization (2018) and JAYA (2017) can be used.
- The current study is performed on assuming that AGC loop does not interact with the AVR loop due to inertial differences between them. In future, AGC studies can be realized in the presence of AVR loop in each area.
- The design of AGC controllers is carried out in continuous mode but further studies may be carried out to design AGC controllers in discrete mode.

APPPENDICES

APPENDIX 1

Parameters used for the Simulink model are:

Pr1 = Pr2 = 2000 MW, f=50 Hz, Base power = 2000 MVA, P_{tiemax} = 200 MW, Hi = 5 MW s/MVA, Di = 8.33 × 10^{-3} puMW/Hz, α12= -1, T_{gi} = 0.2 s, K_{ri} = 0.3, K_{Pi} = 120 Hz/puMW, T_{ti}= 0.3 s T_{ri} = 7 s, T_{Pi} =20 s, R_i= 2.4 Hz/puMW (for i=1,2,3,4), T_{12} = 0.086 puMW/rad, B_i = β_i = 0.425 puMW/Hz, T_R = 5 s, T_W = 1 s, T_{GH} = 0.2 s, T_{RH} =38 s, X = 0.6 s, Y = 1 s, $2\pi T_{12}$ = 0.545 puMW/Hz, a = 1, b = 0.05 s, c = 1, T_{CD} = 0.2 s, T_{CR}= 0.01 s, T_F = 0.23 s.

APPENDIX 2

Parameters used for Boiler Dynamics are:-

C_B= 200, T_D= 0, T_F= 25, T_{IB}= 90, K_{IB}= 0.02, T_{RB}= 69, K_1= 0.85, K_2= 0.095, K_3= 0.92 [66].

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LIST OF PUBLICATIONS

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